PROVIDING SKID RESISTANT PAVEMENTS

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Abstract: Pavement skid resistance information and data is comprehensive but scattered throughout the literature. Here the state of the art and the state of the practice involving various methods of providing pavement surfaces (roads and runways) that reduce wet weather skidding and hydroplaning are summarized and reviewed; also identified are those areas where the practice lags behind the state of the art. Source information is also furnished for the serious student and researcher of the subject. Field and laboratory tests and specifications of skid measurement and predictability are discussed. Polish resistance of various aggregate types are listed as is the skid resistance of various pavement surfaces. The effect of characteristics of the materials and surfaces of pavement construction are presented in relationship to the design, construction and maintenance of road and airport pavements. Details of design, construction and maintenance for effective skid resistance are covered. Of special significance is the section on "The Future". The paper was contributed to by a group of experts in the field.

One of the most important factors in the safe operation of the modern motor vehicle is the development of necessary tire-pavement friction (skid resistance). It is well-known that during an emergency stop, the last chance for avoiding an accident resides with the level of skid resistance developed between the tire and pavement during braking. In most cases, emergency situations lead to over-reaction on the part of the driver, which often results in a locked-wheel skid.

There is a substantial drop in skid resistance of pavements during wet weather. This creates a serious situation since experience has shown that the average driver does not reduce driving speed under wet conditions.

It is also unfortunate that most tire manufacturers' advertisements vividly display the remarkable stopping ability of their tires. This can lead to overconfidence on the part of the driver, especially since no one explains that such stopping ability depends on many factors besides the advertised claims for the tire, such as the significant changes that occur due to tire wear. A "bald" tire on a wet pavement presents a very hazardous condition. Perhaps this is best stated from a quotation by R. W. Yeager (1) in his paper on "Tire Hydroplaning: Testing, Analysis and Design": "The road surface is a relatively lasting, stable, rigid platform and is conducive to resisting tire hydroplaning if properly designed. These qualities are absent in the tire. The improvement that a tire tread potentially offers is governed by the level of drainage and friction capability of the surface."

On the basis of the above statement and assuming the driver and the tires are competent, then one could conclude that the responsibility for the attainment of necessary tire-pavement friction under the variable environmental and vehicle operating conditions mainly rests with the paving engineer. This also appears to be the thoughts of the writers of NCHRP Synthesis 14 on Skid Resistance (2) wherein we find, "Next to congestion, pavement slipperiness is the greatest sin a public agency can, in the eyes of the public, permit to befall highways and streets. Indeed, when skidding accidents occur, the public is more likely to blame the pavement than anything else." We should add that although the public is not directly involved in terms of operations, the same feelings are of as great importance in the takeoffs and landings of commercial and military airplanes.

The problem of providing economical pavements which generate the proper tire-pavement friction would be difficult enough, but when the constraints of noise, excessive tire wear, pavement roughness, and road geometry must also be considered, one begins to understand the magnitude of the problem.

During the interval between the First International Skid Resistance Conference and this one, numerous studies on tire-pavement friction have been published and a number of outstanding papers have been made available to the paving engineer (2)(3)(4)(5)(6). The purpose of this report is to review the state of the art and the state of the practice involving various methods of providing pavement surfaces (highways and runways) that reduce wet weather skidding and hydroplaning, and identify where the state of the practice lags behind the state of the art.

In order to fulfill the preceding objectives we will consider:

. What are the basic requirements for a satisfactory skid resistance surface?

. What is being done to provide and maintain skid resistance surfaces?

. What remains to be done?

. What is our future plan of approach to the ultimate solution of our problem?

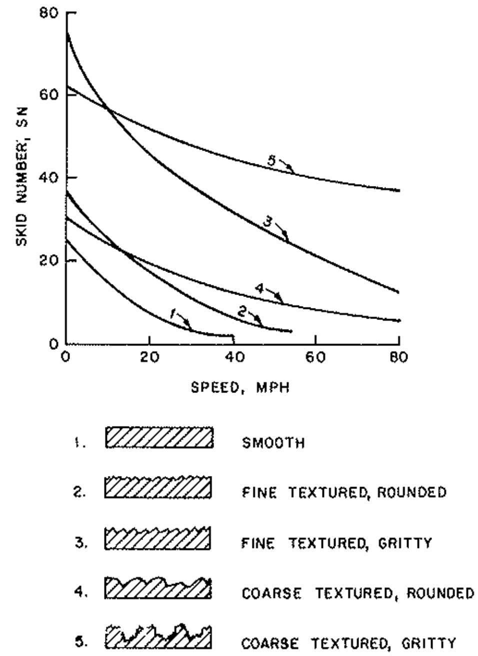
Fortunately at this stage of development, we appear to have reasonable agreement on the basic requirements for a satisfactory skid resistance surface. Among the many factors which affect pavement friction, the most important are the microscopic and macroscopic roughness of the pavement surface as well as the polish-wear characteristics of mineral aggregates. The recognition of these two texture scales which affect the friction and surface drainage properties of either a road or airport pavement allows one to classify various pavement surfaces in terms of skid resistance.

Figure I (3) and Figure II (7) show the influence of micro- and macrotexture and, of greater importance, the necessity of having both of these characteristics available at high operational speeds. As an example, Figure I shows the excellent skid numbers that may be attained by a fine-textured gritty surface below 30 mph (13.4 m/s) and the loss in skid resistance above this speed. This pavement surface may be a very acceptable surface for city streets, but would be inadequate for high speed highways and certainly not for airport runways. The paving engineer must be fully cognizant of the variation in tire-pavement friction with speed.

Figures I and II also indicate the beneficial effect of texture in the generation of skid resistance. The important function of texture is to provide drainage channels so water can escape from under the tire at faster vehicle speeds. This allows the tire tread elements to make positive contact with the pavement surface.

Having identified the pavement surface characteristics required for adequate skid resistance, the paving engineer is also concerned with maintaining such a texture during the service life of the pavement. This is done by obtaining materials which will have a high resistance to polish-wear action of traffic. The balance of this paper will be devoted to the study of materials, and the design and construction methods used to provide adequate tire-pavement friction during the operational life of airport and road. Also considered will be the maintenance operations required when surfaces fall below the desired skid resistant levels.

Figure I. Classification of pavement surfaces according to their wet friction and drainage properties.



REFERENCE:
NCHRP # 37 "TENTATIVE SKID-RESISTANCE REQUIREMENTS FOR MAIN RURAL HIGHWAYS" PAGE 24, FIG. 24

Figure II. Pavement Surface Characteristics.

PAVEMENT	TEXTURE		FLUID PRESSURE ALLEVIATION	
	MICRO	MACRO	VISCOUS	DYNAMIC
SMOOTH	LOW	LOW	POOR	POOR
SMOOTH STONES	LOW	MEDIUM	POOR	GOOD
SANDPAPERY	HIGH	LOW	EXCELLENT	POOR
FRACTURED STONES	HIGH	MEDIUM	EXCELLENT	GOOD
GROOVES	LOW	HIGH	FAIR	EXCELLENT
GROOVES	HIGH	HIGH	EXCELLENT	EXCELLENT
POROUS	MEDIUM	HIGH	GOOD	EXCELLENT

REFERENCE:
"ELEMENTS AFFECTING RUNWAY TRACTION" W. B. HORNE
SAE PAPER - NO 740496, MAY 1974 TABLE II

Materials

Assuming that proper design systems and construction methods are available for producing adequate skid resistant surfaces, then the most important consideration is the choice of suitable aggregate for bituminous pavements and the mechanical texturing of portland cement concrete pavements.

Excluding those bituminous pavements produced mainly from fine aggregates, the skid resistant properties of asphalt pavements depend primarily on the coarse aggregates, whereas in portland cement concrete pavements, the fine aggregate characteristics are considered the more important, at least until the surface has worn sufficiently to expose the coarse aggregates.

Four characteristics should be evaluated in the selection of aggregates for skid resistant surfaces. These are: texture, shape, size, and resistance to wear and polish.

It should be noted that characteristics such as texture, mineral constituents, chemical composition, and certain physical properties are controllable by the paving engineer through aggregate source selection. Once the source is selected, further characteristics such as shape (angularity), particle size and range of sizes (gradation), may be produced by processing. Microtexture or roughness of aggregates is a very important characteristic in terms of skid resistance of the pavement. For a portland cement concrete pavement, microtexture refers to fine-scale roughness contributed by individual small asperities of the fine aggregate particles in the mortar. This would also be the case for surface treatments with fine aggregate asphalt seal coats (sand seals and screenings) and asphalt slurry seals. On the other hand, in asphalt concrete and larger aggregate seal coats, the microtexture of the larger aggregate sizes is the most important.

Microtexture of an aggregate particle must be specified or determined at the time of its incorporation into the pavement, but of greater importance is the change in such texture during service life. Minerals of varying hardness in the aggregate matrix may wear differentially under traffic resulting in a continually renewed non-polished surface. This also happens when the individual aggregates have sand size particles composed of hard grains which are weakly cemented. On the other hand, if the cementing matrix is strong, the individual grains will be tightly held and polished by traffic. The rate of polish depends on the hardness of the grains, frequency of contact with traffic and the type of polishing media or abrasive material on the roadway surface.

Shape and Size

Shape and size of the individual aggregates are other important variables controlling skid resistance. The angularity of coarse aggregates contributes to tire-pavement friction in the case of asphalt concrete and screening (aggregate) seal coats by establishing points of contact, that protrude above the water level, with the tire rubber. Angularity is most readily attained by rock crushing operations. However, aggregates of different mineral composition with the same angularity may wear-polish at very different rates. A potentially slippery situation may develop if rapid wear and polish reduces the angularity of the points in contact with the tire rubber. Such characteristics should be determined by laboratory testing as discussed later.

Aggregate size is controlled by the grading requirements. In the case of screenings for seal coats, the sizes of the aggregate are a very important consideration in the final surface in terms of angular projections to different heights so as to provide rubber envelopment and drainage patterns. In the case of asphalt concrete, size is important in creating the character of surface exposed. Variance in maximum aggregate size even from the same aggregate source may result in different changes in tire pavement friction under equivalent traffic exposure.

Wear Resistance

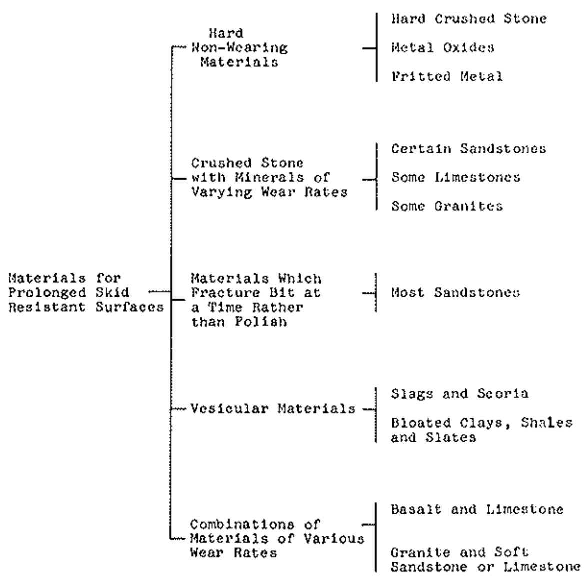
Having chosen an aggregate of appropriate microtexture and angularity and a proper maximum size and gradation, the paving engineer must determine if such a combination will produce the desired tire-pavement friction and maintain such skid resistance during the service life of the pavement. As mentioned previously, aggregates may exhibit different systems of wear and polish depending on their mineralogical composition. There is also the possibility of using aggregates composed of several minerals of various hardness that will result in differential rates of wear in a pavement.

An excellent summary on systems for maintaining high skid resistance under conditions conducive to wear and polish is given by B. B. Gallaway (6). Quoting from portions of this paper, "Surface microtexture renewal processes may be aided by proper selection of aggregates forming the structural skeleton of the mix. The choices that may be available include granulating materials such as sandstone; conglomerates which contain rock flagments that possess great resistance to disintegration and wear, like a quartz conglomerate; certain limestones with uniformly dispersed small sharp particles (Quartz in a limestone matrix); certain iron ore gravels and vesicular materials such as selected slags; scoria; and manufactured aggregate of the lighweight type such as expanded clays, shales and slates.

"Another mechanism that has met with moderate success utilizes the concept of differential rates of wear of at least two aggregates of distinctly different wear rates in the mix. In service such a mixture is worn and eroded by traffic and to some extent by environmental factors at such a rate as to create a continuous and effective skid resistant pavement surface. The soft particles wear in advance of the harder particles leaving the latter in relief.

As this relief is accentuated, the hard particles are removed by the shearing action of traffic. The process repeats itself to maintain a particle exposure which contains a preponderance of particles that never remain exposed to the action of traffic long enough to polish to low level. The Highway Departments of New York, Virginia, Kentucky, Tennessee, Louisiana and Texas, among others have utilized this approach with varying degrees of success for a period of several years." Figure III from this paper presents this information in outline form.

Figure III. Materials



(B.M. Gallaway - AAPT-42-401-1973)

One of the difficult problems in proper selection of aggregates in the United States is the enormous amount of limestone available as aggregate. Some limestone aggregates polish rapidly and lead to low tire-pavement friction values in a relatively short period. Numerous studies by the individual states and the National Crushed Stone Association have shown that it is possible through proper combinations of aggregates of different wear rates to use most sources of limestone aggregates. Studies indicate that blending is effective in proportion to the amount blended in the proper size range (coarse for asphalt concrete and fine for portland cement concrete) and the polish resistance of the blending aggregate. However, blending requires careful testing and evaluation (described later) during preliminary studies leading to mix design.

As mentioned previously, good skid resistance requires a satisfactory microtexture on the aggregate particles for both low and high speeds and the retention of this texture during the service life of pavements. The action of the tire rubber plus the available abrasive material causes a continuing wear of the pavement surface. Also through a polishing action, aggregate microtexture is reduced. All of this action in most cases leads to a reduction in pavement skid resistance. However, as noted in Figure II, careful use of different aggregates may provide differential wear and a continuing renewal of surface texture.

Tests and Specifications

One of the most difficult problems presently facing the paving engineer is the development of tests and specifications to enable him to characterize the microtexture of aggregates and the degree of retention of such microtexture during service life of the pavement.

There is a necessity for continuing field evaluation of the wear-polish characteristics of various aggregates and combinations of aggregates having different mineralogical compositions. Although continuing field efforts are important it is even more essential that the paving engineer have laboratory tests to provide him with answers for decisions on the suitability of aggregate sources. The importance of such tests should be stressed since the proper choice of an aggregate is not only based on its angularity, microtexture properties, and its susceptibility to polish-wear but also on the availability and cost as well as numerous other required properties. As is well appreciated the design of a pavement is a balancing act and tests that do not provide significant answers and guidance may result in costly mistakes.

Tests of significance in characterizing the resistance to wear-polish are the various petrographic tests which describe the aggregate and its mineralogical composition. This analysis may prove very useful in selection of aggregates if such tests or combinations of test results are correlated with field performance. In addition, special cases require special tests. In the case of limestones and dolomites which sometimes polish very rapidly, the acid insoluble residue test is being explored and has been used in some specifications. As with many tests of this type there is controversy on the interpretation and use of the results.

Recent guidelines (8) comment on the acid insoluble residue test as follows: "It is recommended that this test be used as a laboratory evaluation test, but not be considered as a principal means of predicting resistance to change in tire-pavement friction as governed by polishing action of traffic. The test should be considered as a very useful tool when used in conjunction with the results of field performance of a given aggregate or combination, or when combined with other laboratory tests such as a polishing test and petrographic analysis."

Perhaps the most significant test for predicting the resistance to change during service life is some type of wear-polish test. Although numerous studies have been performed in this connection a fully acceptable test is not presently available. However, the well-known British Wheel Polishing Machine is being studied by ASTM together with other devices for wear and polish determinations. Texas uses this machine for an accelerated polish test for coarse aggregate (Texas H.D. Test Method 438-A, January 1, 1974).

There are two approaches in the attempts to provide design information on aggregate wear and polish resistance, other than experience from field testing. The first involves a laboratory system which determines the change in microtexture of selected aggregate particles. The second involves laboratory simulation of field conditions.

The British Wheel Polishing Machine is an example of the first system. The quantitative measure of microtexture is a very difficult problem and it is best presently done with a low speed friction tester such as the British Portable Tester. This instrument provides friction readings which are relatable to the lower speed range (below 30 mph [13.4 m/s]) in which the dominant factor is microtexture of the aggregate particles. Through the use of this system one may obtain information on coarse aggregates for use in asphalt concrete and aggregate (screening) seal coats such as 1/2-3/8 and 1/4 inch. However, it is not possible to study fine materials with this method.

It is apparent that the second approach is the most logical development for characterizing the total effect of traffic on various pavements or surface treatments. Laboratory systems that simulate field conditions are under active study throughout the world with the use of some form of circular track as the most popular device. Other systems include a stationary spinning wheel wearing and polishing on a fixed area of the specimen and smaller instruments that employ small rotating rubber devices scrubbing on circular specimens. In any case, one of the most difficult problems with such simulation systems is the forming of a test specimen that represents the pavement surface. As an example, the preparation of portland cement concrete test surfaces must provide the same finish and strength as found in the field and with the mortar, water and aggregates in the same proportion relative to field conditions. This may or may not be possible during preliminary design. The use of additional water, for example, during construction finishing operations may result in a weak mortar. A strong mortar is necessary since a mortar weak in strength may wear at a rapid rate and lose good microtexture aggregate. In this case, rapid wear is the dominant factor in the future field condition, but may not show in laboratory studies.

It appears possible to produce realistic test specimens for the various forms of asphalt surfaces although sufficient results are not available to provide firm recommendations.

A problem with a circular track-type machine is the possible displacement of the surface because of the scrubbing motion of the wheel rotating on a short radius. A further problem is the difficulty of tracking in the same area. Most units presently under study, therefore, have a variable radius feature.

A wear and polish machine must produce accelerated results so most test methods employ some additional form of abrasive. There is a definite need for standardization of the abrasive to be used, the grain size or sizes and the time periods for testing with the same or different combinations of the abrasive.

As has been mentioned previously, both microtexture and macrotexture are involved in providing proper skid resistance over the range of speeds encountered in pavement and runway operations. Although microtexture comes into play at all speeds, macrotexture is essential at speeds above 30 mph (13.4 m/s). Therefore, it seems necessary that the full friction curve over a range of speeds be obtained from the wear-polish efforts with the circular or linear track. The British Portable Tester will provide readings that indicate the change in microtexture and represent the friction curve up to about 30 mph (13.4 m/s). Beyond this point macrotexture is of importance. The measurement of changes in macrotexture may be accomplished by use of either the Schonfeld method (33), the sand patch test or the outflow meter. However, these measurements must be correlated with friction readings from field studies.

Another system is actual field studies of trafficked surfaces. Skid resistance measurements are taken at frequent intervals with standardized (ASTM) equipment. There is a need for frequent measurements since there can be significant variations caused by relatively minor changes in environmental conditions. The Pennsylvania DOT studies indicate that this system will provide information of value within one to three years under heavy traffic. There is growing indication that practical equilibrium conditions are reached during this period. If we are to obtain useful data, it is essential that everyone place as many field sections as possible together with duplicate test surfaces in the laboratory. This effort will firm up our future efforts to standardize a method of determining the effect of aggregate wear and polish on tire-pavement friction values over the entire range of speed.

Summary

The development of a standardized laboratory device for wear and polish studies including methods of friction measurements over the entire range of operational speeds is presently of great importance in the many areas of the United States especially where limestone aggregates are the main source of supply. In these areas it may be necessary to avoid such materials or blend them with varying percentages of properly sized aggregates known to have superior wear-polish resistance. A suitable laboratory test would provide vital information for making the most economical selection. Although extensive studies have been performed (9) using a circular track, the only method of measurement of friction change was the British Portable Tester. This does not provide all of the information needed.

At the present time, tire-pavement friction values depend on experience with different aggregate types (noted in Figure II). This experience gained from field and laboratory studies makes possible the selection of aggregate combinations to overcome the problem of rapid polishing aggregates. There is an essential and immediate need for a standardized laboratory test method for producing test specimens, wear and polishing techniques, and proper methods of measuring friction which will predict changes in tire-pavement friction over the entire vehicle speed range. It is necessary that such methods be applicable to all pavement types. To be successful the system must also account for the action of weathering of the aggregate.

Design

A primary factor in achieving a skid resistant roadway or runway is the design of the pavement wearing course. The necessity of achieving a skid resistant surface is just one of a number of factors that must be considered by the designer. Some of the others are:

- Smooth riding qualities.
- Limit excessive tire wear and noise. (Noise is not a factor for runway pavement design.)
- Structural stability in order to withstand forces imposed by maneuvers of vehicles, environment, etc.
- Exhibit desirable qualities for day and night driving under changing environmental conditions.

The attainment of these properties is dependent on the careful selection of the properties of the aggregates and the choice of the cementing agent. The design of the several listed types of surfaces follows:

1. Portland Cement Concrete
2. Asphalt Concrete
   a. Continuous Grading
   b. Gap-Graded or Continuous Grading Mixture with Special Aggregate Additions to Surface
   c. Open-Graded
   d. Sand Asphalt
3. Slurry Seal Coats
4. Aggregate Seal Coats

Portland Cement Concrete

Guidelines for Skid Resistant Concrete Pavement Construction have been recently drafted by joint AASHTO-ARBA-AGC Task Force Number 15. These Guidelines (10) present the latest practical state of the art as follows:

Many factors affect the skid resistance of concrete pavement (28). Among the most important factors are the fine texture (grittiness) of the surface, contributed by the fine aggregate, and the coarse texture formed by the method of finishing. The durability of the surface texture is a function of the wear-resistant qualities of the concrete and the character and volume of the traffic.

Mix Design

Mix design formulation for concrete pavements should consider the quality and durability required to produce and retain good textures, during and following construction. The design of quality concrete mixes is adequately covered in current publications, bulletins, and specifications as issued by the Portland Cement Association, Federal Highway Administration, Federal Aviation Administration, American Concrete Institute and American Association of State Highway and Transportation Officials, as well as many other trade associations and state and federal agencies. Research previously referred to, (28) has shown that, to obtain better wear resistance in the pavement surface, special consideration must be given to the following factors:

- Wear resistance of concrete increases as the cement factor is increased.
- Wear resistance of concrete increases as the water-cement ratio is decreased.

A review and study of this information will indicate that, when designing a concrete mix for a pavement which will carry high traffic volumes or involve conditions that will subject the surface to highly abrasive action, the water-cement ratio should be lower (0.50 or less) than normally required for adequate durability under less severe conditions.

To provide good skid resistance, the proportion of fine aggregate in the concrete mix should be near the upper limit of the range that permits proper placing, finishing, and texturing. The sand content should provide an adequate amount of mortar for proper surface texturing without the addition of water or excessive manipulation.

Air Entrainment

Entrained air should be used in all concrete pavements because of the beneficial effects to both plastic and hardened concrete. An important benefit is to protect the textured surface of the pavement from the effect of alternate cycles of freezing and thawing and the application of deicing salts. Air entrainment also improves concrete in the plastic state by:

- Reducing segregation when hauling in nonagitating conveyances and during placing operations.
- Increasing workability.
- Reducing bleeding.
- Reducing the amount of water required for satisfactory workability.

Each of these factors contributes to the production of an adequate and durable surface texture.

The amount of entrained air needed to produce durable concrete varies with the maximum size coarse aggregate. The Joint Task Force (8) recommends the grading be within the following ranges:

Maximum Size of Coarse Aggregate, In.	Air Content, Percent by Volume
1-1/2, 2, or 2-1/2	5 ± 1
3/4 or 1	6 ± 1
3/8 or 1/2	7-1/2 ± 1

When entrained air is not required for protection against freeze-thaw or deicers, these air contents may be reduced by about one-third, while still obtaining the other benefits of air entrainment.

Aggregates

Where abrasion-resistant aggregates are not economically available, locally available aggregates with relatively low resistance to polishing may be used in the bottom layer of pavement. More expensive, hard and angular polish resistant aggregates would be required in a relatively thin surface course placed while the lower course concrete is still plastic. While this is not yet a common practice in this country, it is expected to be used more often as high quality aggregates become more scarce. The practice is in wide use in Europe.

Fine Aggregate

Research to date indicates that the siliceous particle content of the fine aggregate as determined by the acid insoluble residue test should not be less than 25 percent (28). The siliceous particle content is very important, and where economically feasible, a higher percentage should be required. Where suitable materials conforming to these requirements are not economically available, alternate methods of achieving a skid-resistant surface should be investigated. These might include blending of fine (natural) aggregates with synthetic aggregates or applying wear-resistant particles to the surface of the fresh concrete.

Coarse Aggregate

Coarse aggregate will not affect the initial skid resistance of concrete pavement, but will have an effect if it becomes exposed due to surface wear. The performance record of the coarse aggregate under consideration should be evaluated in terms of skid resistance.

Asphalt Concrete

After consideration of local material availability and environmental conditions, the designer must establish the tire-pavement friction need primarily on the traffic speed. As previously mentioned, a certain degree of microtexture is always needed for both low and high speed traffic; however, high speed traffic requires, in addition, an adequate macrotexture for rapid drainage.

There are a number of different types of asphalt concrete and surface treatments involving asphalt as a binder. Therefore, the designer has much flexibility when working with surface types containing asphalt as a binder. However, the designer must keep in mind that the choice of a surface type in terms of skid resistance must be balanced with other important factors such as availability and characteristics of local materials, climate, traffic and other factors.

The designer must select his aggregates to provide sufficient microtexture as well as a proper choice of crushed particles and gradation to insure adequate macrotexture. Generally aggregates fitting the selected requirements, if exhibiting resistance to wear and polish, will also aid in providing sufficient stability to the pavement. Presently used mix designs such as the Hveem and Marshall methods may be used to obtain the desired asphalt content. The determination of the optimum asphalt content is a very critical design decision, not only for pavement skid resistance but also for structural adequacy. An excess of asphalt cement in any pavement type or surface treatment may rapidly lead to "bleeding" or a "flushed" surface, one of the most serious wet weather skid hazards and a very difficult maintenance problem.

As discussed previously polish resistant aggregates may be scarce in some areas. Under these circumstances, skid resistant mixes may be designed by blending imported coarse polish resistant aggregate with polish susceptible fines. At the present there is rather limited knowledge on the percentages to be used in the blend.

Another method that may be used in this situation is a sprinkle treatment (10). In this case, one may design a continuously graded mix containing a polish susceptible coarse aggregate and, following laydown and prior to rolling, sprinkle the surface with 3-7 pounds/sq. yd. of a polish resistant precoated coarse aggregate. This method has also been used for a number of years in England where very dense mixes, gap-graded, high in sand are laid. These mixes have a very smooth surface, so they are finished with a sprinkle treatment. The designer should be aware that the two designs relative to the application of surface aggregates are for meeting the same criteria, but should be selected on a different basis. In the first system, the surface aggregate is for the purpose of preventing rapid polish of the coarse aggregate in the mixture. In the second case, the purpose is not only to provide resistance against polish, but also to provide a drainage system since the underlying mix within itself will produce a smooth rolled surface.

Another excellent anti-skid pavement is now known as an open-graded friction course. This mix contains about 30-40% voids and has a high film thickness. The voids and heavy texture created by a coarse grading provide an excellent nonskid surface. Both surface drainage and sub-surface porosity are provided so as to drain surface water away rapidly. If the aggregate properties, gradation and asphalt content are properly selected, the resulting mix will not only provide microtexture but, of great importance, outstanding macrotexture. This mix has been found to be a highly satisfactory asphalt concrete surface course for runways (11, 12). Its performance for high speed highways has been excellent.

The designer must be aware of certain overall requirements for open-graded pavement mixtures. Since this type of pavement permits very rapid downward movement of water, the underlying pavement must be impermeable to prevent entrance of free water into the structural section. Cross-slope must be sufficient to allow rapid movement of water through the open-graded surface onto the adjacent shoulder. This is of special importance in hilly country where rapid longitudinal flow of water through an open graded surface may build up water to above the surface in swales, creating a severe hydroplaning situation at these locations.

The most recent design procedure together with gradations and other aggregate properties are found in references 11, 12, 13, and 14.

Another form of surface is sand asphalt mixes. Kentucky Bureau of Highways has proposed four types of sand asphalt surfaces (15) as follows:

Type 1 - dense-graded; for general use.
Type 2 - dense-graded; skid resistant; for moderate speed traffic.
Type 3 - open-graded; skid resistant; intended for moderate traffic.
Type 4 - open-graded; skid resistant; intended for high speed,heavy traffic.

Reference 15 contains proposed specifications for these different types as well as a paper by J. H. Havens on porous sand-asphalt mixtures. This paper describes the development of Type 3 and Type 4 mixtures wherein modification of a sand asphalt paving mixture leads to adequate microtexture and also to direct removal of surface water by downward drainage in the same manner as the previously described open-graded friction course. This would then provide the necessary drainage for high speed traffic.

The recommendations put forward for open-graded sand asphalt (15) have been partially implemented by the Kentucky DOT and the continual development of the state of the art should soon permit the full use of sand asphalt mixtures for the full range of highway speeds. They recommend that sands be selected in terms of mineral composition, gradation and particle shape. The need for excellent wear-polish characteristics of the aggregate, even for lower speed sand asphalt surfaces, is clearly indicated. The dense-graded, moderate speed surface, requires the sand to be either crushed slag or a select angular high-silica material containing at least 75% SiO_2. This requirement must be met on the portion of sand retained on all sieves down to and including the 100 mesh sieve. Field studies by Kentucky clearly indicate the need for controlled wear or attrition under traffic and the accompanying continuous renewal of the all-important microtexture.

Slurry Seals

Slurry seals in most specifications are a form of sand asphalt mixture. The main difference is in the method of preparation and construction. An asphalt emulsion is used in the slurry seal mixture and the percentage of material passing No. 200 sieve is higher than normal. Unless a larger size aggregate is used, most slurry gradations lead to a microtextured surface with little macrotexture for drainage under high speed traffic. Therefore, the material should be considered for use mainly on moderate speed roads unless the designer uses gradations involving larger sized aggregates. As with sand asphalt mixtures, the problem of wear-polish must be carefully considered. Of great importance is the use of proper design tests for asphalt content since these seals are critical in terms of "bleeding."

Aggregate Seal Coats

Aggregate or screening seal coats involving different maximum sized aggregates have been used on pavement surfaces for many years. The designer has flexibility with this type of surface since he is able to provide microtexture and a choice of a maximum size aggregate allows development of gradations that will produce different amounts of macrotexture depending on the volume and speed of traffic.

Design methods are available (16, 17, 18). This state of the art is being used in most States and other agencies for determining the amount of required asphalt. A continuing problem to the designer is the selection of satisfactory aggregates, especially in terms of resistance to wear and polish. Presently, most specifications require a crushed aggregate and many define the geologic type of aggregate. A special problem to the airfield engineer is the selection of aggregate quantities so as to eliminate loose aggregate.

At the present time, methods of design are following the most recent state of the art for the various asphalt surface systems. Once again the problem that must be solved is the development of laboratory methods for preparing test specimens of the different surface types that will simulate the final texture found in the field after completion of construction. Following this, one must standardize a method for wear and polish and a procedure for measurement that will provide measures of change in micro and macrotextures and the significance of such change in the wet tire-pavement friction values for various operating speeds.

Construction

One of the most important requirements for attaining satisfactory initial skid resistance as well as minimum change during the service life is the use of proper construction methods. Methods provided by the specifications must be rigidly followed since such methods are an integral part of the designer's overall procedure for providing a satisfactory surface.

Portland Cement Concrete

One of the surfaces whose tire-pavement friction is heavily influenced by variables in construction techniques is portland cement concrete pavement. The creation of a satisfactory macrotexture or surface dtainage system for this type of pavement is primarily dependent on the construction procedure followed during surface finishing operations.

The state of the art for concrete pavement finishing shows many recent improvements. The old traditional method of forming striations by burlap dragging does not consistently furnish surface sufficiently textured. Other methods are under intensive investigation. Numerous field trials are underway on both highways and runways. Recent proposed guidelines (8) recommend burlap finishing only where low speed limits are in effect. Instructions for burlap finishing in combination with plastic grooving are available (30). According to reference (19), 46 states in 1969 were approving a burlap-drag finish of highways; however, in most cases the burlap drag finish resulted in less texture depth than recommended by leading organizations involved with concrete pavement technology.

It is interesting to consider the possible reasons for failure of the normal burlap drag system to provide adequate resistance to wear and polish. According to Reference 19, research on actual pavements under traffic disclosed that for texturing methods using burlap drags, brooms, and belts, generally the wear rate increased with texture depth. "Probably this rapid rate of wear is due to the fact that most of the texture above the general plane of the surface has less strength and abrasion resistance than the mass of the slab." Experience indicates that the situation presented above may not be due to the inadequacy of the burlap method as specified by the designer, but the actual nature of the finishing operation. For instance, the use of excessive water during the final finishing operation.

After problems occurred with the burlap drag, the use of brooms for finishing was instituted. This treatment produces a deeper texture with better drainage, and several States now approve the use of this method. However, according to Reference 19 most engineers preferred a fairly light brooming to minimize noise from roadways (noise is no problem for runways).

The development of sawed grooves in the hardened concrete of highways and airport runways as a system for increasing drainage and thereby reducing the danger of hydroplaning is well known (20, 21, 25, 26). The high reduction in accidents clearly indicated that grooving might be very effective for the original concrete surface. Research continues on methods for texturing plastic concrete. An excellent survey of the status of these methods is available (19). A continuing problem is the direction of sawed grooving. All grooving on airport runways has been in the transverse direction which, based on cross slope and water movement, etc., is the most efficient direction (29). The British have demonstrated that transverse grooving for highways is effective (4). On the other hand, extensive wet weather accident studies in California (22, 24) have clearly indicated excellent results with longitudinal grooving, especially on curves.

On the basis of the results from presently available studies (19), the state of the art is to groove both highways and runways employing combs with steel tines while the concrete is in the plastic state condition. The depth and width of the grooves is still a subject for further field studies. However, a tentative guideline has been suggested by the American Concrete Paving Association (30).

Methods for forming plastic grooves are still in a stage of development. A factor of great importance, as with other forms of finishing operations, is timing for texturing. The optimum time to texture depends on such variables as consistency of the surface mortar, temperature, humidity, and wind velocity. In other words, correct timing must be determined on the job as the job progresses. Presently, experience must be the final judge. There is little doubt that research into texturing of portland cement concrete pavements should be given the highest priority in the immediate future by paving engineers. As stated in a number of places in this paper, it does little good to form an adequate texture in a portland cement concrete pavement if the texture virtually disappears within a few years. In fact, skid-prone surfaces due to such wear was the reason for the development of grooving of existing highways. If the surface mortar strength is properly maintained during construction operations, then the primary construction factor influencing durability and wear resistance of the concrete surface is the effectiveness of curing. Curing compounds have been developed and machines built for uniform application. The use of presently available knowledge result in a durable ourface. However, in future field trials involving plastic grooving, careful observations should be made of the coating of the sides and bottom of the grooves. Effective coating of these areas is of great importance, especially at the groove-surface edges where spalling could occur. Another concern is that the grooves be of sufficient width and depth so that the curing compound coating does not materially decrease the area of the groove. It should be noted that this could effectively reduce the drainage capacity of the groove and defeat the purpose of the operation since compound in this area will not be removed by wear of traffic.

Another possible method for preventing wear of the surface is the use of hardening agents such as polymers. This type of treatment is in the experimental state (23). Because of high cost, laboratory and field studies are necessary prior to use.

Asphalt Surfaces

As previously stated in the section on Design, there are two major ingredients in providing skid resistance in asphalt concrete mixtures: large-scale texture, and fine, gritty texture, each is controlled by the aggregate size gradation and mix design. Therefore, a proper design involving a continuous grading, if rigidly followed during construction, should lead to a satisfactory tire-pavement friction.

When special aggregate additions (sprinkle treatments) are made to the surface during construction, certain difficulties may be encountered. This is probably caused by the newness of the system and the need for special equipment. Such equipment has been designed and built by the Virginia Department of Highways and used successfully to apply a precoated aggregate. Such a system is used to provide a skid resistant layer over a mix containing locally available polish-susceptible aggregates. This type of construction requires carefully-controlled construction practices or serious problems may occur with bleeding or rapid polish of the susceptible aggregates. Open graded friction courses require careful construction control (11, 13, 14, 29). Control of mixing temperatures, limitations during adverse ambient periods, proper preparation of existing surface including cleaning and tack coating are some of the important variables that should be under strict control. Many miles of roads and, recently, airport runway areas have been successfully constructed with such porous friction courses. The state of the art is being followed with some well-defined methods for proper construction practices.

Sand asphalt mixes also have well-defined and recommended construction practices (15).

All forms of seal coats, sand, slurry and aggregate require the use of proven construction methods, satisfactory environmental conditions, careful quality control of materials and adequate traffic control. Improper construction has resulted in aggregate loss from seal coats, while the prevention of such losses from roadways is important, it is critical to runways. Construction equipment for seal coat operations has been developed to a very satisfactory state.

Distributors, when kept in proper condition, are capable of spreading an accurate desired amount of binder in a uniform transverse and longitudinal direction. The spreading of aggregates (screenings) in a rapid and uniform manner can now be accomplished by available equipment. Rolling with both pneumatic and steel-wheeled rollers is easily accomplished. However, the state of the art still requires a great deal of experience. Weather conditions at the time of sealing, and traffic control in the first hours after construction, are very critical to the future performance of the seal coat. References 17, 18, and 29 should be carefully studied.

In summary, we can now say with assurance that our present construction procedures can build surfaces for either roadways or runways that provide satisfactory skid resistance. As pointed out previously, the production of a "durable" texture for portland cement concrete pavement is still under investigation and the necessary machines to perform what appears to be a satisfactory solution are still under development.

Even with adequate design, asphalt surfaces may present future problems in maintaining proper tire-pavement friction values because of poor construction procedures. Hankins writes, private communication from Texas Highway Department) "We feel future work is needed on the effects of construction on skid resistance. When we study the polish rates of different construction jobs even using exactly the same mix, large variations in skid resistance are noted as traffic applications cumulate. Some of this variance is due to 'weathering' or seasonal effects, but there is also variance resulting from construction differences."

Probably the most serious skid problem encountered with asphalt pavements is bleeding or failure of surface treatments. This can be prevented by known mix design procedures and proper construction control.

A very important objective for the future should be the continuing effort to improve construction procedures so that a uniform pavement texture is attained that complies in all respects with the design of that surface in terms of original and service life skid resistance requirements.

Maintenance

The present state of the art of design and construction of skid resistant pavements can provide an anticipated service life. However, construction problems, materials variations and increases in traffic beyond that assumed during design may cause an accelerated service wear and polish to occur, leading to an unsatisfactory skid resistance short of the calculated service life of the facility. Therefore, to be assured that a satisfactory roadway or runway is maintained throughout the service life, the continued use of the pavement will require some form of rehabilitation in order to insure a reliable skid resistance, rideability and structural adequacy. It may even be necessary to cover the existing surface which will require a new design and adequate skid resistance.

Portland Cement Concrete

A method of maintaining skid resistance of portland cement concrete pavements is the sawing of grooves in large areas of concrete surfaces. This technique is outlined in the chapter on Construction. The present state of the art is summarized in reference 26.

Methods for modifying existing concrete surfaces to increase skid resistance are acid treatment, different forms of mechanical abrading and sawed grooving (previously mentioned). References 2 and 27 provides information on the use of such methods. According to reference 2 the benefits from acid etching are rather short lived; usually such treatment will be effective for less than a six-month period. There are a number of different methods for mechanical abrading of existing concrete surfaces. One method employs a machine with hardened cutters rotating on a drum. Another machine uses several percussive hammers mounted side by side. These strike the pavement at a rapid rate and each impact removes a small amount of the existing surface material. These methods improve the tire pavement friction and increase drainage; however, the degree of improvement and the duration of such an improvement is difficult to assess since the nature of the existing surface will govern the amount of change in texture.

Asphalt Concrete

Asphalt concrete pavements and seal coats may suffer a loss in skid resistance in a number of ways. The existing surface may become worn or polished or, because of an excess of asphalt or loss of surface aggregates, a "bleeding" condition may occur.

In the case of isolated "bleeding" a heater planer treatment may be used for removal of the excess surface asphalt and, coupled with an immediate application of screenings or sand, the tire-pavement friction may be definitely increased. However, this treatment should, in most cases, be considered as temporary since excess asphalt throughout the pavement may again cause a "bleeding" condition.

Depending on the surface condition, grooving may be performed on asphalt concrete pavements. Such pavements should be those with a high aggregate content and of such age that the asphalt binder is relatively hard. At the present time, insufficient information is available on the state of the surface that will insure the grooving to be "durable".

Probably the best system for improving the tire pavement friction value is the application of a new asphalt concrete surface. All of the previously discussed surfaces (seal coats, blankets, etc.) may be used for this work. The thickness will depend on whether such an overlay is to correct only skid resistance or is also being used for improving structural adequacy. In any case, the same care in design and construction must be used for resurfacing as used on the original pavement.

A serious problem encountered on runways of any material is the buildup of rubber from tires of aircraft. This markedly reduces the tire-pavement friction. A number of methods are available for removing the rubber, including chemicals, high pressure water blasting, sand blasting, and shot peening, to improve friction.

The Future

The paving engineer has the responsibility to provide adequate tire-pavement friction for contemplated operating conditions and for a satisfactory period of service. At the present time he does not have the required tools to fulfill these requirements with the necessary degree of confidence, especially when one considers the economic aspects of pavement design and construction. The following areas are recommended for high priority attention by researchers and paving engineers. A most important objective for the future is the development of laboratory methods, properly correlated with field studies, that will provide test specimens which represent all forms of pavement surfaces, a wear and polish system that simulates the action of traffic and, finally, methods of friction measurement that will recognize micro and macrotexture effects through the operating range of vehicle speeds. The accomplishment of these tasks is far from complete. Their importance cannot be overstressed since an increasing amount of effort is being expended on determining minimum standards for skid resistance. Once such standards are adopted, the designer must have the tools to design a surface to meet the standards.

Another immediate need is for intensive study of construction practices for both asphalt and portland cement concrete. Design of equipment to produce an adequate surface texture for portland cement concrete pavement is needed. Such a surface to provide the desired initial requirements for micro and macrotexture and prevent such values from falling below a minimum value during the assumed service life.

Studies should also be initiated on construction control parameters that influence the uniformity of pavement friction values and surface undulations (this latter is of special importance to runways).

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