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STEEL SLAG UTILIZATION IN ASPHALT MIXES

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ABSTRACT

Steel slags are the major byproduct from the conversion of iron to steel in the basic oxygen (major type), electric arc and open hearth (minor type) steelmaking processes. Steel recovery from the slag results in a processed aggregate with both positive (wear resistant, skid resistant, rough textured, angular, well graded, stripping resistant) and negative (heavy, expansive) features. Considerable experience, particularly since 1970 in Southern Ontario, has shown that the use of steel slag in asphaltic concrete minimizes potential expansion and takes advantage of the positive features in giving high stability, stripping resistant asphalt mixes with excellent skid resistance. (It should be noted that steel slag must not be used in confined applications or Portland cement concrete.) The high stability of steel slag mixes offers a distinct advantage where rutting resistance is required and this has been demonstrated in industrial areas. The excellent skid resistance provided has been monitored in both urban and highway applications, and steel slag asphalt mixes (open and dense graded) are often used for critical pavements. While these positive applied features of steel slag asphalt mixes are emphasized, practical design guidance is also provided covering special features that must be dealt with to ensure satisfactory performance such as uniformity, deleterious materials, unit weight and potential expansion. It is clear that steel slag will continue to make a positive contribution to high quality asphalt mix aggregate requirements in areas of steel production.

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INTRODUCTION

Since an earlier CTAA paper in 1973 on steel slag asphalt mixes[1] when there had been little use of such mixes in Canada, the use of steel slag in asphalt mixes has come of age in Southern Ontario with several suppliers of steel slag aggregate (Red-D-Mix, Steetley, Levy, IMS[2]) and applicable Ontario Ministry of Transportation and Communications (MTC) specifications for mixes such as dense and open graded friction courses.[3,4] The purpose of this paper is to review developments in steel slag asphalt mixes starting from a brief description of the range of slags available for use in pavement construction and maintenance[5].

Ferrous slags (iron blast furnace, steelmaking, foundry, ferro-alloy) are probably the industrial byproducts of greatest interest to pavement construction, given their fairly wide availability and scope of uses. Optimal uses appear to be in blended cements (ground BF slag and Portland cement blend) for granulated blast furnace slag, and aggregate in asphaltic concrete for steel slags. In considering the use of ferrous slags, there are several important factors to note: pavement use is not new (iron slags were used during Roman road building in England); they are not wastes, but valuable byproducts processed for the construction industry; there is a continuing trend towards cementitious applications; and blast furnace slags (relatively low bulk density -typically 1300 kg/m^3 for air-cooled -and stable with no expansion tendencies) must not be confused with steel slags (high bulk density -typically 1900 kg/m^3 - and potential expansive nature related to uncombined oxides)[6].

Iron blast furnace slag results from the fusion of fluxing stone with coke ash and the siliceous and aluminous residues remaining after the reduction and separation of iron from the ore. The blast furnace operation is a continuous process with the carefully controlled raw materials being fed in (burden) and the uniform products, molten iron and liquid slag, being drawn off at regular intervals. Selective cooling of the liquid slag results in four distinct types of blast furnace slag: (1) air-cooled (solidification under ambient conditions), which finds extensive use in conventional aggregate applications; (2) expanded or foamed (solidified with controlled quantities of water, sometimes with air or steam), which is mainly used as a lightweight aggregate; (3) granulated (solidified by quick water-quenching to vitrified (glassy) state), which is mainly used in blended cement manufacture; and (4) pelletized (solidified by water and air-quenching in conjunction with a spinning drum), which is used both as a lightweight aggregate and in blended cement manufacture.

Nonferrous slags such as copper and nickel slag can be used in granular base and structural fill construction, and related applications such as ballast. Boiler slags are used in a number of applications such as seal coat, asphaltic concrete and granular base construction. While most ferrous slag is utilized, there is still much scope to utilize nonferrous and boiler slags that are often disposed of with consequent environmental impact. With the present indications of materials and energy shortages, there is a new concern that all byproduct slags be utilized effectively[5].

STEEL SLAG PRODUCTION AND GENERAL PROPERTIES

While much steel slag from the various steelmaking processes (open hearth, basic oxygen, and electric arc) is suitable for return to blast furnace burden, there is still a large quantity available that can be effectively utilized in road construction. In considering steel slags, two points must be emphasize; there is typically a large variation in steel slags, even for the same plant and furnace; and economic worth of steel slags for return to blast furnace burden and other potential applications such as fertilizer must be recognized. The various steel making processes generally introduce restrictions in the uses of steel slags in comparison to blast furnace slags. Steel slags have a high bulk density and potential expansive nature (volume changes of up to 10 percent or more attributable to the hydration of calcium and magnesium oxides), while blast furnace slags have a relatively low bulk density and are stable. Since serious damage may result from indiscriminate use of steel slags in confined applications, potential long-term volume changes must be checked before such usage. Obviously, steel slags should not be used in Portland cement concretes or related mix types such as lean concrete since expansion will result in rapid destruction of the concrete. However, there are many applications where expansion is tolerable, has been controlled by suitable aging or treatment, or where sealing of the steel slag with an asphalt cement coating eliminates any problems[5]. Further, the potential for selective use, based mainly on the free line content, has been developed in some countries[7].

The expansive nature of steel slags can be traced back to the steelmaking 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. Chemical compositions for typical Canadian open hearth and basic oxygen furnace steel slags are compared with those of blast furnace slag, the proportions are quite different, with the higher iron content being reflected in the high specific gravity of 3.2 to 3.5 for steel slag compared to 2.2 to 2.5 for air-cooled blast furnace slag. The mineral composition of steel slags is fundamentally different from blast furnace slags where the calcium and magnesium oxides are always combined in silicate and aluminosilicate minerals, and consists essentially of calcium silicates, calcium oxide-ferrous oxide solid solutions, oxides, and free lime. Steel slag phase compositions are similar to that of a weak Portland clinker and, while the dicalcium silicate present is in the potentially metastable β form, it appears to be inactive. 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. Magnesium oxide hydrates more slowly and contributes to the long-term expansion that may take several years to develop in the field, even when old steel slag dumps are being used.

A separate problem that can occur with steelmaking slags is contamination with steel works rubbish such as refractories. Inevitably, some refractories get into the steel slag from furnace linings, but the major problem results from using ladles and pits as waste receptacles in the furnace areas. Fortunately, the value of steel slags is increasingly being recognized, particularly for return to blast furnace burden, and contamination is avoided. Small quantities of refractories do not appear to cause problems in highway applications. In addition to meeting specific coarse and fine aggregate gradations[3,4], for steel slag the MTC requires the total amount of non-slag constituents (furnace brick, incompletely fused fragments, lime, wood, rock, etc.) to not exceed 3 percent by mass and wood content alone

TABLE-1 Chemical composition of iron blast furnace slags, Portland cement and steel slags[6].

	Iron Blast Furnace Slag			Steel Slag	
Constituent, %	Usual Range	Typical	Portland Cement	Open Hearth	Basic Oxygen
Calcium oxide (Ca)	36-45	37.6	64.1	25.8	41.3
Silicon dioxide ($Si0_2$)	33-42	34.8	22.0	16.4	15.6
Aluminum oxide (Al_2O_3)	10-16	8.1	5.5	2.4	2.2
Magnesium oxide (MgO)	3-16	15.4	1.4	10.0	6.9
Iron (FeO or Fe_20_3)	0.3-2	0.8	3.0	26.0	20.0
Sulfur (S)[a]	1-3	1.3	2.I[b]	--	--
Manganese oxide (MnO)	0.2-1.5	0.61	--	11.2	8.9
Titanium dioxide (TiO_2)	--	0.31	--	0.8	0.5
Free lime (free CaO)	--	0.47	--	2.1	3.3

a Principally as calcium sulfate
b SO^3

to not exceed 0.5 percent by mass[4]. It should be noted that it is the liming material and incompletely fused fragments (*i.e.* free lime and/or magnesia) that are of particular concern, and the MTC requirements are under review.

Processing of steel slags for steel recovery is very important as it results in an angular, generally well-graded, material that is relatively free of metallics, and the recovered steel (2 to 4 percent of raw steel production) is a valuable scrap. It appears that improved or even new methods for removing the steel from steelmaking slags would be highly desirable since this is a very space and time consuming activity. Slag modifications to lower the viscosity in the molten state, thus allowing the steel to separate, have been developed and patented, but not used commercially. Similar processes are being developed to give a steel slag suitable for cement manufacture. Since the steelmaking slags are reduced in size, and water is involved during processing, it is likely that hydration of calcium oxide occurs and the aging process is accelerated. Processed steel slag is still high in iron, lime, and manganese, so that it is possible to return steelmaking slag (particularly the large sizes) to blast furnace burden.

EXPANSION TESTS

There is a large amount of steel slag used for applications such as bases, and many old steel slag heaps or fills are being built on, or used for construction purposes. It is critical that these steel slags be checked for potential expansion, since even aging for long periods in large dumps does not guarantee the elimination of expansive behavior (particularly if unprocessed so large lumps are involved). Leachates are not considered a problem from the typical data in Table 2 and Trow Ltd testing.

TABLE 2 - Analysis of Filtrate, mg/l[a,b] *Typical ferrous slag solubility test data (Calspan Corporation)For Environmental Protection Agency)*[5].

Slag	Cr	Cu	F	Mn	Pb	Zn	pH
Blast furnace (iron)	<0.01	<0.03	1.9	<0.01	0.20	<0.01	10.6
Open hearth (steel)	0.01	0.04	3.1	<0.01	0.30	<0.01	12.5
Basic oxygen (steel)	0.03	0.03	4.0	<0.01	0.20	<0.01	12.5
Electric arc (steel)	0.27	0.03	1.5	<0.01	0.44	<0.01	12.4
Iron and steel foundry	0.05	0.25	ND[c].	0.06	<0.20	0.12	10.6
Ferrochrome	0.02	0.02	NO	0.30	0.40	0.20	9.9
Ferronickel	0.01	0.74	NO	0.07	1.00	2.00	8.5
SilicatBIlganese	<0.01	0.17	NO	0.10	<0.20	0.05	6.8
Ferromanganese	0.02	0.04	NO	2.10	<0.20	0.03	5.9

[a] One solubility test for each slag. Two parts distilled water (pH 5.5) to one part slag gently agitated for 72 h. Mixture filtered through 0.45 um. micropore and filtrate analyzed. Selected samples probably represent the more comminuted fraction of slag. Ni <0.05 mg/l for all slags and Co <0.02mg/l for ferronickel slag.

[b] All ferrous slags listed considered non-hazardous. (Toxic materials not leached at greater than 1 mg/l. Greater tolerances for F, Mn, and Zn.).

[c] ND= Not Determined

It was considered desirable to develop a simple, economical, and rapid test procedure for evaluating the expansion potential of steel slags[8]. The procedure adopted involves preparing steel slag specimens and a non-expansive control using the Standard Proctor method and stainless steel molds with perforated base plates to allow for moisture movement during the immersion period. The specimens are then totally immersed in a water bath at 82 ±1°C and the vertical expansion with time monitored. Since the expansion levels of 5 to 9 percent observed at 82°C (about three times that at 60°C) are similar to the levels of long-term expansion often observed in the field, this test temperature was adopted. A short monitoring period of one to seven days appears adequate to detect potential expansive behavior. The actual steel slag gradation involved for a project should be tested since the expansive behavior is clearly a function of gradation. Also, surcharge weights to simulate overburden conditions can be used.

Tests have 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. It should be noted that aging steel slag in large heaps or pieces is not very effective, as steel slag remains expansive for extremely long periods if not directly exposed to weathering. This expansion potential monitoring procedure for steel slags has been improved and adopted by the Pennsylvania Department of Transportation (Penn DOT) as PTM 130 with two major modifications: the test temperature has been reduced to 71 ±3°C; and the test involves 7 days fully submerged followed by 7 days unsubmerged but saturated at 71 ±1°C [9]. PennDOT uses this test for the acceptability of steel slag Type C aggregate under strict conditions.

> "By-product of a steel making process. Tough, hard, durable pieces of steel slag, reasonably uniform in density and quality. After crushing, grading and forming a stockpile, take a sample from the stockpile and submit it to MTD for testing to determine expansive characteristics, in accordance with PTM No. 130. The stockpile will be accepted for use if the total expansion, as determined by PTM No. 130, is less than 0.50%. Once a stockpile is accepted, do not add to it if it is for Department use. If the stockpile does meet expansion requirements, cure the aggregate stockpile as follows: Rework the stockpile soaking the aggregate completely with water. Keep aggregate in a uniformly moist condition in the stockpile for a period of at least 6 months. Take a sample after this curing period and submit it to the MTD for testing in accordance with PTM No. 130. Submit to the engineer, for review and acceptance, the proposed method of constructing and controlling the stockpile during the cure period. The stockpile will be accepted for use if the total expansion is less than 0.50%. If the stockpile does not meet this requirement, use an additional curing period of 2 months from the time of the last sampling, before resampling and testing. Aggregate manufactured from steel slag is not acceptable for pipe or structure backfill, or in cement concrete. Steel slag may be used for subbase, selected granular material, shoulders, selected material surfacing, and in bituminous surface courses, if accepted."[10]

It is recommended that this PennDOT requirement, and related test procedure, be adopted by contractors or agencies considering the use of steel slag for granular subbase, unless satisfactory performance can be demonstrated by other means.

STEEL SLAG AGGREGATE FOR ASPHALT MIXES

The discussion in the previous section was concerned .with the potential expansion of steel slag that has not been coated with asphalt cement. As indicated in following sections, the use of steel slag in asphaltic concrete results in an excellent product, and the processing involved and asphalt cement film coating the steel slag limits potential expansion. However, the question still often arises concerning the need for aging steel slag prior to use in asphaltic concrete, and there have been a few cases of surface pop-outs and/or ravelling related to over-size and/or excess deleterious limey material. These problems appear to be related to a lack of attention during processing. General experience indicates that if the finer steel slag sizes are used (minus 13.2 mm) and contamination is avoided at the steel works, aging is not critical prior to use in asphaltic concrete. If tighter quality control of steel slag aggregate for use in asphaltic concrete is considered necessary, the following suggested requirements should be considered with suppliers: contamination by refractories and rubbish to be avoided at the steel slag processing area; a minimum weathering period of one month following steel slag processing to be completed before screening; a minimum of 5000 tones of weathered and screened steel slag (coarse and fine) to be developed and maintained before shipment to ensure gradation and composition consistency; free lime content of weathered steel slag to be monitored (ethylene glycol extraction, for instance) and average not to exceed a specified percentage (this level has not been established, but is probably in the six percent range); and any agglomerated and/or crusted stockpiled steel slag (coarse and fine) to be re-screened. It should be noted that avoiding under-asphalted mixes and ensuring adequate mixing is also important to achieving desired steel slag asphaltic concrete pavement performance.

FEATURES OF STEEL SLAG ASPHALTIC CONCRETE FOR MUNICIPAL, HIGHWAY AND INDUSTRIAL PAVEMENTS

Steel slag has been used in binder and surface course asphaltic concrete mixes in the Hamilton-Toronto area since 1969, with a large growth in use the past five years related to both its general acceptance for municipal street work and increasing MTC highway application in dense graded friction course (skid resistance) and open graded friction course (skid resistance and tire-pavement noise reduction)[5,11,3,4]. This growth in steel slag asphaltic concrete use and friction course applications has given Ontario world leadership. Steel slag is also used in hot mix for winter patching with several advantages being demonstrated: fairly dry so heating costs reduced; retains its' heat very well; and the high unit weight and stability tends to hold patches in place. Steel slag asphaltic concrete has been found to be excellent for industrial and heavy duty applications. While it has been possible to develop steel slag slurry seal mixes in the laboratory, field experience to-date indicates the inherent variability of steel slag aggregate (particularly free lime content) limits this potential application. Steel slag use in surface treatments (cover chips and coated chippings) should grow as it has been developed in other areas and recently demonstrated by Dofasco/Red-D-Mix.

Typical conventional gradation requirements for steel slag use in asphaltic concrete mixes are given in Table 3, and the MTC have developed specific requirements for friction course mixes[3,4]. Marshall method characterization of typical steel slag asphaltic concrete mixes, as summarized in Table 4, indicates the following general features: they are designed in the same way as any other mixes and no problems have been experienced in meeting relevant specifications; they combine very high stabilities (1½ to 3 times greater than most other mixes) with good flow properties, resulting in a mix that resists rutting after cooling, but is still compactable; they have excellent resistance to stripping of asphalt cement from the steel slag as anticipated from the free lime content of Table 1; and they have bulk densities 15 to 25 percent greater than most conventional mixes that can result in a cost disadvantage on a volumetric basis. The high stability of steel slag asphaltic concrete mixes offers a

TABLE 3 - *Typical gradation requirements for steel slag*[a].

Coarse Aggregate	
Sieve	Percent Passing
16.0 mm	100
13.2 mm	96-100
9.5 mm	50-73
4.75 mm	0-10
Fine Aggregate	
Sieve	Percent Passing
9.5 mm	100
4.75 mm	90-100
2.36 mm	72-100
1.18 mm	50 - 90
600 µm	32-70
300 µm	14-40
150 µm	5-15
75 µm	0-5

[a.] MTC Form 1003, August, 1981, HL1 and HL3 requirements

TABLE 4 - *Typical properties of steel slag asphaltic concrete mixes*

Marshall Designs[a]	
Property of Laboratory Compacted mix	Range
Stability (kN)	16-22
Flow index (mm)	4.0-5.5
Voids in mineral aggregate (%)[b]	17-19
Air voids (%)	3-4
Asphalt cement content (%)[c]	5.5-6.0
Bulk. Density	2.85-2.90
Immersion-Marshall Stripping Test Results[a]	
Retained stability (%)	75 – 85
Stripping rating number[d]	3 - 4

a. Testing in accordance with MIC Laboratory Manual.
b Uncorrected (i.e. not saturated surface dry).
c. Percent by weight of total mix
d. A stripping rating number of 3 indicates no stripping, of 4 indicates slight stripping, etc.

distinct advantage for applications where rutting resistance is required, such as industrial roads and parking areas subjected to heavy axle loads. Resilient moduli research by the author[12] has shown that the resilient modulus (Mr) values of steel slag asphaltic concrete tend to be some 20 to 80 percent higher than for conventional mixes at typical design temperatures (29°C). Also, steel slag asphaltic concrete mixes have relatively lower resilient Poisson's ratio (Vr) values than most conventional mixes. As high Vr values at elevated temperatures are an indicator of deformation susceptibility, the lower steel slag asphaltic concrete (Vr) values support the observation that these mixes typically demonstrate high in-service stability and rutting resistance. The higher stability of steel slag asphalt mixes and resilient moduli values can be used to design thinner steel slag asphaltic concrete pavements on both an empirical and rational basis.

SKID RESISTANCE OF STEEL SLAG ASPHALTIC CONCRETE

Experience with steel slag asphaltic concrete in several countries indicating very satisfactory skid resistance for most applications has also been demonstrated in Ontario. During 1974, the MTC constructed 17 asphaltic concrete test sections on Highway 401 (Toronto bypass section) to evaluate methods for improving rigid pavement skid resistance with thin overlays. Extremely high traffic volumes are involved with a total daily traffic of 199,000 (1976) using a twelve lane collector and express lane system. Dense graded surface course mixes, dense graded friction course mixes and open graded friction course mixes were placed using limestone, traprock, steel slag and air-cooled blast furnace slag aggregates, or combinations. These test sections have yielded valuable general information on the skid resistance for high traffic volume conditions: initial target skid numbers must be substantially greater than recommended minimum levels; early decline in skid resistance is due to coarse aggregate immersion into the matrix under wheel loads; dense and open graded mixes of 100 percent crushed aggregates with fairly high PSV (traprock, steel slag and blast furnace slag – PSV greater than about 40 to 50*),* and high stability, provide skid numbers close to, or above, recommended minimum levels; crushed fines result in much better macrotexture than mixes containing sand; and adequate macrotexture is achieved when the stone projection above the matrix is 0.5 mm, or greater. It is clear that factors contributing to high mix stabilities are important to maintaining skid resistance. Continuing monitoring also shows that the skid numbers have leveled off rather than continuing to decrease at a reduced rate. Weathering influences, which are generally seasonal and particularly demonstrated by steel slag, appear to be regenerating microtexture at about the same rate that traffic polishing is involved[13,14].

Polished stone values (PSV, high values desirable) and aggregate abrasion values (AAV, low values desirable) summarized in Table 5[14] support the general finding that the all-steel slag and all-blast furnace slag mixes have shown the best skid resistance performance of the Highway 401 sections. Also, a study of skid, resistance in the urban context has shown that steel slag asphaltic concrete mixes appear to provide superior skid resistance to other mixes. The wet road accident rate did not significantly exceed the dry road accident rate for steel slag asphaltic concrete surfacings, while the

TABLE 5 - Typical PSV and AV Values for Aggregate

Aggregate	PSV	AAV
Steel slag	55 to 59	2 to 4
Blast furnace slag	54	14
Sandy dolomite	53	4
Granite	45 to 47	-
Traprock	45	2
Igneous and metamorphic gravel	43 to 47	-
Quartzite	42	-
Limestone	41 to 45	8

reverse was generally true of other surfacings.

Based on highway, laboratory, and urban studies, it appears that steel slag asphaltic concrete mixes of adequately coarse gradation provide satisfactory skid resistance for most applications. Indeed, for Ontario, they appear to be the most skid resistant aggregate currently available and are included in the MTC specifications[3,4].

CONCLUSIONS

From the previous discussion, it is possible to indicate the demonstrated applications for steel slag asphalt mixes in order of relative merit; surface course mixes that take advantage of the excellent skid resistance and good wear resistance of steel slag asphaltic concrete; industrial paving where the high stability and consequent rutting resistance is an important asset; winter patching; and binder courses where some depth reduction related to higher resilient moduli is possible. It would appear there is scope for using steel slag as chips in surface treatments that should be developed to take advantage of its skid resistance and quickly achieved stability.

REFERENCES

1. Emery, J.J., Drysdale, R.G. and Nicholson, P.S., Steel Slag Asphalt Mixes, Proceedings, Canadian Technical Asphalt Association, Vol. 18, 1973.

2. MTC, Designated Sources for: Aggregates, Coarse – HL1, DFC, DS:102, Ontario Ministry of Transportation and Communications.

3. MTC, Dense Friction Course Mix, Special Provision No. 321, Ontario Ministry of Transportation and Communications, June, 1983.

4. MTC, Open Friction Course Mix, Special Provision No. 311, Ontario Ministry of Transportation and Communications, January, 1983.

5. Emery; J.J., Slag Utilization in Pavement Construction, Extending Aggregate Resources, ASTM STP 774, American Society for Testing and Materials, 1982.

6. Emery, J. J., Slags as Industrial Minerals, Proceedings, Third Industrial Minerals International Congress, Metal Bulletin Group, London, 1978.

7. Rellermeyer, H.M. and Maas, H.G., Utilization of BOS Slags at August Thyssen Hütte AG, Annual Open Hearth Steelmaking Conference, Toronto, 1979

8. Emery, J.J., A Simple Test Procedure for Evaluating the Potential Expansion of Steel Slag, Selected Workshop Papers, Roads and Transportation Association of Canada, 1974.

9. PennDOT, Method of Test for Evaluation of Potential Expansion of Steel Slags, Test Method No. 130, Pennsylvania Department of Transportation, June 1976, Revised May 1978.

10. PennDOT, Form 408, COARSE AGGREGATE, 703.2 (a) 4. Steel Slag, Pennsylvania Department of Transportation, 2000

11. Lewis, D.W., Resource Conservation by Use of Iron and Steel Slags, Extending Aggregate Resources, ASTM STP 774, American Society for Testing and Materials, 1982.

12. Emery, J.J., Characterization of Flexible Pavement Components, Proceedings, Paving in Cold Areas, Vol. 2,1982. .

13. Emery, J.J., Lee, M.A. and Kamel, N., Skid Resistance Predictive Models for Asphaltic Concrete Surface Courses, Pavement Surface Characteristics and Materials, ASIM STP 763, American Society for Testing and Materials, 1982.

14. Emery, J. J., Skid Resistance Requirements and Predictive Models for Asphaltic Concrete Surface Courses, RTAC Forum, Vol.5, No.3, 1983.