December 2006
Technical Memorandum: UCPRC-TM-2006-10

Friction Testing of Pavement Preservation Treatments: Literature Review

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Work Conducted Under Name of Program "Friction Testing of Pavement Preservation Treatments" as part of Maintenance Task Order FY06/07

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DOCUMENT RETRIEVAL PAGE				**Technical Memorandum No.: UCPRC-TM-2006-10**
Title: Friction Testing of Pavement Preservation Treatments: Literature Review				
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Prepared for: California Department of Transportation Div. of Research and Innovation and Division of Maintenance Office of Pavement Preservation		**FHWA No.:** CA111200D	**Work Submitted:** April 30, 2008	**Date:** November 1, 2006
Work Conducted Under Name of Program: "Friction Testing of Pavement Preservation Treatments" as part of Maintenance Task Order FY06/07	**Status:** Stage 6, final version			**Version No.:** 1

Abstract:
This memorandum reviews the different devices used to measure pavement surface friction, and the correlation between friction results measured using California Skid Tester (CST), the British Pendulum Tester (BPT), and other devices. It also reviews the methods used to calibrate friction results measured at different pavement temperatures, and the performance of fog seals, including the friction on fog seals.

Keywords:
friction, skid resistance, fog seal, British Pendulum Tester, California Skid Tester

Proposals for implementation:
- Establish temperature corrections for the BPT for temperature range experienced in California and determine the influence and variability of equipment and operators on measured BPN values.
- Conduct an experimental test program on an existing pavement with representative materials used for fog seals in California to compare the results of friction measurements using the CST, the BPT, and other equipment evaluated in this literature review.

Related documents:

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PROJECT OBJECTIVES

The Office of Pavement Preservation of the Division of Maintenance of the California Department of Transportation (Caltrans) has identified a need for a correlation between the California Portable Skid Tester (CST, California Test Method [CTM] 342) and the British Pendulum Tester (BPT, ASTM E303-93). The Division wants this correlation so fog seals can be tested to determine whether they meet minimum requirements for friction prior to opening to traffic. If those requirements are not met, the project contractor would be required to perform work that brings friction above the minimum requirement.

The primary goal of this research is to determine whether the friction measurements made with the CST and the BPT correlate, and, if they do, how strongly they correlate. A secondary goal of this research is to investigate the change in friction caused by fog seals by measuring friction just before placement of the fog seal and soon after. Additional goals, to be completed if time and budget permit, are to investigate the friction change in the two-month period after a fog seal is placed; and, to compare friction measured using the CST, the BPT, and the Dynamic Friction Tester.

This memorandum provides a literature review that summarizes the information available regarding previously developed correlations between the CST, the BPT, and other friction-measuring devices, and the application and performance of fog seals.

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ABBREVIATIONS, TERMS, AND STANDARDS USED IN THE TEXT

ASTM	American Society for Testing and Materials
AC	Asphalt concrete
BPT	British Pendulum Tester
BPN	British Pendulum Number
RRL	British Road Research Laboratory (now known as the Transport Research Laboratory, TRL)
CST, also referred to with CTM 342-95	California Portable Skid Tester
CT Meter	Circular Track Meter
DGAC	Dense-graded asphalt concrete
DF Tester	Dynamic Friction Tester
FHWA	Federal Highway Administration
FPP	Foundation for Pavement Preservation
F60	Friction component of IFI at 60 km/h
FRS	Friction measurement of a device at a slip speed *S*
IFI	International Friction Index
IRI	International Roughness Index
MPD	Mean profile depth
MTD	Mean texture depth
NCHRP	National Cooperative Highway Research Program
OGAC	Open-graded asphalt concrete
PIARC	Permanent International Association of Road Congresses
PCC	Portland cement concrete
SFC	Sideways Force Coefficient
SCRIM	Sideways Force Coefficient Routine Investigation Machine
SN	Skid number
S	Slip Speed
S_p	Speed Constant
T	Temperature, degrees Celsius
T(K)	Temperature, degrees Kelvin
Tx	Texture
t	Time
BPR Skid Trailer	U.S. Bureau of Public Roads Skid Trailer

REFERENCED STANDARDS*

- ASTM E274-97-06, "Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire"
- ASTM E303-93, "Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester"
- ASTM E445/E445M-88, Standard Test Method of Stopping Distance on Paved Surfaces Using a Passenger Vehicle Equipped with Full-Scale Tires"
- ASTM E501-94, "Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests"
- ASTM E524-06, "Standard Specification for Standard Smooth Tire for Pavement Skid-Resistance Tests"
- ASTM E670-94, "Standard Test Practice for Side Force Friction on Paved Surfaces Using the Mu-Meter"
- ASTM E965-96, "Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique"
- ASTM E1845-01, "Standard Test Practice for Calculating Pavement Macrotexture Mean Profile Depth"
- ASTM E1911-02, "Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester"
- ASTM E1960-03, "Standard Practice for Calculating International Friction Index of a Pavement Surface"
- ASTM E2157-03, "Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter"
- ISO/CD 13473, Characterization of Pavement Texture Utilizing Surface Profiles: Estimation of Mean Profile Depth, Committee Draft from ISO/TC 43/SC 1/WC 39, ISO 1994

* Reference standard years assigned in this list represent the most recent version as of this writing. For example, a standard number followed by "-06" refers to the standard in 2006.

1 PAVEMENT FRICTION TESTERS AND CORRELATIONS

Pavement friction depends on both the microtexture of aggregates and the macrotexture of the overall pavement surface. Microtexture, usually defined as small-scale texture up to 0.5 mm wavelengths, is largely a function of the surface texture of aggregate particles, while macrotexture is a larger texture between about 0.5 mm and 50 mm wavelengths *(1, 2).* Of the two texture types, microtexture affects the adhesion area between aggregate and tire rubber and controls the pavement friction level at low speeds, while macrotexture has a greater effect on hysteresis friction. Unlike microtexture, macrotexture also helps to provide a drainage channel for water to escape. Macrotexture assumes a greater role at high speeds and is the controlling factor in the speed dependency of friction *(1).* To adequately assess the pavement friction for operational vehicles, the effects of both the microtexture and macrotexture need to be evaluated in testing and analysis. It is important to provide both microtexture and macrotexture parameters to ensure appropriate frictional characteristics on wet pavements *(2).* In pavement engineering, a number of devices have been developed to measure and characterize pavement surface friction, with different degrees of consideration of the two texture types. Because each device measures friction in a different way, mainly due to the mechanical action employed and the characteristic or response that is measured, it can be difficult to directly compare the output from different devices.

An important factor that influences the measurement of friction is *slip speed*, which is defined as the velocity of a test tire surface relative to the pavement surface. The *slip ratio* is the ratio of the *slip speed* to the device/vehicle speed. A free-rolling wheel has a slip speed and slip ratio of zero; while a fully locked wheel has a slip speed equal to the vehicle speed and a slip ratio of unity. The maximum value of friction is usually obtained when the slip ratio is between 10 and 20 percent *(3).* The general relationship between friction and slip ratio is shown in Figure 1.

1.1 The PIARC Model and the International Friction Index (ASTM E1960-03)

The PIARC (Permanent International Association of Road Congresses) International Experiment to Compare and Harmonize Texture and Skid Resistance Measurement, conducted in Belgium and Spain in the fall of 1992, developed the International Friction Index (IFI). This index allows for the harmonizing of friction measurements taken with different equipment and/or at different slip speeds to a common calibrated index. ASTM E1960-03 provides for harmonization of friction reporting for devices that use a smooth-tread test tire. The IFI includes measurements of both macrotexture and friction on wet pavements: a speed constant derived from the macrotexture measurement that indicates the speed-dependence of the friction and a friction number corresponding to a slip speed of 60 km/h (38 mph).

The IFI is based on the assumption that the friction is a function of speed and macrotexture and that for a specific pavement surface macrotexture, the value of friction is reduced as the speed increases. The equation for this relationship is shown below and in Figure 2:

$$FR60 = FRS \times e^{\left(\frac{S-60}{S_p}\right)}$$

where *FR60* is the calculated friction of a device at 60 km/h, *FRS* is the measured friction at a slip speed of *S* km/h, and S_p is the speed constant of the IFI, which accounts for the pavement macrotexture.

The calculated friction at 60 km/h for a specific device is then transformed using a linear function of the form:

$$F60 = A + B \times FR60 + C \times Tx$$

where *F60* is the calculated Friction Number of the IFI, *A, B,* and *C* are device-specific constants and *Tx* is the surface texture measured in accordance with ASTM E1845-01.

The initial version of the ASTM standard (ASTM E1960-98) allowed the harmonization of new friction-measuring devices by comparing the new device with a device that was used in the PIARC experiment; however the current version of the ASTM standard specifies the DF Tester as the standard harmonization device.

The IFI can be used to harmonize friction values from different devices. The results from three different friction devices (British Pendulum Tester [Section 1.2.2], Locked-Wheel Skid Trailer [Section 1.2.4], and Dynamic Friction Tester [Section 1.2.8]) and a surface texture device (Circular Track Meter [Section 1.3.2]) are used to compute values of the IFI. The measurements were all taken at the same location on an HMA pavement within a five-day period.

The mean profile depth was 0.84 mm and this was converted into a speed constant (S_p) using the following equation from ASTM E2157-03:

$$S_p = -3.76 + 107.6 MPD_{CTM}$$

S_p = 86.6 km/h

The calculations are shown in Table 1.1 and the *F60* values show a very good agreement among the three devices.

Table 1.1: IFI Calculations for Three Devices at the Same Location

Variable/Constant	DF Tester	BPN	Locked Wheel Skid Tester
S (km/h)	20	10	64
FRS	0.648	72	51
S_p (km/h)	86.6	86.6	86.6
FR60	0.408	40	0.54
A	0.081	0.056	-0.023
B	0.732	0.008	0.607
C	0	0	0.098
F60	**0.38**	**0.38**	**0.37**

1.2 Friction Measurement Devices

1.2.1 California Portable Skid Tester (CTM 342)

Operation of the California Portable Skid Tester (CST) (Figure 3) involves the spinning of a rubber-tired wheel up to a speed of 80 km/h (50 mph) while it is off the ground, then lowering it to the pavement and noting the distance the wheel travels against the resistance of a spring before stopping. During testing the device is attached to the rear of a suitable stationary vehicle. Glycerin is used to wet the full circumference of the test tire before the test. The CST operates initially with a slip ratio of one since the test wheel is rotating but the test carriage is not moving relative to the pavement. Once the wheel is in contact with the pavement the slip ratio changes to zero since there is no braking effort applied to the wheel. In addition, the test is not conducted at a constant speed as there is no further energy applied to the wheel once it touches the ground.

1.2.2 British Pendulum Tester (ASTM E303-93)

The British Pendulum Tester (BPT) (Figure 4), developed by the British Road Research Laboratory (RRL, now the Transport Research Laboratory, TRL), is a dynamic pendulum impact-type tester used to measure the energy loss when a rubber slider edge is propelled over a test surface. The results are reported as British Pendulum Numbers (BPNs) to emphasize that they are specific to this tester and not directly equivalent to those from other devices. The major advantage of the tester is that it can be used in the field as well as in the laboratory. However, this tester is a low-speed device (about 10 km/h [6 mph] swing speed) that measures the skid resistance related to surface microtexture rather than macrotexture. Since pavement friction is affected by both of these, the British Pendulum Tester does not correlate well with measurements from full-scale tires that operate at high speeds (64 km/h [40 mph]) or more *(5).* The BPT operates with a slip ratio of unity.

1.2.3 Drag Tester

The Drag Tester (Figure 5), a.k.a. the Penn State Drag Tester, is a hand-carried portable field tester, developed by H.W. Kummer in 1963 at Pennsylvania State University. As the operator walks the tester, it slides a rubber shoe (the same type used on the British Pendulum Tester) along the pavement. The friction resistance experienced by the rubber shoe is measured through a hydraulic system and displayed on a gauge. It is unknown whether this device is still being used. The description of the Drag Tester is included in this technical memorandum as it was used in a Caltrans study in the 1960s and correlations between this device and the California Portable Skid Tester are presented in Section 1.4.1.2.

1.2.4 Locked-Wheel Skid Trailer (ASTM E274-06)

The Locked-Wheel Skid Trailer (ASTM E274-06) measures the steady-state friction force on a locked test wheel as it is dragged under constant load and at constant speed (typically at 64 km/h [40 mph]) over a wet pavement surface. In this test, water is sprayed on the pavement surface in front of the test tire when the tire reaches test speed in order to simulate wet conditions. Friction of the pavement surface is determined from the resulting force or torque and is reported as *skid number* (SN). A higher SN indicates greater frictional resistance *(6).* Friction measured from this device is related to braking without antilock brakes. The Locked-Wheel Skid Trailer operates with a slip ratio of unity.

Both rib and smooth tires can be used in the test, and they have been standardized by ASTM E501-94 and ASTM E524-88, respectively. The friction measurements with a rib tire are insensitive to macrotexture because the grooves in the tire tread provide channels much larger than the macrotexture of pavement surfaces. Friction measurements with a smooth tire, however, are sensitive to both the microtexture and macrotexture.

The skid resistance of paved surfaces in the U.S. is often determined using the Locked-Wheel Skid Trailer (Figure 6). From a survey conducted in the NCHRP Synthesis 291 it was found that almost all (39 out of 50) state highway agencies are using the locked-wheel device in field pavement friction testing *(2).* Two significant advantages of this device are that: (a) it produces a nearly continuous measure of skid resistance, and (b) it operates at near highway speeds, enabling the measurement of large sections of roadway without the need for lane closures.

1.2.5 Mu-Meter (ASTM E670-94)

The Mu-Meter (Figure 7), which is primarily used on airport runways in the United States *(2),* measures the side force friction of paved surfaces by pulling two freely rotating test wheels angled to the direction of motion (7.5°) over a wetted pavement surface at a constant speed (typically 64 km/h [40 mph]) while the test wheels are under a constant static load. Friction measured from this device is related to the ability of a vehicle to maintain control on curves. The Mu-Meter operates with a slip ratio of 0.13.

1.2.6 Automobile Method (ASTM E445/E 445M-88)

The automobile method is the most natural way to determine the skid resistance of a pavement. In this method, an automobile is driven on wet pavement at a typical speed of 64 km/h (40 mph), and then its wheels are locked until the vehicle comes to a stop. The stopping distance is measured to represent the non-steady skid resistance. In this test procedure, the slip ratio is unity.

1.2.7 GripTester

The GripTester is a fixed slip device commonly used in Europe (Figure 8). The test wheel rotates with a constant slip, i.e., the wheel is lightly braked to provide a difference in velocity between the test wheel and the speed of the tester. The slip ratio is usually between 10 and 20 percent. This is usually accomplished by incorporating a gear reduction of the test wheel drive shaft from the drive shaft of the host vehicle, or through hydraulic retardation of the test wheel *(2).* Friction measured with this device is related to braking with antilock brakes. The GripTester can either be pushed by an operator (<5 km/h [3 mph]) or towed behind a vehicle at higher speeds (50+ km/h [30 mph]).

1.2.8 Dynamic Friction Tester (ASTM E1911-02)

The Dynamic Friction Tester (DF Tester) is a portable device for measuring dynamic coefficient of friction (Figure 9). The tester consists of a horizontal spinning disk fitted with three rubber sliders that are made of the same materials as the friction test tires (ASTM E501-94). Usually the disk rotates at a tangential velocity of 90 km/h (55 mph), and is then lowered onto the wet pavement surface. Friction is measured continuously as the disk slows. The DF Tester operates with a slip ratio of unity. The DF Tester is relatively small and can test a site in a few minutes. When used with pavement macrotexture measurement, such as mean profile depth (MPD), DF Tester results can be used to calculate the IFI and to calibrate other friction testers that use a smooth-tread tire, as described in ASTM E1960-03.

1.2.9 Summary

The friction measurement devices described in this section can be summarized in terms of spot measurement versus continuous measurement, partial or fully fixed slip mode, and high or low speed. Spot measurements require lane closures in order to operate and are subject to operator bias when selecting test locations. Likewise low-speed devices require some form of traffic control (either lane or rolling closure), but it might not be possible to operate high-speed devices in a construction zone due to physical limitations on run lengths or other safety factors. The productivity of the device needs to be considered as well in order to obtain a suitable number of measurements so that a representative value for a test section can be obtained.

With the exceptions of the California Portable Skid Tester (CST), the Drag Meter, and the Automobile Method, all the other devices have been harmonized (in conjunction with macrotexture measurements) to calculate a common friction index, the IFI. A harmonizing equation for the CST could be developed by using the device in parallel with the DFT and a macrotexture measurement. A comparison of the devices, except for the Drag Meter and the Automobile Method, is presented in Table 1.2.

Table 1.2: Friction-Measuring Devices

Device	Stationary (spot)/ Continuous Measurement	Operational Mode	Slip Ratio	Test Speed (km/h)
California Portable Skid Tester	Stationary	Free wheel	1.0	80
British Pendulum Tester	Stationary	Slider	1.0	10
Locked-Wheel Skid Trailer	Continuous	Locked wheel	1.0	64
Mu-Meter	Continuous	Side force	0.13	20–80
GripTester	Continuous	Fixed slip	0.145	30–90
Dynamic Friction Tester	Stationary	Slider	1.0	0–90

1.3 Texture Measurement Methods

Texture measurement methods are described in this technical memorandum because the pavement macrotexture depth is required to calculate the International Friction Index. Macrotexture is defined as texture that has wavelengths between 0.5 mm and 50 mm, and peak-to-peak amplitudes that normally vary from 0.01 to 20 mm.

1.3.1 Volumetric "Sand Patch" Test (ASTM E965-96)

The "Sand Patch" test measures the average depth of the pavement surface macrotexture. In this test, a known volume of material (typically sand [100% passing #50 sieve and 0% passing #100 sieve] or glass spheres of a uniform size [0.2 mm]) is carefully spread in a circle on the pavement surface to fill the surface voids. The surface of the material should be level with the highest points of the aggregate (Figure 10). The average macrotexture depth is calculated by dividing the volume of material by the average diameter of the circle. The calculated texture depth is called the *mean texture depth* (MTD).

1.3.2 Circular Track Meter (ASTM E2157-03)

The Circular Track Meter (CT Meter) uses a high frequency laser to measure surface profile. The laser head travels around a circular path with a radius of 142 mm; the perimeter of the circle is divided into eight segments with a length of 100 mm. This allows for the calculation of the MPD in accordance with ISO 13473. The CT Meter is often used in conjunction with the DF Tester in order to allow the IFI to be determined.

1.3.3 High-Speed Texture Lasers

High-speed texture lasers are usually used in conjunction with longitudinal profile measuring equipment to measure pavement roughness. A laser operating at a frequency of 16 kHz generally provides sufficient accuracy for calculating pavement roughness (IRI) when the test vehicle is operating at highway speeds. In order to obtain data of sufficient accuracy and quantity to measure macrotexture, a laser needs to operate at a frequency of at least 32 kHz for data collection at highway speeds. The use of a high frequency laser allows for the collection of both pavement roughness and macrotexture metrics. The ASTM standard (E1845-01) provides a process to calculate the MPD from longitudinal profile data.

1.4 Correlation of Testers

Different testers measure different aspects of pavement friction. Even when the same tire or slider is used, other details may vary, such as speed, mode of operation, and water film control. Therefore, it is impossible to obtain a 1:1 correlation between friction measurement results from different types of testers. NCHRP Synthesis 14 *(5)* discussed the reasons for the difficulty in obtaining good correlations, which mainly lie in the complexities of the friction behavior of rubber and tires. The friction of a tire on pavement consists of two components: adhesion and hysteresis. The relative contribution of the two components changes with the microtexture and macrotexture of pavement surface. Microtexture affects the adhesion component most strongly, while macrotexture has a greater affect on the hysteresis component. The adhesion component can disappear if the surface is completely covered by a water film, whereas the hysteresis component can disappear on a perfectly smooth surface. Both components change with speed and temperature and other factors in a complex way. Therefore, as stated in NCHRP Synthesis 14:

> "…general correlations are, at least in a practical sense, not possible and that when correlations are found, it is either because the surfaces on which they were obtained included only a limited range of types, or the testers do not differ significantly in operating principles, or the expected precision of the correlation is low. In short, when a correlation is found this should be considered fortuitous, rather than as fulfillment of a justified expectation."

1.4.1 California Skid Tester (CTM 342)

<u>1.4.1.1 California Skid Tester versus British Pendulum Tester</u>

In 1968, Caltrans studied the correlation between the California Skid Tester (CST) (CTM 342) and the British Pendulum Tester (BPT) *(8)* (earlier referred to as the [British] Portable Skid Resistance Tester, e.g., Giles et al. *[22])*. To provide a large range of friction values, different pavement surfaces were tested, including portland cement concrete (PCC), dense- and open-graded asphalt concrete (AC), and screening seal coats. In the study, the California Skid Tester was first calibrated against UC Berkeley Professor Moyer's skid trailer to simulate the worst conditions encountered by traffic (locked wheel, smooth tire, wet pavement, and a speed of 80 km/h [50 mph]). A linear relationship was developed between the results measured with the CST and the BPT, as shown in Figure 11. However, the report neither presented any of the data that was used to develop the correlation nor discussed the goodness of correlation and the range of scatter of the data.

Figure 11 shows the recommended British Pendulum Tester values with the tentative California Skid Tester minimum. The figure also shows the minimum acceptable friction in Virginia, which was obtained from D. C. Mahone's chart of correlation *(7)* between the British Portable Tester and a Virginia skid test car at 64 km/h (40 mph). Using D. C. Mahone's chart, a friction value of 0.45 in Virginia is equivalent to about a friction value of 0.30 on the California scale. This led to the conclusion that readings on the California tester above 0.28 should probably be satisfactory for all sites, with the possible exception of curves *(8).*

1.4.1.2 California Skid Tester versus Drag Tester

In a 1967 study in California, Skog *(10)* found the correlation between the CST and the Penn State Drag Tester to be poor when different types of surfaces were compared (Figure 12). A significant correlation existed when only PCC surfaces were used in the analysis. This is not surprising in view of the totally different configurations and test speeds of the two testers. The Drag Tester was operated at a low speed while the CST was calibrated for 80 km/h, so the skid number/speed gradient could significantly affect the correlation.

1.4.1.3 California Skid Tester versus Locked-Wheel Skid Trailer

In 1968 Skog and Johnson *(11)* studied the correlation between the CST and the U.S. Bureau of Public Roads (BPR) Skid Trailer (a locked-wheel skid trailer essentially in accordance with ASTM E274) by measuring the friction results of seven types of pavement surfaces, including PCC and AC, at eleven locations in the vicinity of Sacramento, California. The BRP Skid Trailer used two rib tires and tested at a speed of 64 km/h (40 mph). The CST was first calibrated against Professor Moyer's skid trailer unit *(12)* with its standard test conditions: locked wheels, smooth tires, wet pavement, and a speed of 80 km/h (50 mph). For a better comparison, additional testing was performed using the BPR unit with its speed changed to 80 km/h (50 mph) and its rib tires replaced by smooth tires. For all the test conditions investigated, correlations indicated that the CST results could be used to predict the BPR skid number (Figure 13 through Figure 15). The study found that the California tentative minimum coefficient of friction, 0.25, which was based on a skid-resistance inventory of a large number of different pavements in the California Highway System and had been checked against those used in England, Virginia, and Florida, corresponded quite well to the tentative minimum skid number (37) for main rural highways as recommended in NCHRP 37 (Figure 14).

During 1969 and 1970, the California Division of Highways conducted a correlation study between the CST and the ASTM E274 Skid Tester *(13).* Two ASTM skid trailer units (A and B) were purchased and included in the study, the purpose of which was to further determine the adequacy of the tentative California minimum coefficient of friction, as checked in an earlier correlation study with the BPR Skid Trailer *(11).*

These tests were conducted as follows: ASTM Skid Trailer A ran three skid tests as rapidly as possible, attempting to get the middle skid test at a specified location. The three tests were then averaged and considered as one. This procedure was repeated both at 64 km/h (40 mph) and 80 km/h (50 mph), and also with the skid tester using standard rib tires and smooth tires. Once this series of tests was done, the CST tested the sites in accordance with California Test Method (CTM) 342. A total of five tests, 7.5 m apart, were run at each site and averaged as one.

Good correlations were obtained between the CST and ASTM Skid Trailer A for the four test conditions investigated in the study, as shown in Figure 16 through Figure 19.

A correlation study was also conducted between the two ASTM Skid Testers. Excellent correlation was obtained at the standard ASTM test conditions. Excellent correlations were also obtained for SN conversions of different test speeds to the 64 km/h standard speed.

Test results also revealed that the standard error of the ASTM skid tester is 0.9 to 1.5 SN for asphalt pavements and 1.1 to 2.0 for portland concrete pavements.

1.4.1.4 California Skid Tester versus Mu-Meter

In 1972, the California Division of Highways conducted a correlation study between the CST and Arizona's Mu-Meter for a variety of surfaces *(14)*. All tests were performed at 64 km/h (40 mph) with a water film on the surface approximately 1 mm thick. It was found that a linear correlation exists between the skid resistance values obtained by the two testers, and that the correlation is best on PCC pavements, as shown in Figure 20 and Figure 21. The report also noted that although a reasonable correlation exists, "it appears that the Mu-Meter values become somewhat erratic on the rougher surfaces."

1.4.1.5 California Skid Tester versus Sand Patch Test

In 1974, Caltrans investigated methods to measure surface macrotexture and their correlations with skid resistance data acquired using the CST *(15)*. Pavement surface macrotexture was measured by the Sand Patch test. A variety of pavement surfaces were tested, including open-graded asphalt concrete (OGAC), dense-graded asphalt concrete (DGAC), chip-sealed and fog-sealed AC, and new, polished, and grooved PCC. The results showed a general trend toward a higher skid number with increasing texture depth. The relationship, however, was neither clear nor definitive, as illustrated in Figure 22.

1.4.2 British Pendulum Tester (ASTM E303-93)

As stated in ASTM E303-93, the British Pendulum Number (BPN) from the British Pendulum Tester (BPT) does not necessarily agree or correlate with other slipperiness-measuring equipment. If a relationship between observed BPN and some "true" value of skid resistance exists, it has not and probably cannot be studied.

1.4.2.1 British Pendulum Tester versus Drag Tester

The Penn State University Drag Tester uses the same slider as the BPT, but it is normally operated at a lower speed than the BPT. Kummer reported good correlation when using a slider made from ASTM E249-64T rubber *(5).*

1.4.2.2 British Pendulum Tester versus Dynamic Friction Tester

The DF Tester measures the friction between three rubber sliders and a wet pavement surface. When the rotating speed is slow, the working mechanism between the DF Tester and the BPT tends to be similar. In NCHRP Synthesis 291, it was found that when the slip speed is 20 km/h (12 mph), the DF Tester friction correlates highly with BPN values, as shown in Figure 23. The measurements at the annual National Aeronautics and Space Administration (NASA) Friction Workshops (1993–1999), however, showed that BPT values are significantly more variable than DF Tester values *(2).*

1.4.2.3 British Pendulum Tester versus GripTester

The correlation between BPT and the GripTester was studied in Australia and the results were presented at the 2005 International Surface Friction Conference in New Zealand *(16).* A limited number of data show a correlation between measurements of the two testers when the GripTester was either towed at 50 km/h (30 mph) or pushed at 5 km/h (3 mph), as shown in Figure 24. The paper, however, did not give the details of the data, such as the pavement surface type and the test temperature.

1.4.3 Locked-Wheel Skid Trailer (ASTM E274)

As stated in ASTM E274-97, the relationship of SN values to some "true" value of locked-wheel sliding friction has not been established, and the SN values do not necessarily agree or correlate directly with those obtained by other pavement friction–measuring methods. Therefore, the SN values are intended for use in evaluating the skid resistance of a pavement relative to that of other pavements or for evaluating changes in the skid resistance of a pavement with the passage of time.

1.4.3.1 ASTM E274 Skid Trailer versus Automobile Method

In general, pavement friction measured with the ASTM E274 skid trailer is numerically higher than that represented by the stopping distance measured by the Automobile Method. This is because the skid number in ASTM E274 is typically determined at a constant speed of 64 km/h (40 mph), but the stopping distance in the Automobile Method is measured after the vehicle decelerates from 64 to 0 km/h (40 to 0 mph). Friction on wet pavements increases as wheel speed decreases. Correlation between the skid number and the stopping distance, however, can be found due to the commonality of the test procedure in both methods. Figure 25 shows the correlation obtained by Mahone and Runkie, as referred to in NCHRP Synthesis 14 *(5).*

1.4.3.2 ASTM E274 Skid Trailer versus British Pendulum Tester

NCHRP Synthesis 14 *(5)* warned that any correlation between BPT and ASTM E274 would be "purely fortuitous" because the BPT not only measures friction at low speeds, but it also brings the edge of a rubber shoe (instead of a tire) into contact with the pavement. NCHRP Report 37 *(17)* gave a correlation that was based on Dillard and Mahone, but cautioned that the correlation "is not very satisfactory."

In 2002, Caltrans measured the skid resistance of some 25-mm and 12.5-mm OGAC pavements in District 1 using both the ASTM E274 skid trailer and the BPT. The skid trailer ran at a speed of 64 km/h (40 mph). The reported value for a given section was determined by averaging the measurements made along the entire section. The reported BPN values were averages of three measurements obtained from randomly selected stations on each section. Testing was performed between September 23 and 25, 2002, at six different sites along three routes and in three counties. The data from this study did not produce a meaningful correlation between the two tests due to the considerable scatter and the limited range of data (Figure 26). However, the report suggested that it would be possible to develop a meaningful correlation between SN and BPN when more data were added and distinctions were made between the different types of mixes *(19)*.

1.4.3.3 ASTM E274 Skid Trailer versus Mu-Meter

Gallaway et al. *(20)* showed that the Mu-Meter and an ASTM E274 tester had a good correlation when both testers used tires without tread and both operated with the pavement wetted by sprinkler truck (Figure 27), but the correlation was not very good when the ASTM E274 tester strictly followed the specifications. In either case, the average maximum deviation from the correlation line was ±5 SN at 64 km/h (40 mph) for tests on the same pavement.

1.5 Temperature Effect

Friction measurement changes not only with testing method and pavement surface type but also with uncontrollable climate variables, one of which is temperature. Temperature affects friction properties because it changes the physical properties of tire rubber and asphalt pavement surfaces, which are both viscoelastic materials. Seasonal variation of pavement friction has long been noticed in the field by researchers *(22)*. The general trend of the variation is that skid resistance decreases during seasons with warmer temperatures and increases during seasons with colder temperatures *(23)*. These variations should be considered when comparing test results measured from different pavement surfaces.

Hill and Henry *(24)* developed a model to account for short-term and long-term seasonal effects based on the analysis of friction and climate data collected on experimental test sites in Pennsylvania from 1978 to 1980, as shown below *(24, 25)*:

$$SN_t = SN_S + SN_L + SN_F \quad \textbf{(1)}$$

where SN_t = Skid number at time t
SN_S = Short-term weather-related variation
SN_L = Long-term seasonal variation
SN_F = Skid resistance independent of short- and long-term effects

Short- and long-term variations were modeled by regression as functions of rainfall, traffic, pavement temperature, and other factors.

Oliver *(26)* investigated the seasonal variation of skid resistance in Australia using the Sideways Force Coefficient Routine Investigation Machine (SCRIM) and found that pavement friction decreased with temperature according the following Equation *(26):*

$$SFC_T / SFC_{25} = 0.563 + 45.9/(T+80) \qquad (R^2 = 0.83) \quad \textbf{(2)}$$

where SFC_T = Side force coefficient of SCRIM at tire temperature T (°C)
SFC_{25} = Side force coefficient of SCRIM at a tire temperature of 25°C

Oliver *(26)* also studied the temperature effect on friction using a British Pendulum Tester. A set of laboratory-prepared surfaces, covering a range of BPNs between 15 and 90 and a range of surface textures between 0 and 1.5 mm, were tested outdoors with temperatures ranging from 7°C to 59°C. A good correlation between the BPN and the pavement temperature was observed, as follows *(26):*

$$BPN_T / BPN_{20} = 1 - 0.00525 \times (T - 20) \quad \textbf{(3)}$$

where BPN_T = Skid resistance value obtained at pavement surface temperature T (°C)
BPN_{20} = Skid resistance value obtained at a pavement surface temperature of 20°C
T = Pavement surface temperature (°C)

In ASTM E303-93, it is required that the rubber compound for the slider pad shall be natural rubber meeting the requirements of the RRL (TRL) or synthetic rubber as specified in ASTM E501-94 and ASTM E524-88. In the British Standard 7976, standard simulated shoe sole (Four-S) rubber and TRL rubber are the two most common types of slider pad material. If the TRL rubber slider is used, a temperature correction factor (Table 1.3) is applied to correct the test results to a standard temperature of 20°C because natural rubber friction is temperature dependent. The ASTM-specified synthetic rubber was formulated to be independent of temperature and therefore no temperature correction is made.

Table 1.3: Temperature Corrections for BPN Readings Using the TRL Rubber Slider (British Standard 7976)

Surface Temperature (°C)	Correction Factor (BPN units)
8 to 11	-3
12 to 15	-2
16 to 18	-1
19 to 22	0
23 to 28	+1
29 to 35	+2

In tropical climates, the TRL recommends that the BPN should be corrected to a standard temperature of 35°C using the following relation *(27):*

$$BPN_{35} = (100+T) / 135BPN_T \qquad \textbf{(4)}$$

where BPN_{35} = Skid resistance value at 35°C
BPN_T = Measured skid resistance value at temperature T
T = Temperature of test (°C)

At this standard temperature, the corrected values will be 3 to 5 units lower than comparable surfaces at 20°C.

In a survey on motor vehicle tires and related aspects commissioned by the European Commission of the United Nations, a British Pendulum Tester was used to measure the surface friction of wet tracks in accordance with ASTM E303-93 using the rubber specified in ASTM E501-94. The following formula was used for temperature correction *(28):*

$$BPN = BPN_T + 0.34T - 0.0018T^2 - 6.1 \qquad \textbf{(5)}$$

where BPN = Corrected skid resistance value
BPN_T = Measured skid resistance value
T = Wetted track surface temperature (°C)

Recently Bazlamit et al. in Ohio conducted laboratory experiments to isolate and quantify the temperature effect on friction *(23).* British pendulum tests were performed on ten mixes at five temperatures (0, 10, 20, 30, and 40°C). Using regression analysis, it was found that a one degree increase in temperature causes a 0.232 decrease in British Pendulum Number for intermediately polished surfaces (Figure 28), and the following equation was developed to predict the BPN at any temperature if the BPN is known at 20°C:

$$\Delta BPN_{T(K)} = 68.0108 - 0.232T(K) \qquad \textbf{(6)}$$

where $\Delta BPN_{T(K)}$ = number to be added to the BPN reading at *T(K)*=293.15°K (20°C) to get the BPN number at temperature *T(K)*
T(K) = temperature in Kelvin

It should be noted that Bazlamit et al. did not state whether they used the rubber specified in ASTM E501-94 or the TRRL rubber. Based on a correlation equation between BPN and SN developed by Kissoff *(29),*

$$SN = 0.862BPN - 9.69 \qquad \textbf{(7)}$$

Bazlamit et al. derived a similar equation to adjust the SN at any temperature:

$$\Delta SN_{T(K)} = 58.453 - 0.1994T(K) \qquad \textbf{(8)}$$

where $\Delta SN_{T(K)}$ = number to be added to the SN reading at *T(K)* = 293.15°K
T(K) = temperature in Kelvin

Luo *(30)* studied the effect of pavement temperature on friction using the SN data measured by a Locked-Wheel Skid Trailer (ASTM E274-97) in Virginia *(30).* Pavement and air temperatures were measured using thermocouples located 38 mm below the surface and close to the pavement surface, respectively. It was found that at low speeds (less than 35 km/h [22 mph] for the smooth tire and 50 km/h [30 mph] for the rib tire), pavement friction tends to decrease mildly as pavement temperature increases. At higher speeds, friction values are mostly insensitive to pavement temperature. Limited data also revealed that the friction values on the open-graded friction course (OGFC) surfaces are insensitive to temperature changes.

The different temperature correction factors suggested in the literature for the British Pendulum Number (BPN) are plotted together for comparison (Figure 29). It can be seen that the correction factors suggested in British Standard 7976 are slightly smaller than those suggested by Bazlamit and the European Commission, and those suggested by Oliver when BPN is around 40. For the temperature range of 15°C to 50°C, the correction factors suggested by Bazlamit, the European Commission, and Oliver (BPN = 40) are similar.

1.6 Summary

The literature review reveals that good correlation between different friction testers may be obtained only when the test conditions and working principles of the testers are similar. Previous studies and research in the literature show that good correlation exists between the California Skid Tester, the Locked-Wheel Skid Tester (ASTM E274), and the Arizona Mu-Meter. British Pendulum Tester values have good correlation with the Drag Tester and the Dynamic Friction Tester operated at a low speed. The correlation between the testers that utilize a test wheel and those that use a rubber slider, however, is generally poor.

The International Friction Index (IFI) that was an outcome of the 1992 PIARC Experiment produced a workable method to allow comparison of different test devices by the combination of friction and texture measurements. Future comparisons between the California Skid Tester, the Locked-Wheel Skid Tester, and any other device should be undertaken through the use of the IFI.

Temperature affects friction; generally higher temperature leads to lower friction values. The temperature effect, however, is dependent on vehicle speed and pavement surface type.

2 FOG SEALS

2.1 Fog Seal Basics

A fog seal is a dilute emulsion applied without an aggregate cover. The purpose of applying a fog seal is to seal and to enrich an under-asphalted surface, to waterproof an open-texture pavement and prevent raveling under traffic, or simply to improve the surface appearance *(31).* Fog seals are suitable for treating raveled and aged pavements in otherwise good condition, but they are not recommended on high-speed roadways or pavements with severe structural damage. Fog seals can also be used to prevent stone loss by holding chips in place. However, for the fog seals to be effective, they must penetrate into the existing asphalt concrete surface. Inappropriate use can result in a slick pavement surface and tracking of excess material.

The materials used in fog seals are asphalt emulsion and water, and, in some cases, additives for special purposes. The emulsion types may be cationic or anionic. The most common asphalt emulsions used are Cationic Slow Seal (CSS-1), CSS-1h, SS-1, or SS-1h, and the typical dilution ratio is one part asphalt emulsion to one part water. Polymers are not commonly used with fog seals.

After construction, traffic should be kept off the fog seal until the emulsion cures. If immediate use is required, traffic should travel at a reduced speed to prevent displacing and picking up the chips.

Fog seal may reduce the skid resistance of pavements by filling the surface texture of pavements. In the Caltrans *Fog Seal Guidelines,* it is recommended that skid resistance shall be measured using CTM 342 after fog seal has cured, and the measured coefficient of friction shall be no less than 0.30 *(32).* After opening to traffic for a certain period, pavement friction may increase due to the wear-off of some asphalt from the pavement surface *(31).* King and King reported the findings of a Federal Highway–funded pavement preservation project that included two sites in California. They found that the friction dropped by 33 percent immediately after application.

2.2 Fog Seal Performance

Fog seals have been used for pavement preservation and maintenance for many years. However, the number of literature references that discuss fog seal performance is limited. Following are some results found in the literature.

Estakhri and Agarwal studied the effects in Texas of a fog seal on chip seal applications, regular asphalt pavements, and laboratory-molded asphalt specimens *(33, 34).* In their study, four test roads were treated with a fog seal on chip seals and observed for two years. It was found that fog seal improved the aggregate retention rates over the corresponding control surfaces for every test road, and a fog seal application to a chip seal should be applied before the first winter after chip seal application. Estakhri and Agarwal also monitored for two years the performance of regular asphalt pavements treated with a fog seal, and found no visual difference between treated and control sections. They also performed laboratory experiments, in which laboratory-compacted cores were treated with fog seal and aged at 60°C for 42 days. The resilient modulus of the aged cores showed no significant effect of the fog seal in reducing the hardening rate of the mixtures. Estakhri and Agarwal finally concluded that fog seals applied at a rate of 0.05 gallon per square yard are not effective at reducing the aging rate but can effectively correct specific surface problems such as raveling.

Outcalt conducted a field experiment in Colorado to study the effects of chip seal and fog seal *(35).* Four test sections were built as follows:

- Section I: Lightweight chips
- Section II: Standard chips
- Section III: Standard chips with a fog seal of High Float Rapid Set (HFRS-2P) emulsion diluted 1:1 and applied at a rate of 0.05 gallon per square yard
- Section IV: Untreated control section

After four years' observation of performance, Outcalt concluded that:

- Overall, the treated sections were in better condition than the control section.
- Skid resistance was high for all sections at the time of final evaluation.
- Fog seals showed a significant improvement in short-term performance in terms of waterproofing and chip retention. However, there was no apparent long-term advantage to applying a fog seal over a standard chip seal.

Asphalt Systems, Inc. used GSP (an emulsified liquid asphalt containing Gilsonite, resin, and asphalt) as a fog seal on Ohio Logan County Rd 154 and monitored the skid resistance and conditions of the road for five years *(36).* It was found that the treated section experienced 23 percent less oxidation than the untreated section and showed little sign of cracking after five years. Skid resistance over the five-year period showed no significant difference between the treated and untreated sections.

Currently, the Federal Highway Administration (FHWA) and the Foundation for Pavement Preservation (FPP) have a five-year study underway to evaluate the effects of spray-applied sealer/rejuvenators on the long-term performance of asphalt pavements. The study includes a national workshop to identify the state-of-practice use of fog seals and other rejuvenators, and test section construction and evaluation. The test sections are to be built in multiple states to evaluate different products and different pavement surface types (dense-graded surface, friction course surface, and chip seal surface). A comprehensive testing plan is used to monitor and to evaluate treatment performance, by four approaches:

- Chemical and rheological analysis
- Nondestructive testing
- Destructive testing
- Pavement performance assessment

The chemical and rheological analysis, to be conducted by the Western Research Institute, will determine the chemical compatibility between rejuvenator/sealant and roadway asphalt, predict the oxidation and aging propensity of roadway asphalt before and after treatment, and assess whether the sealer/rejuvenators can improve the rheological properties of the in-situ binder.

Nondestructive testing will evaluate pavement stiffness before and after treatment using a portable seismic pavement analyzer, and determine the degree of pavement oxidation using a portable magnetic resonance device.

Destructive testing will involve obtaining cores from the field, and then cutting and testing them in a dynamic shear rheometer.

Functional pavement performance assessment will measure the pavement texture using a Circular Texture Meter (CT Meter), the surface friction using a Dynamic Friction Tester (DF Tester), and the infiltration/waterproofing properties using a skid abrader outflow meter.

The chemical, structural, and functional performance of the test sections will be closely monitored in this study so that the time from the initial loss to subsequent recovery of surface friction can be determined.

2.3 Summary

The literature review reveals that fog seals may initially reduce pavement friction due to the presence of binder coating the exposed aggregate surfaces, but that the seals have no long-term adverse effect as that binder is removed by traffic over time. Generally, fog-sealed surfaces and untreated surfaces have similar skid resistance for most of their service life. The in-progress FHWA/FPP fog seal study is expected to significantly improve our knowledge of the effects of fog seals on pavement performance, and to provide improved design, construction, and evaluation practices.

3 SUMMARY AND RECOMMENDATIONS

This literature review has been the initial phase of a study (1) to establish a correlation between the California Portable Skid Tester (CST) and the British Pendulum Tester (BPT), and (2) to investigate the change in friction resulting from the application of fog seals by measuring it immediately before and soon after the seals are applied to examine the potential for use of the BPT and other equipment (e.g., the Dynamic Friction Tester, DFT) for determining whether the pavement surfaces meet minimum friction requirements prior to opening to traffic. If these requirements are not met, a contractor would be required to perform actions that would improve friction values to the required levels.

This literature review has indicated the following:

1. Good correlation between different friction testers may be obtained only when the test conditions and working principles of the testers are similar. Previous studies show that good correlation exists between the CST, the LWST, and the Arizona Mu-Meter. The BPT values have good correlation with the Drag Tester and the DFT operated at a low speed. The correlation between the testers that utilize a test wheel and those that use a rubber slider, however, is generally poor.
2. The International Friction Index (IFI) provides a workable methodology to allow comparison of different friction testing devices by combining friction and texture measurements (CTM) into a single parameter. Thus, consideration should be given to the use of IFI for comparisons between the CST, Locked-Wheel Skid Trailer (LWST), BPT, DFT, and other friction devices that might be evaluated.
3. Temperature affects friction measurement, and generally higher temperatures result in lower friction values. However, this influence is dependent on vehicle speed and pavement surface type.
4. Fog seals have been used for pavement preservation and maintenance for many years. The number of references that discuss fog seal performance, however, is limited. The available information indicates that: (a) fog seals may initially reduce pavement friction due to the presence of binder coating the exposed aggregate surfaces, but that the seals have no long-term adverse effect as that binder is removed by traffic over time, and (b) fog-sealed surfaces and untreated surfaces have similar skid resistance values for most of their service lives.

Based on this review of existing information, a test program that meets the following initial objectives is recommended:

1. To use the BPT for California temperature regimes, it will be necessary to establish the influence of temperatures larger than those for which correction factors are available. In addition, it will be necessary to establish the influence of equipment and operator variability on measured BPN values to insure that

measurements made in different locations by different operators will be comparable if the equipment is used to measure the surface friction of fog seals after their application.

2. An experimental test program on an existing pavement section using a number of the current materials used for fog seals in California should be conducted early on to compare the results of friction measurements using the CST, the BPN, the FHWA DFT, the CTM, and the Caltrans LWST to establish the feasibility of using the BPT, DFT and, CTM in lieu of the CST.

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FIGURES

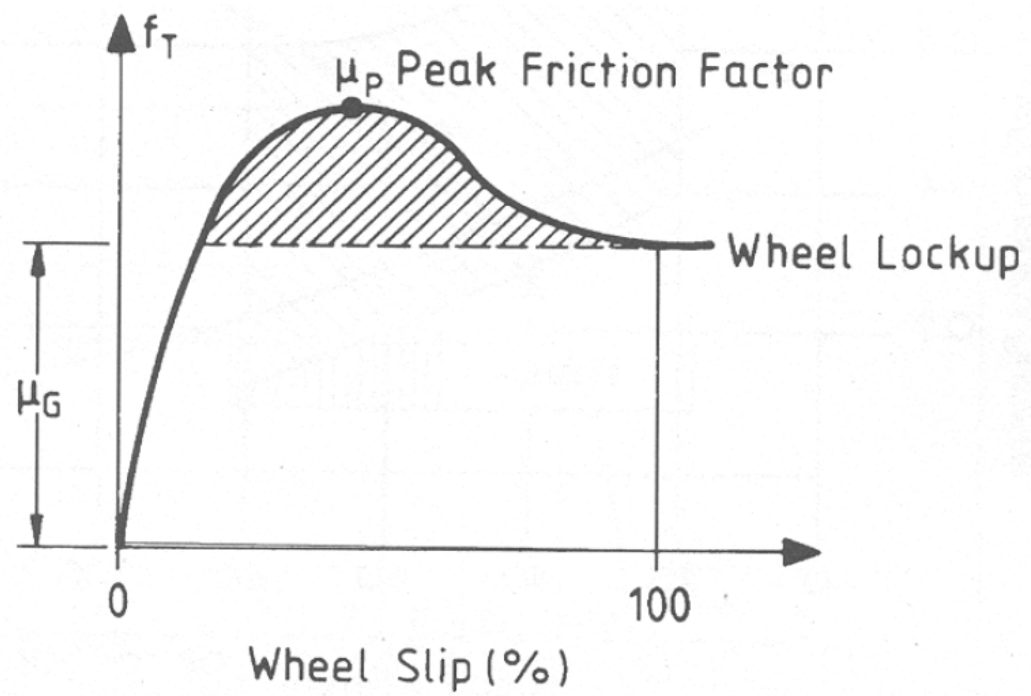


Figure 1: The Friction Curve. ***(3)***

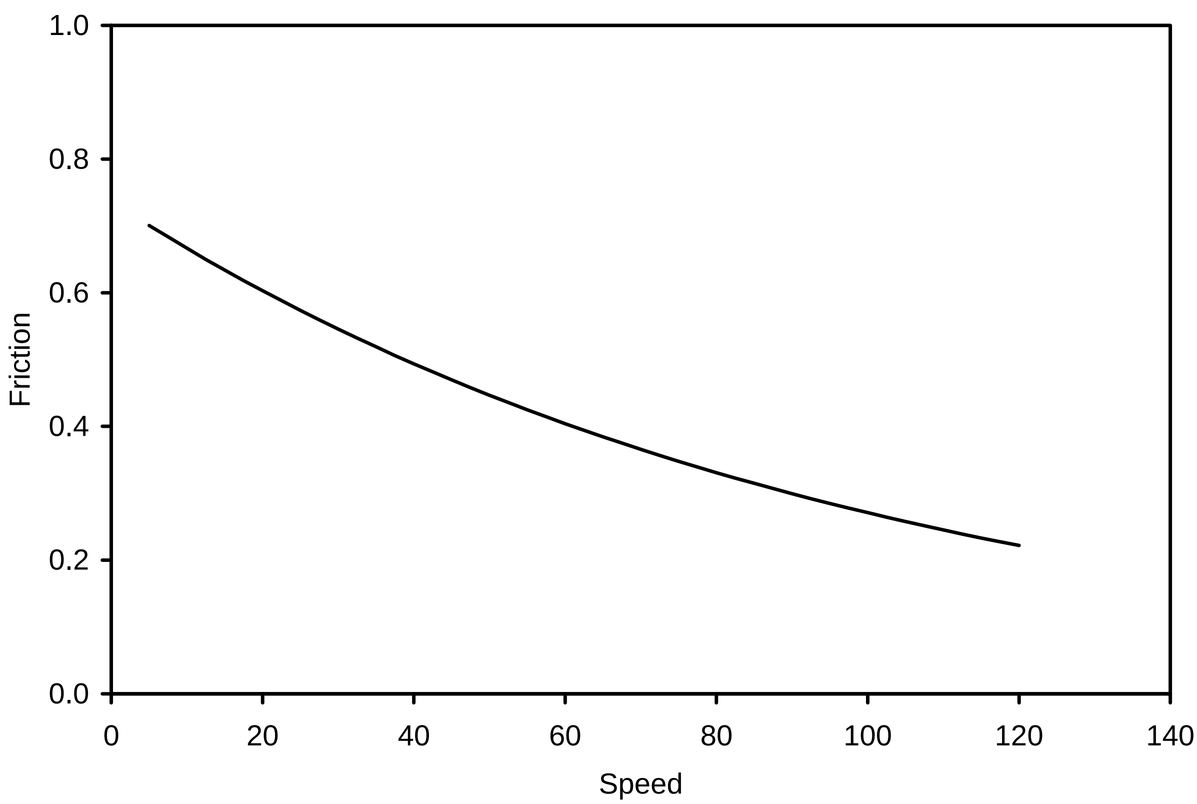


Figure 2: The relationship between speed and friction for a given macrotexture.

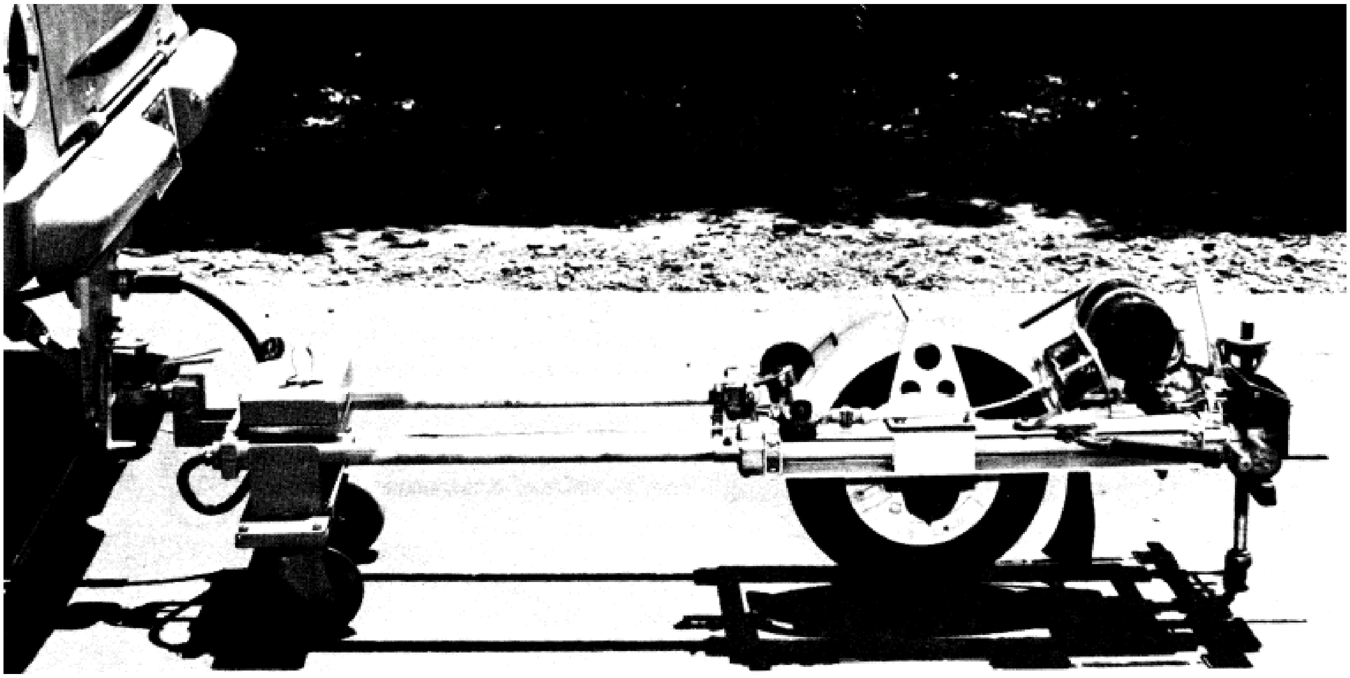


Figure 3: A California portable skid tester. ***(5)***

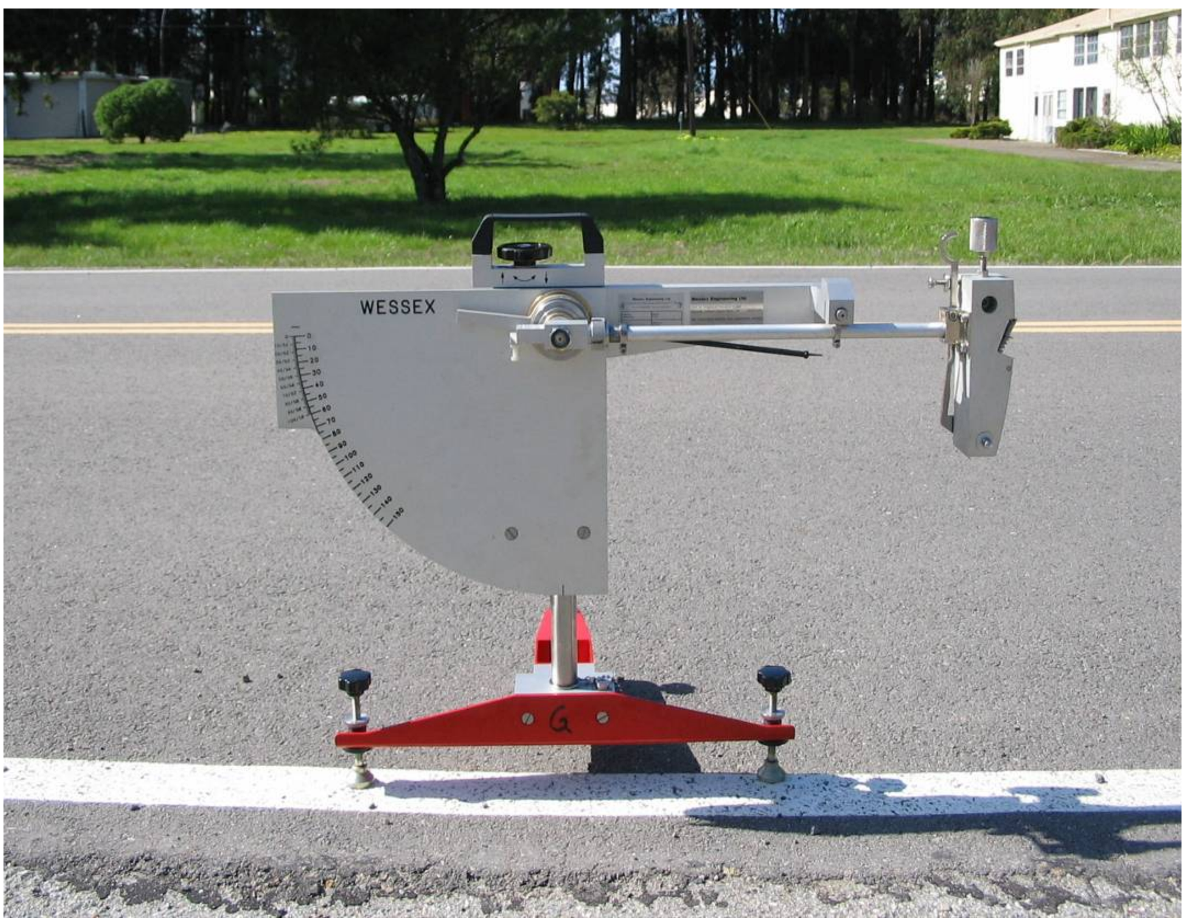


Figure 4: A typical British Pendulum Tester.

Figure 5: A Penn State Drag Tester. ***(5)***

Figure 6: A typical ASTM standard skid trailer. ***(19)***

Figure 7: A Mu-Meter. ***(5)***

Figure 8: GripTester.

Figure 9: A Dynamic Friction Tester. (21)

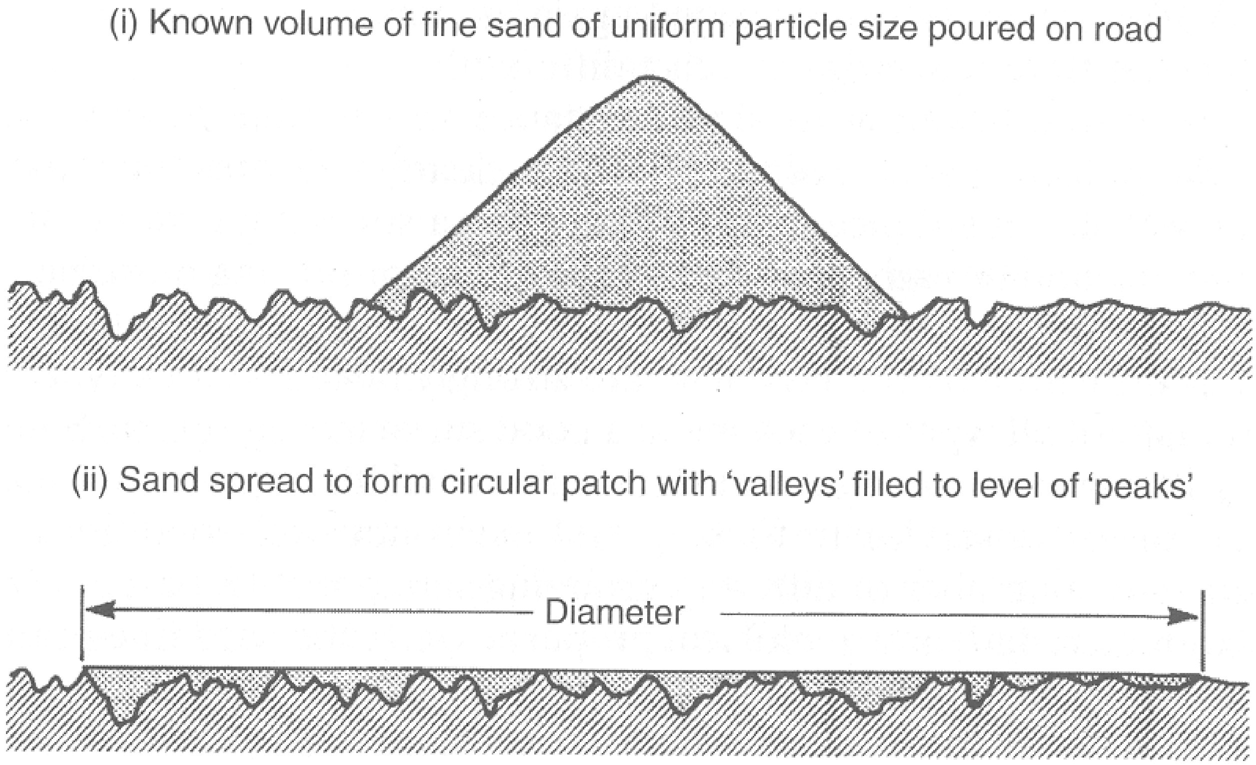


Figure 10: Measurement of macrotexture using a volumetric method (4).

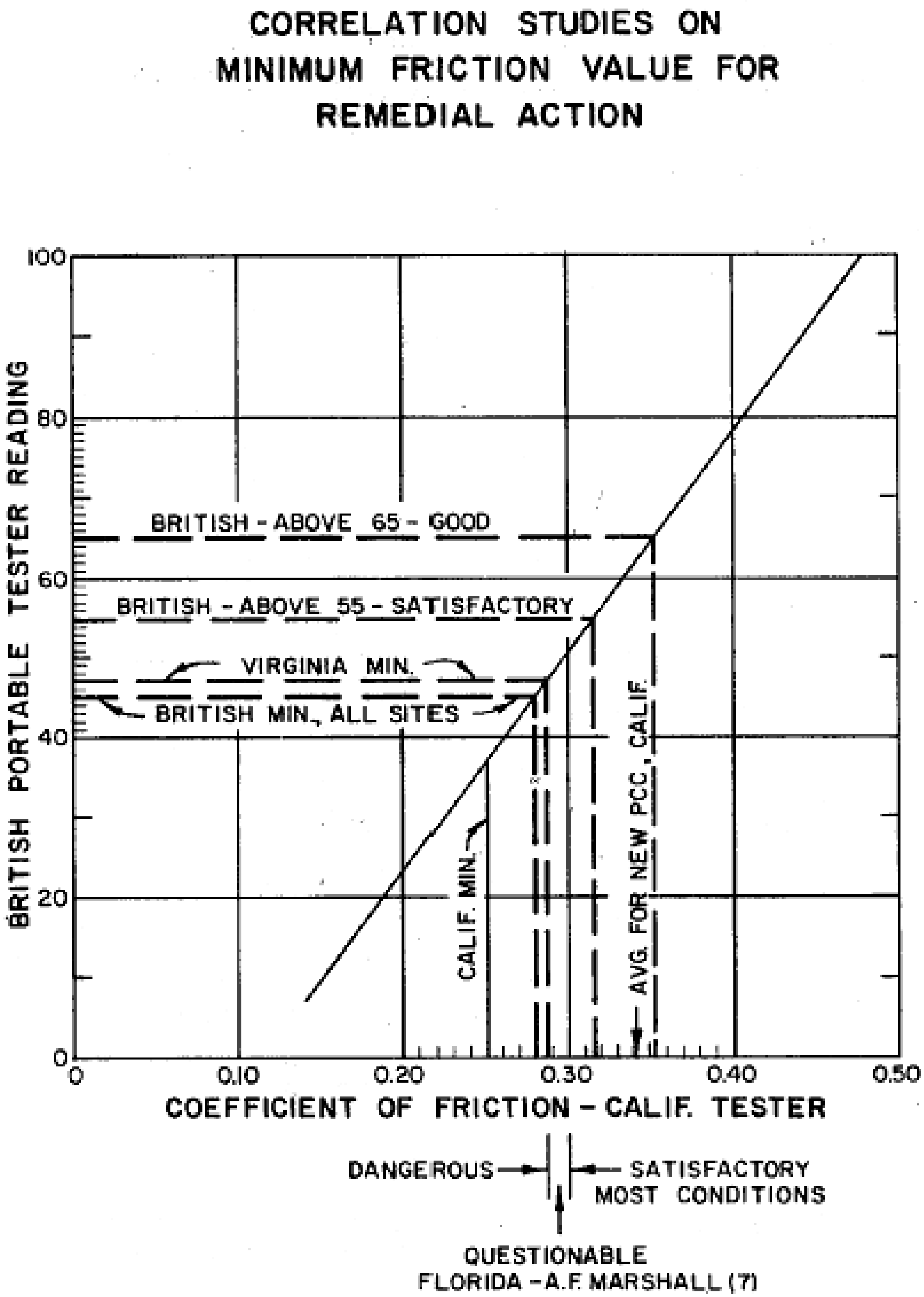


Figure 11: Correlation of California Skid Tester and British Portable Tester. ***(8)***

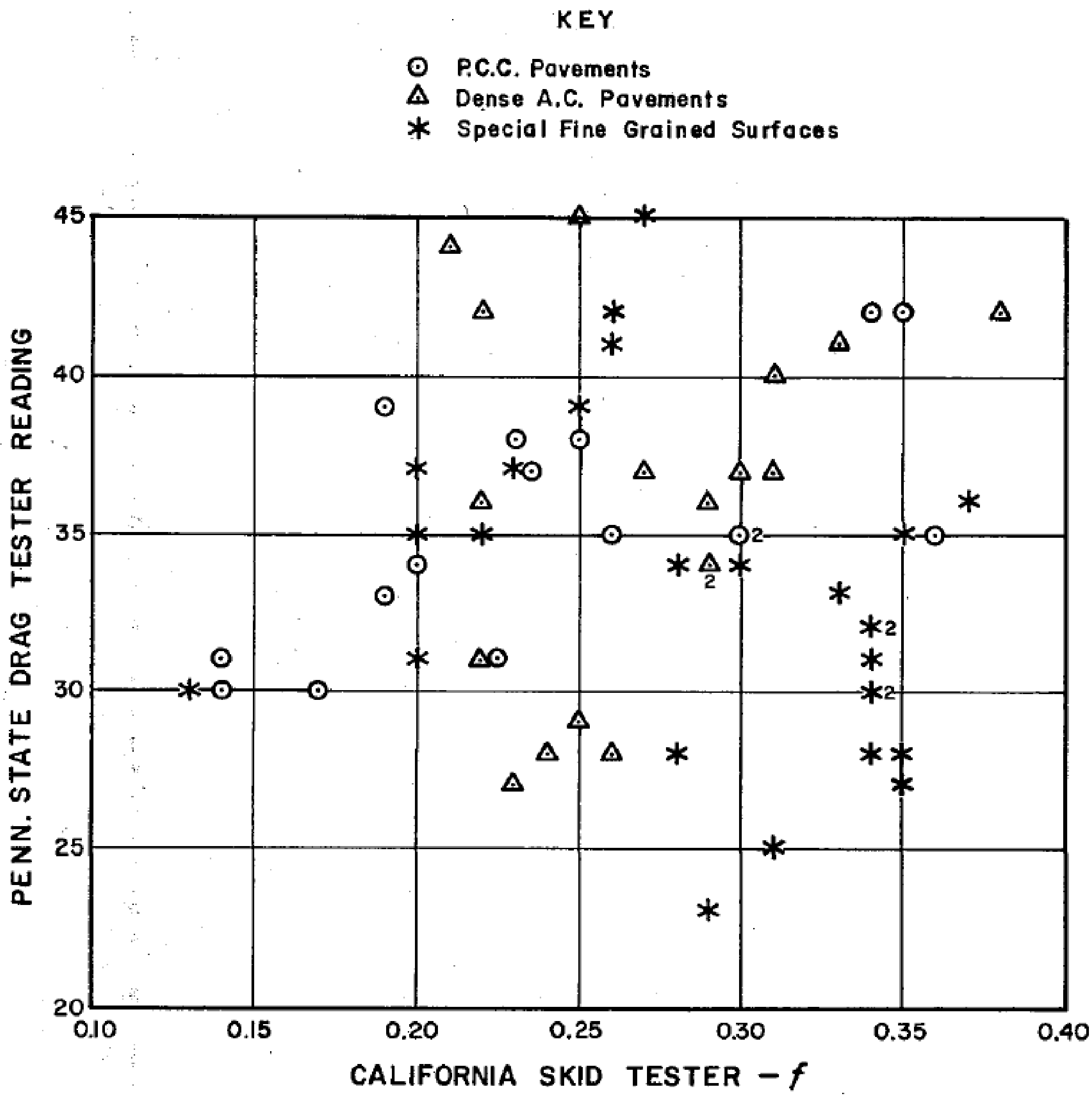


Figure 12: Correlation of California Skid Tester and Pennsylvania State Drag Skid Tester. ***(10)***

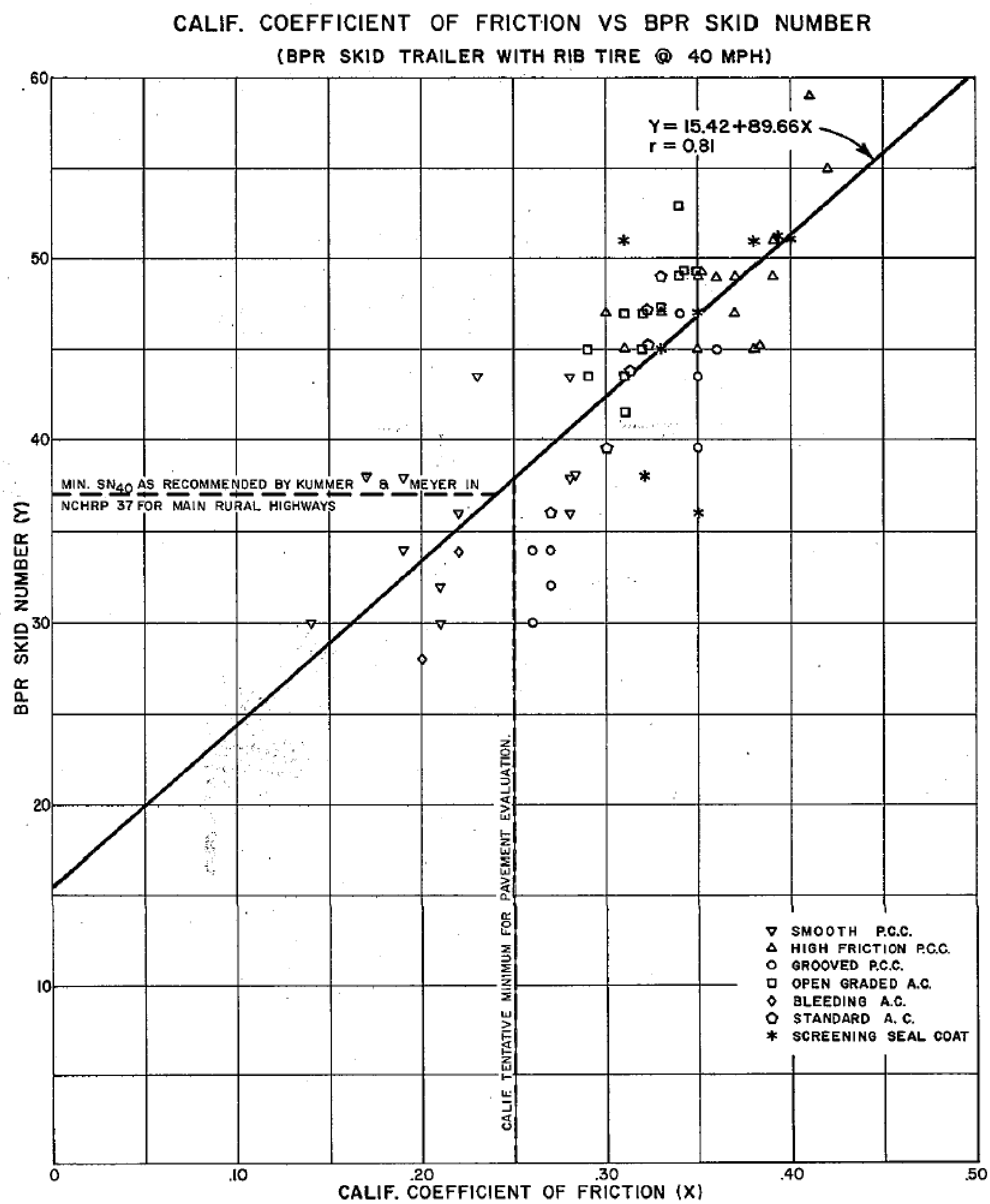


Figure 13: Correlation of California Skid Tester and U.S. Bureau of Public Roads Skid Trailer (BPR Skid Trailer with rib tire at 64 km/h). ***(11)***

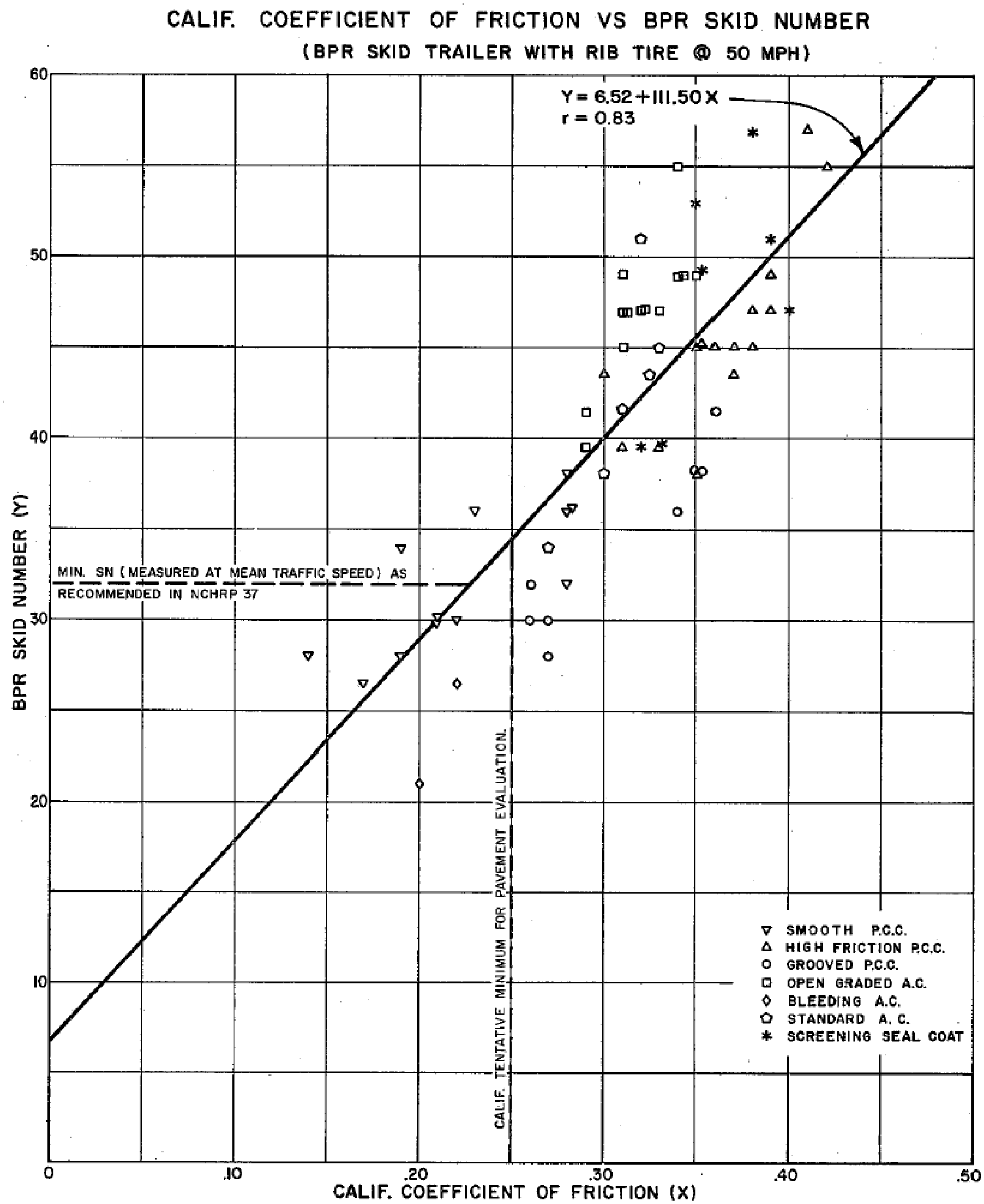


Figure 14: Correlation of California Skid Tester and U.S. Bureau of Public Roads Skid Trailer (BPR Skid Trailer with rib tire at 80 km/h). ***(11)***

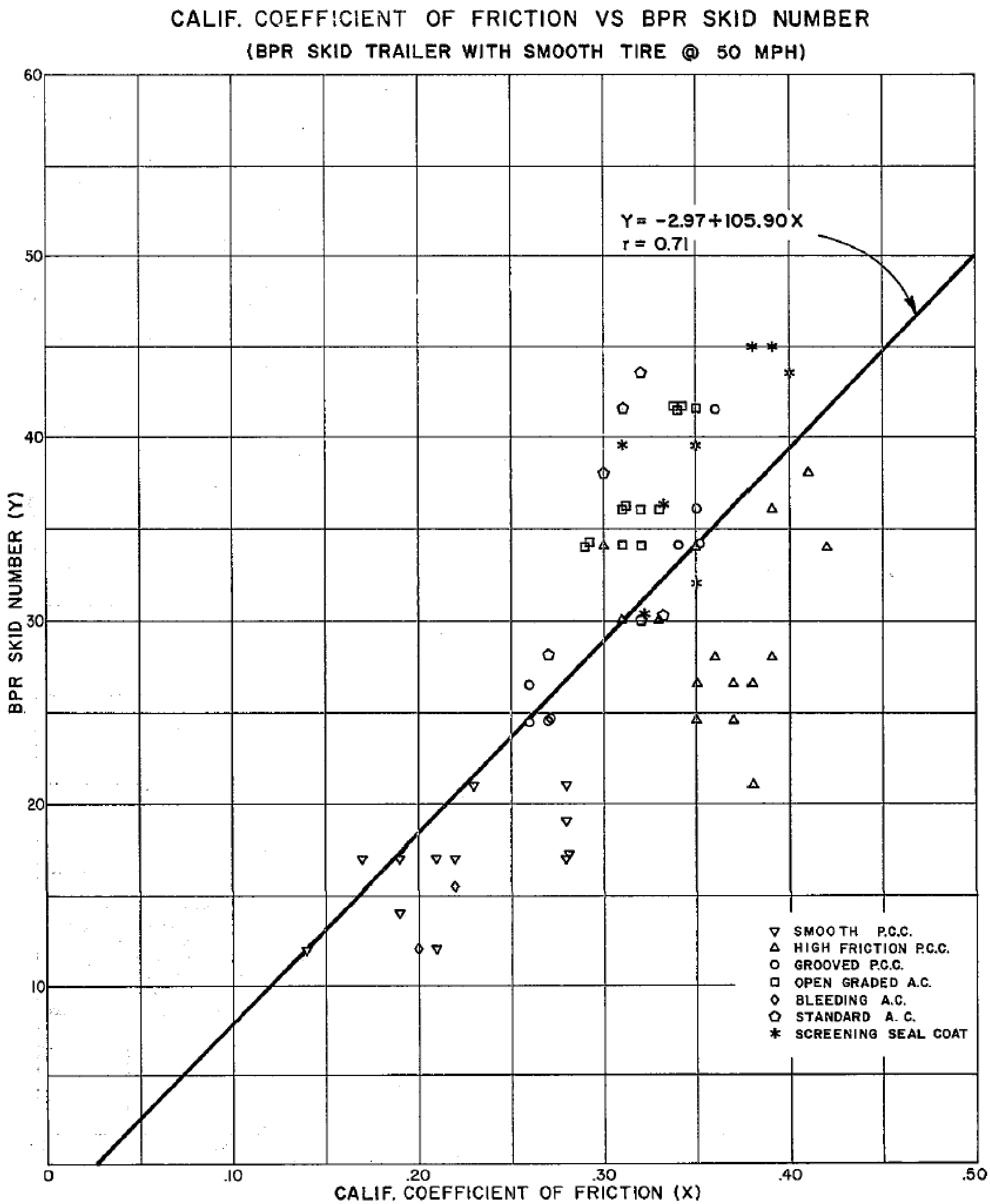


Figure 15: Correlation of California Skid Tester and U.S. Bureau of Public Roads Skid Trailer (BPR Skid Trailer with smooth tire at 80 km/h). ***(11)***

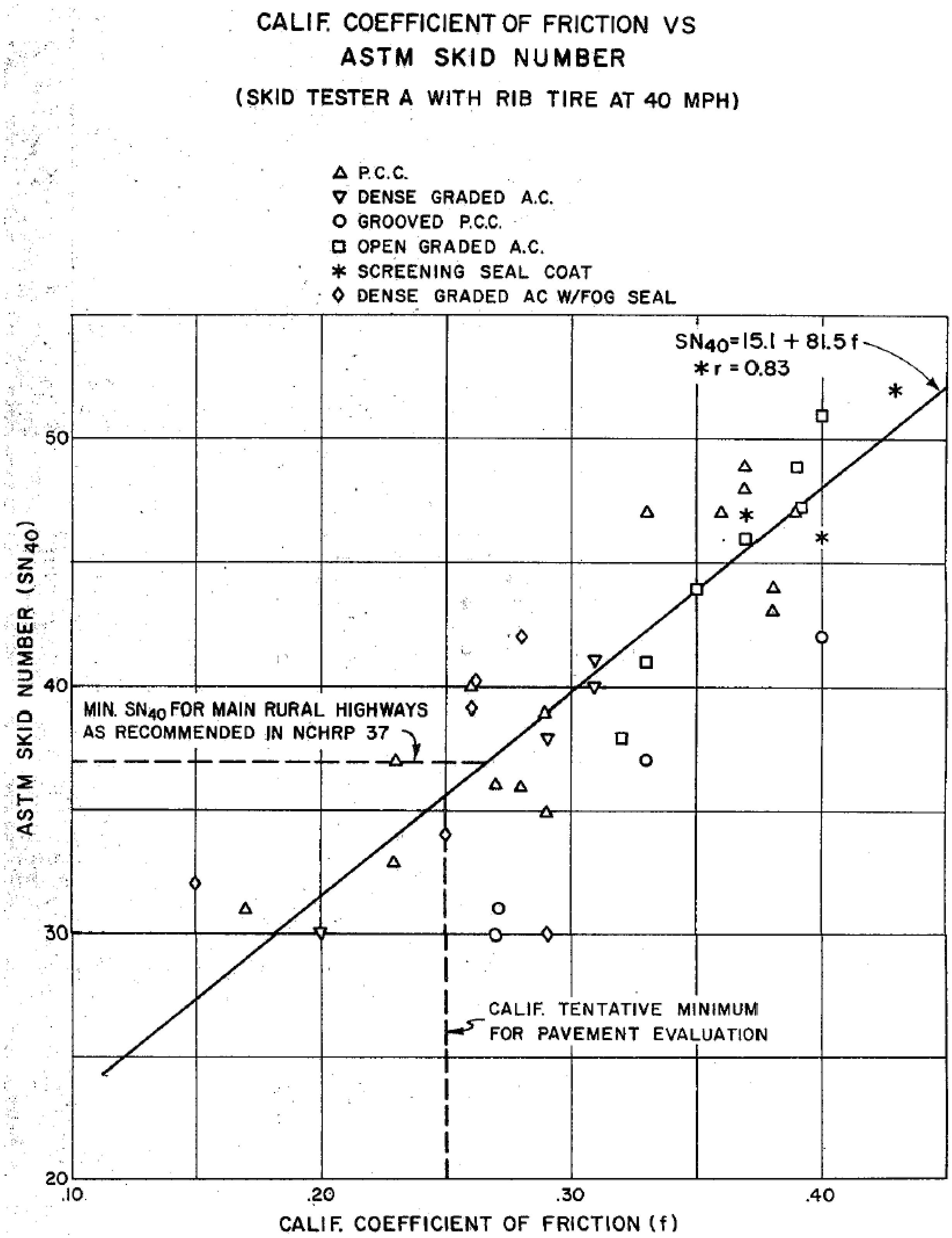


Figure 16: Correlation of California Skid Tester and ASTM E274 Skid Trailer (ASTM Skid Trailer with rib tire at 64 km/h). ***(13)***

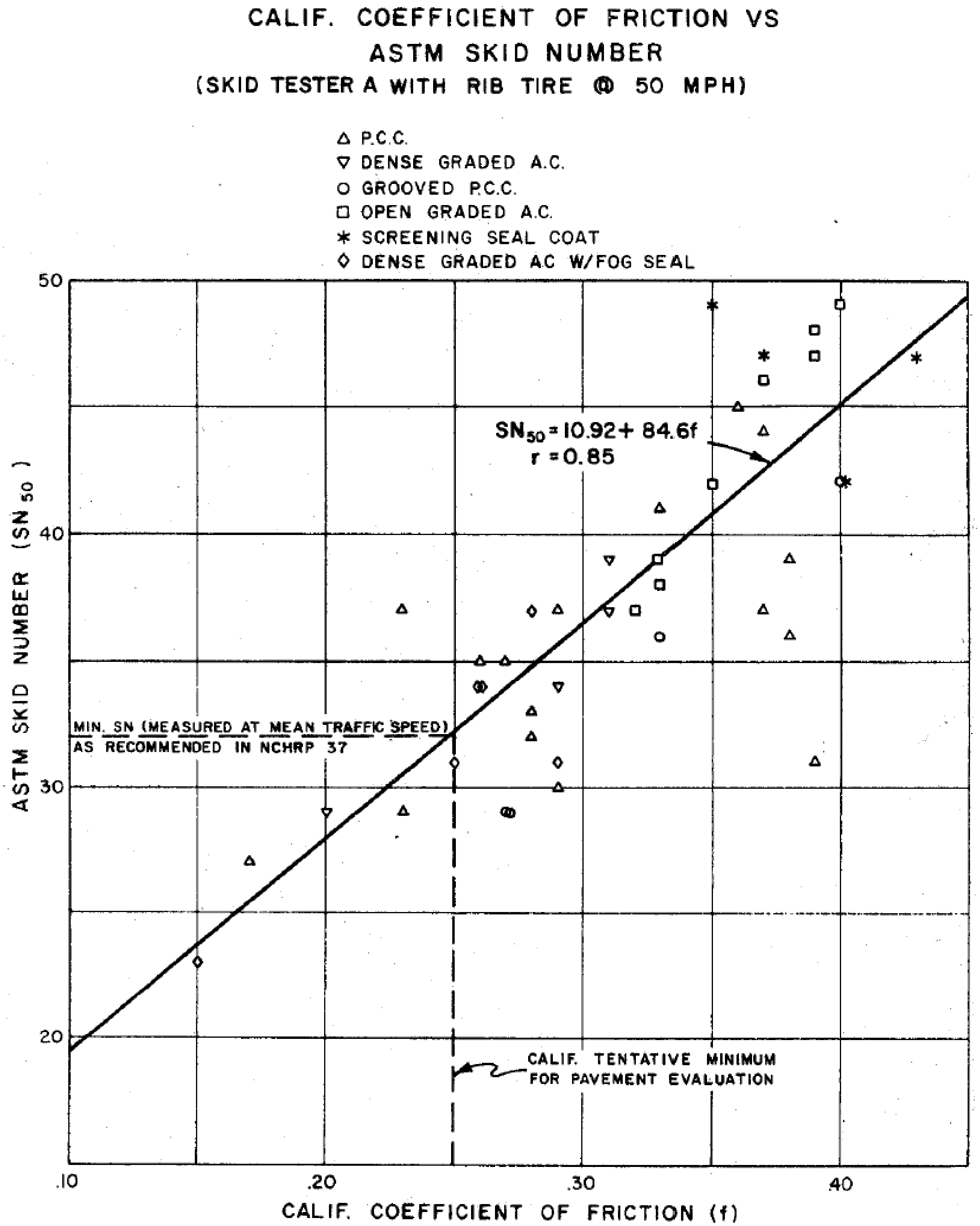


Figure 17: Correlation of California Skid Tester and ASTM E274 Skid Trailer (ASTM Skid Trailer with rib tire at 80 km/h). ***(13)***

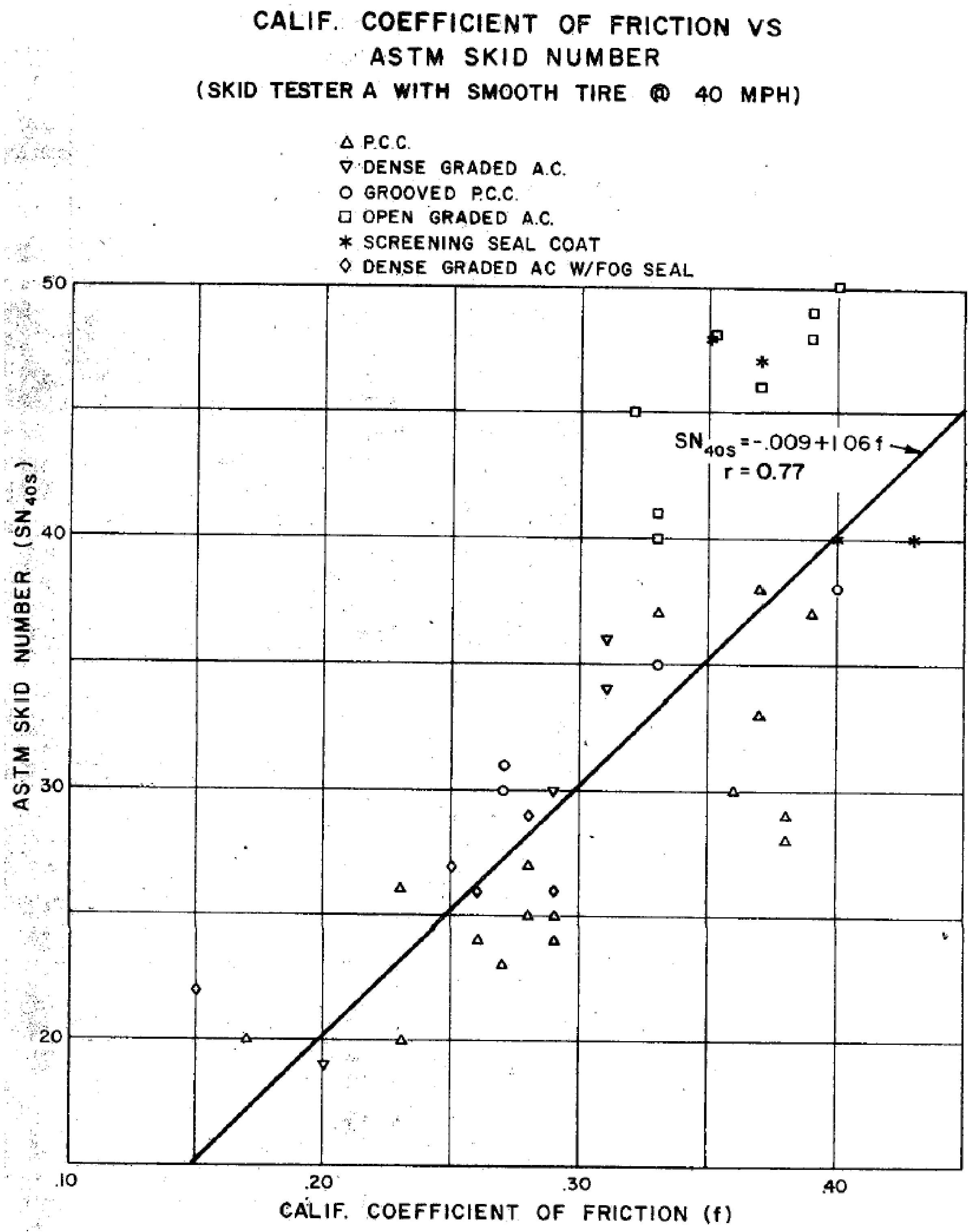


Figure 18: Correlation of California Skid Tester and ASTM E274 Skid Trailer (ASTM Skid Trailer with smooth tire at 64 km/h). ***(13)***

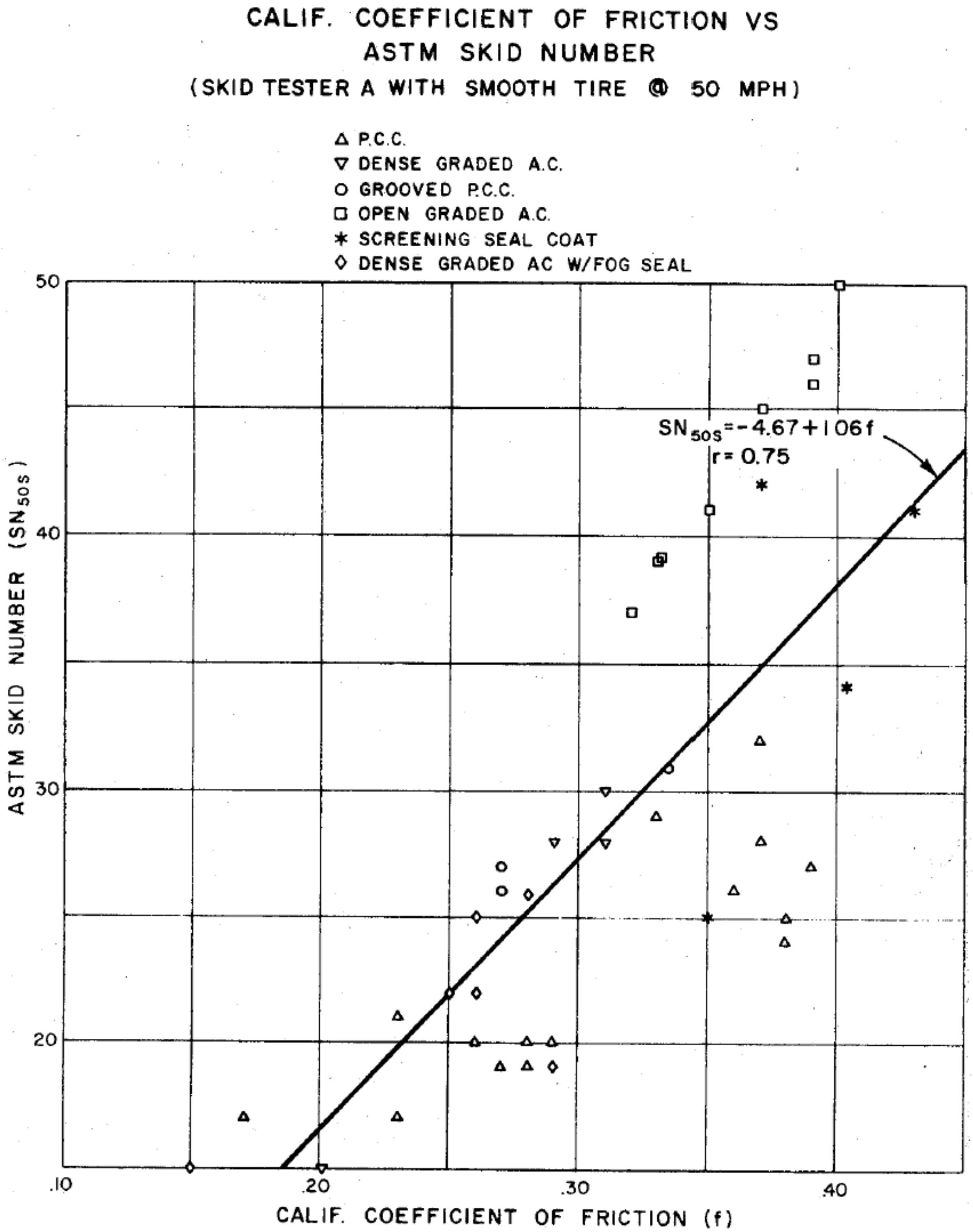


Figure 19: Correlation of California Skid Tester and ASTM E274 Skid Trailer (ASTM Skid Trailer with smooth tire at 80 km/h). ***(13)***

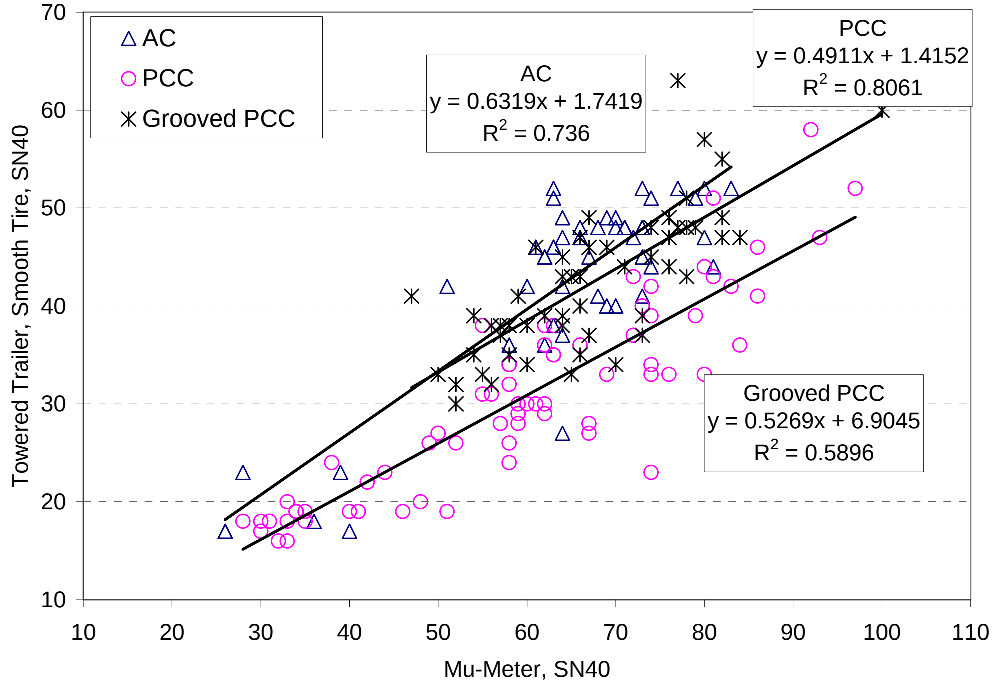


Figure 20: Correlation of California Skid Tester (smooth tire) and Arizona Mu-Meter (re-plot from data in Reference *14).*

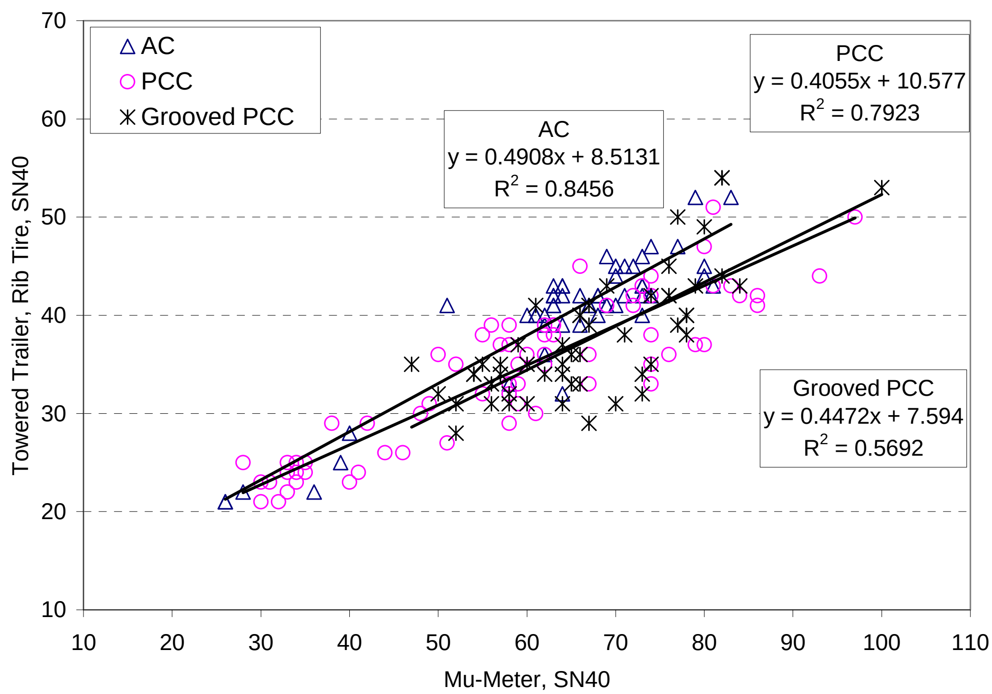


Figure 21: Correlation of California Skid Tester (rib tire) and Arizona Mu-Meter (re-plot from data in Reference *14).*

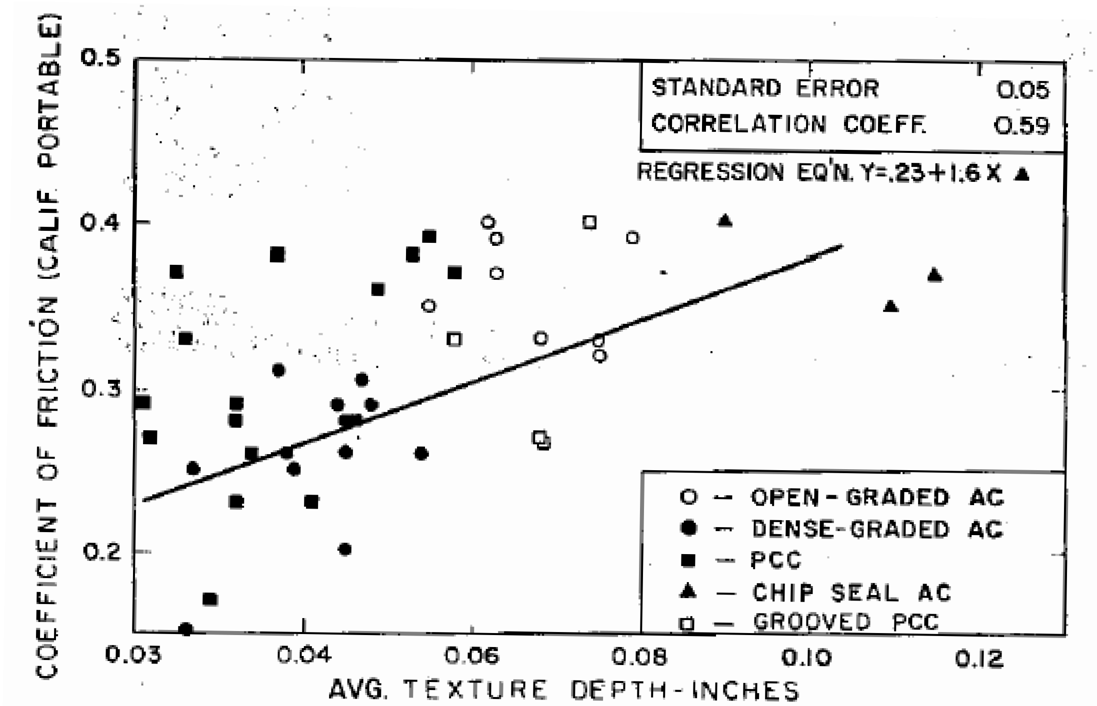


Figure 22: Correlation of coefficient of friction by California Skid Tester and Sand Patch texture depth. ***(15)***

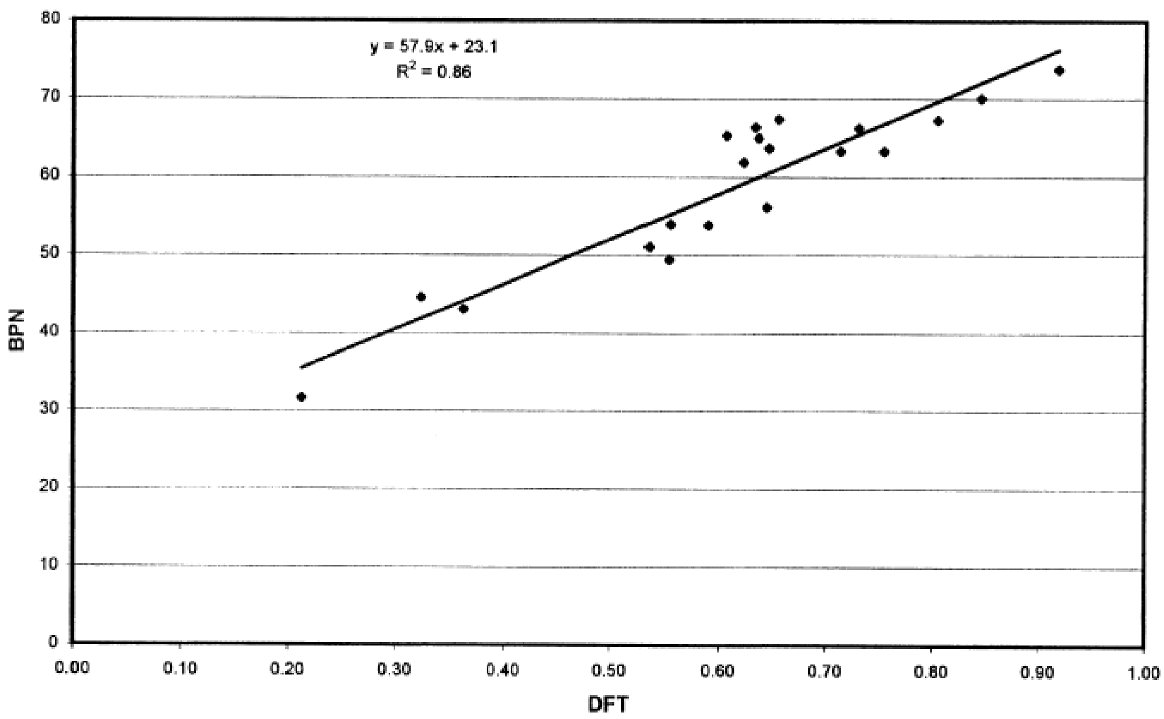
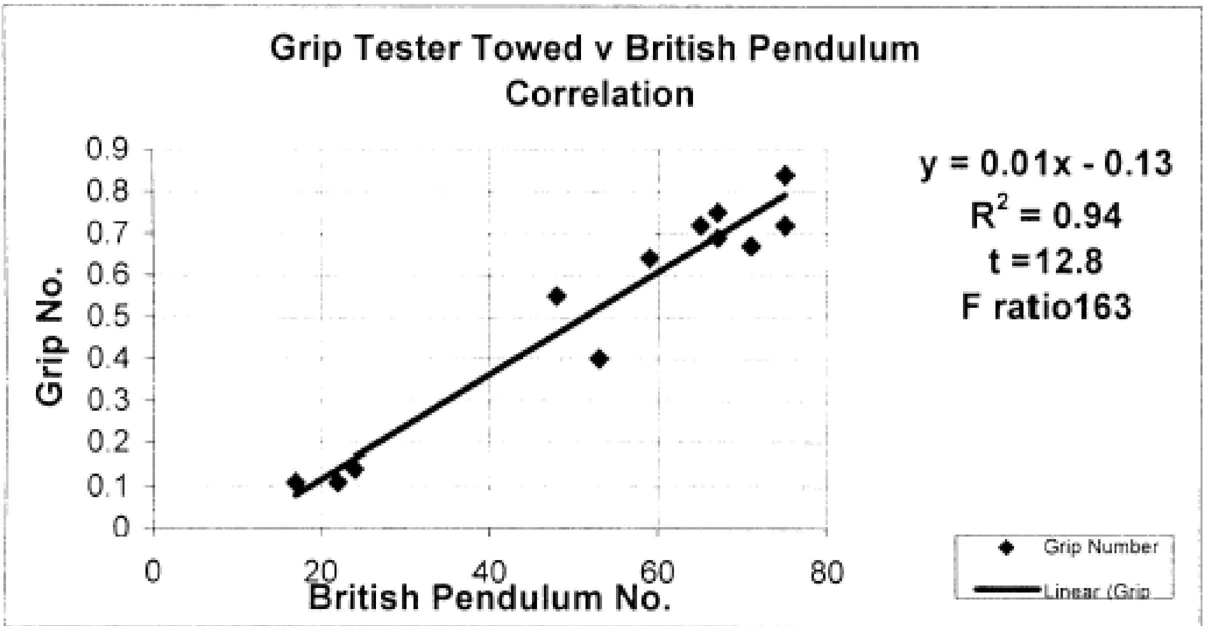
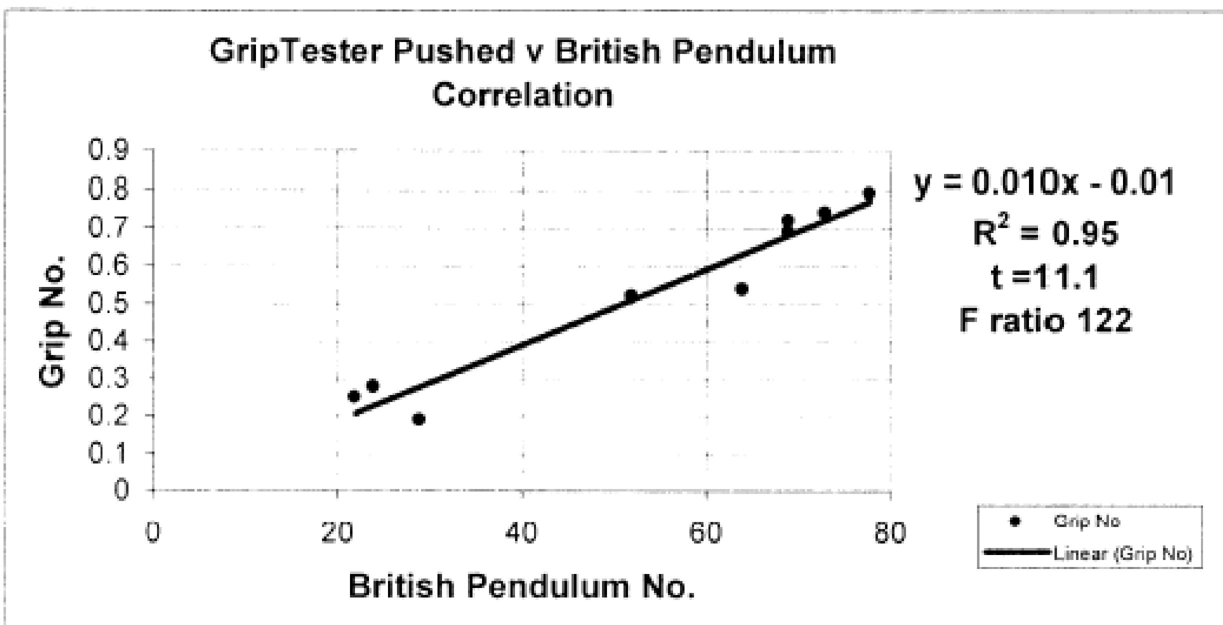


Figure 23: Correlation of British Pendulum Number to dynamic friction tester for sites at the NASA Wallops Flight Facility. ***(2)***



(a)



(b)

Figure 24. Correlation of British Pendulum Number to GripTester (a – towed, b – pushed). ***(16)***

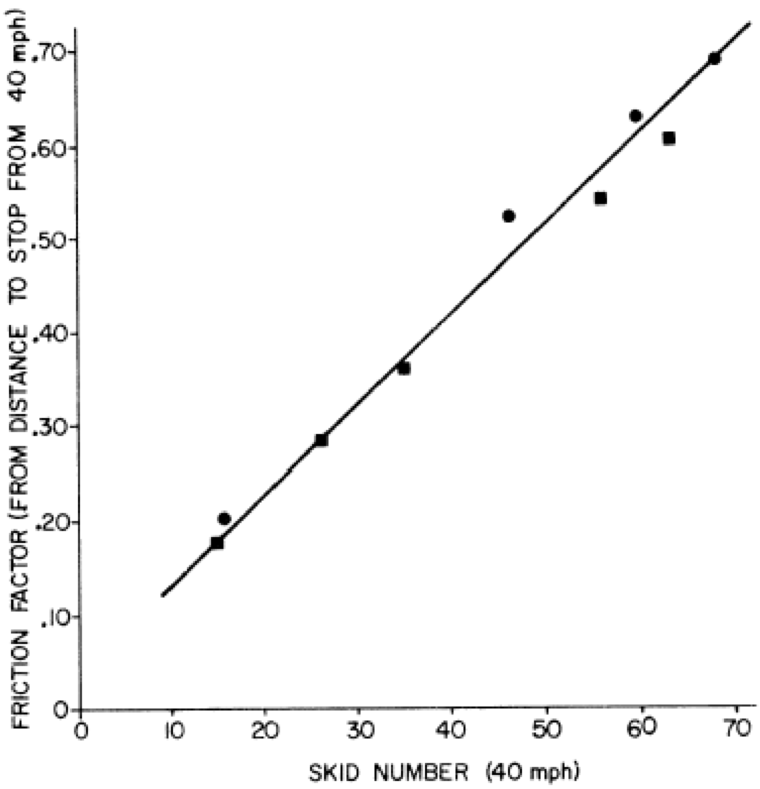


Figure 25: Correlation between stopping distance friction factor and skid number. ***(5)***

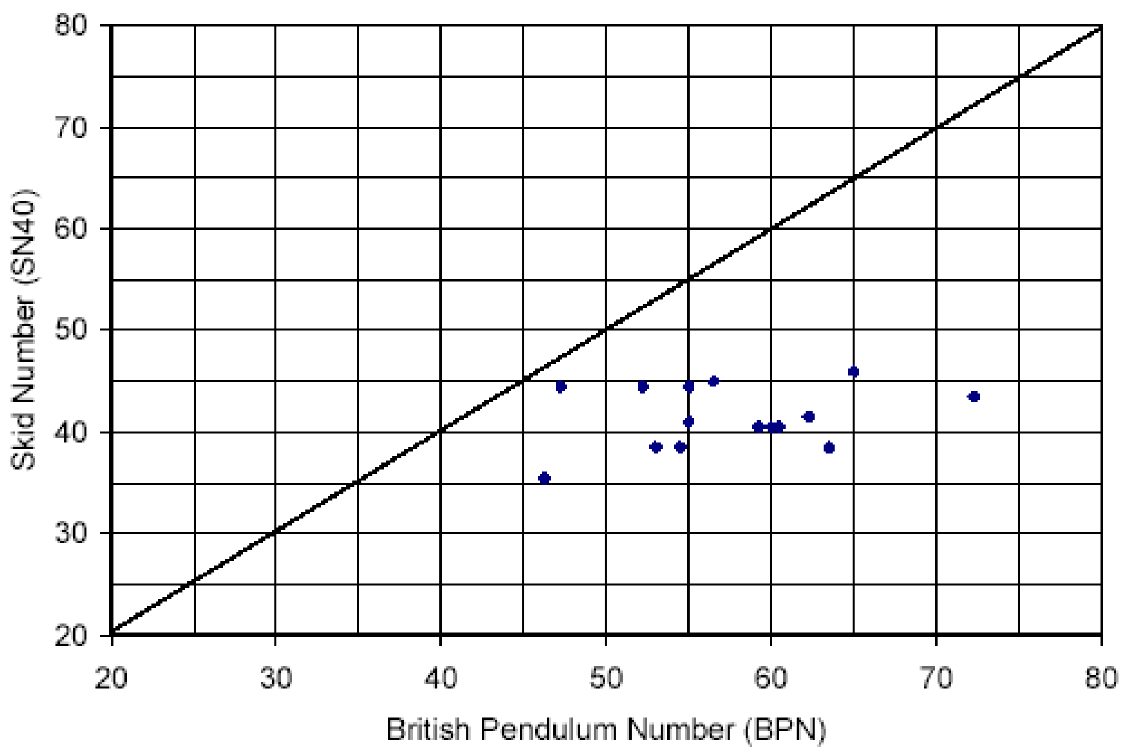


Figure 26: Relationship between SN40 and BPN measured on open-graded asphalt concrete pavements. ***(19)***

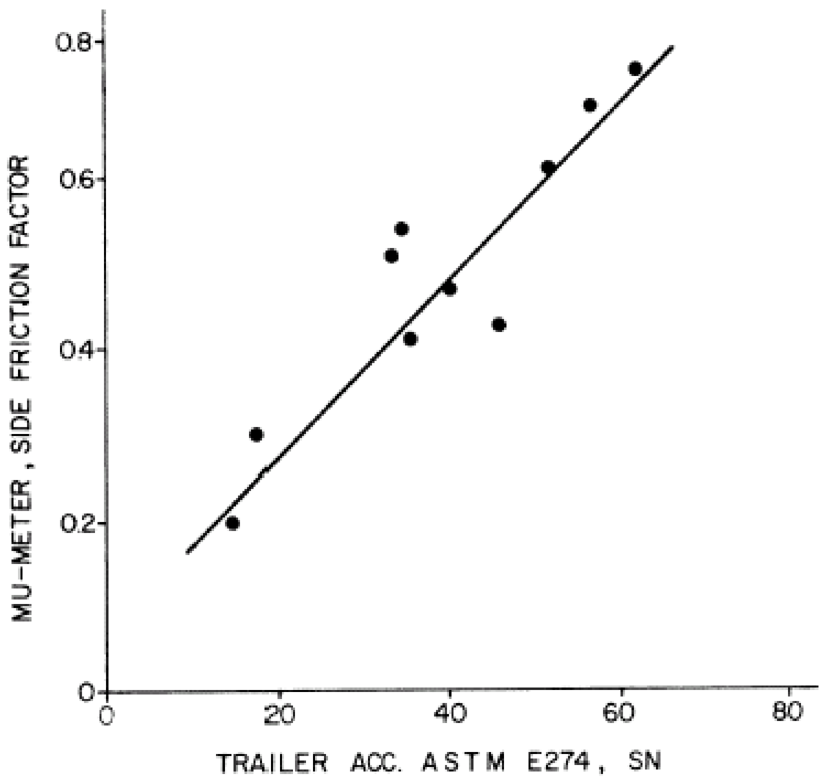


Figure 27: Correlation between Mu-Meter and trailer conforming to ASTM E274. ***(5)***

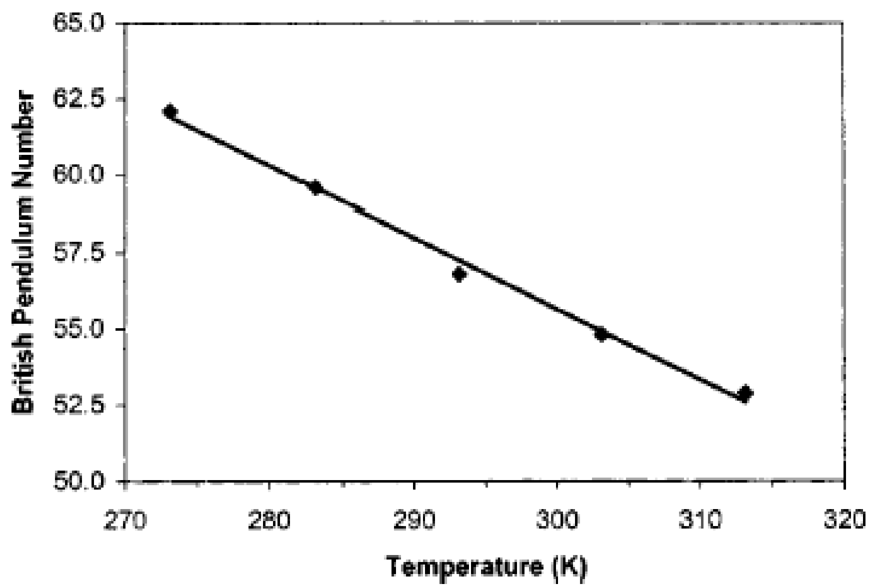


Figure 28: Linear regression fit to BPN versus temperature for ten study sites when specimens were intermediately polished. ***(23)***

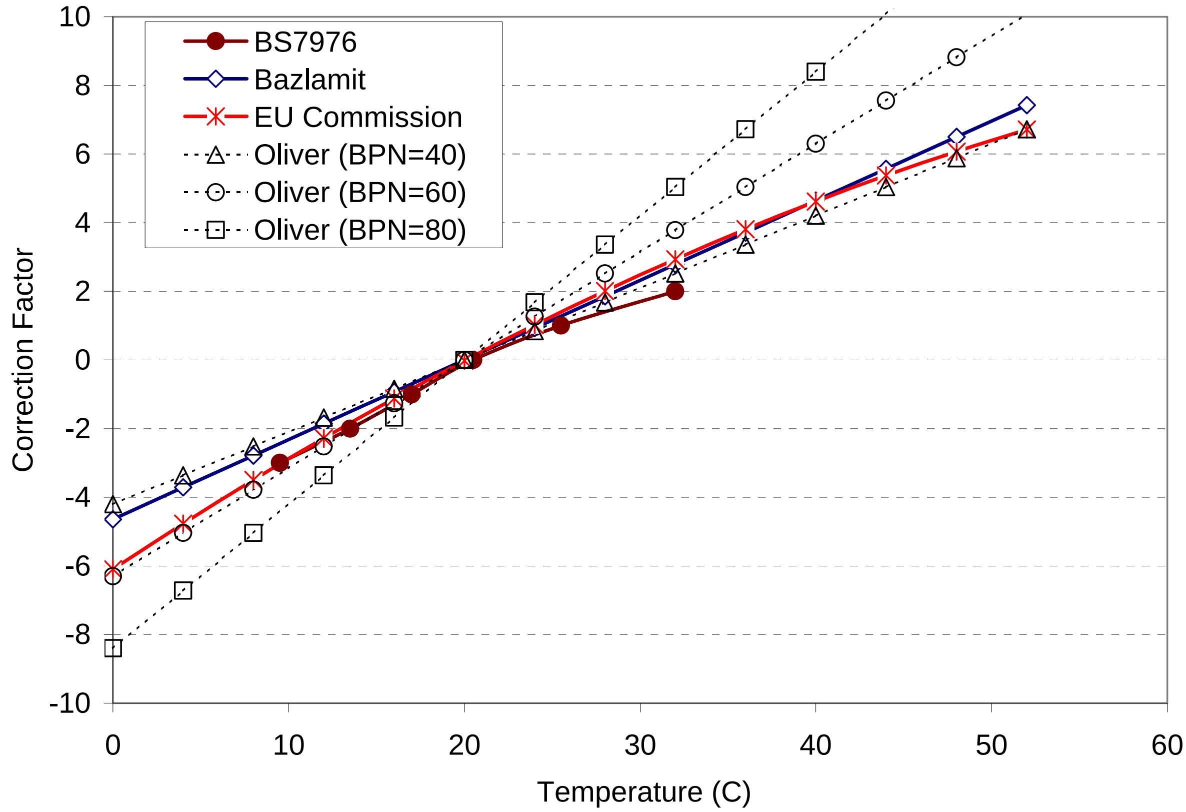


Figure 29: Temperature correction factors for British Pendulum Numbers suggested by different researchers.