REVIEW OF STEEL SLAG UTILIZATION IN SAUDI ARABIA

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ABSTRACT

The SSA produced during the direct reduction of the iron in an electric arc furnace is being utilized in the asphalt concrete and for the construction of subbases and aggregate base course in pavements in Saudi Arabia and worldwide. Special specifications, sufficient records of its use and performance on major projects around the world, including Saudi Arabia, indicate that the utilization of steel slag has resolved several environmental issues. In addition, the use of such product in some special applications has been a successful step in finding good quality material as a partial or full replacement of the ever-diminishing natural materials. During the last six years, more than three million metric tons of SSA was utilized as a substitute for local natural aggregates in Saudi Arabia. This utilization was in several projects, such as road bases, sub-base, vibro-flotation, ground stabilization, ballast, pavement foundation beds and high-density reinforced concrete. The Ministry of Communications (MOC) in Saudi Arabia has approved the use of steel slag in road construction, provided proper mix design is achieved. This acceptance was incorporated after a thorough investigation of its compatibility and feasibility. This paper provides an overview on the worldwide utilization of SSA, particularly that in Saudi Arabia. Case studies of the utilization of steel slag in the road construction are also discussed.

Keywords: *Steel Slag Aggregate (SSA), Asphalt Concrete, Specification, Road base.*

الملخص

يستخدم خبث الحديد الناتج عن استخلاص الحديد بواسطة أفران القنطرة الكهربائية في الخلطات الإسفلتية وطبقات الأساس في الطرق في المملكة العربية السعودية ودول العالم الأخرى. وقد دلّت المواصفات الخاصة وسجلات الأداء الكثيرة في المشاريع الرئيسة على أن استخدام خبث الحديد يساعد على حلّ العديد من المشاكل البيئية.

إضافة إلى أن هذا الاستخدام أدى إلى التعويض الجزئي أو الكلي للمصادر الطبيعية التي تتناقص باستمرار. ففي خلال الست سنوات الماضية تم استخدام أكثر من ثلاثة ملايين طن من خبث الحديد كبديل للحصى الطبيعي في المملكة العربية السعودية، وقد كان هذا الاستخدام في أرضيات الطرق وأساساتها، وغيرها من المشاريع. وقد تم اعتماد استخدام خبث الحديد من قبل وزارة المواصلات في المملكة وذلك بعد اختيار التصميم المناسب وبعد الدراسات المستفيضة حول جدوى هذا الاستخدام. وتعطي هذه الورقة عرضاً للاستخدام العالمي لخبث الحديد مع التركيز على المملكة، إضافة إلى استعراض بعض مشاريع إنشاء الطرق.

1. INTRODUCTION

In the present economic climate, it is becoming increasingly important to maximize the assets. The establishment of new industrial areas result in an increase in the production of by-products which are considered waste if they are not utilized subsequently. It is, therefore, imperative to reduce waste and preserve available natural resources. Further, the waste products have to be disposed off properly such that the environmental impact is minimum. The proper disposal and handling of large quantities of waste material is expensive and will definitely have some environmental impact. On the other hand, some of the waste or by-products could be utilized in the recycling process, manufacturing of new products or as a constructional material. Steel and iron industry is one of the biggest waste disposal industries, therefore the research and utilization of SSA is a beneficial to the steelmaker whilst giving Engineers access to a high performance raw material. Steel slag aggregate (SSA) produced in the local steel industry should no more be considered as a waste material as it is a proven commodity, a by-product and high quality material for use in the construction industry. Since the start of steel industry in 1982 in Saudi Arabia, the steel slag was considered as a waste material and was dumped in the form of huge stockpiles of approximately 4 million tons. The process of promoting the use of SSA in the construction industry was initiated in 1994-95.

Steel slag is a by-product of the steel making process and has a complex chemical structure, comprising mostly of oxides and silicates that are formed through the oxidation of various additives within the steel. There are two major methods of producing steel: the basic oxygen furnace (BOF) process and the electric arc furnace (EAF) process. Slag products, such as blast furnace slag, coal slag, copper slag, etc, have been successfully utilized in civil construction works or producing abrasive and cements.

This paper provides an overview on the worldwide utilization of steel slag in the construction industry, particularly in Saudi Arabia. Case studies of the utilization of steel slag in the road construction are also discussed. Latest research and field experience, specially on the steel slag produced in Saudi Arabia with a successful achievement of the goal of utilization of more than 3.5 million metric tons during the past 6 years, indicated that this material can be a good substitute for locally available natural aggregates.

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2. WORLDWIDE UTILIZATION OF STEEL SLAG

Slag is produced in almost 29 states of United States by 17 companies. Special specification, sufficient record of its uses and performance on major projects around the world indicate that both steel (BOF or EAF) slag is a material of choice. In Batlimore [Graham, 1992] the outstanding characteristics demonstrating one of the advantages of using slag bituminous concrete is high skid resistance (under wet or dry conditions) provided throughout the service-life of the pavements.

SSA and asphalt mixtures were used to provide 1 to 1.25 inch thick surface layer for a number of roadways in Indiana between 1979 and 1981 [Noureldin and Mc Daniel, 1990]. Bituminous test sections were constructed using six different combination of coarse and fine aggregate to produce mixtures with a wide range of gradations and proportions of steel slag coarse aggregates. Skid resistance numbers measured using ASTM E274 indicate that the use of SSA in asphalt surface mixtures provide pavement surfaces with good skid resistance. Asphaltic paving mixtures using steel slag aggregate displayed exceptionally high stability, which may improve the rut resistant when used in pavement surface layers. In addition, mix produced utilizing steel slag aggregate 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. This thinner layer could play an important role in compensating for the high-density disadvantage of steel slag asphalt mixtures.

Another study [Stock et al., 1996] reported the use of steel slag in bituminous road construction in South Yorkshire and its environs for the past 60 years. Above 300,000 tons of steel slag per year was utilized for road construction. As an assessment of skid resistance of asphalt surfaces incorporating steel slag, side force coefficient Routine Investigation Machine (SCRIM) was measured on various categories of roads (100 mm and 14 mm surface dressings). The data from both surveys show that steel slag road surfaces have at least as good long-term skid resistance properties as those of comparable natural aggregate road surfaces under similar traffic conditions [Stock et al., 1996].

SSA has also been successfully utilized in countries with high ambient temperatures that cause major problems in asphalt surfaces. Amongst the various countries around the world with hot climates, such as Singapore, Malaysia, Australia, South Africa, Saudi Arabia and Italy, have already realized the superior properties of steel slag asphalt [Jones, 2000]. Permanent deformation can occur at a very early stage in the life of asphalt surfacing material, when the road surface temperature begins to approach the softening point of the bitumen. The high surface temperature causes the asphalt to become plastic and then deform very easily resulting in rutting. One way of counter acting this problem is to use polymer-modified bitumen (PMB). Though these binders are very successful in combating rutting they are more expensive than standard penetration grade bitumen, thereby increasing the overall cost of the asphalt. Another factor associated with permanent deformation of asphalt, is the shape of the aggregate used in its manufacture. Steel slag aggregate forms a more angular particle on crushing and the effect of aggregate interlock, resulting from the improved shape, increases the internal friction within the asphalt, which exhibits higher stiffness and excellent resistance to permanent deformation [Jones, 2000].

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Australian Steel Mill Services (ASMS) designed and constructed heavy-duty haul road within the Port Kembala steel works by utilizing steel slag aggregates [Lemass, 1992]. The steel slag aggregates utilized in ASMS asphalt improved the adhesive qualities due to slag vesicularity, high internal stability resulting from wet strength in excess of 200 kN, and superior skid resistance due to the aggregate rough surface texture and high polishing aggregate friction value. Slag aggregate in road bases have proven themselves to be ideally suited for road pavement construction over a long period of time. The self-stabilizing properties of slag road-base enable flexible pavement depth to be minimized and binder requirements reduced.

The utilization of steel slag in pavement construction was studied by [Emery et al., 1982]. They made an overall review of the current and potential utilization of ferrous, non-ferrous and boiler slag in pavement structure. It was found that the optimum uses of iron blast furnace slag were in cements, base stabilization and asphalt concrete. Steel making slag that is not recycled can be used to enhance the performance asphaltic concrete (high stability and skid resistance) and may have applications in base and shoulder stabilization.

Experience in the United States, Belgium, Japan, Netherlands and Germany has shown that SSA, properly selected, processed, aged, and tested, can be used as granular base for roads in above-grade applications. Steel slag aggregate exhibits a number of very favorable mechanical properties for use in granular base [Collins and Ciesielski, 1994]. States in the Midwest and the eastern United States have extensive experience with the addition of steel slag to hot mix asphalt concrete. Their experience indicate that the addition of steel slag may enhance the performance characteristics of the pavement.

[Hunt and Boyle, 2000] in their study compared the test sections constructed with 30 % and 15 % of slag. They did not report any increase in the resistance to rutting and skid during the five-year monitoring of the pavement. The difference between the two sections was not measurable as only 15 to 30% steel slag was used in the test mix and the steel slag was finer than the conventional (12.7 to 6.3 mm) material replaced. Therefore they recommended additional trials using the Superpave mix design system, which may help in optimizing the gradation and asphalt demand.

3. CHARACTERIZATION OF STEEL SLAG PRODUCED IN SAUDI ARABIA

3.1 Physical Properties

The load supporting capacity of an aggregate type is of great concern as aggregate are the primary load carriers in a compacted asphalt paving mixtures. Once the water cooled steel slag is declared environmentally safe, it is crushed and screened to produce four regular graded sizes, namely 1.5 inch, 3/4 inch, 3/8 inch, and 3/16 inch [Aiban and AbdulWahab, 1999]. Slag aggregates produced are cubical and angular in shape, rough in surface texture, and homogenous in character. A number of cavities are seen on the aggregate surfaces resulting from air bubbles entrapped during the cooling of slags [Heckett, 2001]. As opposed to the microscopic pores of porous natural aggregates these macroscopic cavities improve the properties of the asphalt concrete. The

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characteristic properties of the SSA and crushed limestone are compared in Table 1. As is evident, the specific gravity of steel slag aggregate is nearly 31 % more than that of the crushed limestone. Also, the abrasion loss and sulfate soundness loss in SSA are about half of that of crushed limestone aggregates.

3.2 Chemical Properties

The main constituents in steel slag are lime, silica and iron oxide. Traces of alumina, magnesia, sulfur, and oxides of manganese and titanium can also be found [Tarco, 2000]. The typical chemical composition of SSA in Saudi Arabia is shown in Table 2. The chemical properties of SSA that are of importance for use in asphalt concrete are alkalinity and free lime content. The presence of free lime particles can lead to volume expansion resulting in cracking of aggregate and asphalt [Tarco, 2000]. According to the data in Table 2, the Magnesium Oxide (MgO) content in the steel slag aggregate is high. The United States Environmental Protection Agency (USEPA) land disposal restrictions, otherwise known as the land bans, have introduced toxicity characteristics regulatory levels. Table 3 summarizes the leachate results of SSA along with TCLP regulatory limits. It is very clear from the results presented in Table 3 that the average values of metals under consideration do not violate the limits set in TCLP regulation levels. Therefore, the use of SSA is safe and should not induce any contamination even in areas where ground water table is shallow.

3.3 Thermal Properties

Due to their heat retention capacity steel slag aggregate have been observed to retain heat considerably longer than conventional natural aggregates. The heat retention characteristics of steel slag aggregates can be advantageous in hot mix asphalt repair in cold weather [Mc. Daniel, 1990].

4. UTILIZATION OF STEEL SLAG IN SAUDI ARABIA

4.1 General

The current annual production of SSA is 350,000 tons and production is expected to reach 500,000 tons. In the hot climate of Saudi Arabia, the permanent deformation/rutting and fatigue failure in the flexible pavements is a common phenomenon. It has cost a fortune to the ministry of roads and other agencies responsible for road maintenance in this country. This necessitates improved design, both in terms of asphalt concrete mixes and aggregate base courses so that the performance can be enhanced. Special specifications, sufficient records of its use and performance on major projects around the world, including Saudi Arabia, indicated that the utilization of steel slag had resolved several environmental issues. In addition, the use of such product in some special applications has been a successful step in finding good quality material, as a partial or full replacement of the ever-diminishing natural materials and thus, the search for an alternative material has become a must for future construction projects.

Table 1. Physical characteristics of steel slag and limestone aggregates.

Parameter	Hadeed SSA*	Limestone**
Specific Gravity	3.69	2.5-2.8
Sand Equivalent	88	Variable
Los Angeles Abrasion Loss (%) [ASTM C131]	15	30-40
Sodium Sulfate Soundness [ASTM C88]	2.2	< 14
California Bearing Ratio [ASTM D1883]	< 400	-
Plasticity Index	Non Plastic	Variable
Corrositiviy/Reactivity/Ignitibility	None	-
pH	11	-
Aggregate crushing value	15 %	-
Aggregate impact value	11	-
Angle of Internal Friction	40-50 degree	-
Hardness (Measured on Moh Scale)	6-7	-
Binder adhesion/stripping [ASTM D3625]	> 97 %	Variable

* [Heckett, 2001] ** [Aiban and AbdulWahhab, 1999]

Table 2. Chemical composition of steel slag aggregates [Heckett, 2001].

Compound	Composition (%)
Calcium Oxide	25-30
Silicon Oxide	10-15
Iron Oxide	30-35
Aluminum Oxide	5-10
Magnesium Oxide	10-15
Phosphorus Oxide	0.5-1
Free Lime Content	0.85 %
Free Magnesium	0.008 %

Table 3. Summary of leachate results of the SSA*

Element	Average (mg/L)	TCLP Limits (mg/L)
As	0.088	5.0
Ba	8	100
Cd	0.04	1.0
Cr	0.01	5.0
Pb	0.02	5.0
Se	0.117	1.0
Ag	0.2	5.0
Hg	0.0	0.2
Fe	69	Not Listed in TCLP list
Cu	0.14	Same
Ni	0.01	Same
Zn	1.6	Same

* [Heckett, 2001] and [Aiban and AbdulWahhab, 1999]

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4.2 Applications

The use steel slag as an aggregate is considered a standard practice in Saudi Arabia and worldwide. Some of the more common usages today include asphalt and concrete aggregates, sub-base, granular base and filter media. Prior to its use as a construction aggregate material, steel slag must be crushed and graded to meet the specified gradation requirements for the particular application, competing to local quarried aggregates in Saudi Arabia. Thus utilization SSA on several projects, can be quite valuable to the construction industry.

The other utilization of SSA, for slurry seal and micro-surfacing, has to be explored. The annual utilization of SSA in construction industry is highlighted in Figure 1. Similarly, the various applications of SSA in terms of quantity is shown in Table 4 which indicates that nearly 67% of local SSA processed was used in road construction only. Since the year 2000, the annual production of SSA in Saudi Arabia is 400,000 tons and almost total production is successfully used in the road construction industry [Heckett, 2001].

4.3 Research and Development

Extensive field and laboratory trials were conducted by several highway agencies in Saudi Arabia to assess the suitability of steel slag usage in road construction [Bayoumy and AbdulWahab 1988, Aiban and AbdulWahab 1997, KFUPM-RI 1996, FehS 1996, and Heckett 1999]. These trials had the objective to check that the steel slag aggregate could replace, partially or fully, the natural crushed aggregate in the asphalt concrete mixes in the hot arid climate. The Ministry of Communications in Saudi Arabia has approved the use of steel slag in road construction, provided proper mix design is achieved. This acceptance was after a thorough investigation of its compatibility and feasibility. In another study [Khan, 1998], blending of SSA with limestone aggregates had significantly improved the properties of both slurry seal and micro surfacing mixes. The actual field performance evaluation with trial sections was, however, recommended as a follow-up of this study before any full-scale construction.

4.3.1 Review of Field Trials in Saudi Arabia

Two field trials were constructed with cooperation of Dammam Municipality in regions exposed to worst loading conditions in Dammam Industrial Area of Eastern Saudi Arabia as part of research study conducted by [Aiban et al., 1997]. Field trials in these locations have indicated an excellent performance of SSA and cement treated calcareous sediments. Similarly, the use of SSA as partial or full replacement of conventional aggregate for road base has shown great improvement when compared to crushed calcareous bases in hydraulic structures. The SSA and SSA-marl mixes have produced a base course that is water-insensitive with very high CBR values.

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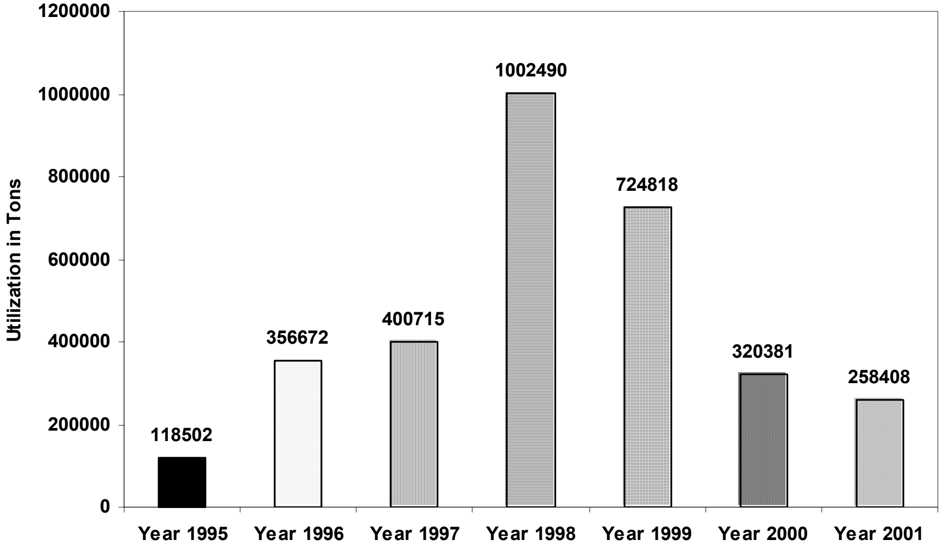

Figure 1. Annual Utilization of SSA in Construction Industry in Saudi Arabia

Table 4. Quantity of SSA utilized for various applications (1996-2001) [Heckett, 2001].

Applications	Quantity (tons)
Hot Mix Asphalt	690,850
Base/Sub-base	1,516,857
Vibro/Ground Stabilization	914,985
Filter Bed Media	28,000
High Density Concrete	45,500
Ballast	15,000
Pavement Foundation Bed	5,800
Recycling Ferro Silica	41,900

In an another study [Aiban and AbdulWahab, 1999] field trial was also conducted in a typical location of Dammam Industrial Area, where the groundwater table was almost at the top of the existing graded base layer. The segment constructed using SSA base course was about 200 m long. Construction started at the end of November 1996 and was monitored carefully at all stages. This section has been regularly monitored and has shown excellent performance for the past four years despite the fact that it was submerged under water on few occasions due to rain and poor drainage. Therefore, the use of locally available SSA is expected to give satisfactory results provided that the aggregate gradation is carefully selected.

Following the aforesaid investigations and successful utilization of steel slag in several road construction projects the use of steel slag aggregates was approved by Saudi Ministry of

Communication (MOC) [KFUPM-RI, 2001]. The steel slag was also used in a 25.5 km three lane, dual carriageway leading to the new airport at Dammam city in the Eastern Province. The steel slag was utilized in all pavement structure of this highway, approximately 427,000 tons of SSA was used in asphalt mix and nearly 275,000 tons was utilized in the aggregate base/sub-base. This project alone consumed nearly 0.7 million tons of steel slag aggregate and was blended with marl despite their many disadvantages, such as grain crushing and water sensitivity to form the road base material and was blended with natural fines for the hot mix asphalt concrete [Heckett, 2001].

This highway is being monitored to assess the in-service long-term performance of steel slag asphalt mix and steel slag aggregate base in the pavement. Based on the mix design and construction contractors this road was divided into three sections for study. One direction (towards KFIA) was divided into three sections according to the construction contractors. One contractor constructed Section 1 and 3. Another contractor constructed Section 2 with a different mix design than Section 1 and 3. Tables 5 and 6 show the mix design properties of aggregate base course and asphalt concrete of the three sections. During the post construction monitoring of this highway, the field data collected included traffic volumes, pavement distress, surface roughness, skid resistance, and deflection measurements. In addition, a number of cores were extracted from the test sections and tested in laboratory to evaluate the in-situ percent air voids and mechanical properties, such as resilient modulus, fatigue, and permanent deformation. It is found that at this time of its service life, the highway pavement is structurally adequate for operating traffic and the pavement surface has acceptable levels of riding quality and skid resistance as shown in Table 7 [KFUPM-RI 2001]. However, Sections 1 and 3 indicated some early distress in the form of linear cracking. Therefore, these sections should be closely monitored at regular interval keeping in mind the early performance of this test highway.

The main conclusion of these trials was that the steel slag produces high quality aggregate, which can be used to obtain asphalt concrete mixes. SSA has mechanical and physical characteristics that make it valuable for use in pavements, as a partial or full replacement of aggregate. Further, the chemical characteristics indicate that the use of SSA is safe and should not induce any contamination even in areas where ground water table is shallow. The steel slag asphalt mixes showed higher skid resistance than the conventional asphalt mixes. However, the steel slag asphalt performance is highly dependent on the aggregate gradation and mix design used in constructing pavements. The analysis of field core early result indicated that, the higher the slag content, the inferior is the mix rutting characteristics as cores taken from mixes with higher slag content had higher permanent deformation than cores taken from mixes with lower slag content. Since rutting problem may be attributed to other mix characteristics (binder type, binder content, and mix design), it is suggested that the rutting potential of the SSA mix should be further investigated [Malkawi et al., 2002]. Further, the cores of the base course or wearing course mixes with higher slag content had higher fatigue live than the cores of mixes with lower slag content especially at lower initial strain level [KFUPM-RI 2001].

4.3.2 Use of Steel Slag Aggregate in Concrete

The feasibility of utilizing SSA in concrete was investigated at KFUPM [Maslehuddin, 1999]. The mechanical properties and durability characteristics of SSA concrete compared to crushed limestone aggregate concrete were evaluated in that study. It was reported that the physical properties of steel slag aggregates were superior to those of crushed limestone. However, the bulk specific gravity of the

former aggregates was more than that of the latter aggregates. The increase in unit weight of concrete, due to the incorporation of steel slag aggregate, in lieu of crushed limestone aggregate, was approximately 17 %. Though the compressive strength of SSA concrete was marginally better than that of crushed limestone aggregate concrete, no significant improvement in the flexural and split tensile strengths was noted in the SSA concrete compared to crushed limestone aggregate concrete.

Table 5. Mix design properties for aggregate base course. [Malkawi et al., 2002].

Mix Design Properties	**Section 1 & 3 (90% steel slag & 10% Natural Aggregate)**	**Section 2 (55% steel slag & 45% Natural Aggregate)**
Maximum Dry Density, g/cc	2.664	2.61
Optimum Moisture Content, %	6.1	5.8
California Bearing Ratio	198	148
Sand Equivalent, %	35	35
Soil Classification	Non Plastic	Non Plastic

Table 6. Mix design properties for asphalt concrete. [Malkawi et al., 2002].

Description	**Mix Properties**						
	Asphalt Content%	Stability Kg.	Stability Loss %	Flow mm	Air Voids %	Bulk Density g/cc	Max'm Sp. Gravity g/cc
Wearing Course Section 1 & 3 (48% steel slag & 52% Natural Agg.)	4.87	1878	5.6	3.5	4.9	2.758	2.899
Base Course Section 1 & 3 (100 % steel slag)	3.73	1611	6.4	3.1	5.6	3.066	3.247
Wearing Course Section 2 (48% steel slag & 52% Natural Agg.)	4.7	1690	6.9	3.2	4.6	2.368	2.484
Base Course Section 2 (61% steel slag & 39% Natural Agg.)	3.75	2150	7.3	2.9	5.8	2.715	2.893

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Table 7. Summary of field data collected on KFIA Dammam Highway [KFUPM-RI, 2001].

Type of Survey	Section 1	Section 2	Section 3
Pavement Condition Survey (PCI)*	>90 Excellent	>90 Excellent	>90 Excellent
Riding Quality Survey	153	169	154
Skid Resistance Survey	72	70	69
Traffic Survey	5365 vpd	5365 vpd	5365 vpd
FWD Survey (ISM) **	22.4 Kg/micron	40.8 Kg/micron	33.4 Kg/micron

* PCI: Pavement Condition Index   ** ISM: Impulse Stiffness Modulus

The pulse velocity of SSA concrete was more than that of crushed limestone aggregate concrete. The water absorbed by SSA concrete was less than that absorbed by the crushed limestone aggregate concrete. The time to initiation of reinforcement corrosion and time to cracking of concrete specimens was more in SSA concrete compared to crushed limestone aggregate concrete. The superior performance of SSA concrete was noted in the concrete specimens prepared with coarse to total aggregate ratio of 0.55 and above. The improved properties of concrete prepared with steel slag aggregate indicate that this material can be beneficially utilized in Portland Cement Concrete. The SSA concretes may be proportioned to have 50% coarse aggregates and 50% fine aggregates to reduce its weight.

5. CONCLUSIONS

1. The engineering and ecological properties of steel slag aggregate are accepted in many countries worldwide including Saudi Arabia and SSA is widely utilized in the construction of pavements. The use of SSA as a road construction aggregate minimizes the use of natural aggregates, thereby maximizing the benefits of available resources.
2. Steel slag has been successfully utilized on different construction projects, particularly in road projects as evidenced by its total consumption of 3.7 million tons.
3. The use of steel slag aggregate in asphalt mix can benefit in many ways. It can out-perform many natural aggregates in terms of skid resistance and higher fatigue life.
4. In KFIA-Dammam highway close monitoring should be scheduled for sections showing early distresses such as surface cracks. A condition survey supplemented by equipment-based survey should be conducted every two years.
5. There is a need to investigate utilization of steel slag in slurry seal and micro-surfacing by making fields trials.
6. Additional trial mixes should be evaluated using Superpave mix design system, which may help in optimizing the gradation and asphalt demand.

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