REFLECTIVE COATINGS FOR COOL PAVEMENTS: INFORMATION SYNTHESIS AND PRELIMINARY CASE STUDY FOR LIFE CYCLE ASSESSMENT

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ABSTRACT

This paper synthesizes existing available information and knowledge to enhance the understanding of the environmental impact of material production and construction of pavement reflective coatings. This work was performed through a literature survey of current technologies and products. Discussed in the paper are the classification, components, production method, typical albedo values and durability, application scope and rate, application method, and a preliminary partial assessment of the environmental impacts of pavement reflective coatings. The preliminary case study shows that compared to HMA and PCC overlays and even slurry seals, reflective coatings could have lower environmental impacts depending on their durability. However, unlike overlays, reflective coatings do not improve the surface smoothness and ride quality and therefore do not improve fuel consumption and user comfort during the use phase, which was not included in this preliminary LCA case study. The reflective coatings and slurry seal also do not improve structural capacity of the pavement.

INTRODUCTION

With extensive and rapid urbanization in much of the world, more land surface has been and is being paved with different types of pavement placed to perform different functions, such as including streets, parking areas, sidewalks, plazas and playgrounds. For example, in 2000 it was estimated that for the city of Sacramento, California approximately 39 percent of the urban land area was paved when seen from above the vegetative canopy *(1,2)*. Conventional impervious pavements, especially that have high solar absorption and high heat emissions, can have high surface temperatures (up to 65-75°C) in the summer depending in climate regions with very high annual solar radiation *(3-7)* and resulting high near-surface air temperatures. High urban temperatures relative to the temperatures of surrounding undeveloped land is referred to as the *heat island* phenomenon. Pavements can contribute to negative impacts associated with high temperatures in urban areas, including reduced human comfort and heath;

increased energy use for cooling of buildings and vehicles; impaired air and water quality *(8)*, as well as accelerated pavement deterioration (e.g., rutting and aging of asphalt pavements and possibly thermal cracking of concrete pavements) *(9).* The extent of these impacts, and the influence of pavements on the heat island phenomenon are the subject of intense debate and current research.

"Cool pavements" have been proposed by the U.S. Environmental Protection Agency (U.S. EPA) and others as one of the main strategies for reducing the contribution of pavement in urban areas to the formation of urban heat islands, along with other strategies including cool roofs and increased use of tree canopies and vegetation. Urban heat islands have been the subject of US EPA practice documents, and are the subject of recently passed California legislation (Assembly Bill 296, Cool Pavement Research and Implementation Act) *(10)*. Although there is no standard definition of "cool pavement", one of the ways to reduce the solar absorption of pavement is to increase the albedo (i.e. solar reflectivity) of the pavement materials *(11-14).* In addition to using light colored aggregate in asphalt materials, whiter cement and other methods to change the pavement mixture materials, reflective coatings can be applied to the pavement surface to increase the albedo *(15-19)*.

Life cycle assessment (LCA) is used to investigate and quantify environmental impacts of a product or service within its life cycle. The International Organization for Standardization (ISO) has developed guidelines for conducting LCA, ISO 14040 series *(20),* and identified four major steps for any LCA: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The process initiates with defining the goal of the study which determines the system boundary and scope of study, duration of the study and a suitable functional unit. The next step is the inventory phase where all the inputs and outputs to the system boundary within the life cycle are quantified. The inputs are normally in the form of raw materials and energy and the outputs are the product/waste (depending of the system boundary) and emissions to air, water, and soil. This is a crucial step in any LCA study and the accuracy of the study depends heavily on this part. LCI results are then classified and categorized in to several environmental impact categories such as global warming, acidification, eutrophication, primary energy consumption, ozone layer depletion and more. In this study *TRACI 2.1*, developed by US EPA, was used to calculate the impacts. The final step is the interpretation of the results which should be ongoing since the beginning to constantly evaluate the results of each step and make required revisions. The *UCPRC Pavement LCA Guideline (21),* was used as the guideline for this study to provide an initial and incomplete evaluation of environmental impacts of using reflective coatings for pavements.

The objective of this paper is to perform a literature survey of existing available information and knowledge to enhance the understanding of the environmental impact of material production and construction of pavement reflective coatings, and to produce a very preliminary and incomplete comparison of the impacts of replacing a pavement surface with reflective coatings and traditional urban pavement materials in California.

SYNTHESIS OF EXISTING INFORMATION ON REFLECTIVE COATING

Classification of Reflective Coating

Reflective coatings can be divided into two categories according to the solvent type: namely solvent-based coating and water-based coating *(1,6,8,11-14,16-19,22-25)*. Solvent paints use a resin to hold the pigment in suspension and to help the pigment stick to the substrate. Solvents are usually added to dilute the resin and pigments so that the final coating can be sprayed for application. Solvent paints form coats or films faster and the coat is generally more durable than a water-based coating. However, these solvents can release Volatile Organic Compounds (VOCs) into the atmosphere, with a negative and toxic impact on both the environment and human beings. On the other hand, water-based coatings use few or no solvents but rather water. Generally, water dilutes the pigment and carries the pigment to the substrate. Therefore, water-based coatings could reduce the VOC emissions and are potentially more environmentally friendly compared to solvent-based coatings *(22-25)*. However, compared to solvent-based coating, the drying time of water-based film is longer and the stiffness and anti-abrasion performance is lower, which typically results in a relatively shorter life.

Components of Reflective Coatings

Reflective coatings consist of polymeric binder blended with functional pigments and other additives *(1,6,8,11-14,16-19,22-25)*. Binder is the main constituent material that holds all the ingredients together. Binder functions to form the film and ensure that all components including resin, fillers and pigments are homogeneously dispersed, significantly influencing the key properties of the final coating such as gloss, durability, flexibility and toughness. The binder can be made up of one or more basic resin or polymer systems. Typical types of binders include polyesters, polyurethanes, acrylics, polyesters, silicates, epoxies, oils, melamine resins, depending upon the substrate and the cured performance required. Pigments that give the color and opacity or covering power are finely dispersed into the binder, with granular solids incorporated into the paint to contribute color. The granular solids can enhance the toughness, texture or simply reduce the cost of the coating. Sometimes, special pigments with high infrared radiation (IR) reflectivity are employed in the reflective coating that will not allow as much IR radiant heat to be absorbed by the film and the substrate. Additives are also added into the coating to provide a wide range of modifications to the composition of the film and film properties. Additives are usually added in small amounts to modify surface tension, improve flow properties, reduce foaming, flatten matt finish, provide anti-graffiti capabilities and modify other relevant properties.

Production Method for Reflective Coatings

As for solvent-based coatings, the first step in producing a coating involves mixing all pigments with polymeric binder and additives to form a paste *(1,6,8,11-14,16-19,22-25)*. If the coating is to be for industrial use, it is usually routed into a sand mill, which is a large cylinder that agitates tiny particles of sand or silica to grind the pigment particles, making them smaller and dispersing them throughout the mixture. The water-based coating production process is very similar to that of the solvent-based coating. The major difference is the substitution of water for solvent and the sequencing of material additions. Preparation of water-based coating begins with mixing together water, ammonia, and a dispersant in a mixer. Dry pigments and some other additives are then added to this mixture. After mixing, the material is ground in a mill and then transferred to an agitated mix tank *(26,27)*.

Albedo and Life of Reflective Coating

Most reflective coatings have high initial albedo values ranging from 0.4 to 0.8 *(1,6,8,11-14,16-19,22-25).* This high albedo value helps increase the final albedo of the finished pavement surfaces with coatings, which reflect a greater portion of incident solar radiation, resulting in lower pavement surface temperatures. However, the durability or life of reflective coatings with the current technologies is relatively short due to weathering and trafficking. As shown in Table 1 below, most coatings can last only 0.5 to 3 years for sidewalks or bike lanes with low traffic. For roads with high traffic, the life or durability of the coats is even shorter. Aging, cracking and peeling of the coating occur during its service, and the albedo will be reduced over time. Periodic recoating is needed to high reflectivity of the pavement with coatings. The application of heat reflective coatings might reduce the friction coefficient of the pavement. Therefore, corresponding anti-skidding measures should be taken to ensure safety for vehicles and bicycles. It is common to add silica sand or ceramic particles to the coating when mixing the paint or during paving the paint on the road to increase the pavement friction and skid resistance.

Application Scope and Application Rate of Reflective Coating

Most reflective coatings can be potentially used for different pavement functions, including highways, streets, bike lanes, sidewalks, parking lots, carriage ways, pedestrian areas, pool decks, patios, drive ways, cross walks, school yards, playgrounds and so on *(1,6,8,11-14,16-19,22-25)*. However, because of the relatively short life of the high albedo properties with current technologies, low traffic roads such as sidewalks, parking lots and school yards are most appropriate for applying reflective coatings. For high traffic roads, the durability of the reflective coatings applied on the pavements may be currently a concern due to trafficking and weathering. In urban areas, pavements used for streets, parking lots, sidewalks and squares will generally have lower traffic and longer life for the high albedo properties.

Different application rates (mass or volume per unit area) can be used for different pavement types. Rough pavement surfaces usually need higher application rates than smooth surfaces to produce the same final albedo. The application rate of reflective coatings typically ranges from 0.25 to 1.0 kg/m^2 (or 20 to 60 ft^2/gal) depending on coating types and pavement type.

Application/Construction Method of Reflective Coating

The application method commonly used for reflective coatings is spraying or rolling with hand tools or machine equipment *(1,6,8,11-14,16-19,22-25)*. Two applications are applied sometimes, consisting of a prime layer followed by second layer, to enhance the durability of the coatings. The pavements after application of reflective coatings usually take some time to dry before opening to traffic. The time required depends on weather conditions (mainly air temperature and wind speed), coating type, and application location.

LIFE CYCLE INVENTORY FOR ENVIRONMENTAL IMPACTS OF TYPICAL REFLECTIVE COATINGS

Typical Reflective Coatings

Table 1 lists four types of typical reflective coatings chosen for life cycle assessment (LCA). Type A mainly employs unsaturated polyester resin and styrene as binder. Unsaturated polyester has been widely used in the paint industry due to its good film-forming property and low cost. However, this coating is more brittle and hence fracturing easily occurs.

For Type B, one type of epoxy resin is used as binder. It is known that epoxy resin has high strength and excellent adhesion. Generally, the epoxy resin has poor anti-aging properties because the epoxy group [—CH(O)CH—] is easy to be break under sunlight *(22-25)*. Therefore, carbon black as one type of functional pigment is usually added into the binder to improve the anti-aging ability. Both Type C and D are water-based coatings, namely acrylic emulsion coating and polyurethane emulsion coating. Type C and D coatings are more environmentally friendly but have shorter lives compared with Type A and B solvent-based coatings. The main components of these two types of emulsion are listed in Table 1. Each coating uses TiO_2 as the main pigment due to its strong covering power and high refractive index.

Table 1: Summary of Typical Reflective Coating Materials for LCA *(28)*

Type	**Components**				**Application Rate** ^{b} **(kg/m^{2})**	**Typical Albedo**	**Albedo Life (Years)**
	Resin or Solvent (CAS No.) ***(Percentage by Mass)***	**Pigment** ***(Percentage by Mass)***	**Additive (CAS No.)** ***(Percentage by Mass)***	**Hardener (CAS No.)** ***(Percentage by Mass)***			
A (solvent -based)	Unsaturated polyester resin (25037665)/styrene (100-42-5) *(60/24)*	TiO2/SiO2/Fe2O 3 *(8/4/1)*	Polysiloxane(68083-14-7)/Ethylene bisstearamide (110-30-5) *(0.5/0.5)*	Cobalt naphthenate (61789-51-30) *(2)*	0.5-1.0	0.3-0.5	1-3^{a}
B (solvent -based)	Bisphenol A epoxy resin (25085-99-8) *(75)*	TiO2/carbon black *(10/0.5)*	Propylene glycol phenyl ether (770-35-4), glyceryl monostearate (31566-31-1) *(3/1.5)*	Tetramethylethylenediamine (110-18-9) *(10)*	0.5-1.0	0.45-0.75	2-3^{a}
C (water-based)	Styrene (100-42-5)/butyl acrylate (141-32-2)/Methyl acrylate(96-33-3) /methacrylic acid (79-41-4) /water *(7.7/13/5.4/3/55)*	TiO2/ZnO *(6/6)*	Ammonium persulfate (7727-54-0)/ ammonium sulfite (10196-04-0)/ ammonium hydroxide (1336-21-6)/ N-dodecyl mercaptan (112-55-0)/ 3-hydroxypropane-1-sulphonate (3542-44-7) *(0.18/0.02/1.0/0.1/1.6)*	Aziridine(151-56-4) *(1)*	0.5-1.5	0.5-0.7	0.5-1.5^{a}
D (water-based)	Polyester polyols (53637-25-5)/cis-1, 4-cyclohexylene diisocyanate (7517-77-3)2,2-Bis(hydroxymethyl)propionic acid (4767-03-7)/water *(18/8/2/54)*	TiO2/SiO2 *(12/0.6)*	Sodium Dodecyl Sulfate (151-21-3) /Polydimethylsiloxane (9016-00-6) *(2/0.4)*	1,6-Diisocyanatohexane (822-06-0) *(3)*	0.5-1.5	0.4-0.8	0.5-1.5^{a}

[a] for sidewalk or bike lane.

[b] density: 1200 – 1,300 kg/m^{3}.

Development of LCI for Reflective Coating

After identifying the chemicals and mass breakdown of the reflective coatings, *GaBi 6.3* software was used to develop a model for each reflective coating and calculate its LCI based on the *GaBi* 2013 database *(28)*.

Table 2 shows the chemicals in each coating with the mass breakdown and the LCI dataset from *GaBi (28)* that was used to model the process. For most cases matching LCI datasets were found and in cases where matching datasets were not available proxy datasets were utilized. The table also shows the region where the LCI datasets are taken from as processes in different regions are different for producing the same products which results in variations in LCI of the same product in different regions. US data were given preference. The datasets developed in this project for material production are for cradle-to-gate meaning all upstream material and energy consumption and emissions and waste are included from extraction of raw materials, transportation and processing in the plant. The LCIs also include an estimated electricity of 0.1 MJ/kg for synthesizing the various chemicals together, which accounts for less than 1% of the total primary energy demand of the coating.

Summary Table of Life Cycle Inventory

The full LCI of each of the reflective coatings consists of hundreds of inputs and outputs. This preliminary study focused on energy consumption, global warming potential, and emissions that impact air quality. Table 3 summarizes the main items of the LCI and LCIA for the reflective coatings. The solvent used in coatings will release volatile organic compound into the air during mixing and constructing process which are different than many traditional paving materials.

PRELIMINARY EXAMPLE COMPARISON OF REFLECTIVE COATINGS WITH CONVENTIONAL TREATMENTS

To conduct a preliminary example comparison between different treatment alternatives, four cases were considered: slurry seal, hot mix asphalt pavement, portland cement concrete pavement and reflective coating. This comparison is not comprehensive and is intended to provide a preliminary first order comparison for a one case with a number of gross assumptions. The goal is to compare CO_2e emissions and primary energy consumption for the four cases assuming a 20-year analysis time for a functional unit of 1 lane-km of the pavement (3.7 m wide). The phases included in the study are material production, transportation of materials to the plant (80 km), transportation of mixes to the construction site (32 km), and construction activities. For reflective coatings it was assumed that they are manufactured in Los Angeles and transported to Davis (640 km). Use phase and end-of-life are not considered. The four cases are:

1. A-D: Four coatings listed in Table 1 assuming each with 1, 2, and 5-year life (20, 10, and 4 applications within the analysis time, respectively);
2. Slurry seal with 5-year life (4 applications within the analysis time);
3. 5 cm hot mix asphalt (HMA) inlay with milling with 10-year life (2 applications within the analysis time);
4. 10 cm white topping with portland cement concrete (PCC) with 20-year life (one application within the analysis time).

Table 2: Chemicals in Each Coating, Mass Breakdown and LCI Datasets Used *(28)*

Coating	Chemical Name	% Mass	Representative LCI Dataset	Dataset Country/ Region
A. Polyester Styrene	Unsaturated polyester resin	60	Polyester Resin unsaturated (UP)	DE
	Styrene	24	Styrene	US
	Titanium dioxide	8	Titanium dioxide pigment	US
	Silicon dioxide	4	Silica sand (flour)	US
	Iron oxide	1	Iron oxide (Fe2O3) from iron ore	DE
	Polysiloxane	0.5	Siloxane (cyclic) (from organosilanes)	DE
	Ethylene bis(steramide)	0.5	Ethanediamine	DE
	Cobalt napthenate	2	Cobalt mix	GLO
B. BPA	Bisphenol A epoxy resin	75	Bisphenol A	US
	Titanium dioxide	10	Titanium dioxide pigment	US
	Carbon black	0.5	Carbon black (furnace black; general purpose)	US
	Propylene glycol phenyl ether	3	Dipropyleneglycol dibenzoate plast	EU-27
	Glycerol monostearate	1.5	Stearic acid	DE
	Tetramethylethylenediamine	10	Tetraacetyl ethylenediamine (TAED)	NL
C. Styrene Acrylate (water-based)	Styrene	7.7	Styrene	US
	Titanium dioxide	6	Titanium dioxide pigment	US
	Butyl acroylate	13	Butyl acrylate	DE
	Methyl acrylate	5.4	Methyl acrylate from acrylic acid by esterification	DE
	Methacrylic acid	3	Methacrylic acid	US
	Zinc oxide	6	Zinc oxide	GLO
	Ammonium persulfate	0.18	Ammonium sulphate, by product acrylonitrile, hydrocyanic acid	US
	N-dodecyl mercaptan	0.1	Methanthiol (methyl mercaptan)	US
	Ammonium sulfite	0.02	Sodium hydrogen sulfite	EU-27
	Hydroxypropane-1-sulphonate	1.6	Soaping agent (sodium alkyl-benzenesulphonate)	GLO
	Azirdine	1	Hydrazine hydrate/hydrazine	DE
	Ammonium hydroxide	1	Tetramethyl-ammonium hydroxide (TMAH)	US
	Water	55	Water deionized	US
D. Polyurethane (water-based)	cis-1,4-cyclohexylene diisocyanate	8	Isophorone diisocyanate (IPDI)	DE
	Polyester polyols	18	Long Chain Polyether Polyols mix	EU-27
	Titanium dioxide	12	Titanium dioxide pigment	US
	Silicon dioxide	0.6	Silica sand (flour)	US
	Sodium dodecyl sulfate	2	Detergent (fatty acid sulfonate derivate)	GLO
	1,6-Diisocyanatohexane	3	Methylene diisocyanate (MDI)	DE
	2,2-bis(hydroxymethyl)propionic acid	2	Adipic acid	DE
	Polydimethylsiloxane	0.4	Siloxane (cyclic) (from organosilanes)	DE
	Water	54	Water deionized	US

Table 3: Major Impacts and Emissions of Reflective Coating for 1m^2 of Surface *(28)*

Selected Impact Categories and Inventories	Polyester Styrene (A)	BPA (B)	Styrene Acrylate (water based) (C)	Polyurethane (water based) (D)
Typical Application Rate (kg)	0.75	0.75	1.25	1.25
Global Warming [kg CO_2-Equiv.]	3.30E+00	2.80E+00	1.95E+00	2.93E+00
Smog Air [kg O3-Equiv.]	1.56E-01	1.21E-01	7.93E-02	1.28E-01
Total Primary Energy Demand (net) [MJ]	6.88E+01	6.81E+01	4.58E+01	6.44E+01
Nitrogen oxides [kg]	6.12E-03	4.70E-03	3.12E-03	4.98E-03
Sulphur dioxide [kg]	2.82E-02	4.90E-03	4.08E-03	6.47E-03
Sulphur trioxide [kg]	1.13E-09	6.15E-10	1.00E-09	1.10E-09
Lead (+II) [kg]	3.35E-06	5.02E-07	4.65E-07	7.53E-07
Carbon monoxide [kg]	1.50E-02	3.62E-03	3.01E-03	5.47E-03
Dust (PM10) [kg]	1.67E-06	1.06E-07	4.85E-07	2.75E-07

The slurry seal was assumed to be Type II with maximum aggregate size of 4.75 mm and application rate of 4.07 kg of residual bitumen per m^2 of surface. HMA was assumed to have 5% binder and 95% aggregate (half coarse and half fine). PCC was assumed to have 15% cement content and 85% aggregate equally comprised of fine and coarse aggregate. Detailed calculations are available in *(29)*.

The data used for LCI are taken from UCPRC case studies report *(30)*, LCI data developed for this study (Table 3), and LCIs developed by UCPRC for California Air Resources Board project on “Life Cycle Assessment and Co-benefits of Cool Pavements”, a collaborative effort between Lawrence Berkeley National Lab, UCPRC, PE International, and University of Southern California *(29)*. US EPA’s *TRACI 2.1* was used as the impact assessment methodology and only global warming potential (GWP) of the cases was calculated and compared in terms of kg of CO_2e. Net calorific value (low heating value) of primary energy demand (PED) in units of MJ was also calculated for each case. In the primary energy calculations feedstock energy of asphalt binder is only shown here (40.2 MJ/kg) and not in the tables and figures.

The results are presented in Table 4 and Figure 1. As the results show, the HMA and PCC overlays have the highest environmental impacts and the slurry seal is similar to coatings type C and D when the application rate is every 2 years. Compared to HMA and PCC overlay, reflective coatings have lower environmental impacts even when they are applied each year but a major point that should be taken into consideration is that unlike overlays, reflective coatings do not improve the surface smoothness and ride quality and therefore do not improve fuel consumption and user comfort during the use phase, which was not included in this preliminary LCA case study. The reflective coatings and slurry seal also do not improve structural capacity of the pavement.

Table 4: GWP and PED of the Four Cases and Assuming Different Service Lives

	GWP (kg CO2e)					PED (MJ)				
Case	Material	Transport	Construction	# Application in 20 yrs	GWP (kg CO2e)	Material Production	Transport	Construction	# Application in 20 yrs	PED (MJ)
1.A	1.22E+04	1.38E+05	2.01E+02	20	3.02E+06	2.55E+05	1.98E+06	2.77E+03	20	4.48E+07
				10	1.51E+06				10	2.24E+07
				4	6.04E+05				4	8.96E+06
1.B	1.04E+04	1.38E+05	2.01E+02	20	2.98E+06	2.52E+05	1.98E+06	2.77E+03	20	4.47E+07
				10	1.49E+06				10	2.24E+07
				4	5.96E+05				4	8.95E+06
1.C	7.20E+03	2.31E+05	2.01E+02	20	4.76E+06	1.69E+05	3.30E+06	2.77E+03	20	6.95E+07
				10	2.38E+06				10	3.48E+07
				4	9.53E+05				4	1.39E+07
1.D	1.08E+04	2.31E+05	2.01E+02	20	4.84E+06	2.38E+05	3.30E+06	2.77E+03	20	7.09E+07
				10	2.42E+06				10	3.54E+07
				4	9.67E+05				4	1.42E+07
2	1.32E+05	4.58E+05	8.62E+02	4	2.36E+06	2.79E+06	6.55E+06	1.19E+04	4	3.74E+07
3	2.33E+04	3.74E+06	3.40E+03	2	7.53E+06	4.18E+05	5.35E+07	4.68E+04	2	1.08E+08
4	1.18E+05	6.92E+06	5.35E+02	1	7.04E+06	6.41E+05	9.91E+07	7.38E+03	1	9.98E+07

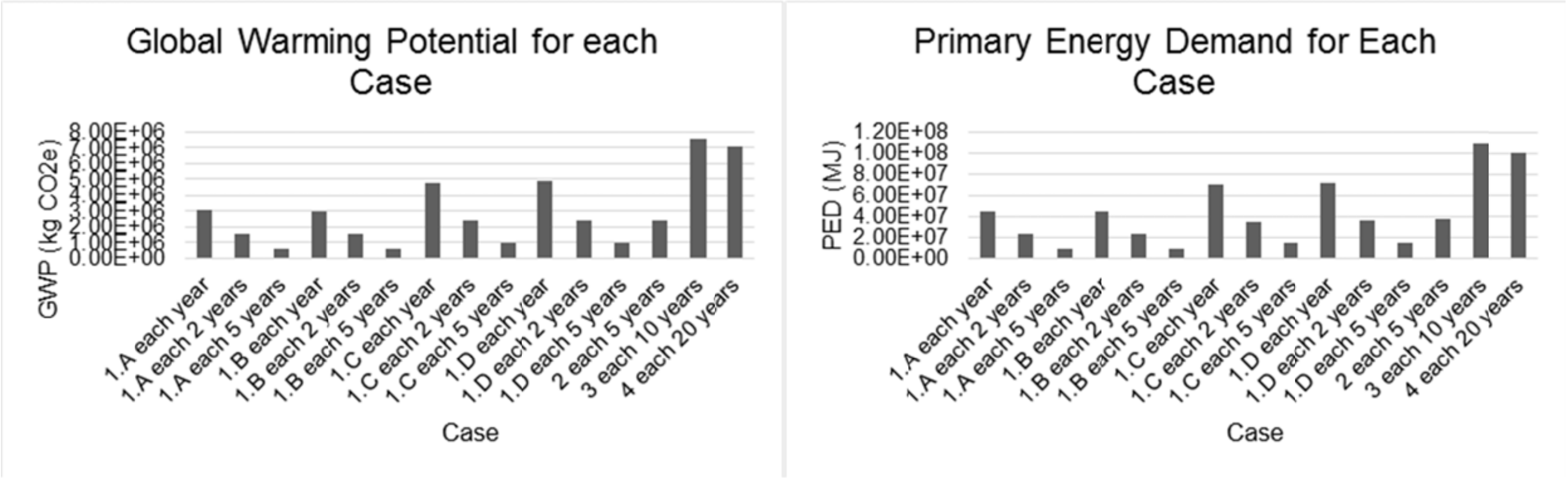

Figure 1: GWP and PED of each case.

SUMMARY AND CONCLUSIONS

This paper synthesized existing available information and knowledge to enhance the understanding of the environmental impact of material production and construction of pavement reflective coatings. . This paper covered classification, components, production method, typical albedo values and durability, application scope and rate, application method, and a preliminary partial assessment of the environmental impacts of pavement reflective coatings. This paper provides information and an example case study for life cycle assessment of pavements with reflective coatings. Main conclusions drawn from this paper include:

1. Reflective coatings currently available fall into two categories: solvent-based coatings and water-based coatings. Solvent-based coatings have longer lives but may release Volatile Organic Compounds (VOCs) into the atmosphere, with a negative impact on both the environment and human health. Water-based coatings have relatively shorter lives, but have less environmental impact.
2. The durability of reflective coatings needs to be improved for more widespread use on both low and high traffic volume roads.
3. The emissions and potential toxicity from reflective coatings should be measured and evaluated to ensure limited negative environmental impacts.
4. A preliminary case study shows that the example HMA and PCC overlays have the highest environmental impacts and the example slurry seal and reflective coatings have lower impacts although unlike overlays, slurry seals and reflective coatings do not improve ride quality or improve structural capacity.

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Part 4: Pavement life cycle assessment tools