CHARACTERISTICS OF AGGREGATES IN EASTERN SAUDI ARABIA AND THEIR INFLUENCE ON CONCRETE PROPERTIES

M. Maslehuddin,*[1] O.S. B. Al-Amoudi,* M. H. Al-Mehthel** and S. H. Alidi**

*King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia.
** Consulting Services Department, Saudi Aramco, Dhahran, Saudi Arabia.

ABSTRACT

The coarse aggregates utilized in concrete by the construction industry in the Eastern Province of the Kingdom of Saudi Arabia are mostly of dolomotic limestone. These aggregates generate considerable dust on crushing and some of them do not meet all the ASTM C 33 criteria. In view of this there is an apprehension as to the applicability of those criteria, particularly the magnesium soundness loss, to the local aggregates. Also, the effect of dust in the aggregates on concrete properties and reinforcement corrosion is not very well investigated. This paper presents the results of a study conducted to assess the characteristics of local coarse aggregates on the properties of concrete. The data indicate that the excess magnesium soundness loss, noted in some of the local aggregates, did not influence the concrete properties. Similarly, excess chloride concentration in some of the aggregates did not affect reinforcement corrosion. Further, up to 10% dust, by weight of coarse aggregates, did not influence the compressive strength of concrete and induce reinforcement corrosion.

INTRODUCTION

Aggregates are the main component of Portland cement concrete. The coarse aggregates (particle size exceeding 4.75 mm) that are obtained either from natural sources or by crushing large size rocks are bound with cement paste or mortar to form Portland cement concrete. The process of crushing large rocks and producing an artificial stone through the use of Portland cement, as a gluing material, has facilitated the production of structural components of various shapes and sizes. Since coarse aggregates constitute about 70% by volume of concrete, their quality significantly influences the properties of concrete. Several criteria, such as ASTM C 33, were developed as guidelines for

[1] Corresponding author: Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia. E-mail: muddin@kfupm.edu.sa.

selecting coarse aggregates to produce durable concrete. With dwindling sources of high-quality coarse aggregates, the validity of these criteria is often questioned. This concern is of particular relevance in the Arabian Gulf region, where not all the available coarse aggregates satisfy the standard selection criteria.

While local and international specifications or codes of practices lay down the selection criteria, the influence of aggregate quality on the properties of hardened concrete is not very well documented. It is possible that coarse aggregates that do not meet a certain criterion may not detrimentally influence the properties of concrete. Therefore, a blanket rejection of an aggregate source based on tests that are not representative of the service conditions would result in under-utilization of the available sources. Moreover, the marginal coarse aggregates could be beneficially utilized to produce lean concrete that can be used in structural components that may not be exposed to aggressive environments or in non-structural concrete. Therefore, it is essential to develop data on the performance of hardened concrete, particularly its durability, in relation to the properties of coarse aggregates.

Another concern regarding the dolomitic limestone aggregates from the local quarries is the excess dust that they generate during the process of crushing. This dust causes increased water demand, resulting in lower strength and greater shrinkage of concrete. Dust also forms a fine interstitial coating between the aggregates and the cement mortar, thereby weakening the bond between these two. The transition zone, being the weakest link of the concrete composite, may further lower the strength and the quality of concrete.

The excess dust in the coarse aggregates is also the source of chloride contamination in concrete. It has been reported [1] that the chloride and sulfate concentration in the dust may be as high as five to six times that in the aggregates. The presence of excess chloride ions at the steel surface may hinder the formation of the passive layer, thereby enhancing the chances of reinforcement corrosion. To remove the dust, the coarse aggregates are normally washed. This is an additional task that a ready-mix concrete plant has to perform. Further, it is difficult to control the volume of free-water that is contributed by washing of the aggregates. This may lead to increased water in the aggregates thereby decreasing the quality of the hardened concrete.

This paper presents the results of a study conducted to evaluate the effect of aggregate quality on the properties of the hardened concrete. The effect of dust content in the coarse aggregates on the strength of concrete and reinforcement corrosion, the two important parameters of interest to the construction industry, was also evaluated.

EFFECT OF QUALITY OF AGGREGATES ON CONCRETE PROPERTIES

Survey of Aggregate Quarries

A total of 21 quarries, nine in Abu Hadriyah, seven in Hofuf, and five on the Riyadh road (near Al-Khurais) were inspected. Following are the observations on the quality of aggregates in the quarries surveyed:

i. The aggregates in all the three locations were predominantly dolomitic limestone. However, layers of sandy limestone were noted in some of the quarries located on the Riyadh road.

ii. The aggregate deposits in Abu Hadriyah are composed of more than one layer and the quality of the coarse aggregates generally decreases with the depth.

iii. The quality of coarse aggregates in the quarries on the Riyadh road does not vary from quarry to quarry. However, the quality of aggregates in the top layers is slightly superior to that in the bottom layers. The top layer generally consists of dolomitic limestone, while the bottom layers are mainly sandy limestone.

iv. Aggregates from Hofuf quarries are of uniform quality and no variation in their properties was noted.

Testing of Aggregates

Coarse aggregates were obtained from two quarries each in Abu-Hadriyah, Hofuf and on Riyadh road and tested for the following:

- Magnesium sulfate soundness loss, according to ASTM C 88.
- Materials finer than ASTM # 200 sieve, according to ASTM C 117.
- Specific gravity and water absorption, according to ASTM C 127.
- Loss on abrasion, according to ASTM C 131.
- Clay lumps and friable particles, according to ASTM C 142.
- Flakiness and elongation index, according to BS 812 Part 105
- Chloride content, according to BS 812 Part 117.
- Sulfate content, according to BS 1377 Part 3.

Aggregate Properties

Some of the important properties of the coarse aggregates selected for this study are summarized in Table 1. From these data, it is evident that the magnesium sulfate soundness loss in the coarse aggregates from quarries located in Hofuf and on the Riyadh road was more than the allowable value of 18% specified by ASTM C 33. The magnesium sulfate soundness loss in the coarse aggregates from the quarries in Abu-Hadriyah was around 9%, whereas it was in the range of 24.5% to 27.5% in the coarse aggregates from quarries in Hofuf and on the Riyadh road.

The quantity of fine materials in all the coarse aggregates was less than the allowable value of 1% specified by ASTM C 33. The quantity of fine material in the coarse aggregates from Abu-Hadriyah quarries tended to be more than that in the coarse aggregates from quarries in Hofuf and on the Riyadh road. This could be attributed to the mineralogical composition of the coarse aggregates. The coarse aggregates from Abu-Hadriyah are basically of calcitic type ($CaCO_3$ is more than 95%) while some quartz was detected in the coarse aggregates from quarries in Hofuf and on the Riyadh road. Calcitic aggregates yield more dust on crushing compared to aggregates containing a hard mineral, such as quartz. Table 2 shows the chemical composition of the selected coarse aggregates.

The water absorption in the coarse aggregates from quarries in Abu-Hadriyah was more than that in the coarse aggregates from quarries in Hofuf and on the Riyadh road. While the water absorption in the coarse aggregates from quarries in Abu-Hadriyah was in the range of 2.3% to 2.4% (Table 1), it was in the range of 1.1% to 1.8% in the coarse aggregates from quarries located in Hofuf and on the Riyadh road. The loss on abrasion in all the coarse aggregates was less than 40% specified by ASTM C 33. The loss on abrasion in the coarse aggregates from quarries in Abu-Hadriyah was slightly more than that in the coarse aggregates from quarries in Hofuf and on the Riyadh road, an exception to this trend was noted in coarse aggregates from Quarry # 1 in Hofuf.

The quantity of clay lumps and friable particles in the coarse aggregates from the quarries in Hofuf was more than that in the coarse aggregates from quarries in Abu-Hadriyah and on the Riyadh road. These values were, however, less than the threshold value of 5% [2]. The chloride concentration in the coarse aggregates from Quarry # 1 in Abu-Hadriyah was twice the allowable chloride concentration of 0.03% [2], while in the coarse aggregates from other sources; it was in the range of 0.01% to 0.028%. Similarly, the sulfate concentration in the coarse aggregates from Quarry # 1 in Abu-Hadriyah was the maximum among all the coarse aggregates investigated in this study. This value was, however, less than the allowable value of 0.4% [2].

In summary, the data in Table 1 indicate that the coarse aggregates from quarries on the Riyadh road and in Hofuf are relatively better than the coarse aggregates from quarries in Abu-Hadriyah. However, these coarse aggregates do not meet the ASTM C 33 requirements for the magnesium sulfate soundness loss. Also, the chloride concentration in the coarse aggregates from Quarry # 1 in Abu-Hadriyah was more than the allowable value of 0.03% [2]. These observations are summarized in Table 3.

Restrictions on the water-soluble chloride concentration in the coarse aggregates are imposed to avoid the initiation of reinforcement corrosion. Chloride ions are known to destroy the passive layer on steel. The depassivation of steel occurs by the reduction of the pore solution pH, which is caused by carbonation or chloride ions. A number of mechanisms by which chlorides break down the passive layer have been proposed, e.g. the chemical dissolution of the film [3], the build up of the metal holes at the film/substrate interface [4] and, due to the high chloride concentration at the iron oxide/pore solution interface that leads to local acidification and pitting [5]. Leek and Poole [6], based on SEM-EDS studies of the passive film breakdown on steel in mortar prisms, have shown that chloride ions initiate corrosion by breaking the bond between the film and the metal.

Irrespective of the mechanisms controlling the depassivation of steel, due to chloride ions, it is clear that these ions play a dominant role in initiating reinforcement corrosion. From this perspective, ACI 318 [7] limits the water-soluble chlorides to 0.15% by weight of cement. ACI 224 [8], adopting a more conservative approach, has suggested that the acid-soluble chloride concentration should not be more than 0.2% by weight of cement. The British Standard BS 8110 [9] allows a maximum chloride concentration of 0.4%.

Rasheeduzzafar et al. [10] indicated that the chloride threshold limit for cement with up to 8% C_3A agrees very well with the ACI 318 [7] limit of 0.15% water-soluble chlorides. Additionally, they reported that ACI, BS, and the Australian Code limits, appear to be conservative for concrete prepared with high C_3A cements. Lambert et al. [11] suggested that the critical level of chloride below which there was no significant probability of corrosion was around 1.5%. They attributed the increased chloride tolerance in their specimens, compared to the BS 8110 [9] limit of 0.4%, to the protective nature of concrete produced under well-controlled laboratory conditions.

As elucidated in the aforesaid discussion, limits are imposed on the chloride ions that can be tolerated in concrete from a reinforcement corrosion perspective. However, the effect of chlorides contributed by the dust in the coarse aggregates on corrosion of reinforcing steel in concrete is not addressed in the literature.

The magnesium sulfate soundness loss in the coarse aggregates from quarries in Hofuf and on the Riyadh road was more than that allowed by ASTM C 33. Due to this non-conformance, there is a hesitation on the part of the construction industry to utilize these coarse aggregates in construction projects. However, it should be noted that international limits, particularly ASTM C 33, on magnesium sulfate soundness loss are established to evaluate the performance of coarse aggregates under cold weather conditions. ASTM C 88, the test method utilized to determine the magnesium sulfate soundness loss, provides information helpful in judging the resistance of coarse aggregates to weathering. This information is particularly useful when such data are not available from the service records of materials exposed to weathering conditions. However, the applicability of these limits under hot/temperate climatic conditions has not been adequately established. Therefore, it will be judicious to assess the influence of the excessive magnesium sulfate soundness loss, noted in the coarse aggregates from quarries in Hofuf and on the Riyadh road, on the performance of concrete prepared utilizing these aggregates.

Casting of Concrete Specimens

Concrete mixtures were prepared using the selected coarse aggregates. A cement (ASTM C 150 Type I) content of 370 kg/m^3, an effective w/c ratio of 0.40 and a coarse-to-fine aggregate ratio of 1.62 were kept invariant in all the concrete mixtures. Prior to their use, the coarse aggregates were sieved to various sizes and washed to remove dust and loose particles. They were then re-mixed to obtain the desired grading. The maximum size of the coarse aggregate was 19 mm and its grading corresponded to size # 7 of ASTM C 33. Desert sand, which is essentially very fine quartz, was used as fine aggregate. The specific gravity of the fine aggregate was 2.57 and the water absorption was 0.57%. The concrete mixtures were designed for a constant workability of 50 to 75 mm slump. Suitable dosages of a naphthalene-based superplasticizer were used in all the concrete mixtures to obtain the desired workability.

Testing of Concrete Specimens

Cylindrical concrete specimens, 75 mm in diameter and 150 mm high, were cast from each of the concrete mixtures. After 28 days of water curing, under laboratory conditions, they were tested to determine the following:

i. Stress-strain characteristics in compression, according to ASTM C 469.
ii. Split tensile strength, according to ASTM C 496.
iii. Pulse velocity, according to ASTM C 597.
iv. Absorption and volume of permeable voids, according to ASTM C 642.
v. Chloride permeability, according to ASTM C 1202.

vi. Reinforcement corrosion: Reinforced concrete specimens, 75 mm in diameter and 150 mm high, were prepared with a 12 mm diameter ribbed steel bar placed at the center of the specimen. A concrete cover of 25 mm was provided to the reinforcing steel at the bottom of the specimen. The specimens were exposed to 5% NaCl solution and reinforcement corrosion was monitored by measuring corrosion current density using the linear polarization resistance method [12].

vii. Chloride diffusion: Concrete specimens, 75 mm in diameter and 150 mm high, were prepared with selected coarse aggregates and they were immersed in 5% sodium chloride solution. The chloride diffusion coefficient was determined following the procedure outlined in Reference 13.

viii. Sulfate attack: Concrete specimens, 75 mm in diameter and 150 mm high, were exposed to 5% $MgSO_4$ plus 5% Na_2SO_4 solution. The sulfate resistance of concrete specimens prepared with the selected coarse aggregates was evaluated by visual examination and by determining the reduction in compressive strength according to ASTM C 267 after three, six, nine, and 12 months of exposure.

Concrete Properties

The properties of concrete specimens prepared with the coarse aggregates selected for this study are summarized in Table 4. The compressive strength of concrete specimens (average of six specimens per batch) prepared with the coarse aggregates from quarries on the Riyadh road was marginally more than that of specimens prepared with coarse aggregates from quarries in Hofuf and Abu-Hadriyah. Similarly, the compressive strength of concrete specimens prepared with coarse aggregates from quarries in Hofuf was slightly more than that of concrete specimens prepared with coarse aggregates from quarries in Abu-Hadriyah. The modulus of elasticity of concrete specimens prepared with coarse aggregates from quarries on the Riyadh road was generally less than that of concrete specimens prepared with coarse aggregates from quarries in Hofuf and Abu-Hadriyah. However, an appreciable difference was noted in the split tensile strength of concrete specimens prepared with the coarse aggregates selected for this study. The pulse velocity in the concrete specimens prepared with the coarse aggregates from quarries on the Riyadh road and in Hofuf was marginally more than that in the concrete specimens prepared with the coarse aggregates from quarries in Abu-Hadriyah.

The water absorption of concrete specimens prepared with the coarse aggregates from quarries on the Riyadh Road was marginally less than that of concrete specimens prepared with the coarse aggregates from quarries in Hofuf and Abu-Hadriyah. The chloride permeability in the concrete specimens prepared with coarse aggregates from the quarries on the Riyadh road was less than that in the concrete specimens prepared with coarse aggregates from quarries in Hofuf and Abu-Hadriyah.

The foregoing discussion indicates that the mechanical properties and absorption characteristics of concrete specimens prepared with coarse aggregates from quarries on the Riyadh road were generally better than those of concrete specimens prepared with coarse aggregates from quarries in Hofuf and Abu-Hadriyah. The data on the reduction in compressive strength, due to sulfate attack, indicate that the type of coarse aggregate did not influence the extent of sulfate attack. This is understandable since sulfate ions react with the cement hydration products rather than the coarse aggregates. However, the rate of sulfate attack may vary depending on the porosity of concrete.

The data on chloride diffusion coefficients also indicate that the type of coarse aggregate did not influence the mechanisms of ionic diffusion. Similarly, the type of coarse aggregates did not seem to have a significant effect on the corrosion resistance of concrete prepared using them.

Correlation between Aggregate Characteristics and Concrete Properties

As discussed earlier, coarse aggregates from quarries on the Riyadh road are relatively better in quality than those from quarries in Hofuf and Abu-Hadriyah. The coarse aggregates from quarries in Hofuf are better than those from quarries in Abu-Hadriyah. As such, the mechanical properties and permeability characteristics of concrete specimens prepared with coarse aggregates from quarries on the Riyadh road were marginally superior to those of concrete specimens prepared with the coarse aggregates from quarries in Hofuf and Abu-Hadriyah. Further, the properties of concrete specimens prepared with coarse aggregates from quarries in Hofuf were better than those of the concrete specimens prepared with coarse aggregates from quarries in Abu-Hadriyah. The chloride diffusion coefficients and the corrosion current density did not vary significantly with the type of the coarse aggregates. Also, the reduction in compressive strength, after 12 months of exposure to the sulfate solution, was not proportional to the magnesium sulfate soundness loss noted in the aggregates.

Tests on the coarse aggregates have shown that the chloride concentration in the coarse aggregates from Quarry # 1 in Abu-Hadriyah was more than the allowable value of 0.03% [2]. The chloride concentration in the coarse aggregates and reinforcement corrosion in the concrete specimens prepared using them are summarized in Table 5. This comparison does not indicate a definite relationship between the chloride concentration in the aggregates and reinforcement corrosion. This indicates that the chloride concentration in the coarse aggregates did not solely influence reinforcement corrosion. Therefore, it is advisable to control the total chloride concentration in the concrete rather than the chloride concentration in the individual constituents. If certain aggregates fail to meet the restriction on chloride contamination, it will be justifiable to demand from the concrete supplier to establish that the total chloride contamination in concrete using these aggregates is less than the allowable value.

The other deficiency noted in some of the coarse aggregates is the excess magnesium sulfate soundness loss. The magnesium sulfate soundness loss in the coarse aggregates from quarries on the Riyadh road and in Hofuf was more than the allowable value of 18%. Some of the concrete properties that are likely to be affected by this deficiency are sulfate-resistance and reduction in denseness due to exposure to moisture variations. Table 6 shows the magnesium sulfate soundness loss in the selected coarse aggregates along with the sulfate-resistance, water absorption and the change in pulse velocity due to moisture variations in the concrete specimens prepared with the selected coarse aggregates. These data do not indicate any definite relationship between the magnesium sulfate soundness loss and the relevant properties, viz., sulfate-resistance and reduction in denseness due to moisture variations. The reduction in compressive strength, due to 12 months of exposure to the sulfate solution, was the maximum in the concrete specimens prepared with coarse aggregates from Quarry # 2 in Abu-Hadriyah; though these coarse aggregates satisfy all the ASTM C 33 requirements. The reduction in compressive strength in the concrete specimens prepared with coarse aggregates from quarries in Hofuf and on the Riyadh road, which do not meet the ASTM C 33 magnesium sulfate soundness loss requirements, was less than that in the concrete specimens prepared with coarse aggregates from Quarry # 2 in Abu-Hadriyah. The denseness, measured in terms of pulse velocity and water absorption of concrete specimens prepared with the coarse aggregates from quarries in Hofuf and on the Riyadh road was better than that of concrete specimens prepared with coarse aggregates from quarries in Abu-Hadriyah. These data point to the fact that the excess magnesium sulfate soundness loss noted in the coarse aggregates from quarries in Hofuf and on the Riyadh road may not deleteriously affect the sulfate-resistance and denseness of concrete specimens exposed to moisture variations. However, it should be noted that the concrete specimens in this study were exposed to sulfate solutions at normal temperatures, i.e., the effect of freezing and thawing was not evaluated. Therefore, it is suggested that the limit of 18% magnesium soundness loss should still be considered for below ground structures in cold weather conditions, such as in the northern parts of the Kingdom. However, this limit may be increased to 25% in temperate climatic conditions. Alternatively, good quality coarse aggregates, i.e., those meeting the magnesium soundness loss requirements, should be utilized for below-ground components, while no limit on magnesium sulfate soundness loss should be specified for the coarse aggregates that are to be utilized in the above-ground components.

EFFECT OF DUST IN COARSE AGGREGATES ON COMPRESSIVE STRENGTH, MORPHOLOGY OF INTERFACIAL ZONE, AND REINFORCEMENT CORROSION

For this part of the study, the coarse aggregates were obtained from a quarry in Abu-Hadriyah. Since the objective of this study was to evaluate the effect of dust content in the coarse aggregates on compressive strength and reinforcement corrosion, the aggregates were sieved to remove the dust. They were then washed thoroughly with sweet water and dried. Table 7 shows the composition of the water used to wash the coarse aggregates. Eight batches of coarse aggregates were then prepared by adding 0, 0.5, 1, 2, 3, 4, 5, and 10% dust to the dry coarse aggregates. The dust (Cl^-: 0.021%; SO_4^{--}: 0.663%) was proportioned by weight of the coarse aggregates. The dry coarse aggregates and the dust were mixed thoroughly in order to uniformly distribute the dust in the coarse aggregate-dust matrix. Further, two other batches of coarse aggregates were also prepared. One batch was prepared by washing it with raw water and the other by removing dust by blowing air. The chemical composition of the raw water used to wash the coarse aggregates is also shown in Table 7. The prepared coarse aggregates were utilized to cast concrete specimens.

The concrete mixtures were prepared with 370 kg/m^3 of ASTM C 150 Type I cement and an effective water-to-cement ratio of 0.40. Suitable dosage of a superplasticizer was added to the concrete mixtures to obtain a slump of 50 to 75 mm.

Cylindrical concrete specimens, 75 mm in diameter and 150 mm high, were prepared for the determination of the effect of dust content on the compressive strength. The concrete specimens, 75 mm in diameter and 150 mm high, with a single 12-mm diameter steel bar that was placed in the center of the concrete specimen were prepared to evaluate the effect of dust content in the coarse aggregates on reinforcement corrosion. The reinforced concrete specimens were exposed to wetting and drying cycles. For this purpose, they were exposed to laboratory conditions and a known volume of sweet water, whose composition is shown in Table 7, was sprayed on each of the specimens twice weekly. The wetting and drying process was carried out for 18 months. Reinforcement corrosion in the concrete specimens exposed to wetting and drying cycles was monitored by measuring corrosion current density (Icorr) utilizing the linear polarization resistance method [12].

The effect of dust content in the coarse aggregates on the morphology of the interfacial zone between the aggregates and the cement mortar was assessed by examining portions of concrete under a scanning electron microscope.

Compressive Strength

Table 8 shows the compressive strength of concrete specimens prepared with varying dust content. The compressive strength was in the range of 37 to 39 MPa, indicating that the dust content in the coarse aggregates did not influence the compressive strength of hardened concrete.

Reinforcement Corrosion

The corrosion current density after 18 months of exposure to wetting and drying is shown in Table 9. The Icorr values in all the concrete specimens were very low being in the range of 0.056 to 0.098 $\mu A/cm^2$. These values are considered low in terms of reinforcement corrosion. According to prevailing convention [14], an Icorr value of less than 0.1 $\mu A/cm^2$ indicates no corrosion while a value of more than 0.3 $\mu A/cm^2$ indicates corrosion activation. Further, no definite relationship could be established between the quantity of dust in the coarse aggregates and the Icorr.

Concrete Morphology at the Aggregate-Paste Interface

Figure 1 is a backscattered electron image (BEI) of the concrete specimen prepared with a dust content of 0.5%. A good bonding of the cement paste with the aggregate is evident with a very thin interfacial zone. The low and high magnification BEIs of the concrete specimen prepared with a dust content of 2% are shown in Figures 2 and 3, respectively. A compact interfacial zone is noted in this specimen also. The BEI (x 400) of the concrete specimen prepared with a dust content of 5% is shown in Figure 4. Debonding of the cement mortar and the coarse aggregate is noted in this specimen. The fracturing of the interfacial zone is evident more clearly in the high magnification (x1200) BEI of the same specimen is shown in Figure 5. The BEI of the concrete specimen with 10% dust content as shown in Figure 6. Debonding of the aggregate with the cement paste is evident even in this low magnification (x 100) BEI.

The BEIs, discussed in Figures 1 through 6, indicated the formation of a compact interfacial zone in the concrete specimens prepared with a dust content of up to 2% while debonding between the aggregates and the cement mortar was noted in the concrete specimens prepared with 5% and 10% dust in the coarse aggregates.

The data developed in this study have indicated that up to 10% dust content in the coarse aggregates does not influence the compressive strength. Similarly, a definite relationship could not be discerned between the dust content in the coarse aggregates and reinforcement corrosion. However, the BEIs of concrete specimens prepared with 5% and 10% dust content have shown debonding at the aggregate-mortar interface; though this has not influenced the compressive strength. Therefore, it is recommended that the dust content in the coarse aggregates be limited to less than 5%.

CONCLUDING REMARKS

Following are the conclusions emanating from the data developed in the reported studies:

a) The selected coarse aggregates satisfied the ASTM C 33 criteria, except that chloride concentration in the coarse aggregates from one of the quarries in Abu-Hadriyah was two times the allowable value of 0.03%. Also, the magnesium sulfate soundness loss in the coarse aggregates from quarries in Hofuf and on the Riyadh road was more than the allowable value of 18%, while it was about 9% in the coarse aggregates from quarries in Abu-Hadriyah.

b) The mechanical properties of concrete specimens prepared with coarse aggregates from quarries on the Riyadh road were better than those of concrete specimens prepared with coarse aggregates from quarries in Hofuf and Abu-Hadriyah. Further, the mechanical properties of concrete specimens prepared with coarse aggregates from quarries in Hofuf were marginally better than those of concrete specimens prepared with coarse aggregates from quarries in Abu-Hadriyah.

c) A definite relationship could not be established between the chloride concentration in the coarse aggregates and reinforcement corrosion.

d) The excess magnesium sulfate soundness loss noted in the coarse aggregates from quarries on the Riyadh road and in Hofuf did not influence the properties of the concrete exposed to conditions evaluated in this research study, namely, sulfate solution and moisture variations.

e) The dust in the coarse aggregates did not significantly influence the compressive strength of concrete.

f) The backscattered electron images of concrete specimens prepared with up to 2% dust in the coarse aggregates indicated a good bond between the cement mortar and the aggregates. However, micro cracks were noted at the aggregate-mortar interface in the concrete specimens prepared with dust contents of 5% and 10%. This debonding, however, had no effect on the compressive strength of concrete.

g) Reinforcement corrosion was not evident on the steel bars in the concrete specimens prepared with up to 10% dust in the coarse aggregates. Similarly, there was no corrosion on the steel bars in the concrete specimens prepared with aggregates cleaned with raw water or by blowing air till all the dust was removed.

RECOMMENDATIONS

Based on the data developed in the reported study, the following recommendations are made.

a) An aggregate source should not be rejected if the chloride concentration is more than the allowable value of 0.03%. It is advisable to control the total chloride contamination in concrete. ACI 318, ACI 224, and BS 8110 do provide adequate guidelines in this direction.

b) The current ASTM C 33 limit of 18% magnesium sulfate soundness loss should still be considered for below-ground structures in cold weather conditions, such as those in the northern parts of the Kingdom. However, this limit may be increased to 25% in temperate climatic conditions. Alternatively, good quality coarse aggregates, i.e., those meeting the magnesium sulfate soundness loss requirements, should be utilized for below-ground components, while coarse aggregates that fail to meet these requirements could be utilized in the above-ground structures.

c) The dust content in the coarse aggregates should be limited to less than 5%. Washing of aggregates with raw water (less than 1,000 ppm chlorides; TDS less than 3,500 ppm) may be allowed, provided it is ascertained that this process does not contribute additional water to the concrete mix. Also, cleaning of the aggregates by blowing air or vacuum suction to remove all the dust may be allowed.

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Table 1. Properties of coarse aggregates.

Property	Source of coarse aggregates					
	Abu-Hadriyah quarry #1	Abu-Hadriyah quarry #2	Hofuf quarry # 1	Hofuf quarry # 2	Riyadh road quarry # 1	Riyadh road quarry # 2
Magnesium sulfate soundness loss, % (allowable value: 18%)	8.84	9.03	27.12	24.54	25.31	27.5
Materials finer than # 200 sieve, % (allowable value: 1%)	0.50	0.65	0.46	0.17	0.20	0.44
Water absorption, % (allowable value: 2.5%)	2.32	2.40	1.80	1.20	1.06	1.10
Loss on abrasion, % (allowable value: 40%)	32.4	33.2	35.1	25.9	23.7	22.6
Clay lumps and friable particles, % (allowable value: 5%)	0.37	0.45	2.81	1.35	0.55	0.35
Chloride concentration, % (allowable value: 0.03%)	0.066	0.028	0.026	0.011	0.017	0.022
Sulfate concentration, % (allowable value: 0.4%)	0.206	0.059	0.083	0.035	0.059	0.067

Table 2. Chemical composition of the selected coarse aggregates.

Mineral	Abu-Hadriyah quarries	Hofuf quarries	Riyadh road quarries
$CaCO_3$, %	99	95	75
SiO_2, %	1	5	25

Table 3. Conformance of the selected coarse aggregates with limiting values.

Source of aggregates	Remarks on aggregate properties
Abu-Hadriyah quarry # 1	Chloride concentration is more than the allowable value
Abu-Hadriyah quarry # 2	Meets all the criteria
Hofuf quarry # 1	Magnesium sulfate loss is more than the allowable value
Hofuf quarry # 2	Magnesium sulfate loss is more than the allowable value
Riyadh road quarry # 1	Magnesium sulfate loss is more than the allowable value
Riyadh road quarry # 2	Magnesium sulfate loss is more than the allowable value

Table 4. Summary of properties of concrete specimens prepared with the selected coarse aggregates.

Concrete properties	Source of aggregate					
	Abu-Hadriyah quarry #1	Abu-Hadriyah quarry #2	Hofuf quarry # 1	Hofuf quarry # 2	Riyadh road quarry # 1	Riyadh road quarry # 2
Compressive strength, MPa	32.6	37.6	40.7	40.0	38.3	48.7
Modulus of elasticity, GPa	31.3	33.3	29.4	28.8	24.0	29.6
Split tensile strength, MPa	3.2	3.3	3.8	3.6	3.2	3.3
Water absorption, %	4.9	4.8	4.6	4.7	4.2	4.1
Pulse velocity, m/s	4,545	4,570	4,646	4,655	4,682	4,670
Chloride permeability, Coulombs	1,150	814	807	904	675	832
Reduction in compressive strength after 12 months of exposure to sulfate solution, %	11.9	25.2	15.1	11.5	19.3	14.7
Chloride diffusion coefficient, 10^{-8} cm^2/s	14.7	15.5	21.1	18.5	19.8	18.4
Corrosion current density after 360 days of exposure to the chloride solution, $\mu A/cm^2$	1.0	0.8	0.8	0.8	1.4	0.8

Table 5. Chloride concentration in the selected coarse aggregates and corrosion current density.

Source of aggregates	Chloride concentration in the aggregates, %	Corrosion current density, $\mu A/cm^2$
Abu-Hadriyah quarry # 1	0.066	1.00
Abu-Hadriyah quarry # 2	0.028	0.85
Hofuf quarry # 1	0.026	0.81
Hofuf quarry # 2	0.011	0.81
Riyadh road quarry # 1	0.017	1.41
Riyadh road quarry # 2	0.022	0.81

Table 6. Magnesium sulfate soundness loss in the selected coarse aggregates and some of the properties of concrete.

Source of aggregates	Magnesium sulfate soundness loss, %	Reduction in compressive strength after 12 months of exposure to the sulfate solution, %	Water absorption after 120 wet-dry cycles, %	Pulse velocity in the concrete specimens exposed to 120 wet-dry cycles, m/s
Abu-Hadriyah quarry # 1	8.84	11.9	5.06	4,597
Abu-Hadriyah quarry # 2	9.03	25.2	4.93	4,732
Hofuf quarry # 1	27.12	15.1	4.68	4,784
Hofuf quarry # 2	24.54	11.5	4.79	4,797
Riyadh road quarry # 1	25.31	19.3	4.39	4,759
Riyadh road quarry # 2	27.5	14.7	4.21	4,720

Table 7. Chemical analysis of sweet and raw water.

Particulars	Raw water	Sweet water
pH	7.5	7.2
Total dissolved solids, mg/l	3338	294
Conductivity, µmhos/cm	5000	480
Turbidity, NTU	4.5	0.8
Alkalinity, bicarbonate as $CaCO_3$, mg/l	180	114
Chloride, mg/l	893	60
Sulfate (SO_4^{--}), mg/l	700	18
Total hardness, mg/l	1187	28
Sodium and potassium, mg/l	449	87

Table 8. Compressive strength of concrete specimens prepared with varying dust in the coarse aggregates.

Dust in the concrete, % by weight of the coarse aggregates	Average compressive strength, MPa
0	37.1
0.5	38.9
1.0	36.5
2.0	36.9
3.0	38.6
4.0	37.1
5.0	37.2
10.0	38.3

Table 9. Corrosion current density in concrete specimens prepared with dust or by cleaning with raw water/vacuum.

Condition of aggregate	Corrosion current density, $\mu A/cm^2$
Clean (no dust)	0.07
0.5% dust	0.06
1% dust	0.06
2% dust	0.06
3% dust	0.06
4% dust	0.06
5% dust	0.06
10% dust	0.07
Cleaned using raw water (see Table 6 for composition of raw water)	0.08
Vacuum cleaned	0.10

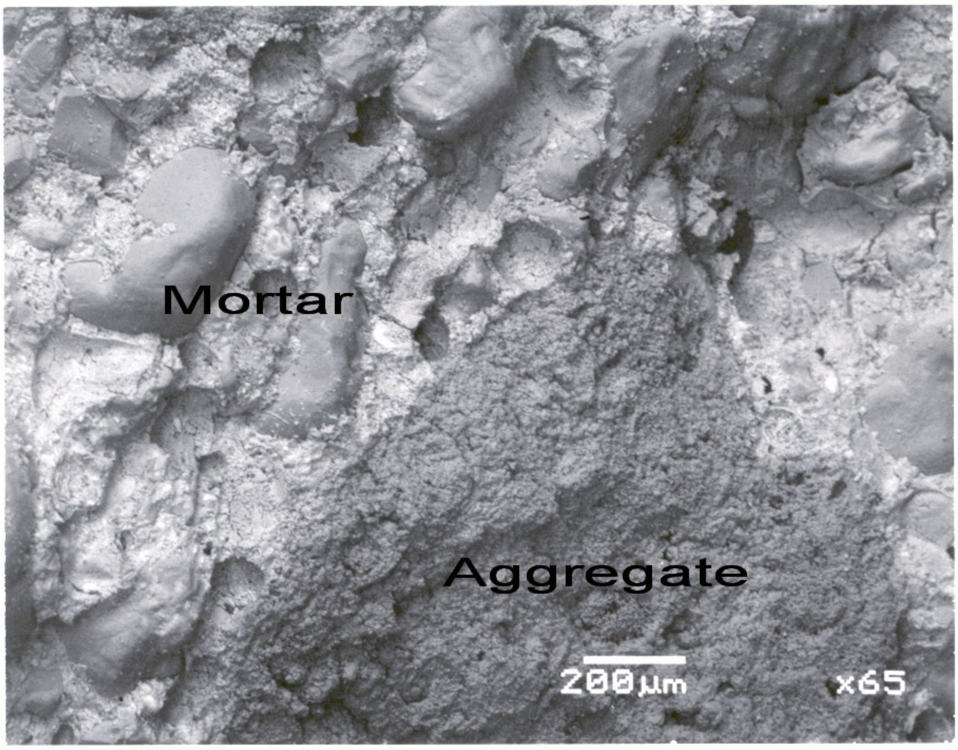

Figure 1. BEI of the concrete specimen prepared with 0.5% dust in the coarse aggregates.

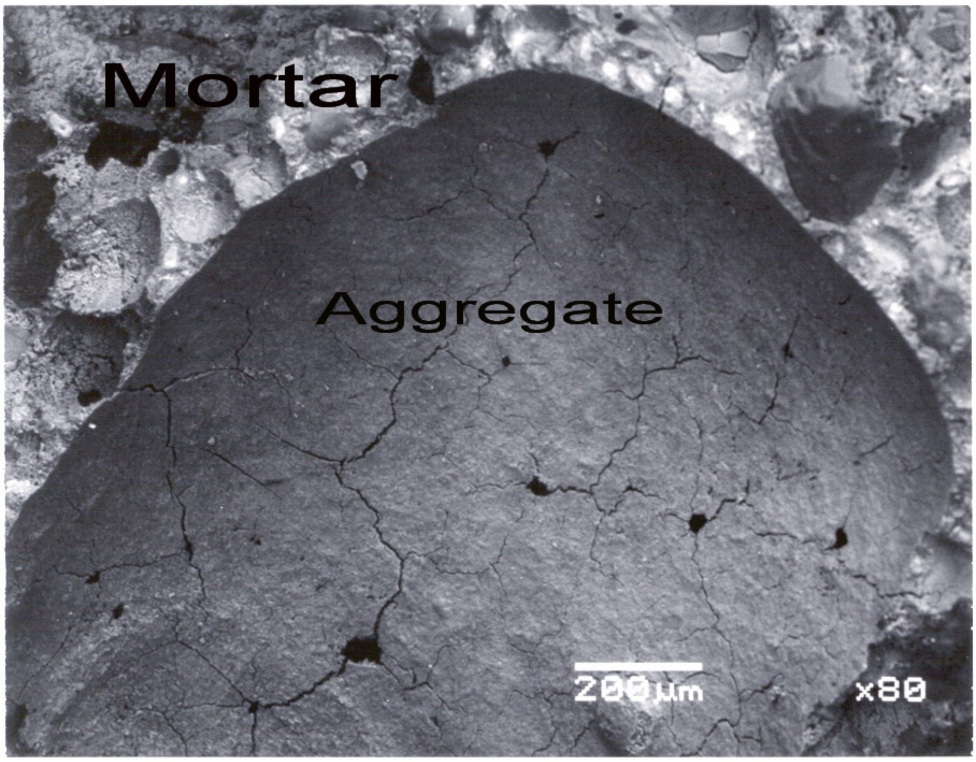

Figure 2. A low magnification (x80) BEI of the concrete specimen prepared with 2% dust in the coarse aggregates.

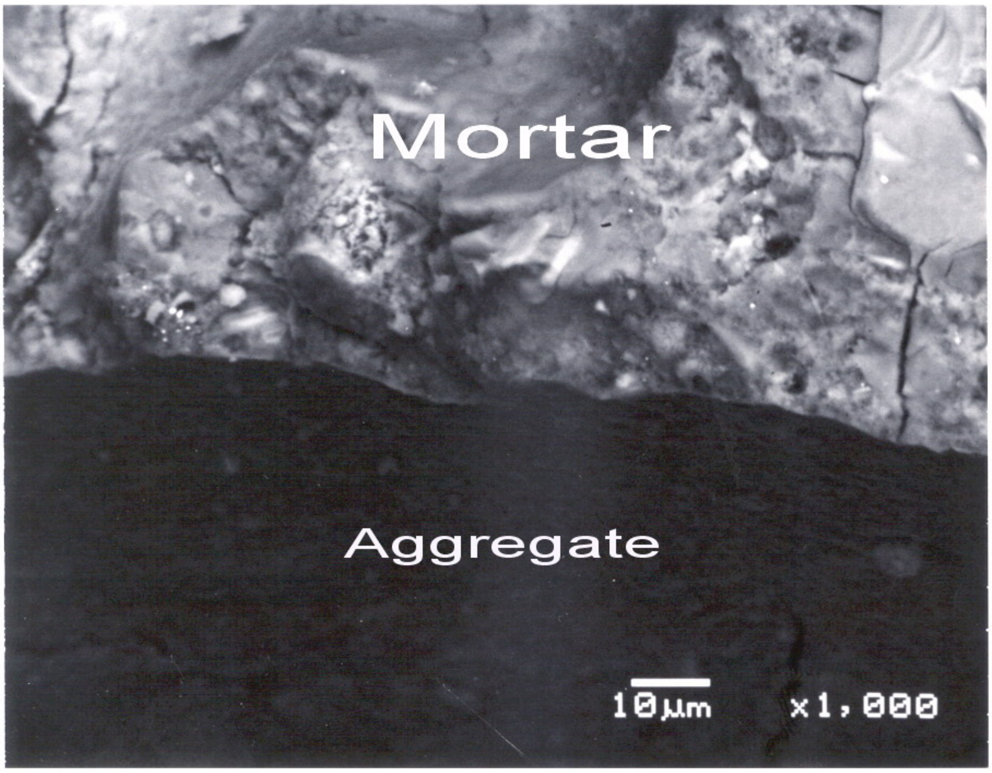

Figure 3. A high magnification (x1,000) BEI of the concrete specimen prepared with 2% dust in the coarse aggregates.

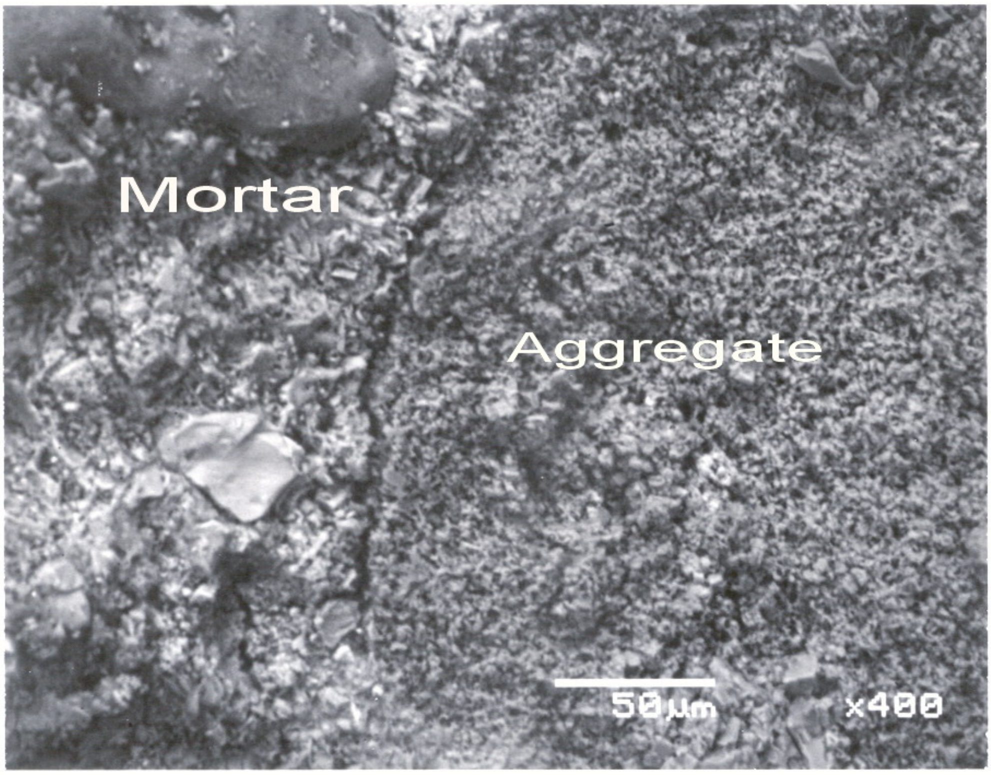

Figure 4. A low magnification (x400) BEI of the concrete specimen prepared with 5% dust in the coarse aggregates.

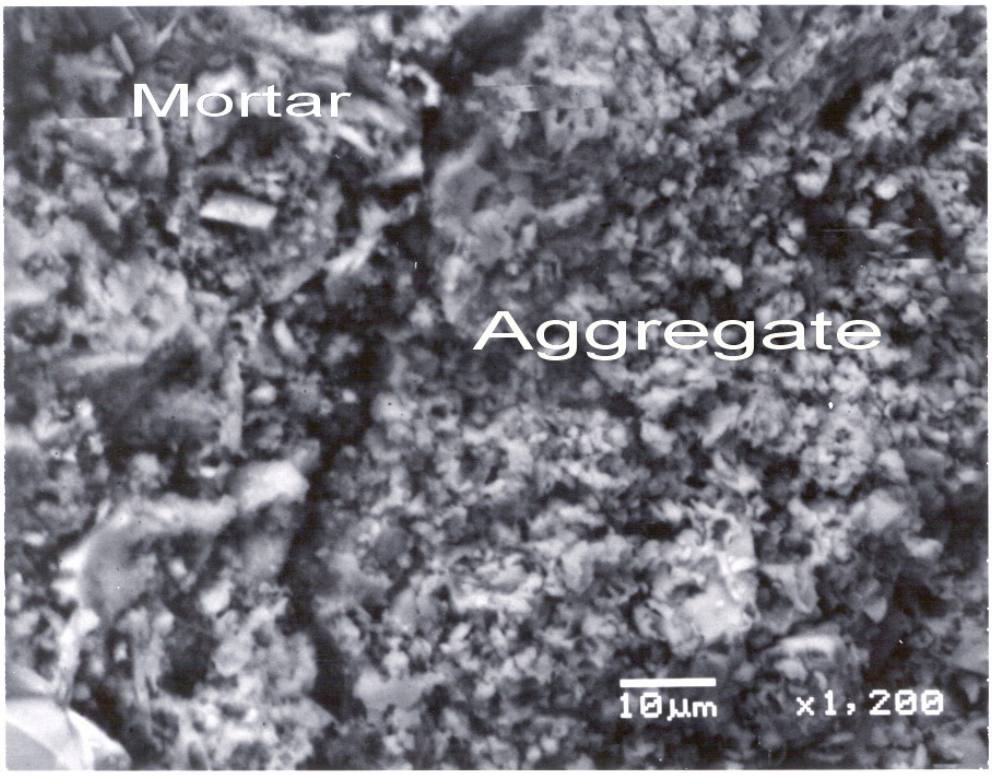

Figure 5. A high magnification (x1,200) BEI of the concrete specimen prepared with 5% dust in the coarse aggregates.

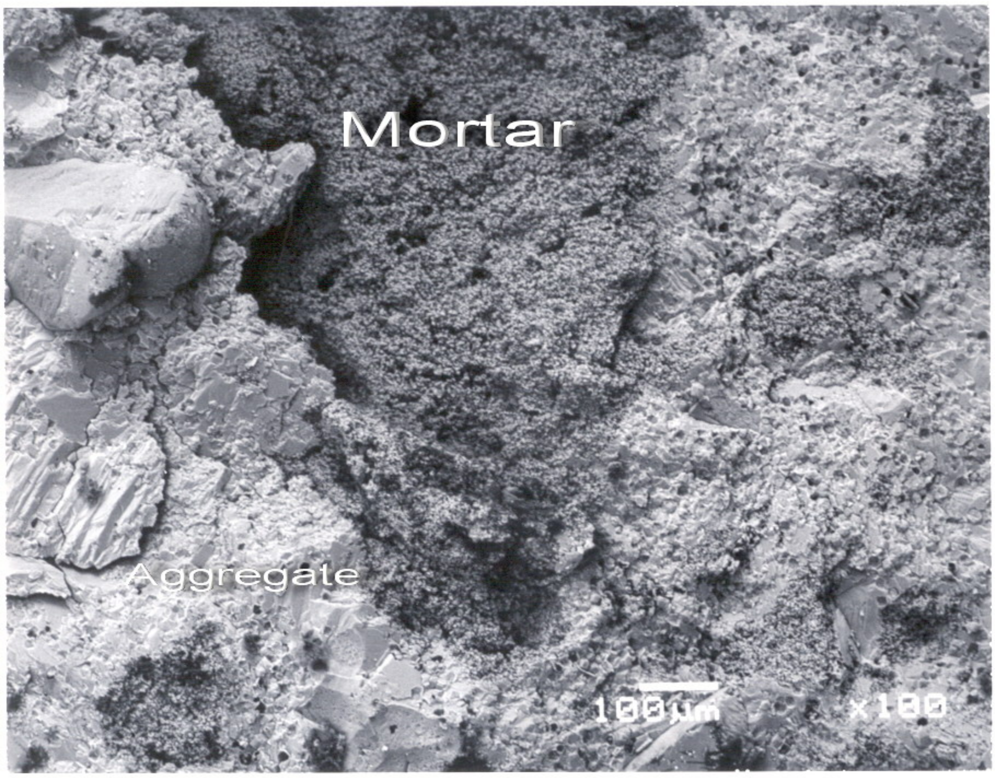

Figure 6. A low magnification (x100) BEI of the concrete specimen prepared with 10% dust in the coarse aggregates.