crete Pavement Surface Textures in Ontario: Development, Testing and Performance. Presented at the 55th Annual Meeting, TRB, 1976.
10. G. F. Salt. Research on Skid-Resistance at the Transport and Road Research Laboratory (1927-1977). Presented at the 2nd International Skid Prevention Conference, Columbus, OH, May 1977.
11. G. F. Salt and W. S. Szatkowski. A Guide to Levels of Skidding Resistance for Roads. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Rept. LR 510, 1973.

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Synthetic Aggregates for Skid-Resistant Surface Courses

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Synthetic aggregates are produced by the thermal or chemical processing of natural or manmade materials. The physical properties of these aggregates vary considerably, depending on raw material and method of processing, and their properties are often considerably different from those of the natural aggregates on which current test methods and specifications are based. Skid resistance is primarily a function of the microtexture and macrotexture of the pavement surface. The physical properties of the individual aggregate particles determine level of microtexture and resistance to wear and polishing, which are important properties in the retention of skid resistance. Various methods of producing synthetic aggregates for skid-resistant surfaces are reviewed. Emphasis is placed on processing methods, available raw materials, and properties of the processed aggregate. The mechanisms by which different classes of aggregates develop microtexture and resistance to wear and polishing are discussed. It is concluded that each of these materials develops skid resistance and resistance to wear and polishing in a different way and that this should be reflected in designs and specifications. Many potentially acceptable synthetic aggregates are energy and capital intensive.

Synthetic aggregates are produced by the thermal or chemical processing of either natural or manmade raw materials and include waste materials as well as aggregates that are produced specifically for construction applications. The physical characteristics of synthetic aggregates vary depending on the raw material and the method of processing. In many cases, the physical characteristics and engineering behavior of synthetic aggregates are considerably different from those of the natural aggregates on which current specifications and test methods are based.

As supplies of readily available natural aggregate become depleted and the demand for skid-resistant pavements increases, synthetic aggregates will of necessity become more important as an aggregate source. In this paper, potential sources of synthetic aggregates are reviewed with respect to existing technology, and the aggregates are differentiated as to aggregates that are "tailor-made" as skid-resistant aggregates and those that are "non-tailor-made", such as lightweight aggregates, slags, and industrial by-products.

SKID-RESISTANCE REQUIREMENTS

The skid resistance of a pavement is primarily a function of its surface texture. It is convenient to divide texture into two components: microtexture with asperities smaller than 0.5 mm (0.02 in) and macrotexture with asperities larger than 0.5 mm. Microtexture is generated by the surface texture of the individual aggregate particles, whereas macrotexture is generated by the gradation and maximum size of the coarse aggregate. Low-speed skid resistance is developed from microtexture. Both macrotexture and microtexture are required for high-speed skid resistance (1).

A relation between pavement texture and skid number at any speed V was developed by Leu and Henry (2):

$$SN_v = ae^{-bv} \quad (1)$$

In this relation, coefficient a can be predicted from microtexture data (BPN or profile data) and becomes smaller as the aggregate is polished. The parameter b becomes larger as aggregate particles wear away and can be predicted from macrotexture data (i. e., sand-patch texture depth or profile analysis). It should be noted in Equation 1 that a particular skid number can be produced by different combinations of macrotexture and microtexture.

Although initial as-constructed skid resistance is an important requirement, it is also important that adequate skid resistance be maintained under the action of traffic. A loss in skid resistance can be produced by polishing (loss of microtexture) or by wear and abrasion (loss of macrotexture). Many aggregates, such as some sandstones, renew their microtexture as they wear away by exposing new, unpolished grains. Resistance to polishing is thus often gained at the expense of wear or abrasion.

To perform satisfactorily as a surface aggregate, an aggregate must

1. Be graded so that it can provide adequate initial macrotexture;
2. Provide adequate resistance to environmental exposure, abrasion, and impact (retain its macrotexture);
3. Provide adequate initial microtexture; and
4. Provide adequate resistance to polishing (retain its microtexture).

TYPES OF AGGREGATE

Different aggregates achieve microtexture and resistance to polishing through different mechanisms. James (3) has developed the following aggregate groups for purposes of classification:

Group	Material
1	Very hard materials
2	Conglomerations of small, hard particles
3	Dispersions of hard particles in a softer matrix
4	Materials that fracture during wear, leaving irregular fracture surfaces
5	Vesicular materials

Experience has shown that hard materials by themselves, without the features of groups 2 through 5, are not satisfactory in terms of resistance to polishing. Group 2 materials rely on the angularity of the mineral grains and sacrificial wear to provide microtexture and resistance to polishing. The group 3 materials require hard, sharp, angular grains that stand out above the soft matrix as wear proceeds. Microtexture in the group 4 materials depends on anisotropic, angular, sharp mineral grains that yield a rough fracture surface. Sacrificial wear or abrasion is necessary for resistance to polishing. Finally, the group 5 materials retain their microtexture as they wear by exposing new, sharp cell walls.

CERAMIC PROCESSING

The ceramics industry has developed highly specialized processing techniques to meet a wide variety of product requirements. Depending on the processing technique and product requirements, materials with a wide range in properties can be produced (4).

Processes

Ceramic processes that are potentially useful in the manufacture of paving aggregates are given in Table 1. The table is arranged according to the nature of the finished product, e.g., sintered, bloated, or glassy. The range of properties of synthetic aggregates is much greater than that of conventional aggregates, and this must be taken into account in their use, particularly in the development of test methods and specification criteria.

With the exception of some forms of thermal-chemical processing, the potential techniques for processing ceramic aggregates are energy intensive and will become more expensive as energy becomes more costly. Exact energy requirements depend on the chemical composition of the raw material, the processing method, and the number of processing steps required.

For example, the extended thermal treatment needed to produce ceramic is more energy demanding than the sintering process in which the raw material is brought to a temperature below melting. Another consideration is the energy content of the raw feedstock. For example, coal-mine refuse, incinerator refuse, and other waste materials contain some unburnt carbon, and this can be used to feed the ceramic processing. If the feedstock is a molten slag, the cost of initial melting can be eliminated. Considerable energy could be saved if certain industrial slags, such as boiler slag, coal-gassification wastes, and pyrolysis slags, were tied directly to the production of aggregate rather than disposed of in the most convenient manner and later reclaimed as aggregate. For example, the energy required to sinter fly ash is about 1163 MJ/Mg (1 million Btu/ton), whereas energy requirements for sintered clay may be in the range of 3490-4650 MJ/Mg (3-4 million Btu/ton) because of the carbon content of the fly ash.

Energy requirements for a number of ceramic processes are given in Table 2 (5). The energy requirements and kiln efficiencies vary considerably, according to the load on the kiln, the quantity of heat, and the temperature required.

Table 1. Potential sources of synthetic aggregate by method of manufacture.

Process	Description	Example	Current Pavement Use	Comments
Sintering	Heating (to below melting point) of agglomerate fines into larger, tougher particles	Brick making; sintered shales, clays; molochite, refractories; fly-ash lightweight aggregate	Texas ("Red Rock")	Agglomerate fine material (e.g., wastes, clays) into hard, large-sized particles; blend ingredients to control differential hardness; properties vary
Sintering with bloating	Heating as in sintering, but bloating gives "expanded" particle	Expanded shale, clay, coal-mine refuse	Expanded shale, clay, coal-mine refuse	Good skid resistance, doubtful durability and wear resistance; control of wear and skid resistance by bubble size, density, and wall thickness
Glass ceramics	Controlled thermal processing of glass to give appreciable crystal growth	Processed blast-furnace slag; Synopal	Extensive use; blast-furnace slag; excellent skid resistance	Development of crystalline phase controlled by processing and composition; desired process waste slags
Glass ceramics with bloating or expansion	Melted glass expanded by internal gas or injected air or steam; appreciable crystal growth on cooling	Expanded blast-furnace slag	May not be advantageous in cost if glass-ceramics process gives adequate differential wear	Expanded blast-furnace slag currently used in block manufacture; no advantage reported over normal blast-furnace slag; cost and environmental disadvantages
Calcining	Heating in solid phase to effect crystal change and drive off water or carbon dioxide	Calcined bauxite	Limited because of expense	Potential as "high-class" material; cost-effectiveness needs to be improved
Chemical processing	Hydraulic cement or other chemical reaction at ambient temperature	Pozzopac, sulfate-fly-ash waste	None	Questionable; low energy input implies material without hardness and wear resistance
Thermochemical processing	Hydraulic cement or other chemical reaction at elevated temperature	None known	None	Inclusion of hard particles in softer matrix suggested; process represents low-energy agglomeration of fines
Glassmaking	Heating to above melting temperature; rapid cooling without crystal growth	Water-quenched boiler slag, steel and blast-furnace slags, slags from incinerators, etc.	Boiler slag; controversial for skid resistance	Marginal as skid-resistant aggregates; modify to glass-ceramics process if possible; vesicularity may extend usefulness
Glassmaking with bloating	Melted slag expanded with gasses produced in process or with injected air or steam; no appreciable crystal growth on cooling	None	None	Vesicularity may improve skid resistance; probably not preferred process but may be necessary with some waste-slag compositions that do not readily crystallize
Recycling	Recycling of portland cement concrete or asphaltic pavements	None	None; ongoing demonstration projects	Alteration of future construction to allow aggregate recycling should be considered; crushed portland cement concrete may give good differential wear
Coatings	Thermally or chemically applied thin surface coatings	None known	None	Limited application unless coating is thick as in composite material; expensive processing

Table 2. Energy requirements for various ceramic processes.

Process	Temperature (°C)	Energy (MJ/kg)	Efficiency (%)
Structural products and refractories			
Kettle calcining, gypsum to plaster	151	1.28	51
Tunnel kiln, fireclay brick	1426	5.23	35
Rotary kiln			
Calcining kaolin	1649	6.97	32
Dead-burning dolomite	1749	10.23	53
Glass containers			
Gas-fired regenerator furnace	1426	6.56	39
Electric furnace	1426	3.95	64
Tunnel-kiln whitewares			
Porcelain	1410	41.86	5
Tableware	1226	6.97	27
Abrasives			
Arc fusion of alumina	2093	5.58	64
Reduction to silicon carbide	1982	29.07	71
Reduction to boron carbide	2399	116.28	52
Synthetic aggregates[a]			
Sintered shale or clay	1204	5.81	-
Sintered coal-mine refuse	-	1.39	-
Sintered fly ash	-	1.16	-
Fusion of municipal waste	2204	5.81	-

Note: t°C = (t°F - 32)/1.8; 1 MJ/kg = 430 Btu/lb.
[a]Estimated values.

Table 3. Laboratory test data for various aggregates.

Material	PSV	AAV	Water Absorption (%)	Los Angeles Abrasion
Synopal	50	35.0	-	23
Calcined bauxite				
RASC	75	3.0	3.6	-
RSG-F	79	5.3	4.3	-
RSG-G	54	3.7	1.1	-
Brick				
Fireclay	63	19.0	-	-
Bauxite	88	38.0	-	-
Silica	58	8.0	-	-
Flint				
Crushed	35	1.0	1.0	-
Calcined	53	0	1.3	-
Expanded shale	60-75	High	-	-
Slag				
Blast furnace	40-63	7-29	-	-
With heat treatment	62	7.7	-	-
With foaming	69	6.2	-	-
Steel	44-67	3	-	-
Limestone	48	-	0.3	18
Expanded glass	45	-	2.4	23
Granite	54	-	0.3	36
Arkosic sandstone	62	-	2.6	-

Use of Existing Ceramic Products as Paving Aggregates

It should be emphasized that, since ceramic products are produced for a specific purpose, their attendant materials specification criteria may have to be reevaluated in any consideration of existing ceramic products for use as paving aggregates. For example, paving aggregates do not have to be refractory. This means that processing requirements as well as raw-material requirements may be less restrictive for paving applications than for the original application. In turn, a considerable cost saving may be realized or a new supply of raw materials may become available. For example, low-grade bauxite that cannot be used as a refractory brick makes an excellent paving aggregate, one that is superior to an aggregate made with a purer grade of bauxite. Thus, a much wider source of raw materials becomes available at a lower cost (6). On the other hand, certain requirements that are not significant for refractory brick—such as resistance to freezing and thawing and impact resistance—are critical for pavement aggregates.

With the exception of lightweight aggregates from shale and clay, there are almost no examples of manufactured synthetic aggregates that are used as skid-resistant aggregates in significant quantities. Blast-furnace slag is an industrial by-product widely used as an aggregate, but neither it nor ordinary lightweight aggregate is produced specifically for skid-resistant purposes. In 1972, Marek and others (7) noted that since 1964 there had been few significant additions to the list of available or potentially available synthetic aggregates. This is still the case. Increased energy costs and environmental restrictions and the shortage of money for capital expenditures have placed additional constraints on the development of synthetic aggregate.

TAILOR-MADE CERAMIC AGGREGATES

Tailor-made ceramic aggregates are materials specially processed for use as skid-resistant aggregates. Processed Synopal and calcined bauxite are perhaps the best-known, best-documented of these materials.

Synopal

Synopal is a silicate-glass ceramic produced by first solidifying the melted raw material to a glass and then heat-treating it to induce crystal growth (method 2 in Table 1). The result is a hard, fine-grained (low-porosity) calcium silicate mineral with an amorphous (glass) matrix. Its high compressive strength [620 MPa (90 000 lbf/in^2)], hardness (7.5 Mohs), and reflectivity under night illumination are its favorable properties. Synopal has been little used in the United States, principally because of its high cost [$55/Mg ($50/ton)] and marginal skid-resistance performance (3). The marginal skid resistance is caused by the fine-grained, dense texture, which provides little differential wear and microtexture. A laboratory polished-stone value (PSV) of 50 is reported for Synopal (Table 3). Although it is no longer produced in the United States, Synopal has been used in test roads in Michigan, West Virginia, Illinois, and other states.

The use of calcined bauxite as a skid-resistant aggregate has been studied extensively in England (6). In these studies, raw bauxite that ranged up to 7 mm (0.28 in) in diameter was calcined in the laboratory at 1500°C to 1750°C (2730°F to 3180°F) in a rotating drum. Cooling rates were essentially furnace rates. The calcining (temperature) schedule was critical: A 30-min hold at temperature resulted in large crystals being tightly bound in an unbloated, glassy matrix. Too little matrix gave a friable aggregate; too much sintering lowered the PSV.

Certain special qualities of calcined bauxite make it an excellent skid-resistant aggregate. Polycrystalline α-alumina is an anisotropic, tough, hard, strong material. Pure sintered α-alumina has a Mohs hardness of 9, and its tensile strength ranges from 410 to 690 MPa (65 000 to 100 000 lbf/in^2). Differential wear and microtexture are obtained by the random orientation of the grains of α-alumina, which tend to retain a blocky structure under wear by traffic. Optimal skid resistance has been obtained by using α-alumina crystals 15-70 μm (0.000 59-0.0028 in) in size bonded by a moderate quantity of glassy matrix. Water absorption of up to 5 percent was characteristic of calcined bauxites that had better polishing resistance. The porosity and glassy matrix and the tendency of the alumina to retain sharp corners on its cleavage planes all contribute to its high PSV. In addition to being very skid resistant, calcined bauxites are highly wear resistant.

PSVs (British pendulum tester values retained after polishing) for a variety of calcined bauxites are given in Table 3. The values range from 54 to 79 and show

a strong dependence on porosity. In contrast, pure α-alumina, an industrial abrasive, has a PSV of 62.

Obviously, calcined bauxite, deposits of which exist in Arkansas, represents an excellent source of skid-resistant aggregate, and its use should be pursued in the United States. Bauxite with clay is also a possible source. The high cost of calcined bauxite [\$33-\$55/Mg (\$30-\$50/ton)] reflects costs for shipping, raw material, and energy for processing. Conventional rotary kilns could, however, be adapted to its manufacture.

Bricks

Limiting its study to materials currently in production, the Transport and Road Research Laboratory (TRRL) has investigated various types of bricks for use as skid-resistant aggregates (6). Brick is a sintered or liquid-phase sintered material that must be pressed to shape before the firing process. Its PSVs range from 58 to 88 and do not show a good correlation with crushing strength or abrasion resistance (Table 3). Common brick is not satisfactory as a skid-resistant aggregate. Generally, brick of a quality acceptable for skid-resistance purposes is refractory and hard fired. This requires a relatively high temperature, which allows considerable crystal growth beyond the initial sintering. Refractory qualities are not necessary in brick that is to be used as aggregate, but the hard firing is necessary to give adequate crystal growth for good resistance to polishing.

As part of a TRRL study of synthetic aggregates of controlled porosity, a refractory brick called mossite was prepared at various porosities. The PSV increased from 53 to 89, and porosity increased from 18 to 43 percent (8). Although excellent correlation was obtained between PSV and porosity, some of the higher PSV values were associated with weak material that had unacceptable aggregate abrasion values (AAVs). An acceptable AAV and PSV were obtained at a porosity of 43 percent and a firing temperature of 1300°C (2370°F) when firing and composition were carefully controlled.

Other Possible Tailor-Made Aggregates

The concept of materials specially tailored for use as skid-resistant synthetic aggregates has been studied in detail by Roy (4). These materials are typified by molochite, which is currently produced as a refractory by firing a China clay to give mullite crystals dispersed in an amorphous phase (44 percent amorphous and 56 percent mullite). Whereas molochite requires a high firing temperature and can be energy intensive to produce, compositions may be made more cost effective by

1. Varying the raw materials,
2. Neglecting the refractory requirement,
3. Fluxing to reduce firing temperature,
4. Bloating to give vesicularity and thereby improve polish resistance, and
5. Blending hard and soft components to give a multiphase aggregate, e.g., using a low-temperature flux to "cement" together a harder high-melting-temperature phase.

A more comprehensive approach to developing tailor-made synthetic aggregates would be to study the phase diagrams that represent compositional ranges within which the most plausible ceramic aggregates could be produced—that is, to include most of the abundant raw materials that would not be out of the cost range. Clearly, many ceramic systems could potentially be used to produce skid-resistant aggregates. With proper research, it should be possible to identify systems that provide appropriate aggregate properties and are cost effective.

NON-TAILOR-MADE SYNTHETIC AGGREGATES

There are a number of potential non-tailor-made sources of skid-resistant aggregates. In some cases, these materials have been used as aggregates (e.g., blast-furnace slag or lightweight aggregate); in other cases, they are yet to be developed as aggregate sources (e.g., taconite tailings, steel slags, and pyrolysis slag). In view of the energy savings, environmental advantages, and potential skid resistance of many of these materials, they should be more fully evaluated as sources of skid-resistant aggregate.

Lightweight Aggregate from Shale and Clay

Lightweight aggregate includes expanded shale, slate, clay, and sintered fly ash. The majority of the lightweight aggregate used in the United States is made from crushed shale fired in rotary kilns. The firing is a sintering process accompanied by bloating (Table 1) in which the bloating is caused by the interlayer water released by the clay particles in the shale (9). If clay is the raw material, it must first be agglomerated by a pelletizing or extrusion process. Most of the lightweight aggregate used for skid-resistance purposes has been used in bituminous pavements in Texas and Louisiana (10). In some instances, it has been used as the sole aggregate; in others, it has been blended with natural aggregates.

The skid-resistant properties of lightweight aggregates are derived from their vesicular nature and their ability to maintain sharp, exposed edges (cell walls) as they wear. The vesicular nature provides the differential hardness and, as wear progresses, the newly exposed bubbles (cell walls) preclude polishing. Consequently, properly designed and constructed lightweight-aggregate surfaces can maintain a high level of skid resistance throughout their service life.

Lightweight aggregates are generally produced as structural aggregate, and the properties of the fired aggregate are adjusted to meet this use. Little research has been done on the properties that optimize both skid resistance and wear resistance. It is likely that the optimal properties of aggregate to be used as skid-resistant aggregate are different from those of aggregate that is to be used in structural concrete. Additional research is needed to better define the properties of lightweight aggregate (such as porosity, cell wall thickness, and bubble size) that optimize both wear resistance and skid resistance, particularly in northern climates.

In addition, field data are needed—particularly data that relate the characteristics of field performance, such as wear and polishability, to aggregate properties. Comparative skid data for lightweight-aggregate pavements are generally scattered in the literature along with data for other aggregates, and data on wear resistance are generally not available. The wear resistance of lightweight aggregate is questionable in northern climates and is perhaps best dealt with by using blended aggregate. Test procedures such as those used in Texas need to be verified for the wear and skid resistance of lightweight aggregates produced nationally.

Lightweight Aggregates Other than Shale and Clay

Lightweight aggregate can also be produced by sintering fly ash. The ash does not bloat during firing but remains at a nearly constant volume. Currently, only two plants produce sintered-fly-ash aggregate, and the production from these plants is consigned to lightweight block and concrete construction. Because of the carbon content of the ash, fly-ash aggregate is less energy intensive than expanded shale [1163 MJ/Mg (1 000 000 Btu/ton) compared with 4650-5814 MJ/Mg (4 000 000-5 000 000 Btu/ton)] and therefore potentially less expensive. Because it does not bloat or skin over during firing and because it has an open bubble structure, fly-ash lightweight aggregate is very porous and potentially very absorptive of asphalt. The wall structure is very thin; on the basis of a visual examination of the particles, it does not appear to be useful as a skid-resistant aggregate because of its potentially poor resistance to wear. Additional developmental work would be required to improve the pore structure to increase wear resistance and reduce absorptivity. This may be a worthwhile effort in view of the hardness of the high silica-alumina fly-ash compositions (7.5-8.0 Mohs).

Another technique for producing lightweight aggregate is the sintering of refuse from coal-preparation plants (11). Two plants currently produce sintered refuse: the By-Lite Corporation of Pennsylvania and a pilot plant at the University of Kentucky. One potential advantage in using this material is its fuel content. Although some supplemental fuel is required for ignition, it is less than 10-25 percent of the total energy required for sintering. Because of high sulfur content and related emissions problems during firing, not all refuse is equally suited for sintering. The bloating of pure refuse is not controllable (i.e., the process is self-determining); however, the addition of clay or sand may control bloating (11). This would also offer the opportunity to dope the refuse with a more skid-resistant additive such as calcined bauxite.

Sintered refuse is reported to be a skid-resistant and durable aggregate. Soundness values are high—40-50 percent—but this is said to be counteracted by asphalt absorbed into the aggregate pores. Wear data are not available, and the potential wear resistance is suspect. More attention should be given to this material, particularly if pore structure can be controlled or if other materials can be blended with the refuse to increase the wear resistance of the sintered product.

Blast-Furnace and Steel-Furnace Slags

Slags make up a large family of nonmetallic by-products from the refining of metals from metallic ores. Blast-furnace slag is the most widely used slag in pavement construction, especially in surfacing mixtures. The demand for blast-furnace slag has resulted in full use of this material, mainly as a construction aggregate.

The composition of blast-furnace slag varies from furnace to furnace, depending on operating practice, raw materials, and the grade of steel being produced (12). The parameters that optimize the production of steel also optimize the properties of the slag for paving purposes. Average chemical composition has been given as 36 percent SiO_2, 12 percent Al_2O_3, 42 percent CaCO, 6 percent MgO, and lesser amounts of FeO, MnO, and S. The various crystalline phases are bound together with a softer glassy matrix. Blast-furnace slags are alkaline in nature.

Mineralogical composition is controlled by rate of cooling and chemical composition; a more rapid rate of cooling and a higher silica content give a finer crystal size. Water-quenched or granulated slag is amorphous and is preferred in cement manufacture. Air-cooled slag is predominantly crystalline and is preferred for use as an aggregate in portland cement and construction of bituminous concrete pavement. Blast-furnace slag may also be expanded by using steam or a jet of water. Expanded slag is used principally in block construction and lightweight concrete.

There are few references in the literature to the mechanism by which slags develop their skid-resistant properties. Not all blast-furnace slags have good resistance to polishing. Undoubtedly, the vesicular and hard nature of the slags plays a major role, but the presence of differential wear is less firmly established.

A British study examined the mineralogical and physiographic properties that influence the PSV of blast-furnace slag (13). The study found that the slag was heterogeneous and that different crystalline compounds predominated in the slags that had different PSVs. Increasing both porosity and crystalline size improved the PSV of the slag, but large porosities gave poor resistance to wear. Increased crystalline size did not alter wear resistance. Typical data for slags and processed slags are given in Table 3 (14).

Steel slag is quite different (14). To its advantage, it is a dense, hard, polycrystalline material. It must be aged in stockpiles, however, to allow the hydration of the calcium and magnesium oxides if it is to be used in a confined situation or in an alkaline environment. To stabilize this potential expansion, steel slags can also be treated by using spent pickling liquors. Steel slag contains varying quantities of iron; recycling it to a blast furnace for additional iron recovery will further affect its variability.

The properties and mineralogy of steel slag are quite varied because of plant-to-plant and within-plant variation. This variation can become an important factor in the use of the material, affecting its expansion potential, mixture design, and skid-resistance potential. Steel slags have reportedly provided surfaces with adequate skid resistance and should be more fully evaluated. But, as the range of PSV values in Table 3 shows, not all steel slags give good resistance to polishing.

Industrial and Mining Wastes

Various waste materials have been proposed as alternative sources of aggregate (15). Most of the feasible ones are either the result of the crushing of rock, mine tailings, refining, or incineration. Examples are metallurgical slags (14), incinerator refuse (16), smelter waste (17), and spent oil shale (18). Laboratory data for some miscellaneous materials are given in Table 3. Many of the industrial slags are glassy whereas others are at least partially crystalline. The as-processed glassy slags, in spite of their hardness, are poor candidates for skid-resistant materials because they lack differential hardness and microtexture. Increased vesicularity through controlled processing may improve their microtexture and provide adequate skid resistance. Many are relatively small in size as a result of being quenched in water [minus 9.5- to 2.36-mm (3/8-in to no. 8) sieve]. They often suffer in toughness because they are glassy and also because they are homogeneous. In the pavement they tend to produce cleavage planes parallel to the pavement surface so that texture is lost with wear. The result is a flat, glassy road surface.

The hard, glassy slags might serve as excellent aggregates if they could be processed to produce crystal-

line rather than glassy particles. Both heat treatment and fluxing would probably be required. Additional research is needed on the processing of glassy industrial slags to improve their properties if they are to become strong candidates for skid-resistant aggregates. Bloating procedures and thermal processing with fluxes to give compositions that crystallize more readily and/or result in vesicularity would appear to be viable research approaches. The limited availability of these slags may preclude any significant expenditure of research and development funding.

A method of producing a "bubble aggregate" has been reported (19). Briefly, organic waste or nonsintering mineral waste is pelletized and then coated with a clay or some other flux. The result is an expanded bubble that has many of the properties of an ordinary lightweight aggregate. In another approach, a composite aggregate has been made on a laboratory scale by fusing a siliceous mining waste with a glass that has a lower melting temperature. This multiphase aggregate gave good skid resistance after being polished on a circular test track (20).

The coal-burning power plant is a major source of industrial waste (21). Boiler slag is produced by water quenching molten slag drawn from a slag tap furnace. The slag is one size—typically 1.18- to 2.36-mm (no. 16-no. 8) mesh—angular, glassy, and lacking in microtexture. In this regard, it is similar to many other glassy industrial slags that lack microtexture and differential hardness. Its sharp corners fracture under traffic and offer poor resistance to polishing. Boiler slag is no longer in widespread use as a skid-resistant aggregate, and there are varied reports as to its effectiveness. Boiler slag has been used in sand mixes, slurry seals, and surface treatments, but little use is reported in the literature.

Bottom ash can be produced in various forms, as a fine sand or as agglomerated or poorly sintered fly-ash particles, and it may even contain some slaglike particles. Most bottom ashes range in size from 0.075-mm mesh to 3 cm (no. 200 mesh to 1.2 in). Bottom ash has not been used to any extent as a surfacing aggregate except in West Virginia. Although it does have excellent differential hardness and microtexture because of its vesicularity, bottom ash does not generally have the toughness required of a surfacing aggregate. When it is used as the sole aggregate, it breaks down under the action of traffic to form a very fine-textured surface that is high in microtexture but lacks macrotexture. Bottom ash may have potential as the fine aggregate in surfacing mixtures if it is crushed before use to control breakdown or if it is blended with conventional aggregates (21).

A host of other mining wastes are potential candidates as skid-resistant aggregates (15). Many of the mining wastes are merely waste rock and can be treated as conventional aggregates. In other instances—uranium tailings for example—there are serious environmental problems to be considered.

AGGREGATE BENEFICIATION FOR SKID RESISTANCE

Aggregates that require beneficiation can be divided into two groups: those that possess adequate durability but inadequate skid resistance and, conversely, those that possess acceptable polishing characteristics but inadequate durability. Beneficiation should therefore be approached from two viewpoints: (a) improving durability for resistance to wear and abrasion and (b) improving polish resistance. Both approaches may be valid for upgrading otherwise marginal or unacceptable aggregates.

Ceramic Processing

Heat treatment is a potential method for beneficiating marginal materials; however, the composition of the material must be such that crystal growth or a phase change occurs during heating (e.g., Synopal, bauxite, slag ceram). Glassy industrial slags that can be worked in the molten state can be improved by the injection of steam or air to create vesicularity. Further improvement can also be achieved by adding fluxing agents and controlling the rate of cooling to improve crystallinity and control grain size. The molten slag can be modified further by doping it with harder mineral particles to provide differential hardness. Examples of ceramic beneficiation given in Table 3 are the calcining of flint (a PSV of 53 versus a PSV of 35 for crushed flint) and the heat treatment of blast-furnace slag (a PSV of 62 and 69 versus a PSV of 52). Other examples include sintered silt and bauxite (a PSV from 68 to 73), fly ash and magnesia (PSV of 67) and rock fines (PSV of 72) (14). In each case, the beneficiation requires calcining or sintering at temperatures of 1100°C-1600°C (2000°F-3000°F) and an energy consumption of 4650-9302 MJ/Mg (4 000 000-8 000 000 Btu/ton).

Coatings and Penetrants

Another approach to beneficiation for improving the skid resistance of a marginal aggregate is the addition of a hard coating to a softer aggregate. For example, alumina might be added to a soft limestone. To be successful, the added material would probably have to be crystalline; a low-temperature, glassy coating would be too soft. More exotic procedures, such as flame spraying, do not seem to be economically feasible. Thick coatings or, more correctly, composite aggregates appear promising from a cost standpoint. Denis and Massieu (22) have prepared a polymer-sand aggregate from various sand-sized and smaller materials by using only 10 percent epoxy.

The use of coatings and penetrants also appears promising for improving aggregates that are deficient in durability or exhibit excessive asphalt absorption. Several organic coatings have been evaluated by using absorptive limestone (23). Both water absorption and asphalt content were reduced. The cost-effectiveness of the combinations reported might be questioned, but there may well be instances in which polymer impregnation would substantially improve durability. Gneiss, for example, which is resistant to polishing, might show adequate durability if it were impregnated with polymethylmethacrylate. Research is currently under way at various agencies to upgrade aggregates that are marginal in both skid resistance and durability. This research is directed at coatings and penetrants that can be used to improve freeze-thaw resistance, the effect of water (stripping), mechanical degradation, and resistance to polishing and wear. A disadvantage of organic coatings is that they are expensive and require considerable handling (24).

SUMMARY AND CONCLUSIONS

Skid resistance is controlled by both the microtexture and the macrotexture of the pavement surface. Macrotexture is controlled principally by the gradation of the aggregate, whereas microtexture is controlled by the properties of the individual aggregate particles. The combined effect of microtexture and macrotexture in determining SN_v at various speeds has been defined in previous research and can be used to estimate the

potential skid resistance of new or untried aggregates before their design or manufacture.

Skid-resistant aggregates must also be resistant to wear and polishing. Differential hardness in the aggregate particles can provide resistance to polishing, but the aggregate must be sufficiently tough and consolidated so that it does not exhibit excessive wear. The designer or engineer is limited with regard to resistance to wear and polishing in that neither test methods nor specification criteria are available that can be universally used to control the wear and polishing potential of different aggregates.

Aggregates provide skid resistance and resistance to wear and polishing by means of a variety of mechanisms. Simply producing a synthetic aggregate that is hard and dense will not result in a skid-resistant aggregate, as the marginal performance of Synopal shows. The same ceramic process may be used to produce aggregates of different classes. For example, it is possible to successfully use sintering (a) to consolidate a hard material, as long as sufficient porosity remains for resistance to polishing, and (b) to produce dispersions of hard particles in a soft matrix so that resistance to polishing is provided by differential wear.

The following conclusions can be stated in relation to the design, manufacture, and specification of skid-resistant aggregates:

1. The processes required to produce or modify aggregates for skid-resistance applications are energy and capital intensive, and these factors must be considered in future aggregate development.
2. Different classes of synthetic aggregate achieve their macrotexture and their resistance to wear and polishing by different mechanisms, and this should be recognized during their development and in their specifications.
3. Materials that are hard and dense are not necessarily good aggregates; differential hardness is required to resist polishing.
4. Industrial waste materials are potential sources of raw materials for aggregate production, but they must generally be reprocessed, especially if they are produced as glassy slags.
5. Sintered alumina-bearing clays or low-grade calcined bauxite, which are potentially excellent aggregates and are amenable to current manufacturing equipment, should be investigated further.
6. A test method is needed for the prediction of wear, particularly for vesicular and friable materials.
7. Required levels of microtexture and macrotexture need to be defined for the various classes of synthetic aggregates; i.e., the a and b parameters in Equation 1 need to be defined for various classes and mixtures of aggregate.
8. Aggregates of controlled vesicularity—intermediate between normal and lightweight aggregate—should be considered since they may offer improved resistance to wear and polishing.
9. Exotic processing techniques tend to be more energy intensive than simpler processes such as sintering; they may also be difficult to adapt to the manufacture of aggregate.
10. Production of aggregate from waste materials should be considered part of the primary process rather than an afterthought of the reclamation process.
11. Composite aggregates, such as low-temperature-melting clays doped with hard fines, are promising, particularly if they can be fired in existing kilns.

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REFERENCES

1. H.W. Kummer and W.E. Meyer. Tentative Skid Resistance Requirements for Main Rural Highways. NCHRP, Rept. 37, 1967.
2. M.C. Leu and J.J. Henry. Prediction of Skid Resistance as a Function of Speed from Pavement Texture Measurements. TRB, Transportation Research Record 666, 1978, pp. 7-11.
3. J.G. James. Calcined Bauxite and Other Artificial Polish-Resistant Roadstones. British Road Research Laboratory, Crowthorne, Berkshire, England, Rept. LR 84, 1968.
4. D.M. Roy. Advanced Technology Materials Applied to Guideways, Highways, and Airport Runways. Program of University Research, U.S. Department of Transportation, Project DOT-05-40009, Feb. 1976.
5. D.J. Whittemore. Energy Consumption in Ceramic Processes. Ceramic Bulletin, Vol. 53, No. 5, 1974, pp. 456-457.
6. L.W. Tubey and J.R. Hosking. Synthetic Aggregates of High Resistance to Polishing: Part 2—Corundum-High Aggregates. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Rept. LR 467, 1974.
7. C.R. Marek and others. Promising Replacements for Conventional Aggregates for Highway Use. NCHRP, Rept. 135, 1972.
8. J.K. Hosking. Synthetic Aggregates of High Resistance to Polishing: Part 3—Porous Aggregates. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Rept. LR 655, 1974.
9. B.M. Gallaway and W.J. Harper. A Manual on the Use of Lightweight Aggregate in Flexible Pavement Systems. Expanded Shale, Clay, and Slate Institute, Washington, DC, 1969.
10. Open-Graded Friction Courses for Highways. NCHRP, Synthesis of Highway Practice 49, 1978.
11. J.G. Rose and D.S. Decker. Sintered Coal Refuse Lightweight Aggregate for High-Friction Bituminous Surface Courses. Paper presented at Annual Meeting, AAPT, San Antonio, TX, Feb. 1977.
12. A.R. Lee. Blast Furnace and Steel Slag: Production, Properties and Uses. Halsted Press, New York, 1975.
13. W.H. Gutt and B. Hinkins. Improvement of the Polished Stone Value of Slag Roadstone by Heat Treatment. Journal of Institute of Highway Engineers, Vol. 4, No. 4, 1972.
14. S.H. Dahir and others; Pennsylvania Transportation Institute. Alternatives for Optimization of Aggregate and Pavement Properties Related to

Friction and Wear Resistance. Federal Highway Administration, U.S. Department of Transportation, 1978.
15. R.J. Collins and R.H. Miller. Availability of Mining Wastes and Their Potential for Use as Highway Material: Volume 1—Classification and Technical and Environmental Analysis. Federal Highway Administration. U.S. Department of Transportation, Rept. FHWA-RD-76-106, May 1976.
16. D. Pindzola and R.C. Chou. Synthetic Aggregate from Incinerator Residue by a Continuous Fusion Process. Federal Highway Administration, U.S. Department of Transportation, Rept. FHWA-RD-74-23, April 1974.
17. M.L. Hughes and T.A. Haliburton. Use of Zinc Smelter Waste as Highway Construction Material. HRB, Highway Research Record 430, 1973, pp. 16-25.
18. G.J. Gromko. A Preliminary Investigation of the Feasibility of Spent Oil Shale as Road Construction Material. TRB, Transportation Research Record 549, 1975, pp. 47-54.
19. P. C. Aitcin and C. Poulin. Bubble Aggregates. Proc., 4th Mineral Waste Symposium, U.S. Bureau of Mines and Illinois Institute of Technology, Chicago, 1974.
20. D.E. Ramsay and R.F. Davis. Fabrication of Ceramic Articles from Mining Waste Materials. Ceramic Bulletin, Vol. 54, No. 3, 1975.
21. D.A. Anderson, M. Usmen, and L.K. Moulton. Use of Power Plant Aggregate in Bituminous Construction. TRB, Transportation Research Record 595, 1976, pp. 18-24.
22. A. Denis and E. Massieu. Sand Resin Mortars for Road Surfacing. Bulletin de Liaison des Laboratoires des Ponts et Chaussées, Supplement 80, Nov.-Dec. 1975.
23. R.N. Dutt and D. Lee. Upgrading Absorptive Aggregates by Chemical Treatments. HRB, Highway Research Record 353, 1971, pp. 43-46.
24. P. D. Cady and others; Pennsylvania Transportation Institute. Upgrading of Poor or Marginal Aggregates for PCC and Bituminous Pavements. NCHRP Project 4-12, draft final rept., 1978.

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