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Recycling of Local Qatar's Steel Slag and Gravel Deposits in Road Construction

Husam Sadek
Department of Civil and Architectural Engineering, College of Engineering, Qatar University, Doha 2713, Qatar

Abstract: Every year, the State of Qatar generates about 400,000 tons of steel slag and another 500,000 tons of gravel as a result of steel manufacturing and washing sand, respectively. The two materials (by-products) are not fully utilized to their best market values. At the same time, infrastructural renewal will take place in Qatar over the next ten years, and there will be a greater demand for aggregates and other construction materials as the country suffers from the availability of good aggregates. This paper presents results obtained on the use of steel slag, gravel and gabbro (control) in HMAC (hot mix asphalt concrete) paving mixtures and road bases and sub-bases. Tests were conducted in accordance with QCS-2010 (Qatar Construction Specifications) and results were compared with QCS requirements for aggregates used in these applications. Based on the data obtained in this work, steel slag and gravel aggregates have a promising potential to be used in HMAC paving mixtures on Qatar's roads, whether in asphalt base and asphalt wearing courses or as unbound aggregates in the base and sub-base pavement structure.

Key words: Steel slag, gravel, by-products, asphalt concrete, sub-base, Qatar.

1. Introduction

In the State of Qatar, steel slag, a by-product of steel manufacturing, is generated in large quantities. In fact, it is estimated that more than 400,000 tons of steel slag are generated annually and they are not efficiently utilized in construction [1]. The disposal of such quantities poses a great burden on Qatar's steel. In addition, gravel, resulting from washing sand, is also produced at more than 500,000 tons per year in Qatar [1]. Simultaneously, infrastructural renewal (roads, bridges, metro, railways, new airport, deep-water seaport, hotels, stadiums, etc.) will take place in the State of Qatar over the next ten years and there will be a greater demand for aggregates and other construction materials. Qatar suffers from the availability of good aggregates that could be utilized in roads, parking, buildings and other construction. In fact, Qatar imports most of its aggregates' needs from neighboring countries. Thus, our environmental responsibilities and potential economic benefits that might be realized dictate that steel slag and other discarded materials should be utilized in the construction sector.

Research is thus needed to promote and investigate, where possible, the recycling of steel slag and gravel deposits in Qatar's construction industry. This paper presents results obtained on the use of steel slag, gravel and gabbro in HMAC (hot mix asphalt concrete) paving mixtures in addition to road bases and sub-bases. All tests were conducted in accordance with QCS-2010 (Qatar Construction Specifications).

2. Literature Review

Waste is an unavoidable by-product of most human activities. Economic growth and rising living standards in many parts of the world have led to an increase in the quantities of generated wastes. Steel slag, a by-product of steel manufacturing, is no exception. It is produced either from the conversion of iron to steel in a BOF (basic oxygen furnace) or by the melting of scarp to

Corresponding author: Husam Sadek, Ph.D., P.E, research fields: hot asphalt mixtures, project management, pavement design.

make steel in the EAF (electric arc furnace). The slag is produced as a molten liquid melt and it is a complex solution of silicates and oxides that solidifies upon cooling. The ASTM (American Society for Testing and Materials) defines steel slag as “a non-metallic product, consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminium, manganese, calcium and magnesium that are developed simultaneously with steel in basic oxygen, electric furnace, or open hearth furnaces” [2].

Chemical composition, mechanical and environmental properties in addition to some undesirable characteristics of steel slag were presented in a previous work [1].

2.1 HMAC

Steel slag has been successfully used in asphalt paving mixtures in the United States, Canada, Europe and Japan [3-8]. It is used as an aggregate in hot mix asphalt wearing courses and surface treatments, including chip seals. Positive properties of steel slag aggregates, when used in asphalt paving, include high stability, excellent stripping and skid resistance, and resistance to rutting. Proper processing of steel slag and special quality control procedures should be in-place when selecting steel slag for use in asphalt paving. ASTM D5106 [2] is the Standard Specification for Steel Slag Aggregates for Bituminous Paving Mixtures. BS 4987: Part I [9] specifies the use of steel slag as one of the aggregate types in coated macadam for roads and other paved areas.

However, the literature [6, 10] cautions against using 100% steel slag aggregate in asphalt paving as such hot mix asphalt mixes might be susceptible to high void space and bulking problems due to the angularity of the steel slag. Hot asphalt concrete mixes with 100% steel aggregates might be prone to over asphalting during production, which could lead to subsequent flushing during in-service traffic compaction. Thus, steel slag aggregates’ use in asphalt paving should be restricted to either the fine or coarse aggregate fraction, but not both, for better aggregate interlocking, lower void space and higher frictional resistance. This can be achieved by blending the coarse or fine steel slag aggregates with conventional natural materials such as gravels (more rounded) for better compatibility of the final asphalt mix.

2.2 Granular Bases and Sub-bases

Steel slag aggregates can be used in the construction of unpaved parking lots, as a railroad ballast, as a shoulder material, and also in the construction of berms and embankment. Experience in many countries including the United States, Belgium, Japan, The Netherlands, Germany, and Saudi Arabia [4, 10-13] has referred that steel slag aggregates, when properly selected, processed, aged, and tested, can be used as granular base for roads in above-grade applications. Positive properties of steel slag include very high stability and good soundness.

Aiban [12] examined the use of steel slag aggregates generated in Saudi Arabia in road bases and he asserted that “laboratory and field data have shown the superior performance of steel slag aggregates over the locally available calcareous sediments. The resulting CBR (California bearing ratio) values are doubled and the water sensitivity is much less when using steel slag aggregates instead of the local calcareous material.”

Though, the literature [10, 14] cautions against using steel slag aggregates in confined applications, such as backfill behind structures, granular bases and sub-bases confined by curb and gutter, and trenches. This has primarily to do with the potential for volumetric expansion of steel slag due to free lime hydration. Also, concerns have risen over the formation of tufa-like precipitates that might clog sub-drains and drain outlets [11, 15].

3. Objective of the Study

The main objective of this paper is to present the results obtained on the feasibility of using steel slag, gravel and gabbro in HMAC mixtures and in road base and sub-bases according to QCS-2010. The conventional aggregate “gabbro” was used as the control mixture.

4. Experimental Program

Steel slag, gabbro and gravel aggregates used in the study were supplied by SAP (Slag Aggregates Producer) from their plant in Mesaieed City in Qatar. A total of 15 bags were delivered to the asphalt laboratory at QU (Qatar University), including 6 tons of slag, 2 tons of gabbro and 2 tons of gravel of different sizes. Gabbro is an igneous rock that has been used in road construction for a long time in this region. The steel slag aggregate was aged at the SAP Plant between 1 and 8 years. SAP delivered all three aggregates in compliance with QCS gradations' requirements.

4.1 HMAC

All HMAC paving mixtures were designed using the Marshall mix design method (ASTM D6926 and ASTM D6927), which is the standard method specified for use in Qatar. The design of an asphalt concrete mixture includes:

(1) Selection of best aggregate blend.

(2) Determination of the optimum asphalt content.

Finally, the mix should meet specifications' requirements and be economical at the same time.

A total of three aggregate types (steel slag, gravel and gabbro), supplied in different sizes, were used in this study. Aggregate blend gradation was prepared to satisfy the gradations' requirements for an Asphaltic Concrete Wearing Course (SC-TYPE 1) in QCS-2010. Maximum aggregate size was 25 mm. The blend gradation and specification limits are plotted in Fig. 1.

A total of six different aggregate combinations were used to prepare asphalt mixtures in the laboratory. For the 50% steel slag with 50% gravel, 50% steel slag with 50% gabbro, and 50% gravel with 50% gabbro mixtures, the quantity of every aggregate size of the blend was divided by two. The conventional unmodified Pen 60/70 bitumen, obtained from the Woqod Company, was used to prepare all Marshall mixes.

Cylindrical bituminous mixture samples with 102 mm diameter and 64 mm height were prepared and compacted in the laboratory according to ASTM D6926. In order to determine the optimum asphalt content for each mix, a series of test samples were prepared for a range of asphalt contents (from 3% to 7%) in 0.5% increments. Three replicate samples were prepared at each asphalt content. All samples were compacted using 75 blows on each side and designed for heavy traffic conditions.

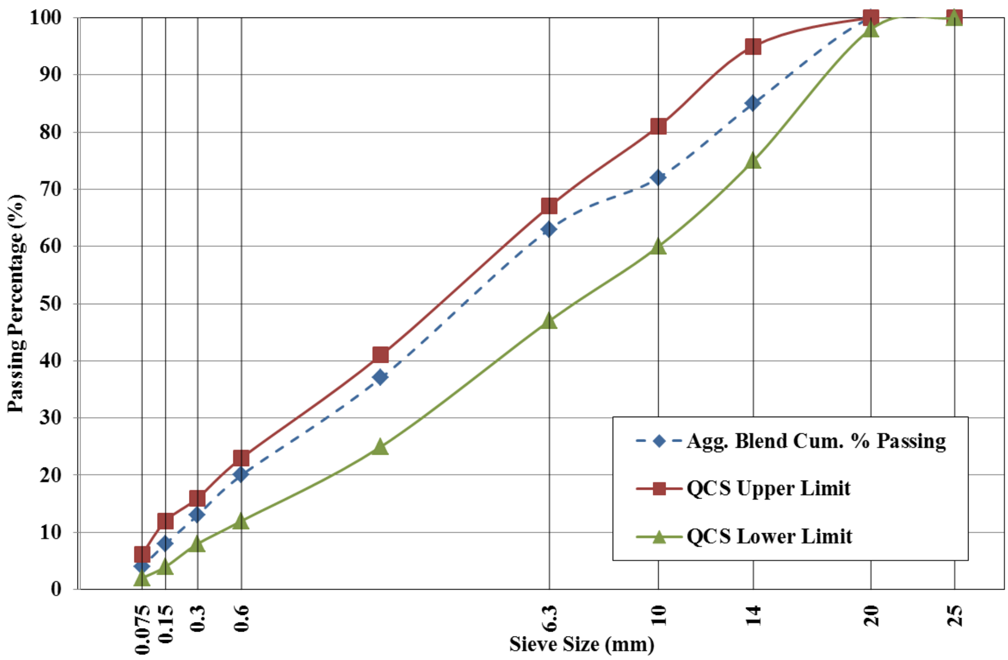

Fig. 1 Design gradation and QCS-2010 limits.

Table 1 Gradation of sub-base aggregate blend.

B.S. sieve size	Cumulative passing (%)	QCS 2010 limits	
25.0 mm	100	100	100
20.0 mm	95	90	100
10.0 mm	67	50	85
5.0 mm	50	35	65
2.36 mm	37	25	50
425 μm	22	15	30
75 μm	10	5	15

4.2 Road Base and Sub-base

On the other hand, different sizes of aggregates were blended to meet the gradation of a sub-base course (Class C) as given in QCS-2010. The gradation of the sub-base material used in this project along with the upper and lower % passing requirements given in QCS-2010 can be seen in Table 1.

For this purpose, different amounts of water was added to sub-base mixes composed of 100% steel slag, 100% gabbro and 100% gravel to determine the OMC (optimum moisture content) using the modified Proctor compaction test (ASTM D1557-12). Samples were compacted using 25 blows in 5 layers using a 44.48 N rammer dropped from a distance of 457.2 mm. Corrected moisture contents were determined after drying samples at an oven temperature of 110 ± 5 ℃ for 24 h.

Then, samples were compacted manually by 62 blows in 5 layers using a 4.5 kg rammer at the OMC in accordance with BS 1377-4:1990. Compacted samples were soaked in water for 96 h before the CBR test is conducted. Two replicate samples were used for each aggregate type to determine the CBR values.

5. Discussion of Results

5.1 Physical Properties

First, physical properties of the steel slag, gabbro and gravel aggregates were investigated. All tests were conducted in accordance with ASTM standards. The steel slag aggregate shown in Fig. 2 has the following general properties:

- Physical state: solid.
- Color: dark gray.
- Shape and characteristics: very rough and porous surface with high angularity.
- Odor: odorless.
- Solubility: insoluble in water, oil and solvents.

The steel slag, gravel and gabbro aggregates failed the liquid limit and plastic limit tests (i.e. the aggregates are non-plastic). In addition, the bulk, SSD (saturated surface-dry) and APP (apparent specific gravity) tests were performed on the steel slag, gravel and gabbro aggregates. Table 2 indicates that all specific gravity values for steel slag (fine and coarse) are greater than those of gabbro and gravel.

Then, the unit weight values for all aggregate types used in this study were determined as shown in Table 3. As a result of its high specific gravity, the steel slag had the highest unit weight compared to other aggregate types. Also, the average absorption values for the steel slag aggregates were 1.06% for coarse and 1.13% for fine aggregates (Table 3). These results are acceptable according to the QCS-2010 specifications. However, the coarse aggregates of gabbro had the lowest water absorption percentage and this is due to the strong inert structure of gabbro aggregates that have the least voids.

Fig. 2 Steel slag aggregates.

On the other hand, the toughness results of steel slag, gabbro and gravel were obtained from the Los Angeles abrasion Test. The average L.A. abrasion for steel slag was 14.9% as presented in Table 3. This was less than the 25%-30% limit established for coarse aggregates and it was less than that of gravel deposits (22.7%), but more than that of gabbro (8.1%). Table 3 presents also the sand equivalent results for the steel slag, gravel and gabbro aggregates. All samples had high percentage values, which were above the minimum threshold specified by the QCS-2010 specifications' requirements. Gabbro had the highest sand equivalent value.

To determine the flakiness and elongation indices, 2 kg of each aggregate type was tested according to BS 812: Sections 105.1 and 105.2, respectively. The results presented in Table 3 alluded that all aggregate types are below the acceptable limit. However, gravel had the highest flakiness and elongation indices. In the soundness test, two sizes from coarse and fine aggregates were tested and the results are presented in Table 3. The data indicate that steel slag had the lowest soundness value, while gravel had the highest one. The soundness value for fine gravel aggregates (30.3%) failed the QCS-2010 requirement of ≤ 18% for asphalt works.

In general, the steel slag aggregates and gravel test results presented in Tables 2 and 3 were comparable to typical values reported in the literature, and they met the QCS-2010 requirements.

5.2 Radiological Properties

A total of 11 samples of asphalt concrete cylinders made of 100% steel slag, were received by the Nuclear Laboratory at QU. Samples were measured directly in plastic bags on a HPGe detector in order to determine which radionuclides had activity concentrations significantly higher than the background level. Each sample was assessed for the following naturally occurring radionuclides from the uranium and thorium decay series, as well as ^{40}K.

Table 2 Specific gravity results of steel slag, gabbro and gravel.

Specific gravity	Steel slag	Gabbro	Gravel
Bulk SG for coarse aggregates	3.39	2.95	2.62
Bulk SG for fine aggregates	3.54	2.86	2.59
SSD SG[a] for coarse aggregates	3.43	2.96	2.64
SSD SG for fine aggregates	3.58	2.90	2.64
APP SG[b] for coarse aggregates	3.52	2.98	2.69
APP SG for fine aggregates	3.69	2.98	2.72

[a] SSD: Saturated Surface Dry; [b] APP: Apparent Specific Gravity.

Table 3 Physical properties of steel slag, gabbro and gravel.

Property	ASTM standard	QCS-2010 specifications		Steel slag	Gabbro	Gravel
		Unbound materials	Asphalt works			
Unit weight (kg/m^3)	C29	-	-	2595	2169	2338
Water absorption for coarse aggregates (%)	C128	-	≤ 1.5	1.06	0.34	1.12
Water absorption for fine aggregates (%)	C128	-	-	1.13	1.38	1.93
L.A. abrasion (%)	C131/C535	≤ 40	≤ 25-30	14.9	8.1	22.7
Sand equivalent for fine aggregates (%)	D2419	≥ 25	> 30	41	47	33
Flakiness index (%)	BS 812	≤ 35	≤ 25-30	1	8	17
Elongation index (%)	BS 812	≤ 40	≤ 25	13	24	26
Soundness for coarse aggregates (%)	C88	≤ 20	≤ 10-15	1	2	7
Soundness for fine aggregates (%)	C88	-	≤ 18	4.2	16	30.3

Table 错误!文档中没有指定样式的文字。4 Activity concentration results from the sample measurements.

	Activity concentration (Bq/kg)				
Sample No./type	^{40}K	^{226}Ra	^{228}Ra	^{228}Th	^{238}U
1. Crushed slag 3/4″	23 ± 14	252 ± 25	144 ± 15	151 ± 15	290 ± 140
2. Slag raw	< 21	212 ± 22	167 ± 18	166 ± 17	270 ± 150
3. River stone raw	98 ± 10	8.0 ± 0.8	4.8 ± 0.8	5.1 ± 0.5	< 36
4. Gravel 5 mm	244 ± 27	15.9 ± 1.6	8.3 ± 2.0	9.2 ± 1.1	< 95
5. Limestone 5 mm	12.5 ± 2.6	4.7 ± 0.5	2.2 ± 0.8	2.3 ± 0.4	< 28
6. Gabbro 7 mm	< 7.7	< 1.5	< 2.6	< 1.6	< 56
7. Slag 5 mm	22 ± 11	237 ± 18	152 ± 16	158 ± 16	300 ± 120
8. Slag powder 0-1 mm	62 ± 15	167 ± 17	128 ± 15	136 ± 14	350 ± 150
9. Slag powder 0-5 mm	36 ± 12	218 ± 16	156 ± 16	172 ± 17	210 ± 110
10. Slag raw (new)	< 17	184 ± 19	182 ± 19	195 ± 20	270 ± 150
11. Slag raw (old)	25 ± 12	213 ± 22	156 ± 16	171 ± 17	280 ± 100

Table 5 Activity concentration results for asphalt concrete of 100% steel slag and bitumen.

	Activity Concentration (Bq/kg)				
Sample type	^{40}K	^{226}Ra	^{228}Ra	^{228}Th	^{238}U
Asphalt concrete	< 8.0	182 ± 18	175 ± 23	195 ± 20	200 ± 90

Each sample was prepared directly into a 200 mL PET container, filling the container as much as possible. No measures were taken to further homogenize the samples. The samples were measured directly on a 50% p-type HPGe detector for a time period of between 2 h and one day, depending on the activity level in the sample. This detector has been efficiency calibrated using a radioactivity standard from NPL, UK. Spectrum acquisition and analysis was carried out using OrtecGammaVision software. All activities were decay corrected to the actual measurement date. In order to correct for disparities between the sample matrix and standard matrix, a post-adjustment geometry correction of the measurement result was performed using efficiency transfer methods. For this geometry correction, slag is assumed to mainly be composed of $CaSiO_3$, while limestone and river stone are assumed to be composed mainly of $CaMg(CO_3)_2$. Gravel is assumed to be composed of 50% $CaSiO_3$ and 50% $CaMg(CO_3)_2$, while gabbro is simulated as basalt. In practice, this chemical composition will have only a slight impact on the final measurement results compared to the effect of the sample density and volume.

For the natural decay series, secular radioactive equilibrium is assumed between ^{226}Ra and daughters as well as ^{228}Ra and daughters. Often, ^{228}Ra can further be assumed to be in equilibrium with ^{232}Th. Activity concentrations have been calculated as follows:

- ^{40}K—directly from 1,460 keV peak;
- ^{226}Ra—from daughter nuclides ^{214}Pb and ^{214}Bi;
- ^{228}Ra—from daughter nuclide ^{228}Ac;
- ^{228}Th—from daughter nuclides ^{208}Tl and ^{212}Pb;
- ^{238}U—from daughter nuclide ^{234}mPa.

Table 4 presents the nuclides of interest and their calculated activity concentrations for each sample. In the cases where the activity concentration of the sample falls below the MDA (minimum detectable activity) of the measurement, the result is reported as less than (<) a value. MDAs and uncertainties are reported at a 95% confidence level.

Table 5 presents the calculated activity concentrations for the asphalt concrete samples made of 100% steel slag aggregates. MDAs and uncertainties are reported at a 95% confidence level.

Table 6 presents the activity concentration indices for different combinations of gabbro/gravel/slag compared

Table 6 Activity concentration indices for different gabbro/gravel/slag mixtures.

Mix type	H1	H2	MOE Standard
G20-100 (100% gabbro)	0.0205	0.0083	≤ 1.0
S20-100 (100% slag)	1.7706	0.7317	≤ 1.0
GL20-100 (100% gravel)	0.1758	0.0698	≤ 1.0
S20-75 (75% slag+ 25% gabbro)	1.3333	0.5508	≤ 1.0
GL20-75 (75% gravel+ 25% gabbro)	0.1369	0.0544	≤ 1.0
S20-50 (50% slag+50% gabbro)	0.8956	0.3700	≤ 1.0
GL20-50 (50% gravel+50% gabbro)	0.0982	0.0390	≤ 1.0
S20-25 (25% slag+75% gabbro)	0.4580	0.1891	≤ 1.0
GL20-25 (25% gravel+ 75% gabbro)	0.0594	0.0236	≤ 1.0
Asphalt concrete (100% slag)	1.4843	0.6110	≤ 1.0
Portland cement concrete (100% slag)	1.2163	0.4992	≤ 1.0

to standard values (H1 and H2) recommended by the Qatari MOE (Ministry of Environment). These standard values were specified by MOE-Laboratories and Standardization Affairs as part of a memorandum issued to a local materials company operating in Qatar that allowed the use of a maximum 20% steel slag in certain asphalt concrete and Portland cement concrete road applications. The memorandum specifies other requirements as part of the whole package. H1 is the activity concentration index standard for the use of steel slag in certain asphalt concrete and Portland cement concrete road applications close to populated and residential areas, while H2 is the activity concentration index standard for the use of steel slag in certain asphalt concrete road applications for freeways and roads outside Doha, Capital of Qatar. It should be noted that all activity concentration indices were calculated based on the values measured in the Nuclear Laboratory at QU and presented earlier in Tables 4 and 5.

Note:

$$H_1 = \frac{C_{TH}}{200} + \frac{C_{Ra}}{300} + \frac{C_K}{3000} + \cdots$$

$$H_2 = \frac{C_{TH}}{500} + \frac{C_{Ra}}{700} + \frac{C_K}{8000} + \frac{C_{Cs}}{2000} + \cdots$$

C_{TH} = Activity concentration value of ^{232}Th (assumed in equilibrium with ^{228}Ra) in Bq/kg;

C_{Ra} = Activity concentration value of ^{226}Ra in Bq/kg;

C_k = Activity concentration value of ^{40}K in Bq/kg;

C_{Cs} = Activity concentration value of ^{137}Cs in Bq/kg.

Table 6 indicates that the use of higher percentages of steel slag, beyond the 20% specified by MOE, will easily meet the H2 requirement of ≤ 1.0 for asphalt concrete road applications such as freeways and roads outside Doha. Even for steel slag usage in certain asphalt concrete road applications close to populated and residential areas, it will be possible to meet the H1 requirement of ≤ 1.0 if other mix design requirements and MOE recommendations are met.

5.3 HMAC Results

After the samples were compacted using the Marshall compactor, the bulk specific gravity and density of specimens were determined in accordance with ASTM D2726. Prior to the stability and flow tests, compacted asphalt samples were immersed in a water bath at 60 ℃ for 30-40 min. All samples were tested in the Marshall Test Apparatus.

Using the graphs of %AV (air voids) vs. %AC (asphalt content), %VMA (voids in mineral aggregate) vs. %AC and Stability vs. %AC, the OAC (optimum asphalt content) can be determined. Examples of these graphs are shown in Figs. 3 and 4.

After determining the OAC for each mixture, three samples were prepared at this optimum and mixture properties were compared to the mix design criteria given in Table 7.

Table 7 Marshall mix design criteria.

Marshall method mix design criteria	Heavy traffic surface & base	
	Min.	Max.
Compaction, number of blows each end of specimen	75	
Stability, N	10,000	-
Flow, mm	2	4
Marshall Quotient/stiffness (=Stability/Flow), kN/mm	4	-
AV (air voids), %	5	8
VMA (voids in mineral aggregate), %	15	-
VFA (voids filled with asphalt), %	50	75
Filler/asphalt ratio	0.75	1.35

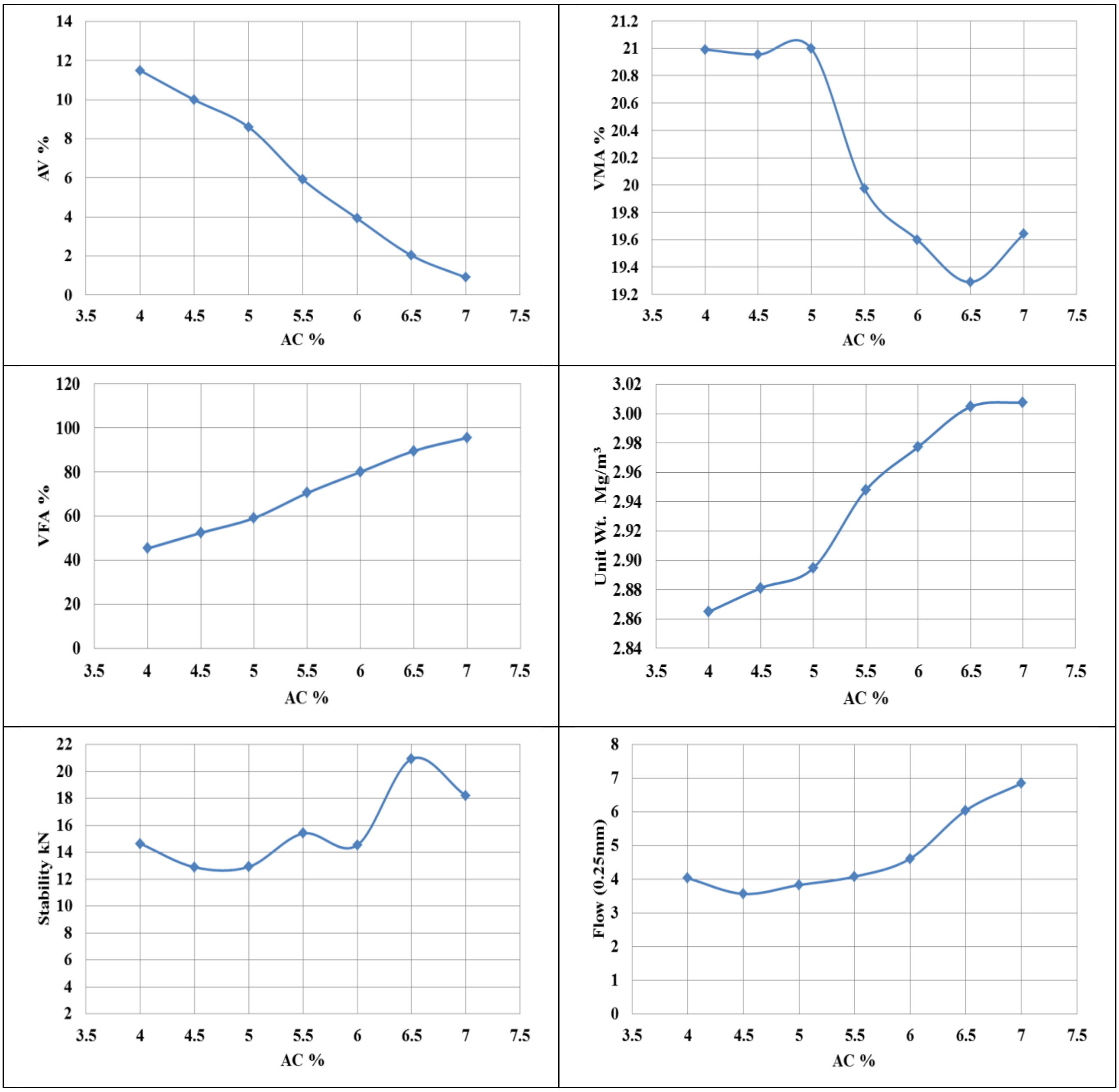

Fig. 3 Marshall test graphs for 100% steel slag asphalt concrete mixture.

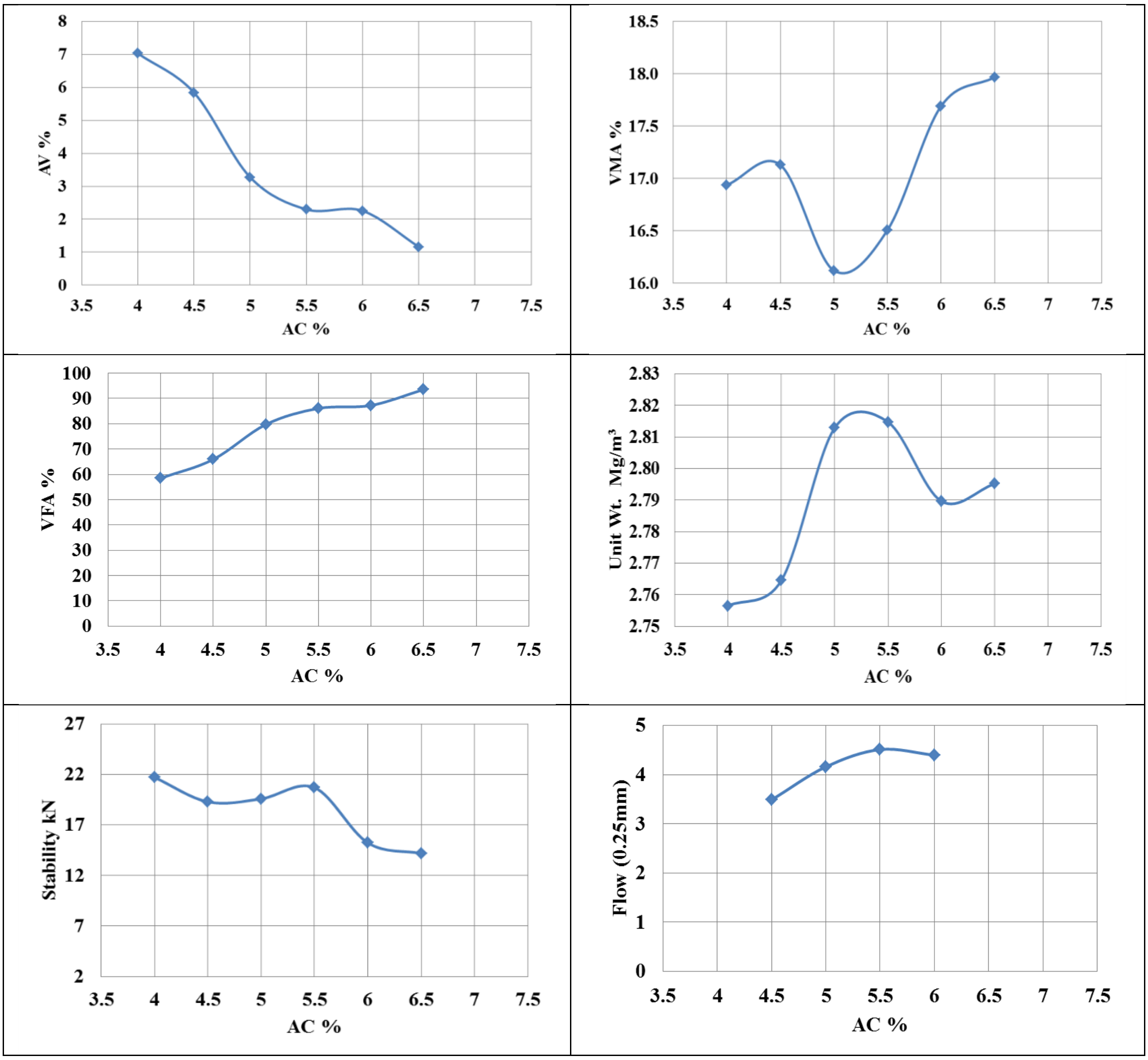

Fig. 4 Marshall test graphs for 50% steel slag + 50% gabbro asphalt concrete mixture.

Calculations were made for each mixture type and the final results are summarized in Table 8.

As presented in Table 8, the 100% steel slag aggregate mixture had the highest optimum asphalt content of 6.39%, which is attributed to the high void space and bulking of the material. However, mixtures prepared using 50% steel slag and 50% gabbro or gravel aggregates produced better stability, lower flow, and lower optimum asphalt content.

In general, Table 8 indicates that all six mixtures have met stability, flow and Marshall Quotient/Stiffness criteria as specified in QCS-2010. VMA values for all mixtures, except for the 100% gravel aggregates mixture, were also satisfied. However, all mixtures resulted in lower air voids contents than that of a minimum value requirement of 5%. All mixtures had higher VFA values than that of a maximum value requirement of 75%. The most probable reason for this is the lack of sand in the mixtures. In this study, it was only attempted to maximize the use of steel slag and gravel aggregates in the mixtures. Aggregate gradations used were within the QCS-2010 lower and upper limits.

Table 8 Marshall mix design results for all mixes.

Mix type	Optimum asphalt content (%)	Stability (N)	Flow (mm)	Marshall quotient/stiffness (kN/mm)	AV (%)	VMA (%)	VFA (%)	Filler/ asphalt ratio
100% Slag	6.39	22,080	3.53	6.25	2.67	19.54	86	0.63
100% Gravel	5.40	15,550	3.1	5.02	2.13	13.0	83	0.74
100% Gabbro	5.35	16,640	3.82	4.36	3.26	15.3	79	0.75
50% Slag + 50% Gabbro	5.19	23,880	3.02	7.91	2.68	16.07	83	0.77
50% Slag + 50% Gravel	5.22	22,200	2.75	8.07	2.96	16.45	82	0.77
50% Gravel + 50% Gabbro	5.08	22,900	3.07	7.46	2.1	12.99	84	0.79
QCS-2010	Min	10,000	2	4	5	15	50	0.75
	Max	-	4	-	8	-	75	1.35

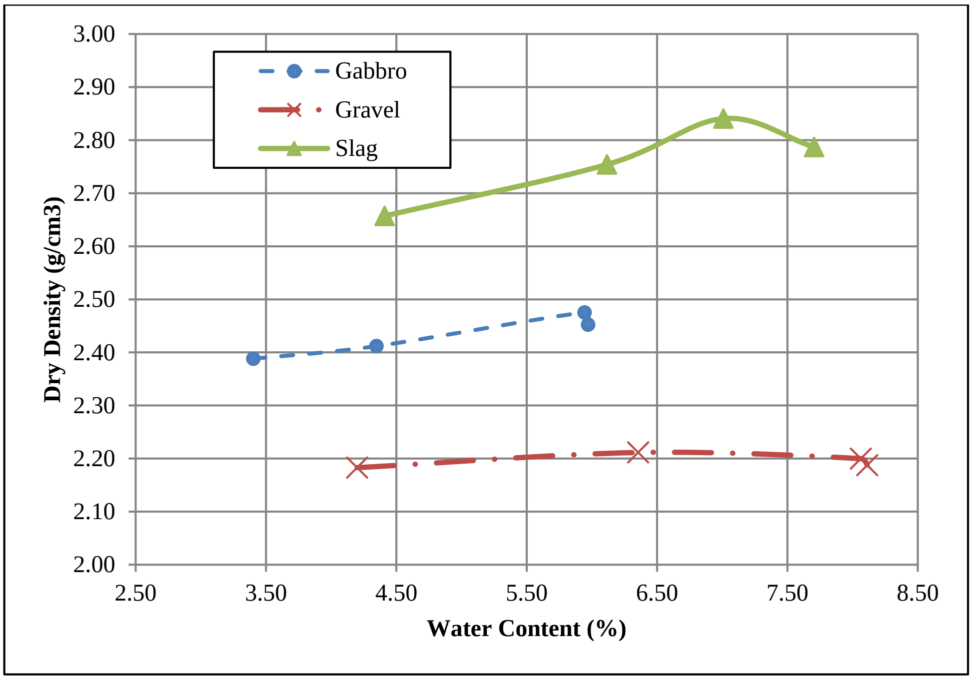

Fig. 5 Modified proctor compaction results.

Table 9 CBR results for soaked samples.

	Slag	Gravel	Gabbro	QCS-2010
CBR (%)	239	143	129	≥ 80

5.4 Road Base and Sub-base Results

5.4.1 OMC

The compaction curves for each aggregate type were established after a sufficient number of water contents were used. The relationship between the dry unit weight and water content for the three aggregates is shown in Fig. 5.

Fig. 5 indicates that the OMCs for steel slag, gravel and gabbro aggregates are 7.0%, 6.4% and 5.9%, respectively. The largest dry density was achieved in the steel slag aggregates.

5.4.2 CBR Results

After determining the OMC for each aggregate type, the CBR test was conducted. Two replicate samples were used for each aggregate type to determine the CBR values. No swelling was observed in the soaked samples. Table 9 presents the CBR values for different aggregate types used in this study. All aggregates satisfied the minimum CBR requirement of 80%

specified in QCS-2010 for base and sub-base materials.

6. Conclusions and Recommendations

The main objective of this research work was to produce the fundamental data needed to establish the suitability of using local discarded materials, such as steel slag and gravel in roads construction (bases/sub-bases and HMAC mixtures).

Physical properties, such as Los Angeles abrasion, flakiness and elongation indices, soundness and sand equivalency values for steel slag, gravel and gabbro aggregates satisfied all criteria set forth in QCS-2010. Nevertheless, fine aggregates of gravel did not satisfy the QCS soundness requirement. Based on the mixtures prepared and the data obtained in this work, steel slag and gravel aggregates have a promising potential to be used in HMAC paving mixtures on Qatar highways, whether as an asphalt base course or as an asphalt wearing course.

In addition radiological properties were investigated and the results indicated that the use of high percentages of steel slag (> 20%) will easily meet the H2 requirement of ≤ 1.0 for asphalt concrete road applications. Even for steel slag usage in certain asphalt concrete road applications close to populated and residential areas, it will be possible to meet the H1 requirement of ≤ 1.0 if other mix design requirements and MOE recommendations are met.

It is also worth mentioning here that asphalt mixtures can be designed using a variety of aggregate structures and blends that may result in different optimum asphalt contents and volumetric properties. Therefore, the results that were obtained here are meant to be an evidence of the possibility of using steel slag and gravel in asphalt mixtures and should not be treated as standard recipes for routine applications.

Steel slag and gravel physical properties, determined in the research project, met the QCS-2010 specifications' requirements for unbound materials. Also, based on compaction and CBR test, steel slag and gravel aggregates have high CBR values that qualify their use in the base and sub-base layers.

Recommendations for further work include the construction of pilot field studies to establish the final validity for the construction use of steel slag and gravel. Such studies might encompass the construction of short road test sections, where steel slag and/or gravel could be used in the asphalt concrete base course, in the wearing (surface) course layer or as unbound aggregates in the base and sub-base layers. Short- and long-term monitoring of such sections will be critical to establish construction practices as well as field performance under actual traffic and environmental (temperature, rain, humidity, etc.) conditions.

References

[1] Taha, R. A., Sirin, O., Al-Nuaimi, N., and Benyahia, F. 2013. *Beneficial Utilization of Steel Slag and Gravel in Construction* (Final Report). Mesaieed: Slag Aggregates Producer.

[2] ASTM D5106. 1991. "Standard Specification for Steel Aggregates for Bituminous Paving Mixtures." ASTM International.

[3] Emory, J. 1984. "Steel Slag Utilization in Asphalt Mixes." In *1986 Annual Conference Proceedings*. Kelowna: Canadian Technical Asphalt Association.

[4] Collins, R. J., and Ciesielski, S. K. 1994. "Recycling and Use of Waste Materials and By-Products in Highway Construction." National Cooperative Highway Research Program, Synthesis of Highway Practice 199, Transportation Research Board, Washington, D.C.

[5] Kandahl, P. S., and Hoffman, G. L. 1982. *The Use of Steel Slag as Bituminous Concrete Fine Aggregate* (Final Report, Research Project No. 79-26). Uniontown: Pennsylvania Department of Transportation.

[6] Hunt, L., and Boyle, G. 2000. *Steel Slag in Hot Mix Asphalt Concrete* (Final Report, Report No. OR-RD-00-09). Salem: Oregon Department of Transportation.

[7] Xue, Y., Wu, S., Hou, H., and Zha, J. 2006. "Experimental Investigation of Basic Oxygen Furnace Slag Used as Aggregate in Asphalt Mixture." *Journal of Hazardous Materials B* 138: 261-8.

[8] Ahmedzade, P., and Sengoz, B. 2009. "Evaluation of Steel Slag Coarse Aggregate in Hot Mix Asphalt Concrete." *Journal of Hazardous Materials* 165 (1-3): 300-5.

[9] BS 4987:Part 1. 1993. *Coated Macadam for Roads and Other Paved Areas. Part 1: Specification for Constituent Materials and for Mixtures.* London: British Standard.

[10] Recycled Materials Resource Center. 2013. "User

Guidelines for By-Products and Secondary Use Materials in Pavement Construction." http://www.rmrc.unh.edu.

[11] Gupta, J. D., Kneller, W. A., Tamirisa, R., and Skrzypezak-Jankun, E. 1994. "Characterization of Base and Subbase Iron and Steel Aggregates Causing Deposition of Calcareous Tufa in Drains." *Transportation Research Record* 1434: 8-16.

[12] Aiban, S. A. 2006. "Utilization of Steel Slag Aggregate for Road Bases." *Journal of Testing and Evaluation* 34 (1): 65-75.

[13] Shen, W., Zhou, M., Ma, W., Hu. J., and Cai, Z. 2009. "Investigation on the Application of Steel Slag-Fly Ash-Phosphogypsum Solidified Material as Road Base Material." *Journal of Hazardous Materials* 164 (1): 99-104.

[14] Carl, B. C., and Burn, K. N. 1969. "Building Damage from Expansive Steel Slag Backfill." *Journal of the Soil Mechanics and Foundations Division* 95 (SM6): 1325-34.

[15] Gupta, J. D., and Kneller, W. A. 1993. *Precipitate Potential of Highway Subbase Aggregates* (Report No. FHWA/OH-94/004). Columbus: Ohio Department of Transportation.