EFFECT OF AGGREGATE QUALITY ON THE PROPERTIES OF CONCRETE

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ABSTRACT

This paper presents results of a study conducted to evaluate the effect of aggregate quality, particularly when they do not comply with the standard requirements, on the properties of concrete. Crushed limestone aggregates from six quarries, five of which did not satisfy one or more of the ASTM C 33 requirements, were utilized to prepare concrete specimens. The concrete specimens were tested to evaluate the mechanical properties, and sulfate- and corrosion-resistance. The results indicate that some of the drawbacks in terms of the C 33 criteria did not affect the physical properties and durability performance of concrete. The excessive magnesium soundness loss noted in some of the aggregates also did not influence the sulfate resistance of concrete.

Keywords: *Aggregates, Concrete, Durability, Mechanical and physical properties*

الملخص

هذه الدراسة تتضمن نتائج تأثير نوعية الحصى ، وخاصة عندما لا تفي بمتطلبات المقاييس العالمية ، على خواص الخرسانة . تم اختيار ستة أنواع من الحصى الجيري من مقالع مختلفة ، خمسة منها لا تفي بمتطلبات المقاييس الأمريكية للفحص والمواد رقم C33 ، لإعداد العينات الخرسانية . وقد أجـريت عـدة اختبارات لهذه العينات الخرسانية ، منها الخواص الميكانيكية ، مقاومة صدأ الحديد ومقاومة الكبريتات . دلت النتائج على أن القصور في بعض أنواع الحصى بمتطلبات المعيار رقم C33 لم تؤثر على الخواص الميكانيكية ، والفيزيائية وخواص ديمومة الخرسانة . كما أن الزيادة في مقدار نقص المتانة في محلول كبريتات المغنسيوم لبعض انواع الحصى لم تؤثر على مقاومة الكبريتات للعينات الخرسانية .

1. INTRODUCTION

Aggregates are the main component of Portland cement concrete. The quality of coarse aggregate significantly affects the properties of concrete since it constitutes about 70% of the volume of concrete. Several criteria, such as ASTM C 33 [1999], were developed as guidelines for utilizing high-quality coarse aggregates to produce durable concrete. However, with dwindling sources of high-quality coarse aggregates, the validity of these criteria is often questioned. This concern is of particular importance in the Arabian Gulf region, where not all the available coarse aggregates satisfy all the standard selection criteria [Al-Abideen, 1987]. In such situations, coarse aggregates are commonly hauled from far off quarries, which increases the cost of construction. 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 perform well in 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 resources.

This study was conducted to investigate the influence of aggregate quality on the properties of hardened concrete. As part of this study, aggregates from six quarries were selected. Concrete specimens were prepared with the selected coarse aggregates and the influence of the quality of coarse aggregates on the mechanical properties and durability characteristics of hardened concrete was assessed.

2. METHODOLOGY OF RESEARCH

2.1 Testing of aggregates

Aggregates from six quarries, two each representing calcareous limestone, dolomitic limestone, and quartizitic limestone, were obtained.

The selected coarse aggregates were tested for the fol1owing:

i. Magnesium sulfate soundness loss, according to ASTM C 88 [1999],

ii. Materials finer than ASTM No.200 sieve, according to ASTM C 117 [1999],

iii. Specific gravity and water absorption, according to ASTM C 127 [1999],

iv. Loss on abrasion, according to ASTM C 131 [1999],

v. Clay lumps and friable particles, according to ASTM C 142 [1999],

vi. Flakiness and elongation index, according to BS 812 [1994],

vii. Chloride content, according to BS 812 [1994], and

viii. Sulfate content, according to BS 1377 Part 3 [1994].

2.2 Casting of concrete specimens

Concrete mixtures were prepared with cement content of 370 kg/m^3, an effective w/c ratio of 0.40 and a coarse-to-fine aggregate ratio of 1.62. Prior to their use, the coarse aggregates were sieved to various size fractions and washed to remove dust and loose particles. They were then re-mixed to obtain the desired grading.

2.3 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 [1999].

ii. Split tensile strength, according to [ASTM C 49 , 1999].

iii. Pulse velocity, according to [ASTM C 597, 1999].

iv. Absorption, according to [ASTM C 642, 1999].

v. Chloride permeability, according to [ASTM C 1202, 1999].

vi. Sulfate resistance: The concrete specimens prepared with the selected coarse aggregates were exposed to a sulfate solution with a concentration of 5% $MgSO_4$ and 5% Na_2SO_4. The sulfate resistance of concrete specimens prepared with the selected coarse aggregates was evaluated by determining the reduction in compressive strength after 12 months of exposure to the sulfate solution.

vii. Reinforcement corrosion: The effect of aggregate type on the corrosion-resistance of concrete was evaluated by exposing the concrete specimens to chloride and chloride-sulfate solutions. Reinforced concrete specimens, measuring 75 mm in diameter and 150 mm high, were prepared with a 12-mm diameter steel bar placed at the center. A cover of 25 mm was provided at the bottom. The reinforcing steel bars were coated with cement paste followed by an epoxy coating at the bottom of the bar and at the concrete- interface to avoid crevice corrosion.

    Reinforcement corrosion in the second and third groups of concrete specimens was monitored by measuring the corrosion potentials, according to ASTM C 876 [1999] and the corrosion current density by the linear polarization resistance method [Stern, and Geary, 1957].

3. RESULTS

3.1 Properties of aggregates

For the purpose of this paper, calcareous limestone aggregates are represented by the acronym CL, while the dolomitic limestone and quartizitic limestone aggregates are denoted as DL and QL, respectively. Some of the important properties of the coarse aggregates selected for this study are summarized in Table 1. These data indicate that the DL and QL aggregates do not meet the ASTM C 33 requirements for the magnesium sulfate soundness loss. Also, the chloride content in one of the CL aggregates was more than the allowable value.

3.2 Physical properties of concrete

The physical properties of hardened concrete prepared with the selected coarse aggregates are summarized in Table 2. A description of the physical properties of concretes prepared with the selected aggregates is provided in the following sections.

3.2.1 Compressive strength

The compressive strength of concrete specimens prepared with CL aggregates was in the range of 33 to 38 MPa, while these values in the concrete specimens prepared with DL aggregates were in the range of 40 to 41 MPa. The compressive strength of concrete specimens prepared with QL aggregates was in the range of 38 to 49 MPa.

3.2.2 Modulus of elasticity

The modulus of elasticity of concrete specimens prepared with CLaggregates was in the range of 31 to 34 GPa, while these values in the concrete specimens prepared with DL aggregates varied from 29 to 30 GPa. The modulus of elasticity of the concrete specimens prepared with QL aggregates was in the range of 24 to 30 GPa.

3.2.3 Split tensile strength

The split tensile strength of concrete specimens prepared with the CL aggregates was in the range of 3.1 to 3.29 MPa, while these values in the concrete specimens prepared with the DL aggregates varied from 3.55 to 3.79 MPa. The split tensile strength of concrete specimens prepared with the QL aggregates was in the range of 3.23 to 3.3 MPa.

3.2.4 Absorption

The water absorption in the concrete specimens prepared with the CL aggregates was more than that in the concrete specimens prepared with the DL aggregates. The water absorption in the concrete specimens prepared with the QL aggregates was less than that of the concrete specimens prepared with the CL and DL aggregates. However, the difference in the water absorption between the concrete specimens prepared with the selected aggregates was not very significant. For example, the water absorption in the concrete specimens prepared with the CL aggregates was in the range of 4.8 to 4.9%, while in the concrete specimens prepared with the DL aggregates it was in the range of 4.6 to 4.7%. The water absorption in the concrete specimens prepared with the QL aggregates was in the range of 4.1 to 4.2%.

3.2.5 Pulse velocity

The pulse velocity in the concrete specimens prepared with the DL and QL aggregates was in the range of 4,646 to 4,682 m/s while it was in the range of 4,545 to 4,570 m/s in the concrete specimens prepared with the CL aggregates.

3.3 Durability characteristics of concrete

The durability characteristics of the hardened concrete prepared with the selected coarse aggregates are shown in Table 3. A description of the durability characteristics of the concrete prepared with the selected aggregates is described in the following subsections.

3.3.1 Chloride permeability

According to ASTM C 1202 classification, chloride permeability in the concrete specimens prepared with the selected aggregates varies from very low to low. The chloride permeability in the concrete specimens prepared with the CL aggregates was in the range of 814 to 1150 Coulomb, while these values in the concrete specimens prepared with the DL aggregates were in the range of 807 to 904 Coulombs. The chloride permeability in the concrete specimens prepared with the QL aggregates was in the range of 675 to 832 Coulombs.

3.3.2 Sulfate attack

The effect of aggregate quality on the sulfate-resistance was evaluated by exposing the concrete specimens to asulfate solution and measuring the reduction in compressive strength. The reduction in compressive strength of concrete specimens prepared with the CL aggregates was in the range of 11.9 to 25.2%, while in the concrete specimens prepared with the DL aggregates it was in the range of 11.5 to 15.1%. The reduction in the compressive strength of concrete specimens prepared with the QL aggregates was in the range of 14.7to 19.3%.

3.3.3 Reinforcement corrosion

The effect of coarse aggregate quality on the corrosion resistance of concrete was evaluated by: (i) the accelerated impressed current technique, and (ii) measuring the corrosion potentials and corrosion current density.

In the accelerated impressed current technique, an anodic potential of 4V was applied on the steel bars and the current required to maintain this potential was recorded at intervals of two hours. These measurements were continued till cracks were noted on the concrete specimens. However, a sharp increase in the current requirement normally denotes the initiation of cracks in concrete due to reinforcement corrosion. The average time to cracking of concrete due to accelerated corrosion of the reinforcing steel was in the range of 575 to 608 hours.

The effect of the type of coarse aggregate on the corrosion-resistance of concrete was also evaluated by measuring the corrosion potentials and corrosion current density. The corrosion potentials were plotted against time and the potential-time curves were utilized to ascertain the time-to-initiation of reinforcement corrosion based on the [ASTM C 876, 1999] criterion of – 270 mV SCE. Reinforcement corrosion in the concrete specimens exposed to a chloride solution was indicated after 36 to 54 days.

The corrosion current density (Icorr) on steel in the concrete specimens prepared with the selected coarse aggregates was also evaluated. The Icorr values in he concrete specimens prepared with the CL aggregates were in the range of 0.85 to 1.00 $\mu A/cm^2$ while the value was 0.81 $\mu A/cm^2$ in the concrete specimens prepared with the DL aggregates. The Icorr values on steel in the concrete specimens prepared with the QL aggregates were in the range of 0.81 to 1.41 $\mu A/cm^2$.

4. DISCUSSION OF RESULTS

The properties of concrete specimens prepared with the coarse aggregates selected for this study are summarized in Table 2 while the durability characteristics are shown in Table 3. The compressive strength of concrete specimens prepared with QL aggregates was marginally more than that of specimens prepared with the CL and DL aggregates. Similarly, the compressive strength of concrete specimens prepared with the DL aggregates was slightly more than that of concrete specimens prepared with the CL aggregates. The modulus of elasticity of concrete specimens prepared with the QL aggregates was generally less than that of concrete specimens prepared with CL and DL aggregates. However, an appreciable difference was noted in the split tensile strength of the concrete specimens prepared with the coarse aggregates selected for this study. The pulse velocity in the concrete specimens prepared with the QL aggregates was marginally more than that in the concrete specimens prepared with the CL and DL aggregates.

The water absorption in the concrete specimens prepared with the QL aggregates was marginally less than that in the concrete specimens prepared with the CL and DL aggregates. The foregoing discussion indicates that the mechanical properties and absorption characteristics of concrete specimens prepared with the QL aggregates were generally better than those of concrete specimens prepared with the CL and DL aggregates.

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The chloride permeability of the concrete specimens prepared with the QL aggregates was less than that in the concrete specimens prepared with the CL and DL aggregates. The reduction in the compressive strength, due to sulfate attack, was the maximum in the concrete specimens prepared with the CL aggregates from one of the sources while a minimum reduction in compressive strength was noted in the concrete specimens prepared with one of the DL aggregates. The data on the reduction in compressive strength indicate that the type of aggregate dose not influence the mechanisms of sulfate attack. This is understandable since sulfate ions react with the cement hydration products rather than the coarse aggregates.

Similarly the type of coarse aggregate does not seem to have a significant effect on the corrosion resistance of concrete prepared using them. The time-to-initiation of cracking, evaluated by the accelerated impressed current technique was almost similar in all the concrete specimens, while the rate of reinforcement corrosion, measured as corrosion current density, in the concrete specimens prepared with the DL aggregates is less than that in the concrete specimens prepared with the other coarse aggregates. The corrosion current density on the steel bars in the concrete specimens prepared with the CL and QL aggregates was almost similar.

As discussed earlier, the QL aggregates are relatively better in quality than the CL and DL aggregates. The DL aggregates are better than the CL aggregates. The mechanical properties and permeability characteristics of concrete specimens prepared with the QL aggregates were marginally superior to that of concrete specimens prepared with the CL and DL aggregates. Further, the properties of concrete specimens prepared with the DL ashow better performance than the concrete specimens prepared with the CL aggregates. The corrosion- and sulfate-resistance of concretes prepared with the selected coarse aggregates did not vary very significantly with the type of the coarse aggregate.

The denseness of concrete specimens, expressed in terms of pulse velocity, of the concrete specimens prepared with the QL aggregates was better than the concrete specimen prepared with the CL and DL aggregates. The concrete specimens prepared with the DL aggregates performed better than the concrete specimens prepared with the CL aggregates.

Tests on the coarse aggregates have shown that the chloride concentration in one of the CL aggregates was more than the allowable value of 0.03%. However, no definite relationship between the chloride concentration in the selected coarse aggregates and the corrosion resistance of concrete could be established. This indicates that the chloride concentration in the coarse aggregates does not solely contribute to the time-to- initiation of reinforcement corrosion. Similarly, no definite relationship could be established between the chloride concentration in the coarse aggregates and the rate of reinforcement corrosion, measured as

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corrosion current density. Therefore, it is advisable to control the total chloride concentration in the concrete rather than the chloride concentration in the individual constituents. If a certain aggregate fails to meet the restriction on chloride contamination, it will be justifiable to demand from the ready mix 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 selected coarse aggregates is the excess magnesium sulfate soundness loss. As discussed earlier, the magnesium sulfate soundness loss in the DL and QL aggregates was more than the allowable value of 18% specified by [ASTM C 33, 1999]. 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. The data on the properties of concrete particularly sulfate resistance, however, did not indicate any definite relationship between the magnesium sulfate soundness loss and sulfate resistance. Reduction in compressive strength, due to 12 months of exposure to a sulfate solution, was the maximum in the concrete specimens prepared with one of the CL aggregates. The reduction in compressive strength in the concrete specimens prepared with DL and QL aggregates, which do not meet the magnesium sulfate soundness loss requirements, was less than that in the concrete specimens prepared with one of the CL aggregates. The denseness, measured in terms of pulse velocity and water absorption of the concrete specimens prepared with the DL and QL aggregates was better than that of concrete specimens prepared with the CL aggregates. These data point to the fact that the excess magnesium sulfate soundness loss noted in the DL and QL aggregates may not deleteriously affect the sulfate resistance and denseness of the concrete 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. However, this limit may be increased for 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 the magnesium sulfate soundness loss should be specified for the coarse aggregates that are to be utilized in the above ground components.

5. CONCLUSIONS

The mechanical properties, namely compressive strength, split tensile strength, and elastic modulus, of concrete specimens prepared with the quartzitic limestone aggregates were better than those of concrete specimens prepared with the calcitic and dolomitic limestone aggregates. Further, the mechanical properties of concrete specimens prepared with the dolomitic limestone aggregates were marginally better than those of concrete specimens prepared with the calcitic limestone aggregates.

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The water absorption and chloride permeability in the concrete specimens prepared with the quartzitic limestone aggregates were less than that in the concrete specimens prepared with the calcitic and dolomitic limestone aggregates.

The sulfate- and corrosion-resistance of concrete specimens prepared using the selected coarse aggregates did not vary very significantly with the type of coarse aggregates.

A comparison of the data on chloride concentration in the coarse aggregates and the corrosion resistance of concrete specimens prepared with them did not indicate any definite relationship between the chloride concentration in the coarse aggregates and the corrosion resistance of the concrete. These data indicate that chloride concentration in the coarse aggregates does not solely contribute to the time-to- initiation and the rate of reinforcement corrosion. Therefore, it is advisable to control the total chloride concentration in the concrete rather than in the individual constituents.

The magnesium sulfate soundness loss in the selected coarse aggregates was compared with sulfate resistance of concrete. No unique relationship between the magnesium sulfate soundness loss and sulfate attack could be established. This indicates that the excessive magnesium sulfate soundness loss noted in the dolomitic and quartzitic limestone aggregates does not influence the properties of the concrete exposed to the exposure conditions evaluated in this research study.

Since the concrete specimens in this investigation were exposed to normal temperature, it is suggested that the limit of 18% magnesium soundness loss should still be considered for below ground structures in cold weather conditions. However, this limit may be increased for temperate climatic conditions.

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Table 1 Properties of the selected coarse aggregates.

Property		Coarse aggregate					
		Calcitic limestone 1 (CL1)	Calcitic limestone 2 (CL2)	Dolomitic limestone 1 (DL1)	Dolomitic limestone 2 (DL2)	Quartzitic limestone 1 (QL1)	Quartzitic limestone 2 (QL2)
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	0.2	0.44
Water absorption, % (allowable value: 2.5%)		2.32	2.4	1.8	1.2	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
Mineralogical composition, % by weight,	Calcium carbonate	99.0	95.0	80.0	75.0	85.0	75.0
	Quartz	1.0	5.0	20.0	25.0	15.0	25.0

Table 2 Physical properties of concrete specimens prepared with the selected coarse aggregates.

Concrete Properties	Coarse aggregate					
	Calcitic limestone 1 (CL1)	Calcitic limestone 2 (CL2)	Dolomitic limestone 1 (DL1)	Dolomitic limestone 2 (DL2)	Quartzitic limestone 1 (QL1)	Quartzitic limestone 2 (QL2)
Compressive strength, MPa	32.62	37.55	40.72	40.00	38.32	48.67
Modulus of Elasticity, GPa	31.25	33.3	29.4	28.8	24.0	29.6
Split tensile strength, MPa	3.17	3.29	3.79	3.55	3.23	3.3
Water absorption, %	4.9	4.8	4.6	4.7	4.2	4.1
Pulse velocity, m/s	4545	4570	4646	4655	4682	4670

Table 3 Durability characteristics of concrete specimens prepared with the selected coarse aggregates.

Concrete Properties	Coarse aggregate					
	Calcitic limestone 1 (CL1)	Calcitic limestone 2 (CL2)	Dolomitic limestone 1 (DL1)	Dolomitic limestone 2 (DL2)	Quartzitic limestone 1 (QL1)	Quartzitic limestone 2 (QL2)
Chloride permeability, Coulombs	1150	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
Time to cracking of concrete, Hours	608	600	594	600	607	575
Time to initiation of corrosion, Days	38	50	46	54	43	36
Corrosion current density after 12 months of exposure to the chloride solution, $\mu A/cm^2$	1.00	0.85	0.81	0.81	1.41	0.81

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