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Effect of coarse aggregate type on mechanical properties of high-performance concrete

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Abstract

Tests were carried out to study the effect of the coarse aggregate type on the compressive strength, splitting tensile strength, fracture energy, characteristic length, and elastic modulus of concrete produced at different strength levels with 28-day target compressive strengths of 30, 60, and 90 MPa, respectively. Concretes considered in this paper were produced using crushed quartzite, crushed granite, limestone, and marble coarse aggregate. The results show that the strength, stiffness, and fracture energy of concrete for a given water/cement ratio (W/C) depend on the type of aggregate, especially for high-strength concrete. It is suggested that high-strength concrete with lower brittleness can be made by selecting high-strength aggregate with low brittleness. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Concrete; Aggregate; Mechanical properties; Compressive strength

1. Introduction

Strength performance remains the most important property of structural concrete, from an engineering viewpoint. The relation between concrete composition and mechanical properties has long been a matter of research interest [1–4]. The strength of the concrete is determined by the characteristics of the mortar, coarse aggregate, and the interface. For the same quality mortar, different types of coarse aggregate with different shape, texture, mineralogy, and strength may result in different concrete strengths. However, the limitation of the water/cement ratio (W/C) concept is becoming more apparent with the development of high-performance concrete, in which the aggregate plays a more important role [5].

For high-strength concrete, which is usually made with a W/C less than 0.4, the strength of the mortar and the bond at the interface may be similar to the strength of the coarse aggregate. In such a case, it may be possible to make use of the full strength potential of the coarse aggregate particles. At the same time, with the strength improved, the brittleness of concrete is also increased, which limits the use of concrete. Thus, using a coarse aggregate of higher strength and lower brittleness, proper texture and mineralogical characteristics may improve the mechanical properties of the concrete. This paper reports the results of a study undertaken to investigate the effect of four different types of coarse aggregate on the compressive strength, flexural and splitting tensile strength, fracture energy, elastic modulus, and characteristic length of concrete designed to achieve three different strength levels.

2. Experimental work

2.1. Raw materials

2.1.1. Cement

ASTM type I, made by the Wusong cement factory, with a 28-day compressive strength of 63.5 MPa.

2.1.2. Ultrafine slag powder

The slag was provided by the Shaofeng cement factory of Hunan, and had a specific surface of 600 m^2/kg.

2.1.3. Aggregate

The fine aggregate was river sand with a fineness modulus of 2.85 from Yangzi river. The coarse aggregates are defined as crushed particles with particle size between

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Table 1
Relative proportions of concrete mix

	Binder[a]				
Water	Cement	Slag	Coarse aggregate	Sand	Superplasticizer[b] (%)
0.26	0.7	0.3	1.41	0.94	1.25
0.44	0.7	0.3	2.91	1.94	1.25
0.55	0.7	0.3	3.0	2.0	0.5

[a] For W/C = 0.26, total binder = 674 kg/m^3; for W/C = 0.44, total binder = 382 kg/m^3; for W/C = 0.55, total binder = 340 kg/m^3.

[b] Percentage by mass of binder.

5 and 20 mm, and included: crushed quartzite (CQ) from Shanghai, crushed granite (CG) from Fujian, limestone (LS) from Hunan, and marble (MB) from Anhui.

2.1.4. Superplasticizer

A sulphonated naphthalene formaldehyde superplasticizer was used.

2.2. Mixture proportions

In order to investigate the effect of aggregate on the different strength levels of concrete, three concrete mixtures were designed to have 28-day compressive strengths of 30, 60, and 90 MPa. For the same strength level concrete mixture, the mixture proportions of all aggregates were the same and the maximum size of the coarse aggregate was 20 mm. The details of concrete mix proportions are given in Table 1.

2.3. Tests

2.3.1. Compressive strength (f_c)

Three 100 × 100 × 100 mm specimens were cast for each concrete mixture.

2.3.2. Tensile splitting strength (f_{st})

This was determined by three 100 × 100 × 100 mm specimens and the value was calculated by the following equation:

$$f_{\mathrm{st}} = \frac{2P}{\pi A} = 0.637P/A$$

where P is the failure loading (N) and A is the area of cross-section (mm^2).

2.3.3. Fracture energy

This was determined by means of three-point bend tests according to the RILEM TC50-FMC (Fracture Mechanics of Concrete) recommendation for determination of the fracture energy of concrete [6]. The beam length, width, and depth were 515, 100, and 100 mm, respectively. The beam specimen used in this study is shown in Fig. 1 and the fracture energy G_{f} of the concrete can be calculated by the following equation:

$$G_{\mathrm{F}} = \frac{W_0 + \mathrm{mg}\delta_{\mathrm{max}}}{A_{\mathrm{lig}}}$$

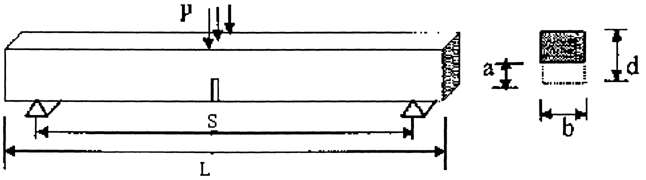

Fig. 1. Three-point bend specimen.

where W_0 is the area under the load-deflection curve (N m), mg is the self-weight of the specimen between supports (kg), δ_{max} is the maximum displacement (m), and A_{lig} is the fracture area $[d(b-a)]$ (m^2); b and d are the height and width of the beam, respectively; a is the depth of the notch.

2.3.4. Elastic modulus (E)

This was determined by the initial slope (P/Δ) of the P–δ curve for a three-point bend beam and was calculated by the following equation:

$$E = \frac{P}{\Delta}\frac{S^2}{4bd^2}\left(6V\left(\frac{a}{d}\right) + \frac{S}{d}\right)$$

For $S/d = 4$,

$$V\left(\frac{a}{d}\right) = \left(\frac{a/d}{1-a/d}\right)^2\left(5.58-19.57\left(\frac{a}{d}\right) + 36.82\left(\frac{a}{d}\right)^2 -34.94\left(\frac{a}{d}\right)^3 + 12.77\left(\frac{a}{d}\right)^4\right)$$

where S is the span of specimen (m); b and d are the height and width of the beam, respectively; a is the depth of the notch. In this experiment, the slope was obtained by linear regression of the curve of P–δ when the load achieved 40% of the maximum load.

2.3.5. Characteristic length

The brittleness of concrete can be expressed by its characteristic length l_{ch} (m), $l_{\mathrm{ch}} = EG_{\mathrm{F}}/f_{\mathrm{t}}^2$, where f_{t} is the tensile strength (MPa).

Table 2
Test results of concrete

W/C	Aggregate	f_c (MPa)	f_{st} (MPa)	E (GPa)	G_F (N/m)	l_{ch} (m)
0.26	CQ	98.2	8.4	48.2	166.1	0.113
	CG	99.1	7.9	36.2	150.2	0.087
	LS	83.4	7.3	33.2	157.3	0.098
	MB	79.8	7.6	33.7	165.2	0.096
0.44	CQ	70.4	5.2	39.5	158.1	0.231
	CG	65.8	5.3	36.2	145.2	0.187
	LS	60.5	5.0	31.5	156.3	0.197
	MB	62.1	5.1	31.0	146.3	0.174
0.55	CQ	44.8	4.1	37.5	143.1	0.319
	CG	43.2	4.2	28.3	135.2	0.216
	LS	46.6	3.9	30.1	152.3	0.301
	MB	45.0	4.2	29.0	142.1	0.234

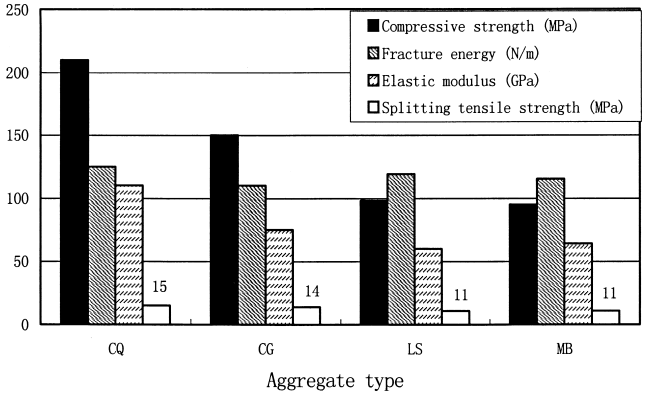

Fig. 2. Mechanical properties of rock.

The mechanical properties of the aggregates were also determined. The tests were performed on cores that were drilled from rock at the production sites of the aggregates. The core diameter was 60 mm. The properties determined were compressive and splitting tensile strengths, the modulus of elasticity, and the fracture energy. The length of the specimens was 120 mm in the first three tests and 300 mm in the fracture energy tests. In the fracture energy tests, the depth of the notch was half of the core diameter.

3. Results and discussion

3.1. Test results

The mechanical properties of the concrete mixes and the rocks for the coarse aggregates are shown in Table 2 and Fig. 2, respectively. The results correspond to the mean values of at least three tests.

3.1.1. Compressive and splitting tensile strengths

Fig. 3 shows the relationship between the compressive strength of concrete and the coarse aggregate. As W/C is lowered, namely for high-strength concrete, the strength of concrete is enhanced with increasing strength of coarse aggregate. However, for normal-strength concrete, the effect of the type of coarse aggregate on the compressive strength is not significant. For normal-strength concrete, bond cracks exist to a considerable extent before the concrete is subjected to any external load. Under load, these small or microscopic cracks extend and interconnect, until, at ultimate load, the whole internal structure is completely disrupted. The aggregates had, in comparison with concrete, relatively high strength and their full potential strength was not used. In high-strength concrete, the strength of paste and interface of cement–aggregate bond is also improved. Under load, the cracks may extend through the aggregate, which makes use of the full strength potential of the coarse aggregate particles. Therefore, in high-strength concrete, the coarse aggregate plays an important role in the strength. The relationship between compressive strength of concrete and the coarse aggregate agrees with results obtained in the other studies [7,8].

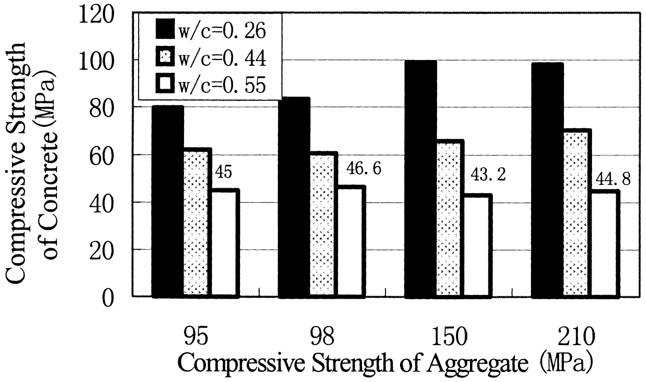

Fig. 3. The relationship between compressive strength of concrete and aggregates.

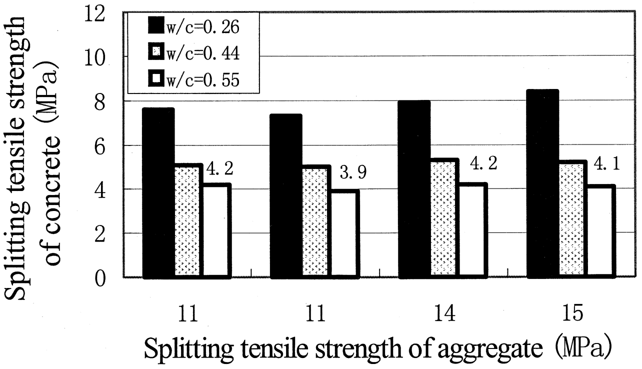

Fig. 4. The relationship between splitting tensile strength of concrete and aggregate.

In contrast to the compressive strength results, the results of the splitting tensile tests show that the splitting tensile strength of concrete is influenced by the splitting tensile strength of aggregates to a small extent (Fig. 4).

3.1.2. Fracture energy and characteristic length

Fig. 5 shows the relationship between fracture energy of concrete and aggregates, for the various W/C and different types of coarse aggregates. As the figure shows, the fracture

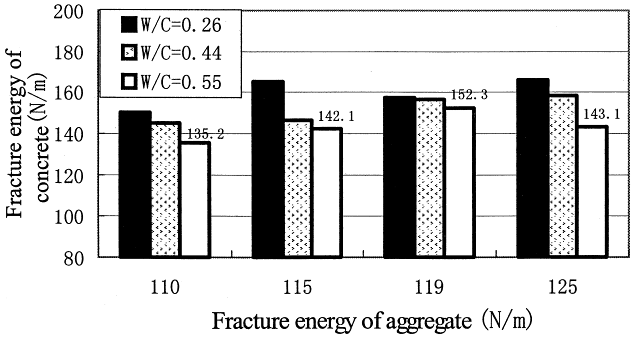

Fig. 5. The relationship between fracture energy of concrete and aggregate.

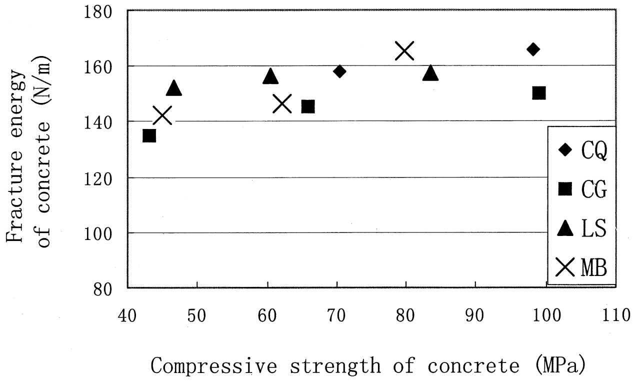

Fig. 6. The relationship between fracture energy and compressive strength of concrete.

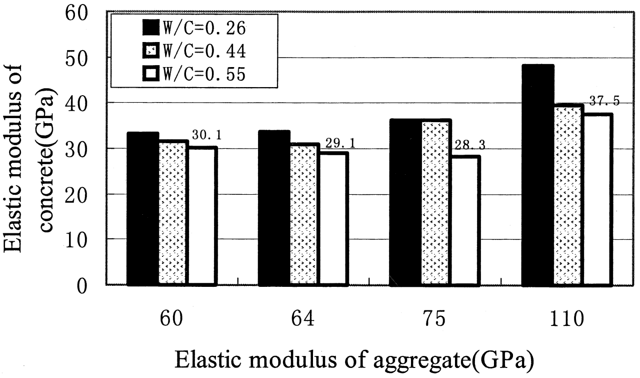

Fig. 8. The relationship between the elastic modulus of concrete and aggregate.

energy of concrete for a given W/C increases with increasing fracture energy of aggregates in three cases, whereas in one case, it decreases. The reason may be that besides the fracture mechanical properties of the aggregates, assuming that the mechanical properties of the aggregates are the same as the rocks, other properties, such as the particle form, the mineralogy, and the roughness of the surface of the aggregates, may have effects on the fracture energy. In handbooks and design codes, the fracture energy is normally expressed as a function of the concrete compressive strength. Fig. 6 shows the results of the fracture energy tests as a function of compressive strength. As can be observed, the fracture energy increases with increasing strength of concrete for any given coarse aggregate type. In normal-strength concrete, coarse aggregate acts as crack arrestors during the fracture process and the cracks pass through the hardened cement paste or propagate around the aggregate. In high-strength concrete, the strength of the hardened cement paste is by definition, high because a very low W/C is used and the porosity of the hardened cement paste is very low. This situation results in a better bond strength and a more monolithic behavior of concrete. Subsequent fracture of concrete takes place through the coarse aggregate particles. Therefore, in high-strength concrete, the fracture energy of aggregate has a greater influence on the fracture energy of concrete than is the case in normal-strength concrete. Fig. 6 shows that the fracture energy of concrete with granite aggregate is less than with quartzite by 10–20% at the same strength level. From the results, it is found that the type of aggregate has an influence on the fracture energy of concrete and certain aggregates can reduce the brittleness of high-strength concrete.

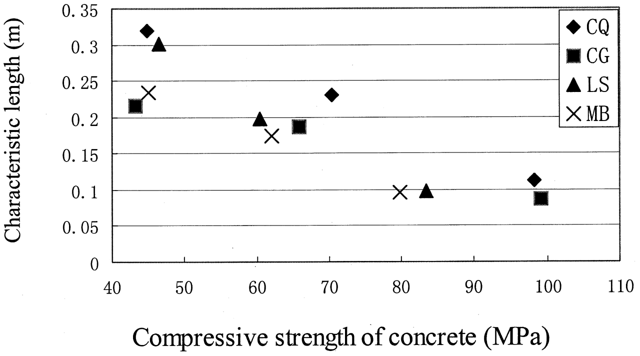

Fig. 7. The influence of strength of concrete on characteristic length.

The brittleness of concrete can be expressed by its characteristic length l_{ch}. As far as the effects of the strength of concrete and the types of the aggregates on the characteristic length are concerned, the same tendencies as the fracture energy are observed. Furthermore, the results show that the brittleness of concrete increases, that is, the characteristic length reduces, with increasing strength, as shown in Fig. 7.

3.1.3. Elastic modulus of concrete

The elastic properties of concrete are known to be influenced by elastic properties of the constituent materials and nature of the interfacial zone between aggregates and paste [8]. Due to the inherent stiffness and large volume fraction it occupies in concrete, the aggregate exerts the major influence on the elastic modulus of concrete. Not only aggregate stiffness, but also aggregate type, affects the elastic modulus. In Fig. 8, for the same W/C, the elastic modulus of quartzite concrete is the highest. The reason may be that the modulus of quartzite is higher than the other aggregate by 30–50%. As the strength of concrete is reduced, the influence of aggregate on elastic modulus of concrete becomes smaller. At the same time, the elastic modulus increases with increasing strength of concrete.

4. Conclusion

The impact of the type of coarse aggregate on the strength of concrete is more significant in high-strength concrete. In high-strength concretes in the present study, about 10–20% higher compressive and splitting tensile strengths are obtained with crushed quartzite compared to marble aggregate. However, in concrete with a target strength of 30 MPa, strength differences between concretes made with different coarse aggregates are reduced. The results of fracture energy show that besides the fracture mechanical properties of the aggregates, the type of coarse aggregates has significant effects on the fracture energy. It is suggested that the high-strength concrete with lower brittleness can be made by selecting high-strength aggregate with low brittleness.

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