Effect of coarse aggregate quality on the mechanical properties of high strength concrete

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Abstract

This paper reports results of a study conducted to evaluate the effect of four types of coarse aggregates, namely calcareous, dolomitic, quartzitic limestone, and steel slag, on the compressive and tensile strength, and elastic modulus of high strength concrete. The highest and lowest compressive strength was obtained in the concrete specimens prepared with steel slag and calcareous limestone aggregates, respectively. Similarly, the split tensile strength of steel slag aggregate concrete was the highest, followed by that of dolomitic and quartzitic limestone aggregate concretes. The lowest split tensile strength was noted in the calcareous limestone aggregate concrete. The type of coarse aggregate also influences the modulus of elasticity of concrete. Weaker aggregates tend to produce a more ductile concrete than stronger aggregates do.

Keywords: Coarse aggregate; Compressive and tensile strengths; High strength concrete; Modulus of elasticity

1. Introduction

The term high strength concrete is used for concrete with a compressive strength in excess of 41 MPa, as defined by the ACI Committee 363 [1]. Others define high strength concrete as that possessing a uniaxial compressive strength greater than that which is ordinarily obtained in a region, because the maximum strength of concrete which is currently being produced varies considerably from region to region [2]. Use of high strength concrete leads to smaller cross-sections and hence, the reduced dead load of a structure. This helps engineers to build taller buildings and bridges with longer spans.

In conventional concrete (compressive strength <41 MPa), the properties of coarse aggregates seldom become strength-limiting, because this type of concrete mixtures typically correspond to a water–cement ratio (w/c) in the range of 0.5–0.7. Within this range, the weakest components in concrete are the hardened cement paste and the transition zone between the cement paste and the coarse aggregate, rather than the coarse aggregate itself [3–7]. Similarly, when designing conventional concrete mixtures, the mineralogy of coarse aggregate is rarely of concern unless the aggregate contains some constituents, such as opal which is a reactive silica mineral that could have a deteriorating effect on concrete durability [8], while for a high strength (compressive strength >41 MPa) concrete, researchers have noted that the hardened cement paste and the transition zone are no longer strength-limiting, but it is the mineralogy and the strength of the coarse aggregate that control the ultimate strength of concrete.

The importance of the mineralogical characteristics of coarse aggregates on the quality of concrete has been pointed out by Farran [9], Maso [10], Alexander and Davis [11], Baalbaki et al. [12], and Giaccio et al. [13]. The effect of the coarse aggregate on elastic properties of high performance concrete (HPC) was also pointed out by Aitcin and Mehta [8], Baalbaki et al. [12], and Aitcin [14]. These authors observed some significant
differences in the elastic modulus and hysteresis loop in the case of HPCs prepared with different coarse aggregates, but with the same water-to-cement ratio \( w/c \). Aitcin et al. [15] investigated the effect of three different coarse aggregates in superplasticized concrete mixtures with identical materials and properties \( (w/c = 0.24) \). They found that for a calcareous-limestone aggregate (85% calcite), a dolomitic-limestone aggregate (80% dolomite), and a quartzitic-gravel aggregate containing schist, the 91 day compressive strengths were 93, 103 and 83 MPa, respectively. Moreover, they concluded that the aggregate–cement paste bond was stronger in the limestone aggregate concrete than in the gravel concrete due to the interfacial reaction effect [15]. Zhang and Gjorv [16] investigated the effect of four coarse aggregate types, available in north California, on the compressive strength and elastic behavior of a very high strength concrete mixture. Based on their study, some significant differences in the elastic moduli and hysteresis loop were observed. A formula was derived by Chang and Su [17] from the theory of granular mechanics to estimate the compressive strength of coarse aggregate to be used in high strength concrete. This study [17] showed that there is a good correlation between the compressive strength of aggregates and some of the engineering properties of concrete.

With increasing use of high strength concrete (HSC) as a structural material, further information on its mechanical properties is required, especially its stress–strain characteristics. Some studies [1,18,19] conducted to date have generally indicated that the empirical relationships between compressive strength and other properties, such as tensile strength, flexural strength, and modulus of elasticity, established for normal concretes cannot always be utilized for high strength concretes. Generally, it is noted that cracking of HSC is more localized and approaches a homogeneous material behavior as compared to normal strength concrete. Also, HSC exhibits more linear elastic behavior and is more brittle than normal strength concrete. Therefore, it is essential to develop data on the mechanical properties of hardened concrete, particularly its strength, in relation to the properties of the aggregates.

This paper reports the results of a study conducted to investigate the influence of coarse aggregate quality on the compressive and split tensile strength and elastic properties of high strength concrete.

### 2. Experimental program

#### 2.1. Materials and test specimens

ASTM C150 Type I Portland cement, with the chemical composition shown in Table 1, was utilized in preparing the concrete specimens. Four types of coarse aggregates, namely calcareous limestone (CC), dolomitic limestone (DL), quartzitic limestone (QZ), and steel slag (SS), were utilized to prepare the concrete mixtures. The physical properties of the coarse aggregates selected for this study and their grading are shown in Tables 2 and 3, respectively, while the quantity of clay lumps in the selected coarse aggregates are shown in Table 4.
Same aggregate grading was used in all the concrete mixtures. Dune sand with a bulk specific gravity of 2.54 and water absorption of 0.65% was used as fine aggregate. All the concrete mixtures were prepared with a water-to-cement ratio of 0.35 and a cement content of 450 kg/m³, and a coarse aggregate to fine aggregate ratio of 1.63. A naphthalene-based superplasticizer was used to improve the workability of the concrete mixtures.

Cylindrical concrete specimens, 75 mm in diameter and 150 mm high, were prepared for determining the compressive strength, split tensile strength, and modulus of elasticity. Mixing was done in a revolving drum type mixer for approximately 3–5 min to obtain uniform consistency. After mixing, the concrete was filled in the cylindrical moulds in two layers and consolidated on a vibrating table to remove entrapped air. After casting, the specimens were covered with a wet burlap and cured in the laboratory at a temperature of 20 ± 2 °C for 24 h prior to demolding and then cured under calcium hydroxide solution till the time of test.

2.2. Test techniques

2.2.1. Compressive strength

The compressive strength of concrete prepared using the selected coarse aggregates was determined by loading the specimens in uniaxial compression according to ASTM C 39 at a constant loading rate of 3.3 kN/s using a servo-controlled hydraulic testing machine of 3000 kN capacity. The compressive strength was determined after 3, 7, 14, 28 and 180 days of curing.

2.2.2. Split tensile strength

The tensile strength of concrete can be experimentally determined by [20]: (1) uniaxial tensile test; (2) split cylinder test; and (3) beam test in flexure. The first method of obtaining the tensile strength is referred to as a direct test for determining the tensile strength, while the second and third methods are indirect tests. The indirect method of applying tension in the form of splitting was suggested by Fernando Cerneiro, a Brazilian engineer [20], and the test is often referred to as the Brazilian test, although it was also developed independently in Japan.

In this study, the split tensile strength of concrete specimens prepared with the selected coarse aggregates was determined according to ASTM C 496.

2.2.3. Modulus of elasticity

The static modulus of elasticity was determined according to ASTM C 469. The specimens were tested in uniaxial compression at a constant rate of loading of approximately 3.3 kN/s using a servo-controlled hydraulic testing machine. A portable data logger was used to record the load and strain readings. longitudinal strains were measured using a compressometer that was fixed parallel to the direction of the applied load. The compressometer was centered at mid-height of the specimen and the compressive deformation was measured using two LVDTs located at diametrically opposite locations on the surface of the specimen. Fig. 1 shows the experimental set up utilized to evaluate the stress–strain characteristics of the concrete specimens prepared using the selected aggregates.

3. Results and discussion

3.1. Effect of aggregate quality on compressive strength of concrete

The effect of aggregate quality on the compressive strength of concrete was evaluated by testing concrete
specimens prepared with CC, DL, QZ and SS aggregates. Fig. 2 shows the variation of compressive strength with age for the concrete specimens prepared with the four types of aggregates selected for this study. As expected, the compressive strength increased with age in all the concrete specimens. Further, the data in Fig. 2 indicate that the type of coarse aggregate has a significant effect on the compressive strength of concrete. The highest compressive strength was measured in the concrete specimens prepared with the steel slag aggregates while the lowest compressive strength was noted in the concrete specimens prepared with calcareous limestone aggregates. After 28 days of curing, the compressive strength of concrete specimens prepared with calcareous, dolomitic, and quartzitic limestone and steel slag aggregates was 43, 45, 47 and 54 MPa, respectively.

The data developed in this study indicate that in a high strength concrete, i.e. concrete prepared with a low water-to-cement ratio and a high cement content, the compressive strength is dependent on the quality of coarse aggregate. In such concrete, the bulk of the compressive load is borne by the aggregates rather than the cement paste alone. The failure in such concretes is often through the aggregates. Since the calcareous limestone aggregates are known to be weaker than the dolomitic and quartzitic limestone aggregates the low load carrying capacity of concrete prepared with calcareous limestone aggregates is understandable. Similarly, the dolomitic limestone aggregates are weaker than the quartzitic limestone aggregates, as such marginally lower compressive strength of concrete prepared with former coarse aggregates compared to that prepared with the latter coarse aggregates is comprehensible.

The data on loss on abrasion summarized in Table 5 of these aggregates provide ample evidence of the weak nature of the calcareous and dolomitic limestone aggregates compared to the quartzitic limestone and steel slag aggregates. The compressive strength of steel slag aggregate concrete was more than that of the quartzitic limestone aggregate concrete. This indicates that this

<table>
<thead>
<tr>
<th>Type of aggregate</th>
<th>Loss on abrasion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcareous limestone</td>
<td>34.4</td>
</tr>
<tr>
<td>Dolomitic limestone</td>
<td>24.2</td>
</tr>
<tr>
<td>Quartzitic limestone</td>
<td>19.2</td>
</tr>
<tr>
<td>Steel slag</td>
<td>11.6</td>
</tr>
</tbody>
</table>

The data on loss on abrasion summarized in Table 5 of these aggregates provide ample evidence of the weak nature of the calcareous and dolomitic limestone aggregates compared to the quartzitic limestone and steel slag aggregates. The compressive strength of steel slag aggregate concrete was more than that of the quartzitic limestone aggregate concrete. This indicates that this
aggregate is very suitable for producing high strength concrete.

When concrete is subjected to compressive loads, failure takes place at one or more of the following locations: (i) within the paste matrix; (ii) at the paste–aggregate interface; or (iii) within the aggregate. In a rich concrete mix, as the one utilized in this study, the possibility of failure within the paste matrix, alone, is very rare, since this phase is very strong. Therefore, the failure plain has to pass through the paste–aggregate interface or through the aggregate. In both modes of failure, the quality of aggregate significantly influences the mode of failure of concrete under compression.

Another point to be noted is that the porous aggregates, such as calcareous and dolomitic limestone aggregates, are capable of absorbing a significant amount of water. Hence, the cement–aggregate bond in such aggregates is better than that of quartzitic limestone and steel slag aggregates. Therefore, the failure of concretes prepared with the calcareous and dolomitic limestone aggregates is presumed to be within the aggregates since the interface in these concrete specimens is strong due to a good bond between the aggregate and the cement paste. Such a failure was noted in the concrete specimens on visual inspection after testing in compression. Higher compressive strength of steel slag and quartzitic limestone aggregate concretes compared with calcareous and dolomitic limestone aggregate concretes may thus be attributed to the quality of the aggregates. As shown in Table 5, the loss on abrasion of calcareous and dolomitic limestone aggregates was more than that in the quartzitic limestone and steel slag aggregates. The higher strength of quartzitic limestone and steel slag aggregates, contributes to increased compressive strength of concrete prepared with these aggregates.

According to Wasserman and Bentur [21], the physical process that occurs at an early age is governed by the absorption of water into the aggregate. Higher absorption eliminates the accumulation of water in the fresh matrix in the vicinity of the aggregate; as a result, the interfacial transition zone in the aggregates with higher absorption is denser. Aitcin and Mehta [8] noted that in a high-strength concrete the hardened cement paste and the transition zone are no longer strength limiting. On the other hand, the mineralogy and the strength of coarse aggregates may control the ultimate strength of concrete, particularly in a high strength concrete.

Baalbaki et al. [12] investigated the influence of three different types of crushed coarse aggregates (dolomitic limestone, quartzite, and sandstone) on the elastic properties of high strength concrete. They found that the highest and lowest compressive strength was of the sandstone and quartz aggregate concretes, respectively [12]. The low compressive strength of quartz concrete may be explained by the relative incompressibility of the aggregates that improves the rigidity of concrete and decreases the strength. On the other hand, the capacity of the sandstone aggregate to deform in one direction allows the stress to be more uniformly distributed; thereby, the whole section contributes to strength, as opposed to the rigid aggregates that tend to concentrate stresses on certain regions of the section, therefore creating premature ruptures [12].

The average rate of strength development, as shown in Fig. 2, was higher at early ages, where the ratio of 7–28 days strengths, ranged from 0.74 to 0.80, compared with 0.73 to 0.82 reported by Berke et al. [22]. Also, the ratio of 28–180 days strength was in the range 0.88–0.93 compared with 0.85–0.95 reported by Berke et al. [22]. This observation is in good agreement with that reported by Carette and Malhotra [23] and also by Slate et al. [18]. According to Carrasquillo et al. [24], the ratio of 7–28 days strengths is between 0.60 and 0.65 in the case of normal strength concrete. The higher rate of strength gain of HSC compared to normal strength concrete is attributed to the high internal curing temperature developed during hydration [18]. The high heat of hydration is associated with the high cement content in HSC mixes. Differences in the rate of strength gain, however, becomes negligible at later ages [18].

3.2. Effect of aggregate quality on split tensile strength of concrete

The split tensile strength was determined after 14, 28 and 90 days of curing. Fig. 3 shows the split tensile strength of concrete specimens prepared with the four
types of aggregates investigated in this study. The split tensile strength increased with age in all the concrete specimens. As can be seen in Fig. 3 the split tensile strength of steel slag aggregate concrete was the highest, followed by that of quartzitic and dolomitic limestone aggregate concretes. The least split tensile strength was noted in the concrete specimens prepared with calcareous limestone aggregates. However, the split tensile strength of concrete specimens prepared with quartzitic and dolomitic limestone aggregates was almost similar after 28 days of curing. After this age, the split tensile strength of steel slag aggregate concrete was 164% of that of calcareous limestone aggregate concrete. Similarly, the split tensile strength of concrete prepared with the dolomitic and quartzitic limestone aggregates was 129 and 130%, respectively, of that prepared with the calcareous limestone aggregates.

3.3. Effect of aggregate quality on the static modulus of elasticity of concrete

Fig. 4 shows the measured values of the modulus of elasticity of concrete specimens prepared with the selected aggregates. These data indicate that the type of coarse aggregate has a significant effect on the modulus of elasticity of concrete. After 28 days of curing, the modulus of elasticity of calcareous, dolomitic and quartzitic limestone and steel slag aggregate concretes was 21.6, 24.5, 28.8 and 29.6 GPa, respectively.

The modulus of elasticity of concrete may be attributed to the soft nature of these aggregates. A more ductile failure results in the concrete specimens prepared with these aggregates.

The importance of coarse aggregate quality on elastic properties of high strength concrete was also pointed by Aitcin [14], and Aitcin and Mehta [8]. Some significant differences in the elastic modulus and hysteresis loop were noted in high strength concrete prepared with different coarse aggregates. Baalbaki et al. [12] also evaluated the effect of coarse aggregates on the elastic properties of high strength concrete. The elastic modulus of high strength concrete was noted to be strongly influenced by the elastic properties of coarse aggregates [12]. Similarly, Giaccio et al. [13] noted that the highest modulus of elasticity of concrete was achieved in basaltic-HSC, followed by limestone-HSC and granitic-HSC. They [13] stated that this could be attributed to a higher percentage of microcracking in limestone-HSC during the first loading applied to measure the modulus of elasticity.

As is apparent from the data in Fig. 4, the static modulus of elasticity was higher for the concretes containing steel slag aggregates and quartzitic limestone aggregate concretes, than for concrete prepared with calcareous and dolomitic limestone aggregates. For higher compressive strength concretes, the modulus of elasticity was higher because of the mortar stiffness and improved mortar–aggregate bond. Hooton [25], Luther and Hanse [26], and Khatri and Sirivivatnanon [27] also found that elastic modulus is primarily a function of compressive strength. Based on the previous discussion, it can be concluded that the effect of the type of coarse aggregate is more significant on the modulus of elasticity as compared to the compressive strength. According to Aitcin and Mehta [8], and Baalbaki et al. [12], the nature of coarse aggregate significantly affects the modulus of elasticity of high strength concrete. This influence was attributed to the highly dense paste structure and paste–aggregate bond, which causes the concrete to behave like a composite material. Therefore, aggregate characteristics could be important in determining the elastic properties of high strength concrete.

4. Conclusions

The quality of coarse aggregate has a significant effect on the compressive strength of high strength concrete. The compressive strength of steel slag aggregate concrete was more than that of crushed limestone aggregate concrete. The compressive strength of concrete prepared with calcareous limestone aggregate was the least. These data indicate that in a high strength concrete, i.e. concrete prepared using a low water–cement ratio and high cement content, the compressive strength is dependent on the quality of aggregate. In such concrete, the bulk of the compressive load is borne by the aggregate rather than the cement paste alone.
The failure in such concretes is often through the aggregates. Since the calcareous limestone is known to be weaker than the dolomitic and quartzitic limestone aggregates, its low load carrying capacity is understandable.

Split tensile strength increased with age in all the concrete specimens. The type of aggregate also influences the split tensile strength of concrete. The split tensile strength of steel slag aggregate concrete was more than that of limestone aggregate concrete. The least split tensile strength was noted in the calcareous limestone aggregate concretes.

The quality of coarse aggregate also influences the modulus of elasticity of concrete. Weaker aggregates tend to produce a more ductile concrete than strong aggregates do.

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