Evaluation of Surface Mixtures of Steel Slag and Asphalt

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The demand for good-quality highway materials continues to increase whereas economical sources are becoming more limited. This demand may become more critical, especially with the policy (adopted by some state highway departments) of banning some aggregate types that have been frequently used in the past for producing paving mixtures. Steel slag aggregates have not yet been used extensively in pavement layers, even though they have been used successfully in the past. Steel slag has performed well in a number of surface-course applications subject to high traffic volumes (when such mixtures have been properly designed and constructed). Research, development, and demonstration work are still required to ensure the full exploitation of steel slag. The suitability of steel slag aggregates in combination with natural sand was evaluated for use in bituminous pavement surface layers constructed to serve high-volume, high-speed, and heavy-load traffic. This evaluation was made through a literature search, a field investigation, and a laboratory characterization of bituminous mixtures prepared with various gradations and proportions of steel slag aggregate. Marshall-sized specimens were tested in the laboratory for tensile characteristics, expansive properties after freeze-thaw cycling, and Marshall stability. The field investigation included a surface condition survey and skid resistance measurements. Use of steel slag in asphaltic mixes is still highly localized in steel production areas. Some highway agencies do not permit its use, although the performance record of steel slag mixtures is reported to be excellent. Some inputs should be considered in further evaluation of steel slag asphaltic mixtures. This process may lead to the development of technical specifications and recommendations for more extensive use of steel slag aggregates in pavement layers.

Many highway departments in the United States and Canada are taking actions to reduce and possibly prevent asphaltic pavement rutting on their highway systems. These actions are warranted because of the increased occurrence of rutting in pavements that have performed satisfactorily for several years. These increases are the results of ever-increasing truck volumes, gross weights, and tire contact pressures. Truck gross weights of over 500,000 lb and tire pressures of over 120 psi have been frequently reported.

Major changes in materials, together with some changes in mix design and construction procedures for asphalt pavement resurfacing and overlays, are currently recommended and applied. The use of some aggregate materials has been severely limited, if not prohibited. Natural sand, for example, is often prohibited from being used as a fine aggregate material in producing bituminous surface mixtures.

The policy of banning the use of various aggregates to obtain higher-quality asphaltic mixtures has its drawbacks, because it usually results in higher construction, maintenance, overlay, and resurfacing costs. Asphalt pavement mix design, thickness design, and construction procedures have to be developed to adapt to the use of poor-quality as well as good-quality aggregates.

Quality assurance specifications of most state highway departments (including Indiana) are getting tighter and tighter. Minimum Marshall stability (as an example) for accepting an asphalt mix is 1,200 lb in Indiana. Other state highway departments are using 1,500 lb as a minimum acceptable value. Minimum values of 2,000 lb are used in Canada and are currently recommended for use by some state highway departments. However, no well-known criteria have tied the Marshall mix design (or any other mix design procedure) to pavement thickness design of asphaltic surface mixtures. If a specific thickness was designed for a mixture with a Marshall stability of 2,000 lb, a greater thickness could be designed for a mixture with a 1,200-lb Marshall stability value and, similarly, a lower thickness could be designed for a mix with a 2,800-lb stability value.

Asphaltic mixtures composed of steel slag as coarse aggregate, natural sand as fine aggregate, and AC–20 asphalt cement were evaluated. Natural sand is considered a poor-quality aggregate and can produce tender asphaltic mixtures subject to rutting. Steel furnace slag is considered an acceptable aggregate type by the Indiana Department of Transportation's *Standard Specifications* (*1*). However, most contractors tend not to use it because of its relatively high cost. The cost per unit weight of steel furnace slag is almost the same as that of any other coarse aggregate type used in Indiana. However, the pavement thickness produced by a ton of steel slag is considerably smaller than that produced by any other coarse aggregate type, because of the high specific gravity (3.4) of the steel slag.

Asphaltic mixtures containing different proportions of steel slag and natural sand were produced and evaluated using Marshall stability and indirect tensile tests (indirect tensile strength, stiffness, and deformation). Other Marshall mix design parameters (air voids, voids in mineral aggregate, and voids filled with bitumen and density) were also investigated.

The combination of natural sand and steel slag produced an asphaltic paving mixture (in the laboratory) with good stability and stiffness. In addition, high stiffness values of laboratory-compacted cores containing steel slags suggest that its relatively high cost could be compensated for by either using it with inexpensive, low-quality fine aggregate or reducing the thickness of asphaltic paving surface layers in which steel slag is used.

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REVIEW OF LITERATURE

Ferrous Slags Production

Ferrous slags are by-products of the iron- or steel-making process. Formation begins when iron ore, coke, and a flux (either limestone or dolomite) are melted together in huge furnaces. When the metallurgical smelting process is complete, the lime in the flux has been chemically combined with the aluminates and silicates of the ore and coke ash to form a nonmetallic product called slag.

During the period of cooling and hardening from the molten state, the slag can be treated to form several specific types, which can in turn be crushed or screened to isolate diverse grades and sizes. The various types of ferrous slag can be classified under four basic headings (*2,3*):

1. Air-Cooled Blast Furnace Slag is produced by pouring molten slag into pits or banks and permitting it to cool and solidify slowly under atmospheric conditions. It can be processed, crushed, and screened into sizes. It is a relatively light-weight type of aggregate.
2. Expanded Blast Furnace Slag is produced by applying a controlled amount of water, steam, or compressed air to molten slag. It is also a light-weight type of aggregate.
3. Granulated Blast Furnace Slag is produced by sudden quenching of molten slag in water. It is a noncrystalline, light-weight, granular material.
4. Steel Slag, a by-product of the steel-making process (using open hearth, electric, or oxygen steel furnaces), has a higher specific gravity (3.2 to 3.6) than blast furnace slags because of its high iron content. Steel slag may be recycled to produce more iron products and one of the three iron blast furnace slags. However, this recycling procedure is usually not economical.

Table 1 presents the chemical composition of steel slag together with that of iron blast furnace slags for comparison purposes (*3*).

General Characteristics of Steel Slag Aggregates

Steel slag consists of crushed angular particles with rough, irregular surfaces. It has essentially no flat or elongated pieces and has a rougher surface texture than gravels and crushed stones. Steel slag is highly resistant to weathering, as are the iron blast furnace slags. Freezing and thawing effects and sulfate soundness losses are reported to be exceptionally low (*3,4*).

TABLE 1 COMPOSITION OF IRON BLAST FURNACE SLAGS AND STEEL SLAG (*3*)

Compound	Iron Blast Furnace Slag (%)	Steel Slag (%)
Calcium oxide	36–45	25–42
Silicon dioxide	33–42	15–17
Aluminum oxide	8–16	2–3
Magnesium oxide	3–16	6–10
Iron (FeO and Fe_2O_3)	0.3–2	20–26
Calcium sulfate	1–3	-
Manganese oxide	0.2–1.5	8–12
Titanium dioxide	0–1	0–1
Free lime	0–1	2–4

Rough-surfaced, angular particles of steel slag develop high internal friction and good particle interlock, which contribute to high stability when used as aggregate for bituminous mixes. Crushed steel slag typically has an angle of internal friction in the range of 45 to 50 degrees (*2*).

The hardness of steel slag, as measured by Moh's mineralogic scale, is usually 7, compared with values of 6 for air-cooled blast furnace slags and 3 to 4 for dolomite and limestone (*2,3*).

The abrasion characteristics of steel slag aggregate are also distinctive. Typical Los Angeles abrasion values (ASTM C131) are in the range of 20 to 25 percent, compared with 35 to 40 percent for air-cooled blast furnace slag and natural dolomite (*2,3*). Therefore, the change in gradation (degradation) under traffic would be negligible if steel slag was used for surface paving layers. Table 2 presents a comparison of some properties of steel slag aggregate and air-cooled blast furnace slag.

The weight per unit volume of slag is significantly higher than that of iron blast furnace slags and all natural aggregates. Bituminous paving mixtures produced using steel slag aggregates will display high density values and generally greater stability and stiffness values than bituminous mixes using any other type of aggregate material.

The distinctive color and texture of steel slag paving mixtures may also be useful in distinguishing traffic lanes from shoulders and keeping highway users alert to impending stops and highway width changes. Rumble strips can be constructed with steel slag to warn drivers of approaching intersections. These may help reduce accident rates at intersections with a high accident frequency and may prevent rutting.

TABLE 2 TYPICAL CHARACTERISTICS OF STEEL SLAG AND AIR-COOLED BLAST FURNACE SLAG (*2,3*)

Parameter	Air-Cooled Blast Furnace	Steel Slag
Bulk specific gravity	2.1–2.5	3.2–3.6
Porosity (%)	Up to 5	Up to 3
Rodded unit weight (lb/ft^3) (ASTM C28)	75–90	100–120
Los Angeles abrasion (%) (ASTM C131)	35–45	20–25
Sodium sulfate losses (%) (ASTM C88)	<12	<12
Angle of internal friction (degrees)	40–45	40–50
Hardness (Moh's scale of mineral hardness)[a]	5–6	6–7
California bearing ratio[b] (%)	Up to 250	Up to 300
Unit weight of Marshall compacted bituminous mix (lb/ft^3)	125–145	160–190
Polarity	Alkaline (pH 8–10)	Alkaline (pH 8–10)
Asphalt content requirements in dense graded mixes (%)	Up to 8	Up to 6.5

[a] Hardness of dolomite measured on same scale is 3 to 4.

[b] Top size ¾ in. Typical CBR value for crushed limestone is 100 percent.

Steel Slag Use in Asphaltic Paving Mixtures

Steel slag aggregates have been used successfully in asphaltic surface mixtures in Europe, Canada, Australia, and parts of the United States (*4,16*). No major problems with the quality and durability of steel slag asphaltic concrete (AC) pavements have been reported. Steel slag has also been used in hot mixes for winter patching. It retains heat very well, and its high unit weight and stability tend to hold patches in place.

Bituminous test sections were constructed in 1974 on Highway 401, Toronto By-Pass, Canada, as part of a program to determine the most suitable material to improve driving quality (*5,7,16*). Highway 401 is considered one of the busiest freeways north of Toronto. Sections constructed with steel slag gave the highest skid numbers during the 4-year study period. In addition, steel slag asphaltic mixtures displayed higher Marshall stability values (3,500 lb from laboratory-compacted specimens and 3,650 lb from field cores) than all other asphalt mixtures used in 18 different test sections. Steel slag asphaltic mixtures provide superior skid resistance. The wet-road accident rate did not significantly exceed the dry-road accident rate for steel slag AC surfacings, whereas the opposite was generally true for all other surfacings.

Highway trials using a blend of air-cooled blast furnace slag (coarser portion) and steel slag (finer portion) in AC surface courses have proven most satisfactory; excellent skid resistance was developed. This type of mix would allow a much fuller use of the finer steel slags (*3*).

Steel slag aggregates have also been used for pavement bases and subbases, shoulders, fills, and berm stabilization. Its use for pavement layers in parking lots and high-speed turns is currently being considered (*3,4,9–12*).

There has been interest in Europe and Australia concerning the use of steel slag in stabilized bases. Stabilized bases consisting of 60 percent blast furnace slag (0 to 60 mm), 25 percent steel slag (0 to 15 mm), and 15 percent granulated blast furnace slag have been placed and compacted with standard highway equipment (at approximately 10 percent water content); the results were reported to be excellent.

Factors To Be Considered When Employing Steel Slag Aggregates

When using steel slag aggregate materials for road construction the following factors should be considered.

Variations in Characteristics

Variations in the characteristics of steel slag and iron blast furnace slags may be expected, because both types are by-products of the iron- and steel-making process, not a slag aggregate-making process. The economic worth of steel slag for return to blast furnace, burden for recycling, and potential application of steel slag as a fertilizer may help cause these variations between plants and even within the same plant and furnace (open hearth, basic oxygen, and electric arc). Although not much variation in aggregate gradation may be expected because of processing and screening procedures, variations in specific gravity and other characteristics may be expected (*3,6*).

Unit Weight

The weight per unit volume of steel slag is significantly higher than that of blast furnace slag and of most natural aggregates. As a result, a larger tonnage of steel slag is required to produce a given volume of bituminous mix or to cover a given area of pavement with a specific thickness. This factor becomes important where long shipping distances are involved in obtaining sufficient materials for construction.

Expansive Nature

Although blast furnace slags are stable, steel slags have a potentially expansive nature (volume changes of up to 10 percent). This expansion can be attributed to the hydration of calcium and magnesium oxides (*2*). Because serious damage may result from the indiscriminate use of steel slags in confined applications, potential long-term volume changes must be checked before such use. Obviously, steel slags should not be used in portland cement concretes (unless shown otherwise by a detailed evaluation), because expansion will result in rapid destruction of the concrete. However, the expansion can be tolerable when controlled by suitable aging or treatment of aggregates with spent acids, or when the steel slag particles are properly coated with an asphaltic binder (*2,5*).

The expansive nature of steel slags can be traced back to the steel-making process, in which the conversion of pig iron to steel involves the controlled adjustment of various impurities and the addition of small quantities of constituents that give special properties to the steel. Although the steel slag constituents are similar to those of blast furnace slag, the proportions are different (Table 1). The calcium and magnesium oxides are not completely combined in steel slags, and there is general agreement in the literature that the hydration of unslaked lime (free CaO) and magnesium oxide (MgO) in contact with moisture is largely responsible for the expansive nature of most steel slags. The unslaked lime hydrates rapidly and can cause large volume changes in a few weeks. MgO hydrates more slowly and contributes to long-term expansion that may take several years to develop in the field. Because steel-making slags are reduced in size and water is involved during processing, CaO hydration may occur and the aging process may be accelerated, thus decreasing short- or long-term expansion.

Steel slags must be checked for potential expansion, because even aging for long periods in large dumps does not guarantee the elimination of expansive behavior (particularly if the slag is unprocessed and large lumps are involved).

A simple, economical, and rapid test procedure for evaluating the expansion potential of steel slags was reported by Emery (*3,16*). The procedure involved preparing steel slag specimens and a nonexpansive control using the standard proctor test. Stainless steel molds with perforated base plates allowed for moisture movement during an immersion period. The specimens were totally immersed in a water bath at 82°C ± 1°C and the amount of vertical expansion was monitored over time. The 82°C test temperature was selected on the basis of the initial expansion test series at 60°C. Expansion levels of 5 to 9 percent observed at 82°C (about three times that at 60°C) were similar to the levels of long-term expansion often observed in the field. A short monitoring period of 1 to 7 days appeared adequate to predict potential expansive behavior in the field. Surcharge weights can be used to simulate overburden conditions. Adoption of the laboratory-accelerated expansion tests at 82°C was given support by a series of long-term expansion tests at 20°C ± 1°C. After 475 days at 20°C, expansion was about half of that observed in 7 days at 82°C.

This test series indicated that aging in stockpiles (preferably after processing and in small quantities), spent acid treatments, and the use of coarser sizes all tend to limit the potential expansion of steel slags. These results are in qualitative agreement with field observations. Aging steel slag in large heaps or pieces is not very effective, because steel slag remains expansive for extremely long periods if not directly exposed to weathering (*3,16*).

The discussion in this section has been concerned with the potential expansion of steel slag that has not been coated with asphaltic cement. The use of steel slag in AC generally results in an acceptable product, because the asphaltic cement film coating the steel slag limits potential expansion. However, the question often arises concerning the need for aging steel slag before use in AC. If the finer sizes are used (<13 mm), prior aging is not critical, because the watering and screen processing during travel through the asphalt plant dryer and screens allow for any immediate expansion. However, a minimum aging period of 30 days is still recommended by many authorities, particularly for the coarser (>19 mm) asphalt mixes (*3,16*).

Steel slag may continue to be put mainly to such uses as railway ballast, pavement bases for shoulders, fills, and ice control grits. However, the economics of handling and using a heavy aggregate, the virtual elimination of any expansion-related problems by the asphaltic cement coating, and the potentially excellent performance of steel slag AC mixes make the use of steel slag aggregate more practical.

FIELD CONDITION SURVEY OF STEEL SLAG BITUMINOUS SURFACE LAYERS IN INDIANA

Steel slag and asphalt mixtures were used to provide a 1- to 1.25-in.-thick surface layer for a number of roadways in Indiana between 1979 and 1981. Tables 3 and 4 present the pavement performance history of these layers (discussed later in detail) together with traffic information.

Skid Resistance Measurements

Skid resistance numbers (friction numbers) measured using ASTM E-274 are presented in Table 3. Initial friction numbers, obtained in the year of construction, were exceptionally high (between 50 and 70). In addition, four out of five roadway sections displayed a reduction of only 0 to 3 percent/year. The roadway section on US-231 (Table 3) was the only section to display a large reduction in friction numbers (12 percent/year). This section was overlayed in 1985 (before the beginning of this study), and the cause of the drop in friction number could not be determined (Table 3).

Friction numbers obtained from the roadway sections presented in Table 3 also match those superior values obtained for steel slags used in other states and countries (*5,15*) and could be attributed to the low abrasion and high hardness characteristics of the steel slag (Table 2).

Visual Inspections

Sections of Indiana's SR-55, US-6, and I-80/90, which were constructed using steel slag aggregates in the surface layers, were visually inspected for surface deficiencies during August 1988. Pavement surface deficiencies on the three sections were similar and followed identical patterns (Figure 1).

TABLE 3 SKID RESISTANCE AND LIFE CYCLE INFORMATION OF STEEL SLAG ASPHALT SURFACE LAYERS IN INDIANA

Indiana Highway	Contract Number	Section Length	Construction Date	Overlay Date	Life Cycle	Initial Friction Number	Updated Friction Number
US-231	RS-12551	7.40 mi.	1980	1986	6 years	59.0	23.9 (1985)
SR-55	RS-13065	6.63 mi.	1981	----	_ 7 years	50.4	50.4 (1984)
US-6	RS-11898	11.70 mi.	1979	----	_ 9 years	69.9	55.6 (1986)
US-20	RS-12422	7.70 mi.	1980	1986	6 years	64.4	59.9 (1984)
US-35	RS-12337	5.97	1980	1986	6 years	67.2	59.6 (1984)
US-12	RS-13062	2.80 mi.	1981	1987	6 years	----	----
I-80/90	Toll Road	17.80 mi.	1980	----	_ 8 years	----	----

NOTES: 1. Type of overlay was sand seal.

2. Friction Numbers (Skid Resistance Numbers) are measured using ASTM E-274, Brake Force Trailer.

TABLE 4 FIELD INFORMATION OF STEEL SLAG ASPHALT SURFACE LAYERS IN INDIANA

Indiana Highway	Contract Number	Directional No of Lanes	Directional ADT*	Surface Thickness, Inch	Crack Intensity
US-231	RS-12551	1	3110	1.00	overlaid
SR-55	RS-13065	1	7238	1.00	high
US-6	RS-11898	1	2425	1.00	high
US-20	RS-12422	2	4765	1.25	overlaid
US-35	RS-12337	1	3460	1.25	overlaid
US-12	RS-13062	3	7500	1.00	overlaid
I-80/90	Toll Road	2	7000	1.25	high

*ADT is the average daily traffic in equivalent passenger cars (1983 information).

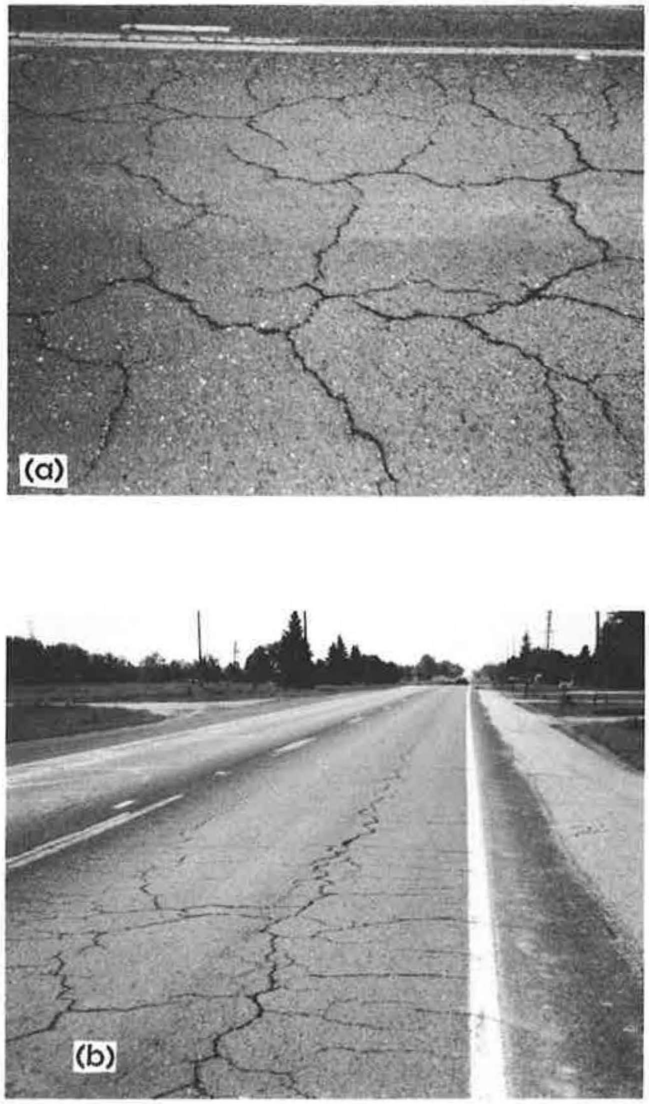

FIGURE 1 Cracking pattern observed on US-6, SR-55, and I-80/90: a, top view; b, longitudinal view.

Interconnected cracks forming a series of large polygons with sharp corners or angles and extending along the entire roadway portion were observed (typical map cracking). No indications of base failure or reduction in resilience of the underlying pavement layers were observed, and only cracks associated with the pavement surface were present. In addition, the pavement surface displayed some white-to-gray discolorations (Figure 2) at or near these cracks (similar to those obtained in the laboratory after successive freezing and thawing). However, absolutely no raveling, rutting, or shoving was observed at any location on those three roadway sections, and the pavement surface appeared to maintain its resilience after 8 years of traffic.

The map cracking could be attributed to age hardening (the pavement was 8 years old), weathering, and shrinkage of the asphaltic surface under climatic conditions. These conditions may have been complicated by the possible insufficiency of asphalt content and pavement thickness for the surface layer. The pavement surface thickness ranged between 1 and 1.25 in. The design asphalt content was 5.5 percent, and some cores displayed an extracted asphalt content of only 4.7 percent.

Another important factor is the possible accelerated hardening of the asphalt binder caused by the ferric and ferrous oxides present in steel slag particles (20 to 26 percent, Table 1). Ferric and ferrous components are typically used as catalysts to accelerate oxidation of asphalt in the production of air-blown asphalts. Air-blown asphalts have higher viscosity and softening point, and lower penetration, ductility, and adhesiveness than regular, straight-run distillation asphalts. Their use in paving mixtures is limited because of their potential for causing cracking.

Pavement Surface Temperature

Surface temperatures were recorded on portions of Indiana US-6, paved with a steel slag asphaltic surface on the westbound side and a natural aggregate (crushed limestone and natural sand) asphaltic surface on the eastbound side. The

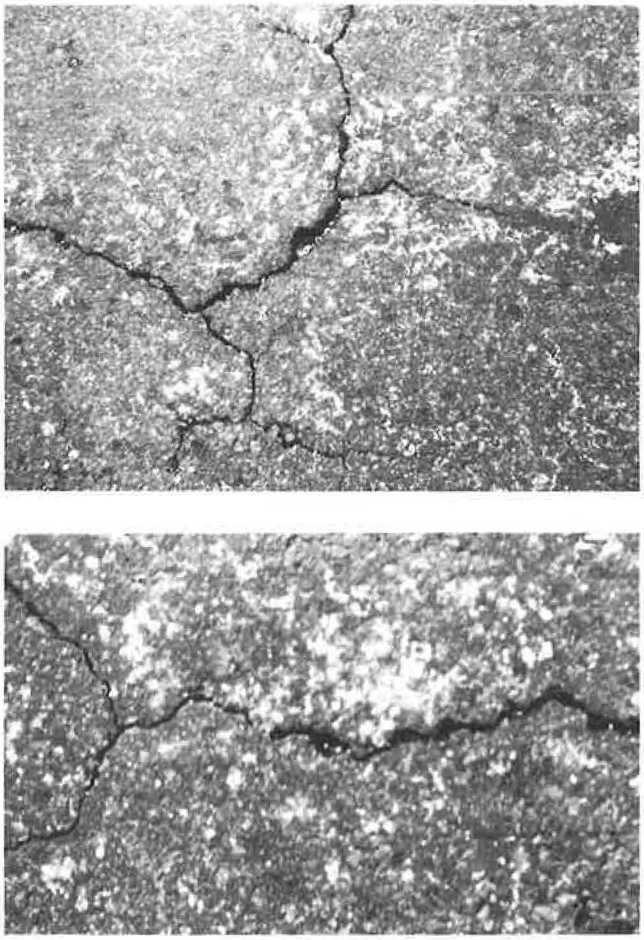

FIGURE 2 Surface discoloration, probably caused by hydration of free lime present in steel slag aggregates.

main objective was to investigate the effect of the large amounts of iron (ferric and ferrous oxide) present in steel slag aggregates and the dark black color of paving surfaces constructed with steel slags on the resulting pavement surface temperature.

An infrared noncontact-type field thermometer was used to measure and record temperature along the cross section of the eastbound side (natural aggregate) and the westbound side (steel slag). A simple statistical analysis of variance (ANOVA) indicated that no significant difference in temperature existed between points within the cross section of the eastbound side. The same result was obtained along the westbound side. Significant differences, however, were obtained between the two sides. The surface constructed using steel slag displayed a surface temperature 5°F to 10°F higher than the other surface. This could be attributed, in part, to the very low specific heat of the ferric and ferrous components in steel slag aggregate, resulting in a greater increase in pavement surface temperature (at the same amount of heat) than other aggregate types.

This factor becomes important when considering the age-hardening rate of asphalt binder, which may be accelerated because of this phenomenon, especially during hot weather. On the other hand, because of the low specific heat of steel slag, the low amount of heat available during winter may be enough to keep pavement surfaces warmer and hence decelerate ice formation during cold weather.

MATERIALS USED AND LABORATORY EVALUATION PROCEDURES

The materials used in the laboratory evaluation were (a) steel slag coarse aggregates (meeting the Indiana specified gradation requirements for No. 11 coarse aggregate), provided by Heckett Slag Products, Harsco Corporation, (b) Hanna natural sand (meeting the Indiana specifications for 23 sand), and (c) ASTM-designated AC–20 (Amoco Oil Company, Inc.). Table 5 presents the gradations of the steel slag coarse aggregate and Hanna sand, and Table 6 presents the characteristics of the AC–20.

Six combinations of coarse and fine aggregate were selected to produce mixtures with a wide range of gradations and proportions of steel slag coarse aggregates:

- Mix 1: 100 percent coarse aggregate (steel slag) and 0.0 percent natural sand (Hanna sand). This mix met the Indiana specifications for No. 11 bituminous-coated aggregate.
- Mix 2: 87 percent steel slag coarse aggregates and 13 percent sand. The amount of sand was the maximum percentage to keep the mix within specification of No. 11 bituminous-coated aggregate.
- Mix 3: 73 percent steel slag coarse aggregate and 27 percent natural sand. This mix contained the minimum amount of sand required to keep the mix within Indiana specifications for No. 11 binder mix.
- Mix 4: 59 percent steel slag coarse aggregate and 41 percent natural sand. This mix contained the largest amount of sand required to keep the mix within Indiana specifications for No. 11 binder mix.
- Mix 5: 47 percent steel slag coarse aggregate and 53 percent natural sand. This mix met the Indiana specification for No. 11 surface mix using the minimum amount of sand.
- Mix 6: 40 percent steel slag coarse aggregate and 60 percent natural sand. This mix met the Indiana specification for No. 11 surface mix using the maximum amount of natural sand.

Table 7 presents the gradations of Mixes 1 through 6, and Table 8 presents the Indiana specifications for No. 11 surface, No. 11 binder, and No. 11 bituminous-coated aggregate.

Marshall mix design procedures were conducted on each of the six mixes using 75 blows per face for specimen compaction. Each specimen's unit weight, percentage of air voids (AV), percentage of voids in aggregate mass (VMA), and percentage of voids in aggregate mass that are filled with bitumen (VFB) were determined in addition to Marshall stability and flow values.

Six specimens were used to represent each asphalt content. Three of those specimens were used for the Marshall mix design procedures. The indirect tensile test (split tension) was conducted at 75°F on the other three specimens to obtain tensile characteristics of Mixes 1 through 6 at different asphalt contents.

The average height of the specimens tested for Marshall stability was measured, and those specimens were exposed to

TABLE 5 GRADATION OF STEEL SLAG COARSE AGGREGATES AND HANNA SAND

Sieve Size	% Passing Steel Slag	Specification Limits*	% Passing Hanna Sand	Specification Limits*
1/2"	100	100	----	----
3/8"	83	75 - 95	100	100
#4	12	10 - 30	98	95 - 100
#8	3	0 - 10	91	80 - 100
#16	2	----	82	50 - 85
#30	2	----	60	25 - 60
#50	2	----	11	5 - 30
#100	2	----	1	0 - 10
#200	1	----	0	0 - 3

***Specification limits are for #11 coarse aggregate and #23 sand, IDOH** Standard Specifications (16).

TABLE 6 CHARACTERISTICS OF AC-20

Test	Value
Penetration, 100 gm, 5 sec., 77°F, 0.1 mm	65
Absolute Viscosity, 140°F, Poise	1890
Softening Point, °F	122
Ductility, 77°F, 5 cm/min., Cm	150+

30 successive cycles of freezing and thawing (17 hr of freezing at −10°F and 7 hr of thawing by soaking in a water bath at 75°F). Average heights were remeasured after the freeze-thaw cycling.

TABLE 7 GRADATION OF MIXES 1 THROUGH 6

Sieve Size	Percent Passing					
	Mix 1[a]	Mix 2[a]	Mix 3[b]	Mix 4[b]	Mix 5[c]	Mix 6[c]
½-in.	100	100	100	100	100	100
⅜-in.	83	85	88	90	92	93
#4	12	23	35	47	58	64
#8	3	14	27	39	50	56
#16	2	12	24	35	44	50
#30	2	10	18	26	33	37
#50	2	3	4	6	7	7
#100	2	2	2	2	1	1
#200	1	1	1	1	0	0

[a] #11 bituminous coated aggregate.
[b] #11 binder.
[c] #11 surface.

LABORATORY TEST RESULTS AND DISCUSSION

Marshall Mix Design Data

Tables 9–14 present the asphalt mix properties for the six designed mixtures. The amounts of natural sand and steel slag coarse aggregate used are given for comparison purposes.

Asphalt Content

Mixes 3 through 6 displayed maximum density and stability at asphalt contents of 5.0 percent, 5.5 percent, 6.5 percent, and 7.5 percent, respectively. The increase in the amount of natural sand (27 percent for Mix 3, 41 percent for Mix 4, 53 percent for Mix 5, and 60 percent for Mix 6) increased the surface area of the mix and consequently increased the amount of asphalt required for proper coating. However, this was not true for Mixes 2 and 1, consisting of 13 and 0.0 percent natural sand, respectively. Mixes 2 and 1 displayed maximum density and stability at asphalt contents of 5.5 and 6.0 percent, respectively, although they contained less than Mix 3. The use of high percentages of rough-surfaced steel slag apparently increased the asphalt requirement.

Asphalt mixes containing 100 percent steel slag coarse aggregate may require relatively high asphalt contents to peak

TABLE 8 INDOT SPECIFICATIONS FOR #11 SURFACE, #11 BINDER, AND #11 BITUMINOUS-COATED AGGREGATES

Sieve Size	#11 Bit. Coated Aggregate	#11 Binder	#11 Surface
1/2"	100	100	100
3/8"	75 - 100	78 - 98	85 - 98
#4	10 - 35	35 - 50	57 - 67
#8	0 - 15	20 - 45	31 - 62
#16	-----	11 - 36	17 - 50
#30	-----	6 - 26	8 - 37
#50	-----	2 - 18	3 - 25
#100	-----	0 - 11	0 - 14
#200	0 - 6	0 - 3	0 - 3

TABLE 9 CHARACTERISTICS OF MIX 1—100 PERCENT STEEL SLAG COARSE AGGREGATE, 0 PERCENT NATURAL SAND

	AC (%)				
	4.5	5.0	5.5	6.0	6.5
Unit Weight, PCF	150.5	151.1	151.5	152.0	151.8
% Air Voids	21.6	20.5	19.41	18.3	17.5
% VMA	34.0	33.3	32.7	31.9	32.0
% VFB	36.5	38.4	40.7	42.6	45.3
Max.th.Density, PCF	192.0	190.0	188.0	186.0	184.0
Marshall Stability, Lbs.	1400	1550	1600	2100	1750
Flow, 1/100 inch	8.0	8.0	9.0	10	10
S_T, Psi	112	124	126	133	126
e_T	0.004	0.005	0.006	0.007	0.008
E, 10^4 psi	7.0	7.0	7.0	8.0	8.0
Freeze-Thaw Cycling Effect	6.7	5.5	5.0	0.1	0.0

NOTE:

1. Effect of successive freezing and thawing cycles was measured by the percent increase in average specimen height before and after exposure to 30 cycles.
2. S_T, e_T and E are tensile strength, strain and stiffness modulus respectively.

TABLE 10 CHARACTERISTICS OF MIX 2—87 PERCENT STEEL SLAG COARSE AGGREGATE, 13 PERCENT NATURAL SAND

	AC (%)			
	4.5	5.0	5.5	6.0
Unit Weight, PCF	156.2	156.5	157.0	156.9
% Air Voids	16.5	15.5	14.4	13.6
% VMA	29.5	29.2	28.3	29.0
% VFB	44.1	46.9	49.1	53.1
Max.th.Density, PCF	187.1	185.2	183.4	181.6
Marshall Stability, Lbs.	1800	2500	2600	2200
Flow, 1/100 inch	10	11	12	15
S_T, Psi	121	144	146	137
e_T	0.006	0.006	0.007	0.008
E, 10^4 psi	7.0	8.0	10.0	8.0
Freeze-Thaw Cycling Effect	5.5	4.0	2.6	0.1

TABLE 11 CHARACTERISTICS OF MIX 3—73 PERCENT SLAG STEEL COARSE AGGREGATE, 27 PERCENT NATURAL SAND

	AC (%)			
	4.5	5.0	5.5	6.0
Unit Weight, PCF	159.5	162.0	158.4	157.8
% Air Voids	10.0	9.2	8.9	8.5
% VMA	23.4	23.0	22.9	23.3
% VFB	57.3	60.0	61.1	63.7
Max.th.Density, PCF	177.2	175.6	173.9	172.4
Marshall Stability, Lbs.	2000	2850	2650	2250
Flow, 1/100 inch	9.0	9.0	10.0	11.0
S_T, Psi	148	160	158	156
e_T	0.007	0.007	0.007	0.008
E, 10^4 psi	8.0	11.0	10.0	9.0
Freeze-Thaw Cycling Effect	5.4	3.6	0.9	0.1

TABLE 12 CHARACTERISTICS OF MIX 4—59 PERCENT STEEL SLAG COARSE AGGREGATE, 41 PERCENT NATURAL SAND

	AC (%)			
	4.5	5.0	5.5	6.0
Unit Weight, PCF	152.2	152.3	154.0	153.6
% Air Voids	11.6	10.7	9.1	8.4
% VMA	23.6	23.2	22.8	22.9
% VFB	50.8	53.9	60.1	63.4
Max.th.Density, PCF	172.2	170.6	169.2	167.7
Marshall Stability, Lbs.	1400	1800	2100	1900
Flow, 1/100 inch	6.0	6.0	8.0	8.0
S_T, Psi	148	156	158	156
e_T	0.007	0.007	0.007	0.007
E, 10^4 psi	8.0	9.0	10.0	10.0
Freeze-Thaw Cycling Effect	4.2	3.6	0.8	0.0

TABLE 13 CHARACTERISTICS OF MIX 5—47 PERCENT STEEL SLAG COARSE AGGREGATE, 53 PERCENT NATURAL SAND

	AC (%)			
	5.5	6.0	6.5	7.0
Unit Weight, PCF	145.0	145.7	148.0	147.7
% Air Voids	11.7	10.6	8.5	7.9
% VMA	24.4	24.3	24.0	24.1
% VFB	52.0	56.5	64.6	67.4
Max.th.Density, PCF	164.2	162.9	161.7	160.4
Marshall Stability, Lbs.	1350	1450	1500	1400
Flow, 1/100 inch	6.0	6.0	8.0	8.0
S_T, Psi	140	147	155	140
e_T	0.006	0.007	0.007	0.008
E, 10^4 psi	6.0	6.0	8.0	7.0
Freeze-Thaw Cycling Effect	0.5	0.1	0.0	0.0

TABLE 14 CHARACTERISTICS OF MIX 6—40 PERCENT STEEL SLAG COARSE AGGREGATE, 60 PERCENT NATURAL SAND

	AC (%)				
	6.0	6.5	7.0	7.5	8.0
Unit Weight, PCF	145.0	145.4	145.6	146.0	145.4
% Air Voids	8.8	8.0	7.2	6.3	6.0
% VMA	22.2	22.0	21.8	21.8	21.9
% VFB	60.4	63.6	67.0	71.1	72.6
Max.th.Density, PCF	159.0	158.0	156.9	155.8	154.7
Marshall Stability, Lbs.	1200	1200	1200	1250	1200
Flow, 1/100 inch	7.0	7.0	7.0	8.0	8.0
S_T, Psi	140	144	146	150	147
e_T	0.007	0.008	0.008	0.008	0.009
E, 10^4 psi	6.0	6.0	6.0	7.0	6.0
Freeze-Thaw Cycling Effect	0.1	0.0	0.0	0.0	0.0

in density and stability. The addition of natural sand (to a certain extent) may reduce the required amount of asphalt for maximum density and stability, as shown in Figure 3.

Unit Weight

Natural sand was used with steel slag coarse aggregate to produce asphalt mixtures with unit weights lower than those obtained when using steel slag sand. Use of steel slag sand can also result in high shipping costs. The steel slag surface mixture (containing steel slag coarse and fine aggregates) used on US-6 displayed a unit weight of 186 lb/ft^3, which is at least 30 percent higher than any other No. 11 surface mixes produced using natural aggregates. Mixes 1 through 6 (Tables 9–14) displayed unit weights of 145 to 162 lb/ft^3, only 5 to 15 percent higher than No. 11 surface mixtures produced without steel slag aggregates. The use of more open graded mixes when using smaller amounts of natural sand is another alternative to avoid the high-density disadvantage of steel slag.

Marshall Stability

Although the high specific gravity of steel slag aggregates is a disadvantage when considering shipping cost, it helps create the superior stability that may be expected from steel slag asphaltic mixtures. Marshall stabilities of 3,500 to 4,000 lb have been frequently reported for steel slag mixtures containing both coarse and fine steel slag aggregates (*3,5,7*).

Natural sand use in asphaltic surface mixtures is generally limited and is banned by some state highway departments. Natural sand combined with dolomite (coarse aggregate) produced asphalt mixes (with different gradations and asphalt contents) with Marshall stabilities of no more than 1,250 lb at optimum asphalt content. Minimum acceptable Marshall stability, by Indiana Department of Transportation specification, is 1,200 lb.

Tables 9–14 present Marshall stability values for Mixes 1 through 6. A stability of at least 1,200 lb was obtained for all mixes at any asphalt content. The use of natural sand (known to produce tender mixes) not only compensated for the high specific gravity of the steel slag coarse aggregate but maintained good stability in combination with steel slag. Mix 3 displayed the largest stability (2,850 lb) and density at an asphalt content of 5 percent (Figures 4 and 5).

Aggregate Gradation Curves

Figure 6 shows the aggregate gradation curves for Mixes 1 through 6, together with the curve for maximum density. Higher Marshall stability values were obtained (at optimum asphalt content) as the mix gradation got closer to the Fuller's maximum density curve, for Mixes 1, 2, and 3. However, lower stability values were obtained for Mixes 4, 5, and 6, which crossed the maximum density curve; these mixes may have been too densely graded. Mixes 4, 5, and 6 had more material passing No. 16 and No. 30 sieves (i.e., they may also have been over sanded).

The gradation curve for Mix 3 suggests that this mix may have had more materials passing the No. 8, No. 16, and No. 30 sieves than were needed, as indicated by the hump in the gradation curve in that region. The same observation can be made for Mix 2, but this mix may have had insufficient amounts of material passing the No. 50, No. 100, and No. 200 sieves.

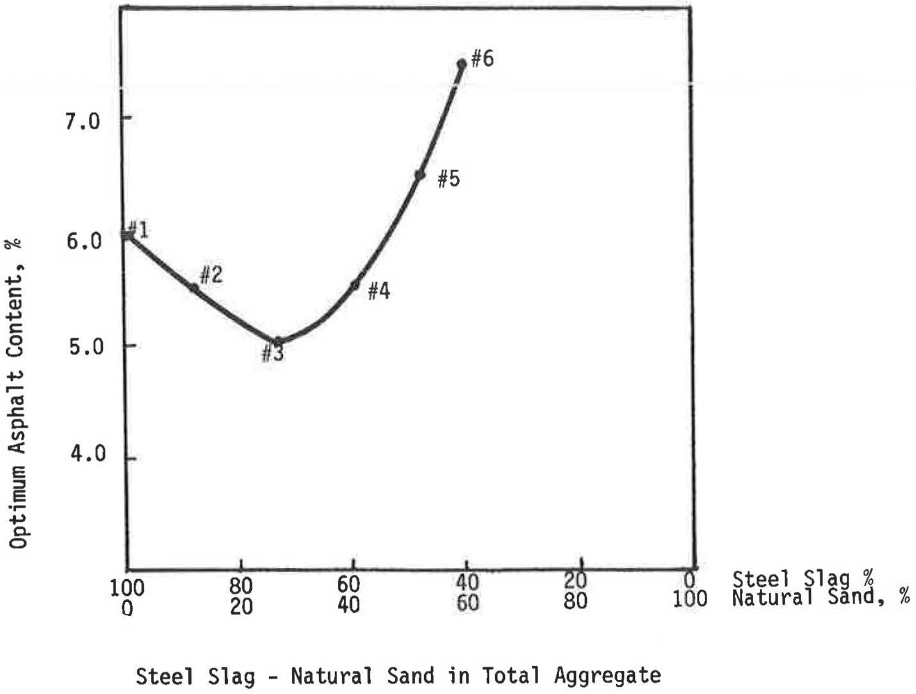

FIGURE 3 Asphalt content requirements for maximum density and stability for six mixes.

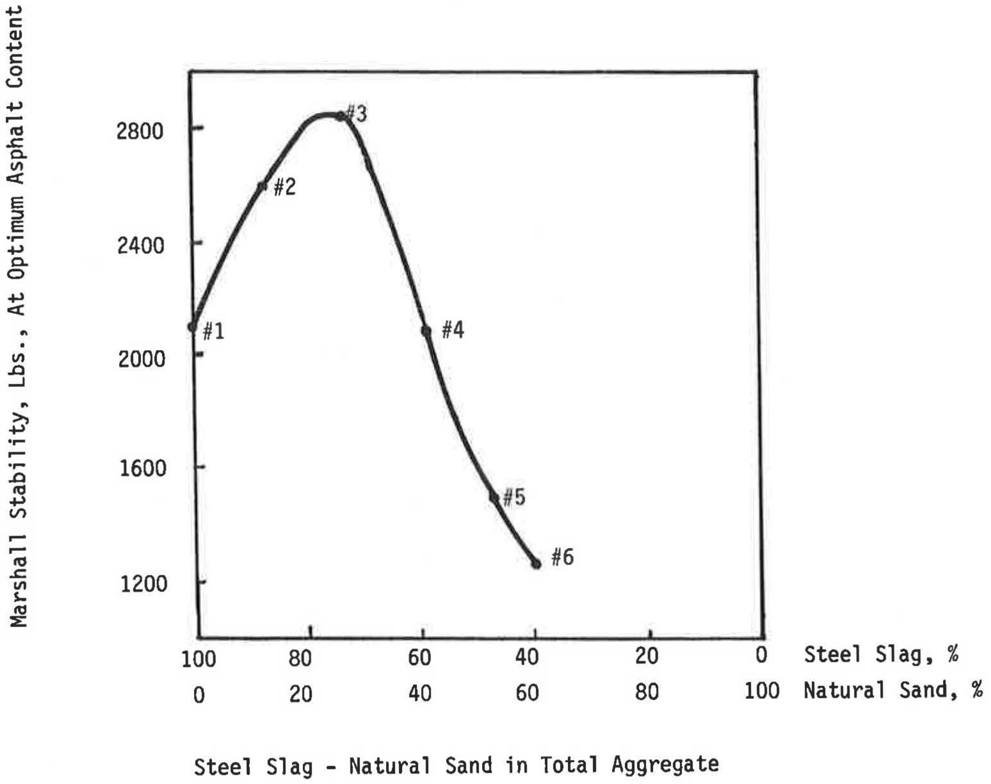

FIGURE 4 Marshall stability at optimum asphalt content for six mixes.

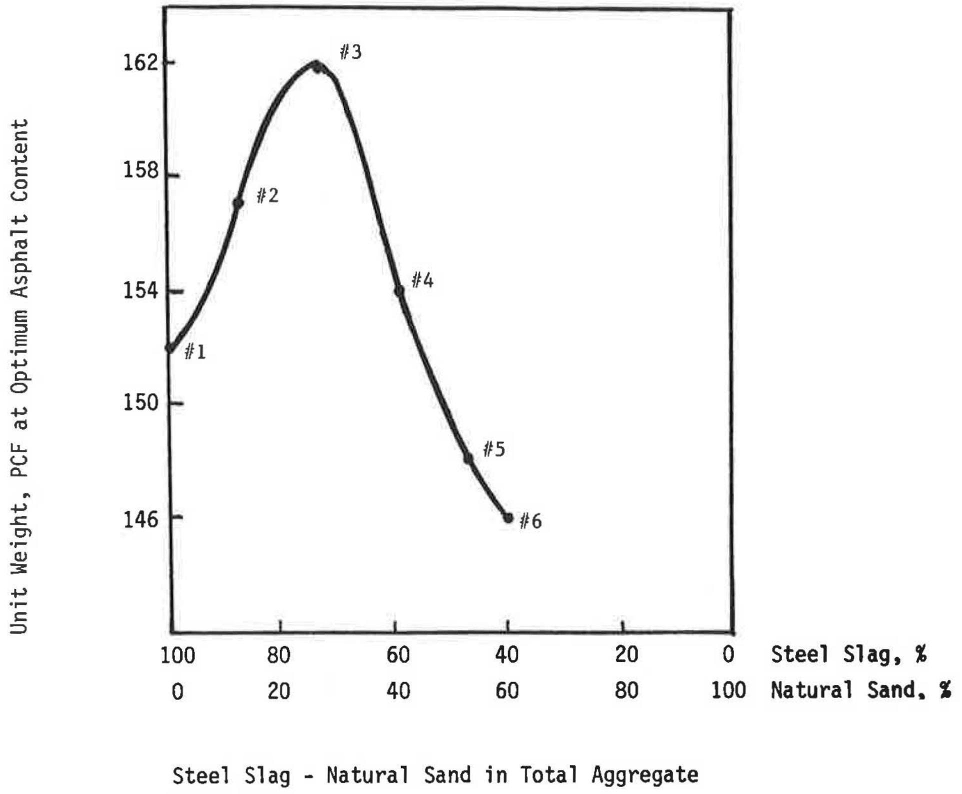

FIGURE 5 Unit weight at optimum asphalt content for six mixes.

Indirect Tensile Characteristics

The indirect tensile test was conducted at 75°F. The following indirect tensile test parameters were used to characterize steel slag asphalt mixtures in the compacted state (*17–23*):

$$S_T = 0.1556\frac{P_{\max}}{H} \qquad (1)$$

where

S_T = tensile strength (psi),
H = specimen height (in.), and
$P_{\max}$ = load at failure (lb).

$$e_T = KX_v \qquad (2)$$

where

e_T = total tensile horizontal strain at failure,
X_v = recorded vertical deformation at failure (in.), and
K = 0.09 at test temperature of 75°F.

$$E = \frac{3.56\ S}{H} \qquad (3)$$

where

E = stiffness modulus (psi),
S = slope of initial tangent of the load-deformation plot (lb/in.), see Figure 7, and
H = specimen height (in.).

Paving mixtures with low tensile strength values have a tendency to develop low-temperature cracking problems in the field, especially when used for surface mixtures. An indirect tensile strength of 150 psi at 75°F is usually considered an average value for asphaltic surface mixtures (*23*). Values of more than 150 psi generally reflect good crack resistance, whereas values of less than 150 psi may be considered low. Paving mixtures with low tensile strain values also tend to be less resistant to cracking, whereas those with high strain values may tend to develop rutting distress. A strain value of 0.008 at 75°F can be considered an average value for asphalt surface mixtures.

The stiffness modulus E measured using the indirect tensile test generally averages 60,000 psi for asphalt surface mixtures. Conceptually, pavement thickness for paving surface mixtures can be reduced when using mixes with a large stiffness modulus or increased when using mixes with a small stiffness modulus.

Tables 9–14 present indirect tensile characteristics for Mixes 1 through 6. Indirect tensile strength values peaked with the same asphalt contents that provided maximum density and stability (Figure 8). They followed almost the same trend as the Marshall stability values, displaying a peak strength at a natural sand content of 27 percent (Mix 3). Except for Mixes 3, 4, and 5, all other mixtures indicated average or below-average tensile strengths for a bituminous surface mix (with 150 psi generally considered average). In addition, the tensile strength values of Mixes 3, 4, and 5 did not exceed the previously specified average value by a significant margin.

Failure tensile strains for all six mixtures (Tables 9–14) displayed average or below-average values for a surface mix-

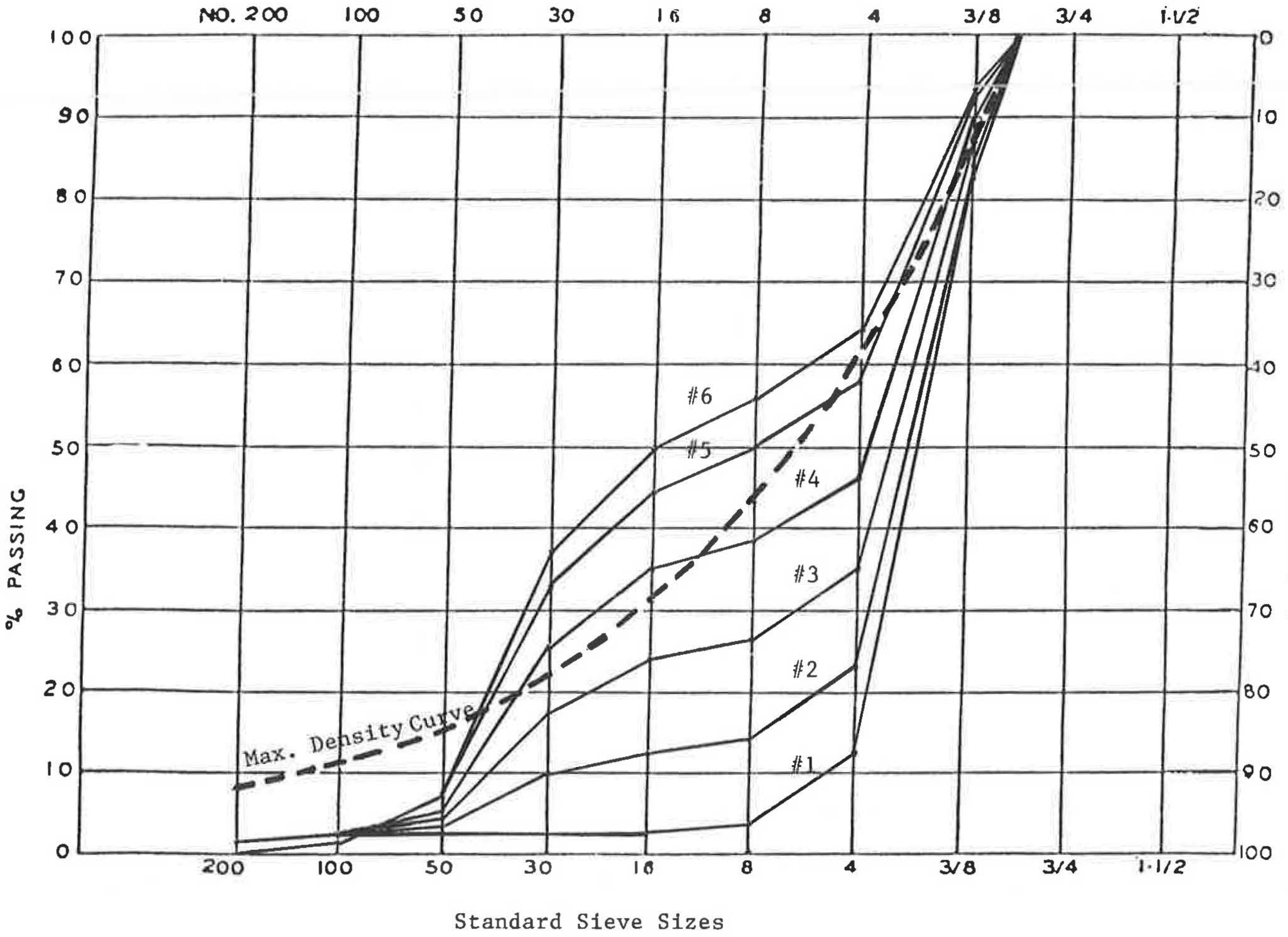

FIGURE 6 Aggregate gradation curves for six mixes.

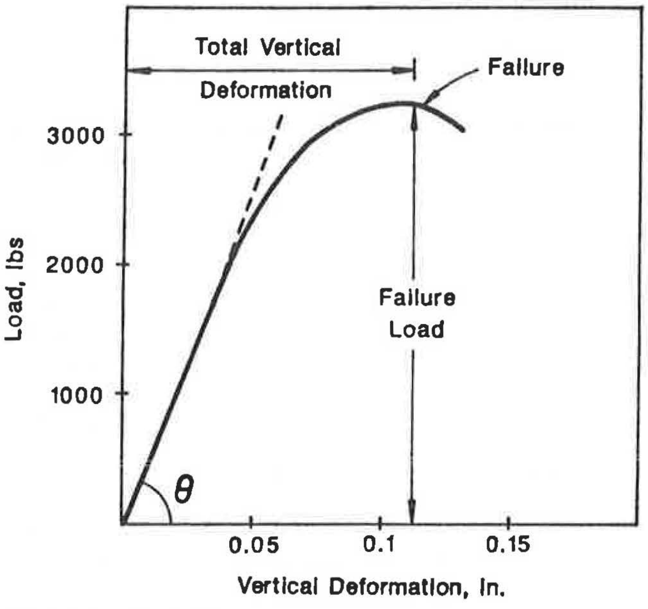

FIGURE 7 Typical load versus vertical deformation trace during indirect tensile test.

ture (with 0.008 generally considered average). Low tensile strength and failure tensile strain could be attributed to the lack of dust (materials passing No. 200 sieve) in the six mixtures and the resulting lack of total binder (asphalt plus filler) content.

Stiffness modulus values (Tables 9–14) for the six mixtures, unlike tensile strength and strain characteristics, were up to 80 percent higher than a typical average value obtained from natural-aggregate AC surface mixes (60,000 psi). The largest values were obtained at the asphalt contents corresponding to maximum density and stability. Mix 3 displayed the largest modulus value followed by Mixes 4, 2, 1, 5, and 6 (Figure 9). Elastic analysis techniques for pavement thickness design indicate the use of an at least 15-percent thinner asphalt surface layer containing steel slag and natural sand. This thinner layer could play an important role in compensating for the high-density disadvantage of steel slag asphalt mixtures.

Freezing and Thawing Effect

All specimens tested for Marshall stability were exposed to 30 successive cycles of freezing and thawing (17 hr of freezing

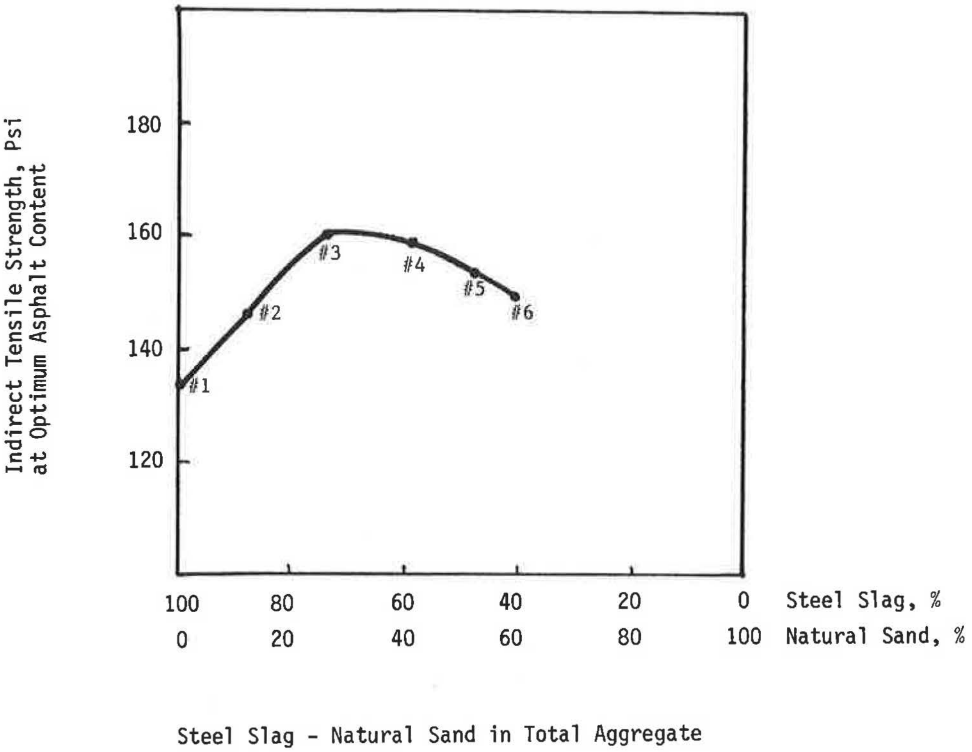

FIGURE 8 Indirect tensile strength at optimum asphalt content for six mixes.

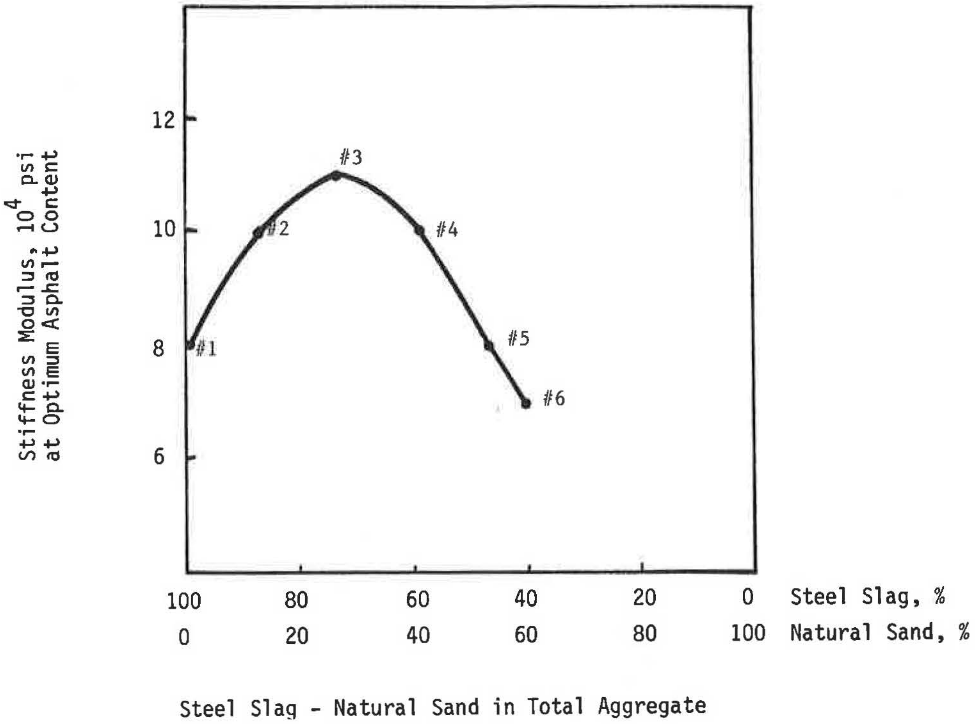

FIGURE 9 Stiffness modulus at optimum asphalt content for six mixes.

at −10°F and 7 hr of thawing by soaking in a water bath at 75°F). Average specimen height was measured for each specimen before and after exposure to freeze-thaw cycling.

Tables 9–14 also present the percentage of change in specimen height caused by freezing and thawing at different asphalt contents for the six steel slag and natural sand mixtures. Values given are the average of three replications. Statistical analysis of variance (ANOVA) for the complete data indicated a significant percentage increase in specimen height after freezing and thawing (up to 6.7 percent increase).

Larger increases were found to be associated with specimens displaying lower asphalt contents formed by using larger percentages of steel slag. In addition, randomly positioned, white-to-gray, powderlike veins were observed on the surface of specimens exposed to freezing and thawing. These veins were probably caused by the hydration of free lime in steel slag aggregates. Veins were also observed in the field at or near surface cracking in the steel slag paving surface mixes.

SUMMARY OF RESULTS

Analysis and evaluation of the laboratory test data combined with the literature search and field investigation provided insight into the characteristics of steel slag and asphalt surface mixtures containing steel slag and natural sand. The test results, however, may be limited to the materials used and test conditions applied in this study.

The main findings can be summarized as follows:

1. The use of steel slag aggregate in asphalt surface mixtures provides pavement surfaces with good skid resistance.
2. Asphaltic paving mixtures using steel slag aggregates display exceptionally high stability, which may prove to be rut resistant when used in pavement surface layers.
3. The potential expansive characteristics of steel slag aggregate may be controlled by using a relatively large asphalt content to provide a thick coating of asphalt around the steel slag particles, thus reducing or possibly preventing direct exposure to moisture. Another alternative is to replace steel slag sand with natural sand. The stability reduction caused by the addition of more asphalt, more natural sand, or both, is tolerable.
4. The use of natural sand with steel slag coarse aggregate not only compensates for the high specific gravity and expansive potential of steel slag aggregate but also maintains good stability for the mixture.
5. The presence of ferrous and ferric oxides in steel slag aggregates may accelerate the hardening of the asphalt binder in the paving mixture and hence aggravate low-temperature cracking of the pavement surface. The use of softer asphalts (AC−10 or Indiana designated asphalt emulsion AE−90, instead of AC−20 and AE−60) is a possible alternative to counteract the accelerated hardening rate.
6. The high unit weight of steel slag mixtures can be significantly reduced by using more open pavement surface mixtures and by replacing steel slag fine aggregate with natural sand.
7. Asphalt paving mixtures produced in this study from steel slag and natural sand displayed average or below-average tensile strengths and failure strain.
8. Asphalt paving mixtures produced in this study from steel slag and natural sand displayed exceptionally large stiffness modulus values. A large stiffness value is an indicator of the possibility of using a reduced pavement thickness.
9. The effect of successive freezing and thawing on laboratory-compacted mixtures of steel slag and natural sand was generally marginal.
10. As a net result, the replacement of steel slag sand by natural sand, designing the asphalt mix slightly opened, using a slightly larger asphalt content than the optimum value, using softer grades of asphalts, and probably using reduced-design thickness may be recommended for steel slag asphalt surface mixtures to compensate for their large unit weight, expansive nature, tendency to accelerate the hardening of the asphalt binder, and relatively large cost. Performance of paving mixtures using these recommendations should be verified under actual field conditions.

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