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Saad Ali Aiban<sup>1</sup>

## Utilization of Steel Slag Aggregate for Road Bases

**ABSTRACT:** Industrial wastes and byproducts have to be disposed off properly so that their environmental impacts are minimized. Alternatively, some of these materials can be utilized in recycling processes, manufacturing of new products, or as construction materials. This paper presents an effective way of utilizing the steel slag aggregate (SSA), which is a byproduct of the steel manufacturing process, in road construction. A comprehensive study was conducted to characterize SSA and determine the potential for its use in road bases. Testing results indicated that SSA is an environmentally safe product and has physical and chemical properties that make it an excellent candidate for road base construction. Laboratory and field data have shown the superior performance of SSA over the locally available calcareous sediments. The resulting California Bearing Ratio values are doubled and the water sensitivity is much less when using SSA instead of the local calcareous material.

**KEYWORDS:** steel slag aggregate (SSA), limestone, calcareous, California Bearing Ratio, road base, Eastern Saudi Arabia, soil stabilization

### Introduction

For the past three decades, the Eastern Province of Saudi Arabia has witnessed substantial industrialization and infrastructure establishment. The utilization of the resulting byproducts, the conservation of natural resources such as aggregate, and the minimization of the structural problems resulting from the use of marginal material in construction is a major objective. Technological advancement and the high rate of development have led to an increase in vehicle gross loads, tire pressures, and traffic volumes that are imparted on pavements. Truck gross weights of more than 115 tons and tire pressures of 1034 kPa are commonly reported. These conditions cause distresses in pavement layers, such as depressions, permanent deformation/rutting, and fatigue failure. These problems are intensified by the harsh environmental conditions in Eastern Saudi Arabia. In many areas the groundwater table is shallow and the subgrades are weak and water sensitive. This necessitates the improvement of the design standards for both asphalt concrete mixes and graded base courses so that the performance can be enhanced. A possible solution is the use of proper material in the construction of road bases and asphalt layers. The work presented here will focus on issues related to the graded base material only.

Soils available in Eastern Saudi Arabia include sabkhas, clays, sands, and calcareous sediments. Sabkhas are considered problematic and need to be avoided whenever possible; however, many roads and construction activities are within the sabkha terrain. Similarly, most of the clays in the area are expansive and can only be utilized in very specific applications such as liners and water retention structure after proper treatment or blending with other soils. Therefore, soils that are available for construction are sands and calcareous sediments. Sands are known for their fine gradation and, thus, their low strength if they are not confined. On the other hand, calcareous sediments, known locally as marls, are considered the best available material for road bases and foundations despite

their many disadvantages, such as grain crushing, water sensitivity, and commonly inaccurate characterization procedures [1]. The utilization of these sediments in different construction activities commonly results in some unexpected construction problems. These problems are attributed to the poor quality aggregate and soil, coupled with the construction industry's unfamiliarity with the inferior properties of these materials and the harsh environmental and loading conditions. Some of the major problems associated with the use of Eastern Saudi soils include:

- (a) The formation of rut depressions and settlements in roads [2–5]. These occur usually during the early stages of pavement life despite the fact that all necessary precautions were taken into account [6,7].
- (b) The high collapse potential of sand, sabkha, and marl soils due to the high salt content of sabkha, the open structure of sabkha and sandy soils [8,9] and the metastable structure of marls when compacted on the dry side of optimum [3].
- (c) The occurrence of differential settlement or upheavals of foundations, especially when marl is used as a foundation material.
- (d) The shallowness of the groundwater in most of Eastern Saudi Arabia [10], that alters the compressibility of the soil and can lead to fines migration.
- (e) Variability in strength and compressibility leading to differential settlement [11,12].
- (f) The low strength of sandy soils [13], marls [2,3,14,15], and sabkhas [16] both in their natural and compacted conditions.

Since calcareous sediments or “marls” are the best construction material in the Eastern Province of Saudi Arabia, few attempts have been made to stabilize these marls to improve their engineering properties. The effects of different additives such as sand, asphalt, emulsified asphalt, lime, and cement have been investigated [2,3,17–21]. Recently, Aiban et al. [1] and Ahmad [22] conducted a comprehensive laboratory and field investigation on the stabilization of these marls. Their results indicate that portland cement is superior in improving many of the properties of marls, including strength, durability, modulus of resilience, and water sensitivity. Several field trials were executed in Dammam, Eastern Saudi Ara-

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FIG. 1—Comparison of pavement status for cement treated calcareous base course section and a section with untreated calcareous base course.

bia, where marl was treated with 4 % portland cement. Some of the trials, which were in service for nearly nine years, show no sign of deterioration, while the pavement in the control “untreated” section is deteriorating as shown in Fig. 1 within a few months after construction [3].

The major practical problems associated with the use of portland cement in the treatment of marl soils relate to construction timing. The blended marl cement mixes should be compacted within three hours after mixing with water, and the cement should be mixed thoroughly right before adding water. In summer conditions, construction thus should be done either in the early morning or late afternoon to avoid excessive evaporation and hardening of the material before compaction. In addition, construction in rainy seasons or in areas with shallow groundwater table conditions is difficult because the amount of water cannot be easily controlled. Therefore, the use of alternative materials that do not have these timing and construction constraints is warranted.

The literature reveals that SSA gives satisfactory results, performed adequately under the harsh environmental and loading conditions that prevail in the Eastern Province of Saudi Arabia, provided that appropriate gradation is used [23]. This is mainly due to the high strength, low grain crushing, high durability, and local availability of the material. In addition, the material performance is neither sensitive to the molding water content nor the moisture content at testing. Therefore, the increase in the moisture content does not reduce the load carrying capacity significantly.

## Research Objectives

Up to the year 1997 the annual production of SSA in Jubail, Eastern Saudi Arabia is 350 000 tons and the production reached 500 000 tons after the recent expansion of Hadeed Company (steel producing company). The stocks available in Jubail in 1996 were about 1.5 million tons (Heckett MultiServ 1997<sup>2</sup>). These huge piles of SSA need to be utilized in construction or disposed off safely. The main objectives of the investigation are: (1) to determine the engineering properties of SSA that are produced by Hadeed Company and processed by Heckett MultiServ-Saudi Arabia Ltd. in Jubail, Saudi Arabia, and (2) to develop suitable approaches for its utilization in construction. Due to the many possible applications in which SSA can be utilized, such as in road bases, back-filling, shallow and deep foundations, portland cement concrete,

<sup>2</sup>Personal communication.

TABLE 1—Chemical composition of steel slag aggregate (SSA).

Compound	Composition (%) <sup>a</sup> (Typical Values)	Composition (%) <sup>b</sup> (Hadeed Slag)
Calcium Oxide (CaO)	25–42	42–45
Silicon Dioxide (SiO <sub>2</sub> )	12–17	14–16
Aluminum Oxide (Al <sub>2</sub> O <sub>3</sub> )	2–4	6–8
Magnesium Oxide (MgO)	6–10	11–15
Iron Oxides (FeO & Fe <sub>2</sub> O <sub>3</sub> )	20–28	8–20
Calcium Oxy-Silicate (CaSO <sub>4</sub> )	...	2.8–3.2
Manganese-IV Oxide (MnO <sub>2</sub> )	8–12	...
Titanium Dioxide (TiO <sub>2</sub> )	0–1	...
Free-Lime	2–4	...

<sup>a</sup>After Lemass [30].

<sup>b</sup>After Bayomy and Al-Abdul Wahhab [24].

filters, drains, slurry seal and micro-surfacing, and hot asphalt concrete and maintenance mixes, this research considers only the utilization of SSA in road bases and foundations.

Research has proven that the use of SSA in road construction appreciably reduces the required pavement thickness [24]. In addition, there has been an increased environmental concern over the disposal of the byproducts of steel production, which could be put into use elsewhere. Furthermore, quarrying operations used to extract conventional aggregates increase dust, produce noise from the quarrying machines and rock cleavage, and result in the destruction of the natural scenic beauty of the quarry areas. The use of SSA material as a road construction aggregate minimizes the use of the raw material, thereby maximizing the benefits of available resources. These factors support the use of SSA as an alternative to conventional aggregates. In addition, SSA characteristics make it a better aggregate as compared to limestone and dolomitic aggregates because SSA has high crushing resistance and low water absorption. This reduces the susceptibility of the graded bases to failures under high axle loads and excessive moisture content.

It should be clear, however, that there exists some concern regarding the presence of free lime (CaO) and free magnesia (MgO) in SSA, with the consequent risk of expansion upon hydration. Table 1 shows the chemical composition of SSA produced in Jubail and shows, for comparison, the typical values reported in the literature for other plants. The volume expansion due to hydration of MgO, CaO, or both, was reported by Ahmed and Lovell [25], Emery [26], Sherwood [27], and Heaton [28]. Aiban [29] has reported some pavement upheavals in Eastern Saudi Arabia. Such expansion limits the use of steel slag to situations where favorable conditions of the expansion are unlikely, as in the case of dense bitumen macadam or where any expansion is not likely to be a serious problem as in the case of surface dressing [27]. SSA can also be used if the void ratio is relatively large and unoccupied by foreign materials, such that these voids can accommodate the resulting expansion. This will be the case when using the slag as is without admixtures.

The work focuses on assessing the possibility of optimizing the gradation of SSA for use in granular road bases while maintaining superior performance against the increasing traffic loads and harsh climatic conditions in the Eastern Province of the Kingdom of Saudi Arabia. Optimization is performed for blends of SSA, sand, and limestone aggregates at different ratios.

The experimental procedure consisted of the following four main tasks:

1. Determination of the leachate characteristics of SSA.

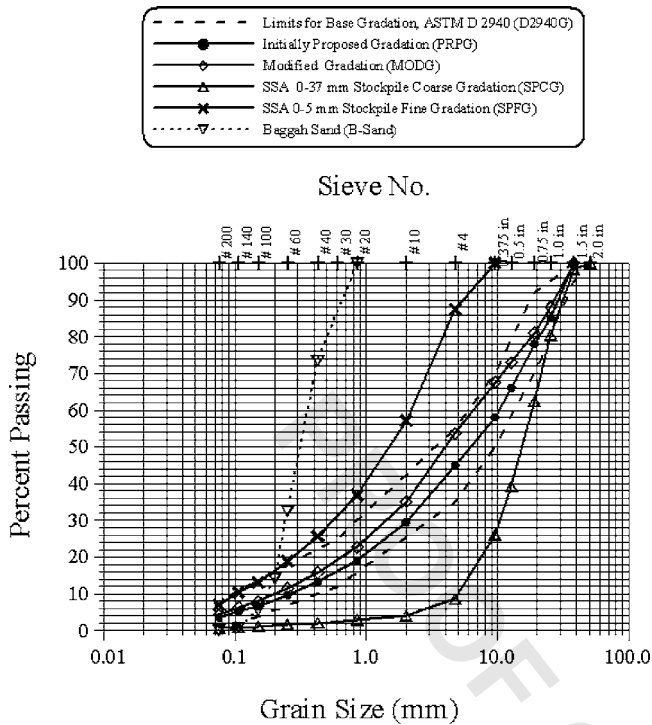


FIG. 2—Grain-size distribution curves for some of the used gradations and Baggah sand.

2. Determination of the properties of SSA.
3. Optimization of SSA for road bases.
4. Construction of field trials using the optimum gradations/mixes.

Testing for the four phases was conducted according to ASTM, EPA, AASHTO, and other relevant standards.

### Characteristics of the Material

#### Gradation of SSA

Two types of SSA were delivered to the Civil Engineering Laboratory at KFUPM: material finer than 5 mm and labeled 0–5 mm and material having sizes up to 37 mm and labeled 0–37 mm. The 0–37 mm material was sieved according to the ASTM sieve size and the material retained on the 1.5 in. (38 mm), 1 in. (25.4 mm), 3/4 in. (19 mm), 1/2 in. (12.5 mm), 3/8 in. (9 mm) sieves, and sieve No. 4 (4.75 mm) was separated into different containers. This was done to enable reconstitution of all samples to the desired gradation, and will eliminate any variations of the gradation and will, therefore, show the effects induced by different gradations. The 0–37 mm material was intended, by the SSA supplier, to be used as a graded base course material. The grain-size distribution of the two materials is shown in Fig. 2.

#### Leachate Characteristics of SSA

The United States Environmental Protection Agency (USEPA) land disposal restrictions, otherwise known as the land bans, have introduced toxicity characteristic regulatory levels. These regulatory levels define the cutoff levels for a waste. Using this regulation, a

TABLE 2—Summary of the EPA hazardous elements, leachate results of SSA and the associated regulatory limits.

Element	Average Values		Remarks
	for SSA, (mg/L)	EPA Regulatory Limits (TCLP)	
Arsenic (As)	0.088	5.0	
Barium (Ba)	8	100.0	
Cadmium (Cd)	0.04	1.0	
Chromium (Cr)	0.01	5.0	
Lead (Pb)	0.02	5.0	
Selenium (Se)	0.117	1.0	
Silver (Ag)	0.20	5.0	
Iron (Fe)	68	...	Not listed in the TCLP list
Copper (Cu)	0.14	...	Not listed in the TCLP list
Nickel (Ni)	0.01	...	Not listed in the TCLP list
Zinc (Zn)	1.6	...	Not listed in the TCLP list
Mercury (Hg)	0.0	0.2	

concentration of any listed constituent in the leachate at or above these levels designates the waste as hazardous, and it remains such until treated. The elements of interest with the threshold concentrations of inorganic ions for determining whether wastes are characteristic hazardous wastes by virtue of leachability are provided in Table 2.

USEPA standards were used in determining the toxicity characteristics of the metal leachate obtained from the SSA. Except for arsenic, mercury, and selenium, all other elements were analyzed using a graphite furnace system. Arsenic (As) and selenium (Se) were analyzed by inductively coupled plasma procedure (ICP-400). Mercury was analyzed using mercury analyzer. The detection of microelements was done by flameless atomic absorption spectrophotometer (AAS), and the detection of macroelements was done by using a flame atomic absorption spectrophotometer. It is clear from the results presented in Table 2 that the average values of the metals under consideration do not violate the limits set in the toxicity characteristic regulatory levels. Therefore, the use of such material is safe and should not induce any contamination even in areas where the groundwater table is shallow.

#### Characteristics of Hadeed Steel Slag Aggregate

Once the material was declared environmentally safe, it was separated into different containers according to their size. The basic characterizations and some of the properties of SSA, including the relevant standard number and the corresponding values for limestone aggregate, are shown in Table 3. Similarly, the chemical composition of SSA is shown in Table 1 and the values show that the main constituents are lime, silica, and iron oxide. The specific gravity of 3.69 is much higher than those of regular soils and will be reflected in the unit weight of the compacted material.

#### Characteristics of Sand and Marl

The dune sand was obtained from the Baggah area from a dune adjacent to the Dammam-Riyadh Expressway near station 1300, to the eastern side of the road. The sand is typical Eastern Saudi sand, which is poorly graded whitish fine quartz sand. The grain size distribution of the sand is shown in Fig. 2. The sand is classified as SP according to the USCS and A3 according to the AASHTO classification system.

TABLE 3—Typical characteristics of steel slag aggregate (SSA) and limestone aggregate (LSA).

Parameter	Steel Slag		Limestone	
	Lee [31]	Hadeed Slag	Typical	Marl Used
Specific Gravity	3.2–3.6	3.69	2.5–2.9	2.71
Liquid Limit (LL)	...	0	Variable	20
Plastic Limit (PL)	...	0	Variable	13
Plasticity Index (PI)	...	Nonplastic	Variable	7
Sand Equivalent [AASHTO T176]	...	88	Variable	22
Los Angeles Abrasion Loss (%) [ASTM C 131]	15–25	18	30–45	42
Sodium Sulfate Losses (%) [ASTM C 88]	<12	1.86 (Coarse Agg.) 1.31 (Fine Agg.)	<14	13
Angle of Internal Friction (degrees)	40–50	...	20–35	...
Hardness (Moh's Scale)	6–7	...	3–4	...
California Bearing Ratio (%) [ASTM D 1883]	<300	119~383	Variable	16~224
Swelling in CBR Mold	...	0	Variable	0
Polarity	pH (8–10)	...	...	...

The marl was obtained from the Abu Hadriyadh area, from Al-Dossary crusher. This marl is currently used as a graded base material by the Dammam Municipality. The grain-size distribution of the marl is shown in Fig. 3. Some of the marl characteristics are shown in Table 3. The marl is classified as GM and A-1 according to the USCS and the AASHTO classification systems, respectively. The marl fines used consist of particles passing U.S. sieve No. 4 from the same marl.

### Optimization of SSA for Road Bases

One of the main objectives of this optimization process was to find the most appropriate gradation for SSA to be used in road bases.

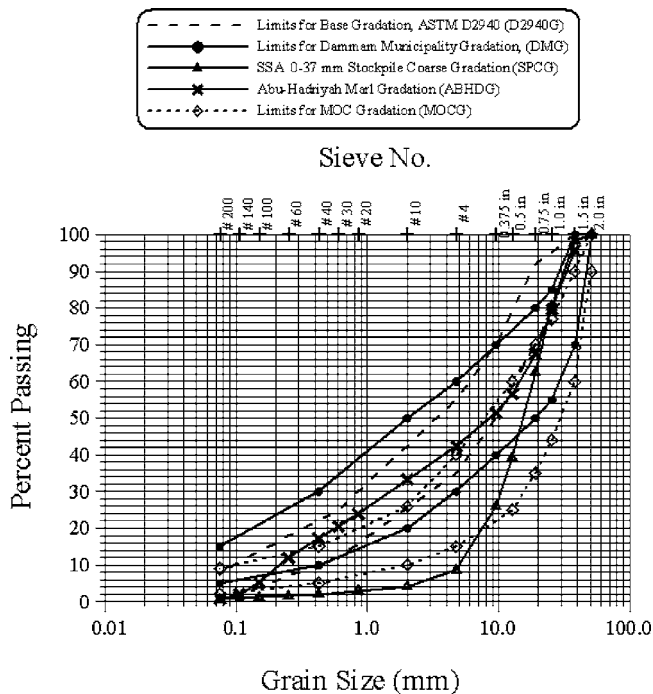


FIG. 3—Grain-size distribution curves for some of the used gradations and Abu Hadriyadh marl.

The second main objective was to find the proper mix ratio for SSA and sand, SSA and calcareous (marl) base course and SSA and marl fines. Several gradations were tried, and SSA was mixed with locally available marl, marl fines, and sand to optimize the mix properties. The CBR test was used in the evaluation of these blends and was considered the decisive parameter. In all CBR tests, samples were prepared according to ASTM Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (56 000 ft-lbf/ft<sup>3</sup> (2700 kN-m/m<sup>3</sup>)) (D 1557), Method D, using the modified Proctor compaction. However, some samples were prepared using vibratory compaction, where samples were vibrated in the CBR mold in three equal lifts for eight min each, under a surcharge of 26.4 kg. In both cases, the oversize correction (using the scalp and replace method) was made where aggregate that was coarser than 19 mm was excluded and replaced by an equivalent amount of material smaller than 19 mm and retained on the 9 mm sieve. The CBR was conducted in accordance with ASTM Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils (D 1883). All samples were reconstituted to the intended gradation to eliminate variation resulting from size variability.

Many gradations and material combinations were tried in the preliminary investigation. One of the gradations was based on the ASTM Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports (D 2940). The following six different base course gradations were evaluated thoroughly during this investigation:

1. The Ministry of Communication (Ministry of Transportation) gradation (MOCG).
2. The ASTM D 2940 base course gradation (D 2940G).
3. The Dammam Municipality gradation (DMG).
4. The company's "Heckett MultiServ" proposed gradation for the coarse (0–37 mm) blend (SPCG).
5. The company's "Heckett MultiServ" proposed gradation for the fine (0–5 mm) material (SPFG).
6. A newly proposed "optimum" gradation (PRPG).

The newly proposed "optimum" gradation required a few trials using different ratios before the proposed one was reached. The grain-size distribution curves of these gradations are shown in Figs.

TABLE 4—Summary of the used gradations with their maximum CBR values and some features.

Gradation	Additives	Maximum CBR	Comments
SPCG	Pure SSA	119	Difficult to compact and thus has low CBR
SPCG	70 % SSA+15 % Marl+15 % Sand	405	CBR > 192, has some water sensitivity
SPCG	20 % Marl Fines+24 % Sand	373	CBR > 280, has little water sensitivity
SPCG	24 % Sand	400	
SPCG/ABHDG	40 % SSA+60 % Marl	368	CBR > 120, has some water sensitivity
SPCG/ABHDG	30 % SSA+70 % Marl	241	CBR > 25, acute water sensitivity
PRPG	Pure SSA	225	CBR > 134, somewhat difficult to compact
PRPG <sup>a</sup>	Pure SSA	174 <sup>a</sup>	CBR > 72 <sup>a</sup>
PRPG	SSA+Sand, different %	406	CBR > 210 and maximum at 15 % Sand
MODG	Pure SSA	383	Water insensitive, easy to compact
MODG	50 % SSA+50 % Marl	397	Significant CBR drop on the wet of optimum
MODG	20 % Marl Fines+12 % Sand	344	Has some water sensitivity
MODG	20 % Marl Fines+18 % Sand	370	Has some water sensitivity
MODG	20 % Marl Fines+24 % Sand	236	Low CBR values
MODG	20 % Marl Fines Replacement	367	Acute water sensitivity
MOCG	Pure SSA	147	Difficult to compact and thus has low CBR
MOCG	SSA+Sand, different %	455	CBR > 400 and maximum at 20 % Sand
MOCG	20 % Marl Fines	253	Low CBR values
MOCG	20 % Marl Fines+24 % Sand	346	Somewhat water sensitive but CBR > 248
MOCG/ABHDG	65 % SSA+20 % Sand+15 % Marl	418	Somewhat water sensitive but CBR > 250
MOCG/ABHDG	60 % SSA+40 % Marl	311	Somewhat low CBR values
DMG	Pure SSA	360	Low moisture content results in low CBR values
DMG	Pure Marl	220	Acute water sensitivity
SPFG	Pure SSA	300	CBR > 150, CBR increases with moisture content
SPFG <sup>a</sup>	Pure SSA	220 <sup>a</sup>	CBR > 30, CBR increases with moisture content

<sup>a</sup>Vibratory compaction.

2 and 3. For all these different gradations, pure (100 %) SSA was used. In addition, blends of SSA and dune sand, marl, and/or marl fines were used at different ratios.

### Laboratory Results

The main objective of the gradation optimization was to improve the load carrying capacity of the material. Table 4 gives a summary of the used gradations with their corresponding maximum CBR values and some of their main features. Additional comments and discussion are presented below and more detailed discussion can be found in the original work [23]. It is clear from the results presented in Table 4 that high CBR values can be obtained for pure (100 %) SSA, sand-SSA blends, and marl-SSA blends, provided that preparation procedure and gradation are accounted for. The SSA in SSA-marl blends can be utilized either as a partial replacement of marl to produce a better quality material or as an additive to supplement deficiencies in certain aggregate sizes of the marl graded base course. In the latter case, a low percentage of SSA is usually required while in the former case, ratios of up to 70 or 80 % SSA can be used.

A major advantage of using the pure SSA is the excellent drainage features. It was, therefore, necessary to find an appropriate SSA gradation that enabled the use of SSA alone without the need to add marl, which is a relatively impervious soil. The use of 100 % SSA insures a free draining layer and will, thus, avoid the use of complicated subsurface drainage systems. In addition, such a layer will prevent capillary from reaching the asphaltic concrete layers.

The coarse gradation proposed by the company, SPCG, was tried first and was found to lack fines. Due to the angularity of the

SSA combined with the coarseness of this gradation, it was difficult to compact the material, and the CBR values were relatively low. The maximum dry density attained was 2.34 g/cm<sup>3</sup> and the corresponding maximum CBR value was 119. Although the material is cohesionless in nature, and therefore, should not be sensitive to the molding moisture content, it was found that the dry density and CBR values increased as the molding moisture content increased up to 4 %. Further increase in moisture content was not effective since the SSA did not retain the extra water and any water above 4 % came out of the compaction mold. It is believed that the SSA has excellent physical properties that should enable the product to give much higher CBR values. However, the poor gradation was believed to be the cause of the relatively low CBR values, and thus, better SSA gradation needs to be determined.

Gradations finer than the SPCG gradation were used. The gradation range (limits) specified by the ASTM D 2940 standard was used as a general guideline. A little coarser gradation than average values was used and was labeled as the proposed gradation (PRPG) as shown in Fig. 2. A 100 % SSA blend was prepared using both Proctor compaction and Vibratory compaction. The CBR and density results are shown in Fig. 4 for the modified Proctor compaction. The CBR values are somewhat lower than what was originally anticipated; however, the modified Proctor compaction resulted in much higher CBR values (134 to 225 for soaked testing and 146 to 185 for unsoaked testing) compared to the vibratory compaction (74 to 109 for soaked testing and 72 to 174 for unsoaked testing). This could be explained by the relatively high dry density in the case of modified Proctor compaction ( $\approx 2.65$  g/cm<sup>3</sup>) compared to those in the case of vibratory compaction (less than 2.5 g/cm<sup>3</sup>). It is also noticed that soaking did not lower the CBR values, but con-

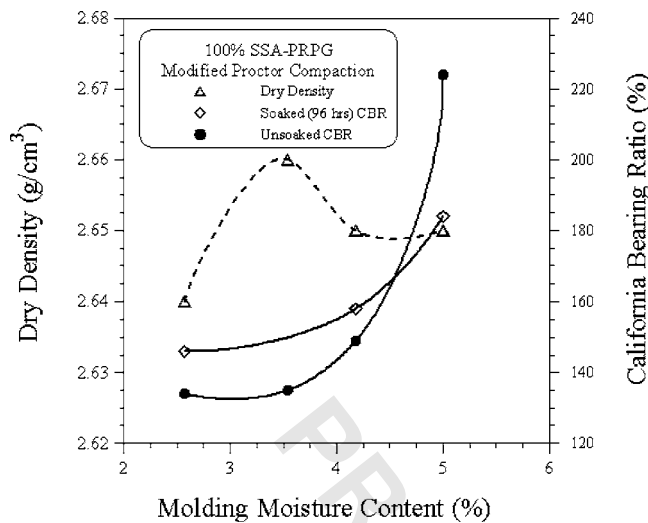


FIG. 4—Variation of the dry density and CBR with the molding moisture content for SSA reconstituted to the proposed gradation (PRPG) and compacted using the modified Proctor.

trary to expectation, the CBR increased due to soaking. Additionally, the molding moisture content has an effect on the CBR values; a molding moisture content of about 5 % seems to give the highest CBR values.

The increase in the maximum CBR value from 119 for the SPCG to 225 for the PRPG confirms that the finer SSA gradation improves the compatibility of the material and thus the CBR values. This encouraged further optimization of the gradation. A finer gradation was reached by adding fine SSA (0–5 mm size) to the PRPG in increments of 5 % and reducing the coarse material (0–37 mm) by the same amount and performing the CBR test. During this part of the optimization, 5 and 6 % molding moisture contents were used. The highest CBR value (383) was obtained when 10 % SSA fines were added to the proposed gradation PRPG as shown in Fig. 5. The resulting gradation was labeled the “modified gradation” (MODG) and is shown in Fig. 2. In the field, this gradation can be obtained by blending 45% coarse SSA (SPCG) and 55% fine SSA (SPFG), assuming consistency in these two gradations.

The modified gradation (MODG) was subjected to further optimization. The variations of both the soaked and unsoaked CBR values with the molding moisture content are shown in Fig. 6. The highest CBR value was reached at a molding moisture content slightly less than 5 %. Above that level, any additional moisture seeped through the mold base. The maximum soaked and unsoaked CBR values are 383 and 358, respectively. The dry density ( $\gamma_d$ ) also increased from 2.76 g/cm<sup>3</sup> at a moisture content of 2 % to 2.88 g/cm<sup>3</sup> at a moisture content of 5 %. This increase in  $\gamma_d$  is mainly due to lubrication and is responsible for the increase in the CBR values. Contrary to expectations, it was noted that the soaked CBR values were higher than the corresponding unsoaked values. The cause of such phenomenon is not known yet, but could have resulted from minor “local” expansion of individual particles, which causes more interlocking and, thus, higher CBR values.

It is worth mentioning that swelling was monitored for all soaked CBR tests, and no swelling values could be measured. This might be attributed to the aging effect, where most, if not all, of the expansion of the SSA should have already taken place because the material was stockpiled for a few months in a humid environment.

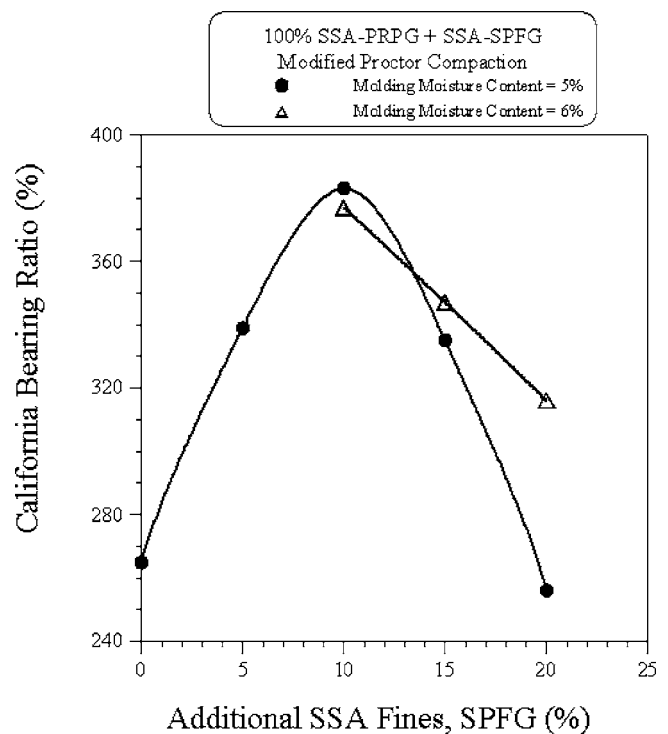


FIG. 5—Variation of the CBR of SSA reconstituted to the proposed gradation (PRPG) and blended with different percentages of SSA fines and compacted using the modified Proctor.

In addition, the high interlocking forces between particles prevented any movement or swelling of the sample and was reflected only in the increase of the CBR values. This phenomenon deserves further attention.

Due to the limited quantity of the 0–5 mm SSA relative to the 0–37 mm SSA, and the need to use free draining material and the fact that the proposed gradation (PRPG) lacks fines and could be the cause for the relatively low CBR values, different percentages of Baggah dune sand (B-Sand) were added to the SSA, and samples were compacted at 5 % moisture content. The CBR values are shown in Fig. 7. It is noticed that the addition of 10 to 15 % sand (B-Sand) results in the highest CBR (an average of 406). This corresponds to an increase of about 80 % when compared with pure SSA reconstituted to the same gradation. Such an increase clearly indicates that the main cause for the low CBR values, for SSA, is poor gradation accompanied by the lack of fines. Furthermore, the sand enhances the compactibility of the mixture, thus increases the density, fills the voids, and ultimately improves the load carrying capacity.

In an attempt to maximize the use of locally available marl which will reduce SSA consumption and, thus, its transportation costs, a blend of SSA with Abu Hadriyah marl was tried. The variations of the CBR and dry density with the molding moisture content for Abu Hadriyah marl reconstituted to DMG are shown in Fig. 8. The maximum CBR value for the pure marl is 224, as shown in the figure. It is clearly seen that the marl has acute water sensitivity and the CBR decreased significantly if the molding moisture content differs from the optimum value. For example, the soaked CBR values decreased from 215 to 105 due to the increase in the molding moisture content from 6.2 to 7.2 %, i.e., due to the increase of 1 % in the molding moisture content on the wet side of optimum. This corresponds to a reduction of more than 50 % in the CBR value. The severe reduction in the CBR values is true for both the wet side

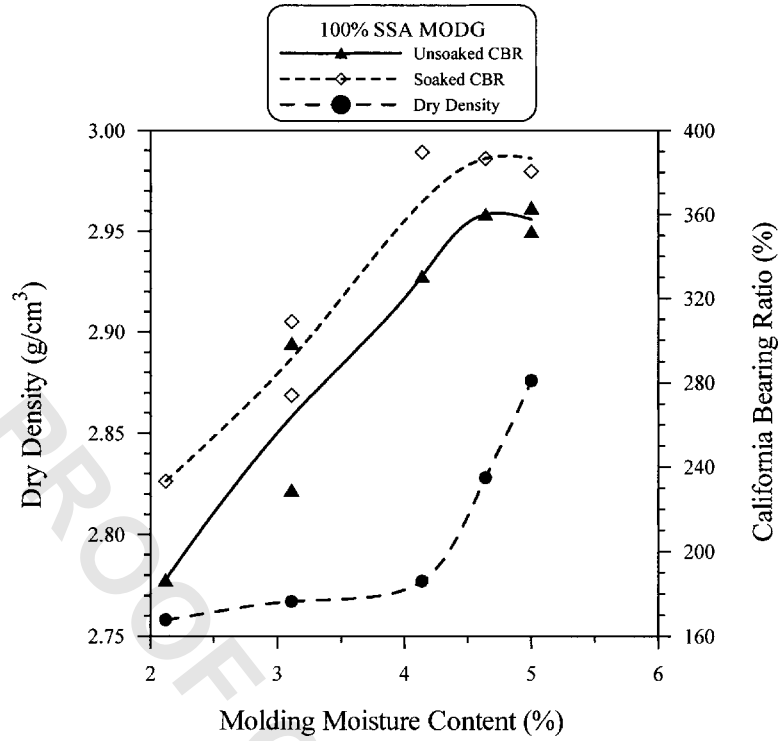


FIG. 6—Variation of the dry density and CBR values with the molding moisture content for SSA reconstituted to the modified gradation (MODG) and compacted using the modified Proctor.

and the dry side of optimum where a complete strength loss resulted even if the sample is compacted to 95 % of its maximum dry density. It is clear that the 95 % compaction line cannot be easily defined for such material, and thus the CBR values are expected to approach zero as shown in Fig. 8. Such behavior was observed for over 50 marl samples obtained from different places within the eastern part of Saudi Arabia at different times.

The water sensitivity of marl is also clear on the dry side of optimum where the CBR decreased from 155 to 75 due to soaking, i.e., a reduction of about 52 %. The addition of SSA resolved these issues as shown in Fig. 8. A blend of equal proportions of SSA and marl produced CBR values reaching 400 and the minimum value was over 220. These values are by far more than the ones produced

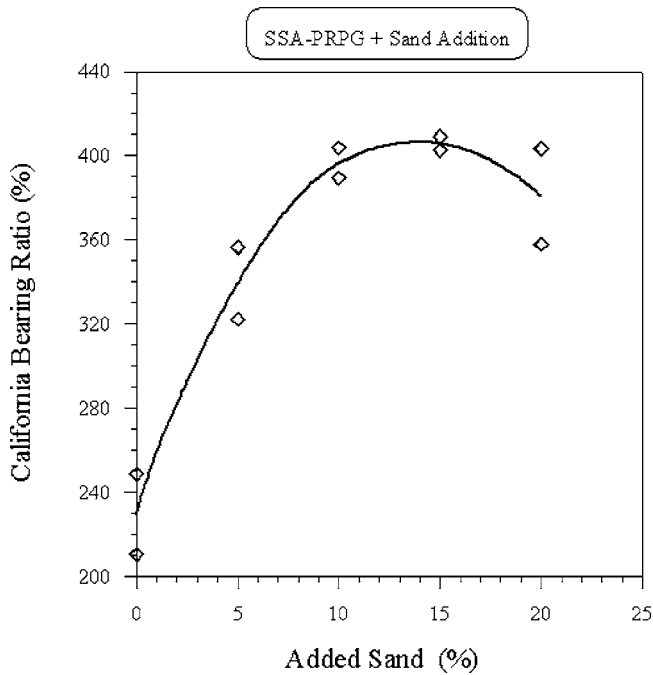


FIG. 7—Variation of the dry density and CBR values with the molding moisture content for SSA reconstituted to the proposed gradation (PRPG) and mixed with different percentages of sand and compacted using the modified Proctor.

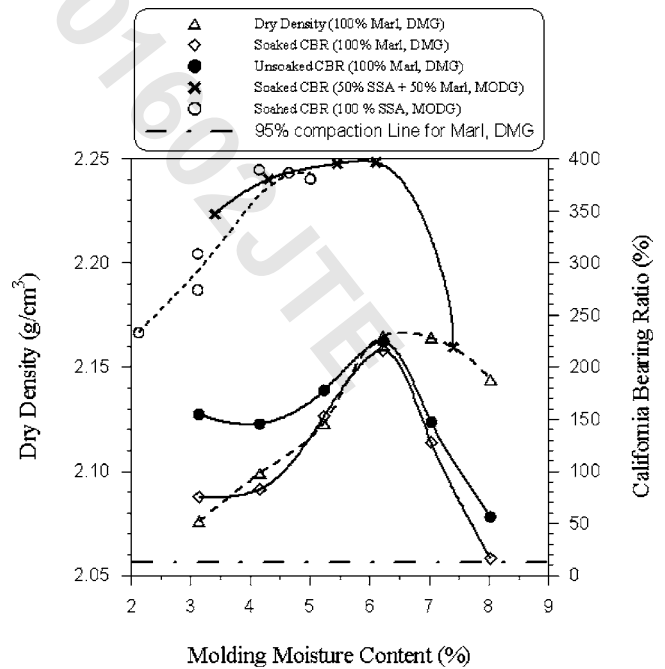


FIG. 8—Variation of the dry density and CBR values with the molding moisture content for pure SSA, pure Abu Hadriyah marl, and a blend of SSA (50%) and Abu Hadriyah marl (50%) and compacted using the modified Proctor.

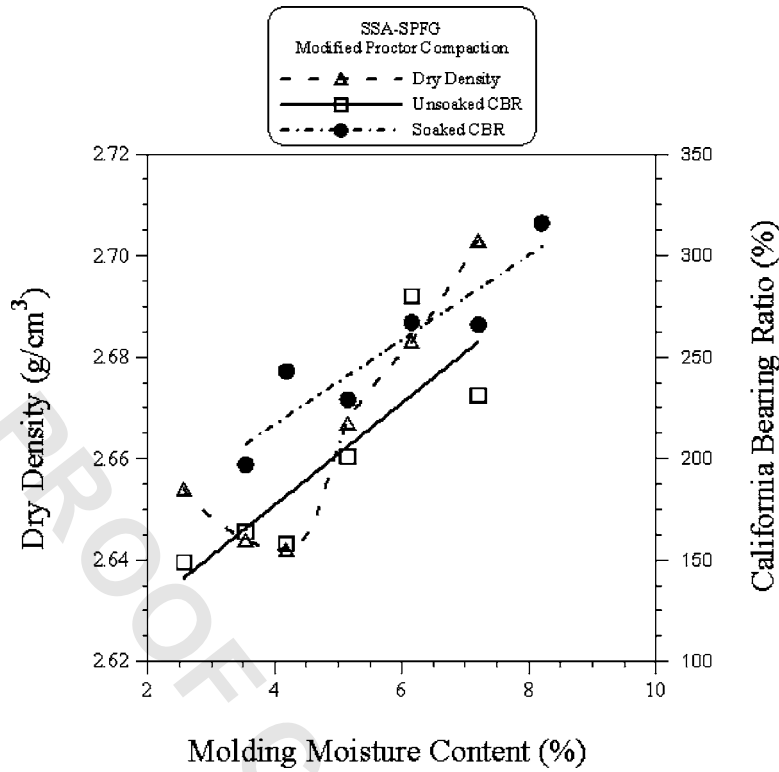


FIG. 9—Variation of the dry density and CBR with the molding moisture content for fine SSA compacted using the modified Proctor.

by pure marl reconstituted to the same gradation. Figure 8 contains, for comparison, the CBR values for pure SSA reconstituted to the MODG and for a blend of SSA (50 %) and marl (50 %). The data clearly show that the pure SSA and SSA-marl blends are far better than the pure marl since they produce higher CBR and both materials are somewhat insensitive to the moisture content when compared to the pure marl.

In addition to the testing of 0–37 mm SSA, 0–5 mm SSA ma-

terial was tested to evaluate its CBR. This material is believed to be a good candidate as a filter- or separation-layer between relatively fine-grained soils and SSA having coarse particles. Figures 9 and 10 show the CBR values for pure fine SSA samples prepared using the modified Proctor compaction and the vibratory compaction, respectively. The vibratory compaction resulted in lower  $\gamma_d$  and CBR values when compared to the modified Proctor compaction. However, in both cases, the CBR values were relatively high for a cohe-

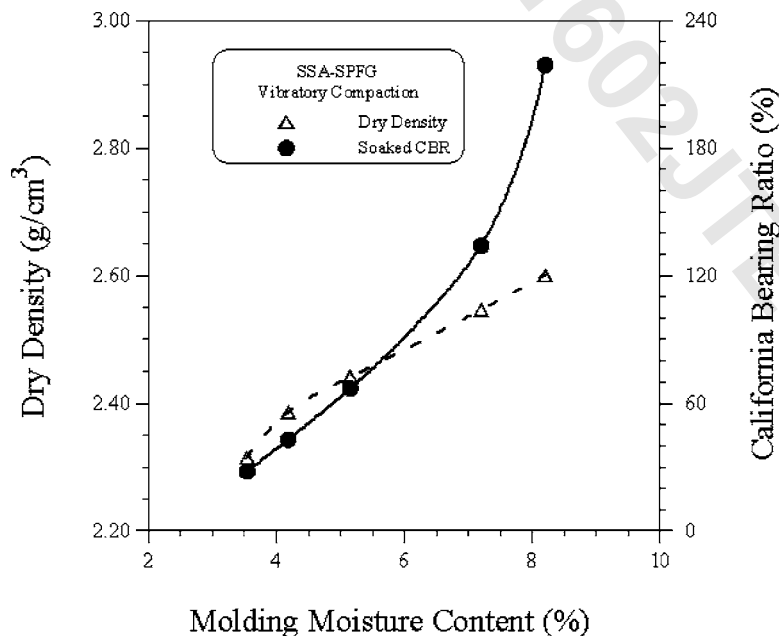


FIG. 10—Variation of the dry density and CBR with the molding moisture content for fine SSA compacted using the Vibratory method.

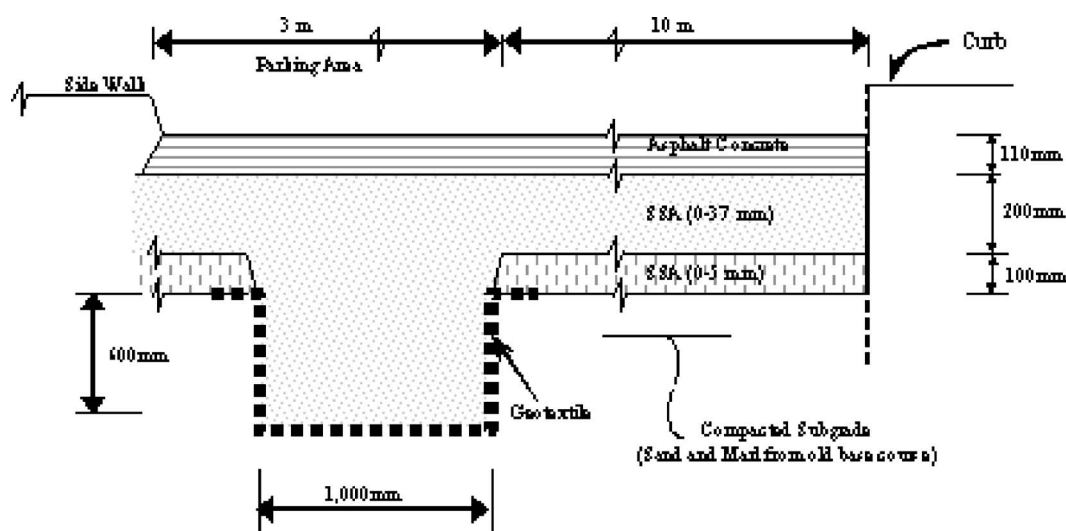


FIG. 11—Cross section of the field trial in the Dammam Industrial Area, using SSA.

sionless material with such grain size range (0–5 mm). The CBR value could easily reach 300 in the case of the modified compaction test and did not get below 140 for all moisture content values used. The CBR values of the fine SSA (0–5 mm) are by far higher than those for calcareous base course material and does not have acute water sensitivity.

### Field Trial

The laboratory results clearly indicate that SSA is an excellent material for road bases due to the high load carrying capacity and durability, and the excellent drainage characteristics of the aggregate. However, there seems to be some difficulty in achieving high density and, therefore, high CBR values when using vibratory compaction for pure (100 %) SSA. Since the field compaction of road bases is somewhat a combination of the vibration and static/dynamic types, a field trial will clarify some of the concerns regarding compactibility of the SSA. The field trial was intended to be at a site that has heavy traffic, poor subsurface conditions, and a shallow groundwater table so that the performance of the SSA base layer can be monitored under such “harsh” conditions. A field trial was planned early in the optimization process in order to construct the trial before the rainy season.

Once the modified gradation (MODG) was reached and the high CBR results were confirmed, a road in the Dammam Industrial Area, Eastern Saudi Arabia was chosen in cooperation with the Dammam Municipality. The section is located in one of the severely damaged and deteriorating parts of the selected road. It is a main exit for traffic from ready-mix concrete and masonry block plants. The groundwater table is almost at the top of the existing graded base layer. The segment constructed using the SSA base course is about 200 m long. A cross section of the road is shown in Fig. 11 and it consists of:

1. A compacted subgrade comprised of the existing marl base material mixed in some places with sand.
2. A 100 mm thick fine SSA (SPFG) filter layer.
3. A 200 mm SSA (0–37 mm) base course reconstituted to the modified gradation (MODG).
4. The asphalt concrete layers (a 70 mm thick base layer and a 40 mm thick wearing layer).

A subsurface drainage system was constructed under the filter layer below the parking lane of the road and consists of SSA (0–37 mm) wrapped in a geotextile. The underdrain has a width of about 1000 mm and a depth of 600 mm. This was connected to the main drainage canal at a later stage.

Construction started at the end of November 1996 and was monitored carefully in all stages. After removing the deteriorating asphalt concrete, the underdrain was constructed and was used to drain the water to enable construction. The old marl base layer was completely remixed and compacted to a minimum relative compaction of 90 %. The compaction of the old marl base, as a subgrade for the SSA section, was possible after dewatering the area using a pump placed at the eastern end of the underdrain (the end of the section and the road) to lower the water.

After compacting the subgrade, dewatering was stopped and the fine SSA (0–5 mm) filter/separator layer (100 mm thick) was placed and compacted either submerged or at a moisture content of 4–5 %. The resulting dry density ranged between 2.70 and 2.8 g/cm<sup>3</sup> with an average value of 2.73 g/cm<sup>3</sup>. The Clegg impact values (CIV) were measured at a few places with an average value of 26. The corresponding CBR value, obtained from the correlation



FIG. 12—A photograph demonstrating the construction of the road using SSA as a base course layer in an area with a shallow groundwater table.

TABLE 5—Modulus values obtained during construction and two days and six months after construction of the SSA trial section in the Dammam Industrial Area.

Layer	Section	Max. Deflection Mills	E, Modulus Values, (ksi)			
			Asphalt	Graded Base	Filter	Subgrade
Subgrade	West	2.2	...	...	...	28
Filter	West	1.16	...	...	25	29
	East	1.04	...	29	30	27
Graded Base Course	Middle	1.08	...	27	27	28
	West	0.99	...	28	29	27
Wearing Course (2 days later)	East	0.67	300	43	...	30
	Middle	0.85	270	49	...	29
	West	0.73	270	76	...	27
Wearing Course (6 months later)	East	0.42	425	192	...	41
	Middle	0.44	350	178	...	37
	West	0.53	400	136	...	30

curves is about 47. The coarse blend (0–37 mm), according to the modified gradation (MODG), was mixed in place in a dry state and compacted at about 5 % moisture content for a thickness of 200 mm. The density ranged between 2.7 and 2.88 g/cm<sup>3</sup> with an average value of 2.78 g/cm<sup>3</sup>. The compacted material has an average CIV value of 48; this corresponds to a CBR value of about 150. It is worth mentioning that compaction was done utilizing conventional vibratory drum compactor. The first two to three passes were performed at high vibration, after which medium vibrations were used for the remaining five to seven passes. In addition, the SSA layers were placed and compacted in an area with a water table covering part of SSA, as shown in Fig. 12. This is considered a major advantage in areas where dewatering becomes difficult and costly. As a matter of fact, the presence of such water will enhance compaction of the SSA. The asphaltic concrete layers (70 mm base and 40 mm wearing course) were then laid down.

During- and post-construction monitoring, using a Dynaflect apparatus, was performed after the compaction of the subgrade, after the construction of each SSA layer, and two days and six months after the placement of the asphalt-wearing course. The backcalculated modulus values are given in Table 5. It is noticed that the backcalculated modulus values for the SSA base layers have increased after the asphaltic layers were placed. This is mainly due to the confinement of the noncohesive SSA layer. The road was opened to traffic in early December 1996. After six months of operation, a significant increase in the backcalculated modulus was observed for the SSA layers where an increase of more than four times the original values (right after the placement of the asphaltic layers) has been recorded. This indicates that the slag quality is not deteriorating with time. This was expected for the SSA since loading will densify the material and SSA has high crushing strength. Such values are expected to increase more when the groundwater level is lowered after connecting the underdrain to the drainage system. It is believed that the road segment is exposed to one of the worst loading and environmental conditions. The road has shown excellent performance for the past seven years and is expected to continue to do so. In fact, the section is used as an entrance to and an exit from the area due to the severe deterioration in the old pavement to the west (entrance side).

## Conclusions

The experimental investigation performed on SSA produced by Heckett-MultiServ-Saudi Arabia Ltd., Jubail, Saudi Arabia, indi-

cated excellent performance of the material. The use of such material in foundations, road bases, asphaltic mixes, and similar applications will solve some of the existing problems. The following concluding remarks can be made:

1. Steel slag aggregate (SSA) has mechanical, physical, and chemical characteristics that makes it valuable for use in different engineering applications as a partial or full replacement for conventional aggregates.
2. The use of SSA does not cause any detrimental effects regarding the environment, and the leachate characteristics are well within EPA limits.
3. The use of SSA for road bases gives satisfactory results provided that the gradation is selected carefully. The resulting CBR values are more than twice those for graded base courses using conventional Eastern Saudi calcareous aggregate. In addition, the water sensitivity of SSA is not an issue, and the molding moisture content and moisture content at testing are not reducing the CBR values below the acceptable limits.
4. The use of SSA alone for the road base has the advantage of free drainage and will not require any subsurface drainage systems.
5. SSA can be blended with locally available sand and marl to improve the strength. This will also minimize the cost of transporting larger quantities of SSA.
6. There is a maximum limit of marl addition to SSA, and this limit is dependent on the type of marl in terms of plasticity and aggregate quality. The addition of at most 60 % Abu Hadriyah marl can give high CBR values and the higher the SSA content the higher the CBR. However, this depends on the SSA gradation, and proper ratios should be investigated for each case.
7. The field trial has shown an excellent performance over the last seven years despite the fact that it was submerged under water on many occasions due to rain and poor drainage.
8. There is a need for the investigation of the long-term chemical interaction between SSA and other soils including marl.

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