CONVENTIONAL CHIP SEALS AS CORRECTIVE MEASURES FOR IMPROVED SKID RESISTANCE

Bob M. Gallaway and Jon A. Epps, Texas Transportation Institute,
Texas A&M University

Chip seals are used to improve the surface friction or skid resistance of streets and highways. Their desirability is discussed. Properties including aggregate gradation, type, size, and mineralogy and surface texture are reviewed; bituminous binder type, viscosity, and amount are discussed and related to field experience. Relations of factors associated with the binder and the aggregate are evaluated. Also evaluated are design, construction, and performance to improve skid resistance of the finished surface.

•THE LITERATURE abounds with articles dealing with the many facets of street and highway renovation or improvement by conventional chip seal, which consists of separate applications of bituminous binder and cover aggregate. Chip seals have for many decades been used primarily for purposes other than improved skid resistance although improved skid resistance would often result from this type of maintenance. In this paper attention is centered on chip seals used as corrective measures for streets and highways with undesirably low surface friction or skid resistance. Pros and cons from the owner-user and producer-contractor viewpoints are discussed. Basic factors such as material properties including aggregate gradation, type, size, and mineralogy; surface texture and size; and bituminous binder type, viscosity, and amount are related to field experience as these factors affect the skid resistance properties of various material combinations under traffic in rural and urban areas.

Past investigations have dealt with basic objectives and benefits of conventional seal coats (2, 3, 4). Researchers have reported on design procedures, aggregate requirements, and construction-related operations (1, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14). More recently, however, investigators have directed increasing attention to the skid resistance properties of seal coats and the desirable attributes of cover aggregate and bituminous binder (15, 16, 17, 18, 19, 20).

Kari, Coyne, and McCoy (21), who described in detail the relationship of the input of the binder to the success of the job, dealt with the desirable properties of binder consistency and durability. Specifically the authors stated that

> Asphalt binders suitable for seal coats must have the following properties:
>
> 1. Be capable of being sprayed uniformly over the road surface. Streaking, bleeding and raveling can be minimized by controlling the uniformity of longitudinal and transverse spread.
> 2. Resist runoff, i.e., not flow off the pavement after application. This insures sufficient binder to prevent loss of cover aggregate on grades and super elevations.
> 3. Wet the aggregate and be sufficiently fluid to permit compaction of the seal. This becomes critical in cold weather due to the increase in asphalt viscosity.
> 4. Rapidly develop cohesion and bond to both the pavement and mineral aggregate. Shoving and scuffing during hot weather will result when cohesion is low.
> 5. Resist displacement by water and other disruptive forces (i.e., gravitational and mechanical forces). Loss of bond between the asphalt and aggregate will result in raveling.

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6. Resist factors influencing aging. Hardening of the binder will result in fracture of the asphalt film and raveling under traffic.
7. Be uniform from one delivery to the next. Product uniformity aids in the successful construction of a seal coat. Product uniformity is dependent upon suitable specifications. All of the desired performance properties listed above are related to or can be described in terms of consistency and durability.

One may readily infer from this list of requirements that a relationship among weather, climate, and binder properties exists and that binder durability is vital. Aggregate properties that are necessary for producing high-quality seal coats include items such as amount of stone, gradation, size, shape, abrasion resistance, color, moisture condition, cleanliness, adhesion, freeze-thaw resistance, and polish susceptibility. Details of the relative effects of these properties are discussed by Herrin, Marek, and Majidzadeh (1); Kersten and Skok (11); McLeod (2); Gallaway and Harper (12); Benson and Gallaway (5); and Wilson (22).

Each method on the design of seal coats contains certain differences based primarily on available materials, individualized traffic demands and to some extent the personal likes and dislikes of the person who developed the method. Design methods deal primarily with application rates for binder and cover aggregate with estimated adjustments for condition of the surface to be sealed, amount and type of traffic expected during the estimated life of the seal, and climatological effects of these factors.

Hveem, Lovering, and Sherman (9) proceeded from the work of Hanson (23) and developed nomograms to estimate amounts of binder and cover stone for given material properties and traffic demands. Nevitt (24), in his work on seal-coat design, stressed a point that has grown continuously in importance over the years—the thrifty use of all materials and efforts. Nevitt also stressed the importance of aesthetics, a point that commands the respect of concerned road maintenance personnel today. Others who have published seal-coat design procedures are Kearby (6), Benson and Gallaway (5), Lovering (25), Kuipers (26), and McLeod (2). Their common design thread is the selection of the proper amount of binder for a given top size and grading of cover stone. Usually a binder quantity adjustment for road surface condition is included. Primarily, this adjustment is based on surface texture, although none of the articles specifically referred to adjustment as being based on surface texture.

Two factors omitted by many writers are those of traffic type, volume, and weight and effect of a soft substrate. Nor was much said about climate in relation to selection of binder viscosity.

Empirical curves were presented by Gallaway (27) for estimating a binder quantity correction for traffic volume. These curves assume average rural traffic, 15 percent of which is trucks. The correction provided for additional binder scaled from no correction for traffic above 1,600 to 2,000 vehicles per day (vpd) for 2 lanes to a maximum correction of 0.05 to 0.06 gal/sq yd (0.23 to 0.27 litre/m^2) for traffic volumes less than about 50 vpd.

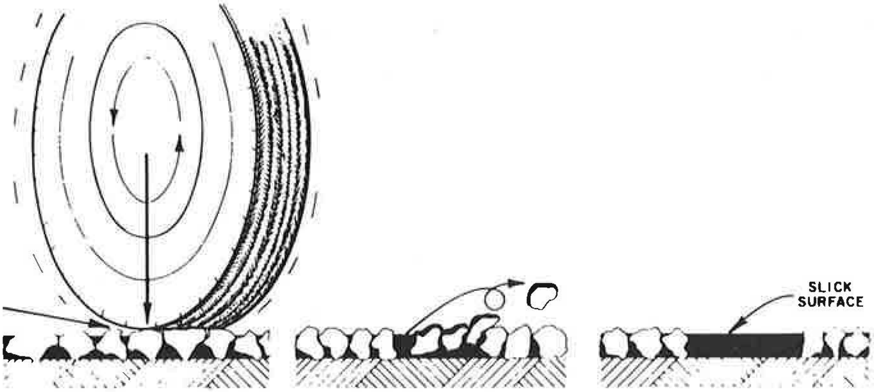
Cover aggregate may be submerged in the binder, not because the design was incorrect but because the stone was forced into the underlying substrate or existing surface. Problems of this type are associated with inadequate compaction (low density) of the surface layer that is to receive a seal. It is often relegated to restricted areas such as patches that have been made before sealing. If parts of the surface require reworking in preparation for sealing, they must be adequately dense to prevent intrusion of the cover stone because intrusion often results in flushing.

For an average rural highway carrying a traffic volume of less than about 2,000 vpd, the percentage of trucks may be expected to be rather low and restricted in loads; therefore, the usual seal coat design will disregard the effect of heavy loads and high tire pressures. The ill effects of this omission are shown in Figure 1. In the construction of this seal coat a full road width distributor was used to apply binder to the entire surface in 1 pass. Loaded haul trucks, not anticipated in the design stage, caused the problem in the flushed lane. The other lane, which apparently has received the design amount of traffic, is performing beautifully.

Excessive horizontal shear forces can cause similar problems; these will exist on

Figure 1. Flushing seal coat caused by unexpected truck traffic.

Figure 2. Flushed seal coat caused by cornering action of traffic dislodging cover stone.



SOFT ASPHALT - FORCES DUE TO VEHICLE TURNING OR CORNERING

AGGREGATE PARTICLES DISPLACED COATED SIDE EXPOSED

AGGREGATE PARTICLES REMOVED BY TRAFFIC

Figure 3. Binder demand affected by surface hunger.

Figure 4. Lack of uniformity of surface to be sealed.

sharp curves and at intersections, particularly, in urban areas. A schematic of this effect is shown in Figure 2. Different approaches may be used to solve this problem. One is to avoid the use of a seal when it would be subjected to this type of traffic. Another possibility would be to select a higher viscosity binder and use this in combination with a smaller-sized cover stone. A smooth-textured stone would not be dislodged as easily as a rough-textured stone, but for safety reasons a low-friction surface should be avoided.

MATERIAL SELECTION

In preparing specifications for a job, one should remember to write them around (a) available materials, (b) contractor capabilities, (c) buyer's willingness to accept contractor's finished product, and (d) for most public streets and highways, general public acceptance of facility performance. Selection of the binder and cover aggregate must be economically justifiable as well as technically sound (25). The general characteristics of the binder have been discussed in detail by many writers (2, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38). Much also has been written on the interaction of the properties of cover aggregate and binder for a given design and environment and how it relates to skid resistance of the surface (18, 19, 20, 39, 40, 41, 42, 43, 44, 45, 46, 47). It is evident from the findings that for prolonged high skid resistance, the selected cover aggregate must possess and maintain both macrotexture and microtexture during its service life. Adequate macrotexture may be available in suitable size ranges in both natural and manufactured aggregates.

Natural aggregates that abrade rather than polish under the action of weather and traffic usually meet microtexture requirements as do aggregates composed of a proper mixture of hard and soft particles. Sandstones are examples of the former and conglomerates, the latter. Hard particles dispersed in a soft matrix such as silica sand in a limestone matrix have also been found suitable as nonskid cover stone (19, 48).

Lightweight manufactured aggregates have been used widely to produce high-friction surfaces. The critical property of such materials is microtexture, which exists throughout individual "stones" as blebs or gas pockets formed during the heat cycle of manufacture. Such microtexture is subject to continuous renewal under the action of traffic. The manufacture of "engineered" aggregates is technically and economically feasible, and proof of performance has been published by James (49), Britton (45), and Gallaway and Epps (42). Again, a key property is that of renewable microtexture, which is often controllable in raw material formulation and in manufacturing.

A factor of primary importance that is often entirely neglected in the design phase is the magnitude of the tumbling force of a pneumatic tire operating in the cornering slip mode, a common mode in urban traffic. The magnitude of this tumbling force is affected primarily by the friction between the tire and the contacted aggregate and the length of the moment arm from the center of rotation of a given stone. This moment arm, therefore, directly relates to the size of the cover aggregate. Or, large stones generally are more easily tumbled than small ones. This assumes roughly equal bond tenacity for all sizes of stone, which seldom prevails because an adequate design calls for a binder quantity equivalent to an embedment depth equal to about half the average stone size. So, a dilemma exists. It is questionable whether conventional seal coats should be used in moderate to heavy urban traffic for this reason. The reasoning is sound, and we recommend against the use of seals under this type of traffic. The use of high-friction aggregate simply aggravates the problem. If one persists in the use of chip seals for medium to heavy urban traffic, extreme care in the design and construction phases of the job is absolutely necessary. Things to be considered include condition of the surface to be sealed (Figs. 3 and 4), type and weight of traffic to be encountered, and climate.

Conventional seal coats are highly effective and economically justified on lightly traveled city streets, county roads, and rural highways subject to traffic volumes up to approximately 4,000 vehicles per lane per day, provided such rural highways do not have numerous steep grades and sharp turns. This type of road would be in the same category as those that carry heavy urban traffic.

Use of single-sized aggregates is logical because one can closely determine binder demand for an assumed embedment depth. The margin for error in arriving at the design binder application rate is greater for single-sized stone. Specifying an aggregate size is simple, but its economical production is often difficult. For some sizes for which there are limited needs, prices are high. Handling and hauling may cause the specified sizes to change and cause rejection at the job site. Although seals made from such select stone are visually pleasing, it is difficult to attribute service performance to stone size alone. One might claim that a certain stone size causes better water escape at the tire-pavement interface at high speeds and under inclement weather conditions, but this would be difficult to prove.

Carefully controlled laboratory tests by Benson and Gallaway (5) and others have shown conclusively that cover aggregates with excess fines cause extensive problems. Because such cover aggregates are usually available at reduced costs, they are used when price is important in material selection. But, results are often disastrous especially when uniformly good skid resistance is desired. Size control is definitely important to uniform skid performance of a road surface. Macrotexture obtained by exposed rugosity of cover aggregate ensures water escape at the tire-pavement interface and in locked-wheel stops. So, a compromise is necessary. Small amounts of oversized and undersized material can be permitted in specifications. However, caution is recommended, particularly on the permissible amount of dust. More than 1 percent dust is highly detrimental to the early establishment of a bond. A disadvantage of oversized material is dislodgment by traffic, which causes flying stones (12). A wide range of sizes makes it difficult to optimize binder quantity. Small particles will be inundated and large stones will be embedded too lightly. Oversized material should not exceed about 2 percent and no material should be retained on the next larger sieve. Example specifications of the Texas Highway Department (THD) are given in Table 1 for item 302, class B cover stone (50). Sizing requirements for THD item 303, lightweight aggregates, are given in Table 2. It is interesting to note that similar grades given in these tables are not sized the same way. The lightweight material is somewhat coarse probably because some breakdown is expected in hauling and handling. And, only 3 grades (size ranges) are given for the lightweight material. Extensive experience in Texas with lightweight manufactured aggregates has shown conclusively that grades other than these 3 are both unnecessary and undesirable. Larger sizes are generally more difficult to produce and are usually structurally weak; smaller sizes create design and construction control problems.

Bituminous binders for seal coats include asphalts and tars, and both materials have performance advantages. The primary differences in the 2 types of binder are temperature susceptibility and wetting ability. Tars are more susceptible to change in viscosity with change in temperature, and they are better wetting agents than are asphalts. Both binders are available in different forms such as cements, cutbacks, and emulsions and in a wide range of viscosities. This wide choice of binder form and property adds to the difficulties of the seal-coat designer. Uniform distribution in the desired amount of residual cement is the general objective in seal-coat work, but performance viscosity is often critically important. Selection of the form of binder may be based on convenience. Let us assume that different forms and viscosities are available and that recommendations will be made in keeping with construction constraints and service demands for improved surface friction. Binder service viscosity should be determined by compromise, considering the primary factors of climate, condition of surface to be sealed, and anticipated traffic including both volume and weight. Other minor factors may be included, but generally these will be found to have an effect so small as to be clouded by lack of construction control. Cold climates require softer binders with viscosities around 300 stokes ($0.03\ m^2/s$) at 60 C (THD AC-3); hot climates require hard binders with viscosities of 1,000 to 1,500 stokes (0.1 to $0.15\ m^2/s$) at 60 C.

Bond tenacity is critical and is determined primarily by binder viscosity at service temperatures and aggregate surface properties and secondarily by depth of stone embedment (51). Establishment of this bond is assumed to be effected by intrusion of the stone into the binder and its preferential wetting (29). Wetting of the stone is enhanced by having the stone clean and dry for hot cements and cutbacks and clean and slightly

Table 1. Class B aggregate for surface treatments.

Sieve Size	Percent Retained Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
1 in.	0	0	0	0	0
⅞ in.	0 to 2	0	0	0	0
¾ in.	20 to 35	0 to 2	0	0	0
⅝ in.	85 to 100	20 to 35	0 to 2	0	0
½ in.	—	85 to 100	20 to 35	0 to 2	0
⅜ in.	95 to 100	95 to 100	85 to 100	20 to 35	0
¼ in.	—	—	95 to 100	—	0 to 5
No. 4	—	—	—	95 to 100	—
No. 10	99 to 100	99 to 100	99 to 100	99 to 100	99 to 100

Note: 1 in. = 25.4 mm.

Table 2. Lightweight aggregate for surface treatments.

Sieve Size	Percent Retained Grade 3	Grade 4	Grade 5
¾ in.	0	0	0
⅝ in.	0 to 5	0	0
½ in.	30 to 50	0 to 5	0
⅜ in.	85 to 100	20 to 40	0 to 2
¼ in.	95 to 100	—	—
No. 4	—	95 to 100	60 to 80
No. 10	98 to 100	98 to 100	98 to 100

Note: 1 in. = 25.4 mm.

Figure 5. Shaded areas of seals using emulsions develop bond more slowly than exposed areas.

Figure 6. Binder demand may vary across pavement and transverse adjustment of spray bar output may be required.

wet for emulsions. Wetting of the stone by the binder requires time. And more time is necessary when viscosity increases at the time the 2 materials are mated. For example, bituminous cements sprayed at 300 F (150 C) on a road surface at 120 F (40 C) will cool to approximately 130 F (54 C) in less than 3 min. Cover stone is seldom applied within this time, and, therefore, one should not assume that the binder is liquid when the stone hits it. Time and force is required for intrusion and wetting. Stone that is wet or dirty or both impairs the wetting rate; these adverse factors must be considered to arrive at the delay time before traffic is allowed on the surface. Emulsions have the advantages of easy intrusion and quick wetting. They also are nonpollutants. McKesson (8) in 1948 reported on the use of emulsions for seals as did Bower (36) in 1960 and Bohn (37) in 1963. Recent improvements in the uniformity and quality control of emulsions plus the adverse effect of cutback on the environment should lead to a continued increase in the demand for emulsions. Quick setting cationic emulsions made from high-viscosity binders are most effective in warmer climates. Lower viscosity base cements should be used in cold climates. A definite advantage of the cationic type is that weather has minor effect. According to J. Dybalski of the Armak Chemical Company such emulsions break primarily by surface attraction and can be formulated for controlled break rates even under conditions of high humidity and cool weather.

In constructing seals that use emulsions, the use of pilot cars is advised for traffic control. Before allowing traffic on a newly sealed surface, a check for degree of break and bond tenacity should be made in shaded areas of the road surface. Break is usually delayed in such areas, and, if the road is turned over to traffic prematurely, excessive whip-off may result in shaded areas (Fig. 5). This problem is associated particularly with anionic emulsions, which break by evaporation or absorption or both. Cationic emulsions are affected only slightly. The shade effect is generally more prevalent in residential areas of cities than elsewhere. Cutback asphalts have been used worldwide as binders for seals for decades (52, 53, 54, 55). The use of cutbacks in cold climates is technically valid, but even in these areas flushing may be a problem during the summer months, according to Robinson (52). As an expedient, cutbacks have been and are being used in the fall in Texas, but bleeding during early summer of the next year is a common fault and makes their use suspect for most other reasons. Two alternate solutions are suggested:

1. Use hot cement and heated cover stone, or
2. Use a cationic emulsion with heated stone, if necessary.

Early establishment of bond is enhanced by lightly precoating the aggregate with 0.5 to 1.0 percent of a medium curing type of cutback. Precoating of cover stone is widely practiced with generally improved results over natural aggregates, at least for early establishment of bond. There is little evidence that friction values are changed appreciably by precoating.

EQUIPMENT AND CONSTRUCTION OPERATIONS

Seal coats are often used on roads that should be completely reconstructed. Many times the results of such a decision are embarrassing. If a surface to be sealed is in need of spot improvement to restore riding quality and improve structural capacity, this should be done 60 to 90 ninety days in advance of the seal-coating operation. Such planned repairs improve the probability of a successful seal. Herrin, Marek, and Majidzadeh (1) made sound recommendations concerning the preparation of the underlying surface. Power brooming is a necessary prelude to binder application. In urban areas a vacuum attachment to the broom is advised and some manual cleaning may be necessary.

Before applying the binder to the throroughly cleaned surface the pressure distributor should be calibrated and checked for operational efficiency. Schuelie (14) has reported on equipment needs for seal-coat work and emphasizes the need for spray bar calibration. Selected districts of the THD require a complete annual recalibration of distributors used in those districts. Additional check tests are made at tne beginning of each day's operation. Because of variations in binder demand across lanes of some pavements, it is often advisable to reduce binder application in the wheel path. An example of variable transverse demand is shown in Figure 6. Reduced application of binder is accomplished by substituting smaller nozzles in the spray bar at the point of reduced demand.

Uniform spreading of the design amount of stone is made easier with a continuous feed machine as opposed to a tailgate spreader. The use of a deflector to aid in the separation and earlier application of the coarser fraction of the cover stone ensures a better job. Some spreader operators remove this deflector to make their job easier, but this is not advised. This deflector is designed to assist in the uniform application of the aggregate. Cover stone application rates are extremely difficult to estimate if the judgment is made immediately behind the spreader. A more reliable approach is to determine by laboratory tests on stockpiled aggregate the amount of stone required to cover a unit area to a single stone depth. This quantity is then translated into field units of square yards of surface per cubic yard of stone. For example, the grade 4 lightweight aggregate of THD item 303 given in Table 2 would require about 9.5 lb/sq yd (5.1 kg/m^2) [based on an assumed unit weight of 50 pcf (800 kg/m^3)] or a field cover rate of about 140 sq yd/cu yd (155 m^2/m^3). Natural rounded gravel, graded as given in Table 1 and weighing about 95 pcf (1 520 kg/m^3), would cover an equivalent area with a unit cover rate of about 18 lb/sq yd (9.8 kg/m^2). Technicans determining laboratory cover rates for the first time will usually err on the high side, often by as much as 15 to 20 percent. This can result in expensive field mistakes. To avoid such mistakes the technician should strive toward a minimum amount of stone to cover a unit area. A convenient unit to use in the laboratory is ½ sq yd or ½ m^2. A suggested approach for a novice is to carefully cover the unit area with what appears to be sufficient stone. Determine the amount used by weighing the stone. In sequential steps remove 5 percent increments and rearrange the remaining stone each time until it is apparent that the unit area is not adequately covered. At this point return one of the 5 percent increments to the surface. This amount should be close to the quantity determined by an experienced operator.

Why all the fuss about minimizing the stone cover rate? First, it is wasteful to apply excess stone. Second, normal-weight stone left loose on the pavement surface is hazardous. Loose stone may be thrown by traffic and cause windshield and headlamp damage. Excess loose stone contributes to low friction on an otherwise safe surface. Third, excess stone contributes to crushing and dusting, both of which are undesirable. Dusting is a traffic hazard in the early use of the road; crushing disturbs a balanced design of stone size and binder quantity, which can result in flushed areas. Naturally, crushing is more of a problem for seals over rigid pavements than it is for seals on flexible surfaces (56). Let us assume that we have applied the selected binder and cover stone at the proper rates and we can turn to the rolling operation. Rolling of cover stone is a necessary and important step in the successful construction of a nonskid seal coat. Although under certain circumstances a flat-wheel steel roller may be used on seals, their general use is not advised. Self-propelled pneumatic rollers equipped with smooth tires inflated to about 30 to 45 psi (207 to 310 kPa) are highly recommended for the seating of cover stone in seal-coat operations. This type of roller is more effective for 2 major reasons, because the kneading action of this type of roller does a better job of fitting the aggregate into a continuous mosaic than does a steel roller and because crushing is reduced substantially. Pneumatic rolling requirements for seals fall in the range of 5 to 7 hours/mile (3 to 4 h/km) of 2-lane highway. Roller speeds in excess of about 7 mph (11 km/h) are not recommended.

After the rolling operation and a delay period of 25 to 48 hours the sealed surface should be lightly broomed to remove any loose stone. Required lane marking of the finished surface should follow as soon as is practical.

LEVELS OF PERFORMANCE

The level of performance that may be expected for a properly designed and constructed seal coat using cover aggregate sized from ½-in. to No. 4 sieve size is shown in Figure 7. The superior skid performance indicated for stone with adequate microtexture is emphasized. Also, it is suggested from Figure 7 that where polishing is in evidence the surface is speed sensitive under wet conditions. Figure 8 treats the effect of increasing volumes of traffic on skid numbers at 40 mph. Polish-susceptible cover stone is undesirable for heavy volumes of traffic.

The expected improvement of existing, dangerously slick surfaces is shown in Figure 9. It is assumed that the improvement results from proper design and construction with cover aggregate in the range of ½-in. to No. 4 sieve size.

SPECIAL PROPERTIES OF COVER AGGREGATE

Special properties of particles—shape, surface texture, durability, and polish susceptibility—as they relate to improved skid resistance of a pavement surface, warrant further attention.

Schonfeld (57), Gallaway and Rose (44), Britton (45), Britton and Gallaway (43), Gallaway, Schiller, and Rose (58), and Gallaway, Rose, and Hutchinson (41) have recently dealt extensively with particle shape, particle surface texture, and pavement macrotexture and microtexture.

It is apparent that estimating friction by Schonfeld's method must, in the case of seals, rely on the coarse aggregate and its size and surface properties (57). Gallaway and Rose (44) in their measurements of the macrotexture of typical Texas highways found that macrotexture related well to friction for an aggregate of a given source and that, for constant microtexture, macrotexture had a primary effect on friction gradient or change in friction with speed. Tabor (59), in his study of hysteresis, emphasized the importance of macrotexture's effect on frictional drag in locked-wheel stops. Van der Burgh and Obertop (60) reported on size and shape of road surface projections and detailed the relationship between various types of rubber and road surface macrotexture. Macrotexture depth and spacing were key parameters.

Britton (45) developed a master curve for the adhesion component of wet tire-pavement surface friction in which a reduced friction number was plotted against a reduced microtexture size parameter. It is evident from this and other reported findings that microtexture has a most important effect on pavement friction. It is further evident from Britton's work that as microtexture size is increased wet friction increases, reaches a maximum value, and then decreases. He also demonstrated that it is technically feasible to produce synthetic aggregates with controlled microtexture.

Currently, many U.S. highways and city streets are being surfaced with commercial grades of lightweight synthetic aggregates. Such aggregates are made primarily by the rotary kiln process from clays or shales. Microtexture of a desirable size range is a property of these materials.

The desirable aggregate property of durability also has its disadvantages because a very hard material, although slow to polish, will polish more than a less durable material. Generally it is necessary to crush such material to maximize the hardness advantage. Aggregates composed naturally of both hard and soft materials therefore have nonpolishing properties. For such materials the attrition of traffic furnishes a surface friction renewal mechanism. Crushing costs of such materials are usually minimal.

Polish susceptibility of aggregates is related primarily to type of mineral and purity. Type of mineral and purity strongly affect hardness and toughness, and these properties in turn determine crushing costs. Granites, traprock, and limestones make up much of the crushed stone used in the United States; these materials vary greatly in polish susceptibility with limestones considered most susceptible, particularly those of high purity and fine-grain structure.

Laboratory and pilot scale tests have been developed to measure polish susceptibility (61, 62, 63). Values coming out of these tests are used in specifying polish resistance of cover stone. One should select the restrictive values with care and take into account service demands, weather, pavement geometrics, terrain, and long-term total costs. Polish-susceptible limestones are entirely satisfactory as cover stone provided traffic volume and weights will not polish the stones to an unacceptably low value. The key to

Figure 7. High-speed performance of typical seal coats under inclement weather conditions.

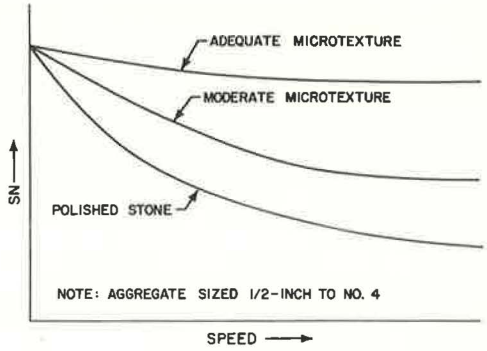


Figure 8. Typical performance of various types of cover aggregates used on conventional seal coats.

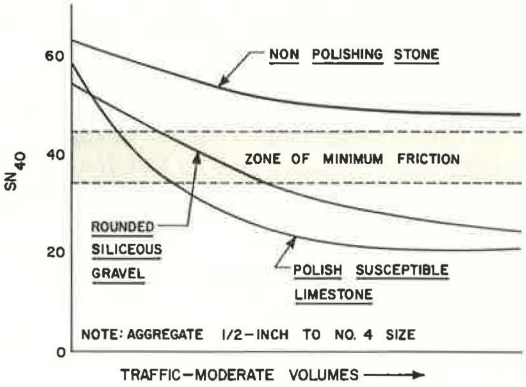


Figure 9. Expected average improvement of polished road surfaces after seal coating with selected aggregates.

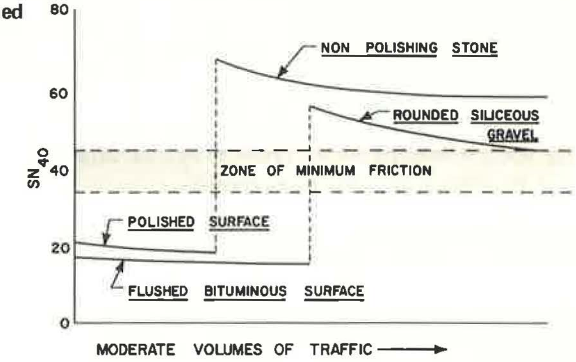
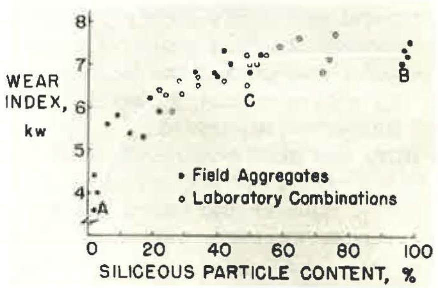


Figure 10. Limestone with adequate silica inclusions produces skid-resistant surfaces with proper design and construction procedures.



the success of polish-susceptible limestone under such service is continued chemical reaction between the stone and the air. This reaction causes microtexture renewal. As a rough rule of thumb, traffic of less than 250 vehicles per lane per day can be tolerated without excessive polishing. When available in sufficient amounts, properly sized silica impurities in limestone ensure nonskid properties. Field confirmation of the serviceability of this type of impure limestone has been common (48). A relationship between wear index (friction) and silica content is shown in Figure 10 (64).

Aside from these special properties of cover aggregate, the importance of good construction control cannot be overemphasized. The very best materials, design, and equipment used under ideal weather conditions can result in miserable failures when skill and pride in construction are neglected.

REFERENCES

1. Herrin, M., Marek, C. R., and Majidzadeh, K. State of the Art: Surface Treatments, Summary of Existing Literature. HRB Spec. Rept. 96, 1968.
2. McLeod, N. W. Basic Principles for the Design and Construction of Seal Coats and Surface Treatments With Cutback Asphalts and Asphalt Cements. Proc. AAPT, Vol. 29, Supplement, 1960.
3. Sprayed Work. In Principles and Practice of Bituminous Surfacing, National Assn. Australian Road Authorities, Vol. 1, 1965.
4. Coulter, T. M. The Design of Bituminous Pavements. Main Roads, Vol. 24, No. 2, 1958.
5. Benson, F. J., and Gallaway, B. M. Retention of Coverstone by Asphalt Surface Treatments. Eng. Exp. Station, Texas A&M Univ., Bull. 133, 1953.
6. Kearby, J. P. Tests and Theories on Penetration Surfaces. HRB Proc., Vol. 32, 1953, pp. 232-237.
7. Kilfer, C. V. The Use and Abuse of Seal Coats. Crushed Stone Journal, Vol. 24, No. 2, June 1949.
8. McKesson, C. L. Fundamentals of Surface Treatment With Emulsified Asphalts. Proc. AAPT, Vol. 17, 1948.
9. Hveem, F. N., Lovering, W. R., and Sherman, G. B. The Design of Seal Coats and Surface Treatments. California Highways and Public Works, Vol. 28, Nos. 7-8, July-Aug. 1949.
10. Mackintosh, C. S. Rates of Spread and Spray in Bituminous Surface Dressing of Roads. Civil Engineer in South Africa, Vol. 3, Oct. 1961.
11. Kersten, M. S., and Skok, E. L., Jr. Criteria for Seal Coating Bituminous Surfaces. Minnesota Dept. of Highways Investigation, Interim Rept., No. 626, 1969.
12. Gallaway, B. M., and Harper, W. J. Laboratory and Field Evaluation of Lightweight Aggregates as Coverstone for Seal Coats and Surface Treatments. Highway Research Record 150, 1966, pp. 25-81.
13. Asphalt Surface Treatments and Asphalt Penetration Macadam. Asphalt Institute Manual Series No. 13, 2nd Ed., Nov. 1969.
14. Schuelie, W. H. Recent Developments in Equipments Used for Seal Coats or Surface Treatments of Existing Bituminous Surfaces. Proc. AAPT, Vol. 24, 1955.
15. Shattuck, C. L. Protective Seal Coats for Bituminous Pavements. Military Engineer, Vol. 49, No. 327, 1957.
16. Creamer, W. M., and Brown, R. E. Application of a New Non-Skid Surface Treatment on Connecticut State Highways. HRB Bull. 184, 1958, pp. 10-16.
17. Building Safer Highways With Slag. National Slag Association, Washington, D.C., Tech. Bull. No. 264, 1968.
18. Gallaway, B. M. Design and Construction of Full Scale Stopping Pads and Spin-Out Curves to Predetermined Friction Values. Jour. Materials, Vol. 5, No. 2, 1970.
19. Gallaway, B. M. Skid Resistance and Polishing Type Aggregates. Jour. Amer. Society Safety Engineers, Vol. 14, Sept. 1969.
20. Gallaway, B. M. Maintenance of Flexible Pavements for Improved Skid Resistance. Proc. Conf. on Skid Resistant Surface Course, Rept. FHWA-RDDP-10-4, Jan. 1973.

21. Kari, W. L., Coyne, L. D., and McCoy, P. E. Seal Coat Performance. Proc. AAPT, Vol. 31, 1962.
22. Wilson, D. S. An Experiment Comparing the Performance of Roadstones in Surface Dressing. Transport and Road Research Laboratory, Harmondsworth, England, RRL Rept. 46, 1966.
23. Hanson, F. M. Bituminous Surface Treatment of Rural Highways. Proc. New Zealand Society of Civil Engineers, Vol. 21, 1934-35.
24. Nevitt, H. G. Aggregate for Seal Coating. Proc. AAPT, Vol. 20, 1951.
25. Lovering, W. R. Seal Coats, Economic Usage. Western Construction, Vol. 29, No. 4, 1954.
26. Kuipers, J. P. Moderne Oppervlaktebehandeling. Wegen, Vol. 29, No. 5, 1955.
27. Gallaway, B. M. A Manual on the Use of Lightweight Aggregate in Flexible Pavement Systems. Expanded Clay, Shale and Slate Institute, 1969.
28. Benson, F. J., and Gallaway, B. M. Study of Some Variables Affecting Retention of Aggregate by Asphalt Surface Treatments. Roads and Streets, April 1954, pp. 113-122.
29. Dickenson, E. J. The Wetting of Air-Dry Stone by Bituminous Binders in the Road Surface Dressing Operation. Jour. Institute of Petroleum, Vol. 47, No. 445, 1961.
30. Mathews, D. H. Adhesion in Bituminous Road Materials: A Survey of Present Knowledge. Transport and Road Research Laboratory, Harmondsworth, England, Research Note RN/3151/DHM, 1958.
31. Mertens, E. W., Coyne, L. D., and Rogers, E. D. Cationic Asphalt Emulsions: Recommended Tests and Specifications. ASTM, STP 294.
32. Lovering, W. R. Selecting Asphalt Binder for Seal Coats. Western Construction, June 1958.
33. Alcoke, W. H. Seal Coats With Latex Tested. Roads and Streets, Vol. 98, July 1955.
34. Gallaway, B. M. Durability of Asphalt Cements Used in Surface Treatments. Proc. AAPT, Vol. 26, 1957.
35. The Report of the Road Research Board for 1957. Dept. Scientific and Industrial Research, England, 1957.
36. Bower, H. C. Cationic Asphalt-Emulsion for Surface Treatments. Roads and Engineering Construction, Vol. 98, No. 2, Feb. 1960.
37. Bohn, A. O. The Breaking of Asphalt Emulsions for Surface Treatments. Proc. AAPT, Vol. 32, 1963.
38. Major, N. G. Basis for Selection of Binders for Chip Sealing. New Zealand Engineer, Vol. 20, No. 12, Dec. 1965.
39. Gallaway, B. M., and Epps, J. A. Current Methods for Improved Tire-Pavement Interaction. Trans. Engineering Jour., 1972, pp. 915-921.
40. Gallaway, B. M. A Review of Current Methods for Producing Skid Resistant Pavements in the United States of America. Proc. AAPT, Vol. 42, 1973.
41. Gallaway, B. M., Rose, J. G., and Hutchinson, J. W. A Summary and Analysis of the Attributes of Methods of Surface Texture Measurements. ASTM, STP 530, 1972.
42. Gallaway, B. M., and Epps, J. A. Tailor-Made Aggregates for Prolonged High Skid Resistance on Modern Highways. Proc. 2nd Inter-Amer. Conf. on Materials Technology, Mexico City, Aug. 1970, pp. 90-99.
43. Britton, S. C., and Gallaway, B. M. Manual for the Construction and Maintenance of Standardized Skid Surfaces. Texas Transportation Institute, Texas A&M Univ., Tech. Rept. 797-4, Nov. 1972.
44. Gallaway, B. M., and Rose, J. G. Macro-Texture, Friction, Cross Slope, and Wheel Track Depression Measurements on 41 Typical Texas Highway Pavements. Texas Highway Dept., Res. Rept. 138-2, July 1971.
45. Britton, S. C. Standard Reference Pavement Surfaces for the Evaluation of Skid Test Equipment. Texas A&M Univ., PhD dissertation, 1972.
46. Csathy, T. I., Burnett, W. C., and Armstrong, M. D. State of the Art of Skid Resistance Research. HRB Spec. Rept. 95, 1968, pp. 34-48.

47. Shupe, J. W., and Lounsbury, R. W. Polishing Characteristics of Mineral Aggregates. Proc. 1st Internat. Skid Prevention Conf., 1959.
48. Gray, J. E., and Renninger, F. A. The Skid-Resistant Properties of Carbonate Aggregates. Highway Research Record 120, 1966, pp. 18-34.
49. James, J. G. Calcined Bauxite and Other Artificial, Polish Resistant Roadstones. Transport and Road Research Laboratory, Harmondsworth, England, RRL Rept. LR84, 1968.
50. 1972 Standard Specifications for Construction of Highways, Streets and Bridges. Texas Highway Department, pp. 213-214.
51. Schweyer, H. E., and Gartner, W. A Study of Tenacity of Aggregates in Surface Treatments. Highway Research Record 104, 1965, pp. 18-35.
52. Robinson, D. A. Roads Surface Dressing in Sweden. Roads and Road Construction, Vol. 42, Nov. 1964.
53. Swaminathan, C. G., and Shulka, R. S. Fluxing of Bitumen for Surface Dressing. Indian Roads Congress, Road Res. Bull. 9, 1964.
54. Swami, S. A. Australian Method of Surface Dressing. Jour. Institution of Highway Engineers, Vol. 12, Jan. 1965.
55. Coulter, T. M., and Punch, J. J. Design, Construction and Maintenance of Roads and Runways. 11th Permanent Internat. Assoc. Road Congress, Rio de Janeiro, 1959.
56. Shelburne, T. E. Crushing Resistance of Surface-Treatment Aggregates. Purdue University, Engineering Bull., Research Series No. 73, Vol. 23, No. 5, Sept. 1940.
57. Schonfeld, R. Photo-Interpretation of Skid Resistance. Highway Research Record 311, 1970, pp. 11-25.
58. Gallaway, B. M., Schiller, R. E., and Rose, J. G. The Effects of Rainfall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depths. Texas Highway Dept., Res. Rept. 138-5, July 1971.
59. Tabor, D. Hysteresis Loss in the Friction of Lubricated Rubber. Engineering, Vol. 186, 1958, pp. 838-840.
60. Van der Burgh, A. J. P., and Obertop, D. H. F. Surface Texture and Non-Skid Properties of Road Surfaces. Proc. Internat. Skid Prevention Conf., Virginia Council for Highway Investigation and Research, Part 2, 1959, pp. 489-496.
61. Maclean, D. J., and Shergold, F. A. The Polishing of Roadstones in Relation to Their Selection for Use in Road Surfacings. Proc. 1st Internat. Skid Prevention Conf., Virginia Council for Highway Investigation and Research, Part 2, 1959, pp. 497-508.
62. Shupe, J. W., and Goetz, W. H. A Laboratory Investigation of Pavement Slipperiness. HRB Bull. 219, 1959, pp. 56-73.
63. Whitehurst, E. A., and Goodwin, W. A. Tennessee's Method of Laboratory Evaluation of Potential Pavement Slipperiness. Proc. 1st Internat. Skid Prevention Conf., Virginia Council for Highway Investigation and Research, Part 2, 1959, pp. 329-332.
64. Colley, B. E., Christensen, A. P., and Nowlen, W. J. Factors Affecting Skid Resistance and Safety of Concrete Pavements. HRB Spec. Rept. 101, 1969, pp. 80-99.