CRITERIA FOR THE SELECTION OF BITUMINOUS-AGGREGATE COMBINATIONS TO MEET PAVEMENT SURFACE REQUIREMENTS

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ABSTRACT

Pavement surfaces have many requirements of which wear resistance and skid resistance are primary. Other secondary but important requirements include measures to prevent or minimize hydroplaning, tire wear, rolling resistance, noise, auto wear and fatigue, glare and light reflection, splash and spray, and appearance. Compromises are often sought to arrive at optimum solutions.

To achieve desired surface characteristics, aggregates used in bituminous surfaces must be hard (Mohs H$\geq$6), preferably have differential mineral hardness, be hydrophobic and have low water absorption . The

aggregate particles should be angular, relatively small ($\leq$ 12.5 mm), and well graded . The asphalt binder must be optimum and of a grade suitable for prevailing loads and temperatures, and the mixture must have high stability while containing optimum air voids and adequate voids in the mineral aggregate.

Wear resistant and skid resistant pavement surfaces can be provided through the judicious selection of natural or synthetic aggregates and employment of proven mix designs. Other surface requirements can and should be incorporated when selecting aggregates and mix designs.

Introduction

The primary consideration in pavement design and construction is to provide a strong (stable) and durable pavement that will facilitate the efficient flow of traffic at desired speeds comfortably and safely in all environmental conditions.

An extremely important part of any pavement is its surface over which vehicle tires roll. The surface has many requirements of which wear resistance, a measure of economy and safety, and skid resistance, a measure of safety, are primary. Other secondary but important requirements include measures to prevent or minimize hydroplaning, tire wear, rolling resistance, auto wear and fatigue, glare and light reflection, splash and spray, and poor appearance. The role of aggregates and mix designs on surface properties and the subsequent benefits and penalties of the surface properties are summarized in Figure 1.

Some of the surface requirements are satisfied by using common optimum measures while others may need contradictory measures; therefore compromises are sometimes sought to arrive at optimum solutions.

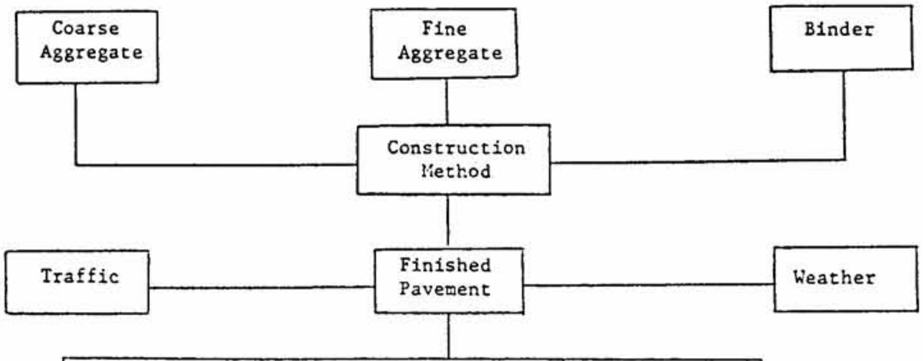
The emphasis in this paper is on how to satisfy the primary requirements, wear resistance and skid resistance, while achieving simultaneously, as much as possible, the secondary requirements.

The primary ingredient in bituminous pavement surface mixtures is the aggregate. Also important are the grade and content of the bitumen (asphalt cement) which is selected for a given mix and the mix design itself. Different mixes may be used in different situations. All these elements of the pavement surface will be discussed in the following paragraphs according to their effect on surface requirements and the basis for their selection. Relationships between surface materials and/or design and surface performance are summarized in Figure 2.

Aggregate Role and the Most Important Properties

The principal role of the aggregate in a bituminous mixture is to provide a strong, durable and skid-resistant pavement surface that will resist abrasive wear, crushing, and rutting, and will provide through the surface life a microtexture that will maintain a minimum level of friction under prevailing conditions, and a macrotexture that will facilitate the fast removal of water from the tire-pavement interface, thus eliminating or significantly reducing unsafe panic skidding on even hydroplaning or wet surfaces.

The most important properties that affect aggregate performance are :



Effect	Impact
Wet Skid Resistance	Safety
Hydroplaning	Safety
Tire Wear	$ Cost
Rolling Resistance	$ Energy
Energy Fuel Economy	$ Energy
Fuel Level	Pollution
Auto Wear & Fatigue	$ Cost
Fatigue & Ride Comfort	Safety
Glare & Light Reflection	Safety
Appearance (color, etc.)	Safety
Electrostatic	Safety
Splash and spray	Safety

Figure 1. Role of Aggregates on Surface Properties and the Subsequent Penalties and Benefits of the Surface Properties

AGGREGATE PROPERTIES

Mineralogy
Percent mineral composition, mineral hardness, crystallinity, grain shape, size, and distribution, grain bonding, chemical stability of minerals.

Other Properties
Particle shape, size, gradation, strength, toughness, resilience, abrasion, polishability, porosity, absorption, density, etc.

BINDER PROPERTIES

Bituminous Materials
Penetration grade, viscosity, ductility, temperature sensitivity, weathering susceptibility

PAVEMENT SURFACE DESIGN

Bituminous Mixtures

Aggregate gradation, asphalt grade and content in mix, mixing, placing, compaction, surface texture, permeability, surface stability

SURFACE PERFORMANCE

Wear and Skid Resistance

a. Wear on macro-scale will cause loss of macrotexture. May cause surface deterioration due to abrasion, degradation, pitting, raveling, rutting, weathering.

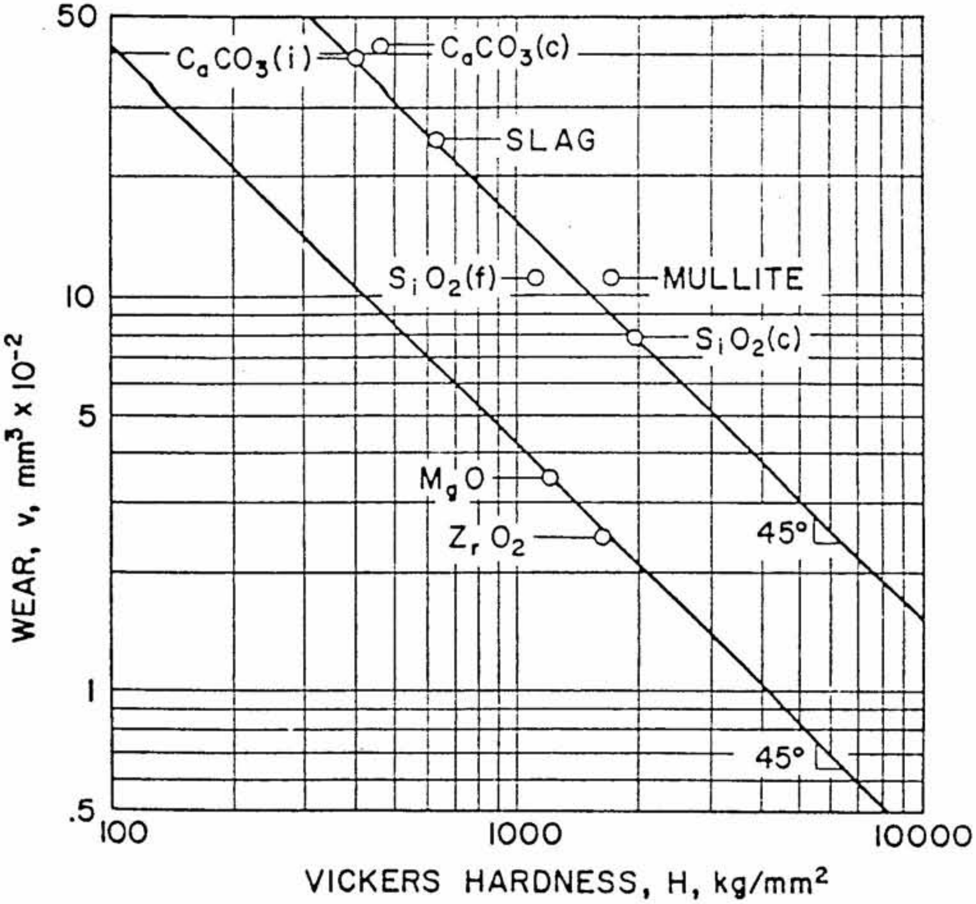
b. Wear on a micro-scale may cause loss of safe skid resistance due to polishability of exposed aggregates and loss of surface particles due to poor bonding (loss of microtexture).

Other

Tire wear, noise generation, light reflection, splash and spray, etc.

Figure 2: Relationships between Surface Materials and/or Design and Surface Performance

1. Hardness of constituent minerals. Mineral hardness combined with strong grain consolidation or bonding to the matrix result in resistance to surface aggregate wear. Stiffler [1] found mineral hardness to be the most important property contributing to wear resistance, (Figure 3). The most common hard mineral found in paving aggregates is quartz (SiO_2) found in quartzite, natural sand and river gravel, while the most common soft mineral found in paving aggregates is calcite ($CaCO_3$) found in the widely available limestone rock used for providing paving aggregates.
2. Differential hardness and the proportion of hard to soft fraction of aggregate constituent minerals. Research performed independently in North Carolina [2] and in Maryland [3] indicated that within each particle of naturally occurring aggregate, a proportion of hard minerals in the range of 40 to 70 percent produces the highest resistance to aggregate polishing, due to differential wear of hard aggregate grains embedded in a softer matrix (Figure 4). Examples of aggregates in this group include arkosic sandstone, granite gneiss, rhyolite and some river gravels.
3. Hard grain or crystal shape, size and distribution



(c = crystalline, f = fused, i = impure)

Figure 3. Log Wear as a Function of Log Hardness for Minerals Softer than Al_2O_3 Abrasive [1]

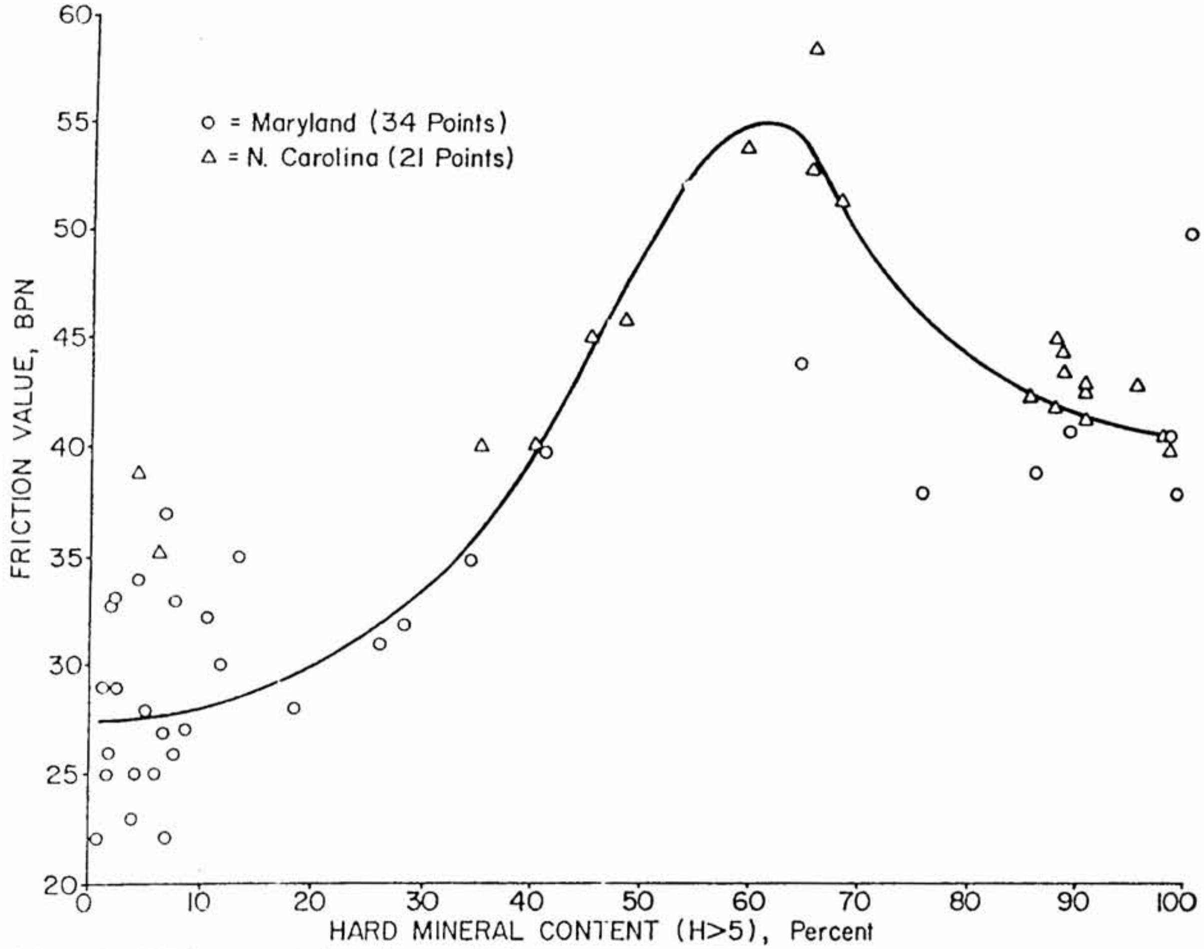
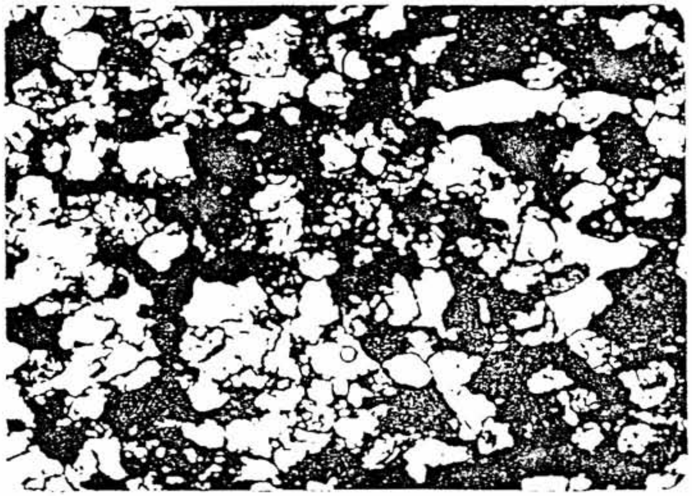


Figure 4. BPN Friction Values (ASTM E 303) Versus Hard Mineral Content [8].

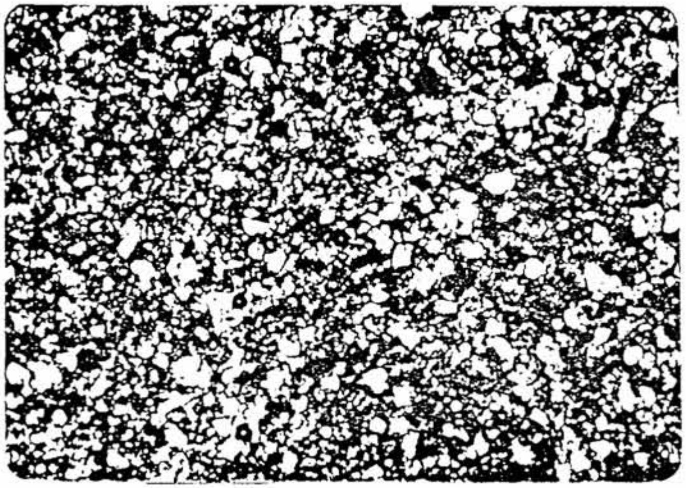
within each aggregate particle influences the resistance to polishing. Angular medium to large grains (100-300 microns) outperform rounded and small grains (Figure 5).

- Shape, size and gradation of aggregate particles in a bituminous pavement surface determine surface macrotexture. Microtexture is a function of aggregate mineralogy - grain hardness, differential hardness, shape, size and distribution. Research has shown that high skid resistance is achieved in a dense bituminous surface when coarse angular aggregate particles in the size range of 6 to 13 mm are used [4]. In open-graded mixes, it is recommended that 80 to 90 percent of the aggregate be in the range of minus 3/8-in. to plus No. 8 sieves (9.5 to 2.36 mm) [5]. Aggregate gradation largely determines surface mix design. Sample gradations of proven good designs are shown in Table 1. [6].

In short, the most important properties are those that make the aggregate both skid-resistant and wear-resistant throughout the expected life of the pavement surface. Performance properties that may alleviate noise generation, tire wear, light reflection, splash and spray, and other performance requirements are also



Angular, medium to large grains in sandstone



Rounded to subrounded small grains in limestone

Figure 5. Comparison of hard, angular medium to large grains in sandstone with soft, subrounded, small grains in dolomitic limestone [illegible]
Ref. [8].

important. They are generally related to pavement surface texture and are discussed under respective performance requirements.

Table 1. Typical Aggregate Gradations

Percent Passing Sieve No. (U.S. Standard)	Equip. Size mm	Dense[a] (Pa.ID-2A)	Grading Open[b] (FHWA)	Fine[a] (Pa.JI-1)	One-Size[a] (Pa. Seal Coat)
1/2"	12.5mm	100	100	-	100
3/8"	9.5mm	80-100	95-100	100	75-100
No. 4	4.75mm	45-80	30-50	90-100	10-30
No. 8	2.36mm	30-60	5-15	60-100	0-10
No. 16	1.18mm	20-45	-	40-70	-
No. 30	0.60mm	10-35	-	20-60	-
No. 50	0.30mm	5-25	-	10-40	-
No. 100	0.15mm	4-14	-	7-25	-
No. 200	0.75mm	3-10	2-5	3-15	-

Synthetic Aggregates

Where wear-resistant and skid-resistant natural aggregates are not available or not adequate for usage in critical sections, e.g. heavily traveled sharp curves and intersections, bridge decks and steep signal approaches, synthetic aggregates may be used. These include calcined bauxite, calcined flint, synopal, fired bricks, sintered slags, expanded slate (solite), expanded shale and sintered claystone [7]. These aggregates develop their wear resistance and skid resistance in various ways; therefore each has to be designed and specified accordingly. Generally, these aggregates have hard crystalline grains and high vesicularity. Many of the potentially acceptable synthetic aggregates are energy and capital intensive, therefore they must be selected for use judiciously and after a benefit to cost evaluation.

Suggested target values for highly skid-resistant and wear-resistant aggregates are shown in Table 2 [8].

Table 2 : Target Values for Properties Which Would Enhance Aggregate Skid Resistance and Wear Resistance [8].

Property	Value Range
Mohs Hardness of Hard Fraction	7-9
Mohs Hardness of Soft Fraction	4-6
Differential Hardness, min.	2-3
Percent of Hard Fraction	
Natural Aggregate	50-70
Artificial Aggregate	20-40
Hard Grain or Crystal size	100-200 um; Avg.150
Hard Grain or Crystal Shape	Angular Tips ($\leq$90)
Percent Porosity (Vesicularity)	25-35
Pore Size, Optimum	125 um
Aggregate Particle Size Range	3-13 mm
Aggregate Particle Shape	Conical, Angular ($\leq$90)
Los Angeles Abrasion, Percent	$\leq$ 20
Aggregate Abrasion Value, Percent[a]	$\leq$ 8
Aggregate Impact Value, Percent[a]	$\leq$ 20
Polished Stone Value, BPN[b]	$\geq$ 75

a According to British Standards Institution, BS 812:75.

b According to BS 812:75 or ASTM D 3319-74T and E 303.

Pavement Texture and Skid Resistance

It is generally well-known that strong relationships exist between surface texture, wear, and skid-resistance [9]. It has been customary to divide texture into microtexture (asperities 0.5 mm or less) and macrotexture (asperities larger than 0.5 mm). Microtexture contributes the friction factor of skid resistance at low speeds as reflected in measurements made by the British Pendulum Tester at 7 mph (11 Km/h) according to ASTM Standard Test Method E303 [10]. Macrotexture facilitates the fast removal of water from the tire pavement interface, thus contributing to the friction level at high speeds [9]. Skid resistance on wet highway pavements includes the contribution of both microtexture and macrotexture and is usually measured using a skid trailer moving at 40 mph (64 Km/h) according to ASTM Test Method E274. A correlation between British Pendulum Number (BPN) and skid trailer skid resistance number (SN) is shown in Figure 6 [6]. This correlation and other similar correlations [11] suggest that to attain the usually recommended minimum safe skid number of 40 (SN_{40} = 40), one must obtain an average BPN in the range of 50 to 55. It may be appropriate at this point to mention that average polished stone BPN values (PSV's) on four aggregates in

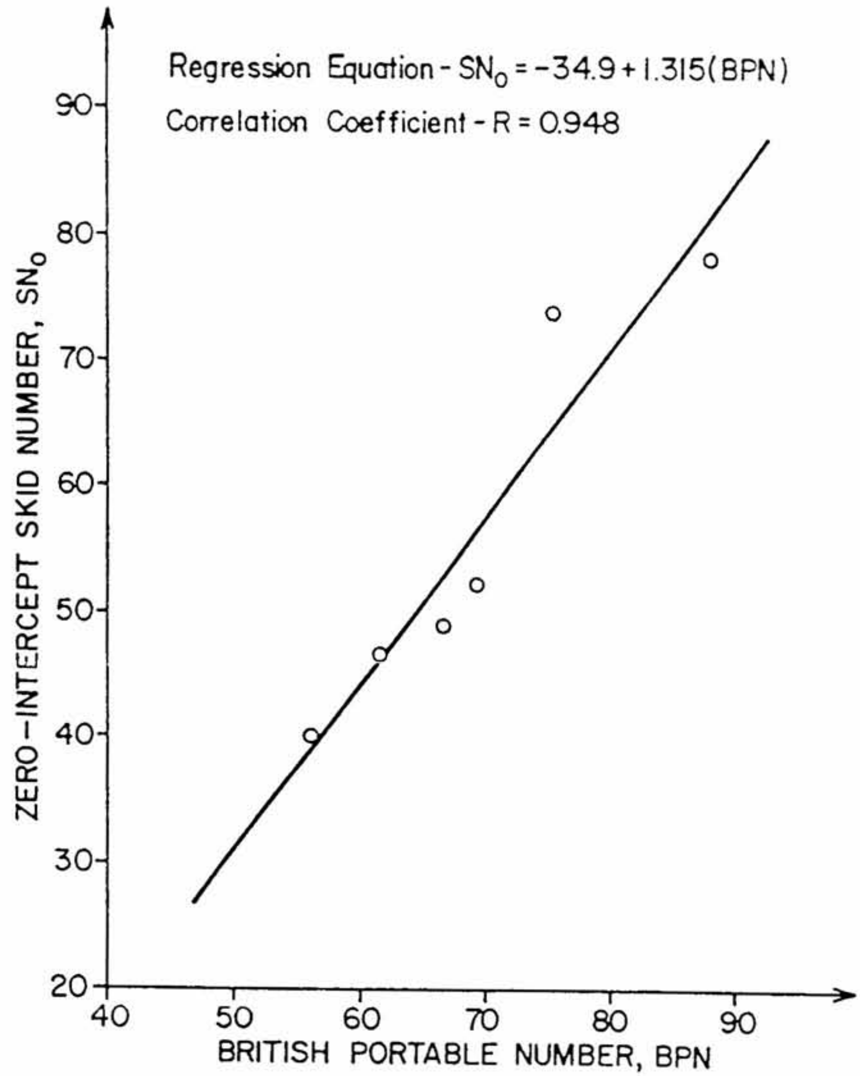


Figure 6. Zero-Intercept Skid Number vs. British Portable Number [6]

Jordan as reported in a recent study [12] were as follows (Table 3):

Table 3 : Polished Stone Values of Four Aggregates in Jordan

Source	PSV
Zarqa limestone	45.6
Ma'an limestone	38.7
Swarfi Basalt	54.8
Aqaba Granite	70.4

The values in Table 3 suggest that the limestone aggregates which are widely available and most commonly used in highway pavements in Jordan do not meet minimum requirements for skid resistance on heavily traveled roadways. It may be that aggregates in the West Bank are similar, therefore special care and/or special surface treatments must be applied for heavily traveled roadways and for critical pavement sections.

Skid-resistant aggregates may be necessary for critical sections, but reduction in travel speed and increase in the surface macrotexture offer some compensation in this respect as may be observed from the following empirical equation developed at the Pennsylvania State University [6]:

$$SN = (1.38 \quad BPN - 31)\ e^{-0.06\ V\ \bar{MD}^{0.5}}$$

Where:

SN = Skid resistance number measured at V mph

V = Speed, mph (1mph = 1.61 Km/h)

MD = Mean texture depth in milli-inches (1 milli-inch = 25.4 microns) as measured using the sand patch method [9].

This equation also may be used to predict closely surface skid number at a given speed from laboratory or field measurements of pavement surface BPN and mean texture depth [6].

Surface Texture and Tire Noise

Despite the lack of adequate models to describe the mechanism of tir-pavement noise generation, some rather tentative but plausible inferences may be drawn as to the selection and the use of tires and surface textures for quieter pavements. Some researchers [13] have shown that tire noise generation on pavement surfaces is largely dependent on the tire tread and design. For example, the noise behaviour of snow tires and cross band tires on conventional pavements is less favorable than ordinary traditional tire designs. However, surface texture does influence tire-surface noise.

Improved noise performance has been obtained with open-graded surface mixtures when compared to conventional dense graded bituminous mixtures [13]. Open -graded mixtures using designs similar to those developed by FHWA [14] (also see Table 1) lead to lower noise levels. Pressurization of texture cavities which results in monopole air pumping is less likely to occur on open-graded surfaces. Furthermore, open-graded textures are not associated with annoying tread frequency noise 'tonals' which occur on smooth textured surfaces [13]. These findings lead to the important conclusion that the objectives of designing surfaces with adequate skid resistance and reduced noise levels are not diametrically opposed as has been traditionally thought.

Surface Texture and Tire Wear

On conventional surfaces, tire wear appears to be largely a function of tire material, design and construction [15]. These characteristics are outside the scope of this paper. Other important factors include pavement texture which depends largely on aggregate shape, size and hardness. Related factors also include environmental conditions of the surface (wet or dry, warm or cold, clean or contaminated), roadway geometry (tangent or curved) and traveling speed. Experiments on tire wear and skid resistance relative to pavement texture were performed by Lees and Williams [16] and others. The conclusion of the results indicates that tire wear and skid resistance both increase rapidly with increasing microtexture above five microns, which is the size required to penetrate water films that are normally 2 to 3 mm thick [4]. When the microtexture approaches 100 microns, the rate of increase in friction tends to level off due to reduced contact area, whereas the rate of tire wear keeps increasing as shown in Figure 7 [16]. Accordingly, Lees and Williams [16] suggest that surface microtexture should ideally be in the range of 10 to 100 um.

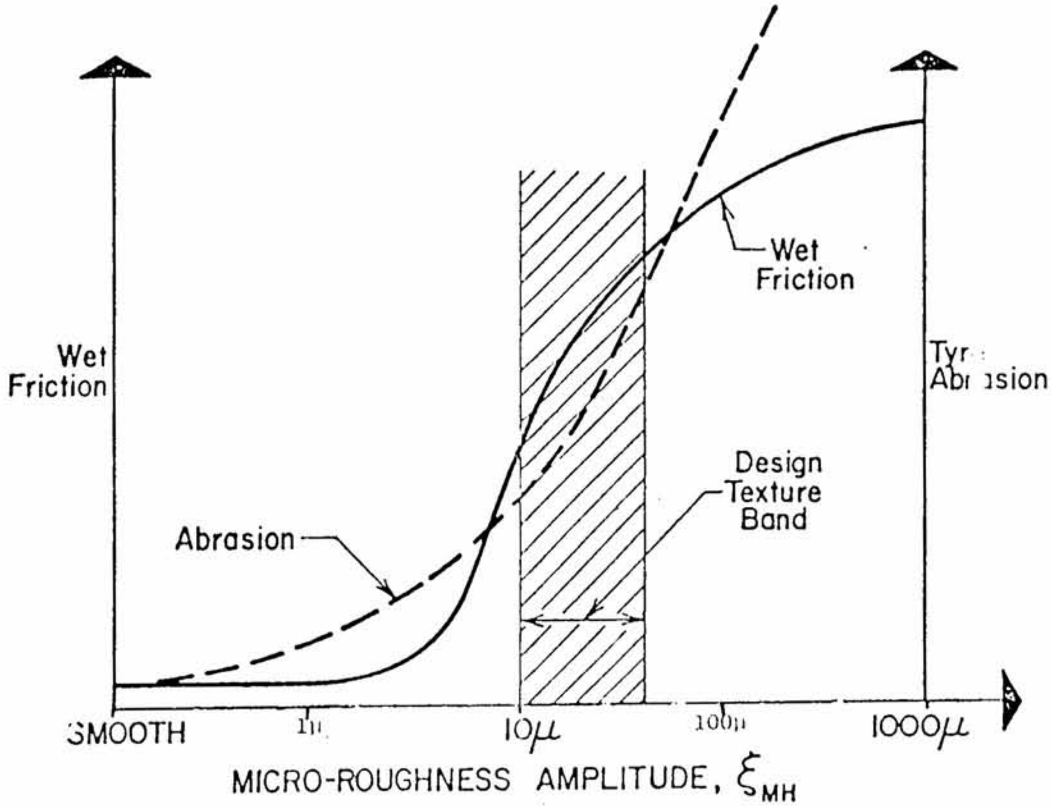


Figure 7. Tire Wear [16]

Light Reflection and Glare

These phenomena are principally related to night visibility, particularly on wet surfaces. The most informative work on this problem was reported by Fredsted [17] in which he discussed some experiments performed on Denmark's highways. He reported that diffuse preferential light reflection was a function of aggregate color and surface texture. Textures that penetrate the water film on the surface improve visibility, and 30 percent light color coarse aggregate in a darker mass produce sufficient color contrast to assist the driver in perceiving the roadway to a safe distance (50-100 meters). This treatment would be most effective if the light color aggregate protrudes 0.6 mm or more above the darker aggregate. Furthermore, it was found that this color contrast applies to white stripes as well.

Glare was substantially improved by having a good surface macrotexture and color contrast, provided that surface drainage was also maintained.

Splash and Spray

Maycock [18] defined splash as the large droplets thrown off the tire and spray as the envelope of very fine droplets which are carried in the turbulent air stream around the vehicle. Performing experiments on "fine cold asphalt surfaces", he found that splash was associated with large water depths and low speeds. Spray is associated with shallow water depths and high speed. Maycock found that at 30 feet (9 meters) behind a commercial vehicle, spray density was very small below 30 mph (48 Km/h) but increased substantially with increasing speed. In the range of 45 to 75 mph (72 to 120 Km/h), spray density varied with speed according to the following equation:

$$\text{Spray density} = \text{constant} \times (\text{speed})^{2.8}$$

Maycock experimented with bituminous surfaces that were described as pervious, slightly pervious, and impervious. He concluded that at 60 mph (97 Km/h) splash and spray on slightly pervious surfaces were only slightly improved, but pervious (open-graded) surfaces were outstandingly good in reducing splash and spray provided that pavement drainage was maintained.

A few years later, Brown [19] confirmed Maycock's conclusion that open-textured surfaces reduce splash and spray significantly. He reported that six experimental surfaces were still effective in reducing splash and spray two years after being laid and after having 2.75 million commercial vehicles pass over them.

Rolling Resistance and Power Consumption

Schuring, et al [20] found that power consumption of pneumatic tires is comparable to power consumed by vehicle components such as muffler, air cleaner, and emission control devices. In fact, the power consumed by the tires is only 5 to 10 percent of the total power losses at operating speeds. It was found that the role played by the type of tire was more influential in determining rolling resistance than the type of surface aggregate. Therefore, it was concluded that changes in fuel consumption due to different aggregate types are very small.

Hydroplaning

This is the case where the vehicle tires lose contact with the pavement surface and ride on the water layer causing complete loss of vehicle control by the driver. Hydroplaning has been explained as an upward hydrodynamic thrust caused largely by the water drag. When the weight of the vehicle is balanced by the hydrodynamic thrust, the vehicle tires lose contact with the pavement and ride the water layer if it reaches a critical depth 0.10 to0.40 in (0.25 to 10 mm), depending on surface texture and tire tread depth [21]. Hydroplaning was found to commence at a vehicle speed approximated by the formula [21]:

$$V_h = 13.2 \sqrt{p}$$

Where :

V_h = speed, mph (1 mph = 1.61 Km/h)

p = tire inflation pressure, psi

Optimal Pavement Surfaces for Different Situations

Relative to surface performance, particularly skid-resistance and wear-resistance, pavements were grouped by Salt [22] into four categories:

1. Easy, defined as lightly traveled roads, driveways, and minor residential streets. In this category almost any conventional aggregate and mix design may be used in the surface.

2. Average, defined as most city streets and rural roads where no steep grades, sharp curves, or unusually hazardous locations exist. In this category conventional mix designs with at least medium grade aggregate should be used, e.g. granite, gneiss, some slates and shales, and carbonate aggregates with high (25% or more) sand-size hard silicions content.
3. Difficult, defined as heavily traveled, high speed highways and steep grades or sharp curves on 'average' highways. In this category good conventional designs e.g. well-designed dense graded or open-graded bituminous friction courses should be used. Aggregates should be of high quality, natural or synthetic e.g. arkosic sandstone, graywacke, quartzite and some slags.
4. Very difficult, which includes curves and approaches to high speed highways, heavily trafficked intersections with pedestrian crosswalks, steep approaches to signal lights and stop signs, etc. The best designs and the best aggregates should be used in this category, including epoxy-calcined bauxite mixes and open-graded bituminous mixtures utilizing arkosic sandstone, gray wacke and other natural or synthetic aggregates of proven performance.

Pavement Systems

Of the surfacing systems which have been most commonly and successfully used to date, and which may be improved as the quality of aggregate and binder improve, are the following systems:

1. Dense-graded asphalt concrete, hot-plant mix, high quality aggregates, binder and mix design.
2. Open-graded asphalt concrete, hot-plant mix, high quality aggregates, binder and mix design.
3. Epoxy-asphalt seal coat using high quality aggregates e.g. calcined bauxite, for very difficult places such as bridge decks, sharp curves and intersections with pedestrian crossings on heavily traveled roadways.

Conclusions and Recommendations

Wear-resistant and skid resistant pavement surfaces can be provided through the judicious selection of natural or synthetic aggregates and high quality binder, and the employment of proven mix designs that will meet requirements for existing and expected roadway geometrics, traffic and environmental conditions.

Reduced glare, splash and spray are achieved simultaneously with providing good skid-resistant textures. Noise abatement and reduction in tire wear may, in addition, require compromises or special measures as, for example, reduction in speed and use of aggregates having microtexture of medium size asperities.

It is recommended that research on local materials and mixes, together with the performance history of local aggregates and mix designs be used as a guide for new construction and pavement rehabilitation.

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