TECH SPEC

NUMBER 13

Slip and Skid Resistance of Interlocking Concrete Pavements

Introduction

Slip resistance for pedestrians and skid resistance of tires on the road are important to safety in traversing walks and streets. While many variables influence slip and skid resistance, interlocking concrete pavements offer surface characteristics that provide resistance and added safety when compared to other pavement surfaces. This technical bulletin describes the slip and skid characteristics of concrete pavers and how they can be used to increase safety for pedestrians and drivers.

Slip Resistance for Pedestrians

A slip resistant surface is one that provides friction necessary to keep a shoe heel or crutch tip from slipping under a range of conditions. Many human and surface characteristics influence slip resistance. They encompass the texture of the surface, footwear, wetness, contamination of the surface, the speed and style of walking, running, turning sharply, going up or down a ramp or steps. In addition, the alertness of an individual to surface conditions, physical condition, and walking style, as well as the ability to adjust one's gait to varying surface conditions also influences slip resistance.

Slip resistance under dry conditions is approximated by measuring the static coefficient of friction, i.e., the horizontal force required to initiate sliding at the instant of motion divided by the static weight (gravity force). For example, a coefficient of friction of 0.7 means that seven tenths of the force holding an object in place will be necessary to initiate movement tangential to the surface on which it is resting. Figure 1 illustrates the definition of slip resistance. By comparison, the dynamic coefficient of friction is the ratio of horizontal to vertical forces when movement occurs at a constant velocity.

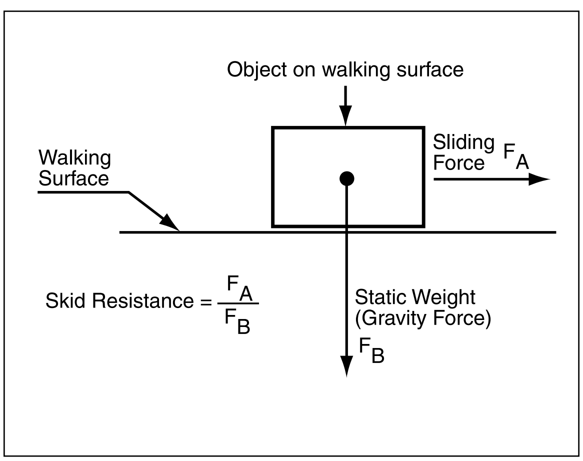

Figure 1. Definition of slip resistance

The static coefficient of friction is ideally measured with no time delay between the application of the sliding force against the gravity force. The sliding force can then be used to measure the slip resistance of wet surfaces. Strictly speaking, the slip resistance of a wet surface cannot be precisely equated to static coefficient of friction. In fact, a false friction force may develop. This is due to the development of adhesion when a measuring device such as a dragsled is placed upon a wet surface (even an instant before it is pulled). The force can often result in the anomalous result where the presence of water can actually improve measured slip resistance.

The Americans with Disabilities Act (ADA) was made U.S. law in 1990 to protect the civil rights of individuals with disabilities. The law provides protection to disabled persons at their place of employment (Title I), from state of local government services (Title II), from public accommodations (Title III), and with telecommunications (Title IV). Title II covers minimum design standards for transportation facilities and Title III covers standards for new construction, as well as alterations to public places and commercial facilities.

The U.S. Departments of Justice and Transportation have issued minimum design standards through the Americans with Disabilities Act Accessibility Guidelines (ADAAG). These guidelines for construction were developed by the U.S. Architectural and Transportation Barriers Compliance Board (ATBCB), also known as the Access Board. The guidelines are subject to periodic revisions and the latest version should be referenced when designing handicapped facilities.

Figure 2. The NIST-Brungraber Mark II tester for slip resistance

Section 302.1 of the 2010 *Standards for Accessible Design* states, "Floor and ground surfaces shall be stable, firm, and slip resistant and shall comply with 302" (1). This document gives no express value for slip resistance. Design and testing standards may be required by the Occupational Safety and Health Administration (OSHA) for workplace safety, by other federal, state, provincial, or local regulations.

Measuring Slip Resistance

There is no single established test method for measuring slip resistance. Devices that test slip resistance are called tribometers. Ideally, a tribometer will measure as "slippery" only those surfaces that pedestrians find "slippery." In pedestrian safety research, a "variable angle" tribometer is typically used; there are currently two manufacturers of these devices in the US. The "Mark II" and "Mark III" tribometers are made by Slip-Test in Atlanta, GA (www.slip-test.com, 770-671-0090), and the "English XL" tribometer is made by Excel Tribometers in Greer, SC (www.exceltribometers.com, 757-897-2853). In addition to sales, both of these firms can conduct slip resistance testing for customers. As an additional reference, the ASTM F13 Technical Committee publishes standards on pedestrian walkway safety (www.astm.org).

Slip Characteristics of Concrete Pavers

Concrete pavers can be made with or without surface treatments, and some may be sealed after installation. Treatments include high sand and cement content in the surface, or those with machine-polished surfaces. Others include stone-like textures made by shot-blasting, hammering, washing, or tumbling the surface. Regardless of the presence or absence of surface treatments/sealers, most concrete pavers can meet the agency or client recommendations for slip resistance. (Pavers with polished surfaces, however, may require testing since their surfaces can be as smooth as marble or other ground surfaces.) The manufactured, textured walking surfaces are typically consistent from paver to paver thus maintaining a high coefficient of friction. Therefore, there is generally not a need to test many paving units.

Should a need for testing arise, designers and purchasers may wish to verify the wet slip resistance of concrete pavers made by ICPI members for specific applications by having tribometer testing performed. In some cases, the slip resistance of concrete pavers may exceed the agency or client recommendations. In some applications they can contribute an additional measure of safety. Such areas can be any area that, when wet, can be a potential slipping hazard, especially for walking-impaired people, or those in wheel chairs. Some examples include crosswalks, ramps, or areas traversed by crutch users and those with artificial legs, and places crossed by wheel chairs including curb ramps at intersections.

Most concrete pavers are manufactured with chamfers on the edges of the wearing surface. The chamfers are small, typically 45° bevels, 4 or 6 mm wide, or they can be rounded. Should the units become vertically misaligned in service, the chamfers help provide a smooth transition from unit to unit, thereby reducing the tripping hazard. Like all pavement surfaces, extreme settlement or heaving can create dangerous tripping hazards and such areas should be repaired. Unlike asphalt and cast-in-place concrete, pavers that are vertically misaligned do not need to be discarded and replaced with a new surface. In most cases, the surface is not destroyed from cracking. Therefore, the concrete pavers can be removed, repairs made to the base, and the same units reinstated without waste or unsightly patches. For further information on reinstatement procedures, see *ICPI Tech Spec 7, Reinstatement of Interlocking Concrete Pavement*. Other ICPI Tech Specs should be consulted for advice on construction specifications, construction procedures, and on edge restraints.

Skid Resistance for Vehicles

Skid resistance is the resistance to motion between the pavement and vehicle tires. Pavement-tire friction is influenced by the following factors (2):

Pavement characteristics such as texture, roughness, and rutting

Pavement texture consists of microtexture and macrotexture. Macrotexture is defined as 0.2 in. (0.5 mm) or greater deviations in the surface (from a true planar surface) that affect tire-pavement interaction. A pavement with good macrotexture contributes to skid resistance of vehicles traveling over 25 mph (40 kph). Concrete pavers with chamfers offer a unique macrotexture that can benefit skid resistance at these speeds. Specifically, the chamfers form small drainage channels on the pavement surface to help disperse water under moving tires.

Microtexture is defined by smaller deviations in the surface, those less than 0.2 in. (0.5 mm). Microtexture is the primary influence on skid resistance of vehicle tires traveling less than 25 mph (40 kph). Microtexture varies with the hardness of the aggregate in concrete pavers. Harder aggregates are less likely to polish under concentrated braking or accelerating tires thus maintaining a high degree of variation in the texture of the surface.

In many cases, concrete pavers conforming to applicable American (ASTM) or Canadian (CSA) standards do not require special aggregates to maintain skid resistance equal to that of asphalt or PCC pavement surfaces. Like other paving materials, selection of aggregates (hardness, sharpness) and surface texture can be controlled in the mix design and manufacturing process for concrete pavers. Should the need arise for special aggregates with high skid-resistant properties, laboratory research on a range of aggregates has provided some criteria for selecting aggregates with high skid resistance (3) (4) for conventional pavements. These can apply to concrete pavers. The criteria include the following:

- Results of petrographic analysis that show hard minerals combined with some softer minerals.
- Angular and large mineral grains in the individual aggregate particles.
- Aggregates with a high range of hardness as measured by the Mohs' scale.
- Sand-sized and total insoluble residue in carbonate aggregates when subjected to acid-solubility tests.
- Resistance to wear in jar mill abrasion tests, small, laboratory circular test tracks, and relating these results to laboratory skid tests on sample pavements.

Roughness is described as large deviations in pavement surface, most of which affect ride comfort and dynamics of the vehicle. A rough pavement can cause the wheels to bounce and this can reduce friction. Rutting in wheel paths also reduces friction, especially when they fill with water from rainfall.

Tire characteristics including tire type, tire tread, and inflation pressure

Tire design and rubber formulations are often a trade-off between wearing and frictional characteristics. Harder rubber tires wear longer but do not offer the same frictional performance as softer rubber. Deep-treaded tires offer better frictional characteristics because they disperse more water. This is especially important at high speeds where the time for dispersing water from under tires is very short. Excess or low tire inflation pressure also can decrease the skid resistance.

Vehicle operational characteristics such as speed, tire slip, axle load, and the type of vehicle.

Speed of the vehicle is one of the dominant factors in skid resistance. As speed increases, the amount of time to disperse water decreases and water on the pavement has a lubricating effect. When the brakes are applied, the velocity of tires decrease. If a tire's velocity decreases at a rate higher than the vehicle's velocity, the tires will slip on the pavement surface. When the brakes lock, the slipping becomes skidding. Anti-lock brake systems (ABS) are designed to balance the speed of the tires with that of the vehicle during braking, thereby preventing skidding and reducing slipping.

Tire-pavement friction generally decreases as axle load increases and trucks generally have a lower coefficient of friction than passenger cars. This is due to differences in tire compounds and hardness, and the higher temperatures at which truck tires operate.

Environmental factors involving wetness, ice and snow, contamination, and temperature

Engineers and road safety officials are most interested in the skid performance of pavement when it is wet since there is a dramatic difference between wet and dry skid characteristics. A pavement does not have to be completely flooded to realize a decrease in skid resistance. A film of water as thin as 0.002 in. (0.05 mm) can substantially decrease skid resistance. Ice, snow, and contamination (mud, oil, gravel, etc.) are all obvious contributors to the loss of skid resistance. Skid resistance decreases as ambient air and tire temperatures rise.

When considering road safety, pavement skid resistance is one of several factors, all of which may contribute to skid-related accidents, near misses, and ultimately characterize a pavement as safe or unsafe. Others influences on pavement skid resistance include:

- Traffic characteristics such as average daily traffic, posted speed, and the percent of trucks in the traffic mix;
- Curves and slopes in the road; and
- Driving difficulty such as the number of turning lanes, access points, traffic signals, and surrounding land use.

Skid resistance is one of many factors influencing agency decisions on when to resurface or reconstruct a road. The age, traffic, a rough ride due to settlement and rutting, and citizen complaints are some other factors. Each agency has its own decision criteria for pavement maintenance and rehabilitation.

Measuring Pavement Skid Resistance

There are two approaches to measuring skid resistance; static and dynamic. Static measuring devices measure resistance while moving across a small portion of the pavement. They do not involve the use of a tire. Dynamic devices make measurements with a tire while moving at a con-

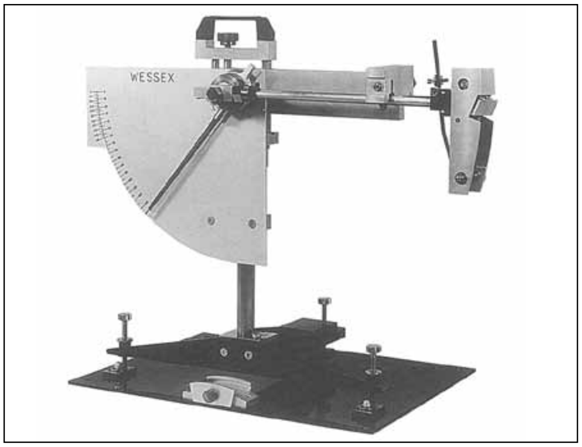

Figure 3. A British Pendulum Tester

stant velocity across the pavement surface. A common device used for static measurement is the portable British Pendulum Tester. See Figure 3. This test method is described in ASTM E 303, *Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester* (5). This device is used for laboratory or on-site testing of skid resistance on surfaces. It consists of a small rubber shoe at the end of spring-loaded pendulum. The tester measures frictional resistance between the rubber shoe and the point of contact with the pavement. The contact area of the shoe against the test surface is about 3 in.^{2} (19 cm^2), so measurements are influenced only by microtexture of the surface.

To perform a test, the test surface is wetted, the pendulum is pulled back, and the shoe rubs across the surface. Friction resistance is read on a scale on the machine as the British Pendulum Number or BPN. A BPN rating between 45 and 55 indicates a satisfactory surface in only favorable weather and vehicle conditions. A rating of 55 or greater indicates a generally acceptable skid resistance in all but the most severe weather conditions. A 65 and above rating indicates a good to excellent skid resistance in all conditions.

The BPN correlates with the performance of a vehicle braking with locked wheels on a wet pavement stopping from 30 mph (50 kph). The tester is not designed to give ratings above 30 mph (50 kph) and results do not readily correlate to results from full-scale dynamic tests using a tire and trailer. The BPN test generally gives higher skid resistance ratings than dynamic tire and trailer tests.

Most dynamic skid resistance measurement methods assess the interaction between a pavement and a locked, non-rotating tire. These test methods employ a standard-sized tire towed in a wheeled device behind a vehicle. A standard amount of water is applied ahead of the tire while moving, the tire is locked while the vehicle maintains a constant speed and the resistance between the tire and the wet pavement is measured. Some dynamic skid testing devices include the Stradograph, the Sideways Force Coefficient Routine Investigation Machine (SCRIM) (8), and the Mu Meter (7).

In the North America, 40 state and provincial agencies use the test procedure described in ASTM E 274, *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire* (8). Figure 4 illustrates the equipment. This test uses a standard test tire towed in a device behind a vehicle. A standard amount of water is applied ahead of the tire while moving, the tire is locked while the vehicle maintains a constant speed, usually 40 mph (65 kph), and the resistance between the tire and the wet pavement is measured. The force required to slide the tire is divided by the wheel load and multiplied by 100. The results are expressed as a skid number (SN) or friction number (FN).

Skid resistance measurements on asphalt pavements will vary with the time of year and weather. Since much skid data has been collected over the years for asphalt pavement, normalization procedures are used to eliminate influences of the season and weather. Weather and seasonal influences on portland cement concrete (PCC) pavements produce less predictable results in skid testing. Therefore, no normalization procedures yet exist for PCC pavements.

Skid Resistance Values for Interlocking Concrete Pavements

A review of the literature on skid resistance of concrete pavers shows their skid resistance to be equal or better than asphalt. Most indicate that, subject to the proper mix design and manufacturing controls, concrete pavers can maintain good skid resistance values throughout the life of the pavement. Studies of static skid resistance by different researchers in various countries used the British Pendulum Tester to assess new and trafficked concrete pavers. A summary of test results follows:

- Shackel (9) measured a bus route in Durban, South Africa after 17 years of traffic. BPN values averaged 61 with a standard deviation of 4.3.
- Clifford (10) conducted numerous tests at various locations in South Africa for the National Institute of Road Research. These tests included the locations and results listed in Table 1.
- Mavin (11)(12) measured BPNs in Melbourne, Australia, at 3 parking lots and on a quarry access

Figure 4. ASTM E 274 Test Equipment consists of a truck and trailer assembly. A tire within the trailer is towed at a given speed, locked, and skidded across water dispensed on the pavement in front of it.

road that received high truck traffic. BPNs on the new parking lots averaged 81 and declined to 53 with over three years of use. While BPNs for new concrete pavers dropped after use in the parking lots, the values did not fall below accepted standards. The 80kN Equivalent Single Axle (ESA) loads on the quarry road ranged from 0 to 150,000 over three years and BPNs increased from 45 initially to 62-65 at 75,000 to 150,000 ESAs.

- Muira et al. (13) compared the performance of concrete pavers to asphalt put into service at the same time in a lightly trafficked street in Japan. After 12 months of service, BPNs for both the concrete pavers and the asphalt were 56-59.
- Sharp and Armstrong (14) showed that concrete pavers at a full-scale test track in Australia had an initial BPN of 70 and progressively decreased after installation and reached a minimum value of 57 after 460 ESAs.
- Garrett and Walsh (15) tested an experimental access road leading to a industrial park and freight facility near Maidstone, England. After one year of testing pavers made by eight different manufacturers, results showed BPNs between 44 and 56. These values were considered above those for county roads with similar traffic and risk levels.
- Lesko (16) performed tests on 7 different areas of concrete pavers in a climbing lane with a 5% slope on a highway in Denmark. Initial BPNs ranged between 65 and 70 with values measured two years later between 49 and 60.
- Domenichini et al. (17) recorded BPNs on an 11-year old, 830 ft (253 m) long street with a 8% to 10% slope in the center of Recoara Terme, a small town in northern Italy. The average daily traffic was 1,230 vehicles in both directions with approximately 4% commercial trucks and buses. Test results indicated BPNs of 49 on concrete pavers located in the wheel tracks and 69 outside the trafficked areas. The study noted that European standards for interlocking concrete pavers recommends a minimum surface BPN of 45.

Table 1–BPN Results by Clifford (10)

Location	BPN Range
1-year old city vehicle maintenance yard	48-61
8-year old residential pavement	54-59
20-year old residential pavements	41-55
5-year old access road to wind tunnel test facility	48-72
3-year old loading and servicing area next to government buildings	52-57
3 to 8-year old main and secondary roads at botanical gardens	45-85

Table 2–SCRIM Tests by Clifford (10)

Location	Average*	Range
1-year old city vehicle maintenance yard	63-71	25-85
5-year old Access road to wind tunnel test facility	62-77	45-85
3 to 8-year old main and secondary roads at botanical gardens	68-72	35-85

*Averages of measurements taken at several locations within the site

The first dynamic testing on concrete pavers was by Lesko (16) at 20, 60, and 80 kph using a Stradograph, a towed, treadless tire pitched at an oblique angle and locked while riding on wet pavement. Test results on 7 different (wet) concrete paver road sections over two years at these speeds showed values did not fall below 0.40 which is considered a satisfactory value for skid resistance.

The SCRIM device was used by Clifford (10) on concrete pavers at three of the sites as part of the aforementioned study that involved a British Pendulum Tester. SCRIM tests are typically at 50 kph or 80 kph using a treadless tire mounted on a vehicle at 20° to the line of travel. The vehicle applies water in front of the loaded test wheel and the side force friction on the tire is measured.

Tests by Clifford with the SCRIM device were conducted at 50 kph. In South Africa, the SCRIM target value for collector roads is 0.45; for arterial roads, 0.50; and for thoroughfares, 0.55. Results in Table 2 show a range from 0.25 to 0.85 with averages between 0.71 and 0.35.

The Interlocking Concrete Pavement Institute (ICPI) engaged The PennsylvaniaTransportation Institute (PTI) to conduct skid measurements on two sections of new interlocking concrete pavement (18). Each section was 2 ft (0.6 m) wide by 150 ft (45 m) long and laid in a 90° herringbone pattern. See Figures 5 and 6.

Five skid resistance measurements were performed at three speeds; 25, 40 and 50 mph (40, 65, and 80 kph) using the test method described in ASTM E 274. The test used a standard grooved test tire described in ASTM E 501, *Standard Specification for Standard Tire for Pavement Skid Resistance Tests* (19). Tests were conducted in October 1997. The average results from the two sections are shown in Table 3. These are expressed as Skid Numbers (SN).

Skid Resistance Requirements

Some states and provinces have minimum skid resistance requirements in construction specifications for new pavements. These help ensure that the new pavement meets certain texture requirements before opening them to traffic. These requirements will vary based on the type of highway pavement, available materials and construction methods.

For testing in-service pavements, some consistency exists among highway agencies on test methods. Many use

Figure 5. The test track section and concrete paver surface at The Pennsylvania Transportation Institute test facility.

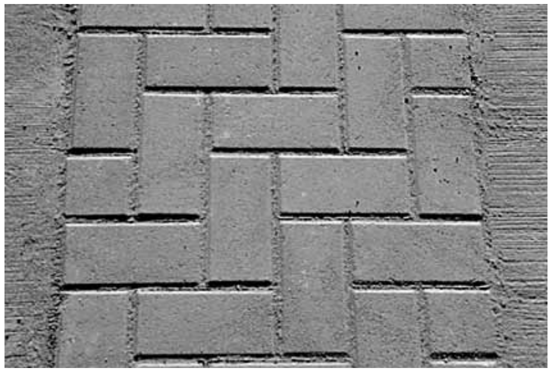

Figure 6. A close-up of the concrete paver surface at the PTI test track.

the ASTM E 274 test method; other states and provinces use the Mu Meter, or have developed their own tire and trailer equipment to derive a skid coefficient or 'f' value. In most cases, the results from these test methods can be correlated to results using the ASTM E 274 test method.

Since test methods and traffic speeds vary over a wide range of conditions, no universal, minimum standard for skid resistance has been established. Typically, pavement engineers utilize the skid number measured using test method ASTM E 274 at 40 mph (65 kph) (i.e., SN_{40}) as a reference value. Some researchers have attempted to define minimum skid requirements at certain speeds, on types of roads, and in particular regions. These can be used as overall guidelines rather than strict requirements when comparing skid resistance of conventional surfaces to interlocking concrete pavements.

One study for roads in Virginia (20) suggested a minimum SN_{40} of 30 for interstate and other divided highways, and a minimum SN_{40} of 40 for two-lane highways. Another study by the National Cooperative Highway Research Project (NCHRP) in 1967 (21) recommended minimum skid numbers for main rural highways. Table 4 shows the minimum skid numbers at various traffic speeds, and those measured at 40 mph (65 kph) on roads with various traffic speeds. The test results on new interlocking concrete pavement test at PTI indicate skid values well above those regarded by engineers as the minimum, and by the studies in references 20 and 21.

Reducing Traffic Accidents with Concrete Pavers

An important study in Japan demonstrates the ability of interlocking concrete pavements to reduce accidents and increase safety at intersections (22). Accidents were monitored over 12 months and vehicle braking distances were measured with a high-speed video camera at an asphalt-paved intersection in Ichihara City. Daily traffic volumes on each street from 7:00 a.m. to 7:00 p.m. ranged between 3,479 and 7,119 vehicles.

After 6 months of monitoring traffic volume and accidents, the asphalt within and on the approaches to the intersection was removed and replaced with concrete pavers. The change in pavement surface reduced the number of accidents by nine from December to May compared accidents counted in the previous June to November period.

The concrete pavers also reduced braking distances. A light-duty van was tested with three drivers on wet and dry conditions stopping from 20, 40, and 60 kph. Stopping distances were shorter on the concrete pavers and the greatest improvement was a reduction of 5 m (16 ft.) at 60 kph as shown in Table 5. The contribution of the chamfers in the surface of the concrete pavers towards dispersing water may explain the reduction in stopping distances at this speed.

Skid Resistance of Aircraft Pavements

Since 1983, over 12 million ft² (1.2 million m²) of interlocking concrete pavements have been used in airfield applications. Tests conducted by airports and the U.S. National Aeronautics and Space Administration (NASA) demonstrate the skid resistant properties of concrete pavers. A NASA study (23) tested concrete pavers at 5 knots and 100 knots/hour speed at the Aircraft Landing Dynamics Facility in Langley, Virginia. The tests utilized a

Table 3—Average SN Values for Interlocking Concrete Pavement Sections (3)

Test Section	Speed mph (kph)	SN	Standard Deviation
A	25 (40)	51.9	0.5
A	40 (65)	46.5	1.1
A	50 (80)	40.0	1.5
B	25 (40)	57.2	1.1
B	40 (65)	49.6	3.0
B	50 (80)	43.1	0.5

Table 4—Recommended Minimum Skid Number for Main Rural Highways (21)

Traffic Speed mph (kph)	SN Measured at traffic spead	SN measured at 40 mph (65 kph)
30 (50)	36	31
40 (65)	33	33
50 (80)	32	37
60 (95)	31	41
70 (110)	31	46

tire and 123 kN loads and 1.7 MPa pressure typical to a Boeing 737 or DC-9 aircraft. Figure 7 illustrates the test equipment and Figure 8 illustrates the test surfaces.

The test results demonstrated substantially higher side force friction values for concrete pavers under wet conditions than plain portland cement concrete surfaces. The report indicated "that for aircraft ground steering maneuvers under wet conditions, the paver blocks would provide better friction than the conventional smooth concrete surface (23)."

Table 5—Stopping distance in meters on asphalt and concrete pavers (24)

	20 kph (12.5 mph)		40 kph (25 mph)		60 kph (37 mph)	
	Dry	Wet	Dry	Wet	Dry	Wet
Asphalt	1.70	3.20	5.85	9.60	14.2	26.7
Concrete pavers	1.68	2.50	5.23	8.15	13.6	21.3

Other skid resistance tests include that by Dallas/Fort Worth International Airport where a Saab skid tester was used to evaluate new interlocking concrete pavements in 1990. The values derived from the test were 0.63 to 0.69 with 0.65 being the average value, all considered very good for a new airfield pavement (24).

Harmonization of Skid Testing

ASTM E 1960, *Standard Practice for Calculating International Friction Index of a Pavement Surface*, (25) has harmonized skid resistance measurements through the calculation of the International Friction Index (IFI) based on measurement of pavement macrotexture and wet pavement friction. The IFI was developed by the PIARC (World Road Association) to compare and harmonize pavement texture and skid resistance measurements. The IFI allows for the harmonizing of friction measurements with different equipment to a common calibrated index. This practice provides for harmonization of friction reporting for devices that use a smooth tread test tire.

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Figure 7. Test equipment for evaluation of the friction properties of concrete pavers at NASA's Aircraft Dynamics Landing Facility (ADLF) in Langley, Virginia

Figure 8. Test surface at the NASA ADLF facility

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