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OPTIMIZING RUBBERIZED OPEN-GRADED FRICTION COURSE (RHMA-O) MIX DESIGNS FOR WATER QUALITY BENEFITS PHASE I: LITERATURE REVIEW

Author:
Masoud Kayhanian and John T. Harvey

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PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

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16. ABSTRACT

Historically, rubberized and non-rubberized open-graded friction courses (OGFCs) have been placed to provide three benefits: to increase traffic safety, to reduce urban highway noise, and to preserve the surface of the main pavement structural section. However, stringent environmental regulations on stormwater runoff management enacted recently have forced transportation agencies with limited right of ways in urban areas to search for creative methods to treat runoff and receive credits for preventing pollution from highways. This literature review was undertaken to explore ways to optimize current RHMA-O mix designs to provide multifunctional benefits, including water quality treatment. The literature review showed that permeability measurement is an essential parameter that influences a wide range of OG (both rubberized and non-rubberized) pavements' performance. Further, current Caltrans aggregate gradations contain a larger fraction of fine aggregate sizes and this may also influence the permeability and functional performance of RHMA-O pavements. Part of this literature review includes an action plan recommending that the next phase of this work include optimizing current Caltrans mix designs and the mix design procedure in the laboratory and undertaking subsequent field investigations.

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7. PROPOSALS FOR IMPLEMENTATION

The following action plan is proposed for the next phase of the project:

1. Make the necessary changes in the new Caltrans mix design method and specifications based on a laboratory study and the existing work described in this literature survey.
2. Construct side-by-side test sections using the Texas design, the current California mix designs, and the new recommended UCPRC mix designs to conduct a three-way comparison.
3. Measure the permeability and other functional performance of the test sections, and monitor water quality samples from them for five years.
4. Perform life cycle cost analysis under multiple functional objectives and recommend the application of OGFC and RHMA-O pavements accordingly.
5. Summarize the results and prepare a final report with appropriate recommendations.

8. RELATED DOCUMENTS

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9. LABORATORY ACCREDITATION

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M. Kayhanian **FIRST AUTHOR**	J.T. Harvey **TECHNICAL REVIEW**	D. Spinner **EDITOR**	J.T. Harvey **PRINCIPAL INVESTIGATOR**	S. Bisrat **CALTRANS TECH. LEAD**	T.J. Holland **CALTRANS CONTRACT MANAGER**

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PROJECT OBJECTIVES

This project, which included a literature review, focused on the following tasks:

1. Conduct a literature review of rubberized and non-rubberized OGFC overlay mix designs being used both in the United States and worldwide
2. Identify from the literature review which of these mix designs provide water quality benefits
3. Identify from the literature review which jurisdictions accept rubberized or non-rubberized OGFC overlays as a water quality improvement option
4. Identify from the literature review what laboratory and field test methods have been used to validate water quality improvement from rubberized and non-rubberized OGFC overlays
5. Identify from the literature review any OGFC-specific maintenance procedures that exist as well as the safety-related aspects of rubberized and non-rubberized OGFCs

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EXECUTIVE SUMMARY

Historically, rubberized and non-rubberized open-graded friction courses (OGFCs) have been placed to increase traffic safety, to reduce urban highway noise, and to preserve the surface of main pavement structural section. These three well-documented benefits are the primary reasons for OGFC installation in the United States (US) and abroad. However, stringent environmental regulations on stormwater runoff management enacted recently have forced transportation agencies with limited right of way to search for creative methods to treat runoff and receive credits for preventing pollution from their paved highway surfaces. It is possible to take advantage of both OGFC types' water quality benefits, but this aspect of their performance is not fully understood and has not been fully investigated. Between 2007 and 2011, Caltrans conducted a study monitoring water quality from both types of pavements and determined that rubberized OGFC was ineffective at providing any water quality benefit. This lack of water quality benefit was directly related to this surface overlay type's low permeability. Further, that low permeability (or drainability) may indicate that the pavement has also lost its other performance benefits (noise reduction and improved safety) and essentially functions as a dense-graded pavement. To explore this finding, Caltrans became interested in performing a literature review to collect additional water quality monitoring data and to find out, if possible, which mix design provides greater treatment or pollution removal. The following conclusions have been drawn from the results and information collected in this literature review:

- Nearly half of US states have used OGFC overlays, and they were constructed predominantly for safety and noise reduction.
- Results from several US surveys showed that some earlier OGFC mix designs failed mainly because of draindown and raveling problems. Draindown problems caused the pavement to behave more like gap- or dense-graded pavement. Raveling problems (which occur in the wheelpaths of OGFC and RHMA-O pavements, including mainline and turning and stop-and-go areas) especially reduced the pavements' longevity, requiring them to be replaced before the end of their expected design service life, a process that was found to be costly.
- Because of draindown problems and the issue of durability (for example, increased raveling) several newer mix designs and mix design procedures were suggested by the Federal Highway Administration (FHWA) and the National Center for Asphalt Technology (NCAT). Under these newer mix design procedures, adding fibers into the mix helped solve the draindown problems and introducing modified binders into the mix design increased durability.
- Addition of both natural and cellulose fibers were found to be useful, but cellulose fiber was found to be less costly. Multiple polymeric modified binders have been studied, and the most useful one with a high success rate was a styrene-butadiene-styrene (SBS) polymer-modified binder. These two mix design improvements increased the service life of the OGFC pavements.

- The implementation of local and state regulations related to recycling of materials and their diversion from landfills, coupled with sustainable transportation initiatives undertaken by the US federal government have provided the opportunity to use scrap tires as a potential modified-binder source.
- Rubber-modified binders are produced by either dry or wet processes, each with a different performance outcome. In California, only the wet process is used.
- At present, crumb rubber-modified binder is used for multiple asphalt pavement applications in the US and abroad; however only four US states (Arizona, California, Florida, and Texas) currently use them in OGFC construction.
- Performance test results showed that the durability of OGFC overlays modified with crumb rubber was comparable to the performance of OGFC modified with SBS polymer binder. In some cases, the performance of OGFC overlays with rubberized binder was superior to those with polymer-modified binders.
- While the application of rubber-modified binder was found to be useful and its benefits (safety, noise reduction, and durability) were similar to those from polymer-modified binder, when contractors were given a choice, they nearly always chose to use polymer-modified binder. This may change with the increased price of polymer-modified binder and/or with regulations mandating the use of scrap tire binder as a part of future asphalt binders.
- At present, there is no standard mix design that can be practiced on a national and international basis. And although the FHWA and NCAT suggest several OGFC mix designs, many states use their own variations to design OGFC and RHMA-O pavements. Because of subtle differences in the mix designs used by different states and international transportation organizations, published performance results are also varied.
- Most rubberized OGFC pavements installed in the US were primarily constructed to increase safety and to reduce noise; hence their ability to provide water quality benefits and prevent pollution has not been recognized or fully investigated.
- Although the Arizona and Florida departments of transportation (DOTs) have used rubberized OGFC for the past 30 years and have evaluated their durability and functional performance extensively, those agencies have not performed water quality evaluations. The California DOT (Caltrans) has also installed numerous RHMA-O overlays throughout the state and measured their performance for noise reduction, permeability, and durability, but the department did not attempt to monitor their water quality until relatively recently—from 2007 to 2011—at three sites with rubberized OGFC. This water quality monitoring was terminated during the second year, however, due to the pavements' low permeability and lack of expected water quality benefits.

- TxDOT has performed more water quality evaluations from their OGFC and RHMA-O overlays than any other state DOT and has obtained favorable results. Because sufficient water treatment or pollution removal was achieved at the OGFC and RHMA-O monitoring sites, unlike the results obtained at sites with conventional dense-graded pavements, the Texas Department of Environmental Quality has recognized the use of non-rubberized or rubberized OGFC as a best management practice (BMP) for highway stormwater runoff management.
- The decision to use OGFC or RHMA-O as a BMP is a local one that is based on a recommendation developed using limited local water quality data that may not be applicable to other traffic and environmental conditions. Without additional water-quality monitoring data within the United States and elsewhere in the world, it is difficult to perform a proper correlation analysis relating water-quality characteristics with different mix designs. Hence, generalized conclusions based on the Texas mix designs cannot be made unless its water quality benefits are verified in California and elsewhere.
- The current limited amount of runoff-water-quality data collected in the US and Europe shows that rubberized and non-rubberized OGFCs are only capable of effectively removing particle-bound pollutants and that the runoff quality is generally cleaner than runoff from dense-graded pavements. The removal of dissolved pollutants by non-rubberized or rubberized OGFC is either negative or minimal.
- OGFC or RHMA-O pavements' ability to remove dissolved pollutants can be enhanced by adding adsorption agents to the mix design. For example, experimental results showed that adding bentonite and zeolite as adsorbent agents into an OGFC mixture was effective in removing dissolved copper (Cu) and zinc (Zn). The results showed that the removal efficiencies of dissolved copper (Cu) and zinc (Zn) with bentonite were about 76 and 74 percent, respectively. However, the impact that adding adsorption agents has on pavement durability is unknown. Further research is needed to verify the above findings with new, improved OGFC and RHMA-O mix designs under laboratory and field conditions.
- The actual treatment or pollution removal mechanism of OGFC and RHMA-O surface overlays is not fully known and has not been fully investigated. However, it has been hypothesized that treatment/pollution removal may occur by three methods: (1) adsorption, (2) filtration, and (3) splash reduction.
- The chemical characteristics of runoff discharged from both non-rubberized and rubberized OGFC is similar, except for higher concentrations of total and dissolved zinc believed to be associated with the crumb rubber used in rubberized pavement. This extra zinc is believed to be dislodged by the action of rubber tires from traffic since it was not observed in an earlier UC Davis controlled laboratory study which tested leachate from rubberized OGFC that was not subjected to traffic loading.
- Evaluation of existing performance data from OGFC and RHMA-O surface overlays showed that their environmental benefits are heavily influenced by pavement permeability, which is suggested for inclusion in the NCAT mix design procedure but is not specified in the current Caltrans mix design procedure.

Hence, the current Caltrans mix design will not effectively address the multifunctional objectives of OGFC and RHMA-O overlays; therefore, preparation of a new mix design procedure that includes permeability specifications is recommended. The new mix design procedure may follow the recent UCPRC approaches and other specifications listed in Chapter 7, Table 7.2.

- Even with optimization and preparation of the best mix design, factors such as traffic speed, loading, and anthropogenic activities may still affect OGFC and RHMA-O pavement performance. Therefore, to prolong performance of the pavement over its design service life, non-rubberized and rubberized OGFC construction should be reserved for locations that limit the influence of anthropogenic activities.
- Examination of national and international field survey studies has revealed that clogging is a major issue in all open-graded surface overlays regardless of their binder type (rubberized or non-rubberized binder). The field survey studies showed that none of the transportation agencies have a surface-cleaning maintenance program, which may reduce the OGFC's functional life and, as a consequence, its environmental benefits, including its runoff water quality treatment. A cleaning method that combines pressure washing and vacuuming, used by several European transportation agencies and in Japan, was shown to be the most effective one for improving the environmental benefits of the OGFCs.
- Non-rubberized and rubberized OGFC were found to have different thermal properties compared to dense-graded mixes and were found to freeze sooner and for longer than conventional dense-graded asphalt pavements. For this reason, non-rubberized and rubberized OGFC usually require more salt or chemicals during winter maintenance than dense-graded mixes. The use of studded tires during winter months was also shown to increase raveling and to reduce the service lives of open-graded pavements by two to five years, resulting in very short lives compared to dense-graded mixes. For all the above reasons, the application of non-rubberized or rubberized OGFC is not recommended for high-elevation sites with extensive snowfall and winter maintenance activities.
- To move forward with the next phase of the project, the following action plan is recommended:
    1. Conduct a laboratory evaluation of Texas-type mix designs using TxDOT design criteria; design similar mixes using California materials (including several aggregate sources and conventional and rubberized binders); compare these mixes' durability, permeability, and air-void contents; and check to see if air voids is a sufficiently accurate surrogate predictor of permeability.
    2. Make the necessary changes in the new Caltrans mix design method and specifications based on the laboratory study.
    3. Construct side-by-side test sections using the Texas mix design, the California mix designs, and the new recommended UCPRC mix designs to conduct a three-way comparison test of each set of specifications and each mix design method (from the previous UCPRC study and new recommendations specified in Chapter 7, Table 7.2) under California conditions.

4. Measure the permeability and other multifunctional performance of the test sections and monitor water quality samples from them for five years. Perform periodic surface cleaning and collect all the other data necessary to conduct a life cycle cost analysis.
5. Perform life cycle cost analyses of OGFC and RHMA-O under multifunctional performance conditions, and recommend application of the mixes accordingly. These analyses will also include the cost of pavement replacement versus regular maintenance.
6. A design guide will be developed to determine the Environmental and Traffic loading ranges for when OGFC and RHMA should be installed.
7. Summarize the results and prepare a final report with appropriate recommendations.

LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of Highway and Transportation Officials
ADOT	Arizona Department of Transportation
AR	Asphalt rubber
ARACFC	Open-graded asphalt rubber asphalt concrete friction course
ARHMA-O	Asphalt rubber open-graded friction course
ASTM	American Society for Testing and Materials
BMP	Best management practice
C-OGFC	Conventional open-graded friction course
CAL/OSHA	California Division of Occupational Safety and Health
Caltrans	California Department of Transportation
CM	Clogging material
CMF	Crash modification factor
COD	Chemical oxygen demand
CR	Crumb rubber
CRHMA-O	Crumb rubber open-graded friction course
CRM	Crumb rubber modifier
CRMB-OGFC	Crumb rubber–modified binder open-graded friction course
Cu	Copper
D	Dissolved
dB	Decibel (noise of sound measurement unit)
DFC	Durable friction course
DGAC	Dense-graded asphalt concrete
DGHMA	Dense-graded hot mix asphalt
DOT	Department of transportation
DRISI	Division of Research, Innovation and System Information
EMC	Event mean concentration
ESAL	Equivalent single axle load
FC-5	Friction course mixture used by FDOT
FDFC	Free-draining friction course
FDOT	Florida Department of Transportation
FDPP	Full-depth permeable pavement
FE	Finite element
FHWA	Federal Highway Administration
FOGFC	Functional open-graded friction course
GAC	Granular activated carbon
GCR	Ground crumb rubber
GDOT	Georgia Department of Transportation
GTR	Ground tire rubber
HMA	Hot mix asphalt
HN	High natural rubber (used by Caltrans)
HP	Highly polymer modified
HVS	Heavy Vehicle Simulator
ISTEA	Intermodal Surface Transportation Efficiency Act
ITS	Indirect tensile strength
ITSM	Indirect tensile strength modules
LCCA	Life cycle cost analysis
LID	Low impact development

LVE	Linear viscoelasticity
MIBK	Methyl isobutyl ketone
MOGFC	Multifunctional open-graded friction course
NAPA	National Asphalt Pavement Association
NC	North Carolina
NCAT	National Center for Asphalt Technology
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NCSU	North Carolina State University
NG-OGFC	New generation of open-graded friction course
NIOSH	National Institute of Occupational Safety and Health
NMDOT	New Mexico Department of Transportation
NO_2	Nitrate
NO_3	Nitrite
NPDES	National Pollution Discharge Elimination System
O&G	Oil and grease
OBC	Optimum binder content
ODOT	Oregon Department of Transportation
OGAC	Open-graded asphalt concrete
OGFC	Open-graded friction course
OGFC-AR	Open-graded friction course modified with asphalt rubber
OGFC-SBS	Open-graded friction course modified with styrene-butadiene-styrene
PA	Porous asphalt
PACES	Pavement Condition Evaluation System
PAH	Polynuclear aromatic hydrocarbon
Pb	Lead
PCC	Portland cement concrete
PCM	Phase change material
PD	Percent difference
PEG	Polyethylene glycol
PEL	Permissible exposure limits
PEM	Porous European mix
pen	Penetrating grade (European pavement grading system)
PFC	Porous friction course
PG	Performance grade (US pavement grading system)
PI	Preliminary investigation
PM	Polymer modified
PMA	Polymer-modified asphalt
PMB-OGFC	Polymer-modified binder open-graded friction course
PMS	Plant mix seal
PP	Permeable pavement
RAC	Rubberized asphalt cement
RAC-G	Rubberized asphalt concrete gap graded
RAC-O	Rubberized asphalt concrete open-graded
RAP	Reclaimed asphalt pavement
RAP	Rubberized asphalt pavement
RHMA-O	Rubberized hot mixed asphalt open-graded
RHVB	Rubberized high-viscosity binder
ROGFC	Rubberized open-graded friction course
ROW	Right-of-way
RPA	Rubber Pavement Association

RPA	Rubberized asphalt pavement
RPFC	Rubberized porous friction course
RTR	Recycle tire rubber
SAM	Stress absorbing membrane
SAMI	Stress absorbing membrane interlayer
SBS	Styrene-butadiene-styrene
SFE	Surface free energy
SGC	Superpave gyratory compactor
SMA	Stone matrix asphalt
ST	Scrap tire (rubber)
SVOC	Semi-volatile organic compound
T	Total
TCEQ	Texas Commission on Environmental Quality
TDA	Tire-derived aggregate
TDS	Total dissolved solids
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TOC	Total organic carbon
TOR	Trans-polyoctenamer rubber
TP	Total phosphorus
TSR	Tensile strength ratio
TSS	Total suspended solids
TxDOT	Texas Department of Transportation
US	United States
USA	United States of America
UV	Ultraviolet
WMA	Warm mix asphalt
WSDOT	Washington State Department of Transportation
Zn	Zinc

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003).

1 INTRODUCTION

1.1 Background Information

From 2007 to 2011, Caltrans conducted a field monitoring study that showed that traditional non-rubberized open-graded friction courses (OGFCs) have a capacity to remove total suspended solids (TSS), total phosphorus (TP), and most total heavy metal concentrations that is comparable to that of the Austin sand filter, the most efficient *best management practice* (BMP) in the Caltrans toolbox. Based on that finding, Caltrans initiated the process of claiming runoff water quality treatment credits from its traditional OGFC pavements, as these provide a way to treat stormwater runoff from both new construction and retrofit projects without requiring the purchase of additional right-of-ways (ROWs) or special maintenance practices or equipment.

That 2007 to 2011 field monitoring study also investigated the quality of runoff water discharged from OGFC pavements modified with rubberized asphalt, which is known as *Rubberized Hot Mix Asphalt Type O* and is referred to in this report as *RHMA-O*. The preliminary results obtained from this portion of the study showed RHMA-O only provided marginal water quality benefits compared to traditional OGFC, principally because the RHMA-O sites were found to have insufficient permeability. For this reason, a study to find ways to reevaluate and/or modify existing Caltrans RHMA-O mix was deemed necessary.

Caltrans would like to include rubberized OGFC application as part of its BMP tool box for several important reasons: (1) to allow Caltrans to improve their discharged runoff water quality and possibly to comply with its National Pollutant Discharge Elimination System (NPDES) Storm Water Permit requirements; (2) to convince the California State Water Resources Control Board (the Regulator) of RHMA-O's efficacy in removing selected pollutants; and (3) to meet its obligation to use a fraction of recycled rubber in new and rehabilitated pavements as mandated by the state of California.

Hence, the use of conventional OGFC and RHMA-O as a treatment BMP fits well within Caltrans's overall stormwater management practice objectives while also meeting the state's regulatory mandate for scrap tire recycling and transportation program sustainability. At present, Caltrans lacks sufficient treatment data to convince the Regulator to award the stormwater quality treatment credits, but the department also does not want to construct more RHMA-O pavements for field trials or conduct additional field monitoring until it has gathered more data about ways to ensure long-term water quality benefits from the literature. This literature review addresses that need by enabling Caltrans to identify optimal mix designs and mix design procedures that consider multifunctionality but do not compromise durability while the department also addresses other environmental issues before it conducts further field investigations and data gathering.

Caltrans's ultimate goal in this regard is to develop appropriate design alternatives for RHMA Type O to meet its water quality requirements while also meeting its sustainability and strategic transportation stewardship goals. To accomplish this, Caltrans has proposed a four-phase project, as stated in the preliminary investigation request form. The focus of Phase I is to perform a literature review of research on the RHMA Type O and OGFC overlay mix designs being used both in the US and worldwide, with an emphasis on the pavements' water quality benefits. Phase II will focus on identifying mix designs suitable for a laboratory study or a simulated field study to evaluate the pavements' safety, durability, and water quality improvement as well as to develop design alternatives, design calculations, and drawings. Phase III will focus on building the selected mix designs identified in Phase II on three California sites and monitoring their water quality benefits and maintenance issues. Phase IV's focus will be on developing plans, specifications, and mix design guidance.

1.2 Focus of the Literature Review and Related Tasks

The main focus of this phase of the project is to perform a literature review and, based on that literature review, to address the following tasks identified in the preliminary investigation (PI) form prepared by Caltrans Division of Research, Innovation and System Information (DRISI):

1. Conduct a literature review of rubberized and non-rubberized OGFC overlay mix designs being used both in the United States and worldwide
2. Identify from the literature review which of these mix designs provide water quality benefits
3. Identify from the literature review which jurisdictions accept rubberized or non-rubberized OGFC overlays as a water quality improvement option
4. Identify from the literature review what laboratory and field test methods have been used to validate water quality improvement from rubberized and non-rubberized OGFC overlays
5. Identify from the literature review any OGFC-specific maintenance procedures that exist as well as the safety-related aspects of rubberized and non-rubberized OGFCs

To properly address the above tasks, the relevant information was gathered and summarized, and is presented in separate chapters according to four major areas: the applications of OGFC and RHMA-O pavement overlays, mix design variabilities, water quality evaluations, and the maintenance challenges associated with these overlays in the United States and abroad. The collected information has been synthesized and a summary response to each of the above tasks appears in a separate chapter. Finally, a set of recommendations and an action plan are provided for future consideration.

1.3 Report Organization

To accomplish the overall objectives of the study, this following chapters of this literature review cover these areas:

- Chapter 2 discusses applications of OGFC and RHMA-O overlays in the US and abroad.
- Chapter 3 covers the variability in OGFC and RHMA-O mix design used by different US states and by departments of transportation (DOTs) outside the US.
- Chapter 4 examines findings about the potential water quality benefits associated with OGFC and RHMA-O overlays.
- Chapter 5 discusses the maintenance challenges associated with OGFC and RHMA-O overlays.
- Chapter 6 contains a summary review synthesis.
- Chapter 7 provides recommendations and an action plan to move forward with the next phase of the project.

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2 APPLICATION OF NON-RUBBERIZED AND RUBBERIZED OPEN-GRADED FRICTION COURSE PAVEMENTS IN THE UNITED STATES AND ABROAD

This chapter mainly focuses on a brief history and overview of the application of both rubberized and non-rubberized open-graded friction courses in the United States and worldwide. Information related to the variability in mix designs used in the US and international departments of transportation (DOTs) are presented in Chapter 3. The major topics covered here include (1) definitions of commonly used terminologies for rubberized and non-rubberized open-graded friction (OGFC) overlays, (2) descriptions of typical rubberized and non-rubberized OGFC overlay pavements, (3) an overview of OGFC application in the US and abroad, and (4) an overview of RHMA-O pavement application in the US and abroad.

2.1 Definitions of Commonly Used Terminologies Used for Rubberized and Non-Rubberized OGFC Pavements

Numerous terminologies are used in the literature in the context of permeable pavements and open-graded friction courses. Sometimes, more than one definition is used to define the same terminology. This inconsistency makes it more difficult when reviewing and comparing the data published from the United States and elsewhere in the world. To remove some of this confusion and to make this literature review more meaningful, this section is devoted to properly defining some of the common terminologies used in the literature and to clarifying their distinctive use within the transportation industry.

The first problem, from the standpoint of the literature review, is related to the phrase *permeable pavement* since it is used loosely to discuss all types of permeable pavements, including open-graded friction courses, even though those pavements' designs and functions are completely different. More important, as summarized in Table 2.1, in both the United States and abroad, multiple terminologies are used for the same type of pavement. For example, the term *porous asphalt* is generally used for full-depth permeable pavement (FDPP) in the US but in Europe and Asia the term is used for open-graded asphalt friction courses. It is important to realize that these two pavement types are distinctively different in terms of design, construction, function, and practical operation. For instance, FDPPs can capture the entire volume of a storm event and retain nearly all the pollutants associated with that roadway's runoff (dissolved or particulate), reducing their discharge into the environment to nearly zero. For this reason, many municipalities—including transportation agencies—consider FDPP application (regardless of the permeable surface pavement type) to be an effective best management practice (BMP) or low-impact development (LID) practice and allow its use. An OGFC layer, on the other hand, does not capture any runoff or treat it completely (for details see Chapter 4), so its application as BMP or LID is not always assumed.

Table 2.1: Description of OGFCs and Numerous Terminologies Used in the Literature by Transportation Agencies, Researchers, and Pavement Industries

Pavement	Definition	Purpose	Terminology Used in the Literature
Open-graded friction course (OGFC)	An OGFC is defined as a single thin layer of permeable asphalt pavement over an existing dense-graded hot mix asphalt (HMA) pavement. The OGFC consists of a uniform aggregate size (usually 9.5, 12.5, or 25 mm) with a minimum of fine and high asphalt binder content (6 to 7 percent) with high void content, ranging from 15 to 20 percent.	OGFCs are generally constructed as nonstructural pavement to reduce noise, increase skid resistance, and reduce splash during rain events to increase driving safety. Due its filtering capability, it is also desired to get credit for selected runoff pollutants.	• NG-OGFC = New generation of open-graded friction course (US after design mix modification) • C-OGFC = conventional open-graded friction course (US to differentiate the binder modified OGFC) • PFC = porous friction course (used by some US DOTs) • PA = porous asphalt (commonly used in Europe and Asia) • PEM = porous European mix (used by European countries)
Rubberized open-graded friction course (RHMA-O)	RHMA-O is the same as the conventional OGFC described above, except the asphalt binder is modified with ground crumb rubber, (GCR) produced from recycled tires (or sometimes mixed with natural rubber). The asphalt rubber binder content is usually higher than the asphalt content used in RHMA-O pavement.	Same as above, except it has been documented that rubberized asphalt is generally quieter than conventional OGFC.	• RAP = rubberized asphalt pavement (US and abroad); this term also being used for “reclaimed asphalt pavement” in the US • RPA = rubberized permeable asphalt (Europe and Asia) • RPFC = rubberized porous friction course (some US DOTs) • RAC-O = rubberized asphalt cement open-graded (old Caltrans terminology) • CRHMA-O = crumb rubber open-graded friction course (US and abroad) • RHMA-O = rubberized hot mix asphalt – open-graded (Caltrans new terminology for old RAC-O) • ARHMA-O = asphalt rubber open-graded friction course (US and abroad) • AR-ACFC = open-graded asphalt rubber asphalt concrete friction course (Arizona DOT)

2.2 Description of a Typical Rubberized and Non-Rubberized OGFC Pavement

OGFC pavement (rubberized or non-rubberized OGFC) is generally constructed as a single open-graded thin layer over an existing dense-graded asphalt pavement (see Figure 2.1). OGFC pavements are usually composed of a large fraction of uniform coarse aggregate with some fine aggregate, and they generally have a higher asphalt binder content than conventional impervious hot mix asphalt (HMA) pavements. When the conventional asphalt binder in an OGFC is modified or replaced with rubber (generally produced from recycled tires), the OGFC pavement is termed *rubberized OGFC*, which the California Department of Transportation (Caltrans) refers to as *RHMA-O.* This latter term is used throughout this report, unless otherwise noted.

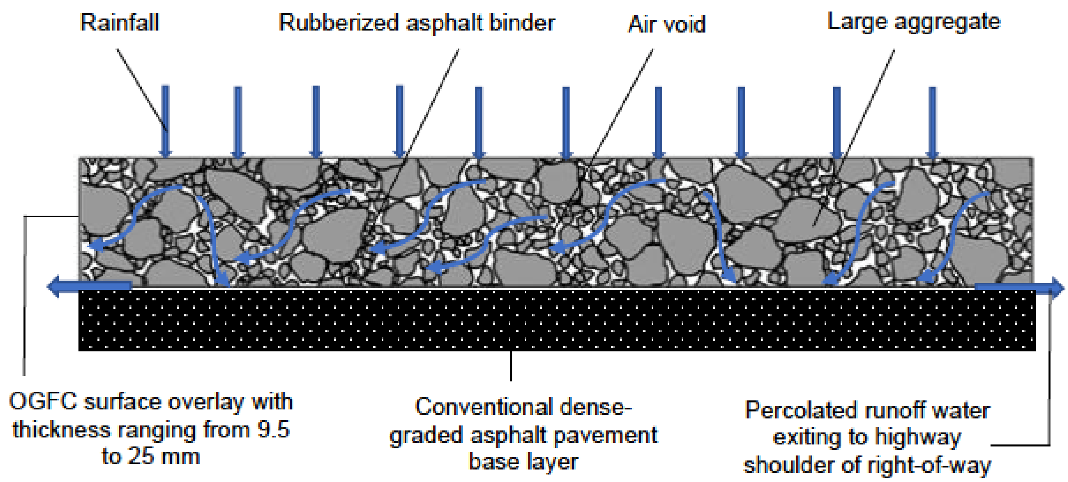


Figure 2.1: Close-up view of non-rubberized or rubberized OGFC overlay pavement.

RHMA-O pavement is typically constructed with a 30- to 40-mm overlay thickness, which corresponds to aggregate sizes of 9.5 and 12.5 mm, respectively. Because of its large aggregates, RHMA-O pavement contains a high percentage of air voids (usually between 15 and 22 percent). This pavement type has no structural function and is usually constructed to improve road safety and to reduce traffic-generated noise. As seen in Figure 2.1, during a rain event, surface runoff passes vertically through the void spaces and when it reaches the impervious dense-graded asphalt it moves horizontally to the edge of the road. This slow movement of water through the surface overlay and the capture of some particle-bound pollutants in its void spaces serve as a partial *runoff water quality treatment* that is considered to be an added advantage of RHMA-O application.

2.3 Overview of OGFC Application in the United States and Abroad

The DOTs in the US, Europe, and Japan who have worked extensively with OGFC have had mixed experiences, some positive, some negative. Those experiences are discussed below and include: (1) a brief history of the development of OGFC, (2) the primary reasons to apply rubberized and non-rubberized OGFCs, (3) the positive and negative experiences of US DOTs who have applied OGFCs, and (4) application of OGFC by transportation agencies in other countries.

2.3.1 A Brief History of OGFC Development

OGFC was developed experimentally to improve roadway safety, and in 1944, California became the first US state to begin using it on pavements. OGFCs gained popularity across the US in the 1970s in response to a Federal Highway Administration (FHWA) program to increase roadway skid resistance (Kandhal 2002). As more OGFC pavements were constructed, their noise-reducing benefit was observed, and then, more recently, their water quality treatment ability was also added to the list of benefits associated with these pavements. As a result, OGFCs and other forms of permeable pavement have come to be seen as environmentally sustainable pavement systems that can be used for highways and urban roads (Ndon 2017).

Since their first development, multiple OGFC mix designs have come into use for OGFC surface layer construction on highways. FHWA published the first OGFC mix design in 1974, then modified it in 1980 and 1990 (FHWA 1990). The original mix design method was based on OGFC's surface capacity and absorption of aggregate. Then, in 2000, the National Center for Asphalt Technology (NCAT) published a new OGFC mix design (Kandhal 2002) that was based on a series of pavement property and performance-related test results needed to meet certain criteria. But even with this new design, a key issue remains for all OGFC pavements: their open gradation and high air-void contents lead to less stone-on-stone contact, and this contact reduction can make them less durable. Additional details about various mix designs and their variabilities will be discussed in Chapter 3.

2.3.2 Primary Reasons for OGFC Application by DOTs in the United States

In the United States, OGFCs are primary used for safety and noise reduction. These benefits are briefly discussed below. It is important to note that RHMA-O pavements also provide both benefits.

2.3.2.1 <u>Safety Benefits</u>

The benefits currently associated with the application of OGFC are its capacity to improve wet-weather pavement friction resistance, to reduce splash and spray from surrounding vehicles, to reduce glare from on-coming headlights during rainy conditions, and to enhance the visibility of pavement markings (Hernandez-Saenz et al. 2016). It has been widely observed that OGFCs provide better skid resistance at the tire/pavement interface than dense-graded asphalt pavements. Because of the high correlation between skid resistance and accident rates, road engineers consider pavement skid resistance to be an important property to consider when designing asphalt pavements. For example, Luce et al. (2007) showed that use of high skid resistance mixtures reduced wet-weather accidents by 54 percent and overall accidents by 29 percent, respectively.

Numerous studies have been conducted in the US to determine comparative skid resistance levels and the various parameters that influence different pavement surface types (including rubberized and non-rubberized OGFCs). A synthesis of the research findings on skid resistance undertaken by different state departments of transportation compiled by Liu et al. (2010) showed that an increase in average friction from 0.4 to 0.55 resulted in a 63 percent decrease in wet-weather accidents. In addition, wet-weather accidents decreased by 71 percent at intersections and by 54 percent on highways with an improvement in pavement skid resistance. The results, obtained from studies in the US, also provided the following conclusions:

- OGFCs have the highest pavement skid resistance of all HMA pavement types.
- Pavement skid resistance increases with decreasing vehicle speed.
- In general, pavements with less surface texture had lower skid resistance
- Skid resistance increases as air temperature decreases.
- The pavement skid resistance initially increases due as binder is worn off the pavement surface, but after that initial increase, skid resistance decreases with increasing traffic volume.
- Skid resistance can be increased by adding crumb rubber as a pavement binder modifier.
- A high aggregate texture level can improve a mixture's skid resistance.

OGFC pavements with low traffic volumes and low vehicle speeds, and which were constructed in locations with low air temperature showed the best skid resistance. However, as will be discussed in Chapter 5, low traffic speeds may favor the rapid clogging of a mix's air void structure and lead to loss of the mix's functional properties (drainability and noise-reduction effectiveness). High aggregate texture, increased mix texture, and the use of crumb rubber-modified asphalt binder need to be considered as alternative material selection and mix design parameters when considering skid potential (Liu et al. 2010).

As noted, OGFC surface layers have been shown to reduce splash and spray from surrounding vehicles, reduce glare from on-coming headlights during rainy conditions, and enhance the visibility of pavement markings during wet weather (Watson et al. 2018). Several other studies were performed to look for the impact of OGFC pavements on the number of accidents during the rain events. For example, Kabir et al. (2012) compared the accident rates of four pavement sections before and after OGFC treatment in Louisiana. They concluded that the OGFC treatment was effective in reducing fatalities and total accidents regardless of the weather conditions. In a separate study, when Chen et al. (2017) assessed 12 pavement sections in Tennessee to learn if OGFC treatment had any effect on accident rates, they found that it significantly lowered accident rates in wet weather conditions.

The safety-related benefits associated with OGFC pavements were also confirmed by several international studies. For example, a study conducted in Japan by Shimento and Tanaka (2010) showed that the rate of fatalities on OGFC pavements was about 1.9 per 100 million miles traveled whereas the rate of fatalities for dense graded asphalt pavement was 6.2 per 100 million miles traveled. Takahashi (2013) also evaluated the safety aspects of OGFC in Japan nationally. This study's results, shown in Figure 2.2, are based on the change in the number of accidents during the year before OGFC construction and the number during the year after, and it compared those results with accident numbers from the same period on a dense-graded pavement. The result clearly indicates that the OGFC significantly reduced the number of fatalities during rainy weather in Japan when compared with standard dense-graded asphalt pavement.

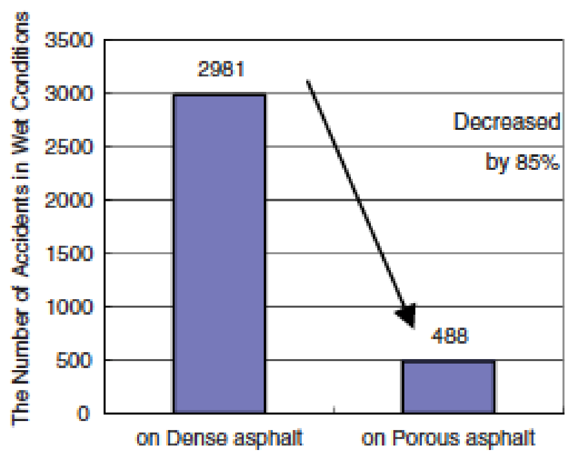


Figure 2.2: Change in accident number from one year before to one year after OGFC construction compared to dense-graded asphalt pavement.
(Source: Shigeki Takahashi [2013], data from 213 rain accident-prone sites nationwide)

However, some studies have challenged those results, claiming that OGFC's improved safety effectiveness is limited, that those supporting studies are inconclusive, and that the hypothesis that says OGFC is effective in reducing wet-weather crashes may not always be true (Elvik and Greibe 2005; Buddhavarupu et al. 2015). For example, Buddhavarupu et al. (2015) analyzed accident data from 43 OGFC pavements and 83 non-OGFC pavements in Texas. Based on their statistical analysis, they rejected the above hypothesis by indicating that road users usually drive faster on OGFC-surfaced pavements than on non-OGFC pavements, and that the higher accident rate on open-graded surfaces may be attributable to those speed increases. Similarly, Lyon et al. (2018) conducted a large-scale study to quantify the safety effects of OGFC treatment. They collected accident data on OGFC and non-OGFC pavements in California, Minnesota, North Carolina, and Pennsylvania, and estimated the crash modification factors (CMFs) for OGFC treatment. CMF refers to the ratio of the expected number of crashes after treatment to that before treatment based on actual field data collection. A CMF less than 1.0 indicates that the treatment reduces the number of crashes on that pavement site. The results obtained by Lyon et al. (2018) showed that OGFC treatment decreasing the accident rate in wet conditions on freeways, but that overall it increased the accident rate on roads in dry conditions. In summary, OGFC treatment only reduced the total accident rate on freeways.

2.3.2.2 Noise Reduction Benefits

The second and most important reason for OGFC application in the United States is related to its noise-reducing ability, particularly for urban residential areas. OGFC has been used strategically to help DOTs meet environmental noise regulations. Most highway noise comes from pavement-tire interaction, especially when traffic speeds exceed 45 miles per hour. This highway noise is an annoyance for humans, negatively impacts the quality of life, and can have adverse economic effects such as lowered real estate property values (Donavan 2007). Because of its high interconnected air-void content, an OGFC mix acts as a resonant cavity structure that efficiently absorbs sound energy generated from the tire-pavement interface.

Bernhard and Wayson (2004) reported that OGFC use reduces the tire-pavement noise by 3 to 6 dBA, which is equivalent to diminishing traffic volume by 50 percent or comparable to the construction of a sound wall.

At the US state-level, the Arizona DOT has successfully implemented the application of OGFC for noise reduction and California has made research advances on noise reduction. At the federal level, the FHWA implemented the "Quiet Pavements Pilot Program" to promote low-noise pavement use, and as part of this program field measurements were made to monitor and catalog different pavement noise levels (Jones 2005). Measurements on wide ranges of pavements by Alvarez et al. (2006) showed the noise measured on OGFC to be less than 93 decibels (dB), whereas the noise levels on most dense-graded pavements were higher than 95 dB. Similar results were obtained in California, indicating that the noise reduction associated with non-rubberized and rubberized OGFC is higher than dense-graded pavement, although it may decrease as the pavement ages (Rezaei and Harvey 2013; Lu et al. 2011; Lu et al. 2009; Ongel et al. 2008). Table 2.2 contains a summary of the noise-reduction measurements on OGFC pavements and dense-graded pavements collected by different state DOTs and US transportation agencies. As shown, the noise reduction measured on OGFC compared with dense-graded pavements within the US ranges from 3 dB to 9 dB (Donavan 2005). The values reported in this table clearly indicate a discrepancy in noise-level reduction among the different state DOTs. The noise-reduction variations are probably related to several factors including, but not limited to, variabilities in mix designs and clogging, as will be discussed in Chapters 3 and 5, respectively.

Similar traffic noise reductions made by using asphalt rubber materials have been documented in California and Arizona by Caltrans and ADOT, respectively, and by many European countries (Belgium, France, Germany, Austria, and The Netherlands) and Canada. These studies showed that traffic noise can be reduced by 40 to 88 percent by using a rubberized open-graded friction course, and that typical noise levels ranged from 93 to 98 dBA (Scofield and Donovan 2003; Scofield 2004). Based on the research results obtained in Arizona, FHWA has granted a 4-dB noise reduction credit to ADOT for specific projects in the ADOT Quiet Pavement Pilot Program. Ongoing ADOT research includes noise measurements of 12-year-old open- and gap-graded asphalt rubber pavements to evaluate long-term noise reduction. Findings to date indicate that noise reduction persists over time, although in some cases a decrease in noise reduction has been noticed. A UCPRC study showed that the noise-reducing capability of OGFC pavements may change with pavement. For example, Bendtsen et al. (2010) developed a model based on noise measurement data and showed that an OGFC's noise-reduction performance is a function of its age, traffic volume, and pavement type, primarily on highways with speeds over 50 mph (80 km/hr). It is important to note that, at present, pavement surface type is specifically excluded from FHWA noise models. However, with the availability of additional data from the California and Arizona DOTs, it is expected that in the near future FHWA will develop a revised noise model with a special emphasis on pavement surface type.

In addition to the safety and noise reduction benefits indicated above, recent water quality evaluation studies performed in Texas, California, and North Carolina showed that the runoff quality generated from OGFC surfaces is cleaner than the runoff discharged from conventional non-permeable asphalt pavement surfaces. This benefit of OGFC has not been fully recognized by United States and international transportation agencies and requires further study. The expected water quality benefits of OGFC and RHMA-O pavements and related issues are discussed in Chapter 4.

Table 2.2: Summary of Noise Reduction of OGFCs Compared to Dense-Graded HMA (unless noted) Pavements Measured in the United States

US State DOT, or Transportation Agency	Study Year	Noise Reduction (dB) of OGFCs Compared to Dense-Graded Pavements
FHWA	1975	2.0
Minnesota	1979, 1987, 1995	High
Maryland	1990	2.3-3.6
Oregon	1994	5.7-7.8 (vs. PCC)
US DOT	1995	1.5
Ohio	2000	3.0-4.0
Washington	2001	3.0-4.0
California	2002	4.0-6.0
NAPA	2002	2.0
Texas	2003	14 (vs. PCC)
NCAT	2004	4.0
Indiana	2004	4.0
Asphalt Institute	2005	1.0-4.0
Asphalt Institute	2006	4.0 (vs. PCC)
Indiana	2008	High
California	2008	1.0-4.0
Texas	2008	2.0-3.0

Source: adapted from Yeo 2001; Kandhal 2004; and Pierce et al. 2009

Note: NAPA = National Asphalt Pavement Association; NCAT = National Center for Asphalt Technology; PCC = Portland cement concrete; FHWA = Federal Highway Administration; US DOT = United States Department of Transportation

2.3.3 Survey Experiences Reported with the Application of OGFCs in the United States

The application of OGFC by different DOTs throughout the United States are documented in several surveys. The first such study, conducted by Huber (2000), indicated that only 19 states were using OGFC, 19 states discontinued their use of OGFC, 4 states had never used them, and 8 states did not respond to the survey. The second national survey, conducted by NCAT, indicated that 20 state DOTs were actively using OGFC pavements (see Figure 2.3). The latest national survey on US OGFC use was conducted in 2017 by University of Tennessee researchers for the Tennessee Department of Transportation (Shu et al. 2017). The aim of this survey study was to collect information and to find ways to reduce the cost and improve the performance of OGFC pavements for the state. A comparison of the results of this recent survey with those from the NCAT survey showed that several states that had been using OGFC discontinued using it, while several new states had begun using it. In general, the percentage of states using OGFC in 2017 remained the same as in 2015. It should be noted, however, that the new survey map prepared by the Tennessee study had an inaccuracy, showing that the Texas DOT no longer used OGFC even though its use in that state was later verified.

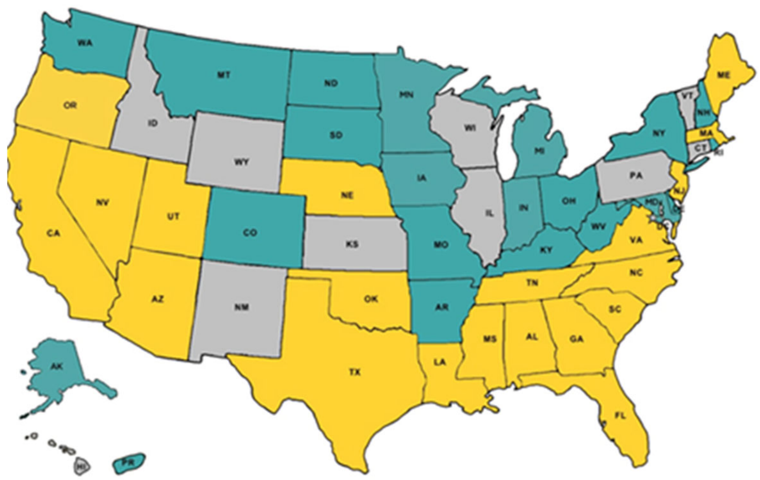


Figure 2.3: Use of OGFC pavement by US state DOTs based on the 2015 NCAT survey (adapted from Watson et al. 2018).

As discussed earlier, while the benefits associated with OGFC application are well known, their use in the United States was limited due to several challenges and problems that are documented in the earlier surveys. The survey results revealed that some DOTs that did not use OGFC believed their mix designs were inadequate because their pavements were raveling and experiencing top-down cracking. Other DOTs reported that the high material cost of OGFC was a problem, as this pavement type usually costs 20 to 40 percent more than conventional dense-graded mixes. They also found winter maintenance (see Chapter 5 for a fuller discussion) to be another serious problem with OGFC pavements: the survey results revealed that OGFC pavements have earlier and more frequent frost and ice formation than conventional pavements. These result from the low thermal conductivity of OGFC, which is due to its porous void structure. Taken together, it was found that maintaining desirable winter ride quality on OGFC pavements required more frequent maintenance and more chemicals, and carried greater costs than maintaining that ride quality on conventional pavements did. The surveys also revealed that OGFC pavement service life is shorter than that of dense-graded mixes; specifically, typical OGFC service life is 6 to 8 years, while for conventional dense-graded mixes it is typically 12 to 15 years. According to the 2015 NCAT survey, these durability and service life issues were the primary reasons many state DOTs chose not to use OGFC.

More recent survey results compiled by Shu et al. (2017) confirmed the results obtained by NCAT and Huber (2000), indicating that the major problems associated with OGFC application were poor performance (62 percent), higher cost (11 percent), and higher maintenance requirements (27 percent). Further, the main reasons some states never considered OGFC were (1) higher winter maintenance requirements, (2) greater costs than benefits, and (3) a lack of quality aggregates. The survey also identified clogging, raveling, and long-term durability problems.

Only a few states were extremely satisfied with the performance of their OGFCs, and these states used modified binder and other additives to improve their mix designs. Interestingly, while most DOTs claimed that clogging was a major concern, 94 percent of these states lacked an OGFC surface-cleaning maintenance program to help prevent clogging.

2.3.4 OGFC Application by Transportation Agencies outside the United States

The first application of OGFC in Europe was in 1972 in Switzerland on an airport runway, and their application on highway pavements began in the mid-1970s (Huber 2000). In Spain, more than 3 million square meters of OGFC were placed in the early 1980s. The Netherlands first used OGFC in 1972, and during the 1980s placement of OGFC became widespread because of its noise-reducing characteristics (Huber 2000). Since 1990, many other European countries including Ireland, Italy, France, Belgium, Denmark, Sweden, Austria, and the United Kingdom have begun using OGFC pavements on their roadways (Huber 2000; Yeo 2001; Kandhal 2004; and Pierce et al. 2009), mainly for noise reduction. Over the years, many of these countries' transportation agencies have conducted studies of those noise reductions, as summarized in Table 2.3.

OGFC is also being used in Australia, Canada, China, Brazil, Malaysia, India, and Japan. These countries generally follow the standard mix designs practiced in Europe and the United States. The main reasons given for these countries use or experimentation with OGFC applications are related to safety and noise reduction.

Table 2.3: Summary of European Studies of OGFC Pavement Noise

European Country/Organization	Study Year	Noise Reduction (dB) of OGFCs Compared to Dense-Graded Pavements
Netherlands	1989	2.5-3.2
Italy	1990	3.0
Germany	1990	4.0-5.0
Sweden	1990	3.5-4.5
France	1990	3.0-5.0
Netherlands	1990	3.0
Nordic countries	1990	3.0-5.0
Belgium	1990	2.0-3.0
Switzerland	1990	1.5-5.0
United Kingdom	1990	4.0-5.0
Denmark	1992	4.0
World Road Association	1993	1.5-3.0
United Kingdom	1993	6.0-7.0 (vs. PCC)
Belgium	1994	7.5 (vs. PCC)
United Kingdom	1997	2.5-5.0
Australia	2001	2.0-3.0
Sweden	2005	7.0-12.0
Spain	2008	1.0

Source: adapted from Yeo 2001; Kandhal 2004; and Pierce et al. 2009.
PCC = Portland cement concrete

2.4 Overview of the Application of RHMA-O Pavement in the United States and Abroad

2.4.1 Types of RHMA-O

The asphalt rubber binder included in a rubberized open-graded friction course (RHMA-O) mix distinguishes this mix type from a conventional OGFC (OGFC) mix. The added asphalt rubber binder improves durability and permits the use of higher mix temperatures in cool climate conditions. The amount of asphalt rubber binder an RHMA-O binder contains determines which one of three types it is: Type I, Type II, or Type III (Smith 2000). RHMA-O Type I is *free-draining friction course* (FDFC), which provides a friction course that has skid resistance and draining characteristics similar to a conventional OGFC. A typical RHMA-O Type I has asphalt rubber binder contents ranging from 7 to 8.5 percent by aggregate weight and air-void contents normally ranging from 16 to 19 percent. RHMA-O Type II is a *durable friction course* (DFC) that utilizes a binder content range from 8.5 to 10 percent by aggregate weight. This mix type has a much higher binder film thickness than Type I, which results in increased durability but with a somewhat lessened drainage capacity, and it has an air void range from 11 to 15 percent. RHMA-O Type III is a *plant mix seal* (PMS) that utilizes binder content ranges from 9 to 11 percent by weight of aggregate and generally has from 8 to 12 percent air voids. Its high binder content produces a mix with improved aging resistance, durability, and resistance to reflective cracking. Due to that high binder content, Type III is not usually used for OGFC pavements.

Pavements with asphalt rubber binder have shown significantly improved binder drain off even with their increased binder contents. This reduced drain off, even at higher temperatures, is attributable to the asphalt rubber binder materials' higher viscosities compared to conventional binder. The rubber added to binders for RHMA-O pavements results in a film thickness increase that has been shown to improve pavement durability (Smith 2000). More information about the development of RHMA-O, and the successes and challenges associated with its application in the United States and abroad, is discussed below.

2.4.2 Historical Development of RHMA-O

The use of tire rubber in asphalt pavements began in 1840, and the process of adding rubber to conventional asphalt binders has continued developing, resulting in today's RHMA-O. The major developments in the history of rubberized asphalt pavement are summarized in Table 2.4. The practice of adding rubber to the binders for asphalt pavements increased substantially in the United States because of federal government efforts to divert recycled tires from disposal in landfills. In December 1991, the US Congress enacted the Intermodal Surface Transportation Efficiency Act (ISTEA), which included a mandate instructing all state DOTs to use a prescribed amount of asphalt rubber (AR) in their federally funded roads. Beginning in 1993, all state DOTs were required to use AR in five percent these roads. Increased mandates were issued to increase the amount to 10 percent in 1994, 15 percent in 1995, and 20 percent in 1996, and to maintain this latter level in perpetuity (Blumenthal 2012).

The federal mandate was not well received by the paving industry or by state DOTs because of a series of factors including: (1) insufficient ground-tire rubber was available in 1991, (2) the AR technology was still under patent protection, which precluded states from using the technology, and (3) at the time, only two states used AR, so the technology was not well understood and was viewed, mistakenly, as a paving technology that was limited to use in hot climates.

Table 2.4: Historical Development of Rubberized Asphalt

Year	Description/Major Development
1840	The earliest experiments of incorporating natural rubber into asphalt to increase its engineering performance properties date back to the 1840s (Mashaan et al. 2012).
1843	The process of asphalt modification involving natural and synthetic rubber was introduced (Thompson 1979).
1923	Natural and synthetic rubber modifications in asphalt were further improved during this year (Isacsson and Lu 1999; Yildrim 2007).
1930	The development of rubber-asphalt materials being used as joint sealers, patches, and membranes began in the late 1930s.
1950	The use of scrap tire rubber in asphalt pavement was reported during this year (Hanson et al. 1994).
1960	In 1960s, Charlie MacDonald working as head material engineer in Phoenix, Arizona, used ground tire rubber as an additive in asphalt binder modification. He found that after completing the mixing of crumb rubber with the conventional asphalt and allowing it to blend for mix duration of 45 to 60 minutes, there were new material properties produced, which resulted in swelling in the size of the rubber particles at higher temperatures allowing for higher concentrations of liquid asphalt contents in pavement mixes (Huffman 1980).
1964	During this year the use of crumb rubber modifier (CRM) in asphalt mixtures was first applied in Arizona on an existing pavement.
1980s	In the mid-1980s, the Europeans began the development of newer polymers and additives for use in asphalt binder modification (Brule 1996).
1991	As part of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, states were mandated, beginning in1994, to use annually increasing percentages of rubberized asphalt in federally funded highway projects as a requirement to continue receiving federal funds. The goal was to incorporate more sustainable options. The requirements began with five percent and were to increase to 20 percent by the end of the specified period.
1992	Caltrans developed a design guideline that allows for reduced overlay thickness for a gap-graded HMA with asphalt rubber on specific types of applications.
1994	In response to the federal mandate, rubber recycling entities invested significant capital to accommodate the increasing production requirements. Initially, there were several problems to fully implement the rubberized asphalt pavement. These problems include, but not limited to (1) most rubberized asphalt technology was patented, making it expensive to use, (2) the technology had certain technical problems and was surrounded by controversy, and (3) several state pilot projects using rubberized asphalt turned out to be unsuccessful.
1995	In 1995, the mandate from ISTEA was repealed, with the federal government instead providing individual grants to states of up to $500,000 toward research and expansion of rubberized asphalt in pavements. While the majority of recycled rubber use remained in tire-derived fuel, it was believed that a significant portion of the crumb-rubber modifier (CRM) manufacturing capacity went out of business as a result of the mandate’s reversal.
2000s	With the prices of asphalt increasing and improvements in technology and familiarity with the product in recent years, the use of crumb rubber has gained interest in pavement modification and has shown that crumb rubber can improve the asphalt performance properties and increase durability (Brown et al. 1997). Rubberized binder is also used in open-graded friction courses and has been shown to add other benefits, including reducing noise, decreasing the impact of splashing, and increasing driving safety during rain events.

Note: the historical summary was prepared based on information compiled from various source.

The federal mandate was created without input from or after discussions with the pavement industry or state DOTs. Consequently, both reacted with condemnation and resented the AR-use mandate. Consequently, because of the lack of participation by DOTs and the low success rate with AR, in 1993 Congress repealed the section of ISTEA that contained the AR-use mandate.

Historically, state-level AR use has been driven by the agency or agencies responsible for development of the scrap tire market; in some cases this was the state department of transportation, in others it was a different state agency, and in others it was both (Presti 2013). However, experience has shown that when a state DOT is an active participant, the use of AR is substantially higher. For instance, a mandate was set in California to use a minimum of 35 percent AR in pavement construction; however, with Caltrans's direct participation, that use has exceeded the mandated level (Caltrans 2016).

2.4.3 Methods for Preparing Asphalt Rubber Pavements: Dry Process versus Wet Process

Crumb rubber modifier (CRM), which is also known as *ground tire rubber* (GTR), is recycled tire rubber that has been ground into fine particles for use as an asphalt binder modifier. In order to use this rubber in a mix design, the rubber must be small enough to be blended with asphalt binder or into an asphalt mix. The makeup of the recycled tires' components can vary slightly depending on the tire vehicle type, care type (truck or passenger), and manufacture. The basic components of modern tires (see Figure 2.4) are about the same, and generally there is little difference between truck and passenger tires and the amount of natural and synthetic rubber content. In addition, the slight variances observed in the percentages of natural and synthetic rubber do not cause any differences in rubberized modified binder performance.

Research by Willis et al (2012) found that the method used to grind the tire rubber is one of the most important factors affecting GTR-modified binder performance. The most common tire-grinding methods include ambient grinding, cryogenic grinding, granulation, and shredding (West 1998). Ambient grinding is performed at or above room temperature, with the scrap tire ground into irregularly shaped particles with a large surface area to promote their interaction with asphalt binder. In the cryogenic process, the rubber is frozen with liquid nitrogen to increase its brittleness and it is then subjected to a hammer mill to shatter the rubber into smooth particles that have a small surface area. The granulation process uses a revolving steel blade to shred the scrap tire into low-surface-area cubed particles. In the shredding process, the scrap tires are reduced to pieces smaller than six inches prior to granulation or grinding. It should be noted that ambient and cryogenic grinding (US DOT 2014) are the two most common methods.

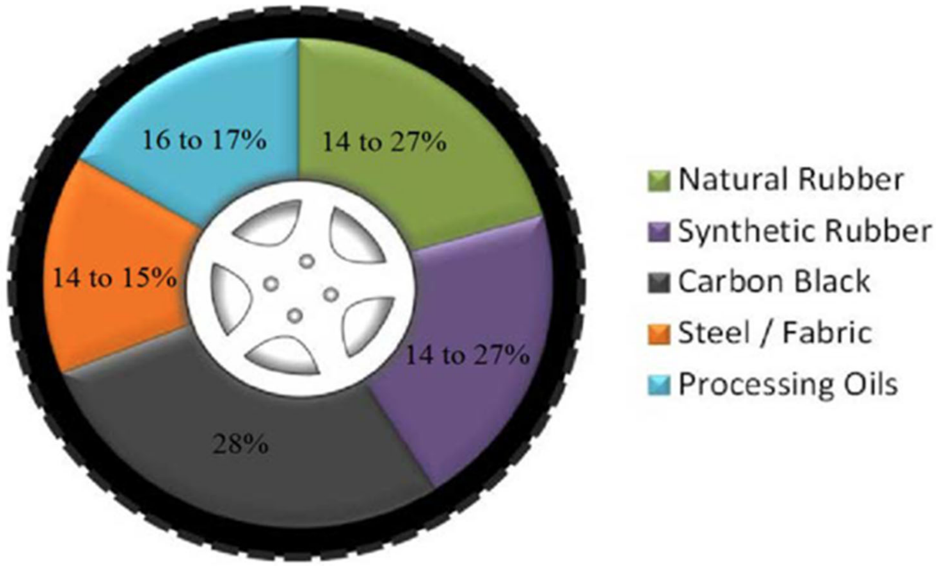
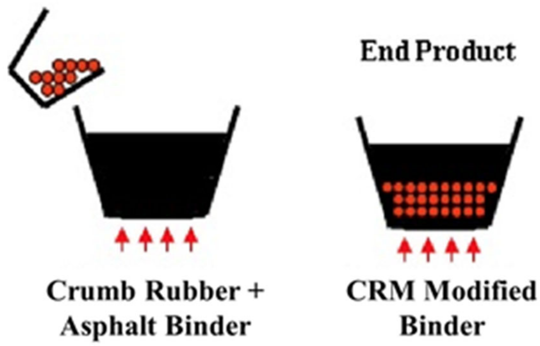


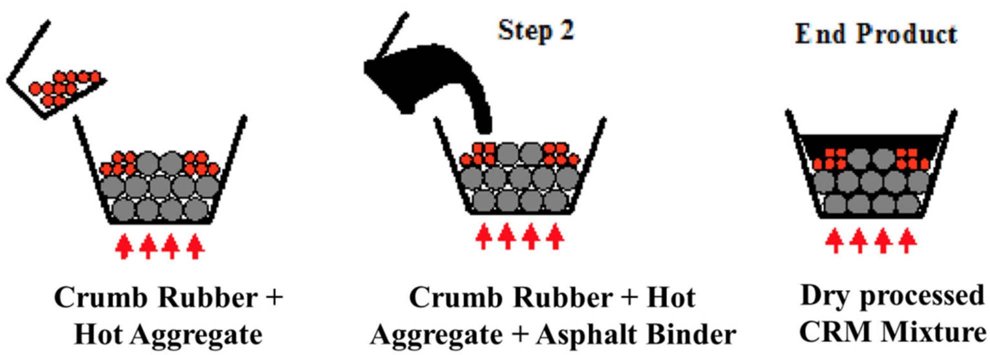
Figure 2.4: Average components of a typical tire (Adapted from FHWA 2014).

At present, two methods are used to blend CRM into asphalt pavement binder: the *wet process* (also referred to as *terminal blending* or *on-site blending)*, and the *dry process*. As shown in Figure 2.5(a), in the wet process, finer mesh crumb rubber is introduced into liquid binder (often with other additives), and this is followed by cooking and "digestion" of the rubber into the binder before it is used in asphalt production. In the dry process, shown in Figure 2.5(b), larger crumb rubber particles are introduced onto hot aggregates, and then asphalt binder is added before the mix is used in asphalt pavement production. Descriptions of these processes are summarized in Table 2.5.

According to the FHWA, modified binder obtained from the wet process is termed as *asphalt rubber* and modified binder obtained from the dry process is termed *rubberized asphalt* (Chesner 1997). The ASTM defines rubberized asphalt differently, basing its definition on the rubber content in the asphalt pavement: when the rubber content is less than 15 percent (<15 percent) it is called *asphalt rubber,* and when the rubber content is higher than 15 percent (>15 percent) it is termed *rubberized asphalt.* Unfortunately, the information found in the literature revealed that most users do not distinguish between the ASTM and FHWA definitions and the terms are used interchangeably. The FWHA also recognized that rubberized pavements produced by the dry and wet processes have vast differences in performance, and advises state transportation agencies to understand these differences before constructing rubber-modified asphalt pavements. In addition, the Rubber Pavement Association (RPA) advises that laboratory and pilot-testing inspections may be necessary to ensure the long-term success of rubber-modified asphalt binder in field implementations. The RPA only recommends tire rubber pavement preparation processes that meet the following three criteria: (1) the process has been subjected to extensive laboratory research and analysis, (2) the pavement project with the associated process has been constructed and its performance has been evaluated under field conditions, (3) the tire-rubber pavement preparation process has been used successfully and routinely by two or more states. The asphalt-rubber wet process is the only one that currently meets these criteria.



(a) Wet process



(b) Dry process

Figure 2.5: Preparation methods for rubberized asphalt binder: (a) the wet process, and (b) the dry process (Adapted from Hassan et al. 2014).

Other concerns associated with the processing of ground crumb rubber (dry or wet) as a binder modifier for RHMA-O pavements have to do with its environmental air quality effects and how those affect worker health and safety. Generally, all asphalt plants—including those using AR—are held to stringent air quality standards and there should be no unusual emissions-related problems with AR pavements (ARTIC 2019). Still, several federal and state-level air quality studies were undertaken to address this. One major air quality study in California performed assessed the air quality impacts of grinding, transporting, and processing the asphalt rubber, and its results showed that the AR pavement met all required air quality specifications and passed all emission tests. The results also indicated that employee exposure to air contaminants were well below the California Division of Occupational Safety and Health's (CAL/OSHA) permissible exposure limits (PEL) and, in most cases, below the detection limit (ARTIC 2019). In addition, the US federal government has funded a comprehensive emissions-testing program of asphalt and asphalt rubber fumes at seven sites. The National Institute of Occupational Safety and Health (NIOSH) conducted a study and its test results were published in a report: the air quality measurements made in this study showed that the emissions caused by using tire rubber in asphalt were no greater than those from conventional asphalt (ARTIC 2019). The only noticeable difference was the heated rubber's aroma, which some found to be objectionable.

2.4.4 Application of Rubberized Asphalt Pavements in the United States

A survey study performed by Bandini (2011) indicated that by the end of 2011 only 23 state DOTs had used crumb rubber in asphalt pavement construction: 17 had used the wet process (terminal or on-site blending) and 6 had used the dry process. In California, Caltrans uses the wet process, the only one permitted by the *Greenbook*. The survey results also indicated that only four state DOTs—Arizona, California, Florida, and Texas—have used rubberized binder in open-graded friction course pavements.

A separate survey study performed by Blumenthal et al. (2013) showed that 25 state DOTs were using crumb rubber in asphalt pavements (see Figure 2.6). According to this survey's results, still many states are reluctant to use crumb rubber, mostly because of some unfavorable history and outdated perceptions. In 2016, Ghabchi et al. (2016) surveyed transportation agencies known to be using crumb rubber in pavement construction. The results of this survey (see Figure 2.7) indicated that crumb rubber materials are used in a wide range of applications, such as in chip seals, fog seals, and crack seals in thin overlays; in stress absorbing membranes (SAM) and stress absorbing membrane interlayers (SAMI), in thick overlays, and in rubberized open-graded friction courses (RHMA-O). From Figure 2.7, it is clear that the majority of DOTs use crumb rubber for chip sealing and thin overlay dense-graded pavement applications. The leading four states currently using RHMA-O include Arizona, California, Florida, and Texas (Ghabchi et al. 2016). The current application of RHMA-O by these four DOTs was verified by the author of this literature review through e-mail and phone communications with representatives of each DOT (Moseley 2019; Barborak 2019; Crerand 2019). Together, these four states recycled almost 36 million scrap tires in asphalt pavement applications from 1995 to 2001 (Willis et al. 2012). In a study conducted for Caltrans in 2005, it was reported that the number of scrap tires used per ton of HMA in the states of Arizona, California, Florida, and Texas, were 4.4, 3.3, 1.9, and 4.9, respectively (Ghabchi et al. 2016). Discussion of some state DOT experiences with field applications and experiments using RHMA-O are presented below. Variations in mix designs and other specifications used for RHMA-O pavements by these states are examined in Chapter 3.

Table 2.5: Typical Processes Used to Prepare Rubberized Pavements

Process	Description
Dry process	The dry process is considered to be an aggregate replacement process rather than a binder addition process. In the dry process, recycled rubber tire (RTR) is added similarly to reclaimed asphalt pavement (RAP) at the mix production plant. The rubber is typically larger particles, between 4 to 18 mesh or 4.75 to 1.00 mm. Cryogenic rubber is typically used in dry process. Gap-graded aggregate mixtures are required to provide space for the rubber particles.
Wet process (on-site blending)	In the AR wet process with on-site blending, RTR is typically field blended at 350 to 400°F (175 to 200˚C) for 45 to 60 minutes. The temperature and time depend on the base asphalt binder grade, percentage, and particle size of the RTR. During this reaction time, the rubber particles absorb some of the asphalt binder's light fractions and swell. This absorption and swelling causes an increase in the viscosity of the AR-asphalt binder blend. With extended reaction times the viscosity will decrease slightly. This has typically been called "digestion" of the rubber in the asphalt binder. The typical RTR addition is 15 to 22 percent by weight of the asphalt and rubber blend. The 15 percent minimum—initially set to maximize use of recycled tires and not for performance-related reasons—has not changed. It is intended as a recipe and may not necessarily produce optimal traffic or environmental performance at the project site. A coarse-graded RTR material, 10 to 14 mesh or 2.0 to 1.4 mm maximum size is used. The larger RTR particle size requires a gap-graded or open-graded aggregate in the mixture to allow room for the rubber particles. If one of these is not added, good compaction is difficult to achieve because the rubber particles push the aggregate particles apart when they are compressed during rolling and they expand when the compaction force is removed. The increase in viscosity that RTR provides to the asphalt binder also requires an appropriate increase in production temperatures for producing and placing mix. Increased temperatures can create unique odors and the potential for smoke. Worker health and safety issues need to be considered. Warm mix asphalt (WMA) technologies have been successfully used to help reduce AR mix production and placement temperatures.
Wet process (terminal blending)	Terminal-blend RTR-modified AR asphalt binder is produced at a supplier's terminal facility and shipped to the mix production plant in a similar way as standard asphalt binder. The RTR used in this process is typically a smaller particle grind, sized to minus 30 mesh or smaller than 0.6 mm. The smaller particles help improve storage stability and minimize RTR particle settlement. In some systems, rubber is completely digested into the asphalt with no particulate matter present. Terminal-blend RTR binders used alone or with polymers can be formulated to produce Superpave performance-graded (PG) binders, typically using 5 to 10 percent RTR by weight of the total binder. Smaller RTR particles and polymers are used in a terminal blend to produce an AR binder that is similar to standard polymer-modified asphalt binder. It is shipped to the mix production plant, stored in the plant's binder storage tanks and mixed with the aggregate, in a way similar to a standard asphalt mixture. It may be used in dense-graded mixes with no modification to the job mix formula. Depending on the technology used, storage stability can be a problem with terminal-blend AR binders. If RTR is simply mixed with the binder, it will settle with time because rubber is heavier than asphalt binder. Settlement time will vary depending on the size of the RTR particles and other additives or methods used to reduce separation. To avoid separation, transport vehicles and storage tanks with agitation capability may be employed. Even with higher solubility AR binders, cleaning of tanks is recommended. Several patented methods have been developed to reduce separation, and newer methods are in development. Continuous agitation in the storage tanks using stirring paddles and recirculation pumps will help reduce separation.

Source: Adapted from FHWA tech brief (2014)

Figure 2.6: States where the DOT uses tire rubber in asphalt pavements (Blumenthal 2013).

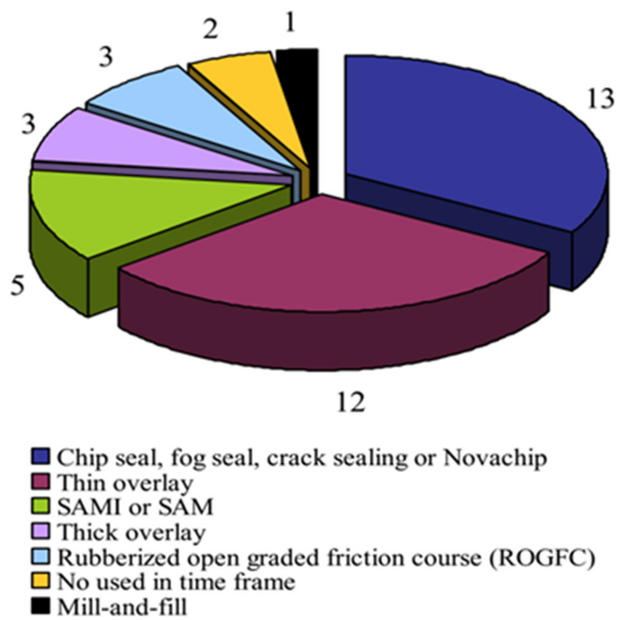


Figure 2.7: State DOT pavement applications that include crumb rubber (source: Ghabchi et al. 2016).
(Note: **these results were based on the 23 state DOTs that use crumb rubber identified by Bandini (2011). Some states used more than one crumb rubber application. At present, only Arizona, California, and Texas actively use rubberized OGFC, but Florida is mostly using polymer-modified binder in OGFC construction.)**

Other than the leading four state DOTs, several other state DOTs have experimented with the use of rubberized asphalt pavement, including RHMA-O: Georgia, New Mexico, Oregon, and Washington. The following material discusses what experiences these eight DOTs have had using or experimenting with CRM as a modified binder for OGFC.

2.4.4.1 Arizona DOT (ADOT)

Arizona Department of Transportation (ADOT) has more than 45 years of experience with incorporating asphalt rubber materials in pavement construction and rehabilitation. In most cases, ADOT has used GTR-modified binders in chip seals as SAMs and SAMIs but the department has also had many successful pavement construction projects statewide using GTR-modified materials (Charania et al. 1992; Flintsch et al. 1994; Miller 1996; Way 2000; Morris et al. 2001; Kaloush et al. 2002; Caltrans 2005). In 1990, ADOT designed and constructed a large-scale project on Interstate 40 in Flagstaff to evaluate the effect of asphalt rubber on reflective cracking in thin overlays. The overlays were constructed on a badly-cracked concrete pavement that was originally built in 1969 with a thickness of 8 inches and total width of 38 feet (Way 1991). The asphalt rubber for the project was produced with 20 percent GTR using the wet process. No other additives or modifiers were used. ADOT reported that the asphalt rubber overlay's performance exceeded expectations (Way 2000) and indicated that after nine service years the overlay was still virtually crack-free and without rutting. The results from this project led to a significant increase in asphalt rubber applications throughout Arizona: between 1990 and 2000 more than 2,000 miles of asphalt pavements containing GTR were built in the state. ADOT also reported that the percent cracking in asphalt rubber overlays was significantly lower than that of non-rubberized conventional overlays.

ADOT has gained extensive experience by placing many gap-graded, crumb-rubber-modified (CRM) mixes. Kaloush et al. (2007) conducted flexural fatigue tests on field specimens extracted from the gap-graded pavements in the state and showed that crumb-rubber modification resulted in higher pavement fatigue life. A more recent study by Way et al. (2015) used four-point bending testing on Arizona mixes and showed that CRM mixes had longer fatigue lives than traditional HMA mixes, which is consistent with field observations over a 16-year period. Comparative results with asphalt pavements showed that cracking percentages occurring over a 10-year period were significantly lower on asphalt pavements modified with rubber than on asphalt pavements without rubber (Way 1999). In the early 1990s, ADOT started using RHMA-O primarily for noise reduction and years of noise measurements on RHMA-O by the Arizona Transportation Research Center study confirmed the noise-reduction benefit of using CRM asphalt in pavement construction (ARTR 1996). These noise measurement results indicated that RHMA-O reduces noise by 5.7 dB. At present, RHMA-O is routinely used on all Arizona's high-volume traffic highways (Shu et al. 2014).

Even though numerous studies were performed to assess or improve the durability and functionality of RHMA-O projects in Arizona, to date ADOT has not investigated it for stormwater treatment quality.

2.4.4.2 California DOT (Caltrans)

The California Department of Transportation (Caltrans) has used recycled ground tire rubber in chip seals since the 1970s and began using them in rubberized HMA in the 1980s (Zhou et al. 2014). Both the wet (field blend) and dry processes were used in early trials. Early Caltrans rubberized HMA pavements were constructed using the dry process, but since 1980 Caltrans has only used wet-process crumb rubber. Caltrans has also used rubber-modified binders containing both crumb rubber and polymer modifiers that could be manufactured at a refinery facility, a terminal-blend wet process.

Early Caltrans rubberized asphalt pavements were referred to as *rubberized asphalt cement* (RAC). These earlier RAC pavements were monitored over time and Caltrans rated their overall mix performance as excellent (DeLaubenfels 1985). By mid-2001, Caltrans had built 210 RAC projects throughout the state (Caltrans 2005) and continued studying their performance. In one special study, Caltrans engineers reviewed the performance of over 100 RAC projects in California and 41 asphalt rubber overlay projects in Arizona (Hildebrand and Van Kirk 1996). In a separate study, Caltrans determined that thin RAC pavements perform better than thicker conventional dense-graded asphalt concrete (DGAC) pavements (Caltrans 2005) and concluded that when they are properly designed and constructed, the performance of RAC materials was superior to conventional dense-graded pavement. One important finding from the study was that the progress of distresses in RAC pavements was much slower than that of structurally equivalent DGAC pavements.

By the end of 2010, approximately 31 percent of all the hot mix asphalt (HMA) placed by Caltrans was rubberized HMA (roughly 1.2 million tons) (Zhou et al. 2014). Caltrans efforts to use asphalt rubber products were also demonstrated in its research and technology development. These included the construction of two full-scale field experiments, five warranty projects, and an accelerated pavement study using a heavy vehicle simulator. Additionally, terminal-blend asphalt rubber and rubberized warm mix asphalts were experimented with on a trial basis.

Caltrans initially referred to its rubberized OGFC as *RAC-O* but has used the term RHMA-O since 2006. The modified binder specifications for RAC-O (i.e., rubberized OGFC) were based on the earlier *AR system,* which has since been renamed the *performance grade* (PG) binder system.

The extensive use of crumb rubber use as a modifier in asphalt pavement, including OGFC, is directly related to a legislative mandate. According to the goals specified in California Public Resources Code Section 42703(a), which mandates that 35 percent of the asphalt pavements Caltrans constructs annually be modified with recycled tire rubber. The data presented in Figure 2.8 show the amount of crumb rubber used since 2000 alongside the goals of the mandate. The data show clearly that since 2015 Caltrans has exceeded its mandated goal of 35 percent.

To determine the most cost-effective approaches for maintaining roadway smoothness and quietness, Caltrans also established the Quieter Pavement Research (QPR) Program (Rezaei and Harvey 2013). This program included several studies evaluating the acoustic properties of pavements and the role pavement surface characteristics play with regard to tire/pavement noise levels. The Caltrans QPR Work Plan included research on both asphalt and concrete pavement surfaces. To execute the program's asphalt surface pavement component, Caltrans initiated Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.16 in November 2004. Among its other objectives, PPRC SPE 4.16 developed preliminary performance estimates for then-current Caltrans asphalt surfaces—including what at the time were called *dense-graded asphalt concrete* (DGAC), *open-graded asphalt concrete* (OGAC), *rubberized asphalt concrete gap-graded* (RAC-G), and *rubberized asphalt concrete open-graded* (RAC-O) as part of a factorial experiment—and for a number of experimental asphalt surfaces with respect to tire/pavement noise, permeability, macrotexture, microtexture, smoothness, and surface distress development (Rezaei and Harvey 2013). One of the study's significant components were the age-related permeability measurements taken on multiple pavement sections throughout California over multiple years (Rezaei and Harvey 2013). Beginning in January 2006, the project included two years' worth of field measurement of tire/pavement noise and other surface properties of asphalt pavements, laboratory testing of field cores, modeling, and performance predictions (Ongel et al 2008). A follow-on study, PPRC SPE 4.19, began in September 2007 and updated the earlier performance estimates using a third year of measurements on most of the pavement sections included in the PPRC SPE 4.16 (Lu et al. 2009). The QPR study continued with measurements taken in 2008 and 2009 under PPRC SPE 4.27 (Lue et al. 2011) and in a fifth year under SPE 4.29 in 2009 and 2010 (Rezaei and Harvey 2012). The results from the study's sixth year, which combined the data from all six years of measurements, were summarized in a final report (Rezaei and Harvey 2013). Some aspects of those findings are presented throughout this report.

Chapter 4 includes a discussion of a limited Caltrans investigation of runoff water quality generated from two of its RHMA-O test sections.

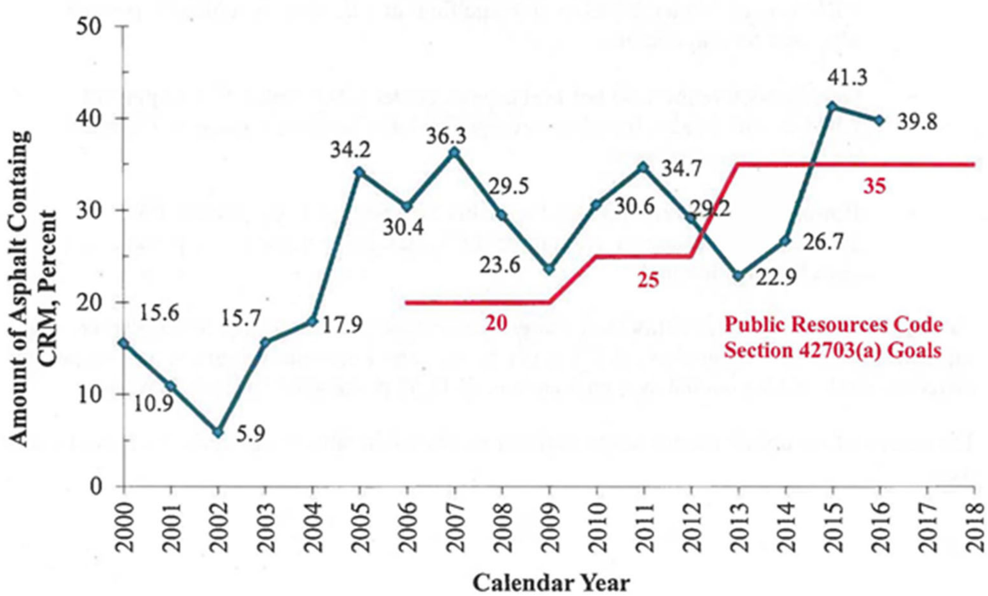


Figure 2.8: Percentage of total asphalt pavement containing CRM used by Caltrans as of 2017.
(Source: Caltrans 2016 crumb rubber report)

2.4.4.3 Florida DOT (FDOT)

The Florida Department of Transportation (FDOT) started using crumb rubber (CR) asphalt mixes in interlayers and seal coats about 45 years ago. FDOT allowed use of CRM in surface treatments and interlayers based on the findings of a project conducted in 1980 (Murphy and Potts 1980), and as of the time of this writing, SAMI binders in Florida include 20 percent CR by weight of asphalt to achieve a high-viscosity. Over the years FDOT has conducted extensive laboratory research and field experiments on its CRM pavements. Some of the department's findings are highlighted below.

In one study, FDOT investigated the effect of different grinding processes on the properties of asphalt rubber and found that GTR particles with more irregular shapes and a greater surface area produce asphalt binders with higher viscosities. The study also concluded that asphalt binders with cryogenically formed GTR have the greatest settlement and least drain down resistance of all the GTR types (West et al. 1996).

In a different study conducted between 1989 and 1990, FDOT conducted three demonstrations based on typical production projects to evaluate the constructability and short-term performance of asphalt rubber pavements with various amounts of GTR (Page 1992). The first two demonstration projects tested the stability and constructability of the mix designs by using different binder contents, which ranged from as low as 3 percent to as high as

17 percent, depending on the project objectives. The third demonstration project explored the sensitivity of dense-graded and open-graded mix properties to changes in CR particle size and binder content. These three projects are discussed below.

Three test sections and a control section were included in the first demonstration project. In this part of the study, three GTR-modified binders with 3, 5, and 10 percent CR by total weight of binder were used. All the mix designs were developed using the Florida DOT Marshall Mix Design procedure. The binder content of the control section was 7 percent; and the base binder and rubber binder contents of the three test sections were 3, 5, and 10 percent, and 7.22, 7.37, and 8.25 percent, respectively. During construction and placement of the mixes, problems, such as mix pickup by rollers and mix tenderness, were observed with the 10 percent CRM mix. The tests on plant-produced materials indicated that all the sections had Marshall stability values similar to the design values except for the mix containing 10 percent CRM; that mix had a stability value that was half of the design value. It was hypothesized that this reduced stability was due to high binder content and low fines particles (Page 1992).

The second demonstration project included four test sections and a control section. In this part of the study, four GTR-modified binders were used with 5, 10, 15, and 17 percent CR by total weight of binder. A total binder content of 6.3 percent was selected for the control section, and the binder contents of the sections with 5, 10, 15, and 17 percent CRM were 7.16, 8.11, 9.18, and 10 percent, respectively. The construction process indicated that the mixture with 10 percent CR had the best constructability (Page 1992).

The third demonstration FDOT project included construction of four different test sections. The results of this part of the study indicated that dense-graded mix properties are more sensitive to changes in CR particle size and binder content than those of open-graded mixes. This sensitivity was attributed to the lower amount of void spaces available in dense-graded mixes.

Based on the results of the previous three demonstration projects, FDOT drafted specifications for crumb rubber use in asphalt pavement surface courses that were validated by other researchers (Choubane et al. 1999) and which are still in use. For the dense-graded and open-graded surface courses, the CR amount was limited to 5 and 12 percent by weight of asphalt cement, respectively. The maximum sizes selected for ground rubber were 300 mm (No. 50 sieve) for dense-graded mixes and 600 mm (No. 30 sieve) for open-graded mixes (Page et al. 1992).

Starting in 1999, a new study was conducted to evaluate the performance of those three earlier demonstration projects for 10 years (FDEP 2011). The major finding of this evaluation was that adding scrap tire rubber to asphalt pavements using the wet process improves the crack resistance of surface mixtures. The test sections constructed using CRM mixes showed cracking on approximately 1 to 6 percent of their surface, depending on the amount of CR. However, the sections constructed with mixes containing virgin binder or dry-process mix showed cracking on about 30 percent of their surfaces. The study included a recommendation to use CR amounts in the 10 to 15 percent range to obtain optimum rubber content (Choubane et al. 1999). According to the Florida Department of Environmental Protection (FDEP), Florida is the only state that uses modified rubber asphalt in the surface course of all state-maintained roads (FDEP 2011). In the most recent revision of FDOT asphalt mixture guidelines, the use of scrap tires in asphalt friction courses and membrane layers was approved (Ellis et al. 2014).

FDOT recently completed a study assessing the mechanical performance and durability of open-graded friction course FC-5 mixtures fabricated with a highly polymer-modified (HP) binder (Arámbula-Mercado et al. 2019). The HP binder complied with the requirements of Section 916-2 of FDOT specifications (FDOT 2019). Several sample specimens were prepared with the FC-5 mixture and HP-modified binder, and the performance results were compared with those sample fabricated with a conventional mixture and a polymer-modified asphalt (PMA) binder. This research study was carried out by conducting comprehensive experimental tests, finite element (FE) computational mechanical simulations, and a life cycle cost analysis (LCCA). The testing included measurements of linear viscoelasticity (LVE), surface free energy (SFE), fatigue cracking, and creep recovery on both binder types under different aging conditions. LVE and SFE testing were performed on samples with both binders and two aggregate types (i.e., limestone and granite). The fracture and durability tests were performed on FC-5 mixtures fabricated with a combination of two binders and two aggregates under different aging conditions. The results obtained from this study showed that the PMA binder and PMA mastics had better LVE properties than the HP binder and mastics. However, the HP binder and HP mastics had superior fatigue cracking and creep recovery in all aging states. The fracture tests conducted on the FC-5 mixtures corroborated these results. The durability tests—which were conducted using the Cantabro test with multiple cycles—also demonstrated that FC-5 mixtures with HP binder were significantly more durable than those with PMA binder. Numerical FE simulations conducted in a long-term aging state indicated that FC-5 mixtures with HP binder were less prone to raveling under operational field conditions. The LCCA showed that the extended service life of FC-5 mixtures with HP binder offered a cost-effective alternative to conventional PMA binder.

PG 76-22 is one of the most commonly used binders in Florida. The state allows the use of both rubber-modified binder (PG 76-22 [ARB]) and polymer-modified binder (PG 76-22 [PMA]) in OGFC mixtures. The application of rubber-modified binder in Florida was mandated for highways with traffic levels below 10 million equivalent single axle loads (ESALs). However, when Florida moved to a market-driven approach for binder modifiers (either polymer or rubber), most contractors chose polymer-modified binders (Moseley 2019). The chart below

(Figure 2.9) clearly shows the gradual decrease in rubber-modified binder usage in the state. According to one study (Moseley 2019), the use of rubberized binder during fiscal year 2018 fell to less than 3 percent of the state's total binder use.

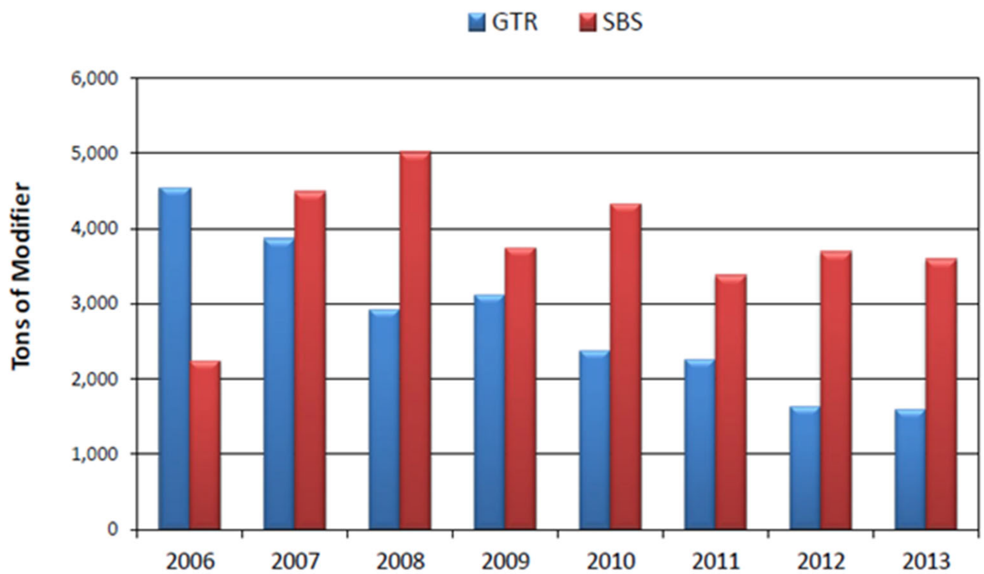


Figure 2.9: Usage of polymer and rubber-modified binder in Florida.
(Source: FDOT)

Even though numerous studies were performed to assess or improve the durability and functionality of OGFC pavements, up to now no stormwater quality investigations have been performed on RHMA-O projects in Florida (Moseley 2019).

2.4.4.4 Texas DOT (TxDOT)

Texas Department of Transportation (TxDOT) has 40 years of experience using asphalt rubber in the construction and rehabilitation of pavements. In Texas, crumb rubber (CR) has been used in four different types of pavement construction: chip seal coats, underseals, HMA, and OGFC (Estakhri et al. 1992). In one study, researchers evaluated the performance of nearly 800 miles of Texas seal coat and underseal projects constructed from 1976 to 1981. The results indicated that using asphalt rubber binder in seal coat construction reduced alligator cracks and raveling more than using conventional HMA to construct the seals did (Shuler et al. 1982). In a later study, it was concluded that asphalt rubber chip seals are a good treatment option for Texas pavements (Freeman et al. 2002). Pavement evaluation results indicated that rubberized HMA projects have significantly better cracking and rutting resistance than conventional dense-graded HMA projects (Tahmoressi 2001). The TxDOT performance results also showed that all rubberized OGFC projects exhibited excellent performance, and that the resistance to cracking and raveling in asphalt rubber OGFC was particularly impressive. From a cost-benefit standpoint, OGFC represents the best application for asphalt rubber (Tahmoressi 2001).

TxDOT has performed several investigations of the water quality generated by runoff from OGFC pavements, and one of these investigations included both RHMA-O and OGFC overlays. Additional information on the latter investigation is presented in Chapter 4.

2.4.4.5 Georgia DOT (GDOT)

The Georgia Department of Transportation (GDOT) has performed a two-phase study examining the long-term performance of porous European mix (PEM) and stone matrix asphalt (SMA) pavements to which dry-process crumb rubber was added in two phases (Shen and Xie 2012; Shen et al. 2012). Phase I of the study included visual inspection of pavement surfaces in the field and laboratory evaluation of core samples. The field test sections were inspected for surface distress following the guidelines in the GDOT Pavement Condition Evaluation System (PACES) manual. The core samples were evaluated in the laboratory based on selected physical and durability properties, including the void ratio, permeability, density, Cantabro loss, and Marshall stability. The visual inspection results showed that the rubberized pavement performance almost equaled that of the polymer-modified PEM—with no rutting, raveling, or cracking—while the Cantabro testing revealed a higher mass loss after three years of service. After five years of service, the rubberized pavement performed slightly better in terms of rut depth, while the other visual indicators remained the same (Shen and Xie 2012). The rubberized SMA pavement had slightly higher Marshall stability and lower flow than the control SMA pavement, and had similar effects on the polymer-modified PEM's surface performance (Shen and Xie 2012).

Phase II of the project investigated the long-term performance of hot asphalt mixes containing crumb rubber modifiers (CRM) added in the dry and wet processes. Eight asphalt mixtures—four PEMs and four SMAs—were designed with PG 76-22 modified with a CRM that was added by either the dry or the wet process. These mixes were compared with control mixes that included a styrene-butadiene-styrene (SBS)-modified PG 76-22. Mixes incorporating a "hybrid"-modified PG 76-22 were also evaluated. First, the samples were weathered in the Georgia Weathering Asphalt Device for 1,000 hours and 3,000 hours than tested to determine their dynamic modulus, fatigue life, rutting, and Cantabro loss. Binders extracted from the weathered samples were then evaluated using a dynamic shear rheometer (DSR), gel-permeable chromatography (GPC), and Fourier transform infrared spectroscopy (FTIR). Second, the interactions of dry- and wet-processed CRM with asphalt binder were compared during storage and paving. Results obtained by Shen et al. (2012) indicated that: (1) adding trans-polyoctenamer rubber (TOR) to the CRM binder improved PG grade and separation resistance; (2) the dynamic modulus of both rubberized PEM and SMA in dry process did not differ significantly from that of the control mixtures or mixtures using the "hybrid"-modified binders before and after weathering; (3) the fatigue life (Nf) of unaged rubberized PEM and SMA in the dry process was similar to that in wet process, although lower than that of control SBS; (4) after 3,000-hrs aging, the fatigue life of the dry-processed rubberized SMA was similar to that of the wet-processed but lower than that of the hybrid and SBS SMA, regardless of strain and stress levels or test temperatures; (5) the rutting and Cantabro loss of the rubberized PEM and SMA in the dry process samples were higher than those of the control SBS after weathering; and (6) CRM and asphalt binder interact during the production and paving stages based on DSR, GPC, FTIR, and AFM results. The effect of weathering on the properties of the asphalt binders in the rubberized, dry-processed PEMs and SMAs was similar to that in the wet-processed mixtures but greater than that in the control SBS.

2.4.4.6 New Mexico DOT (NMDOT)

In 1984 the New Mexico Department of Transportation (NMDOT) had its first experience with a rubberized HMA pavement prepared via the dry process. This pavement's performance was monitored for nine months and it was found to have performed well structurally during winter months. During hot weather, however, the pavement lost structural capacity and failed. In 1985, NMDOT constructed its first wet-process rubberized pavement, and within its first year of service the pavement surface showed excessive premature cracking. After these two unsuccessful projects, NMDOT stopped using crumb rubber in asphalt pavements for 10 years (Tenison 2005). Then, in 1994, NMDOT constructed six rubberized open-graded friction course—specifically, RHMA-O—projects. Performance monitoring of these RHMA-O sections indicated that they performed better than conventional OGFC pavements in the state. It was also reported that cost of RHMA-O was 33 percent higher than that of conventional OGFC (Tenison 2005). For this reason, NMDOT does not use RHMA-O except for specific reasons.

2.4.4.7 Oregon DOT (ODOT)

From 1985 to 1994, the Oregon Department of Transportation (ODOT) constructed 17 test sections using crumb rubber mixes based on both the dry and the wet process throughout the state. These test sections were evaluated through visual condition ratings (based on ODOT's modified SHRP method) and the ride values measured by a South Dakota-type profilometer. The results indicated that performance of the dense-graded wet process and dry process crumb rubber mixes was noticeably worse than the control sections. However, the rubberized open-graded mix (RHMA-O) with 12 percent rubber content passing a 180-µm sieve (No. 80 sieve) performed slightly better than the control section. No construction issues were encountered with gap-graded dry-process mixes, but raveling occurred shortly after construction. It was concluded that among the sections tested, the dry-process mixes exhibited the worst performance. It was also indicated that higher temperatures were needed in field operations for mixes with high-viscosity rubber binders than for unmodified control mixes (Hunt 2002). Currently, ODOT does not recommend the use of OGFC in the state's colder and higher elevation regions.

2.4.4.8 Washington State DOT (WSDOT)

The Washington State Department of Transportation constructed three OGFC pavement projects—in the cities of Lynwood, Medina, and Bellevue—and monitored their performance for noise reduction and durability (pavement wear), and then evaluated them in a life cycle cost analysis (Anderson et al. 2013). Each of the projects included an open-graded friction course built with sections containing crumb-rubber (OGFC-AR) and polymer-modified (OGFC-SBS) asphalt binders. Their performance was compared with control sections of traditional 1/2-inch HMA pavement. The binder properties and aggregate gradation of the OGFC-AR and OGFC-SBS mix designs are summarized in Table 2.6 and Table 2.7, respectively. The mix design for the OGFC-AR on the Lynnwood project was based on the Arizona Department of Transportation's rubberized OGFC mix design. The OGFC-AR mixes for the Medina and Bellevue projects were prepared in-house and they differed slightly from the ADOT design used for Lynnwood. One big difference in the Bellevue project was the use of hydrated lime as an anti-stripping additive, as ADOT specifies hydrated lime for all of their HMA mixes.

Table 2.6: Mix Design Binder Properties of Three WSDOT Rubberized and Non-Rubberized OGFC Projects

Project	Asphalt Content (%)	Binder Grade	Rubber Content (%)	Anti-Stripping Additive (%)
Rubberized OGFC (OGFC-AR)				
Lynnwood	9.2	PG64-22	22.0	ARR-MAZ 6500 (0.50)
Medina	8.8	PG64-22	23.5	ARR-MAZ 6500 (0.25)
Bellevue	9.4	PG64-22	20.0	Hydrated Lime (1.0)
OGFC Modified with SBS (OGFC-SBS)				
Lynnwood	8.3	PG 70-22	3.4±1	ARR-MAZ 6500 (0.25)
Medina	8.8	PG 70-22	3.4±1	ARR-MAZ 6500 (0.25)
Bellevue	8.6	PG 70-22	3.4±1	Hydrated Lime (1.0)

Data source: Anderson et al. (2013)

Table 2.7: Mix Design Aggregate Gradations Used for the Three WSDOT Rubberized and Non-Rubberized OGFC Projects

	Sieve Size			
Project - Pit Source	**3/8**	**#4**	**#8**	**#200**
Rubberized OGFC (OGFC-AR)				
Lynnwood - B-335	100	34	8	1.5
Medina - B-335	100	31	8	1.6
Bellevue - A-189	100	35	8	1.9
OGFC Modified with SBC (OGFC-SBS)				
Lynnwood - B-335	100	37	10	2.1
Medina - B-335	100	36	12	2.3
Bellevue - A-189	100	38	12	2.0

Data source: Anderson et al. (2013)

The test sections were constructed between 2006 through 2009, and each was monitored for four years. The monitoring results showed that the rubberized and SBS-modified OGFCs sections were quieter than the control HMA. The rutting/wear on both OGFC-AR and OGFC-SBS test sections were higher than on the control HMA section. Rutting/wear on two of the projects exceeded the depth of the rubberized overlay and reached a level that would require early replacement of the pavement. The increases in noise and rutting/wear occurred primarily during the time periods when studded tires were legal in the state and are believed to be the primary cause of these increases. The life cycle costs of the OGFC pavements with respect to noise reduction were 8 to 12 times higher than the HMA, making them unrealistic choices. The life cycle costs with respect to pavement performance were double for the OGFC-AR. Based on the monitoring results of the three test section projects, WSDOT concluded that the application of OGFC-AR and OGFC modified with SBS were not a viable option as a noise mitigation strategy for the state.

2.4.5 Application of RHMA-O by Transportation Agencies outside the United States

While OGFC application is common in Europe and many other parts of the world, RHMA-O application is not. The minimal use of CRM in rubberized asphalt pavements abroad can be correlated with a lack of regulations mandating scrap tire use for pavements, and many non-US transportation agencies are still experimenting with RHMA-O applications. This literature review found that only a limited number of transportation agencies outside the United States have used crumb rubber as a modified binder in open-graded friction course pavements; the ones that have include Portugal, China, and Brazil (Way et al. 2012). Summary discussions of these countries' experience with RHMA-O application appear below.

2.4.5.1 Portugal

Portugal began to use RHMA-O surfaces in 2003 to provide a smooth riding surface, good wet-weather skid resistance, and less tire-pavement noise (see Figure 2.10). The RHMA-O was reported to have a noise level 5 to 6 dBA lower than a typical dense-graded hot mix asphalt and 8 to 10 dBA lower than a typical concrete surface (Way et al. 2012).

Figure 2.10: Dense-graded asphalt cement (AC) hot mix and asphalt rubber open-graded friction course (ARFC) surfaces in Portugal.

2.4.5.2 China

During 2010 it was reported that 300 hundred million scrap tires were generated in China (Way et al. 2012). The estimated number of scrap tires generated there currently exceeds 400 million annually. In the 1980s a few laboratory and field tests were conducted using dry-process-generated scrap tire rubber in dense-graded hot mix asphalt pavements. In 2004, experiments using tire rubber modifier produced by both the dry and wet processes began. Between 2004 and 2007, many experimental test sections and test projects were constructed using asphalt rubber as a chip seal coat interlayer referred to as a *stress absorbing interlayer* (SAMI). Test sections of RHMA-O hot mixes were also constructed using a mix design gradation closely approximating the materials placed in Arizona (see Figure 2.11). From 2007 until the time of this writing, the use of wet-process asphalt rubber has grown, like it has in the United States. It is also worth noting that in China, RHMA-O surfaces are typically 25-mm thick, with rubberized asphalt content ranging from 8 to 9 percent binder by weight of the mix. Their Marshall stabilities ranged from 2.8 to 3.8 kN and their flow values ranged from 30 to 36 (0.1 mm). The reported water permeability on average after construction was about 1L per minute by Chinese test (Cao et al. 2009).

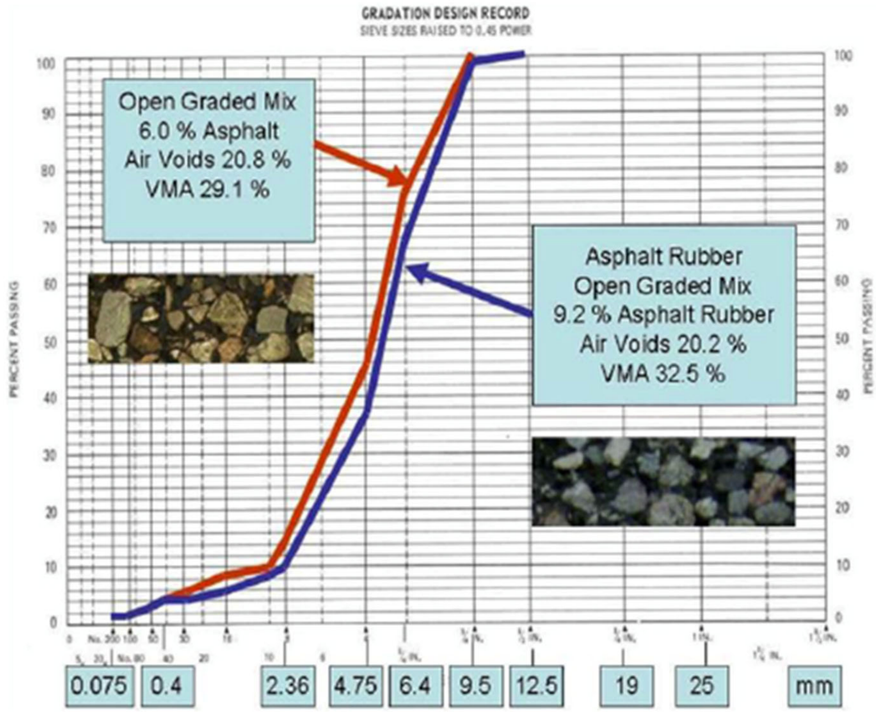


Figure 2.11: Arizona DOT rubberized and non-rubberized OGFC gradation and binder content.

With AR use in China increasing, attention has turned to measuring the tire/pavement noise of various pavement surfaces. Reported noise measurement results (Cao et al. 2009) have shown that RHMA-O produced the lowest noise levels among the pavement types tested. It was reported that RHMA-O noise was 5 to 6 dBA lower than a typical dense-graded asphalt hot mix and 8 to 10 dBA lower than a typical concrete surface (Cao et al. 2009).

Another study performed in China by Yu et al. (2015) collected performance data for one OGFC section and two dense-graded control sections under high speeds and heavy truck loads. The performance investigation covered permeability, skid resistance (microtexture level and macrotexture level), rutting, roughness, and noise on truck lanes, passenger car lanes, and overtaking lanes. The overall assessment was that the three pavement sections provided satisfactory performance over the investigation period. However, the OGFC section alone lost its permeability substantially during its service life and gradually lost its skid resistance and the noise-reduction capabilities.

2.4.5.3 Brazil

A rubberized open-graded friction course was first commissioned by the Rio de Janeiro State Highway Department for the Highway RJ-122 project in Rio de Janeiro province (Way et al. 2012). The existing highway pavement was paved during the 1970s and its surface was extensively cracked, which made driving on it unsafe and uncomfortable (see Figure 2.12). This highway's traffic volume was high and composed mainly of heavy trucks, and therefore the pavement needed to be rehabilitated to handle heavy loads. As a result, a rubberized pavement mix design was selected for the Highway RJ-122 overlay project (Pinto and Sousa 2012).

Figure 2.12: Highway RJ-122 pavement in Brazil before and after overlay placement with an ARFC surface.

The overlay constructed on the existing highway consisted of three layers of a dense-graded hot mix leveling and reshaping layer, followed by application of a 4.5-cm asphalt rubber gap-graded structural layer and a 2.5-cm asphalt rubber open-graded surface (see Figure 2.13). The completed highway RJ-122 overlay pavement's structural and functional characteristics have received the highest ranking of all the pavements in Brazil's federal and state networks (Way et al. 2012). Of particular note were its excellent skid resistance, with its 0.7 value, and ride smoothness.

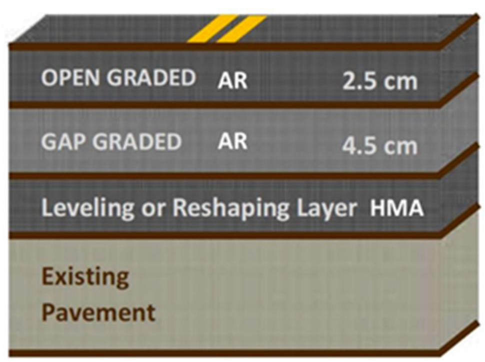


Figure 2.13: New pavement structure in Brazil with 2.5 cm of open-graded asphalt rubber and 4.5 cm of gap-graded hot mix asphalt rubber.

The Brazilian top layer RHMA-O mix was prepared with a rubberized asphalt content of 8.5 percent binder by weight of the mix. The aggregate gradation used in Brazil was the same as the Arizona RHMA-O mix (see Chapter 3). The RHMA-O and supporting structure was evaluated in place with use of a heavy vehicle simulator

(HVS). The HVS applied a 15-ton dual tire load to the RHMA-O surface at a rate of 1,000 wheel passes per hour. Approximately, 150,000 wheel loadings were applied to simulate the long-term wear (10 to 20 years) of very heavy traffic (i.e., representing 2,500,000 ESALs). The simulation results showed that (1) the falling weight deflection of the center geophone went from 25 to 33, which is well below the accepted Brazilian failure criterion of 64; (2) there was no observed cracking after the loading was completed; (3) the permanent deformation (rut depth) was 3.7 mm after loading, also below the Brazilian design failure criterion of 7 mm; (4) the British pendulum test was 52 before loading and 53 after loading, which is well above the Brazilian design failure criterion of 47; and (5) the sand patch was 89 mm before loading and 90 after loading, which was well within the Brazilian acceptance band of 0.6 to 1.2 mm.

3 REVIEW OF OGFC AND RHMA-O MIX DESIGNS USED IN THE UNITED STATES AND ABROAD

To properly compare and evaluate the performance of the varied rubberized and non-rubberized OGFC pavements used in different studies and among different transportation agencies, it is important to understand their different mix designs. Mix design variability also plays an important role in assessing these pavements' required maintenance issues and their runoff water quality. Both rubberized and non-rubberized OGFC pavements must be permeable enough to drain surface runoff and discharge it away from the surface and off the roadway; they must also provide acceptable performance and have a long service life. Constructing suitable rubberized or non-rubberized OGFC mixtures generally requires three major components: (1) high-quality materials, (2) a well-designed gradation, and (3) optimum binder content. A newer generation of OGFC mixtures may also include additives such as modified binders, stabilizing agents, and fillers or anti-stripping agents. Unfortunately, no standard mix design is available and the numerical values suggested for aggregate gradation, binder content, and additives range widely. Because of that, multiple mix designs have been prepared and are practiced by different state departments of transportation (DOTs) and international transportation agencies. This chapter will examine some of the differences in mix designs used in the United States and abroad, and will then evaluate the performance of these pavements with respect to their durability, function, water quality treatment, and maintenance issues.

3.1 Non-Rubberized OGFC Mix Designs Used in the United States

As noted earlier, 25 state DOTs in the United States currently use non-rubberized OGFCs primarily for safety and noise reduction, although the transportation departments in Texas, North Carolina, and California have only performed limited water quality evaluations of these pavements. TxDOT is the only such agency to perform water quality evaluations of runoff from both OGFC and RHMA-O overlays. The data collected so far is insufficient to allow a correlation analysis of mix design and water quality characteristics to be undertaken. Instead, what follows examines some of the subtle differences that exist among the various mix design parameters used by different DOTs.

3.1.1 Variability in Type and Quality of Aggregate

Granite, limestone, gravel, and sandstone are the most commonly used aggregate types in the US, although some state DOTs also consider traprock and blast furnace slag for their OGFC mix designs. Based on the survey results of aggregate use discussed in Chapter 2, 14 states use granite, 11 use limestone, and 5 use gravel. To ensure that the mix design includes high-quality aggregates, they must meet the physical characteristics specified in Table 3.1. Each characteristic's importance level has been ranked according to a survey from National Cooperative Highway

Research Program (NCHRP) Report 640 (Cooley et al. 2009). The typical values shown in the table were summarized based on existing OGFC specifications from several different transportation agencies. As can be seen, typical values for aggregate characteristics range widely and this factor alone makes it more difficult for inexperienced pavement engineers to select an appropriate design gradation. In addition, the large variation makes it harder for states lacking experience with OGFC construction.

Table 3.1: Required Physical Characteristics for Aggregates in OGFC Mix Designs

Characteristic	Importance Level	Test Method	Test Indicator	Typical Values
Polish resistance	1	AASHTO T 278, T 279	Polished Stone Value	45-60 (min.)
Durability	2	AASHTO T 104	Soundness loss	12-20 % (max.)
Angularity	3	ASTM D7064	Fractured face count	2 or more fractured faces: 75-95% (min.)
Abrasion resistance	4	ASTM C131, AASHTO T 96	Abrasion loss	12-50% (max.)
Shape	5	ASTM D4791	Percentage of flat and elongated particle	5:1 ratio: 5-10% (max.) 3:1 ratio: 20% (max.)
Cleanliness	6	ASTM D2419, AASHTO T 176	Sand Equivalency	45-55% (min.)
Absorption	7	ASTM C127	Water absorption	2-4% (max.)

Adapted from Watson et al. (2018)

3.1.2 Variability in Aggregate Size Gradations

Besides an aggregate's physical characteristics, selection of an appropriate aggregate gradation is among the most important factors to consider in preparing a suitable OGFC mix design. Two rules of thumb to be followed when selecting a suitable aggregate gradation for an OGFC mix design: (1) the gradation must allow coarse aggregates to come into contact, and (2) the gradation must guarantee highly connected air void spaces. Generally, three gradations limits are evaluated: the coarse limit, the fine limit, and the middle of the recommended gradation limit. However, at the time of this writing, there is no accepted standard for OGFC mix design gradation in the United States. For this reason, each DOT usually develops its own mixed aggregate gradation. Table 3.2 lists the aggregate gradations for OGFC mixtures that are currently used by different US state DOTs. As can be seen, depending on the application, some DOTs have developed more than one aggregate gradation. The table also shows the aggregate gradation recommended by the National Center for Asphalt Technology (NCAT). The NCAT-recommended gradation band gaps at sieves 9.5 mm and 4.75 mm, with ranges from 35 to 60 percent passing the 9.5 mm sieve and 10 to 25 percent passing the 4.75 mm sieve. This gradation is also documented in ASTM D7064, *Standard Practice for Open-graded Friction Course Mix Design.* The table also shows that most states use aggregate gradations that deviate from the recommended NCAT mix gradation, and from each other. Most DOTs primarily use a 19.0 mm maximum aggregate size design, and the majority of them are gapped between the 9.5 mm sieve and the 4.75 mm sieve. The aggregate gradations for Alabama, Georgia, Louisiana, and South Carolina are almost identical and closely resemble NCAT's recommended mix gradation. In addition, the OGFC mixtures use substantially lower amounts of fine aggregates than conventional dense-graded hot mix asphalts (DGHMAs). However, states also use different fine aggregate percentages. The upper limit for Caltrans fine aggregate is the highest among all the state DOTs. Caltrans RHMA-O mixes use either a 3/8 or 1/2 inch (9.5 or 12.5 mm) maximum size gradation. These higher fines contents and smaller maximum sizes result in the Caltrans open-graded mixes having lower air-void contents and permeability than those of many other states. Long-term permeability and void content measurements of different open-graded paved surfaces (rubberized and non-rubberized) throughout California have shown that permeability diminished slightly with accumulated traffic activity and pavement age (Rezaei and Harvey 2013).

3.1.3 Asphalt Base Binder Specifications and Binder Modifications

OGFC mixes have been constructed successfully with both modified and unmodified binders, although use of modified binders has become prevalent since they are effective at increasing the service life of OGFC pavements and preventing draindown from OGFC mixtures. In the United States, the most common modifiers for OGFC mixtures are rubber (e.g., crumb rubber modifier and ground tire rubber) and styrene-butadiene-styrene (SBS) polymer. These modifiers can provide OGFC mixtures with a stiffer asphalt binder, which leads to increased cohesion in the aggregate stone skeleton. For this reason, OGFC mixes with modified asphalt binders usually have higher resistance to rutting, cracking, and raveling, and exhibit better durability in the field.

At present, only some US state DOTs and European agencies abroad specify a particular binder type. Those that do specify a required binder type for construction of OGFC and for porous European mixes (PEMs) are presented in Table 3.3. It is important to note that binder types in the United States are graded using the performance-grading (PG) system and in European countries the penetration grading (pen) system is used.

Table 3.2: Aggregate Gradation Specifications for OGFC Mixtures Used by Different State DOTs

State DOT	OGFC Mix Aggregate Gradation							
	19 mm (3/4")	12.5 mm (1/2")	9.5 mm (3/8")	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	0.6 mm (No. 30)	0.075 mm (No. 200)
AL	100	85-100	55-65	10-25	5-10	-	-	2-4
AZ1	-	-	100	30-45	4-8	-	-	0-2
AZ2	-	-	100	31-46	5-9	-	-	0-3
CA1	-	95-100	78-79	28-37	7-18	-	0-10	0-3
FL	100	85-100	55-75	15-25	5-10	-	-	2-4
GA1	-	100	85-100	20-40	5-10	-	-	2-4
GA2	100	85-100	55-75	15-25	5-10	-	-	2-4
GA3	100	80-100	35-60	10-25	5-10	-	-	1-4
LA1	-	100	90-100	25-50	5-15	-	-	2-5
LA2	100	85-100	55-75	10-25	5-10	-	-	2-5
MS	-	100	80-100	15-30	10-20	-	-	2-4
NC1	-	100	75-100	25-45	5-15	-	-	1-3
NC2	-	100	75-100	25-45	5-15	-	-	1-3
NC3	100	85-100	55-75	15-25	5-15	-	-	2-4
NE	100	95-100	40-80	15-35	5-12	-	-	0-3
NJ1	-	100	89-100	30-50	5-15	-	-	2-5
NJ2	100	85-100	35-60	10-25	5-10	-	-	2-5
NJ3	-	100	85-100	20-40	5-10	-	-	2-4
NM	-	100	90-100	25-55	0-12	-	0-8	0-4
NV1	-	100	90-100	35-55	-	5-18	-	0-4
NV2	-	100	95-100	40-65	-	12-22	-	0-5
OR1	-	99-100	90-100	22-40	5-15	-	-	1-5
OR2	99-100	90-98	-	18-32	3-15	-	-	1-5
SC	100	85-100	55-75	15-25	5-10	-	-	0-4
TN	100	85-100	55-75	10-25	5-10	-	-	2-4
TX1	100	80-100	35-60	1-20	1-10	-	-	1-4
TX2	100	95-100	50-80	0-8	0-4	-	-	0-4
NCAT	100	85-100	35-60	10-25	5-10	-	-	2-4

Adapted from Watson et al. (2018)

3.1.4 Additive Stabilizing Agents

Stabilizing additives are generally added to OGFC pavements for two reasons: (1) to improve the durability of OGFC mixtures by preventing draindown and (2) to increase pavement tensile strength. Draindown can occur during the production and transportation of an OGFC mix, and when it does occur, a significant amount of the mix's asphalt binder will be lost. This binder loss can decrease pavement durability and, consequently, may lead to premature raveling or cracking development. According to the results of a survey by Colley et al. (2009), the most common stabilizers state DOTs use are cellulose fiber (15 states) and mineral fiber (11 states), and crumb rubber (4 states). Warm mix asphalt (WMA) technology can eliminate the need to add stabilizing agents, but not many DOTs have fully implemented the technology yet. Stabilizing agents are typically added to an OGFC mixture at a rate of 0.2 to 0.5 percent by total weight (Cooley et al. 2009). Cellulose fiber has high absorption so it enables keeping the binder content high and reinforces the asphalt film. Mineral fibers exist in two forms: manufactured and naturally occurring. Asbestos, the only naturally occurring fiber, was used as mineral filler in asphalt pavements in the 1960s until its negative human health impact was discovered. The most common manufactured mineral fibers are mineral wool and rock wool. Manufactured mineral fibers are not as absorbent as cellulose fiber and can sometimes create harsh mixtures that are hard to compact.

Table 3.3: Binder Types Specified by US DOTs and European Countries for OGFC Mix Designs

Transportation Agency	Specified Binder Type
United States DOTs	
Alabama	PG 76-22
Florida	PG 76-22, PG 76-22 HP, PG 76-22 PMB, PG 76-22 RMB
Mississippi	PG 76-22
North Carolina	PG 76-22, PG 64-22
Texas	PG 76-22
Virginia	PG 70-28
European Countries	
UK	100 pen
Italy	80/100 pen
Spain	80/100 pen

Partially adapted from Watson et al. (2018)

Fillers or anti-stripping agents are also recommended for OGFC mixtures sometimes to improve the bond between the aggregates and the asphalt binder, and to prevent moisture damage to the mixtures. Fillers and anti-stripping materials commonly used in OGFC mixtures include hydrated lime, limestone dust, and liquid anti-stripping agent.

3.1.5 Determination of the Optimum Binder Content

After a mix design gradation and binder type are selected, the optimum binder content (OBC) is determined. The three methods used to determine OBC are generally categorized as (1) absorption calculation, (2) visual determination, and (3) compacted-specimen evaluation. Finding OBC usually requires trials of three or four different asphalt contents, with a 0.5 percent increment above and below the initial asphalt content used.

The absorption calculation method utilizes the oil absorption capacity and the apparent specific gravity of aggregates to empirically estimate the OBC of an OGFC mixture. This method does not take into account the influence that binder type and aggregate type have on OBC. In addition, this method cannot ensure that an OGFC mixture with the design OBC will perform satisfactorily in the field.

The visual determination method refers to the pie-plate or Pyrex bowl test. In this method, approximately 1,000 grams of uncompacted OGFC mix is placed in a glass pie plate and oven-heated at 160°C for one hour. After that, the pie plate with mix is removed from the oven to cool to room temperature. Once it has cooled, the plate is inverted for a visual determination of whether or not the trial binder content is the OBC. This visual determination is extremely subjective, and requires an experienced technician/engineer to judge the results. To overcome this issue, Pernia et al. (2016) employed an image analysis technique to quantitatively determine the OBC of OGFC mixes. This approach is similar to the draindown test, which can evaluate the stability of an OGFC mix.

The compacted-specimen evaluation method directly targets the performance of an OGFC mixture to determine its OBC. The specimens are compacted either at a level of 50 gyrations using the Superpave gyratory compactor (SGC) or at a level of 50 blows per each side using a Marshall compactor. The following engineering properties of the compacted specimen are evaluated:

- Air voids, which are related to the permeability of pavement;
- Voids in coarse aggregate (VCA) of the dry-rodded aggregate (VCA_{DRC}) and VCA of the mix (VCA_{MIX}), which is to ensure stone-on-stone contact;
- Cantabro loss, which is related to durability;
- Draindown, which is related to stability;
- Permeability; and
- Tensile strength ratio (TSR), which is related to moisture susceptibility.

Table 3.4 summarizes OBC values for several mix properties determined with three compacted-specimen evaluation criteria used nationally to determine an OGFC mix's OBC. In general, the OBC values for these properties based on these three mix design criteria agree with each other. The compacted-specimen evaluation method is more desirable than the other two methods for reflecting the mix's field performance, but this method still cannot ensure the OGFC mix designed will provide satisfactory field performance. For example, the existing studies reported that some premature distresses including raveling, shoving, and excessive rutting, were found in OGFC pavements. This is because other important engineering properties (e.g., cracking and rutting resistance) should also be considered in OGFC mix design.

Table 3.4: Optimum Asphalt Binder Content Properties for OGFC Mixes Using Three Compacted Specimen Evaluation Methods

Mix Property	NCHRP 640	ASTM D7064	NAPA Series 115
Air Voids (%)	18 – 22	≥18	≥18
Unaged Cantabro Loss (%)	≤15	≤20	≤20
VCA_{MIX} (%)	$<VCA_{DRC}$	$\leq VCA_{DRC}$	$\leq VCA_{DRC}$
Tensile Strength Ratio	≥0.70	≥0.8	≥0.8
Draindown at Production Temperature (%)	≤0.3	≤0.3	≤0.3
Permeability, m/day (cm/sec)	100 (≈0.12)	100 (≈0.12)	100 (≈0.12)

Adapted from Watson et al. (2018)
VCA_{MIX} = Voids in coarse aggregate for the compacted mix
VCA_{DIR} = Voids in coarse aggregate for the dry rodded-condition

In 2013, Tsai et al. (2013) performed a study to determine optimum binder content (OBC) for OGFC mixes to suggest revisions to California Test 368, *Method of Test for Optimum Bitumen Content (OBC) for Open Graded Asphalt Concrete,* using OGFC mix designs proposed by the National Center for Asphalt Technology (NCAT). The study included three binder types (PG 64-10, PG 64-28 PM, and asphalt rubber [AR]), three aggregate types (Sacramento, Watsonville, and San Gabriel) and three gradations (coarse, fine, and middle). It was found that, regardless of binder or aggregate type, the optimum gradation selected per the NCAT approach—usually a coarse gradation with fewer fines—did not guarantee the success of an OGFC mix design. None of the mixes with a coarse gradation, fabricated using the optimum asphalt binder content, simultaneously met the criteria for percent air-void content, draindown, and Cantabro loss. The resulting test data also showed that binder type is the most significant factor affecting both draindown performance and Cantabro performance. The UCPRC study proposed a volumetric-based OGFC mix design including performance-related testing for rutting that will provide a better way to determine the initial binder content rather than basing it on the bulk specific gravity of the aggregate blend as suggested by NCAT (Tsai et al 2012). Permeability measurements could be added to the method proposed by UCPRC to further ensure that it meets performance-related requirements for reducing hydroplaning and improving stormwater quality.

3.2 Non-Rubberized OGFC Mix Designs Used in Europe

In Europe, OGFCs are currently referred to as *porous European mixes* (PEMs). The recommended aggregate mix for PEM design in Europe is similar to that recommended for OGFC mixes used in the US. A few small differences noted in aggregate gradation used in a typical PEMs and OGFC as shown in Table 3.5. As can be seen, PEM is more gap graded than OGFC and for this reason PEMs have higher void contents (for example, 18 – 22 percent in PEM compared to <18 percent for OGFC) and greater permeability than OGFCs (Watson et al. 1998). Also, aggregate standards are higher in Europe than in the United States (Huber 2000).

Table 3.5: Comparison of US OGFC and Europe PEM Aggregate Gradations

Sieve size Inch or sieve No. (mm)	Percent Passing for 12.5 mm Open-Graded Mix Design			
	Caltrans OGFC	Suggested US OGFC		European PEM
		FHWA	NCAT	
¾ in (19 mm)	100	100	100	100
½ in (12.5 mm)	95 – 100	85 – 100	85 – 100	90 – 100
3/8 in (9.5 mm)	78 – 79	55 – 75	35 – 60	35 – 60
No. 4 (4.75 mm)	28 – 37	15 – 25	15 – 25	10 – 25
No. 8 (2.36 mm)	7 – 18	5 – 10	5 – 10	5 – 10
No. 30 (0.595 mm)	0 – 10	–	–	–
No. 200 (0.075 mm)	0 – 3	2 – 4	2 – 4	1 – 4

Many European countries now construct PEMs on their highways, including Denmark, Germany, Sweden, The Netherlands, France, Italy, Spain, and the United Kingdom (Gibbs et al. 2005). PEMs in Europe are usually constructed for safety and noise reduction (Gibbs et al. 2005). While most European countries follow the recommended PEM mix design, a review of their mix designs nevertheless showed a wide range of aggregate gradations (Ongel et al. 2007). In general, however, while the European aggregate gradations use larger aggregate sizes, the Caltrans mix design allows the largest suggested fines percentage aggregate gradation of all the mix designs found in the literature review.

European countries generally are more satisfied with their OGFC pavements, and this may be attributable to multiple factors (Ongel et al. 2007). The major difference between the OGFCs used in Europe and the United States is that the European mix designs have higher coarse gradations, and are generally placed in thicknesses of 40 to 50 mm (1 1/2 to 2 inches). The nominal maximum aggregate size in European mixture ranges from 11 mm (7/16 inches) to 16 mm (5/8 inches). Smaller and larger size aggregates are used less frequently. Polymer-modified binders, fibers, and sometimes both are commonly used in European OGFC mixtures to obtain a thick, strong binder film that maximizes resistance to aging and raveling. One other important difference between European and US OGFC mix designs is related to air-void contents: these values in Europe range between 20 and 25 percent, while in the United States the air-void content values in open-graded mixes are less than 20 percent. Further, European mix designs specify either horizontal or vertical permeability, while the United States has no specifications for minimum permeability values. The tensile strength ratio is generally specified to be at least 50 percent in Europe OGFC mix design, but only a few US states specify a tensile strength ratio, and, if there is one, the required value is usually above 80 percent (Ongel et al. 2007).

3.3 Rubberized OGFC (RHMA-O) Mix Designs Used in the United States

3.3.1 Overview

As previously noted, more than half of US state DOTs have tried or are experimenting with use of crumb rubber modifiers (CRM) as part of their asphalt pavement construction. Initially, CRM use in the United States began because of a 1991 federal government mandate, but most states stopped using the material as soon as the mandate was dropped in 1995. At present, DOTs in only four states—Arizona, California, Florida, and Texas—still use rubberized OGFC pavements. These transportation agencies found that including CRM-modified paving materials in RHMA-O provides a number of benefits, including increased resistance to rutting, fatigue, and reflective cracking, and improved durability that results from a higher binder content than is present in conventional asphalt pavement (Caltrans 2005). However, without a regulatory mandate, most contractors prefer polymer-modified binder to rubber-modified binder when given a choice. Several international transportation agencies have also experimented RHMA-O use, but polymer-modified binder use is still more common. In general, international applications of RHMA-O are based on the mix design practiced in the US. Unfortunately, this mix design has not been standardized in the United States and for this reason current US RHMA-O users—the DOTs in Arizona, California, Florida, and Texas—use multiple mix designs. This literature review revealed a variability in the values and specifications in these DOT's mix designs that may influence the performance of RHMA-O pavement. The material that follows focuses on this variability and its results and considers the following major variable mix design parameters: (1) crumb rubber size gradation, (2) aggregate size gradation, (3) crumb rubber processing (wet versus dry), and (4) minimum rubber content and rubber binder specifications.

3.3.2 Variability in Crumb Rubber Size Gradation

The crumb rubber gradations selected and specified by the Arizona, California, Florida, and Texas departments of transportation, based on their grade (scrap tire or high natural rubber) for their respective asphalt rubber binders, are summarized in Table 3.6. The table shows that only Caltrans allows use of high natural rubber, which contains about 25 percent natural rubber, and that the other states use only scrap tire rubber. More important, none of these four states' gradations are the same and some use more fines than others. The higher fine gradation in rubber may contribute to draindown and low permeability, which in turn will cause a reduction in drainage infiltration and lower water treatment capability.

Table 3.6: Crumb Rubber Gradations Specified by Different State DOTs

Sieve size (% passing)	Gradation of Crumb Rubber Specified by DOTs for Different Type or Grade									
	Calt.	Calt.	TxDOT	TxDOT	TxDOT	ADOT	ADOT	FDOT	FDOT	FDOT
	ST	HN	ST, A	ST, B	ST, C	SC, A	ST, B	ST, A	ST, B	ST, C
2.36 mm (#8)	100	100	100	--	--	100	--	--	--	--
2 mm (#10)	98-100	100	95-100	100	--	95-100	100	--	--	--
1.18 mm (#16)	47-75	95-100	--	70-100	100	0-10	65-100	--	--	100
600 μm (#30)	2-20	35-85	--	25-60	90-100	--	20-100	--	100	70-100
425 μm (#40)	--	--	--	--	45-100	--	--	--	--	--
300 μm (#50)	0-6	10-30	0-10	--	--	--	0-45	100	40-60	20-40
150 μm (#100)	0-2	0-4	--	--	--	--	--	50-80	--	--
75 μm (#200)	0	0-1	--	0-5	--	--	0-5	--	--	--

Source: Way et al. (2011)
Calt. = Caltrans, ST = scrap tire rubber, NH = natural high rubber, A, B, and C indicate different type or grade of scrap tire rubber

3.3.3 Variability in Aggregate Size Gradation

Table 3.7 summarizes the aggregate size gradation that four leading state DOTs use for RHMA-O pavement application, and shows that the states' aggregate gradation sizes vary substantially. A major difference that can be seen is that California's mix design includes gradations with a higher percentage of fine aggregates than the other states' designs. This higher fine-aggregate content percentage in Caltrans mix designs may contribute to lower permeability and reduced water quality treatment (discussed in Chapter 4).

Table 3.7: Aggregate Gradations for RHMA-O Mixtures Specified by Four State DOTs

Gradation Size, mm (in. or sieve no.)	State DOT				
	Arizona	Florida	Texas	Caltrans (12.5 mm)	Caltrans (9.5 mm)
19 (3/4")	100	100	100	100	100
12.5 (1/2")	--	85-100	95-100	95-100	100
9.5 (3/8")	--	55-75	50-80	78-89	90-100
4.75 (No. 4)	30-45	15-25	0-8	28-37	29-37
2.36 (No. 8)	4-8	5-10	0-4	7-18	7-18
1.18 (No. 16)	--	--	--	0-10	0-10
0.75 (No. 200)	0-2.5	2-4	0-4	0-3	0-3

Data source: Caltrans (2005)

3.3.4 Variability in Crumb Rubber Processing

As discussed in Chapter 2, the crumb rubber required to produce the modified binder for asphalt pavement applications can be processed differently, using either a dry or a wet process. In general, when rubberized asphalt is used for OGFC construction a high viscosity binder is required, and it is important to note that the process used to treat the crumb rubber can influence its qualities, and therefore those of the binder. For example, TxDOT uses wet-process high-viscosity binders for their open-graded friction course, but wet-process, no agitation binders can be used in any TxDOT dense-graded mix as a substitute for a performance-graded or viscosity-graded binder. FDOT does use wet process rubber in both open-graded and dense-graded friction courses, but Caltrans has a moratorium on use of high-viscosity binders prepared by wet processing only in their open-graded mixes. ADOT has allowed use of PG 76-22 TR+ as a substitute for high-viscosity binders in some gap-graded mixes, but considers the no-agitation binder to be a different material than its high-viscosity binders, which results in a binder content decrease as large as 2 percent when it is used as a substitute. Therefore, as noted, in general, the wet process is the preferred processing method when preparing high-viscosity rubberized OGFC pavement. More information from recent research on the impact of crumb rubber processing on RHMA-O pavement performance will be discussed in Section 3.4.

3.3.5 Variability in Minimum Rubber Content and Rubber Specifications

Minimum CRM content and the other related specifications designated by ASTM and the states of Arizona, California, Florida, and Texas for design and construction of RHMA-O are summarized in Table 3.8. As shown, ASTM and the state DOTs other than Caltrans specify scrap tires as a rubber source. Caltrans asphalt rubber binder (ARB) is instead a combination of asphalt binder, asphalt modifier, and CRM, which is defined as ground or granulated scrap tire crumb rubber plus high natural scrap tire crumb rubber. Ground scrap-tire rubber and natural scrap-tire rubber are both derived from recycled tires. CRM is comprised, respectively, of 75 percent scrap-tire crumb rubber and 25 percent high-natural crumb rubber by total weight of the CRM. The combined asphalt binder and asphalt modifier content is 80 percent of the total weight of the ARB, and the CRM content is 20 percent of the total weight of the ARB. Between 2 and 6 percent of the total weight of asphalt binder is asphalt modifier.

Another important variability is related to the amount of CRM used in RHMA-O pavements. For instance, the TxDOT and Caltrans specifications base rubber content on the weight of binder, whereas the Arizona and Florida specifications base rubber content on the total weight of the mixture. This difference in minimum CRM content can significantly influence the performance of RHMA-O pavements. Variations in minimum and maximum interaction temperature and in minimum interaction time also exist. These variations in CRM content and other related specifications may explain the different states' and researchers' findings regarding RHMA-O performance. This is discussed further below.

Table 3.8: Minimum CRM Contents and Other Related RHMA-O Mix Specifications Used by Different State DOTs and the ASTM Recommendation

Parameter	State DOT				ASTM
	ADOT	FDOT	TxDOT	Caltrans	
CRM type	ST	ST	ST	HN	ST
Min CRM content (%)*	20	12	15	20	15
Base asphalt cement grade	PG 64-16 PG 58-22 PG 52-28	PG 64-22	PG 58-28 PG 64-22	PG 64-16	NS
Asphalt modifier (extender oil) content (%)	NA	A/NU	A/NU	2.5-6.0	A/NU
Minimum interaction temperature	163 °C	150 °C	--	190 °C	177 °C
Maximum interaction temperature	190 °C	175 °C	--	226 °C	190 °C
Minimum interaction time (min)	60	15	--	45	UD

Notes: A = allowed, NA = not allowed, A/NU = allowed/ not used, UD = user defined, NS = not specified, ASTM = American Society for Testing and Methods; ST = scrap tire rubber; HN = high natural rubber that is 25% natural rubber and 75% scrap tire rubber

*The minimum CRM content for TxDOT is based on the total weight of the binder, and the minimum CRM content for ADOT, FDOT, Caltrans, and ASTM is based on the total weight of the pavement.

3.4 Laboratory and Field Investigations to Optimize Mix Design Performance

Numerous laboratory and field investigations have been conducted to optimize the performance of OGFC or RHMA-O mix designs based on single and multiple design variables. While none of these laboratory or field studies specifically focused on water quality evaluation, these performance assessments may indirectly impact a mix design's ability to improve water quality. For instance, mix design optimization based on aggregate size and increased void content will improve pavement permeability and hence enhance an open-graded pavement's ability to improve water quality treatment. The laboratory and field performance optimization studies are organized by what they focused on: aggregate size gradation, asphalt base binder specification, asphalt binder modification, stabilizing additives, and optimum binder content.

3.4.1 Performance Optimization Based on Aggregate Size Gradation

The influence of aggregate size gradation on OGFC or RHMA-O pavement performance has been investigated by numerous researchers. Lu et al. (2009) performed a series of experiments to investigate the effects of several important mix variables identified in studies of field test sections, including nominal maximum aggregate size, aggregate gradation, binder type, additive, air-void content, and aggregate shape, on mix properties related to pavement surface performance. The study also included several other mix designs that had good or promising performance histories, and compared them with current Caltrans mixes in terms of laboratory test results. Specimens were prepared and tested in the laboratory. The performance indicators evaluated in the laboratory included durability, permeability, sound absorption, and friction. Durability testing included raveling, moisture damage, reflective cracking, and rutting. Friction indicators included both macrotexture and microtexture levels.

The study found that mixes with small aggregate sizes and either an asphalt rubber or polymer-modified binder, the Georgia 12.5-mm OGFC mix, and double-layer porous asphalts have good overall laboratory performance in terms of sound absorption (i.e., higher void content and permeability), which is correlated with tire/pavement noise, and durability.

Mansour et al. (2013) investigated the effect of aggregate gradation used by 20 different United States highway agencies on the performance of OGFC. Performance was compared by evaluating draindown, permeability, Cantabro abrasion loss, indirect tensile strength, and rutting resistance. The results indicated that gradation does influence the performance of OGFC mixtures. An increase in the void ratio of the aggregate structure contributes to significant increases in porosity and permeability. However, indirect tensile strength and durability (as measured by the Cantabro abrasion test) generally decreased as the mixture porosity increased. Further, the effects of rutting did not correlate with mixture or aggregate porosity, but were more dependent on gradation and binder properties. This study concluded that an OGFC mixture can be optimized for performance requirements (permeability or strength) based on the void ratio of the gradation.

Hernandez-Sanchez et al. (2016) stressed the importance of controlling certain properties of aggregate, such as particle shape (angularity and form), abrasion, soundness, cleanliness, and absorption. Alvarez-Lugo et al. (2014) also suggested that for optimum mix design the aggregate gradation must be specified in a narrow band of aggregate sizes for specific OGFC functional responses. Herndon et al. (2016) performed a study in South Carolina to compare the results of OGFC pavements based on aggregate breakdown. To reduce breakdown of aggregate, the authors suggested constructing test sections using alternate gradations (nearly same-sized aggregates with low fines content) while maintaining the desired OGFC mix properties. The authors also suggested increasing the binder contents to accommodate any breakdown that might occur during the construction and using thicker OGFC lifts.

Aggregate gradation size has also been shown to impact OGFC clogging performance. For instance, Faw et al. (2009) showed that OGFCs prepared with larger aggregates and minimal fines size gradations were less impacted by clogging. In a laboratory investigation, Varghese, and Shankar (2010) determined that aggregate gradation size impacted the clogging and declogging of OGFC mixes. Tests were conducted to evaluate the effect of three different clogging materials on four different OGFC aggregate gradations. Permeability tests were conducted using the falling-head concept on cylindrical OGFC specimens. The influence of the particle size ratios and the effective air voids on the permeability of fresh, clogged, and declogged OGFC specimens was analyzed. The experimental results on the observed permeability were compared with those predicted using theoretical models.

Although, the theoretical models tended to overestimate the permeability values, statistical analyses indicated good correlations with the observed results.

Huang (2004) evaluated clogging based on the particle size ratios corresponding to the permeability criteria (R15) and the clogging criteria based on the filtration capability of pavement. These two clogging criteria can be determined based on the particle sizes D15 and D85, which refer to the particle diameters below which 15 and 85 percent of the finer particles exist, respectively, for drainage OGFC and clogging materials (CMs), as shown in Equations [1] and [2]. In the case where aggregates are used as filter materials and drainage layers, RS and R15 are required to satisfy the conditions RS ≤ 5 and R15 ≤ 5.

$$R_{15} = \frac{D_{15}^{OGFC}}{D_{15}^{CM}} \quad [3\text{-}1]$$

$$R_{S} = \frac{D_{15}^{OGFC}}{D_{85}^{CM}} \quad [3\text{-}2]$$

According to these equations, the probability that fine particles will be captured in the void spaces of OGFC constructed with larger aggregates is much lower than the probability associated with an OGFC that has a high percentage of fine aggregates. In a later study, Martin et al. (2014) arrived at the same conclusion. The results obtained by Martin et al. (2014) revealed (1) that permeability decreased with higher percentage of aggregate materials passing the number 4 (4.75 mm) sieve, indicating that the higher the fines the lower the permeability; (2) that mixtures having a larger D15 exhibited higher permeability; and (3) that after the declogging process, only approximately 69 percent of the initial mixture permeability was restored on average. The inability to restore 100 percent of the permeability is most likely due to the migration of sediment particles (sand, in this case) into the OGFC mix's internal void structure, from which it cannot easily be removed.

Pattanaik et al. (2018) investigated the influence of electric arc furnace (EAF) steel slag, which is under consideration as a partial replacement for coarse (above 2.36 mm) natural aggregates, on the clogging of OGFC mixes. OGFC mixes for this study were prepared using two types of aggregates (natural and EAF steel slag), and two modified bituminous binders (polymer modified, and crumb rubber modified). The physical properties of the EAF steel slag were assessed to determine its suitability for OGFC mixes. Steel slag in five different percentages—0, 25, 50, 75, and 100 percent—were used to replace natural aggregates in the OGFC mix designs. The falling-head concept was used to measure permeability on cylindrical OGFC specimens. Graded sand was used to determine the effects of clogging and declogging on the OGFC mixes' permeability. The results showed that the percentage of EAF steel slag replacement was found to be strongly correlated to porosity, which directly relates to the mixes' permeability both before and after clogging. The secondary clogging rate was approximately 50 percent of the initial clogging rate for both the polymer-modified, and crumb rubber-modified OGFC mixes. The declogging process was able to restore an approximate average of 86 and 93 percent of the initial permeability, respectively, for the PMB-OGFC and CRMB-OGFC mixes.

Drainability is one of the main characteristics of OGFC mixtures, and it is the primary reason these mixes are used as a surface course in asphalt pavements in the United States (Alvarez et al. 2010). However, the two methods currently suggested for evaluating the drainability of OGFC mix designs are to either examine target total air-void (AV) content—as an indirect indication of permeability—or to directly measure permeability in the laboratory. Alvarez et al. (2010) suggested that these approaches are ineffective for ensuring adequate drainability in field-compacted mixtures. Thus, Alvarez et al. (2010) suggested alternative methods that include (1) using water-accessible AV contents as a surrogate for the total AV content to indirectly assess permeability and (2) applying the water flow value (outflow time) to evaluate the field drainability of OGFC mixtures. The expected permeability value, determined using a modified version of the Kozeny-Carman equation, was recommended to predict permeability for mix design and evaluation purposes. The permeability evaluation suggested by Alvarez et al. (2010) focused on determining an OGFC mix's initial drainability. However, their recommendation is not currently followed and future research should be performed to evaluate the AV clogging rate, service life, and corresponding actions to extend the service life of OGFC mixtures.

3.4.2 Performance Optimization Based on Asphalt Base Binder

Hernandez-Sanchez et al. (2016) analyzed information related to different mix designs and determined that base binder type is a critical parameter that influences RHMA-O pavement performance, especially in terms of permeability and abrasion. Hernandez-Sanchez et al. (2016) determined that an asphalt base binder's PG grade is typically two grades stiffer than the normal binder used for DGHMA mixtures in a specific environmental zone. This may be the primary reason that both FDOT and TxDOT currently use PG 76-22 as the asphalt base binder in construction of OGFC pavements.

3.4.3 Performance Optimization Based on Asphalt Binder Modifier

To increase the durability and other performance functions of OGFC pavements, the asphalt base binders are usually modified with either rubber-modified binder or polymer-modified binders. Caltrans uses both modifications in RHMA-O pavement construction. One polymer commonly used for asphalt binder modification is styrene–butadiene–styrene (SBS) polymer. Studies have been performed to evaluate the comparative performance of rubber-modified binder and SBS-modified binder. For instance, Nazzal et al. (2016) evaluated the long-term field performance and life cycle costs of pavement sections constructed with terminal-blend ground-tire-rubber-modified (GTR-modified) mixtures and compared them to results from sections constructed using SBS-polymer-modified mixes. All the study's selected pavement sections were located at sites with varying traffic conditions, and were evaluated periodically during the first two-and-a-half, six, eight, and ten years of their service life. Laboratory testing was also conducted on core samples obtained from these sections to examine their resistance to fatigue and low-temperature cracking, as well as to moisture-induced damage. The field evaluation of pavement sections constructed with the GTR-modified mixes revealed good performance after 10 years of service, a result similar to that obtained on sections where polymer-modified mixes were used. The core samples from the GTR-modified sections showed fatigue cracking resistance similar to those obtained from the polymer-modified sections, but they also showed slightly better resistance to low-temperature cracking and moisture-induced damage. Finally, the sections with a GTR-modified mixture had slightly higher life cycle costs than those constructed with polymer-modified mixes, a result attributed to the higher initial cost of the GTR asphalt mixtures used in these sections. This cost factor may one reason that contractors almost always choose to use polymer-modified OGFC over GTR-modified blends, as evidenced by FDOT and in Europe.

Punith et al. (2012) performed a study focusing on the use of OGFC mixtures containing reclaimed polyethylene-modified binder, crumb rubber-modified binder (CRMB), and neat 60-70-grade binder with cellulose fibers. The mixes' relative performance was evaluated in the laboratory by adopting two different types of Marshall compaction. The performance results were assessed by using the draindown test, the Cantabro stone loss test, a permeability test, an indirect tensile strength test, a resilient modulus test, a rutting test, and a skid resistance test. The study's results showed that adding fiber stabilizers and polymerized asphalt significantly reduced the potential for draindown in OGFC mixtures. The mixes compacted on one face by 50 blows of a Marshall hammer were found to give improved results with respect to abrasion and other related OGFC mix properties. The test results indicated that polymer modification of the binder enhances the relevant engineering properties of the OGFC mixtures.

A study performed by Ma et al. (2018) sought to evaluate the durability and strength of OGFC mixtures through laboratory testing using three binder types: one rubberized high-viscosity binder (RHVB), two styrene-butadiene-styrene (SBS)-modified binders, and PG 76-22 and PG 70-22. Various additives, including fiber, hydrated lime, and dibenzylidene sorbitol (DBS) polymer, were used in the OGFC. Comprehensive laboratory testing was conducted, including tests for strength, binder draindown, Cantabro abrasion, moisture susceptibility, rutting, thermal stress restrained sampling, and permeability. The following results were found: RHVB significantly improved the overall performance of the OGFC; the SBS additive improved its high-temperature performance but lowered its cracking resistance at low temperature as well as its durability; the fiber added enhanced the OGFC's durability and anticracking performance at low temperature; added hydrated lime improved the OGFC's moisture stability but weakened its durability. It was concluded that RHVB and polyester fiber should be used in all OGFC mixes, that SBS additive is good for OGFCs in high-temperature areas, and that hydrated lime can be added to OGFC in rainy areas.

Arámbula-Mercado et al. (2019) performed a study for the Florida DOT to assess the mechanical performance and durability of OGFC FC-5 mixtures fabricated with a highly polymer-modified (HP) binder. FDOT examined the performance of HP binder since contractors prefer it to rubber-modified binders. The HP binder complies with the requirements of Florida DOT (FDOT) specifications, Section 916-2 (FDOT 2019). Samples with the FC-5 mixture and HP modifier binder were prepared and their performance results were compared with those from samples fabricated with a conventional mixture and polymer-modified asphalt (PMA) binder. The results obtained from this study showed that the PMA binder and PMA mastics had better linear viscoelasticity (LVE) properties than the HP binder and mastics. However, the HP binder and HP mastics had superior fatigue cracking and creep recovery in all aging states. Fracture tests conducted on the FC-5 mixtures corroborated these results. The durability tests—which were conducted using the Cantabro test with multiple cycles—also demonstrated that the FC-5 mixtures with HP binder were significantly more durable than those with PMA binder. Numerical finite element (FE) simulations conducted in a long-term aging state indicated that FC-5 mixtures with HP binder were less prone to raveling under field conditions. A life cycle cost analysis (LCCA) showed that the extended service life of FC-5 mixtures with HP binder offered a cost-effective alternative to conventional PMA binder.

Partl et al. (2009) tested two different OGFC mixes manufactured with asphalt rubber binder, one containing expanded clay, to examine their moisture and temperature sensitivity differences. The results were compared with data from traditional OGFC obtained in an earlier study. The comparison's results demonstrated that OGFC with asphalt rubber binder not only had superior fatigue resistance, but it also had significantly less moisture sensitivity than the traditional porous and semi-porous asphalt mixtures. This was also true when expanded clay grains were present. These properties probably arose not only from the remarkable properties of asphalt rubber binder but also from the higher binder dosage, which produced a bituminous film around the aggregates that was thicker than that in traditional hot mix asphalts. The expanded clay slightly lowered the moisture sensitivity and fatigue life performance properties of the OGFCs with asphalt rubber binder. On the other hand, the presence of the expanded clay appeared to improve the OGFC mixes' temperature cycle resistance due to its higher heat capacity. As a result of this study, Partl et al. (2009) suggested using rubberized mixes instead of traditional OGFC mixes to improve pavements' mechanical properties and durability. Mashaan et al. (2012) showed that the addition of crumb rubber as an OGFC modifier improves rutting resistance and produces pavements with better durability by minimizing the distresses afflicting in conventional hot mix asphalt pavement.

As part of an innovative research project supported by the European Union, Radziszewski et al. (2012) examined the properties of various asphalt rubber binders using two neat unmodified binders, two kinds of crumb rubber, and different types and amounts of plasticizers. The study's results indicated that asphalt rubber binder displays properties comparable to or better than the polymer-modified bitumen typically used in European road construction. Despite the two binders' comparable performance, however, rubber-modified pavements are generally more expensive and for this reason not many European countries current use RHMA-O overlays.

Alvarez et al. (2012) compared the asphalt–aggregate interfaces formed with the asphalt rubber (AR) and polymer-modified (PM) asphalt binders specified for fabrication of OGFC mixes in Texas. Six pavements with PM asphalt and four with rubber modified asphalt and five different aggregates were assessed. The results of the comparisons suggest that, in terms of the energy indices computed, the fracture resistance, susceptibility to moisture damage, and the wettability of the AR asphalt–aggregate systems were comparable to those of the PM asphalt–aggregate systems.

Ibrahim et al. (2014) evaluated the relationship between rubber size, rubber content, and binder content in determination of optimum binder content (OBC) for OGFC. Marshall specimens were prepared with four different rubber sizes: 20 mesh [0.841 mm], 40 mesh [0.42 mm], 80 mesh [0.177 mm], and 100 mesh [0.149 mm] with different concentrations of rubberized asphalt (4, 8, and 12 percent) and different percentages of base asphalt binder content (4 to 7 percent). The appropriate optimum binder content was then selected according to the results of the measured air voids, binder draindown, and abrasion loss test. Test results showed that crumb rubber particle size can affect optimum binder content in OGFC, specifically:

1. Mixes modified with coarser rubber crumb and lower bitumen content tended to have higher abrasion loss.
2. Coarser rubber crumb had a narrower window of selection of optimum binder content: as mesh size decreased, higher binder and crumb rubber content can be used.
3. While extra bitumen provided higher strength, mixes with higher binder content were subject to greater binder draindown. The study also found that higher rubber content increases the viscosity of bitumen, which also increases the film thickness and subsequently lowers the void sizes in the mix. Finer rubber crumbs, on the other hand, seem to be less sensitive to the increment of rubber and binder content. This results in a wider window for selecting optimum binder content.
4. The flexibility in the optimum binder content range provided by bitumen modified with finer crumb rubber (80 and 100 mesh) allows for a wider range of optimum binder content selections. However, the lower and the upper limits of the optimum binder content (5 and 7 percent) fall near the maximum and

minimum allowable limits air-void contents, 18 and 25 percent. Therefore, when producing rubberized bitumen, it is advisable to use an intermediate optimum base binder content value between 6 and 6.5 percent to allow for a certain tolerance level and while still ensuring a high-quality product.

Shen and Xie (2012) examined the long-term performance of porous European mix (PEM) and open-graded friction course (OGFC) pavements to which crumb rubber was added using the dry process. Test sections were visually inspected for surface distresses, following the guidelines in the Georgia Department of Transportation (GDOT) Pavement Condition Evaluation System (PACES) manual. Core samples were evaluated in the laboratory on selected physical and durability properties, including void ratio, permeability, density, Cantabro loss, and Marshall stability. The results showed that the performance of rubberized OGFC almost equals that of polymer-modified PEM with no rutting, raveling, or cracking, while the Cantabro test showed a higher mass loss after three years' service. After five years' service, the rubberized pavement performed slightly better to rutting depth, while other visual indicators remained the same. The rubberized OGFC pavement had slightly higher Marshall stability and lower flow than the control OGFC pavement, with similar effects on the polymer-modified PEM's surface performance.

Shen et al. (2013) investigated the long-term performance of several mix designs containing crumb rubber processed by the dry and wet methods. A total of eight mixtures were prepared, four porous European mixes (PEMs) modified with rubber, and four modified with SBS. The base binder for both mixtures was PG 76-22. Results of the study revealed that (1) adding crumb rubber binder improved the PG grade and separation resistance; (2) the fatigue life (Nf) of unaged rubberized PEM prepared using the dry process was similar to that produced using the wet process; (3) after 3,000 hours of aging, the fatigue life of the dry-processed rubberized PEM was similar to that of the wet-processed but lower than those of the control and the SBS-modified, regardless of strain and stress levels or test temperatures; (4) the rutting and Cantabro loss of the rubberized PEM in the dry process were higher than those of the control SBS after weathering; and (5) the effect of weathering on the properties of the asphalt binders in the rubberized, dry-processed PEMs and was similar to that in the wet-processed mixtures but greater than that in the control SBS. The results of this study confirmed that for RHMA-O construction, the wet process is preferred to the dry process.

Shirini and Imaninasa (2016) evaluated the influence of crumb rubber (CR) on the performance of OGFC. The performance of OGFCs fabricated with 10, 15, and 20 percent CR were compared with a control OGFC modified with 5 percent CR. The performance parameters investigated were rutting resistance, draindown resistance, skid resistance, moisture susceptibility, and permeability. Results showed that CR and SBS modification reduced OGFC permeability, but their use also improved rutting resistance significantly. In general, the 10 percent CR modification to the OGFC satisfied all the pavement's design requirements and improved its performance. In general, the OGFC with 10 percent CR performed approximately the same as OGFC modified with SBS. Further, the study found that increasing the percentage of CR beyond 10 percent improved resilient modulus, skid resistance, and moisture damage resistance at first, but then it had a negative effect on these properties.

Xie and Shen (2016) evaluated rubberized and polymer-modified PEMs test sections in Georgia through visual inspection and laboratory testing. The visual inspection results indicated that the performance of rubberized PEM pavements almost equaled that of polymer-modified PEM (as the controls) in terms of rutting or cracking. However, the Cantabro test results showed a higher mass loss on rubberized PEM after three years of service. After five years of service, the rubberized PEM site still performed slightly better than the polymer-modified PEM in terms of rutting resistance even though the site underwent about twice the cumulative traffic of the control.

Xie and Shen (2016) performed laboratory and field testing to investigate the effect of weathering (ultraviolet [UV] light, oxidative, and water) on the performance of rubberized PEMs. Three rubberized PEM mixes were produced by three processes: the dry process, the wet process, and terminal blending in the laboratory. A non-rubberized PEM mixture modified with SBS polymer was also produced for comparison. The compacted PEM mixes were weathered for 1,000 and 3,000 hours. Afterward, each mix was measured for dynamic modulus, rutting/moisture resistance, and Cantabro loss, and the mixes' aging condition was assessed. Additionally, the rubberized and SBS-modified PEM field test sections in Georgia were investigated by a visual inspection and laboratory testing of core samples. The results indicated the following:

1. Weathering had increased the PEM mixes' elastic properties and rutting resistance, had no significant effect on their moisture resistance, and decreased their raveling resistance.
2. Weathering affected the performance properties of rubberized PEM mixes produced using the dry process more than those produced using the wet process and more than those of the SBS control PEM.
3. The first 1,000 hours of weathering had a greater effect on the dynamic modulus and Cantabro loss of the PEM mixes than the last 2,000 hours of weathering.
4. All the tested PEM field sections (dry process-produced, wet process-produced, and control) showed excellent performance after three and five years of service.

Sangiorgi et al. (2017) investigated the effectiveness of adding crumb rubber by the dry method to OGFC mixtures. Rubberized OGFC mixtures were prepared by incorporating CR into SBS-modified asphalt pavement, and comparing indirect tensile strength (ITS), indirect tensile stiffness modulus (ITSM), moisture susceptibility, permeability, Cantabro, rolling bottle, draindown, creep test results with those from a control mix. The study's results proved that although the introduction of CR reduces vertical permeability and permanent deformation resistance, it improves the bitumen/aggregate affinity and controls the draindown rate without added fibers. On the other hand, the use of CR decreased the ITSM value at low temperature, which indicates a lower susceptibility to thermal cracking.

In summary, the combined results obtained from all the above studies make it possible to conclude that the performance of rubber-modified binder used in OGFC is comparable to polymer-modified binder. However, rubber-modified binder production is more complicated, requires more energy, and is generally more expensive. For these reasons, if choice is given, most contractors prefer the use of polymer-modified binder over the use rubber-modified binder for the construction of OGFC.

3.4.4 Performance Optimization Based on Stabilizing Additives

Stabilizing additives, principally mineral or cellulose fibers, have been found to be an important component of mixes since they prevent draindown (Hernandez-Sanchez et al. 2016). Faghri et al. (2002) performed a study to improve OGFC mix designs by adding fiber and/or polymer binder modifiers to mixtures. In this study, cellulose fiber was the selected stabilizing additive and styrene-butadiene-styrene as the selected binder modifier. OGFC mixes were prepared using the in-house Arizona, and Georgia mix designs. The in-house mix design samples were prepared based on the FHWA OGFC standard. Specimens were prepared with and without modifiers using Marshall mix procedures. The effects of fiber and modifiers were tested experimentally using various standardized procedures, including percent air void measurement for porosity, falling-head testing for permeability, and indirect tensile testing for strength. In general, the results indicate that introducing fiber modifiers led to minor improvements in the samples' strength characteristics but these modifiers also contributed significantly to reducing permeability. On the other hand, introducing polymer modifiers nearly doubled both sample strength and permeability, and increased the air voids. When both polymer modifiers and fiber were used, further strength improvement was observed but the permeability increase was not as large as that with polymer modifier alone. Consequently, Faghri et al. (2002) concluded that the best strength/permeability characteristics are achieved when polymer modifier only is used in OGFC mixtures**.** However, an older study by Hassan et al. (2005) suggested that the mix containing fibers and SBR polymer was selected as an acceptable mix design with an optimum asphalt content of 6.5 percent.

Some researchers indicated that fiber and polymer addition may not always be needed to improve open-graded pavement performance. For example, Wurst and Putman (2013) evaluated the feasibility of using warm mix asphalt (WMA) technologies to produce quality OGFC mixtures without the need for stabilizing fibers. The study focused on a comparison of Evotherm WMA and foamed WMA mixes with traditional HMA OGFC using three primary criteria: draindown, permeability, and abrasion resistance. Based on draindown and durability testing results, this laboratory study indicated that OGFC mixtures made with WMA technologies and without fibers outperformed HMA OGFC mixtures without fibers. When compared with HMA OGFC mixtures containing fibers, the WMA OGFC mixes without fibers had significantly higher permeability rates due to their increased porosity. In all cases, the WMA OGFC mixes without fibers exhibited greater durability than the HMA OGFC mixtures without fibers after long-term aging. This study also showed that the binder content of WMA OGFC mixtures without fibers can be increased by at least 0.5 percent without sacrificing performance with respect to increased draindown or reduced permeability. The study also concluded that excluding fibers from OGFC mixes may help contractors produce a more consistent finished pavement, potentially without an increase in cost. However, this conclusion must be validated with field trials.

The use of warm mix rubberized asphalt was also experimented with by Jones et al. (2012) in California. This study's field experiment results with rubberized WMA indicated that it had significantly better workability than the hot mix controls, and without the controls' smoke and odor. The study's field experiment also showed that rubberized mixes could be hauled for up to four hours and placed with ease while still achieving the required compaction. In general, equal or better performance was observed over four years with warm mix rubberized asphalt pavement. Based on these research results, Caltrans placed more than one million tons of rubberized warm mix asphalt during the 2011 paving season (Jones et al. 2012). The same technology may be used for RHMA-O pavement construction, although further research and development may be required.

3.4.5 Performance Optimization Based on Optimum Binder Content

Numerous methods are currently used internationally to design OGFC and RHMA-O mixtures. The results of this literature review indicate that some design procedures produce a range of design binder contents instead of a single value. This lack of guidance for inexperienced designers could result in pavement performance issues that prevent future use of rubberized and non-rubberized OGFC pavements (Putman and Kline 2012). Approaches to determining optimum binder content can be grouped into three categories: (1) those that base OBC on the properties of compacted specimens; (2) those that calculate OBC on the basis of the oil absorption capacity of aggregate; and (3) those that base OBC determination on the visual inspection of loose mix. The OBCs determined from 14 different research studies showed variability among the different procedures for the same aggregate source (Putman and Kline 2012). The largest variability came within the properties of compacted specimens. For many of the procedures in the compacted specimen's category, the outcome was a range for the OBC. In some cases, this range was as wide as the range of binder contents evaluated in the procedure (5 to 7 percent). This does not provide any guidance to the designer as to what the OBC should be for a particular mixture.

Additionally, in some cases, the lowest binder content evaluated in the range was accepted as the OBC. However, this quantity is likely to be too low to ensure long-term durability in the field, as evidenced by the relatively high abrasion loss values for mixes containing lower binder contents. Variability in some of the test methods—and specifically, variability resulting from the Cantabro test—may be one factor that contributes to these mix design methods yielding a range of acceptable binder contents. An advantage that these multiple methods provides is that they evaluate mixes' performance properties (permeability and durability) at different binder contents, and this can provide an informed designer with valuable information.

The procedures in the other two categories (oil absorption and visual determination) resulted in a single value for OBC for each procedure, which can be an advantage depending on the experience of the designer. The OBC values from the oil absorption procedures showed higher variability than the values from visual determination, but not nearly as much variability as the compacted specimen procedures. The visual determination procedures, although subjective in nature, provided the most OBC consistency among the three procedure types. However, these procedures do not require that a designer evaluate the mix performance properties at the OBC determined, which presents a downside to these types of design methods. When tested at the OBCs, these mixtures demonstrated the adequate permeability required for many OGFC pavement applications, as well as the abrasion resistance necessary for long-term durability.

A research study conducted by Alvarez et al. (2011b) at Texas A&M University on how to improve OGFC mix designs led to a set of recommendations that have been integrated into an improved method that the Texas DOT has adopted. The revised method includes the following:

1. Determination of the total AV content, through the use of a calculation procedure, to obtain the mix's theoretical maximum specific gravity, Gmm, and a dimensional analysis to determine the mix's bulk specific gravity, Gmb;
2. Proposed use of water-accessible AV content as a surrogate for the total AV content for mix design and evaluation;
3. Recommended use of water flow value (outflow time) and the expected permeability (E[k]) value, respectively, to assess field drainability and to estimate the permeability of both laboratory- and field-compacted (i.e., road cores) mixtures;
4. A suggestion to use the Cantabro loss test to assess mix durability;
5. Improved criteria for verification of stone-on-stone contact for mix design and field-density control during construction were recommended to guarantee adequate stability and durability; and
6. A recommendation to improve fabrication of Superpave® gyratory compactor specimens and sampling of field-compacted mixtures (by using road cores).

At present, rubberized asphalt use in the United States is driven by regulatory mandate. Blumenthal (2012) suggested that industry efforts should be directed at getting rubberized pavement specifications into the accepted construction practices of all states and at coordinating the efforts of federal, state, and county organizations that are encouraging the use of recycled and industrial materials in road construction. Through these coordinated efforts, AR can be presented as a product that can satisfy policy-driven ends while it also provides the performance characteristics needed to complete a pavement job satisfactorily.

Hernandez-Saenz et al. (2016) evaluated the OBC methods of 15 states and found that 10 used the compacted method, 3 used both the absorption of the predominant aggregate fraction and visual determination, and only 2 used the combined methods mentioned above (i.e., Georgia and New Jersey). It is important to highlight that the only methodology that analyzes a mix's specific properties is the one based on compacted specimens, and this may partly explain its popularity. The method based on the aggregate absorption only studies the predominant aggregate fraction and not study the full mixture, and consequently it does not evaluate the expected performance of the mixture. The visual determination methodology is mostly based on a procedure whose main focus is to guarantee a mix's workability, primarily by preventing draindown. For RHMA-O design, Caltrans currently determines optimum binder content using neat PG grade asphalt and examines the HMA's draindown characteristics to arrive at the OBC (Zhou et al. 2014). This OBC determined is then multiplied by 1.4 for RHMA-O and 1.65 for RHMA-O with hybrid binder to generate the final OBC. This is an empirical approach. Caltrans is working with the University of California Pavement Research Center to develop a more rational method for determining binder content for open-graded mixes.

This literature review found that internationally, transportation agencies typically use binder contents in the range of 9 to 10 percent by weight of the aggregate in rubberized OGFC applications, and that the rubberized asphalt binder is typically composed of 80 percent asphalt (bitumen) and 20 percent recycled tire rubber (Way et al. (2012).

4 POTENTIAL WATER QUALITY BENEFITS ASSOCIATED WITH OGFC AND RHMA-O PAVEMENTS

This chapter presents information on water quality issues related to rubberized and non-rubberized OGFCs reported in the literature. The major topics discussed include the following:

1. RHMA-O and OGFC surface runoff water quality studies performed in the US,
2. Water quality evaluations of OGFC and RHMA-O performed in Europe,
3. Comparison of water quality characteristics from RHMA-O and OGFC pavements,
4. Comparison of runoff water quality generated from the OGFC and RHMA-O surface overlays to the effluent water quality from selected best management practices (BMPs),
5. Approval of OGFC or RHMA-O as a BMP for runoff treatment to get credit for selected pollution removal by transportation agencies in the US, and
6. Potential improvements to OGFC or RHMA-O mix designs for higher pollutant removal efficiency.

4.1 BACKGROUND

Since of RHMA-O application is less common in the US than non-rubberized OGFC application, only a limited number of water quality evaluations from RHMA-O surface overlay have been performed. For example, in California just one such water quality investigation has been attempted and it was unsuccessful due to the pavement's low permeability. No water quality investigations of RHMA-O application have been performed at the international level. At present, only one successful water quality evaluation has been performed, a study by the Texas Department of Transportation (TxDOT) on both OGFC and RHMA-O surface overlays.

4.2 RHMA-O and OGFC Surface Runoff Water Quality Studies Performed in the US

As noted, many state transportation departments (DOTs) have used or still use OGFC on their paved highway surfaces. Many of these DOTs have prepared reports that concentrate their evaluation of OGFCs mostly on their ability to reduce noise, improve skid resistance, and increase safety by eliminating splashing during rain events. Only California, North Carolina, and Texas have performed water quality investigations of OGFC overlays.

4.2.1 TxDOT Paired OGFC and RHMA-O Water Quality Investigations

The Texas DOT (TxDOT) performed several water quality studies to determine the potential benefits of OGFCs (TxDOT calls OGFC PFC, porous friction course) to remove pollution from highway right of ways so the department could receive pollution credits. One of these investigations was performed at highway sites constructed with an open-graded friction course modified with rubberized asphalt binder. The runoff water quality from RHMA-O was compared with that from conventional OGFC. TxDOT also performed several investigations of water quality from OGFC overlays. For comparative purposes the results and conclusions drawn from these TxDOT water quality investigations are presented below.

An RHMA-O water quality investigation was performed on two Mopac highway sites that were located between 35th and 45th Streets in Austin, Texas. Mopac is a highway with a curb-and-gutter section paved with a 1.5 inch thick OGFC overlay in 2010. These rubberized OGFC sites were located a few blocks north of the non-rubberized Mopac highway OGFC sites where stormwater runoff was monitored during 1998 (Barrett et al. 1998). Different asphalt binder mixtures were used on the north- and southbound lanes. This difference in pavement binder provided the option to compare the water quality results from different mix designs. The Mopac's northbound lanes are paved with asphalt-rubber (A-R) binder, and the southbound lanes are paved with a performance-graded binder (PG 76). A-R binders require a minimum of 15 percent crumb rubber modifier and in general costs more than PG 76 binders. The specification for the aggregate mixture and the binder content for these two OGFC sites are shown in Table 4.1. As the table shows, the northbound OGFC modified with A-R binder includes smaller aggregate sizes than the southbound OGFC with non-rubberized binder (PG 76). It is worth noting that the values shown in Table 4.1 are not an exact comparison with two different gradations, where the OGFC is allowed more large aggregates. This means that the OGFC most likely had greater permeability. A true water quality comparison could only be conducted if both pavement types had been constructed with the same gradation mixes.

Table 4.1: Aggregate Mixture and Binder Specification for Two OGFC Sites on the Mopac Freeway

Aggregate/Binder Specification	OGFC	RHMA-O
Aggregate size/no. (mm)		
¾ in (19 mm)	100	100
½ in (12.5 mm)	80-100	95-100
3/8 in (9.5 mm)	35-60	50-80
No. 4 (4.76 mm)	1-20	0.0-8
No. 8 (2.38 mm)	1-10	0.0-8
No. 200 (0.75 mm)	1-4	0.0-4
Pavement specification		
Binder type	PG-76	Asphalt rubber (A-R)
Binder content	5.5-7.0	8.0-10

Source: Adapted from Sampson et al. (2014)

Stormwater runoff monitoring along Mopac OGFC sites was conducted between January 9, 2011, and October 11, 2012. Sample collections from both sites were obtained using automatic sampling equipment. Over the course of the study, 30 storm events were sampled and analyzed from the southbound OGFC site and 31 from the northbound OGFC site. The following water quality constituents were monitored: TSS, TKN, NO_3/NO_2, total P and dissolved P, Cu, Pb, and Zn.

The monitoring results obtained from the two rubberized and non-rubberized OGFC sites were compared with the water quality data collected in 1998 from the nearby conventional asphalt pavement (Barrett et al. 1998). For the purposes of this comparison, the median was selected over the mean because the distribution of each constituent was skewed as a result of outliers. Table 4.2 provides the results of this comparison for both sites. As shown, compared to measurements taken at the conventional pavement site, reductions of selected water quality constituents at the OGFC and RHMA-O sites ranged between 56 and 99 percent. Values for the dissolved metals and TKN were not included in the study because results for those from the conventional pavement were not available. Clearly, it can be seen that when OGFC (rubberized or non-rubberized) pavements function properly, the same water quality treatment (except for Zn concentration) benefits can be achieved as those discussed in the following sections of this chapter.

Table 4.2: Comparison of the Average Median Concentration at the Two PFC Sites Compared with the Conventional Asphalt Pavement

Constituent	Unit	Median Conventional Impervious Pavement	Median Concentration		% Reduction	
			OGFC	RHMA-O	OGFC	RHMA-O
TSS	mg/L	152	12	12	92	92
NO_3/NO_2	mg/L	0.7	0.3	0.3	61	56
Total P	mg/L	0.5	0.1	0.1	81	86
Total Cu	µg/L	50	13	13	75	74
Total Pb	µg/L	130	2	2	99	98
Total Zn	µg/L	285	37	86	87	70

Source: Adapted from Sampson et al. (2014)

4.2.2 Other TxDOT OGFC Water Quality Evaluations

TxDOT has performed many other evaluations of water quality from multiple OGFC pavements. Its first OGFC overlay water quality monitoring study was conducted on northbound US Highway 183 in Austin (Barret 2006). Average daily traffic for this site was estimated to be 43,000. The stormwater quality generated from the OGFC site was monitored alongside that from a conventional asphalt pavement near the OGFC site. Stormwater runoff from both sites was monitored from February 2004 to June 2006. Runoff samples were collected with GKY *FirstFlush* samplers. The samples were collected over a 34-foot long section with width of about 1 ft (300 mm), which means that the total area of roadway sampled was only about 34 sq. ft (3 m^2). The passive stormwater samplers used for collection can hold up to 5 L (1.3 gal) of water. Each sample was analyzed for the various water quality parameters, and the event mean concentrations (EMCs) of the selected constituents measured from the OGFC and conventional impervious asphalt pavement sites are shown in Table 4.3.

Table 4.3: Average Reduction of Selected Water Quality Constituents for OGFC Compared with the Conventional Asphalt Pavement

Constituents	Symbol	Unit	Conventional Asphalt Pavement	OGFC (or PFC)	Reduction (%)
Total suspended solids	TSS	mg/L	117.8	9.95	91
Total Kjeldahl nitrogen	TKN	mg/L	1.13	1.10	2
Nitrate/Nitrite as N	NO_3/NO_2	mg/L	0.43	0.47	-14
Total P	P-T	mg/L	0.13	0.08	35
Dissolved P	P-D	mg/L	0.04	0.06	-50
Chemical oxygen demand	COD	mg/L	64.00	62.8	2
Total copper	Cu-T	μg/L	26.80	13.6	49
Dissolved copper	Cu-D	μg/L	5.90	10.6	-80
Total lead	Pb-T	μg/L	12.6	1.28	90
Dissolved lead	Pb-D	μg/L	<1	<1	NA
Total zinc	Zn-T	μg/L	167.40	40.7	76
Dissolved zinc	Zn-D	μg/L	47.1	32.7	31

Source: Adapted from Barrett (2006)

As the table shows, based on the constituents monitored, concentrations of TSS, and total lead (Pb), copper (Cu), and zinc (Zn) are significantly lower in runoff generated from the OGFC surface than in runoff generated from the conventional asphalt surface. A negative sign on constituent reduction indicates that an increase in concentration was observed; however, these differences were not statistically significant (Barret 2006).

A second water quality investigation was a follow-up to the monitoring in the earlier OGFC stormwater runoff monitoring, but it also included additional OGFC sites in the Austin area. Three OGFC sites were selected for this monitoring study, which was performed from 2006 to 2009 (Eck et al. 2010). Two of the sites were located on Loop 360 near RR 2222 in Austin. The third site was located on RR 620, near Cornerwood Drive in Round Rock. Loop 360 had been overlaid with OGFC from Lake Austin to US Highway 183, except at traffic signals and bridges. RR 620 was paved with PFC from IH 35 to the intersection at Cornerwood Dr. The average annual daily traffic (AADT) on PR 2222 and PR 620 during 2005 was estimated 48,000 and 32,000, respectively.

The duration of the stormwater runoff monitoring and the number of samples collected at these three sites were inconsistent, however. As noted, water quality for the first site along Loop 360 near RR 2222 was monitored from October 2004 to February 2006, and during this period passive samplers were used. In December 2006 the site's passive samplers were replaced with active samplers, and monitoring continued until March 2009. The replacement collection systems were installed to capture runoff from a larger pavement area, and a flume, flow meter, and automatic samplers were also installed to fully assess the runoff quantity and quality. A total 47 samples were collected from Site 1. Site 2 was located 0.3 miles south of Site 1, on the shoulder of the northbound lane near Lakewood Drive. Passive samplers were used at this monitoring site and were located about 200 feet apart, one each for the OGFC and conventional pavements. Stormwater runoff monitoring at Site 2 was conducted from February 2007 to March 2009 and a total of 15 samples were collected from this site. Site 3 was located on either side of Cornerwood Drive on the southbound shoulder of RR 620. Two passive samplers were used at this site, about 450 feet apart. Stormwater runoff monitoring at Site 3 was conducted from February 2009 to March 2009, and a total of eight samples were collected there. The samples from each site were analyzed based on the selected constituents indicated above.

The results of the paired samples from Site 1 were shown in Table 4.3. Additional monitoring at this site confirmed the previous results, indicating that the concentrations of TSS, TP, and total metals were significantly lower in runoff generated from the OGFC surface than in runoff from the conventional asphalt surface. However, the concentrations of nitrate/nitrite, dissolved copper, dissolved zinc, and dissolved phosphorus were not significantly different for the two paved surface types. These data indicate that the OGFC has little to no treatment effect on the dissolved constituents in stormwater runoff. Five years of additional monitoring data collected at this location showed that the OGFC provided similar treatment over that period.

The results of paired samples for the 15 storm events at Site 2 are shown in Table 4.4. As shown, the concentration of constituents from PFC is significantly different than that from the conventional asphalt pavement and the overall performance is similar to Site 1. And as at Site 1, a negative reduction in dissolved nutrients and dissolved copper was also seen at Site 2.

Table 4.4: Average Reduction of Selected Water Quality Constituents at Site 2 for OGFC Compared with Conventional Asphalt Pavement

Constituents	Symbol	Unit	Conventional Asphalt Pavement	OGFC (or PFC)	Reduction (%)
Total suspended solids	TSS	mg/L	148	18.00	88
Total Kjeldahl nitrogen	TKN	mg/L	1.10	0.92	16
Nitrate/Nitrite as N	NO_3/NO_2	mg/L	0.17	0.25	-52
Total P	P-T	mg/L	0.15	0.05	63
Dissolved P	P-D	mg/L	0.03	0.03	0.00
Chemical oxygen demand	COD	mg/L	75.00	60.00	20
Total copper	Cu-T	µg/L	30.00	13.0	57
Dissolved copper	Cu-D	µg/L	6.30	9.0	-44
Total lead	Pb-T	µg/L	11.00	1.3	88
Dissolved lead	Pb-D	µg/L	<1	<1	NA
Total zinc	Zn-T	µg/L	130	21.0	84
Dissolved zinc	Zn-D	µg/L	18.00	11.0	40

Source: Adapted from Eck et al. (2010)

The results from the eight paired samples collected at Site 3 on RR 620 during 2009 are reported in Table 4.5. As shown, the average constituent reduction from OGFC compared to the conventional impervious pavement is similar to that observed at the other two sites (Sites 1 and 2). Statistically significant reductions were observed for TSS, TKN, TP, COD, and total metals. In general, the runoff concentrations from the conventional pavement were substantially higher than those observed on Loop 360.

4.2.3 California DOT (Caltrans) RHMA-O and OGFC Water Quality Investigations

Caltrans has performed one field water quality monitoring study to determine if rubberized (RHMA-O) and non-rubberized OGFCs can provide any highway runoff pollution removal benefits. This field water quality monitoring investigation from 2007 to 2011 was performed at 14 monitoring stations—eight OGFC, two RHMA-O, and four HMA—at seven sites representing different California regions with varying climate and rainfall conditions (Caltrans 2012). This investigation's main objective was to evaluate the quality of stormwater runoff generated from these two OGFC overlay types and to compare them with the quality of runoff discharges from conventional dense-graded hot mix asphalt (HMA). Monitoring was only performed during the rainy seasons of 2007 to 2011. The ultimate goal of the investigation was to evaluate whether or not the rubberized and non-rubberized OGFC overlays' ability to remove pollutants would qualify them as a BMP for highway management.

Table 4.5: Average Reduction of Selected Water Quality Constituents at Site 2 for OGFC Compared with Conventional Asphalt Pavement

Constituents	Symbol	Unit	Conventional Asphalt Pavement	OGFC (or PFC)	Reduction (%)
Total suspended solids	TSS	mg/L	222.0	14.8	93
Total Kjeldahl nitrogen	TKN	mg/L	2.11	0.69	67
Nitrate/Nitrite as N	NO_3/NO_2	mg/L	0.35	0.26	25
Total P	P-T	mg/L	0.22	0.05	77
Dissolved P	P-D	mg/L	0.04	0.02	37
Chemical oxygen demand	COD	mg/L	121.0	38.0	68
Total copper	Cu-T	μg/L	24.0	9.1	63
Dissolved copper	Cu-D	μg/L	7.73	5.9	24
Total lead	Pb-T	μg/L	19.6	1.3	93
Dissolved lead	Pb-D	μg/L	<1	<1	NA
Total zinc	Zn-T	μg/L	173	24.0	86
Dissolved zinc	Zn-D	μg/L	21.4	12.0	44

Source: Adapted from Eck et al. (2010)

The study's initial plan called for water quality monitoring at all the rubberized and non-rubberized OGFC sites. However, during the third year of monitoring (the 2009 to 2010 monitoring season), porosity and permeability testing were performed on both overlay types to evaluate and quantify their treatment capabilities. In this project, a rate of 150 inches/hour/lane (0.016 cm/s) was selected as the cutoff value for characterizing the OGFC overlays as "permeable" (Caltrans 2012). The permeability measurements showed that several RHMA-O overlays failed to meet the permeability criterion selected by Caltrans, and therefore water quality monitoring of these particular overlays was discontinued after two years. But although assessment of these sites was discontinued, the water quality runoff monitoring at the OGFC sites and the rest of RHMA-O sites continued. It is important to note that the cut-off criteria were based on the limiting TSS median concentration and on permeability measurements. With these criteria, the Davis OGFC site (209-5T) failed to meet the permeability cut-off value selected by Caltrans; despite this, the site continued to be tested for water quality. In addition, results at the Red Bluff OGFC site (209-2T1) showed it to be highly permeable (1,380.5 in/hr/lane), but its TSS median concentration was higher than the 20 mg/L median cut-off TSS concentration (46.5 mg/L). Earlier permeability measurements taken as part of a different study on various Caltrans OGFC and RHMA-O sites showed that there is a significant difference between the permeability within the wheelpath and at other locations within the traffic lane (Rezaei and Harvey 2013), and hence fully assessing the true permeability of OGFC and RHMA-O pavements requires many measurements. Therefore, further evaluation of this cut-off permeability value should be considered, and perhaps permeability values should be evaluated based on the rain intensity where the open-graded mix is to be used and the multi-functionality of OGFC and RHMA-O pavements.

This Caltrans study also monitored numerous water quality constituents and water quality parameters for its duration. For some constituents, both total and dissolved fractions were monitored. Statistical analyses of the paired runoff quality from the OGFC overlays and the conventional asphalt pavements showed that generally the concentrations of solids and particle-bound pollutants were significantly lower in the OGFC overlays. The data shown in Table 4.6 compares three paired sites' average event mean concentrations (EMC) and removal efficiencies of selected constituents for three OGFC sites with those from conventional HMA pavements. As can be seen in the table, except for the total zinc and total nitrogen concentrations at Site 209-2, the OGFC runoff is cleaner with respect to the total concentration of constituents. In addition, the monitoring results showed that RHMA-O and OGFCs are ineffective at removing dissolved constituents. For instance, the average EMC for dissolved copper, lead, and zinc in the runoff discharged from three OGFC overlays were either the same or substantially higher than the conventional HMA. The water quality results for selected constituents monitored in California were different than those obtained from Texas. That difference could be attributed to multiple factors, which may include but not be limited to the following:

1. The influent runoff water from HMA in Texas being cleaner than that in California (for example, having the same treatment effect, the lower concentration of pollutants from HMA pavement produces a higher reduction in pollutant concentration).
2. A difference in pavement mix design, as shown in Table 4.7,
3. Lower traffic volume and loading,
4. Climate conditions that included with more frequent rainfall throughout the study years, which may contribute to self-cleaning, and
5. Environmental conditions less impacted by surrounding land use activities.

It is important to note the higher average event mean concentrations (EMCs) of zinc in runoff generated from both the OGFC and RHMA-O sites than from the runoff generated from the conventional HMA sites (see Figure 4.1). As shown in Figure 4.1, the large fraction of total and dissolved zinc concentrations from OGFC and RHMA-O were above 150 and 50 µg/L, respectively compared to the conventional HMA. This extra concentration of total and dissolved zinc is believed to be associated with the crumb rubber used to modify the binder (Barrett and Larsen, 2013). The extra zinc concentration from the rubber binder was probably generated due to raveling from traffic, since the extra zinc concentration was not generated in a rubberized pavement under a controlled laboratory study where traffic and loading were not factors (see Section 4.4, Table 4.10).

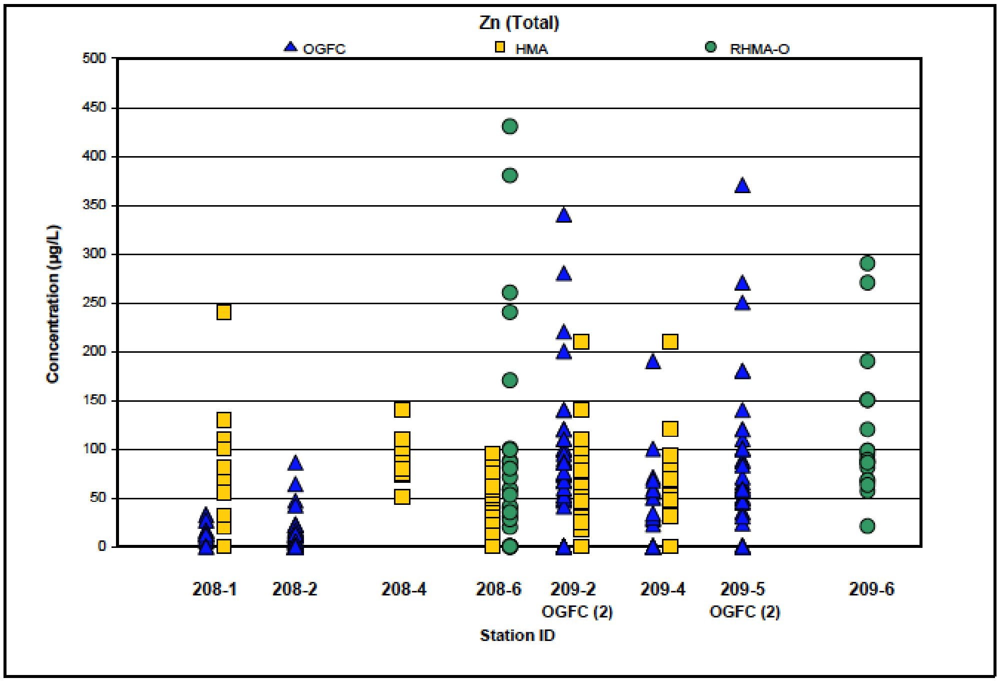
Table 4.6: Comparison of Average EMC Concentrations and Removal Efficiencies for Selected Constituents Monitored from OGFC Overlays and Conventional HMA Pavements

	Average Event Mean Concentration (EMC) or Percent Difference (PD)								
	Pair Site 208-1			Pair Site 209-2			Pair Site 209-4		
Constituent	HMA (EMC)	OGFC (EMC)	PD (%)	HMA (EMC)	OGFC (EMC	PD %	HMA (EMC)	OGFC (EMC)	PD %
TSS	45	4	91	25	12	52	35	11	67
TP	0.9	0.7	22	0.12	0.08	33	0.13	0.09	30
TN	1.0	0.6	40	1.7	1.8	-5	2.05	2.0	2
T-Cu	12	6	50	10	7	30	13	10	23
D-Cu	2.5	3.5	-40	3.5	3.8	-8	5.2	5.2	0
T-Pb	3.2	0.2	93	2.5	1.8	28	5	2.1	58
D-Pb	0.07	0.07	0	0.1	0.09	10	0.14	0.2	-42
T-Zn	63	12.5	80	80	120	-50	75	48	36
D-Zn	6	5	17	22	62	-181	23	30	-30

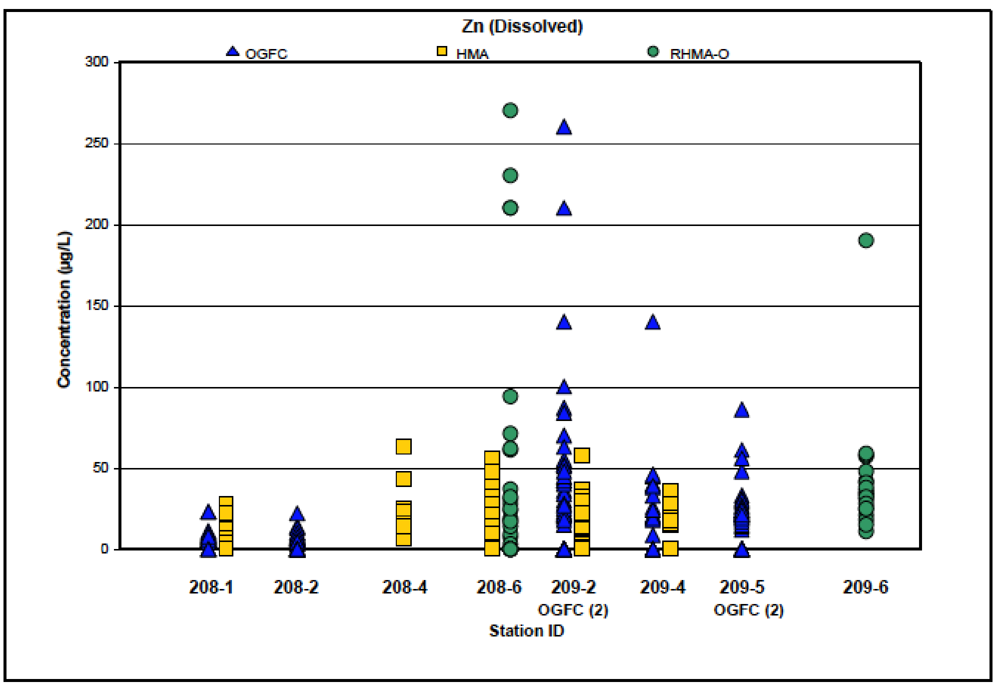
Note: D= dissolved, T=total, EMC = event mean concentration, PD = percent difference compared to HMA pavement
Data source: Caltrans (2012)

Table 4.7: Aggregate Mixture and Binder Specification for OGFC Sites Used for Caltrans Water Quality Monitoring Evaluation

Aggregate/Binder Specification	RHMA-O Gradation (% passing)	
	TxDOT	Caltrans
Aggregate size/no. (mm)		
¾ in (19 mm)	100	100
½ in (12.5 mm)	95-100	95-100
3/8 in (9.5 mm)	50-80	78-89
No. 4 (4.76 mm)	0-8	28-37
No. 8 (2.38 mm)	0-8	7-18
No. 30 (1.18 mm)	--	0-10
No. 200 (0.75 mm)	0-4	0-3
Pavement specification		
Binder type	Asphalt rubber (AR)	PGn64-16
Binder content	8-10	9-10
Fiber additive	yes	No



(a) Total Zn



(b) Dissolved Zn

Figure 4.1: Concentration of total and dissolved Zn from rubberized and non-rubberized OGFC compared with conventional impervious HMA sites monitored during from 2007 to 2011. (*Note*: the concentration of total and dissolved Zn for runoff generated from conventional HMA impervious surface is generally lower compared OGFC and RHMA-O overlays.)
Source: Caltrans (2012)

4.2.4 North Carolina DOT OGFC Water Quality Investigation

A water quality investigation monitoring four OGFC sites was performed in North Carolina. The study did not include pair sample collections from nearby impervious pavements. The monitoring sites were located along a 48-km stretch of eastbound Interstate 40 (I-40) between Raleigh and Wilmington. The first site (NC1) was located near mile marker 330, and the second site (NC2) was located between mile markers 332 and 333; both sites were in Johnston County. The third OGFC site was located between mile markers 352 and 353 in Sampson County (NC3), and the fourth site (NC4) was located near mile marker 360 in Duplin County. Water quality samples were collected from September 2008 through May 2010. ADT counts for sites NC1 through NC4 were 20,000, 20,000, 18,000, and 17,000, respectively (Eck et al. 2012).

Automatic flow-weighted samplers were used at all four OGFC sites (NC1-4). Slot drains were installed 0.3 to 0.6 m from the edge of the pavement to capture all runoff from the highway. Two slot drains were installed at each site; the opening of each slot drain measured 6.1 m long by 50 mm wide. Runoff from the roadway was captured in the slot drains; the outflow from both slot drains was combined into a single 15-cm-diameter pipe and routed to a 30-degree v-notch weir for flow measurement. ISCO 730 bubbler modules measured the flow depth over the weirs, and ISCO 6712 automatic samplers were used to take flow-weighted, composite samples during each storm event. Each sample was analyzed for TSS, TKN, NO_2/NO_3, ammonium nitrogen (NH_4), and total phosphorus (TP).

The results obtained from the four North Carolina OGFC sites are shown in Table 4.8. The authors compared the results obtained in North Carolina to the same water quality parameters measured in Texas, which are also included in Table 4.9. The results obtained in North Carolina were generally of the same magnitude as those from Texas. Although not all particle-bound pollutants were measured in North Carolina, based on the limited data from TSS and TP, the results obtained from there reinforce the finding that runoff from OGFC contains substantially fewer particles and particle-associated contaminants than runoff from conventional pavement. The slight variation in the nutrient results between those measured in North Carolina and Texas may be explained by factors such as different sampling methods, traffic loads, climate, pavement designs, and ages.

Table 4.8: Water Quality Results for Selected Constituents Measured at Four OGFC Sites in North Carolina Compared to Values Measured in Texas

Constituent	Median Concentration (mg/L)					
	NC1 (n=23)	NC2 (n=23)	NC3 (n=20)	NC4 (n=20)	Texas (n =69)	Overall p-values
TSS	9.0	17	8	8.4	8.40	0.015
TKN	0.82	0.97	1.01	1.09	0.70	0.13
NO_3/NO_2	0.39	0.40	0.76	1.06	0.27	<0.00
TN	1.29	1.47	1.72	2.37	0.98	<0.00
NH_4	0.39	0.34	0.46	0.34	--	--
TP	0.05	0.05	0.08	0.10	0.04	0.10

Source: Eck et al. (2012)
Note: n= sample number

For example, as shown in Table 4.9, the OGFC mix design used in North Carolina has more fine materials and a different binder type than the design used in Texas. These differences may affect permeability and impact the overlays' treatment performance. Another important environmental factor at the North Carolina sites may have influenced the OGFCs' treatment performance. Specifically, the higher nutrient levels in North Carolina are likely due to atmospheric ammonia deposition from volatilized swine waste, as the North Carolina sites lie within the densest concentration of "hog belts" in the United States (Eck et al. 2012). In addition, variations in soil type may have allowed leaching of different amounts of phosphorus to sorb to particles captured in discharged runoff (Eck et al. 2012). Further, as already noted, the monitoring sites in Texas and North Carolina had underlying differences in sampling methods, traffic loads, climate, and pavement design and age.

Table 4.9: North Carolina and Texas OGFC Mix Design Specifications

Aggregate/Binder Specification	North Carolina	Texas
Aggregate size/no. (mm)		
¾ in (19 mm)	100	--
½ in (12.5 mm)	80-100	100
3/8 in (9.5 mm)	35-60	--
5/8 in (6.3 mm)	1-20	75-100
No. 4 (4.76 mm)	1-10	25-45
No. 8 (2.38 mm)	1-10	5-15
No. 200 (0.75 mm)	1-4	1-3
Pavement specification		
Binder type	PG-76	PG-64
Binder content	5.5-7.0	5.0-8.0
Fiber additive	Yes	Yes

Source: Eck et al. (2012)

4.2.5 Laboratory Water Quality Evaluations of Tire Rubber and Rubberized Asphalt Pavements

Aside from the water quality investigations presented above, several other water quality studies were performed under laboratory conditions to assess the leachate quality produced from crumb rubber and rubberized asphalt pavements. The first laboratory study was performed by Vashisth et al. (1998) in Rhode Island in three-phases to assess the water quality characteristics of leachates generated from rubberized asphalt pavement. The first phase assessed the possible pollutants associated with crumb rubber as binder modifier. In the second phase, a water quality evaluation was performed on crumb rubber samples under simulated environmental conditions. And in the third phase, water quality evaluations were performed on modified asphalt samples exposed to simulated rainfall conditions.

In the first phase of the experiment, crumb-rubber modifier (CRM) samples produced by the wet and dry processes were exposed to nitric acid and at pH 2 and the resulting solutions were analyzed for trace metals. It was found that zinc concentrations were three to four orders of magnitude greater than the concentrations of other trace metals (cadmium, chromium, copper, lead, and nickel). The most likely source of the zinc was thought to be zinc oxide, an ingredient in CRM. Leachate from CRM was also tested for selected organic compounds, but no detectable polynuclear aromatic hydrocarbon (PAH) compounds were measured.

In the second phase of the study, Vashisth et al. (1998) prepared two types of HMA pavement specimens using the Marshall method. The first group was modified with CRM and the second group was prepared as a control and contained no CRM. Samples were tested at pH levels of 2, 7, and 12, and at temperatures of 20°C and 45°C to represent the average and maximum asphalt pavement temperatures in the field. Leachate from these samples were tested for metals, including cadmium, chromium, copper, lead, nickel, and zinc. The results showed a general trend in which higher concentrations of metals were leached from the both rubberized pavement specimens (CRM samples processed by the wet and dry processes) than from the control specimens. For lead, nickel, and zinc the differences were generally larger for the dry process samples than for the wet process samples, possibly because of more CRM is used in the dry process. Higher concentrations of benzothiazole were found in both the wet and dry process CRM samples than in the control samples. The total concentration of PAH compounds ranged from 60.2 to 601 ng/L for the control samples, 374 to 710 ng/L for the dry process CRM samples, and 97.3 to 727 ng/L for the wet process CRM samples.

In the study's third phase, Vashisth et al. (1998) compacted asphalt pavements modified with CRM as binder and exposed these sample to different light, traffic, and rain simulations. Instead of using simulated light, the samples were actually placed in a high-density polyethylene (HDPE) box with a clear lid and exposed to sunlight. To simulate traffic, a steel-wheel mobile compactor was used on top of Teflon plates. A 125 mm, 30 minute rainstorm was simulated using water with pH values of 4.3 and 7.0 for different samples. The leachate samples were analyzed for metals and organic compounds. The results revealed that metal concentrations were low for both pH values, and that only two metals were detected for the dry process samples. Compared with the metal concentrations of the control, little difference was found between the concentrations from the rubberized pavements prepared using the wet and dry processes. Simulated runoff from both rubberized specimens indicated that the concentrations of benzothiazoles, hydroxybenzotriazole, and PAHs were higher than the control. However, the authors concluded that these detected concentrations were low, and that under field condition they would be further diluted by runoff during rain events and might not even be detectable.

In a different investigation, Azizian et al. (2003) conducted a series of laboratory leachate tests to evaluate important processes that affect the chemical composition, aquatic toxicity, and fate of leachates from CRM in highway applications. The surface leaching test performed is applicable to both the permeable and impermeable highways. The leachate samples were prepared through batch leaching and flat-plate leaching tests. In the batch leaching test, solids are crushed and sieved (4-1/4 inch) and then immersed in distilled water (1:4 solid:liquid mass ratio) in a sealed 2-l polycarbonate bottle; they are then tumbled at room temperature for a time and the leachate is filtered to remove the solids (Azizian et al. 2003).

The flat plates are prepared by compacting the rubberized asphalt specimens (standard 4-inch diameter 4-inch cylinders) using the Marshall method (AASHTO T 245). Rubberized asphalt materials were either prepared in the laboratory or obtained from field projects. Rubberized asphalt was obtained pre-mixed directly from Massachusetts Department of Transportation. Preparation of the asphalt-based materials for laboratory testing followed the Oregon Department of Transportation (ODOT) 1993 mix design procedure, which was used to estimate the expected optimum binder content (5.4 percent of total mix by mass). Locally available aggregates were used in the asphalt assemblages. After mixing, the asphalt assemblages were aged following the procedure established by the Strategic Highway Research Program (AASHTO R 30). Numerous chemical (inorganic and organic) analyses as well as toxicity tests were performed on the leachate samples. The samples were analyzed at five-hour intervals for one week, until saturation concentration was reached. The results showed that about 50 percent of the final leachate concentration was reached within the first 10 hours. Leaching rates during this time are probably highly representative of first-flush chemical releases from new construction materials; typical leaching rates of weathered materials probably are best described by the slower loss rates observed after several days of leaching. Leaching from the flat plate test showed significant mass transfer limitations compared to the batch leaching tests, with no toxic effects being measured in the flat plate leachate.

In the batch leaching, the benzothiazole concentration was about 0.54 mg/l after seven days. Benzothiazole is a highly toxic compound with an EC50 of 0.68 mg/l. Aluminum and mercury also were detected in the leachate at concentrations of 1.5 and 0.02 mg/l, respectively. Reduced concentrations of benzothiazole, aluminum, and mercury after sorbing to soils rendered the leachate completely nontoxic. Volatilization and biodegradation reduced the benzothiazole concentration by about 90 percent, to 0.04 mg/l, with subsequent removal of the toxic effect. Photolysis did not affect the benzothiazole concentration and its toxicity was not changed. This suggests that benzothiazole is a volatile and biodegradable compound, but that it resists the photolysis oxidation process. Azizian et al. (2003) concluded that contaminants from rubberized asphalt leachates are thus degraded or retarded, and under field condition they should not be transported into nearby soils and groundwater.

In 2009, the University of California, Davis performed a controlled laboratory study for Caltrans to find out whether or not permeable pavement surfaces themselves are a source of pollution and, if they are, what their major pollutants are. An experimental apparatus was designed and fabricated for this study to evaluate the leachate quality generated from a range of open-graded and dense-graded asphalt and concrete pavements specimens (Kayhanian et al. 2009a). The pavement-surfacing materials tested included rubberized asphalt concrete open-graded (RAC-O), rubberized asphalt concrete gap-graded (RAC-G), open-graded asphalt concrete (OGAC) and polymer-modified OGAC (two binder sources each for OGAC and polymer-modified OGAC, resulting in four different binders), terminal-blend-modified binder gap-graded (MB-G), dense-graded asphalt concrete (DGAC), and portland cement concrete (PCC) mixes. Nine specimens of each of these pavement materials were prepared for testing at temperatures of 4, 20, and 45°C with three replicates of each. An additional specimen of each asphalt pavement surfacing material was tested to address the influence of age on water quality. A representative leachate sample was collected from the surface and subsurface and each leachate sample was evaluated for pH, conductivity, turbidity, hardness as $CaCO_3$, total suspended solids (TSS), total dissolved solids (TDS), total organic carbon (TOC), metals (As, Cd, Cr, Cu, Pb, Ni, and Zn), total nitrogen (TN), total phosphorus (TP), polyaromatic hydrocarbons (PAHs), oil and grease (O&G), and chemical oxygen demand (COD). In addition, composite leachate samples produced from all the pavement specimens were tested for toxicity.

The results of this study (Kayhanian et al. 2009a) showed the following:

1. The concentration of most organic and inorganic chemical constituents generated from the leachate of the specimens was below or within the reporting limit (detection limit),
2. Temperature did not significantly change the leachate pollutant concentration,
3. Aging (heat treatment) of the surfacing pavement materials did not contribute to additional pollutant concentration,

4. Dissolved chemical constituent concentrations (except concentrations of chromium) in the leachate of all pavement types were generally negligible, and
5. Acute toxicity based on the survival of the water flea species *(Ceriodaphnia dubia)* was negligible for nearly all fresh and aged leachate samples.

Table 4.10 lists the values of a number of water quality parameters and constituent concentrations from pavement materials under controlled laboratory conditions and from actual California highway runoff. As can be seen, the concentration of pollutants from the leachates of pavement specimens under the controlled laboratory study is negligible compared to highway runoff pollutant concentration. The findings corresponding to the controlled laboratory study (Kayhanian et al. 2009a; Kayhanian et al. 2009b) and a recent review of highway runoff characteristics prepared by Kayhanian et al. (2012) which concluded that the major source of pollutants from road surface runoff is anthropogenic and mostly associated with vehicles and airborne deposition. As an example, polyaromatic hydrocarbons (PAHs) were not detected during the controlled laboratory study but were reported in urban and highway runoff, and found to be primarily related to the combustion of transportation fuels (Lau et al. 2005; Kang et al. 2009). Similarly, the toxicity of leachate produced from the controlled laboratory study was negligible, whereas the toxicity in highway runoff was more pronounced; especially during the first-flush period (Kayhanian et al. 2008).

In a separate recent study, Maeda and Finney (2018) performed a laboratory and field study to investigate the rate at which potential water quality contaminants (organic and inorganic) may leach from tire-derived aggregate (TDA) as a function of time. The results of laboratory experiment showed that benzene, methyl isobutyl ketone (MIBK), cadmium, zinc, iron, manganese, total phosphate, and total suspended solids leach from TDA and that dissolved oxygen is altered by TDA. A dramatic decrease in release rate over time was observed for all constituents under all water exposure conditions. The results obtained from the field experiment showed that a TDA soil system removes many constituents from urban stormwater runoff, including acetone, cadmium, chemically oxidizable organic compounds, iron, lead, manganese, MIBK, oil and grease, phosphate, and zinc. The results suggest that the concentration of contaminants in leachate produced from TDA will not pose any risk to the water quality of receiving water bodies over the short-term or long-term.

Table 4.10: Concentration Ranges for Water Quality Parameters Measured from Pavement Materials under Control Laboratory Conditions and from California Highways during Rain Events

Water quality parameters and constituents	Symbol	Unit	Reporting Limit (RL)	Concentration (range) for pavement materials only	Concentration (range) for actual highway runoff in California
Conventional					
Electric conductivity	EC	μS/cm	0.1	RL-350	5-743
Hardness	as $CaCO_3$	mg/L	2	5-90	2-400
pH	pH	pH unit	NA	7.5-11	4.5-10
Total suspended solids	TSS	mg/L	1	RL-2	1-3000
Aggregate constituents					
Chemical oxygen demand	COD	mg/L	1	<RL-10	1-500
Dissolved organic carbon	DOC	mg/L	1	<RL-5	1-283
Total organic carbon	TOC	mg/L	1	<RL-10	1-530
Oil and Grease	O&G	mg/L	5	<RL	5-14
Metals (total)					
Arsenic	As	μg/L	1	<RL	0.5-70
Cadmium	Cd	μg/L	0.2	<RL	0.2-30
Copper	Cu	μg/L	1	<RL	1.2-270
Lead	Pb	μg/L	1	<RL	1-2600
Nickel	Ni	μg/L	2	<RL	1-130
Zinc	Zn	μg/L	5	<RL	5.5-1680
Nutrients					
Total Phosphorus	Total P	mg/L	0.03	<RL	0.03-4.7
Total Nitrogen	Total N	mg/L	0.1	<RL-1	0.1-18
Polycyclic aromatic hydrocarbons	PAHs	μg/L	0.05	<RL	1-25
Toxicity	*Toxicity*	%survival	NA	No toxicity was observed	30% of samples were toxic

Notes:
RL = reporting limit, NA = not applicable
The higher range concentration was only detected for concrete specimens.

In summary, the results obtained from the above laboratory investigation and the other relevant studies (for example, Solano et al., 2012 and Rhodes et al., 2012) clearly showed that a significant concentration of zinc was leached from crumb rubber under a batching study. As described by Maeda and Finney:

> Laboratory batch tests are a common method to determine potential constituents that may leach from TDA. This method typically consists of submerging a known mass of TDA in a known volume of stagnant water. There is not a standard protocol for the masses of TDA and water for this type of test and it is therefore common to express this information using a solid to liquid ratio (i.e., mass of TDA to volume of liquid). These experiments help characterize the behavior of TDA in water, but conditions are often not representative of what would occur in the field. Results from laboratory batch tests typically provide an overestimation of the concentration of contaminants since actual applications of TDA would typically have flow-through conditions with the presence of dispersive and adsorptive effects.

The concentration of Zn in leachate was higher when crumb rubber was shredded to smaller particles (Rhodes et al, 2012). However, as shown by the controlled laboratory study at UC Davis, when crumb rubber was added as a binder modifier for rubberized open-graded pavement, the amount of zinc that leached into the water passing through pavement specimen was significantly less than the detection limit. This may be due to one or both of the following factors: (1) the larger crumb rubber particle sizes used for rubberized OG pavement, and (2) binding of the rubber which is partially digested in the asphalt and then coated on the aggregate, which would make less of it available to leach. The release of rubber from a pavement can occur during trafficking due to raveling, and raveling may be reduced by optimizing the current RHMA-O mix design. Further, zinc leachate from RHMA-O–paved surfaces may also be reduced by adding an adsorbent agent to the improved mix design. Both of these issues require further research that may be pursued under the next phases of the study.

4.3 RHMA-O and OGFC Water Quality Studies Performed in Europe

As noted, most countries in Europe use polymer-modified binders and the application of RHMA–O in these locations is rare. As a result no water quality evaluations of RHMA-O are available. However, several European studies have evaluated the quality of runoff from highways where OGFC surfaces have been applied. Those studies are discussed below.

4.3.1 Water Quality Evaluation in Germany

One of the earliest investigations of runoff water quality from OGFC overlays was published by Stotz and Krauth (1994). This study analyzed the runoff generated from a 40 mm OGFC overlay in Germany for one year. The selected yearly pollutant loadings generated from this study were compared with the calculated yearly loads of the same pollutants generated from a highway paved with conventional asphalt that was monitored earlier (Stotz 1987). The solid loads from the OGFC layer were found to be approximately 50 percent lower than those generated from the conventional asphalt paved highway. Stotz and Krauth (1994) also compared the summer and winter pollutant concentrations in runoff generated from the OGFC layer. The concentration of all pollutants, except total lead and total iron, were higher in the winter than in the summer. Some of these concentration increases could be attributed to winter maintenance activities.

Another earlier runoff quality investigation was performed by Colandini et al. (1995) in which they analyzed the clogging material in OGFC to determine the correlation of pollutants removed with particle size distribution. These clogging materials were obtained from maintenance equipment that used a high-pressure water spray and vacuuming. For this study, the clogging materials were processed and fractionated as either fine (<125 μm) or coarse (<2 mm) sand sizes. The chemical analysis of clogging material based on these two particle-size groups is shown in Table 4.11. As can be seen, a higher concentration of total metals is associated with finer particle size. This study also found that fine particles represented 25 percent of the mass of clogging particles but contained between 40 and 50 percent of the total heavy metal contents.

Table 4.11: Average Concentration of Selected Metals Found in Clogging Material Collected from OGFC Overlays

Constituent	Unit	Average Concentration Based on Particle Size	
		Fine Particles (<2 mm)	Coarse Particles (<125 μm)
Copper (total)	mg/kg	320	438
Lead (total)	mg/kg	1258	1474
Zinc (total)	mg/kg	796	975
Cadmium (total)	mg/kg	2.01	3.25

Source: Adapted from Colandini et al. (1995)

4.3.2 Water Quality Evaluation in France

In France, Ranchet (1995) conducted a two-year-long water quality monitoring study of conventional asphalt pavement and of a highway site constructed with an OGFC overlay to determine the overlay's impact. The selected constituents' average concentrations in runoff generated from both surface pavements are compared in Table 4.12. As shown, the concentration of all constituents (except TKN) from runoff generated by OGFC layer is less than the runoff from conventional asphalt pavement.

Table 4.12: Comparison of Selected Constituent Concentrations in Runoff Generated from an OGFC Overlay and Conventional Asphalt Pavements in France

Constituent	Unit	Average Value		
		Conventional Asphalt	OGFC Overlay	Removal Efficiency (%)
Total suspended solids	mg/L	61	57	7
Total Kjeldahl nitrogen	mg/L	1.4	2.3	-64
Total hydrocarbons, (total)	mg/L	3.2	1.7	47
Copper (total)	µg/L	16	6	63
Lead (total)	µg/L	< 2	< 1	NA
Zinc (total)	µg/L	190	63	67
Cadmium (total)	µg/L	< 0.1	< 0.1	NA

Source: Adapted from Ranchet (1995)

In a separate water quality investigation in France, Pagotto et al. (2000) compared the quality of highway runoff from different pavement types. The selected highway site was originally paved with conventional asphalt pavement and its runoff was monitored for a year. A 30 mm OGFC overlay was later constructed at the same site and the postconstruction runoff was monitored for a year. The water quality concentration results for selected constituents are shown in Table 4.13. As can be seen, the greatest reduction occurred in total suspended solids and total metals. The reduction in dissolved metals was lower, indicating that the majority of metals were present as particulates. The removal of dissolved metals may occur through adsorption by the pavement or the clogging materials as well as biosorption of heavy metals, which is less likely under the pavement's non-ideal environmental conditions. Contrary to previous water quality studies in Europe, a reduction in TKN was also observed in this study and there was no change in chemical oxygen demand from the runoff of both pavement types.

Table 4.13: Comparison of Concentrations of Selected Constituents from Runoff Generated by OGFC Overlay and Conventional Asphalt Pavements in France

Constituent	Unit	Average Values		
		Conventional Asphalt	OGFC Overlay	Removal Efficiency (%)
Total Suspended Solids	mg/L	46	8.7	81
Total Kjeldahl nitrogen	mg/L	2.1	1.2	43
Chemical oxygen demand	mg/L	80	80	0
Chlorine	mg/L	18	16	11
Hydrocarbons, total	mg/L	1.2	0.09	93
Cadmium, total	µg/L	0.88	0.28	68
Cadmium, dissolved	µg/L	0.32	0.13	59
Copper, total	µg/L	30	20	33
Copper, dissolved	µg/L	19	16	16
Lead, total	µg/L	40	8.7	78
Lead, dissolved	µg/L	3.3	2.2	33
Zinc, total	µg/L	228	77	66
Zinc, dissolved	µg/L	140	54	61

Source: Adapted from Pogotto et al. (2000)

4.3.3 Water Quality Evaluation in The Netherlands

Another water quality evaluation of runoff generated from OGFC layers was initiated in the Netherlands in 1994 and continued for over four years. Berbee et al. (1999) compared the quality of runoff generated from an OGFC layer with runoff generated from conventional asphalt pavements. The porous asphalt overlay was approximately 50-mm thick and three-years old at the start of the study in 1994. The comparative chemical results for selected constituents are shown in Table 4.14. As shown, the constituent concentrations in runoff generated from the OGFC were significantly lower than in the runoff from the conventional asphalt pavement. The highest reduction was related to the total suspended solids concentration.

Legret et al. (1999) also investigated the ability of porous asphalt overlays to remove a large portion of the particulate heavy metals found in stormwater runoff. This study was performed in a laboratory by spraying actual highway runoff water over artificially clogged OGFC cores to simulate rain events. The captured water filtered through the OGFC core samples, which were chemically analyzed for heavy metals. The results showed that concentration of total heavy metals (lead, copper, cadmium, and zinc) in infiltrated water was substantially reduced, indicating that most of the particulate metals were retained through captured particles within the void spaces.

Table 4.14: Comparison of Selected Constituent Concentrations for Runoff Generated from OGFC Overlay and Conventional Asphalt Pavements in the Netherlands

Constituent	Unit	Range of Values		
		Impervious Asphalt Pavement	OGFC Overlay	Removal Efficiency (%)
Total suspended solids	mg/L	330	36	89
Total Kjeldahl nitrogen	mg/L	2.5	1.4	45
Chemical oxygen demand	mg/L	146	17	88
Chlorine	mg/L	< 1	< 1	NA
Copper (total)	mg/L	127	61	52
Lead (total)	mg/L	78	12	85
Zinc (total)	mg/L	359	75	79
Cadmium (total)	mg/L	0.8	0.1	88

Source: Adapted from Berbee et al. (1999)

4.3.4 Water Quality Characteristics of OGFC in the US Compared to Europe

Table 4.15 shows the averaged results from European and US studies pertaining to the concentrations of selected constituents in effluents from OGFC overlays. As the table shows, except for the concentrations of TSS and Zn, generally comparable results were obtained from the US and European studies. The higher concentration of TSS in Europe is may be related to winter maintenance, in which sand particles are carried from conventional impervious asphalt pavements to OGFC surfaces. In addition, the comparison results obtained for dissolved pollutants from OGFCs and conventional impervious pavement in Europe confirmed the findings by US studies indicating that the removal of dissolved pollutants was either minimum or negligible. Therefore, based on the limited results obtained in both the US and Europe, it can be concluded that as long as the void spaces of OGFC and RHMA-O remain unclogged (i.e., pavement permeability is assured), there is a high probability that both OGFC types will perform similarly and provide fairly similar water quality treatment results regardless of their location. The only difference found between the two pavement types is related to their long-term durability and functional performance, which is highly dependent on mix design.

Table 4.15: Comparison of the Average OGFC Effluent Concentration for Selected Water Quality Parameters Measured in the US and Europe

Constituent	Unit	Average OGFC effluent concentration	
		Europe*	**US****
Total Suspended Solids	mg/L	34	9
Total Kjeldahl nitrogen	mg/L	1.3	1.4
Copper, (total)	µg/L	13	9.4
Copper (dissolved)	µg/L	16	12.3
Lead, (total)	µg/L	3.2	1.2
Lead (dissolved)	µg/L	0.7	0.6
Zinc, (total)	µg/L	46	40.6
Zinc (dissolved)	µg/L	27	38.7

*The average values were estimated based on the available data from Germany, France, and The Netherlands.
*The average values were estimated based on the available data from Texas, North Carolina, and California.

4.4 Comparison of Water Quality Characteristics from RHMA-O and OGFC Pavements

One issue that needs to be addressed is whether the water quality treatments accomplished by RHMA-O and OGFC overlay surfaces differ significantly. Since insufficient data are currently available to perform an adequate analysis, the issue was addressed by examining a single water quality investigation that TxDOT performed using a statistical test on selected water quality constituents (Sampson et al. 2014). The statistical analysis was performed to see if there were any significant differences between the median concentration of constituents monitored from RHMA-O and OGFC overlays. The results of this analysis are shown in Table 4.16.

As can be seen in the table, the water quality treatment rendered by the mixes is similar except for the total and dissolved zinc (these results are indicated by shading). This difference can be explained by the rubberized asphalt binder used in RHMA-O; the recycled tire rubber introduced into that mix contains a higher concentration of zinc than the petroleum-based PG 76 binder used in OGFC pavement.

Based on the limited available data and since the treatment or pollution removal mechanisms from RHMA-O and OGFC are the same, it was expected that the two pavement types would achieve comparable pollutant removal levels except for zinc. Generally, however, OGFC and RHMA-O pavements are effective at removing particulate pollutants and have minimal ability to remove dissolved pollutants—and they sometimes have negative removal efficiency. Therefore, from a water quality point of view, as long as the void spaces of their overlay surfaces remain open and the pavement remains highly permeable during its service lifetime, it is expected that both rubberized and non-rubberized pavement will provide similar water quality treatment performance.

Table 4.16: Comparison of Selected Constituents Median Concentrations of Rubberized and Non-Rubberized OGFC Mix Designs

Constituent	Unit	OGFC	RHMA-O	P value*
TSS	mg/L	12	12	0.425
NO_3/NO_2	mg/L	0.27	0.30	0.209
Total P	mg/L	0.09	0.06	0.281
Total Cu	µg/L	13	13	0.484
Total Pb	µg/L	1.63	2.4	0.087
Total Zn	µg/L	37	86	<0001
Dissolved P	mg/L	0	0	0.363
Dissolved Cu	µg/L	9	9	0.352
Dissolved Pb	µg/L	1	1	0.492
Dissolved Zn	µg/L	20	51	<0.0001

Source: Adapted from Sampson et al. (2014)
*The statistical analysis was performed based on 95% confidence interval (e.g., p = 0.05).

4.5 Comparison of Runoff Water Quality Generated from the OGFC or RHMA-O Surface Overlays to the Effluent Water Quality from Selected BMPs

Water quality results from runoff samples collected from OGFC overlays in Texas and California were compared with effluent from approved BMPs for highway stormwater runoff management: TxDOT compared the quality of runoff collected from OGFC discharge with the quality of a typical effluent obtained from both Austin sand filters and right-of-way (ROW) vegetative strips. The first comparative evaluation was conducted to compare the pollutant results removed from two curb-and-gutter Mopac OGFC sites with the effluent values from water treated by vegetated shoulder strips where the inflow water came from the surface of a conventional impervious-asphalt-paved surface in Austin Texas (Kearfott et al. 2005; Eck et al. 2010; Eck et al. 2012). The removal efficiencies achieved by the vegetated shoulder and the OGFC are shown in Table 4.17. As can be seen, the reduction in TSS was almost identical and the removal efficiency for NO_3/NO_2, TP, Cu-T, and Pb-T were higher for the OGFC. Total zinc was the only constituent that showed any real decrease in efficiency, and this could be due to the asphalt rubber binder used at the northbound OGFC site. In general, the results of this study suggest that a curb-and-gutter OGFC configuration does not hinder the ability of OGFC to improve water quality.

Table 4.17: Removal Efficiency Comparison for Selected Pollutants for OGFC and Vegetated Shoulder for Highway Runoff Treatment in Texas, US

Constituent	Unit	Removal Efficiency (%)	
		Vegetated Shoulder	OGFC
TSS	mg/L	93	92
NO_3/NO_2	mg/L	-28	59
Total P	mg/L	71	84
Total Cu	μg/L	62	74
Total Pb	μg/L	92	98
Total Zn	μg/L	87	78

Source: Adapted from Sampson et al. (2014)

In a separate TxDOT water quality evaluation study, Eck et al. (2010) compared the abilities of OGFCs to remove selected stormwater runoff constituents with the performance of Austin sand filters. Table 4.18 lists the removal efficiency comparison results obtained along the Mopac by the OGFC and the vegetated shoulder. The performance results are comparable, even though the sand filters require extra land and extended treatment time while the OGFC pavement surface itself performs the treatment without additional land in the right-of-way or the addition of a constructed BMP. The OGFC may require additional maintenance and resurfacing, but details about this are not fully known at this time.

To compare the economics of using OGFC against the use of existing approved BMPs (i.e., Austin sand filter or vegetated filter), Eck et al. (2010) performed a life cycle cost analysis. The most sensitive variable was found to be the cost of obtaining additional land for the right-of-way. Using construction prices from the year 2008, OGFC was found to be more economical than the Austin sand filter and as land prices rise it becomes more economical than a vegetated filter strip.

Table 4.18: Comparison of Highway Runoff Pollutant Removal Efficiencies of Selected Constituents by OGFC and Austin Sand Filter in Texas, US

Constituent	Unit	Removal Efficiency (%)	
		Austin Sand Filter	OGFC
TSS	mg/L	89	92
NO_3/NO_2	mg/L	17	59
Total P	mg/L	59	84
Total Cu	μg/L	72	74
Total Pb	μg/L	86	98
Total Zn	μg/L	76	78

Source: Adapted from Sampson et al. (2014)

The runoff quality generated from OGFC overlays in California was also compared to the typical effluent quality from sand filters that were previously used as a BMP and monitored by Caltrans for treating impervious pavement highway runoff. The sand filter is considered to be one of the more effective BMPs currently on the Caltrans list of approved stormwater treatment technologies. This comparative analysis was performed to determine whether the improvement in water quality from an OGFC overlay was comparable to that achieved with a sand filter. The comparative performance of OGFC and Austin sand filter for selected constituents is shown in Table 4.19. As shown, with the exception of TSS, the effluent quality obtained from OGFC was better that the effluent quality from the Austin sand filter. Because of these exceptional performance results, OGFC can be considered as a potential BMP for selected areas, particularly for highways that require the purchase of additional ROW land or to construct a BMP.

Table 4.19: Comparison of Concentrations of Selected Pollutant from OGFC and Austin Sand Filter in California

Constituent	Unit	Effluent Concentration		Better Effluent Quality from OGFC than Sand Filter
		Austin Sand Filter	OGFC Pavement	
TSS	mg/L	5.5	6.5	N
Total N	mg/L	2.0	0.8	Y
Total P	mg/L	0.02	0.01	Y
Total Cu	µg/L	8.5	6.5	Y
Dissolve Cu	µg/L	7.0	4.2	Y
Total Pb	µg/L	1.4	0.5	Y
Dissolve Pb	µg/L	1.0	0.1	Same
Total Zn	µg/L	26	18	Y
Dissolved Zn	µg/L	18	10	Y

Source: Data source: Caltrans (2011)

N= No; Y = Yes

4.6 Approval of OGFC and RHMA-O as a BMP for Runoff Treatment to Get Credit for Selected Pollution Removal by Transportation Agencies in the United States

As previously noted, only four US state DOTs—Arizona, California, Florida, and Texas—use RHMA-O as an overlay on highways. While Arizona and Florida have performed numerous studies to evaluate the various performance aspects of RHMA-O, these states have not yet performed any evaluations of runoff water quality from these pavement types. During the past 15 years, however, the Texas DOT has performed these types of evaluations of OGFC and RHMA-O paved surfaces, and because of the encouraging results regarding pollutant removal efficiency obtained, the Texas Commission on Environmental Quality (TCEQ) approved the surfaces for BMP use on uncurbed roadways. This decision was also based on information collected in past OGFC water quality studies, which were typically completed on roadway segments with vegetated strips along the shoulder. The following specific language was used in the recent (Texas DOT 2017) stormwater management plan.

> *New specification of materials used to construct roadways such as permeable friction courses (PFC) also serve as a filter for runoff, as stormwater flows through PFC (pages 72 and 73, paragraph 1of [Texas DOT 2017]).*
>
> *TxDOT has developed and implements a set of pollution prevention measures that will reduce the discharge of pollutants in stormwater from the following activities:*
>
> - *Changing operations to minimize the exposure or mobilization of pollutants to prevent them from entering surface waters. TxDOT has incorporated, where applicable, a PFC surface treatment into roadway construction - the latest Texas Department of Transportation Storm Water Management Program 73 May 2017 controls for stormwater quality since 2004. A PFC reduces splash and spray from vehicular traffic, minimizing the pollutant wash-off and reducing potential pollutant transport. TxDOT, through research and testing, determined that PFC has proven to reduce a certain percentage of pollutants before they reach surface waters. TxDOT studies have indicated a concentration reduction of the following parameters of concerns:*
>   - *88 percent reduction of Total Suspended Solids (TSS);*
>   - *63 percent reduction of Total Phosphorus;*
>   - *57 percent reduction of Total copper;*
>   - *88 percent reduction of Total lead;*
>   - *84 percent reduction of Total zinc; and*
>   - *40 percent reduction of dissolved zinc.*

A Caltrans field-monitoring study conducted from 2007 to 2011 also demonstrated the capacity of OGFCs to produce runoff water quality with lower TSS, TP, Total copper, Total lead, and Total zinc concentrations. OGFC's removal efficiency for these pollutants was comparable to that of the Austin sand filter, one of the most efficient tools in the Caltrans BMP toolbox. Caltrans now considers OGFC to be an approved BMP treatment for its toolbox, and has begun claiming runoff water quality treatment credits from OGFC pavement use. Adding OGFC as a BMP gives Caltrans an alternative way to treat stormwater runoff at new construction areas and selected retrofit sites, eliminating the need to buy any additional right-of-ways (ROWs) or to install constructive BMPs.

Researchers from North Carolina State University (NCSU) have examined the water quality characteristics of runoff from several highway sites with OGFC overlays (Eck et al. 2010). Their findings showed that the results of a study conducted by the state of North Carolina were comparable to those of another such study performed in Texas. Based on the NCSU's results, its researchers recommended to the North Carolina Department of Transportation that OGFC be considered as a BMP for the removal of pollutants from the state's highways. However as of July 25, 2019, the North Carolina Environmental Quality Department had not yet approved the use of OGFC as a BMP.

When considering the application of OGFC as a BMP for highways, drainage function should be taken into account in design considerations. For example, current practice for establishing OGFC overlay thickness mostly focuses on aggregate size, ensuring that the layer must be thicker than the largest aggregate to obtain the desired structural properties. The approach ignores the essential drainage functions provided by OGFC. An alternative approach could design an OGFC layer thick enough to contain a design storm event (for example, a two-year storm), and then verify that this thickness exceeds the minimum established by aggregate size (Eck et al. 2010). Texas DOT has developed tools to quantify the drainage process of OGFC layers for steady state and unsteady conditions, and for simple and complex roadway geometries. These tools can be used to make informed decisions during the OGFC design process (Eck et al. 2010). The process of selecting appropriate OGFC thickness based on a proposed rational method was also described in NCHRP 640 report (Cooley et al. 2009).

4.7 Potential Improvement of OGFC or RHMA-O Mix Design for Higher Pollutant Removal Efficiency

The results presented in this chapter provide a great deal of evidence that OGFC and RHMA-O surface overlays generally have the ability to remove particulate pollutants, but their ability to remove dissolved pollutants is minimal or negative. Since, open-graded overlay pavements—either rubberized or non-rubberized—do not capture any runoff volume, most dissolved pollutants are discharged to the highway right-of-way, where they must still be captured and treated. This additional treatment may require installation of an extra structural BMP within the highway ROW, which can be costly. Therefore, it is desirable to have OGFC or RMHA-O mix designs that can provide a full range of water quality treatments (including removal of dissolved pollutants) comparable to existing approved BMPs while also providing adequate durability and permeability over their service lives. Several research studies suggesting OGFC mix additives to improve water quality treatment are presented below.

A critical issue that must be addressed is OGFC pavements' capacity to provide adequate drainage. If an emergency lane is paved with OGFC, artificial drainage must also be incorporated into the pavement to prevent water from ponding within the pavement structure. Also, research by James (2003) found that the amount of splash and spray from a pavement has a significant effect on the dispersion of pollutants. In that research, James also compiled a summary of road pollutants and their sources and possible negative impacts, and found that changing from a traditional (dense) asphalt pavement to a porous one can greatly affect pollutant runoff. Specifically, the research found that draining rainwater through surface pores produces a filtration effect that removes most of the particulates suspended in rainwater. This filtration process effectively removes road pollutants such as the heavy metals and PAHs (polynuclear aromatic hydrocarbons) that are attached to dirt particles; porous asphalt has been found to remove approximately 90 percent of the particle-bound PAHs and heavy metals present in water runoff. One drawback is that the pollutants are trapped in the pavement's surface pores, where they build up and make the surface more difficult to recycle at the end of its lifetime.

One potential negative effect on water pollution that might result from a change to increased OGFC use is related to winter maintenance; specifically porous asphalt requires more extensive use of de-icing salts than nonporous asphalt. This change creates adverse effects on runoff pollution in two ways: it increases concentrations of de-icing chemicals in the runoff and it increases the secretion of heavy metals that are already trapped within the pores of the surface. However, the reported necessary increase in use of de-icer relative to ordinary dense asphalt varies considerably. The percentage increase in the frequency in applying deicer also varied, ranging from 30 percent to 100 percent and the quantity of de-icer from 30 percent to 450 percent. For the reasons stated above, Caltrans maintenance guidance prohibits the application of OGFC pavements in higher elevation and heavy snowfall areas (Caltrans Open Graded Friction Course Usage Guidelines, unknown date).

As previously noted, OGFC pavements are also ineffective at removing dissolved pollutants from stormwater runoff. This ineffective removal efficiency of dissolved pollutants from porous asphalt pavement was recently verified in the state of Washington by Jayakaran et al. (2019). To explore ways to improve the removal efficiency of OGFCs for dissolved pollutants, Wang et al. (2011) conducted an experimental study by adding adsorption additives to the OGFC mixtures. In that study, the commonly used granular activated carbon (GAC) was added as adsorption material and the resulting new mixture was termed *functional open-graded friction course* (FOGFC). Several physical and environmental characteristics of this FOGFC were then evaluated. This study concluded that FOGFC performance was similar to that of conventional OGFCs while it also was capable of removing dissolved pollutants. The optimum GAC dose was determined based on a minimum pavement specimen permeability of 80 m/d. The optimum GAC was established at 0.3 percent, corresponding to a TOC removal efficiency of approximately 12.5 percent. These experiments showed that there was change in TSS removal efficiency. No additional tests were performed to evaluate the removal of dissolved metals or other dissolved pollutants, but the authors recommended further research.

The removal of dissolved metals and dissolved phosphorus in stormwater treatment generated from highways has been achieved by adding metal oxides into the media of BMPs, such as sand filters. For example, dissolved phosphorus was successfully removed stormwater runoff by Erickson et al. (2012) who mixed iron filings into sand media in sand filters. Erickson et al. (2012) determined that the addition of 5 percent iron filings (by weight) captured, on average, 88 percent of the influent phosphate for at least 200 m of treated depth. The addition of iron filings and their capture of phosphates had no significant effects on the filter's hydraulic conductivity. A model was also developed by applying the column study data to predict the iron-enhanced sand filter's field performance, and the model's prediction was verified by measuring the filter's phosphate removal output in the field. It is possible that the treatment concept developed by Erickson et al. (2012) can be applied when preparing RHMA-O or OGFC mix designs; adding iron oxide to the mix designs would improve the mix's adsorption capability and hence might also provide further treatment of the dissolved metals and dissolved nutrients. These iron oxide or other metal oxides are available in sand-sized and smaller diameters, and incorporating them into the RHMA-O or OGFC mix design not be too challenging, as the following study shows.

Ahmed et al. (2015) evaluated a *multifunctional open-graded friction course* (MOGFC) for in-situ treatment of both particulates and dissolved copper and zinc from highway runoff. A typical cross section of MOGFC along with the mechanism of pollutant removal (including dissolved pollutants) is schematically shown in Figure 4.2. MOGFC was prepared by adding bentonite and zeolite as two adsorbents into the OGFC mixture. These two different types of adsorbents were selected based on cost, applicability, and availability. A series of laboratory tests were conducted to evaluate the adsorption capacity of the adsorbents and the metal removal performance of MOGFC. The results obtained showed that the maximum adsorption capacity of bentonite and zeolite was 1.44 and 10.63 mg/g for copper and 1.18 and 1.96 mg/g for zinc, respectively. The metal removal efficiency of MOGFC improved significantly after the adsorbent agents were introduced into the OGFC. The maximum removal efficiency of dissolved copper and zinc with bentonite and zeolite were 76.3 percent and 73.7 percent and 41.8 percent and 43.7 percent, respectively. The lower removal efficiency of zinc compared to copper agreed the result observed in adsorption capacity of adsorbents. Ahmed et al. (2015) suggested that other adsorbent materials can be investigated, and observed that an optimal mix for OGFC or RHMA-O still requires further research and development.

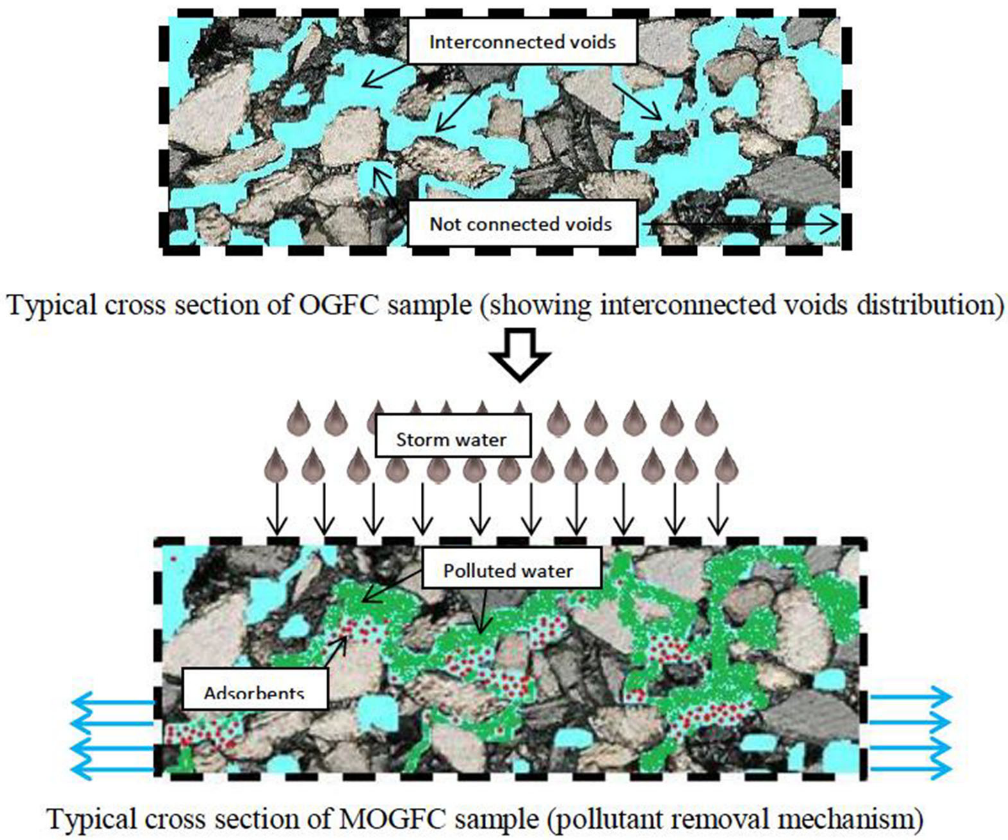


Figure 4.2: Typical cross section of MOGFC compared with OGFC for pollutant removal.
(Source: Ahmed et al. 2015)

5 MAINTENANCE CHALLENGES ASSOCIATED WITH OGFC AND RHMA-O PAVEMENTS

While there may be subtle differences in the mix designs of OGFC and RHMA-O pavements, there are no differences in the maintenance practices and challenges for both pavement types. At present, no transportation agencies in the United States, including Caltrans, practice any cleaning maintenance on their OGFC or RHMA-O paved surfaces. To make this literature review as comprehensive as possible, this chapter presents its findings on the challenges and related issues associated with OGFC and RHMA-O pavement maintenance. The information presented in this chapter could also be used for preparing a life cycle cost analysis. The major topics discussed include (1) the clogging issues related to RHMA-O or OGFC overlays and the cleaning maintenance practices used in the US and abroad, (2) the winter maintenance issues and practices related to RHMA-O and OGFC overlays in the US and abroad, and (3) the corrective and preventive maintenance practices used in the US and abroad.

5.1 Clogging Issues Related to RHMA-O or OGFC Overlays and Cleaning Maintenance Practices Used in the United States and Abroad

5.1.1 Overview of Clogging Issues

How well rubberized and non-rubberized OGFC pavements serve their intended design purposes (i.e., safety, noise reduction, or water quality benefits) is highly dependent on maintaining their high void contents and permeability for the duration of their service life. RHMA-O or OGFC void space clogging after construction can occur in two ways: load-related clogging and particle-related clogging (see Figure 5.1). Load-related clogging is caused by traffic that causes rutting, and particle-related clogging is due to a reduction in the pavement's void contents by the accumulation of particles and dirt. It is important to note that the void content reduction due to rutting is permanent and irreversible. However, the void reduction due to particle clogging within the void space may be reversed and the pavement's function restored close to its original state if the particles are removed. Therefore, it is important to understand the nature of open-graded pavement clogging behavior when considering corrective measures, including cleaning maintenance, as opposed to pavement replacement prior to the end of the pavement's service life. Surface-cleaning practices employed on RHMA-O or OGFC overlays in the US and abroad are presented below.

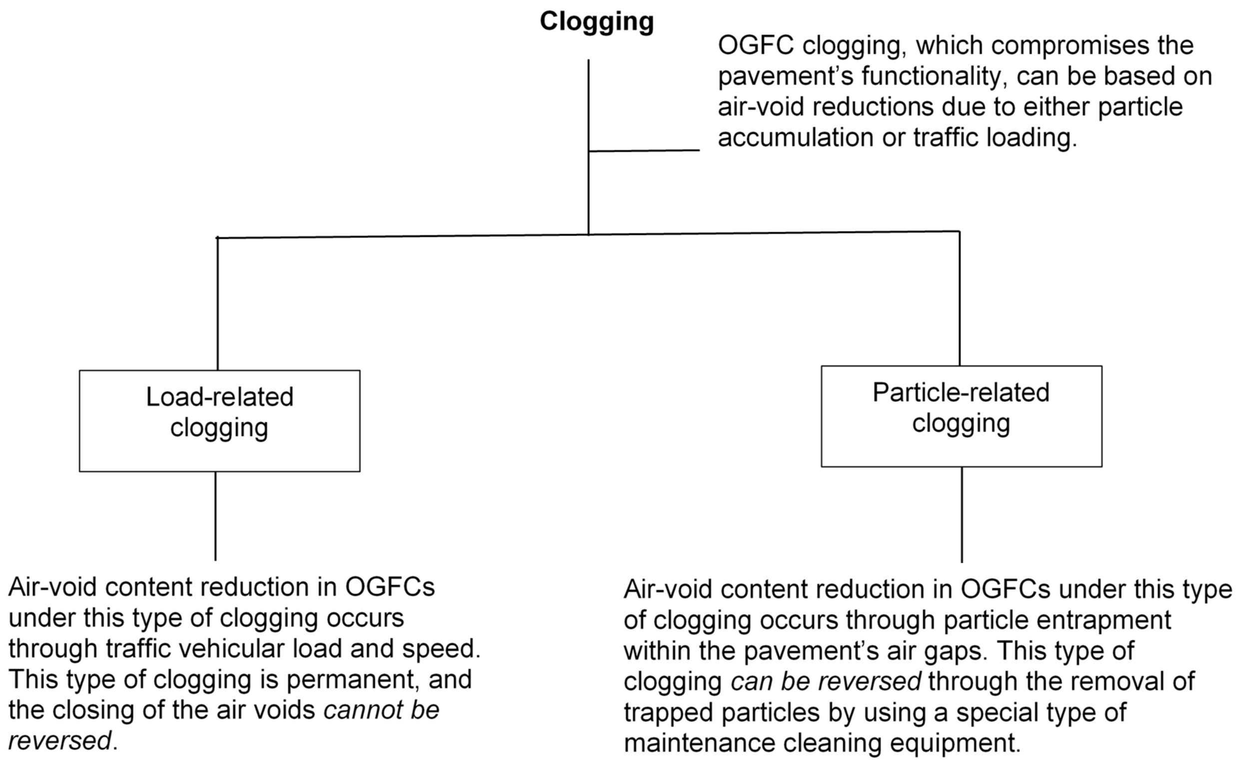


Figure 5.1: Void reduction of OGFC due to particle-related or load-related clogging.

Clogging due to particle accumulation within the void spaces of OGFC has been studied by numerous investigators. Some have found that particle clogging usually occurs in the pavement's upper layer (Kayhanian et al. 2012a, Mata and Leming 2012, Yong et al. 2013). Which clogging processes are at work depends on characteristics of the pavement (e.g., void content and pore size) and the solids that reach the pavement. The particles that cause clogging may originate from pavement wear due to tire friction erosion from adjacent areas, vegetation, or the application of sand (if allowed) during winter months (Ferguson 2005). Even without sand application during winter, solid particles will reach the pavement surface via vehicles traveling from other roads that have been sanded (Ferguson 2005). Thus, the permeability of pavements must be maintained to obtain the full benefits of open-graded pavements over the full course of their service life.

In a simulation of runoffs lasting 100 and 250 hours, Sansalone et al. (2012) showed that hydraulic conductivity (k_0) was reduced four fold by particle loading. In a separate study, Yong et al. (2012) showed the influence of climate on physical clogging by determining that a variable inflow rate with a drying period can cause more clogging than continual wetting with no dry periods. Clogging was found to be highly correlated with cumulative volume and flow rate. Al-Rubaei et al. (2013) indicated that the long-term effective performance of OGFC is related to mix design and regular cleaning maintenance. In another study, Chen et al. (2015) prepared seven suspension liquid types for particle-related clogging evaluation. The solid portion of each liquid that was trapped in the OGFC air voids, those that passed through the OGFC sample, and those retained on the sample surface were calculated after permeability tests to determine the critical particle sizes attributable to particle-related clogging. The results showed that the critical sizes of trapped particles in the OGFC mixtures were within the ranges 0.15 to 0.3 mm and 1.18 to 2.36 mm.

Coleri et al. (2013) performed a particle-clogging investigation on OGFC under controlled field conditions using rainfall simulations with and without traffic loading. The traffic loading was simulated with heavy vehicle simulator (HVS), and the rainfall simulation was performed with a known particle size distribution and a typical highway runoff TSS concentration of 120 mg/L. Core samples were taken from both simulation studies and porosity profiles were prepared for all samples based on imaging analysis. The results of an imaging analysis of core samples based on rainfall simulation without traffic loading showed that clogging occurred on the upper surface layer of the OGFC, which is mostly related to particle loading. One alternative is to replace the clogged surface layer before the end of its service life. These clogged particles may also be removed by some alternative types of cleaning methods. These alternatives can be evaluated through a life cycle cost analysis. However, Coleri et al. (2013) also determined that void reduction (clogging of void content) at a paired site, where an OGFC mix with that same design was subjected to HVS traffic, was much higher than at the site without HVS loading. From this study, Coleri et al. (2013) concluded that the majority of clogging occurred due to rutting caused by traffic loading. The proposed improved mixed design to be discussed in Chapter 7 may provide a solution that alleviates the problems noted above.

In addition to the particle- and load-related clogging that can occur years after pavement construction, OGFC and RHMA-O clogging can also be related to binder drawdown, which can occur soon after construction or on hot days when the asphalt binder becomes less viscous and drains toward the bottom of the pavement. Roseen et al. (2012) suggests that the observed decrease in infiltration capacity of a porous asphalt parking lot during its first summer after construction was likely due to binder drawdown. A mix design that minimizes binder drawdown can help minimize clogging (Gunderson 2008) and the addition of fibers or polymer additives to the mix can be used to minimize drawdown (NAPA 2003). Gunderson (2008) reported that binder can swell during hot summer months and that this process will also cause a reduction in infiltration capacity even if drawdown does not occur. This phenomenon has been shown to repeat in a cyclical fashion, with infiltration rates increasing in the winter and decreasing in the summer. Decreased infiltration rates will persist as long as temperatures remain high but increase again when the temperature drops.

Several studies were performed to determine the impact of a mix design's aggregate size gradation on the clogging of OGFC pavements. For instance, study conducted by Bentsen et al. (2005) observed that there was a strong tendency for clogging on open-graded pavements with 5-mm aggregate (which were clogged after 15 to 20 months), whereas a pavement with 8-mm aggregate remained in a much better condition for a longer time. Chen et al. (2015) prepared eight types of OGFC mixtures with different air-void contents, gradations, and nominal maximum aggregate sizes to evaluate deformation-related clogging. Wheel rutting tests were conducted on the OGFC samples with different loading times under 700 kPa and 900 kPa load levels at 45°C and 60°C, after which permeability tests were conducted at different time intervals using the developed permeameter. Permeability losses after different wheel loading and time intervals were calculated to explore the effects of the initial air-void content, nominal maximum aggregate size, temperature, and loading pressure on deformation-related clogging. The results showed that with increasing wheel loading times, the OGFC mixes' permeability decreased continually after a sharp initial decline. Permeability loss due to deformation-related clogging can be effectively reduced by using a larger nominal maximum aggregate size and larger air voids.

This literature found several investigations undertaken to assess clogging (or void reduction) in OGFC pavements under field and operating conditions. While core sampling and image analysis is a useful method for evaluating the clogging profile of open-graded pavement, this approach is time consuming and expensive (e.g., Kayhanian et al. 2012a, Ahmed 2015). Alternatively, surface clogging can be evaluated with simple permeability measurements, and Rezaei and Harvey (2013) did this in a long-term comparative study of the permeability of RHMA-O, OGFC, conventional dense-graded, and rubberized gap-graded pavements. In this study, 11 to 14 test sections for each type, which were distributed around the state and with ages up to 16 years, were monitored over 6 years. Replicate measurements were made on each test section, and the results are shown in Figure 5.2. As shown, the permeability of RHMA-O (denoted on figure as RAC-O) is as good as and comparable to OGFC (denoted on figure as OGAC). Other research studies presented in this review have shown that the durability and functionality of the rubberized OGFC sections to be comparable to those of the sections with polymer-modified binders.

Unfortunately, there is no universal approach used for permeability measurement in the US and abroad (Li et al. 2013). Several new standards have been prepared for open-graded surface permeability measurement and some studies have been conducted to use permeability to assess clogging of open-graded pavements (e.g., Fay and Akin 2013; Aldirim et al. 2007; ASTM 2009; ASTM 2011; Yildirim et al. 2007; Ongel et al. 2009; Kayhanian et al. 2012; Li et al. 2013; Razzaghmanesh and Beecham 2018). More importantly, even though some new methods have been specially developed to measure the permeability of a specific pavement type, these new methods can still be used to measure the surface permeability of other pavement types (Li et al. 2013). Hence, the relative permeability measurement of pavement by a single device and method soon after the construction and throughout the life service of the pavement is more important than the type of device or method used for permeability measurement.

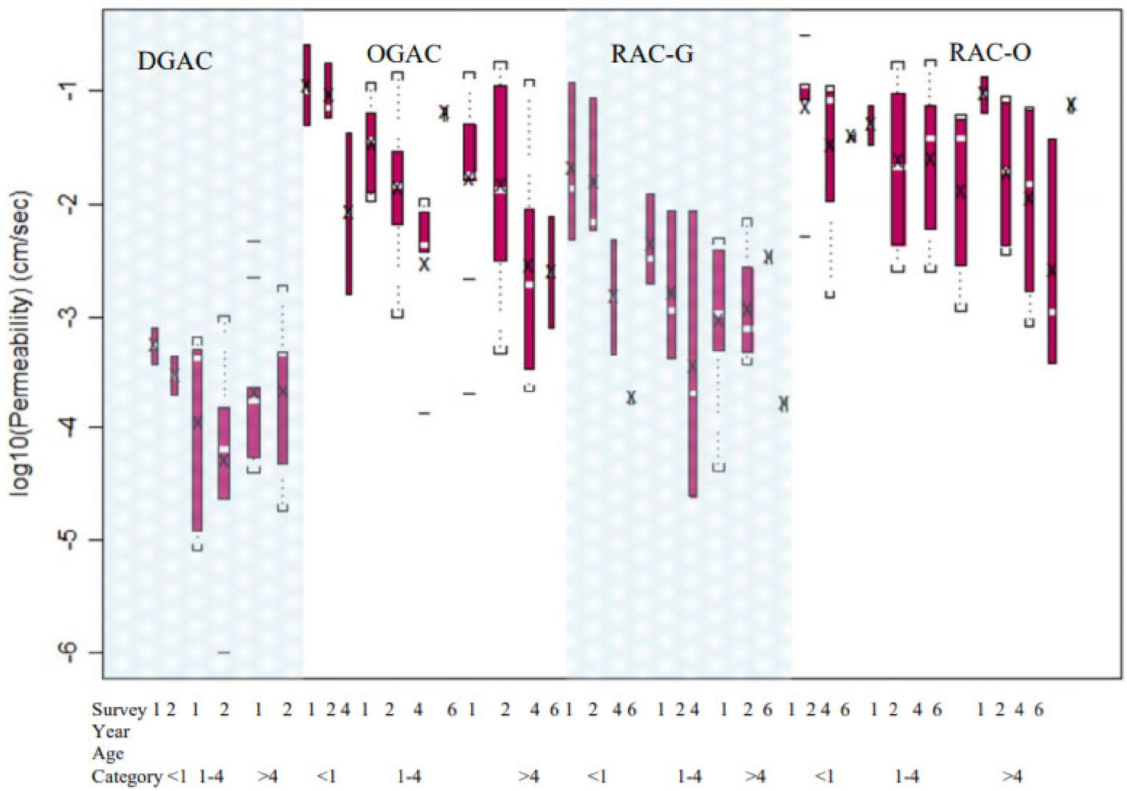


Figure 5.2: Permeability measurements over six years of multiple California dense-graded, gap-graded, and open-graded (rubberized and non-rubberized) pavements with ages between zero and 16 years.

5.1.2 Surface Cleaning Practices Used in the United States for Unclogging the OGFC or RHMA-O Overlays

As previously noted, several surveys were conducted among US departments of transportation to evaluate the state practices for cleaning the surfaces of OGFC or RHMA-O pavements (Hubber 2000; Rogge 2002; Colley et al. 2009; Bandini 2011, Blumenthal 2013, NCAT 2015 and Ghabchi et al. 2016). In most cases the results of these surveys revealed clogging to be one of the major concerns related to practical applications of OGFC or RHMA-O on highway surfaces. But while clogging was reported to be a major problem, many state DOTs still do not have a regular maintenance programs for cleaning and unclogging their OGFC and RHMA-O pavements' surfaces. Like many other state DOTs, Caltrans does not currently clean its OGFC and RHMA-O surfaces. However, when RHMA-O or OGFC is used a BMP for highways runoff treatment in certain areas specifically to obtain those pavements' potential water quality benefits, annual or other appropriate cleaning maintenance may be required. Therefore, when RHMA-O or OGFC is used as a BMP in the future, there may be two alternative approaches for dealing with this potential problem: (1) to replace the pavement sooner than the end of its expected life service, and (2) to perform regular cleaning maintenance. These two alternatives could be evaluated through a life cycle cost analysis.

5.1.3 Surface Cleaning Practices Used Internationally for Unclogging OGFC or RHMA-O Overlays

At present, rubberized OGFC is not commonly used by agencies internationally since most contractors prefer to use polymer-modified rather than rubber-modified binder for the construction of OGFC overlays. Outside of the United States, OGFC use is common in Europe and Japan. The issue of clogging of void spaces within OGFC has been reported by many European transportation agencies (Gibbs et al. 2005). The clogging issue in Europe appeared more prevalent on low-speed highways than high-speed highways. Unlike US DOTs, many European transportation agencies usually consider regular or occasional surface cleaning for clogged surfaces. Table 5.1 summarizes some of the European countries' experiences and observations regarding OGFC surface clogging and required cleaning. As can be seen, no consensus exists among European countries on the frequency of cleaning or on whether pavement cleaning is effective. In Japan, OGFC highway overlays are constructed for safety and noise reduction throughout the country and their surfaces are regularly cleaned. In both Europe and Japan, OGFC pavements cleaning is performed using specially manufactured vehicles that are discussed below.

The most common and effective cleaning method cleaning found so far is a combination of high-pressure water-washing followed by vacuuming. Several different specialized trucks equipped with mounted cleaning equipment have been developed: one type sprays high-pressure water that then vacuums up the debris, and another that applies high-pressure air and then vacuums up the debris; these have been used for OGFC surface cleaning in Europe and Japan (Isenring et al, 1990; Abe and Kishi 2002, Ahmed 2015). Generally, the high-pressure water and air-cleaning equipment clean the OGFC surface in one pass. These types of equipment can operate in low- or high-speed cleaning modes (i.e., at speeds of 1 to 2 km/h or 2 to 10 km/h). The high-speed mode can only be used when a pavement is partly clogged. When an OGFC surface pavement is densely clogged, the lower speed mode should be used.

A newer generation of high-pressure water, truck-mounted cleaning equipment used in Europe and Japan is now equipped with a water re-use treatment component that treats the vacuumed water and reuses it. Figure 5.3 and Figure 5.4 show examples of two of these. This newer equipment type uses less water and, with the recycled water available, can extend cleaning operation times. Field trials with both models showed them to be successful at restoring OGFC-layer permeability. It is important to note that, regardless of the type of cleaning equipment, cleaning should be performed while the OGFC layer is still permeable, as cleaning completely clogged OGFC layers is more difficult or less practical (Isenring et al. 1990). As noted in Table 5.1, some transportation agencies reported that it may be possible keep the OGFC surface permeable longer through regular cleaning maintenance practice, as opposed to replacing the OGFC more frequently to ensure that the surface is permeable. Replacement due to reduced permeability from clogging would generally occur sooner than the expected service life controlled by raveling.

In Japan the high-pressure air-cleaning equipment with vacuuming (see Figure 5.5) has also been used. These machine types are referred to as “function maintenance” machines since their application is intended to maintain the pavement’s noise-reduction function. This high-pressure air cleaning equipment operates between speeds of 10 and 20 km/h. Compared with high-pressure water cleaning equipment, the use of high-pressure air cleaning equipment found to be more cost-effective (Nielsen et al. 2005).

Figure 5.3: Vägren truck high-pressure cleaning equipment used for OGFC cleaning in Sweden.
(Source: Ahmed 2015)

Table 5.1: Clogging Observation and Cleaning Experience Gained from European Countries

Country	Clogging Observation and Cleaning Experience
Denmark	Observations in Denmark indicate that on roads with lower AADT, OGFC clogging began within the pavements' first year. The Danish Transportation Agency cleans its OGFC surfaces with a specialized high-pressure water blast (100 bar/125 pounds per square inch [psi]) and vacuums them immediately afterward to remove the fluid and solids. After vacuuming, the water is filtered and recycled for future cleaning operations. In Denmark, OGFC surfaces are cleaned for the first time 3 months after construction, and cleaning is done semiannually thereafter. Since the solids contain heavy metals, they must be disposed of in an approved facility. The literature from Denmark also indicates that if a pavement is not cleaned regularly, after two years or less it can become too clogged to be cleaned effectively. When a pavement's permeability falls to less than 8 cm/min, the pavement is considered too dirty to be cleaned (initial permeability is about 60 cm/min). Test sections indicate that by the fourth year the permeability of low-speed OGFC pavement is significantly reduced, and so are the pavements noise reduction benefits.
France	The literature from France reports that OGFC pavement clogging is a common problem but that surface cleaning has been found to be ineffective, so it is not done. Instead transportation agencies have tried to overcome the problem by using a modified mix design (i.e., double-layer OGFC). If the overlay surface is completely clogged, a new overlay is constructed, and milling is employed to rehabilitate the pavement surface. OGFC pavement is no longer used in developed areas because of fast clogging.
Italy	In Italy, 34 percent of the highway system has OGFC. The literature shows that experience with new OGFC in Italy has generally been good in terms of safety and noise reduction but that clogging has been an issue. Italian road agencies have tried several OGFC surface-cleaning methods, but they were not beneficial. For this reason, the pavements' noise-reduction capability has decreased substantially over their service life. When necessary, OGFC surfaces have been rehabilitated by milling and replacement with a new OGFC surface.
Netherlands	The literature indicates that in The Netherlands clogging began to manifest six months after construction, but that it did not affect noise reduction by more than 1 to 2 dB. OGFC pavements here are regularly cleaned using high-pressure water blasting (100 bar/125 psi) and then vacuumed twice yearly, but the cleaning is highly dependent on traffic, speed, and other factors. The Dutch have noticed that cleaning must be done before clogging becomes complete, since it is impossible to completely clean the OGFC surface after it does. Because of extensive clogging issues, the Dutch use OGFC pavements in rural areas and but not in urban areas.
Sweden	Clogging has been reported in Sweden and one controlled field cleaning study was performed to evaluate the effect of cleaning equipment (Ahmed 2015). Cleaning was performed using a Skanska maintenance vehicle—named VägRen—that uses both high-pressure water and vacuuming. The results showed that the VägRen cleaning vehicle was effective and generally increased the air voids by 83% after cleaning (Ahmed 2015).
United Kingdom	British maintenance experiences in the literature indicate that OGFC pavements tended to clog and were subject to raveling after a fairly short life.

Note: The summary presented in this table was partially adapted from Gibbs et al. (2005)

Figure 5.4: Truck-mounted high-pressure water washing and vacuuming equipment used for OGFC cleaning in Japan.
(Source: Nielsen 2005)

Figure 5.5: High-pressure air with vacuuming equipment used to remove clogging of OGFC surface pavements in Japan.
(Source: Nielsen 2005)

5.1.4 Frequency of Surface Cleaning

The literature review revealed that no consensus has yet been reached on how frequently to clean OGFC and RHMA-O surfaces to unclog them or to prevent clogging. Multiple factors—including ones related to the environment, geography, climate, and mix design—can play a role in clogging and how frequently cleaning is required, so the literature review found conflicting reports on both the effects of clogging and on cleaning maintenance (Razzaghmanesh and Beecham 2018).

Most transportation agencies agree that to help maintain open-graded surfaces' permeability and drainage properties that OGFC pores should be cleaned before they become totally clogged. On high-speed roads, the vehicles that use the road themselves generate a cleaning effect in the wheel tracks by the action of the tires passing over the porous surface. The faster the traffic speed, the greater the cleaning effects are, and clogging is therefore a bigger problem on low-speed roads or roads in an urban environment (Sandberg and Ejsmont 2002). Self-cleaning can also occur during rain events. Therefore, OGFC application in geographic areas that get regular rain events with shorter antecedent dry periods between them may stay cleaner.

A 1995 study of porous surfaces conducted by the Organization for Economic Cooperation and Development (OECD) suggested cleaning OGFCs every two years after the initial paving. Studies carried out in the Netherlands have suggested that on main highways and motorways, cleaning OGFC surfaces in the driving lanes is unnecessary because of the self-cleaning action following rainfall. Further, those studies suggest that how frequently OGFC surfaces are cleaned should be determined by the degree of clogging, which can be measured through the surface pavement permeability (Hamzar and Hardiman 2005; Larson 2004, Kayhanian et al. 2012a, Coleri et al. 2013, Li et al. 2013). For instance, Brosseaud and Anfosso-Ledee (2005) took permeability measurements of trial sections' surfaces when they were new and then annually for four years. The results showed that permeability decreases after one year ranged between 29 and 35 percent, and an additional decrease was observed in the following three years. In addition, Taksumoto et al., (2003) showed that the permeability of OGFC trial sections in Japan decreased between 15 and 35 percent 12 months after construction. Bendtsen et al. (2005) cleaned open-graded pavements biannually using high-pressure water/air suction, but since the study was unable to establish that significant clogging-level reductions occurred before and after the pavements were cleaned, they made no recommendation about cleaning frequency. But while researchers have not reached a consensus, they generally recommended that permeability first be measured soon after construction is completed, and then annually to investigate the effect of clogging and to determine if there is a need for surface cleaning.

5.2 Winter Maintenance Issues and Practices Related to RHMA-O and OGFC Overlays in the United States and Abroad

5.2.1 Winter Maintenance Overview

Winter maintenance activities are probably one of the less standardized practices for OGFC but, at the same time, they are one of the major reasons agencies have reservations about using OGFC pavements and why some have discontinued OGFC use. Generally, OGFC and RHMA-O pavement applications are less common in colder regions of the United States. Several cold-climate states such as Colorado, Oregon, Wisconsin, and Washington use modified binder in their mix designs to continue using of OGFC. All the European countries use modified binder in their PEM mix designs, mainly to add to their durability and functionality during winter. In Japan, OGFC application has been practiced routinely in cold regions. Overall, transportation agencies have indicated that the major issue in operating and maintaining their open-graded overlay pavements in winter involves keeping their surfaces ice-free to protect public safety. Some of the challenges of winter maintenance, the practices employed, and experiences obtained in the US and abroad are discussed in the following sections.

5.2.2 Winter Maintenance Practices in the US

A survey study conducted by Huber (2000) revealed that many US state DOTs find winter maintenance of OGFC to be problematic. The Huber survey results showed that in some cases the damage caused by studded tires and snowplows was so extensive that states in cold regions do not recommend the use of OGFCs. That study also reported that salt application on OGFC pavements was generally higher than on dense-graded pavements, and that an increase in salt application was mostly related to OGFC layers' having a lower thermal properties than typical dense-graded layers. For example, it was determined that the general heat conductivity of OGFC layers is about 40 to 70 percent less than that of dense-graded layers (Huber 2000). In addition, Huber (2000) determined that OGFC layers were about 3.6 to 5.4°F cooler than dense-graded layers. This means that an OGFC surface layer reaches a temperature below-freezing sooner than a dense-graded layer, and this results in the formation of ice/frost. OGFC overlays also stay frozen for a longer period of time than dense-graded layers. For this reason, along with the damage caused by studded tires during the winter months, Huber (2000) concluded that the application of OGFC in cold regions is less desirable. At present, Caltrans has similar policy in which they don't install OGFC in cold regions (Caltrans Open Graded Friction Course Usage Guidelines, unknown date).

As part of a separate winter maintenance practice evaluation in the United States, Rogge (2002) concluded that the rutting caused by studded tires was the most serious maintenance problem for OGFCs. OGFC surfaces were also found to be more susceptible to gouging by snowplows as they offer less resistance to the snowplow's blade. More serious damage was observed in areas with repeated plowing. The Oregon DOT Maintenance Division has attempted to use run shoes on plows and also to reduce plow speeds to combat the gouging problem and with these measurements they were partly successful. However, that DOT has also discontinued its use of OGFC pavements in mountain snow zones (Rogge 2002). Further, Rogge (2002) also found results similar to those obtained by Huber (2000) confirming that the thermal conductivity of OGFC was lower than dense-graded pavement and that OGFC froze sooner and stayed frozen for a longer period of time. Rogge (2002) also confirmed that de-icer chemicals flow into OGFC pavement instead of staying on the surface and so these pavements require larger amounts of de-icing chemicals than dense-graded asphalt pavements.

A study performed by TxDOT showed that the durability and maintenance problems exhibited by OGFCs under winter weather conditions, especially the fast formation of black ice, have prevented their widespread use throughout Texas (Yildirim et al. 2006). However, the study results also showed that anti-icing procedures have proven effective in combating black ice, freezing rain, and light snow. The study recommended that de-icing chemical agents be used when ice and snow have already bonded with the pavement surface. The study also reported that de-icing procedures require more materials than anti-icing procedures and are less capable of maintaining safe road conditions. The study also noted that sand may only be used in emergency situations in response to surprise ice or snow events, especially since the sand may cause clogging and long-term damage to OGFC pavements. In these circumstances, materials other than sand should be considered to provide friction.

Yildirim et al. (2006) developed the *i-Button* methodology for detecting ice formation on OGFC pavements, and it was implemented at three North Texas locations. This black-ice detection methodology, which makes use of sensors embedded inside and outside the pavement, appears to be sound. The *i-Button* sensors embedded in field OGFC pavements proved to be reliable under field conditions and with exposure to traffic, and they yielded an unprecedented set of highly detailed data. The results of the experiment agreed with the survey results, indicating that OGFC is the first to freeze and the last to thaw in winter conditions.

5.2.3 Winter Maintenance Practices outside the United States

Litzka (2002) and Gibbs et al. (2005) provided a good overview of the observations made and experience gained by European countries in OGFC winter maintenance. The information presented in these two reports is summarized in Table 5.2. The summary shows that in Europe winter maintenance of OGFC surface pavements is usually accomplished by application of salt or related chemicals, but that the different European transportation agencies take different approaches. While no consensus exists among those countries' approaches, they all reported that OGFC surfaces generally require a higher application rate of de-icing chemicals (25 to 50 percent) than dense-graded pavements.

In short, winter maintenance of OGFC pavements is a complicated problem and there might not be a definitive single maintenance solution (Isenring et al. 1990; Padmos 2002). Greib (2002) also suggested that since road salts behave differently on different OGFC surfaces, special locally adjusted strategies are needed. As if in support of this conclusion, Brousseaud et al. (2005) stated that experience is the only true method for developing a winter OGFC maintenance program.

As was noted earlier, OGFCs have a tendency to freeze more rapidly than dense-graded pavements. For instance, Iwata et al. (2002) conducted an experiment in Japan to compare the temperature of OGFCs and dense-graded surfaces during cold weather. The results of this study showed that during daytime, the OGFC surface layer was about 3.6°F (2°C) lower than nearby dense-graded surface layers. During snowfalls, the temperature of OGFCs was about 0.4°F (0.2°C) lower. Only during nighttime were the OGFC surface layers' temperature higher than that of the dense-graded surface layers, by approximately 1°F (0.5°C). Their generally colder temperatures explain why the OGFC pavements required more salt during the winter, a finding confirmed by many of the transportation agencies in the US and Europe (see Table 5.2). However, the extra void spaces in OGFC can help reduce the number of salt applications and amount of salt applied for high-traffic and high-speed motorways. The decrease in the salt under these conditions is due to pumping action that vehicles cause by passing over the OGFC surface pavements, as the tire-surface action continually circulates the salt solution within the pavement's void structure. The lower salt application requirement for highly trafficked OGFC surface pavements was documented by Iwata et al. (2002).

A study performed by Fay and Akin (2013) confirmed the findings of the Iwata et al. (2002) study on winter pervious pavement maintenance that liquid chemicals applied to OGFC pavement surfaces are easily transported into their interior (thus preventing them from acting with snow and ice for long time periods); and that the chemicals' absence from the surface allows snow and ice to remain there longer than they do on conventional dense-graded hot mix asphalt (DGHMA) surfaces. Moreover, because of their lower heat conductivity (which is approximately 40 to 70 percent lower than DGHMA mixtures), OGFC structures have lower temperatures than regular DGHMA, allowing ice and snow to accumulate faster, slowing thawing, and producing more rapid refreezing (Fay and Akin 2013). This is the opposite of the freezing conditions observed on full-depth porous asphalt pavements, where less freezing occurs at the surface and 60 to 77 percent less salt is required (Houle 2008; Roseen et al. 2014; Wenck 2014). The lower salt load application required on full-depth porous asphalt pavement is attributed to the ability of full-depth permeable pavements to retain their infiltration capacity throughout the winter, even in cold climates (Roseen et al. 2014). This allows water from melted snow to infiltrate through the pavement's greater depth rather than remain on its surface and freeze.

Chen et al. (2019) investigated the effectiveness of composite phase change materials (PCMs) on the performance of OGFC under freeze-thaw cycles, along with the benefits of temperature adjustment. Volumetric changes measured in the freezing-thaw cycles proved that composite PCM improved the stability of OGFC volumes in dry and saturated conditions. The effect of the freezing-thaw cycles on the performance of PCM was minor. Use of PCM could help reduce the adhesion strength of ice to OGFC and thus retard ice formation. The study's findings suggest that the cement-encapsulated material, such as polyethylene glycol/silicon dioxide (PEG/SiO_2), can be used to adjust the internal temperatures of OGFC and improve its performance relative to freezing-thaw cycles.

Table 5.2: Winter Maintenance Practices and Experience Gained from Use of OGFCs in Europe

Country	Winter Maintenance Practice and Experience
Austria	Surface temperature measurement of OGFCs in Austria showed that OGFC surfaces were generally about 1.8°F (1°C) cooler than dense-graded surfaces. Extended freezing temperatures on OGFCs caused slushy materials to swell, making them a potential hazard. To prevent slushy material from swelling on OGFC surfaces, salt is applied immediately after snowplows pass. The extra salt placed on the OGFC surface, which exceeded the amount placed on dense-graded pavements (25 to 50 percent extra salt), resulted in increased use of de-icing materials and increased maintenance costs.
Denmark	Winter maintenance in Denmark showed that, because of their thermal properties, OGFC pavements develop higher icing conditions than dense-graded asphalt pavements. For snow and ice control, Danish road agencies uses a wetted salt solution. It was reported that the OGFC surfaces increase salt consumption by 50 percent. Danish researchers also expressed concerns about transitions from dense-graded to open-graded surfaces because they may "spook" drivers in winter conditions, and they indicated that short sections of OGFC surfaces should be avoided. To reduce this risk during winter, not using OGFC in intersections was recommended.
France	In France, because of freezing, OGFC is not used in areas with altitudes above 600 m. In prolonged winter storms, salt is supplemented by a calcium chloride solution to remove thick ice and packed snow from the OGFC surface. Further, a combination of dry salt, wet salt, calcium-enhanced wet salt, and straight calcium chloride solution is used, depending on OGFC pavement conditions.
Germany	In Germany, winter maintenance of OGFC surfaces is generally considered more expensive and slightly more difficult than maintenance of dense-graded surfaces. The standard quantity of salt applied to OGFC surfaces is 0.02 lb/yd^2 (10 g/m^2), however, within problem areas the required quantity of salt may reach 0.08 lb/yd^2 (40 g/m^2). The availability of weather forecasting systems helps facilitate a timely response to winter maintenance activities.
Italy	In Italy, salt is generally applied to wet pavements in quantities of 0.02 to 0.04 lb/yd^2 (10 to 20 g/m^2) as a preventive maintenance technique. During snowfalls, the dry-rodded salt is again applied at the same rate. After snowplows have removed the snow, another 0.02 to 0.06 lb/yd^2 (10 to 30 g/m^2) of road salt is applied, depending upon road conditions. Italian researchers noted that changing the maximum aggregate size in OGFC mix designs from 20 mm to 16 mm led to a significant improvement in road conditions during winter conditions. Winter maintenance observations showed that OGFC allows the wet salt to drain to the subsurface and hence about 50 percent more anti-icing materials are required than for dense-graded layers. Because salt brine in runoff is an environmental concern in Italy, they now switched using a combination of magnesium and calcium based de-icing agents. With respect to traffic safety, it was shown that late application of anti-icing techniques led to safety concerns. Experience in Italy showed that the application of salt on OGFC is more difficult and costly than on dense-graded pavement. One recommended alternative solution was to place heating elements under OGFC layers to maintain the surface temperature at or above the freezing level (Giuliani 2002).
Netherlands	Reports from The Netherlands noted that OGFC requires additional maintenance during winter and that about 50 percent more salt applications are generally used than with dense-graded

Country	Winter Maintenance Practice and Experience
	pavements. To prevent freezing, Dutch transportation agencies apply pre-wetted salt as soon as the pavement begins to freeze.
United Kingdom	Transportation authorities in the United Kingdom noticed that less winter salt is required with the twin-layers OGFC, observing that the thin upper layer held the salt on the road surface for a longer time and hence required less salt. With thicker, single layer OGFC, much of the salt disappeared into the voids below the surface and hence more de-icing salt was needed.

Note: this summary was compiled from information presented in Litzka (2002) and Gibbs et al. (2005).

A study performed by Takahashi (2013) showed that the service lives of OGFCs constructed in colder regions of Japan are much shorter than in warmer regions, as shown in Figure 5.6. These results indicate that 58 percent of OGFCs in warm climates had a service life of 11 years, whereas only 20 percent of the OGFCs in cold climates attained that service life. The shorter service life of OGFCs in Japan's snowy areas was found to be related to abrasion caused by the tire chains used during extreme winter maintenance activities (Takahashi 2013). For this reason, OGFC and RHMA-O construction in high elevations with a prolonged winter season and high snowfall is not recommended.

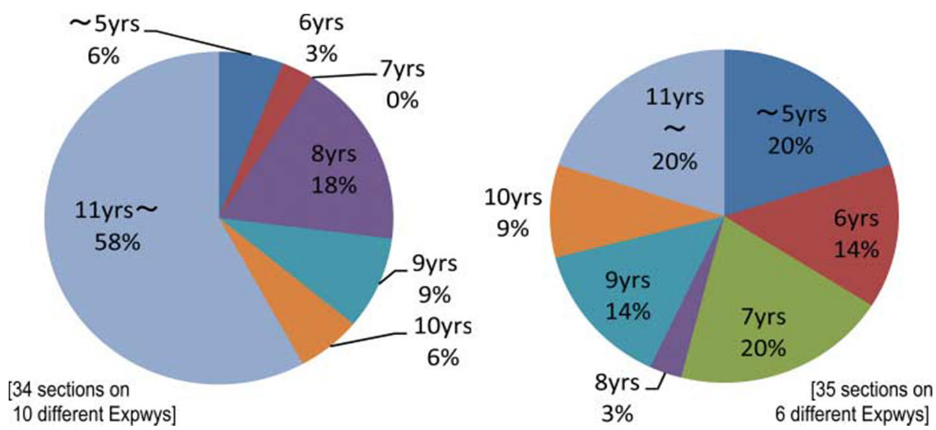


Figure 5.6: Service life of OGFC in warm (left) and snowy (right) regions of Japan.
(Source: Shigeki Takahashi [2013])

5.3 Corrective and Preventive Maintenance Practices Used in the United States and Abroad

As previously noted, raveling is a common problem associated with open-graded pavements (OGFC or RHMA-O) is (Huber 2000; Rogge 2002; Bandini 2011, Blumenthal 2013). One way that many US transportation agencies deal with this problem is by applying fog seals as part of OGFC preventive maintenance (Rogge 2002). Fog seals provide a thin film of neat asphalt binder on the surface and, therefore, are believed to extend the life of OGFC pavements (Rogge 2002). The FHWA recommends applying fog seal in two passes (at a rate of 0.05 gal per sq. yd. in each pass) using a 50:50 mixture of asphalt emulsion and water without a rejuvenating agent (FHWA 1990).

The results of a survey by Rogge (2002) showed that while fog seals may marginally prolong OGFC pavement life, they also were found to reduce the permeability of OGFCs. Although application of fog seals is fast and economical, the process requires a minimum lane closure of one-half day, which can create traffic control challenges on two-lane roads or high-volume four-lane roads. Fog seals also reduce pavement friction immediately after application (Rogge 2002), although friction increases significantly during the first month as the seal is worn by traffic. Most of the fog seals applied to OGFCs during the four-year study were corrective, not preventive (Rogge 2002). Fog seal application was viewed as a way to make up for an asphalt shortfall or as a last-ditch effort to hold a pavement together. The raveling problem with OGFCs can be reduced by modifying the binder in the mix design, as was discussed earlier.

As noted, the application of fog seals to open-graded layers reduce their frictional properties, but that friction increases significantly in the first month after application as traffic wears away the fog seal. Fog seals do not affect the macrotexture of OGFC layers, so they retain their reduced potential for hydroplaning. Rogge (2002) concluded that the expected benefits of fog seals to prolong the thickness of OGFC layers were not substantiated with quantitative studies. Additionally, Rogge (2002) recommended that chip seals may be applied when it is acceptable to abandon the free-draining characteristics of OGFC layers and the pavement structure is sound. However, although chip seals are more expensive than fog seals, they seal the surface more completely than fog seals (Rogge 2002). Despite this, the respondent from Oregon stated in Rogge's survey that they had concerns about use of chip seals related to the increased potential for moisture damage in underlying layers. None of the agencies responding to the survey indicated that they currently utilize fog seals. Wimsatt and Scullion (2003) stated that it was standard practice by Texas DOT to use seal coats over distresses open-graded surfaces.

The use of chip seals in the US was also found to be mainly a preventive measure, however, even though they cost more than fog seals. In addition, chip seal tends to completely seal the pavement surface, essentially eliminating the open-graded feature of OGFC. Although chip seal application solves the problem of reduced pavement friction immediately after application, it introduces another problem: the potential for rocks to fly off the surface. Emulsion chip seals are more widely used within Oregon DOT than "hot asphalt" chip seals and were rated as more successful in the maintenance supervisor survey (Rogge 2002).

When an OGFC surface overlay is fully clogged its performance is similar to that of a dense-graded mix, which has relatively low permeability; and therefore OGFC overlays can be considered for rehabilitation at the end of a pavement's service life (Hubber 2000). When applying OGFC in this situation, it is recommended to remove the existing open-graded layer and replace it with a new open-graded layer. The Oregon DOT has been recommended milling and inlay using an OGFC mix to repair existing OGFC when quantities of the material are large enough to justify this activity. But, if only a small quantity is needed for patch repairs, a dense-graded conventional asphalt mix is suggested instead (Rogge 2002). The FHWA advises considering the continuity of drainage from OGFCs when undertaking patch repairs (FHWA 1990), and suggests applying only a light tack coat (preferably emulsion) to the vertical faces of the existing pavement when making patch repairs with OGFC material. FHWA recommends this because heavy tack coats will impede the flow of water through the patch. In Britain, OGFC materials only are recommended for patch repairs to both small and large potholes. In Britain, patching with dense-graded mix is limited to patch repair sizes 1.64 ft by 1.64 ft, and if a dense-graded mix is used due to urgency, it must be replaced later with OGFC mix later (Pucher et al. 2004).

OGFC pavements can also develop transverse and longitudinal cracks while in service. Narrow cracks are usually invisible on an OGFC surface because of its open texture. When cracks do appear on the surface they need to be sealed. Sealing transverse cracks is not a problem because the crack sealant will not impede the flow of water within the OGFC, which takes place in a transverse direction (Cooley et al. 2007). But sealing longitudinal cracks in OGFC is problematic because the crack sealant could impede the transverse water flow within the OGFC. One potential solution, although it is expensive, is to mill off the OGFC in a narrow strip right over the longitudinal crack and place an inlay with OGFC material. If a longitudinal crack is present in the underlying course, it too must be sealed properly. Only a light tack coat should be applied to the vertical faces of the existing pavement. The other option is to rehabilitate the pavement if the crack severity becomes too great (Cooley et al. 2007).

Raveling was also found to be a common problem in Europe (Ruiz et al. 1990). The raveling generally occurs shortly after traffic is applied to the pavement layer. Ruiz et al. (1990) indicated that this problem generally originates from placing OGFC at lower temperatures during construction, insufficient compaction, or draindown problems. In most cases, European countries extended the service life of their OGFC pavements by using polymer-modified binder in their OGFC mix designs. After the end of the pavement service life or when the OGFC has completely lost its noise reduction and safety functions, the European countries usually use milling as corrective maintenance by replacing the old OGFC with a newer OGFC surface layer.

A recent long-term performance study by the UCPRC showed that tire/pavement noise is greatly influenced by the surface mix type and mix properties, age, traffic volume, and the presence of distresses (Rezaei and Harvey (2013). Overall, it was found that open-graded pavement performance (rubberized and non-rubberized) diminishes in terms of durability and functionality with age, showing a decrease in permeability after six to seven years. The long-term measurements also indicated that OGFC pavements are more prone to raveling development than RHMA-O mixes after six to eight years of trafficking.

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6 REVIEW SUMMARY AND SYNTHESIS

This chapter presents a summary of the literature reviewed and a synthesis of the information gathered.

6.1 Summary Overview

As discussed earlier, OGFCs were originally designed and constructed to improve driving safety. Their noise-reducing environmental benefit was documented later. However, in recent years, water quality benefits have been added to the list of the overall benefits they provide because of OGFCs' ability to remove particle-bound pollutants from runoff. For example, the Texas DOT (TxDOT) has added OGFC to its list of BMPs for highway stormwater runoff management. But while, their benefits continue to be documented non-rubberized and rubberized OGFC overlays still have some drawbacks that need to be overcome. Figure 6.1 depicts the multifunctional characteristics of an ideal OGFC or RHMA-O overlay, a pavement that would possess the following characteristics:

- Optimal structural performance (low raveling and rutting)
- Maximal environmental benefits (reduce noise, increase safety, improve water quality)
- Low maintenance requirements (low or no clogging with less winter maintenance)

Although finding an optimal mix design and the associated mix design procedure that provides all these benefits—with minimal problems or drawbacks—is the goal of transportation agencies in both the United States and abroad, this literature review was unable to identify one. But the study did find that research seeking to optimize one or more of the characteristics of OGFC under laboratory and field conditions is being performed continually. This chapter provides a summary synthesis of all the information presented in Chapters 2 through 5. This synthesis was prepared to directly address the tasks identified in the preliminary investigation (PI) form, as outlined below:

- Conduct a literature review of rubberized and non-rubberized OGFC overlay mix designs being used both in the United States and worldwide
- Identify from the literature review which of these mix designs provide water quality benefits
- Identify from the literature review which jurisdictions accept rubberized or non-rubberized OGFC overlays as a water quality improvement option
- Identify from the literature review what laboratory and field test methods have been used to validate water quality improvement from rubberized and non-rubberized OGFC overlays
- Identify from the literature review any OGFC-specific maintenance procedures that exist as well as the safety-related aspects of rubberized and non-rubberized OGFCs

Closing thoughts and how to move forward with the project's next phase are presented in Chapter 7.

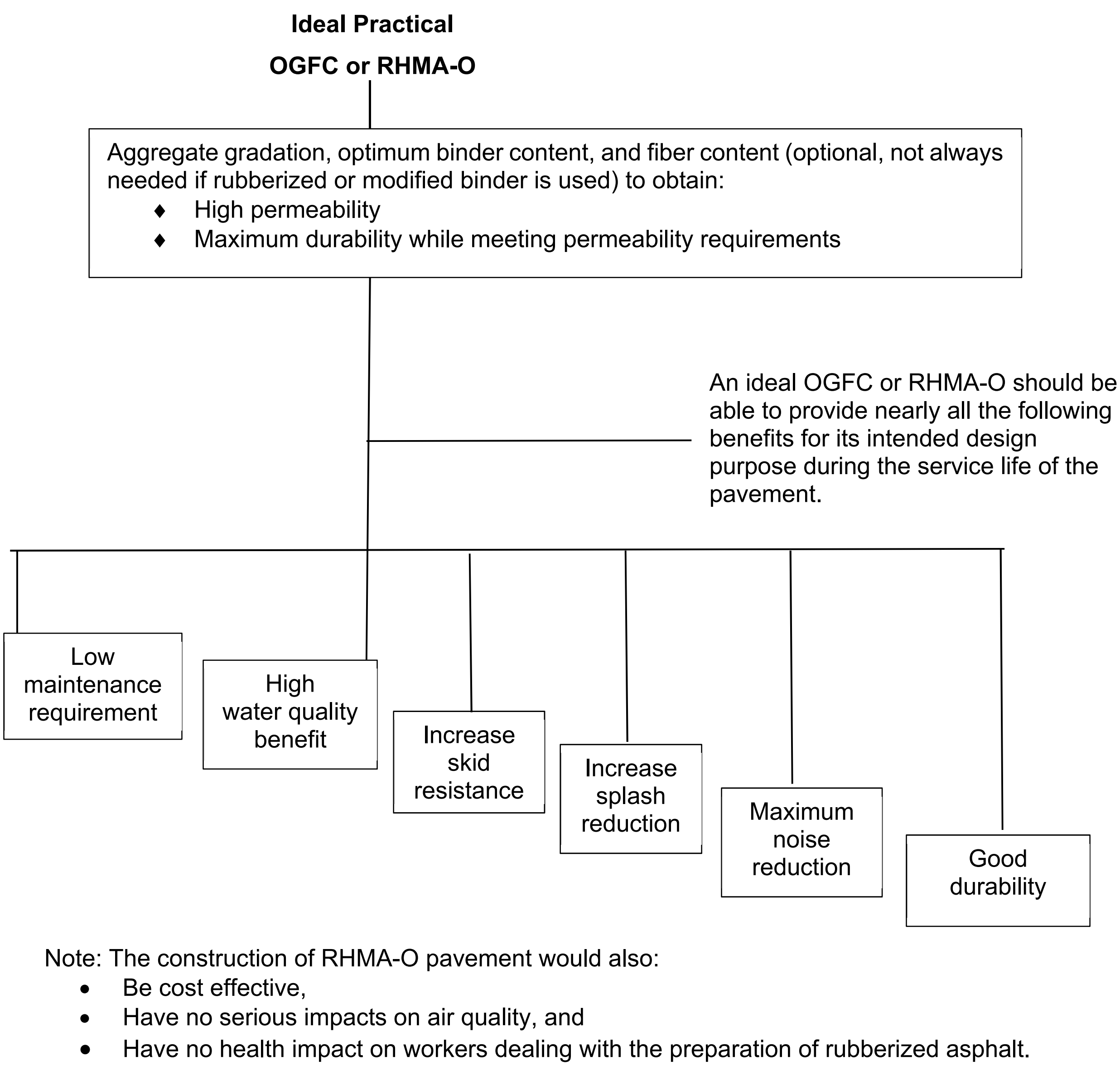


Figure 6.1: Characteristics of an ideal practical OGFC or RHMA-O pavement.

6.2 Synthesis of Literature Review

The review synthesis is structured to address each of the tasks identified for this project.

6.2.1 Summary of Rubberized and Non-Rubberized OGFC Overlay Mix Designs in Use in the United States and Worldwide

Non-rubberized OGFC pavement was developed in the United States in the 1930s, but since the 1970s it has been constructed on highways in Europe and Asia as well. OGFCs were originally constructed to improve driving safety because they reduce the potential for hydroplaning, reduce splash and spray, and improve visibility. Later OGFC construction was undertaken to take advantage of its additional benefits, which include resistance to permanent deformation, increased smoothness (and, hence, improved fuel economy), and reduced tire/pavement noise levels, this latter benefit being the main reason for OGFC construction in Europe and Japan. Recently, improved runoff water quality also has been cited as an additional potential benefit of rubberized and non-rubberized OGFC, although unlike those other benefits this one has not been fully investigated or recognized by transportation agencies.

In the absence of a standard mix design in the United States, differing approaches to OGFC mix design have been taken. Until at least the year 2000, some state departments of transportation (DOTs) were using the FHWA Technical Advisory T5040.31 (1990) mix design, while others were applying diverse criteria to establish the design binder content. These criteria included specific draindown tests, visual evaluation of draindown, retained coating after boiling, evaluation of the minimum voids in mineral aggregate, and others. In earlier OGFC mix designs, only the Oregon DOT specified a minimum air-void content. At the time of this writing, however, a significant number of state DOTs have begun implementing an OGFC design method NCAT suggested in 2000 that integrates several basic parameters: draindown resistance, minimum air-void content (greater than 18 percent), abrasion loss (Cantabro test performed using Superpave gyrator-compacted [SGC] specimens), and retained tensile strength ratio. Permeability evaluation is still considered optional although the NCAT method indicates minimum desirable values for this parameter, which should be evaluated in the laboratory.

Most European design methods for OGFC establish optimum binder content by determining the maximum binder content that will allow a minimum specified air-void content to be obtained. In general, this air-void content is greater than 20 percent and can be as high as 26 percent (for example, as in Denmark). The draindown test is also performed to avoid draindown issues during mixing, handling, and placement. In some of Europe, a minimum binder content amount that will ensure adequate mix resistance to disintegration is also used, with that value determined using the Cantabro test. Some of these European countries now require an evaluation of the weight loss from not just Cantabro-tested dry specimens, but they also require a similar evaluation using moisture-conditioned samples. In Switzerland, the retained tensile strength ratio is used only for OGFC design. Some European countries require a specific minimum permeability in the field as an OGFC design parameter, and it is measured immediately after placement of the mix. The use of modified binder for preparing OGFC pavement in Europe is common practice, as it has notably increased pavement service life. The incorporation of fibers has also become a common practice in Europe for preventing draindown problems in OGFC pavements.

The original mix designs used for OGFCs during the 1970s and 1980s resulted in draindown becoming a major problem during construction, although this was partly corrected by adding stabilizing agents such as cellulose fiber. Other problems associated with the early design of OGFCs were raveling and rutting, but these were corrected by binder modifications that were mostly made using polymeric binders. Later, with the start of tire-recycling from landfills and enforcement of government regulations, use of rubberized binder became popular. Rubber-modified binder was found to be as effective as polymer-modified binder; especially for noise control, but rubberized binder preparation required more initial effort than polymer modification, and since the new technology was patented it was not readily available to most local transportation agencies. Because of these problems, as well as the added costs required for rubberized-binder use, the majority of contractors chose polymer-modified ones when given a choice of binder type. For example, when the Florida DOT recently allowed contractors to choose the binder type they wanted for their projects, use of rubberized asphalt pavement dropped substantially. The same reasoning applies in most European countries, which still mostly construct non-rubberized OGFC pavements.

Similarly, as for OGFC or RHMA-O overlays, again there are no standardized mix designs available and for the most part the mix designs suggested by FHWA, NCAT, and the European Union are the ones used in common practice. Currently, four US state DOTs use RHMA-O overlays: Arizona, California, Florida, and Texas. The states' mix designs differ but there are ongoing efforts to prepare an optimum mix design with the best performance outcomes. For example, TxDOT recently developed a guideline to improve mix designs so they enhance the determination of volumetric properties (density, total AV content, and water-accessible air-void content) and the evaluation of drainability, durability, and stone-on-stone contact of OGFCs mixtures (Alvarez et al. 2011).

There are four primary steps to take when designing an OGFC mix: selection of appropriate materials, selection of a design aggregate gradation, selection of optimum asphalt binder content, and performance testing. In the United States, nearly 70 percent states use the recommended US or European mix design method (i.e., the compaction method) for OGFC mix design while the remaining 30 percent use mix designs of their own. Compactions were performed using the Marshall hammer and the Superpave gyratory compactor. When the Marshall hammer was used, the most common compactive effort was 50 blows per face. When the Superpave gyratory compactor was used, the prevalent design compactive effort was 50 gyrations. When designing mixes some state DOTs also performed tests for draindown, moisture susceptibility, Cantabro abrasion loss, and permeability.

The European mix designs are different than the designs used in the US. The fundamental differences are listed below:

- Air voids of European mixtures tend to be considerably higher than those of the US mixtures.
- All European transportation agencies specify minimum air voids, whereas few US agencies do.
- European transportation agencies generally allow coarser aggregates with lower fines.

- European transportation agencies almost always exclusively use modified binders (mostly with SBS) for OGFC mix design, whereas only some US DOTs use polymer-modified binders.
- Aggregate quality standards are higher in Europe.
- The higher air-void contents specified in European mixtures require hard aggregates with a minimal tendency to break or degrade during construction.
- Field permeability measurements are required in Europe, whereas laboratory permeability measurements are only suggested (and not always practiced) in the US.

6.2.2 Summary of Mix Designs Identified for Optimal Water Quality Benefits

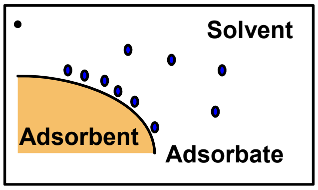
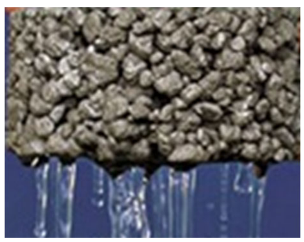
This literature review showed that while OGFC surface overlays are constructed in many countries, RHMA-O surface overlay use in the United States is limited to four states: Arizona, California, Florida, and Texas. OGFC and RHMA-O overlays are both used exclusively to improve safety and to reduce noise, and these benefits are well established in the literature. However, the water quality benefits associated with OGFC or RHMA-O have only been recognized recently, and since they have not been fully investigated their full potential benefits are unknown. Yet these water quality benefits may be significant, especially because of the stringent environmental regulations related to stormwater pollution prevention management programs in the US. Unfortunately, because the original OGFC and RHMA-O pavement installations were not focused on obtaining water quality benefits, not many transportation agencies performed water quality evaluations of these surfaces. Hence, with the limited amount of water quality data available it is not possible to perform a proper correlation analysis between water quality and the different mix designs. Therefore, the analysis and discussion presented below is only based on a limited quantity of water quality data collected on both OGFC and RHMA-O pavement surface types.

Table 6.1 presents a summary of the information presented in Chapter 4 about OGFC or RHMA-O overlays' expected water quality benefits and the issues related to the quality of runoff discharged from them. While the discharged runoff from OGFC or RHMA-O overlays are reported to be cleaner, the cleaning mechanisms have not been fully investigated. It has been hypothesized that the treatment or removal of pollutants from non-rubberized or rubberized OGFC overlays occurs by three methods: adsorption, filtration, and splash reduction. These are summarized in Table 6.2. The runoff treatment due to adsorption, without the addition of artificial adsorption materials into the mix design, is expected to be very low. However, with the limited available research on this topic and inadequate data availability, the proportional treatment accomplished by this method compared to the other two methods is unknown.

Table 6.1: Summary of Water Quality Benefits and the Related Issues Associated with OGFC or RHMA-O

Topic	Major Finding(s)
Potential treatment methods	The exact mechanisms of runoff treatment through RHMA-O and OGFC are unknown. However, it has been hypothesized that the treatment occurs by adsorption, filtration, and splash reduction (see detail description in Table 6.2).
Particulate pollutant removal	Both OGFC and RHMA-O overlays found to remove particle-bound pollutants. The removal of particulate pollutants on highways with low traffic volume and climate regions with frequent rain seems to be higher than on highways with high traffic loads and lower rainfall with higher antecedent dry periods. Higher particulate pollutant removal was also achieved with mix designs containing lower fines and higher percentage of larger aggregate.
Dissolved pollutant removal	OGFC and RHMA-O overlays have been found to be ineffective at removing dissolved pollutants, while some negative removal efficiencies of dissolved pollutants have even been reported, suggesting that these pollutants are more concentrated and that some are contributed through pavement mix design material (e.g., an extra zinc concentration may be due to natural or synthetic rubber in rubberized binder). Removal of dissolved pollutants can be enhanced by adding selected adsorption materials (e.g., iron oxide) to pavement design mixtures.
Water quality concerns	Laboratory studies of leachate produced from rubber or rubberized asphalt pavement reported the presence of some organic pollutants, although their concentrations were extremely low and were deemed not to pose any environmental impacts on the receiving water. Low levels of toxicity were observed in leachate produced from direct batch testing of crumb rubber, but the level of toxicity in leachate produced from rubberized pavement in the laboratory was shown to be insignificant.
Typical design failure and impact on water quality	Premature failure of some OGFCs due to the effects of raveling and rutting have been observed. Some improvements have been made with asphalt pavement binder modification using synthetic polymer or rubber (natural or from scrap tires, or a combination) modifications to increase the pavement's durability. Nevertheless, heavy traffic load, environmental factors, winter maintenance activities, etc., can negatively impact the function of open-graded overlays by reducing their porosity and permeability, and consequently diminishing their runoff treatment capability over the design service life.
Impact of surface cleaning on water quality	Generally, the surface cleaning of open-graded pavement is not practiced in the US. European and other international agencies perform cleaning on open-graded surfaces to maintain their noise-reduction ability and for safety. Surface cleaning of open-graded overlays has been shown to provide improve permeability under laboratory and field conditions. For optimal performance, the cleaning must be performed before the void space is completely clogged, and it is generally recommended that cleaning be performed annually before the rainy season starts. It is unknown if there is a direct relationship between surface cleaning and water quality under actual highway operation. However, based on known treatment methods, it is expected that when the surface permeability increases it will automatically improve the effectiveness of pavement water quality treatment.
Impact of mix design on water quality	Based on the limited available data, it has been shown that a mix design containing larger aggregate size gradation with a lower size gradation of fines produced better water quality. This was evident when comparing the runoff water quality discharged from RHMA-O pavements in Texas and California. The runoff water quality from Texas was generally higher than California since the aggregate mix gradation used by Caltrans had larger fraction of fine particles than that of the TxDOT.

Table 6.2: Possible Stormwater Runoff Treatment Methods Used by OGFC and RHMA-O Pavement Overlays

Treatment Method	Pictorial View	Description	Treatment Significance
*Adsorption**		Treatment via adsorption by OGFC or RHMA-O overlays occurs based on the ionic strength of the runoff and the paved surfaces and mostly applies to dissolved pollutants. The adsorption capability of open-graded surface overlays can be enhanced using additives such as iron oxide.	The removal of dissolved pollutants by OGFC and RHMA-O overlays was found to be negative or extremely low.
Filtration		Treatment by filtration occurs when particle-bound pollutants within the void spaces of OGFC and RHMA-O overlay pavements are captured. Filtration continues as long as the pavement's permeability is assured, and an adequate volume of void space is available for capturing those pollutants during the pavement's service life. The continuous and effective filtration throughout the service life of open-graded overlays depends on several factors, including but not limited to optimum mix design, regular surface cleaning, and self-cleaning accomplished by high-speed traffic and frequent rainfall.	Filtration treatment capacity can remain high as long as clogged surfaces are cleaned, and void spaces remained open. Filtration may be more effective on high-speed roadways and in areas with fewer environmental impacts and more frequent rainfall.
*Splash reduction***		The pollutant reduction observed in runoff discharged from OGFC and RHMA-O overlay pavements occurs when the pollutants washed off vehicles during the rain events is minimized by splash reduction. Hence, lessening pollution by reducing splash is not actually considered a treatment method; instead it is a method for preventing pollutant discharge onto paved surfaces. This preventive removal of pollutants from highway runoff with OGFC and RHMA-O overlays can be achieved as long as the void space and permeability of the surface overlays are maintained during their service life.	As long as the void space and drainability remain high during the service life of the pavement, the runoff discharged from open-graded surface overlays is expected to be cleaner than the runoff discharged from dense-graded pavements.

*Note: The mass of adsorbed constituents depends on their concentration in solution. The adsorption rate is governed by an equilibrium process in which the rate of adsorption (onto the surface) = rate of desorption (off the surface), as is shown below:

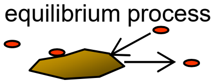


**Photo from Watson et al. (2018)

Retaining RHMA-O and OGFC overlays' filtration capability over their service life depends on keeping the void spaces open for duration of their service. While self-cleaning is desired, depending on a site's characteristics, particles might continuously accumulate within the void spaces of the RHMA-O and OGFC layers. If this occurs it will cause a significant reduction in permeability and consequently diminish their expected water quality and other environmental benefits. As was discussed in Chapter 5, in addition to particle accumulation, over their the years of operation, the void spaces in the wheelpaths of OGFC and RHMA-O overlays may also be reduced by the effects of rutting through loading, and this will also contribute to lower permeability and runoff water treatment effects. This latter problem is heavily dependent on the pavement's mix design and construction. For example, research study performed by UCPRC (Rezaei and Harvey, 2013) showed that the permeability of OGFC and RHMA-O pavements lessened gradually as a function of pavement age (see Figure 6.2). Again, with the limited research results available and without knowing the actual treatment mechanisms at work during rain events, it is difficult to discretely assess the contribution of filtration treatment compared to the overall removal of pollution by non-rubberized and rubberized OGFCs. For example, one important question that needs to be addressed is, how long will the filtration continue before pavement permeability reaches to a threshold level without surface cleaning or replacement?

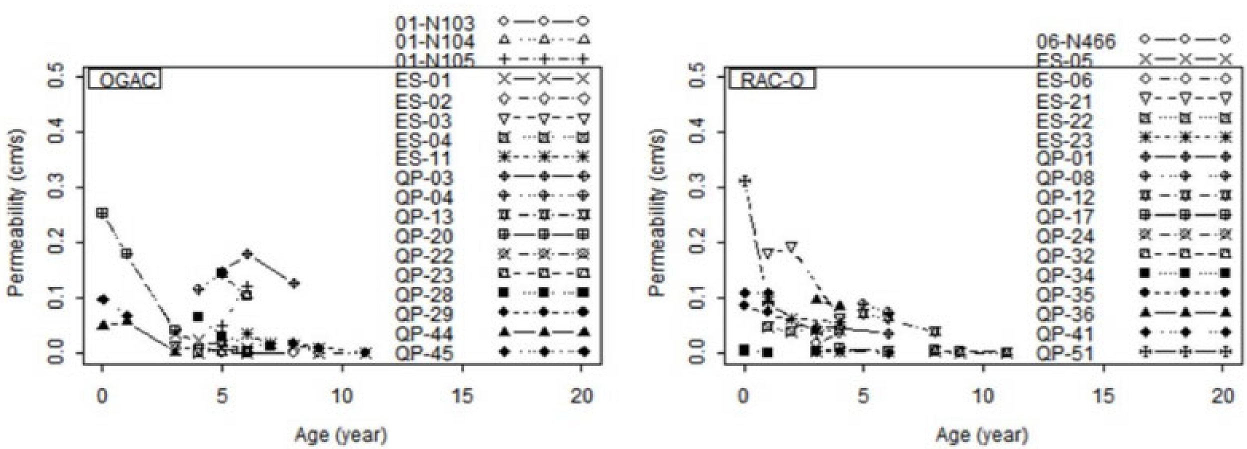


Figure 6.2: Permeability against pavement age based on different pavement type for multiple sites in California. (Source: Rezaei and Harvey, 2013)

Finally, some or even a major fraction of the pollutants on OGFC and RHMA-O overlays is believed to be removed through splash reduction during the rain events. If it is proven that the effects of splashing generate cleaner runoff and lower pollution on open-graded pavements, then Caltrans and other transportation agencies must recognize that those pollutants attached to vehicles will be washed away as soon as the vehicle moves from an OGFC (or RHMA-O) overlay surface to an impervious pavement section. The total mass of pollution discharged from a stretch of highway surface may remain the same. From this perspective, it appears that OGFC and RHMA-O are able to produce cleaner runoff without capturing the runoff volume and treating it—as commonly practiced by most constructive BMPs. Hence, the application of OGFCs on highways in areas with sensitive biological species prone to toxic effects is not recommended. But, their application in areas with limited land available in a right-of-way for BMP construction is very beneficial. Equally important, because splash reduction during rain events depends solely on the presence of open void spaces, the pavement's permeability must be maintained—a capacity that optimal mix designs and proper site selection may improve for a longer periods (as described earlier). And even with an optimal mix design, there is still a possibility that a rubberized or non-rubberized OGFC pavement will clog. Therefore, to keep the OGFC and RHMA-O above a threshold operating condition for permeability it may be necessary to replace the pavements when permeability is reduced, which may be more frequently than would occur if the criterion for replacement is raveling. This might be more costly than regular cleaning. Life cycle cost analysis should be used to determine the more cost-effective approach..

This literature review revealed that early water quality evaluations of OGFC surface overlays have been performed in several European countries including The Netherlands, Germany, and France. These studies were all performed prior to the year 2000, and it is worth noting that all of these European OGFC surface overlays were modified with polymer binders. The review found that in the US, TxDOT performed several evaluations of water quality from OGFCs between 2004 and 2010. One TxDOT study even monitored the water quality from several OGFC sites constructed with rubberized and non-rubberized binders. Limited water quality evaluations of runoff discharged from OGFCs were also performed by the California (Caltrans) and North Carolina DOTs. But even though, the states of Arizona and Florida have extensive experience with rubberized OGFC installations, they have not monitored the runoff water quality from these overlays. The limited availability of water quality data (other than those have been cited in this report) was confirmed in direct communications with representatives from the Arizona, Florida, North Carolina, and Texas state DOTs.

The results presented in this review show that the runoff quality generated from rubberized and non-rubberized OGFC overlays—based on the characteristics of particle-bound pollutants—is cleaner than the runoff generated from traditional impervious asphalt pavements. To demonstrate this, the average concentrations of selected constituents for runoff quality monitored at several US and European OGFC sites are summarized in Table 6.3. The data in the table show comparable runoff quality from OGFC overlays in the Europe and the US, and that this runoff quality is generally cleaner than that from conventional impervious pavements. The slight variation in runoff quality for selected pollutants in Europe and the US may be due to several factors including, but not limited to, to mix design, environmental factors, frequent rainfall, and traffic speed. The reduction of dissolved pollutants from OGFC overlays compared to traditional impervious asphalt pavements was found to be the same or worse.

Table 6.3: Average Concentrations of Selected Highway Runoff Constituents Monitored from OGFC Overlays and Percent Difference Compared to Traditional Impervious Asphalt Pavement

		Average Concentration for OGFC Overlays and % Difference Compared to Impervious Pavement			
		Europe		US	
Constituent	**Unit**	**OGFC**	**%Difference**	**OGFC**	**% Difference**
Total Suspended Solids	mg/L	34	61	9	80
Total Kjeldahl nitrogen	mg/L	1.3	8	1.4	20
Copper (total)	µg/L	13	52	9.4	47
Copper (dissolved)	µg/L	16	16*	12.3	-25
Lead (total)	µg/L	3.2	30	1.2	75
Lead (dissolved)	µg/L	0.7	2.2*	0.6	-5
Zinc (total)	µg/L	46	72	40.6	65
Zinc (dissolved)	µg/L	27	54	38.7	-13

NA = not analyzed
Note: the average values were estimated based on all available OGFCs and comparative monitoring
*Based on the only available data from The Netherlands

A comparative runoff water quality evaluation from rubberized OGFC is not possible due to the limited data available from the US and abroad. To date, TxDOT is the only state that has performed a limited water quality monitoring study on both OGFC and RHMA-O sites. Caltrans has also attempted to monitor the quality of runoff water discharged from RHMA-O overlays but the study was terminated due to the overlays' low permeability, although the basis for the permeability cutoff value, the test method, and the percentage of sections that failed the cutoff value (e.g., wheelpath versus non-wheelpath) were not identified in this literature review. Also, no publication information was provided for the information from the aborted California comparison of OGFC and RHMA-O. Based on the limited data collected from TxDOT, it was determined that the removal of pollutants by both rubberized and non-rubberized OGFC occurs in the same fashion and the characteristics of the runoff are similar, except for zinc (Zn). The extra zinc concentration observed in the RHMA-O overlay was due to its rubber binder and most of the zinc was probably dislodged due to raveling from high-speed traffic. This extra zinc concentration was not leached from rubberized OGFC in a controlled laboratory study that did not include traffic loading but did have water continually flowing through the material (Kayhanian et al. 2008). With proper site selections, under field investigation, the traffic and loading effect can be compared between conventional OGFC and RHMA-O pavements under similar traffic and environmental conditions. .

6.2.3 *Summary Identifying Jurisdictions Accepting OGFC or RHMA-O Overlays as a Water Quality Improvement Option*

The literature review revealed that, as of this writing, transportation agencies have not fully recognized the use of OGFC or RHMA-O as a water-quality improvement treatment option. As noted earlier, only four state DOTs (Arizona, California, Florida, and Texas) use RHMA-O as an overlay on their highways. While Arizona, California, and Florida have performed many studies evaluating the various performance aspects of RHMA-O, only California attempted to collected limited water quality data; so far, the other two states have conducted no evaluations of water quality from these pavements. Over the past 15 years, however, the Texas DOT has performed both extensive OGFC discharge water quality evaluations and limited RHMA-O site discharge water quality evaluations, and compared the runoff quality at those sites with the effluent from several BMPs.

TxDOT compared the quality of OGFC-discharged water with the quality of typical effluents from Austin sand filters and ROW vegetative strips. The first evaluation was conducted to compare the measured results of pollutants removed from two curb-and-gutter OGFC sites in Austin, Texas, with the values obtained from the nearby effluent treated by vegetated shoulder strips where inflowing water came from the surface of a conventional impervious asphalt paved surface (Kearfott et al. 2005). In a separate TxDOT water quality evaluation study, Eck et al. (2010) compared how OGFCs performed in removing selected constituents from stormwater runoff with the performance of Austin sand filters. The removal efficiencies achieved by vegetated shoulders, by the Austin sand filter, and by OGFC is shown in Table 6.4. As can be seen, the reduction in total suspended solids (TSS) was almost the same, and the removal efficiency of NO_3/NO_2, total phosphorus, total copper, and total lead were higher for OGFC. Total zinc was the only constituent where OGFC showed a real increase in removal efficiency though this may be due to the asphalt rubber binder used at the northbound OGFC site. The comparative results were found to be significant, particularly because sand filters usually require additional land acquisition and extended runoff treatment time, whereas the pollution removal achieved by OGFC within the surface overlay was accomplished without additional ROW land or additional construction of a BMP. Still, since the OGFC may require regular surface cleaning maintenance and resurfacing after 5 to 8 years, those must be considered as part of the overall implementation costs. Additional data collection and a life cycle cost analysis is needed to fully justify the application of OGFC as a BMP for highway stormwater runoff management.

Based on the encouraging TxDOT results, the Texas Commission on Environmental Quality (TCEQ) approved the use of OGFC and RHMA-O as a BMP for uncurbed roadways. The specific language used for the application of OGFC as a BMP was indicated in Section 4.6 of this review report and can be viewed in the May 2017 TxDOT stormwater management plan *(ftp.dot.state.tx.us/pub/txdot-info/env/toolkit/515-01-pmt.pdf).*

Table 6.4: Removal Efficiency of Selected Pollutants in Highway Runoff from OGFC Compared with Vegetated Shoulders and Austin Sand Filter in Austin, Texas, US

Constituent	Unit	Removal Efficiency (%)		
		Vegetated Shoulder	Austin Sand Filter	OGFC
TSS	mg/L	93	89	92
NO_3/NO_2	mg/L	-28	17	59
Total P	mg/L	71	59	84
Total Cu	μg/L	62	72	74
Total Pb	μg/L	92	86	98
Total Zn	μg/L	87	76	78

Source: Adapted from Sampson et al. (2014)

In addition, researchers from North Carolina State University (NCSU) evaluated the characteristics of runoff water discharged from several highway sites with OGFC overlays. The NCSU researchers obtained results that showed that the results obtained by the state of North Carolina were comparable to those obtained in Texas (Eck et al., 2012). Based on their favorable water quality result, the researchers from NCSU recommended that OGFC be considered as a BMP for pollutant removal from North Carolina highways. However, communication with the North Carolina Environmental Quality Department at the time of this writing revealed that as of July 25, 2019, OGFC use had not yet been approved as a BMP in North Carolina.

6.2.4 Summary of Laboratory and Field Test Methods Being Used to Validate Water Quality Improvements from OGFC and RHMA-O Overlays

In addition to the field-monitoring studies discussed above, this literature review also found several laboratory water quality studies that were undertaken to assess the leachate quality produced by crumb rubber and rubberized asphalt pavements. The first such study was performed in Rhode Island in three phases by Vashisth et al. (1998) to assess the water quality characteristics of leachates generated from rubberized asphalt pavement. In the experiment's first phase, crumb rubber modifier (CRM) samples that were produced by wet and dry process were exposed to nitric acid at pH 2 and the solution was analyzed for trace metals. It was found that zinc (Zn) concentrations were three to four orders of magnitude greater than the concentrations of other trace metals (cadmium [Cd], chromium [Cr], copper [Cu], lead [Pb], and nickel [Ni]). The most likely source of zinc was thought to be zinc oxide, an ingredient in CRM. Leachate from CRM was also tested for selected organic compounds, but no detectable polynuclear aromatic hydrocarbon (PAH) compounds were measured. In the second phase of the study, Vashisth et al. (1998) prepared two types of HMA pavement specimens using the Marshall method. The first group of specimens was modified with CRM and, as a control, the second group of specimens was prepared without CRM. The samples were tested at pH levels of 2, 7, and 12, and at temperatures of 20°C and 45°C to represent the average and maximum asphalt pavement temperatures in the field. Leachate solutions from these samples were tested for metals including cadmium, chromium, copper, lead, nickel, and zinc. The results showed a general trend in which higher metal concentrations were leached from both rubberized pavement specimens (CRM samples processed by wet and dry process) than from the control pavement specimens. The differences for lead, nickel, and zinc were generally larger for the dry process samples than the wet process samples, possibly because a greater amount of CRM is used in the dry process. Higher concentrations of benzothiazole were found in both the wet and dry process CRM samples than in the control samples. Total concentration of PAH compounds ranged from 60.2 to 601 ng/L for the control samples, from 374 to 710 ng/L for the dry process CRM samples, and from 97.3 to 727 ng/L for the wet process CRM samples. In the third phase of the study, Vashisth et al. (1998) prepared specimens of compacted asphalt pavement modified with CRM as binder and exposed them to different light, traffic, and rain simulations. But instead of simulating natural lighting conditions, the samples were placed in a high-density polyethylene (HDPE) box with a clear lid and exposed to natural sunlight. To simulate traffic, a steel wheel mobile compactor was used on top of Teflon plates. A 125 mm, 30 minute rainstorm was simulated using water with pH values of 4.3 and 7.0 for the different samples. The leachate samples were then analyzed for metals and organic compounds. Metal concentrations were found to be low for both pH values, and only two metals were detected from the dry process samples. It was determined that, compared with the control, there was little variation in the metal concentrations between the pavements prepared with rubberized pavement prepared under wet and dry process. Simulated runoff from both rubberized specimens indicated that the concentrations of benzothiazoles, hydroxybenzotriazole, and PAHs were higher than the control. However, the authors concluded that these detected concentrations were low and that under field conditions they would be further diluted with runoff during rain events and may not even be detectable.

In another laboratory investigation, Azizian et al. (2003) conducted a series of laboratory leachate tests to evaluate the important processes that affect the chemical composition, aquatic toxicity, and fate of leachates from CRM in highway applications. The results of this study showed that about 50 percent of the final leachate concentration was reached within the first 10 hours. Leaching rates during the first 10 hours represent well the case of first-flush chemical releases from new construction materials; typical leaching rates of weathered materials are probably best described by the slower loss rates observed after several days of leaching. Leaching from the flat-plate test showed significant mass transfer limitations compared to the batch leaching tests, with no toxic effects being measured in the flat-plate leachate. Azizian et al. (2003) concluded that contaminants from rubberized asphalt leachates are thus degraded or retarded, and that under field conditions they should not be transported into nearby soils and groundwater.

One controlled laboratory study was performed for Caltrans by the University of California, Davis to address whether or not the permeable pavement surface itself is a source of pollution and, if it is, to determine what the major pollutants of concern are. For this control study, an experimental apparatus was designed and fabricated to evaluate the leachate quality generated from a range of open-graded and dense-graded asphalt and concrete pavements specimens (Kayhanian et al. 2008). The pavement-surfacing materials tested included rubberized asphalt concrete open-graded (RAC-O), rubberized asphalt concrete gap-graded (RAC-G), open-graded asphalt concrete (OGAC), and polymer-modified OGAC (two binder sources each for OGAC and polymer-modified OGAC, resulting in four different binders), terminal-blend modified-binder gap-graded (MB-G), dense-graded asphalt concrete (DGAC), and portland cement concrete (PCC) mixes. For each of these pavement materials, nine specimens were prepared for testing at temperatures of 4, 20, and 45°C, with three replicates of each. In addition, one specimen of each asphalt pavement surfacing material was tested to address the influence of age on water quality. A representative leachate sample was collected from the surface and the subsurface, and each leachate sample was evaluated for pH, conductivity, turbidity, hardness (as $CaCO_3$), total suspended solids (TSS), total dissolved solids (TDS), total organic carbon (TOC), metals (As, Cd, Cr, Cu, Pb, Ni, and Zn), total nitrogen (TN), total phosphorus (TP), polyaromatic hydrocarbons (PAHs), oil and grease (O&G), and chemical oxygen demand (COD). In addition, composite leachate samples were produced from all the pavement specimens and tested for toxicity.

The results of this control laboratory study (Kayhanian et al 2009) showed that (1) the concentration of most organic and inorganic chemical constituents generated from the leachate of specimens was below or within the reporting limit (detection limit); (2) temperature did not significantly change the leachate pollutant concentration; (3) aging (heat treatment) of the surfacing pavement materials did not contribute to additional pollutant concentration; (4) dissolved chemical constituent concentrations (except concentrations of chromium) in leachate of all the pavement types were generally negligible; and (5) acute toxicity based on the survival of the water flea species (*Ceriodaphnia dubia)* was negligible for nearly all fresh and aged leachate samples.

In other recent research, Maeda and Finney (2018) performed a laboratory and field study investigating the rate at which potential water quality contaminants (organic and inorganic) may leach from tire-derived aggregate (TDA). The results of their laboratory experiment showed that benzene, methyl isobutyl ketone (MIBK), cadmium, zinc, iron, manganese, total phosphate, and total suspended solids leach from TDA and that dissolved oxygen is altered by TDA. A dramatic decrease in release rate over time was observed for all the constituents under all water exposure conditions. The results obtained from the field experiment showed that a TDA-soil system provides removal of many urban stormwater runoff constituents, including acetone, cadmium, chemically oxidizable organic compounds, iron, lead, manganese, MIBK, oil and grease, phosphate, and zinc. The results suggest that the concentration of contaminants in leachate produced from TDA will not pose any risks to the receiving water body's quality in the short term or the long term.

6.2.5 Summary of the Maintenance and Safety Aspects of OGFC and RHMA-O Overlays

Rubberized and non-rubberized OGFC pavement maintenance approaches can be generally grouped to deal with the following issues: (1) clogging and surface cleaning, (2) winter maintenance and related issues, and (3) corrective and rehabilitation maintenance. Table 6.5 contains a summary of this review's major findings about the challenges and other issues pertaining to the maintenance required for rubberized and non-rubberized OGFC overlays. The table's summary arrangement corresponds to the three categories noted above.

The literature review revealed that although clogging is a problem common with applied OGFC (non-rubberized or rubberized) surface overlays. But even though OGFC cleaning is a common practice in Europe and Japan, none of the US transportation agencies that use these overlays clean the clogged layers. The review also found that transportation agencies around the world practice preventive and corrective surface maintenance, and that that winter maintenance of OGFCs is generally perceived to be problematic. The study did not identify any definitive method for addressing OGFC winter maintenance and found that most of the winter maintenance techniques in use were developed and practiced based on local agencies' experiences. However, the available literature did make clear that OGFC pavements require a different winter maintenance program than typical dense-graded pavements. Worldwide results showed that OGFCs layers reach freezing temperatures before dense-graded layers and remain at freezing temperatures longer, so maintaining these pavements in winter requires more salt and chemical agents than maintaining dense-graded pavements. As previously stated, the literature from the U.S., Japan, and non-urban highways in Europe suggests that, in general, areas prone to heavy snowfalls are not good candidates for OGFC overlay and recommends against their use in these areas. In addition, areas that contain a lot of dirt or debris (e.g., near farms) also are not recommended for OGFC placement. Rehabilitation of OGFC layers is reasonably uniform around the world. In most instances, rehabilitation involves milling the existing OGFC layer and replacing it with another OGFC layer or another type of HMA. The literature did suggest that OGFCs should not be overlaid unless they are sufficiently clogged.

From a safety point of view, OG pavement application was found to be highly beneficial: it improves pavement friction resistance in wet weather, reduces splash and spray from surrounding vehicles, reduces glare from on-coming headlights in rainy conditions, and enhances the visibility of pavement markings. Numerous national and international studies have been conducted to determine the comparative levels of various parameters that influence the skid resistance of different pavement surface types (including rubberized and non-rubberized OGFCs). For instance, the results of research studies showed that an increase in average friction from 0.4 to 0.55 results in a

63 percent decrease in wet weather accidents. In addition, the research results showed that wet weather accidents were decreased by 71 percent at intersections and by 54 percent on highways due to the improved skid resistance. Compared to dense-graded impervious pavements, OGFCs reduced the overall number of accidents and the number of accidents occurring during rain events by 29 and 54 percent, respectively. The best skid resistance with OGFCs was obtained on pavements constructed in low air temperature areas and that have low volume and slow traffic. The best skid resistance with OGFCs was obtained in pavements with low volume, slow speed traffic, constructed in a low air temperature area. However, low traffic speeds may favor rapid clogging of the mixture's air-void structure and lead to a loss of the mix's functional properties (drainability and noise reduction). High aggregate texture, an increase of mix texture, and the use of crumb rubber-modified asphalt binder need to be considered as alternative parameters for the selection of materials and mix designs regarding skid potential. For example, the results of the study performed by UCPRC (Figure 6.3) showed by Mean Profile Depth (MPD) measurements that OGFC tends to ravel faster than RHMA-O over the six years of measurement with pavements up to 16 years old because the binder was not modified by the rubber, and that this happens everywhere, not just under stop-and-go conditions (Rezaei and Harvey, 2013).

While most researchers validated the benefits of OGFC for safety, some studies challenged that the safety effectiveness of OGFC was limited and that the research was inconclusive. These researchers argued that the hypothesis that claims OGFC is effective in reducing wet-weather crashes may not always be true. For example, research was performed based on an analysis of accident data from 43 OGFC pavements and 83 non-OGFC pavements in Texas. The researchers' statistical analysis found that road users usually drive faster on OGFC-surfaced pavements, and the higher accident rate, compared to the rate on non-OGFC pavements, might have resulted from those higher speeds.

Similarly, another study used large-scale accident data collected from OGFC and non-OGFC pavements in California, Minnesota, North Carolina, and Pennsylvania, and its results were used to estimate crash modification factors (CMFs) for OGFC treatment. CMF refers to the ratio of expected number of crashes after treatment to that before treatment. A CMF less than 1.0 indicates that the treatment reduces the number of crashes on a pavement type. The results of this study showed that the OGFCs were only effective in decreasing the accident rate in wet freeway conditions, and that the accident rate actually increased in dry road conditions. In short, the study found that OGFC treatment only reduced total accident rates on freeways. Therefore, based on the above results and their overall safety effects, the application of OGFC in an area with few rainfall events may not be fully justified.

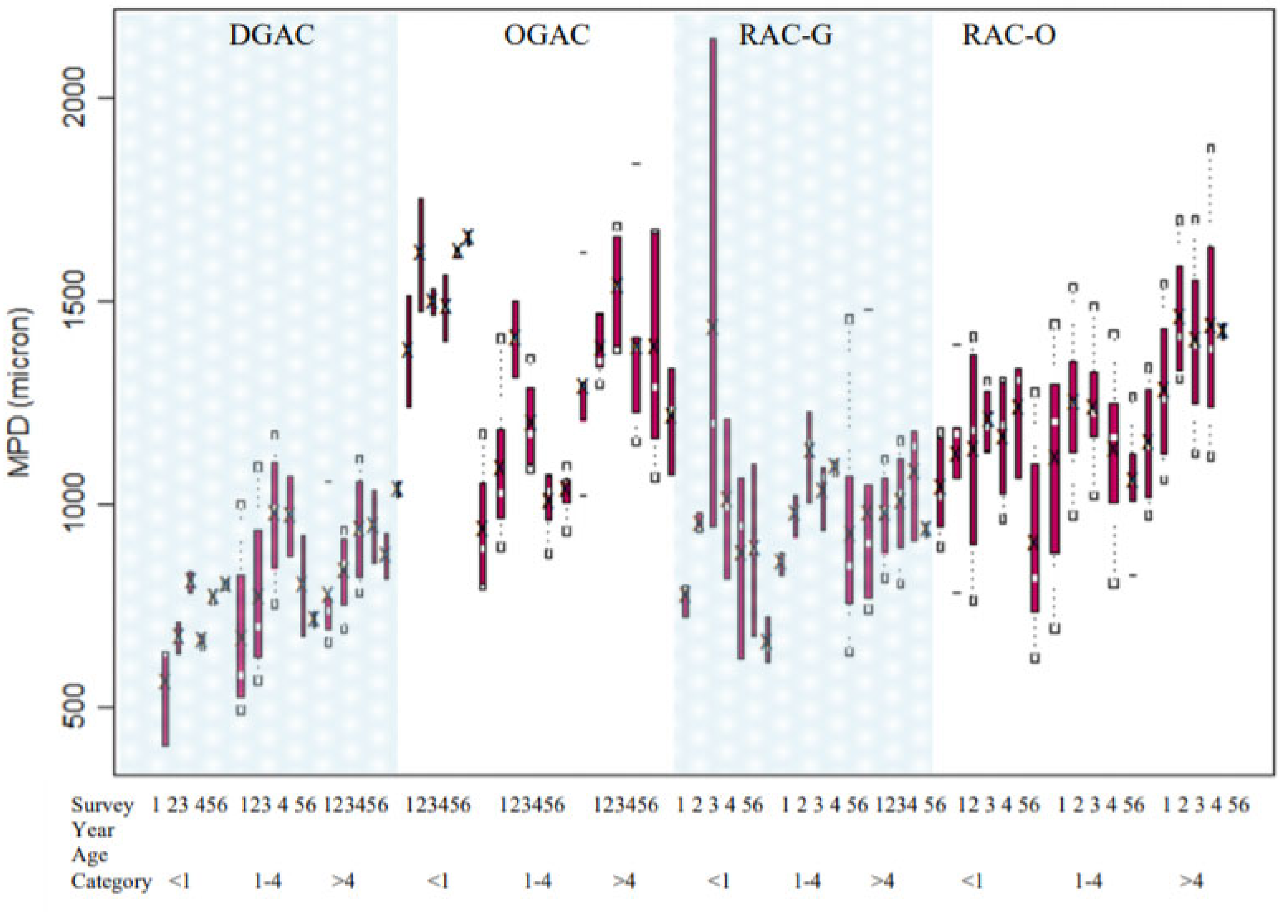


Figure 6.3: Distribution of MPD values for different mix types and different age categories across the six years of data collection. (Source: Rezaei and Harvey, 2013)

Table 6.5: Summary of Major Findings Regarding the Maintenance Challenges and Related Issues Associated with Rubberized and Non-Rubberized OGFC Overlays

Topic	Major Finding(s)
Clogging and surface-cleaning issues	
Clogging	Clogging of OGFCs is fairly common and has been reported by transportation agencies in the US and abroad. OGFC clogging is attributable to accumulations of solid particles within their void spaces or to rutting due to traffic loading. The clogging due to rutting is irreversible, although the clogging due to particle accumulation may be reversed. The degrees of clogging reported by various agencies varied substantially. Some reported that clogging occurred soon after construction while others reported that the pavement performed well throughout its service life. Multiple factors contributed to the variations reported they include but are not limited to (1) traffic speed and loading, (2) environmental factors (i.e., dust transfer from agricultural activities, low rainfall with long dry periods), (3) climate conditions, (4) mix design, and (5) pavement construction.
Surface cleaning	Surface cleaning of RHMA-O and OGFC is not practiced in the US, but it is very common in Europe and Japan for lower-speed roads and highways. Some experimental cleaning has been performed in Japan for high speed highways. The most effective cleaning methods use a specialized truck equipped that applies high-pressure water that is vacuumed up immediately afterward. The vacuumed water is then treated through a reclamation process and reused on site to save water and prolong the cleaning operation. In Japan, a second method found to be used effectively is the application of high-pressure air followed by vacuuming.
Frequency of cleaning	Transportation agencies have not reached a consensus on an ideal cleaning frequency, and as of this writing, there is no standard available method for evaluating surface clogging and determining when to clean the surface. The reported cleaning frequencies varied from once every six months to whenever the agency determined that cleaning was required. It was generally recommended to clean OGFC surfaces annually. If RHMA-O and OGFC surface cleaning is to be followed as a BMP for water quality treatment, annual treatment should be seriously considered.
Winter maintenance and related issues	
Thermal conductivity	The thermal heating properties of open-graded pavements are about 40 to 70 percent less than typical dense-graded pavement.
Ice formation	Because of their lower thermal heating properties, the surfaces of open-graded pavements are usually 3 – 5°C colder during the day and 1 – 2°C colder at night, and hence they freeze faster and require more salt or chemicals than dense-graded pavements. Research findings suggest that shape-stabilized phase change materials (PCMs) such polyethylene glycol/silicon dioxide (PEG/SiO_2) can be used to adjust the internal temperatures of OGFC or RHMA-O and improve the performance of OGFC subject to freeze-thaw cycles.
De-icing chemical	De-icers are utilized after the formation of snow and ice with the objective of removing them. The most common product used for de-icing is salt in different forms (i.e., pre-wetted salts or rocks of salts).

Topic	Major Finding(s)
Anti-icer chemicals	Anti-icers are applied to prevent ice and snow formation. The most common anti-icers used are dry salt, wet salt, wet salt enhanced with calcium, calcium chloride solution, and magnesium chloride solution.
Salt and chemical usage	Due to their lower surface temperatures and longer freezing times, OGFCs generally require 50% more salt. However, the extra void spaces in OGFC are helpful in reducing the amount of salt application required on high-traffic and high-speed motorways. The decrease in salt required under these conditions is due to the pumping action caused by vehicles passing over the OGFC surface, as the tire-surface action continually circulates the salt solution within the pavement's void structure. In addition, the availability of weather forecasting systems in conjunction with the use of thermocouples on paved surface and satellite technology can help combat black ice formation and reduce chemical use during freezing rain and light snow.
Pavement damage	Raveling caused by studded tire use is the most serious problem associated with maintenance practice. In Europe, studded tires are not allowed on open-graded pavements and are prohibited in high elevations with heavy snowfall. Open-graded surfaces are also found to be more susceptible to gouging by snowplows, as they offer less resistance to snowplow blades.
Corrective and rehabilitation maintenance	
Fog seal, chip seal, and milling	The most common corrective measures used for open-graded pavements in the US are the application of fog seals and chip seals. However, these methods may reduce permeability and create hydroplaning. When an open-graded pavement is fully clogged, it basically behaves like a dense-graded pavement and will have to be replaced at the end of its service life. European countries extended their OGFC pavements' service lives by using polymer-modified binder in their OGFC mix designs. These countries usually apply milling as a corrective maintenance measure, replacing the old OGFC surface layer with a new one after the pavement's designed service life or when the OGFC has completely lost its function.
Service life	Ideally, rubberized and non-rubberized open-graded pavements should be replaced after their designed service life. *Service life* can be defined as the length of time an OGFC maintains its functional and performance properties. At present, there is not enough literature to draw conclusions about the functional and performance lives of OGFCs. Although the performance of some OGFC pavements declines just a few years after their installation, the literature review suggests that most agencies can expect 7 to 10 years of service life. A study also showed that smaller aggregate sizes in a mix design increase pavement durability (Lu et al., 2009). RHMA-O and OGFC pavements' service lives can be shortened with winter maintenance activities and without a regular cleaning maintenance program. Winter maintenance activities alone were found to shorten the service life of OGFCs by 2 to 5 years. Polymeric binder modification was shown to extend pavement service life in cold climates. What effect rubber binder modification has on service life is not known since its application in colder climates is limited and no data are presently available.

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7 RECOMMENDATIONS AND ACTION PLAN TO MOVE FORWARD WITH THE NEXT PHASE OF THE PROJECT

This chapter includes a set of conclusions and recommendations for optimizing the current Caltrans OGFC and RHMA-O mix designs, and an action plan for moving forward with the next phase of the project.

7.1 Conclusions

The following conclusions have been drawn from the results and information collected in this literature review:

- Nearly half of US states have used OGFC overlays, and they were constructed predominantly for safety and noise reduction.
- Results from several US surveys showed that some earlier OGFC mix designs failed mainly because of draindown and raveling problems. Draindown problems caused the pavement to behave more like gap- or dense-graded pavement. Raveling problems (which occur in the wheelpaths of OGFC and RHMA-O pavements, including mainline and turning and stop-and-go areas) especially reduced the pavements' longevity, requiring them to be replaced before the end of their expected design service life, a process that was found to be costly.
- Because of draindown problems and the issue of durability (for example, increased raveling) several newer mix designs and mix design procedures were suggested by the Federal Highway Administration (FHWA) and the National Center for Asphalt Technology (NCAT). Under these newer mix design procedures, adding fibers into the mix helped solve the draindown problems and introducing modified binders into the mix design increased durability.
- Addition of both natural and cellulose fibers were found to be useful, but cellulose fiber was found to be less costly. Multiple polymeric modified binders have been studied, and the most useful one with a high success rate was a styrene-butadiene-styrene (SBS) polymer-modified binder. These two mix design improvements increased the service life of the OGFC pavements.
- The implementation of local and state regulations related to recycling of materials and their diversion from landfills, coupled with sustainable transportation initiatives undertaken by the US federal government have provided the opportunity to use scrap tires as a potential modified-binder source.
- Rubber-modified binders are produced by either dry or wet processes, each with a different performance outcome. In California, only the wet process is used.
- At present, crumb rubber-modified binder is used for multiple asphalt pavement applications in the US and abroad; however only four US states (Arizona, California, Florida, and Texas) currently use them in OGFC construction.

- Performance test results showed that the durability of OGFC overlays modified with crumb rubber was comparable to the performance of OGFC modified with SBS polymer binder. In some cases, the performance of OGFC overlays with rubberized binder was superior to those with polymer-modified binders.
- While the application of rubber-modified binder was found to be useful and its benefits (safety, noise reduction, and durability) were similar to those from polymer-modified binder, when contractors were given a choice, they nearly always chose to use polymer-modified binder. This may change with the increased price of polymer-modified binder and/or with regulations mandating the use of scrap tire binder as a part of future asphalt binders.
- At present, there is no standard mix design that can be practiced on a national and international basis. And although the FHWA and NCAT suggest several OGFC mix designs, many states use their own variations to design OGFC and RHMA-O pavements. Because of subtle differences in the mix designs used by different states and international transportation organizations, published performance results are also varied.
- Most rubberized OGFC pavements installed in the US were primarily constructed to increase safety and to reduce noise; hence their ability to provide water quality benefits and prevent pollution has not been recognized or fully investigated.
- Although the Arizona and Florida departments of transportation (DOTs) have used rubberized OGFC for the past 30 years and have evaluated their durability and functional performance extensively, those agencies have not performed water quality evaluations. The California DOT (Caltrans) has also installed numerous RHMA-O overlays throughout the state and measured their performance for noise reduction, permeability, and durability, but the department did not attempt to monitor their water quality until relatively recently—from 2007 to 2011—at three sites with rubberized OGFC. This water quality monitoring was terminated during the second year, however, due to the pavements' low permeability and lack of expected water quality benefits.
- TxDOT has performed more water quality evaluations from their OGFC and RHMA-O overlays than any other state DOT and has obtained favorable results. Because sufficient water treatment or pollution removal was achieved at the OGFC and RHMA-O monitoring sites, unlike the results obtained at sites with conventional dense-graded pavements, the Texas Department of Environmental Quality has recognized the use of non-rubberized or rubberized OGFC as a best management practice (BMP) for highway stormwater runoff management.
- The decision to use OGFC or RHMA-O as a BMP is a local one that is based on a recommendation developed using limited local water quality data that may not be applicable to other traffic and environmental conditions. Without additional water-quality monitoring data within the United States and

elsewhere in the world, it is difficult to perform a proper correlation analysis relating water-quality characteristics with different mix designs. Hence, generalized conclusions based on the Texas mix designs cannot be made unless its water quality benefits are verified in California and elsewhere.

- The current limited amount of runoff-water-quality data collected in the US and Europe shows that rubberized and non-rubberized OGFCs are only capable of effectively removing particle-bound pollutants and that the runoff quality is generally cleaner than runoff from dense-graded pavements. The removal of dissolved pollutants by non-rubberized or rubberized OGFC is either negative or minimal.
- OGFC or RHMA-O pavements' ability to remove dissolved pollutants can be enhanced by adding adsorption agents to the mix design. For example, experimental results showed that adding bentonite and zeolite as adsorbent agents into an OGFC mixture was effective in removing dissolved copper (Cu) and zinc (Zn). The results showed that the removal efficiencies of dissolved copper (Cu) and zinc (Zn) with bentonite were about 76 and 74 percent, respectively. However, the impact that adding adsorption agents has on pavement durability is unknown. Further research is needed to verify the above findings with new, improved OGFC and RHMA-O mix designs under laboratory and field conditions.
- The actual treatment or pollution removal mechanism of OGFC and RHMA-O surface overlays is not fully known and has not been fully investigated. However, it has been hypothesized that treatment/pollution removal may occur by three methods: (1) adsorption, (2) filtration, and (3) splash reduction.
- The chemical characteristics of runoff discharged from both non-rubberized and rubberized OGFC is similar, except for higher concentrations of total and dissolved zinc believed to be associated with the crumb rubber used in rubberized pavement. This extra zinc is believed to be dislodged by the action of rubber tires from traffic since it was not observed in an earlier UC Davis controlled laboratory study which tested leachate from rubberized OGFC that was not subjected to traffic loading.
- Evaluation of existing performance data from OGFC and RHMA-O surface overlays showed that their environmental benefits are heavily influenced by pavement permeability, which is suggested for inclusion in the NCAT mix design procedure but is not specified in the current Caltrans mix design procedure. Hence, the current Caltrans mix design will not effectively address the multifunctional objectives of OGFC and RHMA-O overlays; therefore, preparation of a new mix design procedure that includes permeability specifications is recommended. The new mix design procedure may follow the recent UCPRC approaches and other specifications listed in Chapter 7, Table 7.2.
- Even with optimization and preparation of the best mix design, factors such as traffic speed, loading, and anthropogenic activities may still affect OGFC and RHMA-O pavement performance. Therefore, to prolong performance of the pavement over its design service life, non-rubberized and rubberized OGFC construction should be reserved for locations that limit the influence of anthropogenic activities.

- Examination of national and international field survey studies has revealed that clogging is a major issue in all open-graded surface overlays regardless of their binder type (rubberized or non-rubberized binder). The field survey studies showed that none of the transportation agencies have a surface-cleaning maintenance program, which may reduce the OGFC's functional life and, as a consequence, its environmental benefits, including its runoff water quality treatment. A cleaning method that combines pressure washing and vacuuming, used by several European transportation agencies and in Japan, was shown to be the most effective one for improving the environmental benefits of the OGFCs.
- Non-rubberized and rubberized OGFC were found to have different thermal properties compared to dense-graded mixes and were found to freeze faster and for longer than conventional dense-graded asphalt pavements. For this reason, non-rubberized and rubberized OGFC usually require more salt or chemicals during winter maintenance than dense-graded mixes. The use of studded tires during winter months was also shown to increase raveling and to reduce the service lives of open-graded pavements by two to five years, resulting in very short lives compared to dense-graded mixes. For all the above reasons, the application of non-rubberized or rubberized OGFC is not recommended for high-elevation sites with extensive snowfall and winter maintenance activities.

7.2 Recommendations for Optimization of Current Caltrans OGFC and RHMA-O Mix Design

Mix design optimization plays an important role in an open-graded pavement's overall performance, especially when the pavement is designed for multiple functional objectives, including safety, noise reduction, and stormwater quality. At present, no single mix design that addresses all these functions that can be recommended to Caltrans. The current Caltrans design methods for non-rubberized and rubberized open-graded mixes specify aggregate gradation sizes and the use of the asphalt draindown test to evaluate a mix's binder content—although only indirectly for rubberized binders. Specifically, draindown testing of rubberized binders must first be done using a conventional binder and a multiplier is later applied to that result to obtain values for rubberized and polymer-modified binders. A further difficulty is that the draindown test has not been verified for modified binders. The current Caltrans mix design methods are still further limited because they do not consider air-void content, permeability, or durability.

Permeability, which is relatively easy to measure in the laboratory, is an important characteristic of OGFC and RHMA-O overlays that impacts pavement performance in the ways summarized in Table 7.1. Up to now, because of the large aggregate size gradations used in OGFCs in most states, these pavements are assumed to have a high air-void content, although this parameter is not specified as part of the mix design specification. As this literature review has noted, Caltrans uses gradations that are similar (1/2 inch [12.5 mm]) or smaller (3/8 inch [9.5 mm]) than those used by some other states. This may be warranted, since rainfall intensity in California is generally less than in those other states that use OGFCs. A tradeoff does exist, though, because while using smaller aggregates sacrifices pavement permeability, it also provides greater pavement durability than using larger sizes. Further, while measuring laboratory permeability is suggested by FHWA and NCAT for mix designs in the US, it is not included in many state departments of transportation (DOT) specifications even though permeability measurement is a requirement of European OGFC mix design. It is therefore recommended that the current Caltrans mix design be optimized based on laboratory and field permeability testing, and in particular it should be based on multifunctional performance.

Table 7.1: Summary of OGFC and RHMA-O Characteristics that Influence Pavement Performance

Characteristic	Aspect	Functionality		Durability	Safety	Water Quality
		Noise	Permeability			
Mixture texture and roughness	High				✓	
	Low	✓				
Asphalt binder type	Modified	✓		✓	✓	✓
	Unmodified					
Air-void content	High	✓	✓		✓	✓
	Low			✓		
Aggregate gradation	Fine					
	Course		✓	✓	✓	✓
Binder content	High					
	Low		✓		✓	✓
Compaction effort	High			✓		✓
	Low	✓	✓			
Maximum aggregate size	Large		✓		✓	
	Small	✓				✓
Binder aging	Fast					
	Slow			✓	✓	✓
Aggregate texture	High			✓		
	Low					
Vehicle speed	Fast		✓			✓
	Slow	✓				
Air temperature	High					
	Low				✓	
Tire type	Studded					
	No studded	✓				
Traffic condition	High					
	Low	✓			✓	

Adapted from Liu et al. (2010)

As can be seen from the table, permeability can be impacted by air-void content, aggregate gradation, binder content, compaction effort, maximum aggregate size, and vehicle speed.

Permeability testing can also be used to assess pavements' water quality treatment performance, which has been ignored until now. For example, assessing the permeability of OGFC and RHMA-O mixtures is required to guarantee high initial drainability and to evaluate their performance, as this parameter's evolution is compared at different times during the pavement's service life.

The research studies presented in this review provided the following conclusions about factors influencing the permeability of OGFC and RHMA-O overlays:

- An increase in asphalt content causes a decrease in permeability.
- Compaction energy reductions produce OGFC mixtures with higher permeability since the total air-void content increases, although this also results in less durability.
- An increase in permeability can be achieved by making the aggregate gradation coarser.
- An increase in the maximum aggregate size causes an increase in permeability.
- The water-accessible air-void content can be used to indirectly assess permeability with better results than those obtained based on total air-void content values.

Current Caltrans OGFC and RHMA-O mix designs cannot satisfy the multifunctional performance characteristics identified earlier, but Table 7.2 presents a set of recommendations for improving the current Caltrans mix designs. Before they can be included as part of the new Caltrans pavement design manual, during the next phase of the project the validity of these recommended values or specifications must be investigated under laboratory and field conditions. The required action plan to accomplish the new mix design objectives is presented in Section 7.3.

It is important to note that while mix design improvements can and will effectively enhance the multifunctional performance of OGFC and RHMA-O overlays, there are also environmental factors that may influence pavement performance. For instance, dust transport from agricultural land use or other land use activities may clog the air-void contents during the pavement's service life, decreasing the permeability that will ultimately impact other pavement performance characteristics, such as noise reduction, splash reduction, and stormwater runoff treatment. Therefore, in the absence of surface-cleaning activities the self-cleaning may not be sufficient in certain areas, especially with anthropogenic impacts; and hence, the initial permeability of OGFC and RHMA-O has been shown to decrease, shortening their service and performance lives and eventually making them behave like conventional dense-graded pavement (Rezaei and Harvey, 2013). This may be mitigated to an extent by installing OGFC and RHMA-O overlays in areas with high traffic speeds and frequent rainfall, where the suction forces generated by high-speed rolling tires may effectively clean the OGFCs and prevent clogging. In Europe and Japan, frequent cleaning with special equipment has shown to be effective for urban roads, but no generalized consensus among international transportation agencies has been achieved on frequency of cleaning.

Table 7.2: Proposed Recommendations for Improving Current Caltrans OGFC and RHMA-O Mix Designs

Mix Design Parameter	Current Caltrans Practice	Recommendation
Aggregate quality and size gradation	Caltrans currently uses an aggregate gradation finer than the one used by the Texas DOT, which has had more success with RHMA-O pavements in terms of water quality.	Decrease the content of finer aggregate sizes and increase the coarse fraction. Identify changes to aggregate gradations that increase permeability without major impacts on durability.
Durability	Not specified.	A new mix design should follow the recent UCPRC method that optimizes durability. The method should include the Cantabro and Hamburg tests, for durability and rutting respectively, and direct draindown testing of the rubberized binder, rather than use of a multiplier based on conventional binder draindown results. The proposed new mix design can be viewed at *www.ucprc.ucdavis.edu/PDF/UCPRC-RR-2013-06.pdf.*
Permeability	Not specified.	Permeability, or at least air-void content as a surrogate for permeability, can easily be implemented in the UCPRC optimum durability method. Permeability criteria should be based on California rainfall intensities. UCPRC has successfully made field permeability measurements on a wide range of pavement surfaces over the years (Li et al. 2013; Ongel et al. 2008; Rezaei and Harvey 2013). For consistency, the lab and field measurements should be performed using the NCAT permeameter falling-head measurement method. UCPRC used this method effectively in both the field and laboratory, and comparison data is available from their OGFC and RHMA-O mix design test sections. Field permeability should be monitored on all pilot projects to check against lab results and to verify the continuous drainability function of overlays. All field test sections' permeability should be measured soon after construction and these measurements should be taken at multiple locations. The permeability of field test sections should also be monitored over time.
Air-void content	Air-void content in the range of 15 – 20 is required, but no specification is used.	It is believed that permeability is integrated into most OGFC mix design procedures, and that some mix designs specify a minimum air-void content. However, laboratory measurement of air-void content has limitations that may not ensure adequate permeability in the field. Therefore, both measurements are recommended.

7.3 Proposed Action Plan to Move Forward with the Next Phase of the Project

Since both rubberized and non-rubberized OGFCs have multifunctional benefits, it may be worthwhile to further improve the current Caltrans mix design The current permeability cutoff value used to halt the evaluation of Caltrans RHMA-O test sections during the 2007 – 2011 Caltrans runoff water quality monitoring study should be reviewed to ensure that it is consistent with California rainfall intensities rather than with those of other states where intensities are greater. Successful implementation of a new mix design will require additional data collection in the lab and under field conditions. Because the Texas Department of Transportation (TxDOT) is the only transportation agency that has collected successful functional performance data and water quality data, the TxDOT mix design may be used as part of the three-way study recommended below.

To move forward with the next phase of the project, Caltrans the following action plan is recommended:

1. Conduct a laboratory evaluation of Texas-type mix designs using TxDOT design criteria; design similar mixes using California materials (including several aggregate sources and conventional and rubberized binders); compare these mixes' durability, permeability, and air-void contents; and check to see if air voids is a sufficiently accurate surrogate predictor of permeability.
2. Make the necessary changes in the new Caltrans mix design method and specifications based on the laboratory study.
3. Construct side-by-side test sections using the Texas mix design, the California mix designs, and the new recommended UCPRC mix designs to conduct a three-way comparison test of each set of specifications and each mix design method (from the previous UCPRC study and new recommendations specified in Chapter 7, Table 7.2) under California conditions.
4. Measure the permeability and other multifunctional performance of the test sections and monitor water quality samples from them for five years. Perform periodic surface cleaning and collect all the other data necessary to conduct a life cycle cost analysis.
5. Perform life cycle cost analyses of OGFC and RHMA-O under multifunctional performance conditions, and recommend application of the mixes accordingly. These analyses will also include the cost of pavement replacement versus regular maintenance.
6. A design guide will be developed to determine the Environmental and Traffic loading ranges for when OGFC and RHMA should be installed.
7. Summarize the results and prepare a final report with appropriate recommendations.

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