Fracture Mechanics of Concrete Structures
Proceedings FRAMCOS-3
AEDIFICATIO Publishers, D-79104 Freiburg, Germany

THE INFLUENCE OF THE TYPE OF COARSE AGGREGATES ON THE FRACTURE MECHANICAL PROPERTIES OF HIGH-STRENGTH CONCRETE

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Abstract

The paper investigates the effects of geologically different types of crushed coarse aggregate on the strength, stiffness and fracture energy of high-strength concrete. The results show that the strength, stiffness and fracture energy of concrete depend on the type of aggregate. However, the results do not reveal the existence of any significant correlations between the mechanical properties of the rocks, which the aggregates are made of, and the fracture energy and compressive strength of concrete.
Key words: coarse aggregates, fracture energy, High-strength concrete

1 Introduction

In a normal-strength concrete, by which is meant concrete with water/binder ratio grater than 0.4, the strength of the aggregate is normally higher than the mortar and the interfacial transition zone. Hence, in a normal-strength concrete the fracture processes mainly take place within the mortar, by which is meant hydrated and unhydrated binder and pores, and the interfacial transition zone. In a high-strength concrete, however, due to the low water/binder ratio and perhaps addition of the silica fume, the strength of the mortar and the interfacial zone can be sufficiently high to involve the aggregates in the fracture processes. Since the strength of the mortar and the interfacial transition zone increase with decreasing water/binder ratio the involvement of the aggregates in the fracture processes increases with decreasing water/binder ratio, Tasdemir et al. (1995).

The volume fractions of the mortar, the fine aggregates and the coarse aggregates in concrete are approximately 30%, 35% and 35% respectively, i.e. the volume fraction of the coarse aggregates is approximately the same as that of the mortar. Since, in a high-strength concrete the coarse aggregates are involved in the fracture processes as well as the surrounding mortar the fracture behaviour of aggregates and their influences on the fracture mechanical properties of concrete should not be neglected when designing high-strength concrete.

This paper presents results of tests which were conducted in order to investigate the effects of the geologically different crushed coarse aggregates, particle size between 8 and 16 mm, on the strength, stiffness and fracture energy of the high-strength concrete.

2 Method

2.1 Concrete compositions

The concrete mixes which were used in the investigation differ with regard to the water/binder ratio, W/B ratio, the content of the silica fume and the type of the coarse aggregates. The binders and the water/binder ratios which were used are shown in Table 1.

Table 1. The binders and the water/binder ratios

Binder	Water/binder ratio		
Ordinary portland cement, (OPC)	0.30	0.40	0.55
OPC and silica fume (S), (OPCS) S/OPC = 0.05	0.30	0.40	

The coarse aggregates are defined as the crushed particles with a particle size between 8 and 16 mm. The aggregates were diabase (DB), fine-grained granite (GF), medium-grained granite (GM), gneiss (GN), quartzite (QS) and quartzite (QH). The aggregates were from different locations in Sweden. The fine aggregates, which are defined as natural particles with a particle size between 0 - 8 mm, were the same for all the concrete mixes. The ratio between the coarse and the fine aggregates was 1.5 in all concrete mixes. The volume fraction of the aggregates was 0.67 in all concrete mixes.

The total number of concrete mixes was 30, i.e. 5 (mortars) x 6 (coarse aggregate types).

2.2 Tests

The compressive, f_{cc}, the tensile splitting, f_{cts}, the flexural, f_{cf}, and the net flexural, $f_{cf,net}$, strengths of concrete were determined. Furthermore, the compressive modulus of elasticity, E_{cc}, and the fracture energy, G_F, of the concrete were determined. The compressive strength was determined by means of cubic specimens, 100 mm edge size. The splitting tensile strength was determined by means of cylindrical specimens, 200 mm length and 100 mm diameter. The compressive modulus of elasticity, i.e. unloading secant modulus within the stress limits 0.5 MPa - $f_{cc,cyl}/3$, was determined by means of cylindrical specimens. The fracture energy was determined by means of three-point bend tests according to the RILEM TC50 draft recommendation. The beam length, width and depth were 840 mm, 100 mm and 100 mm respectively. The net flexural strength was determined by means of the fracture load of the specimens which were used in the fracture energy tests. The flexural strength was determined by means of three-point bend tests on the halves of the beams which were used in the fracture energy tests.

All specimens were cast in steel moulds from the same batch. The specimens were demoulded the day after casting and were stored in the lime saturated water until the day of testing at 28 days of age. However, in accordance with Swedish standards, the compressive test specimens were removed from the water five days after casting. The specimens were stored in the laboratory climate until the day of testing at 28 days of age.

The mechanical properties of the aggregates were also determined. The tests were performed on the cores which were drilled at the production sites of the aggregates. The core diameter was 60 mm. The properties which were determined are compressive and the tensile splitting strength, 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 Test results

The mechanical properties of the concrete mixes and the rocks, coarse aggregates, are shown in Table 2 and Figure 1 respectively. The results corresponds to the mean values of at least three tests.

Table 2. Test results

W/B ratio	Agg.	f_{cc} MPa	f_{cts} MPa	f_{cf} MPa	$f_{cf,net}$ MPa	E_{cc} GPa	G_F N/m
0.30 OPC	DB	129	6.4	10.3	8.4	51	191
	GN	120	6.3	9.0	7.2	39	146
	GF	114	6.3	9.0	6.7	42	163
	GM	121	5.9	8.0	7.3	41	164
	QS	126	6.9	9.5	7.7	41	170
	QH	124	5.9			41	147
0.40 OPC	DB	84	5.2	8.0	6.3	44	199
	GN	86	4.6	6.1	6.1	34	144
	GF	82	5.2	7.7	5.9	37	163
	GM	93	4.9	7.6	6.1	36	170
	QS	93	5.2	7.2	6.1	36	201
	QH	90	5.0			36	129
0.55 OPC	DB	55	4.3	5.4	5.2	38	133
	GN	55	4.3	7.0	5.1	29	128
	GF	58	4.4	6.3	6.0	33	193
	GM	57	4.0	7.0	5.1	32	130
	QS	57	4.8	6.4	5.3	31	152
	QH	56	3.7			32	128
0.30 OPCS	DB	126	6.3	10.5	7.8	49	161
	GN	131	6.2	10.6	7.5	40	139
	GF	121	6.8	10.8	8.8	42	192
	GM	129	6.3	10.8	7.9	42	174
	QS	135	7.1	10.2	8.3	42	160
	QH	128	6.5			42	176
0.40 OPCS	DB	104	5.8	7.8	6.6	45	161
	GN	104	5.0	7.2	6.4	33	154
	GF	102	5.5	7.9	6.8	38	144
	GM	96	5.2	7.9	6.3	37	145
	QS	104	5.9	8.1	6.9	35	154
	QH	101	5.7			38	163

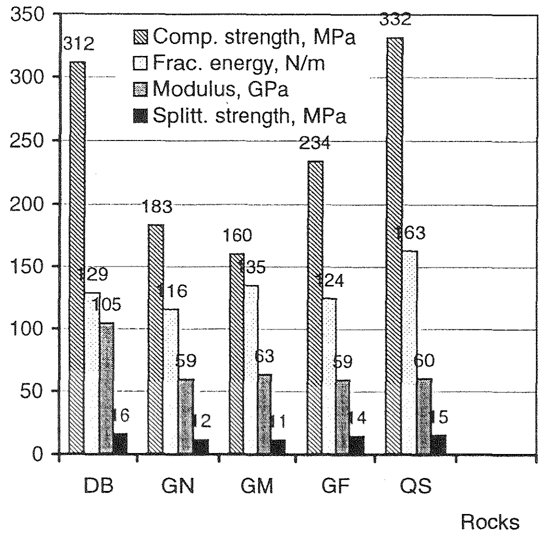

Fig. 1. Mechanical properties of coarse aggregates

4 Discussion

4.1 Compressive and splitting strength

Figure 2 shows the compressive strength of the concretes as functions of the W/B ratio. The curves are obtained by fitting equation 1 to the results of the compressive tests. As the figure shows, the effect of the type of coarse aggregate on the compressive strength is not considerable. The reason may be that the aggregates which were used had, in comparison with concrete, relatively high strength. Furthermore, application of statistical methods has not revealed any significant correlations between any of the fracture mechanical properties of the aggregates and the compressive strength of the concrete.

$$f_{cc} = K \cdot \left(\frac{1}{wbr_{eff}} - a \right) \tag{1}$$

$$wbr_{eff} = \frac{W}{C + \beta \cdot S}$$

K and a are curve fitting constants. W, C and S are the contents of water, cement and silica fume respectively. β is an efficiency factor which was equated to 2 during curve fitting.

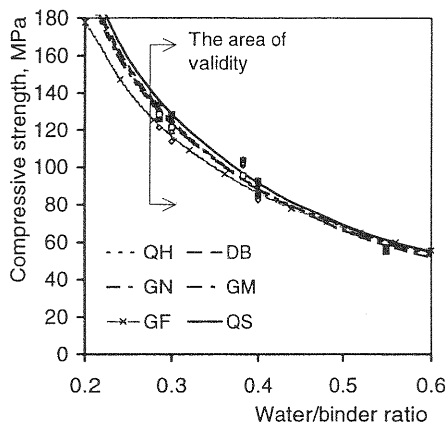

Fig. 2 The compressive strength as a function of W/B ratio

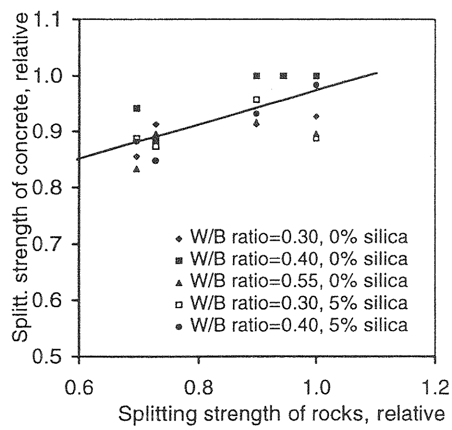

Fig. 3 The relative splitting strength of concrete as a function of the relative splitting strength of rocks

In contrast to the compressive strength the results of the splitting tests show that the splitting strength of concrete is to some extent influenced by the splitting strength of aggregates, Figure 3.

The modulus of elasticity of diabase is 105 GPa which is considerably greater than the modulus of elasticity of the other rocks. As can be observed in Table 2 the modulus of elasticity of concretes which contain diabase is greater than concretes containing the other types of aggregate.

4.2 Fracture energy and characteristic length

Figure 4 shows the variation of fracture energy with the W/B ratio for concretes which contain different types of coarse aggregates. The concretes which are presented in the figure do not contain silica fume. As the figure shows, the fracture energy increases with decreasing W/B ratio in two cases whereas in one case it decreases. Furthermore, in three cases the fracture energy assumes a maximum value in the intermediate range of the W/B ratio. Application of statistical methods has not revealed any significant correlations between any of the fracture mechanical properties of the rocks and the fracture energy of the concrete. 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. Perhaps these properties play an important role when considering the micro-cracking which takes place outside of the fracture process zone. These effects of the mentioned properties on the fracture energy have not been investigated.

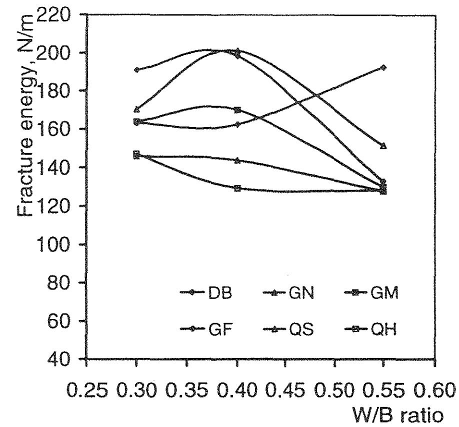

Fig. 4 Influence of the aggregate type and W/B ratio on the fracture energy of concrete, 0% silica content

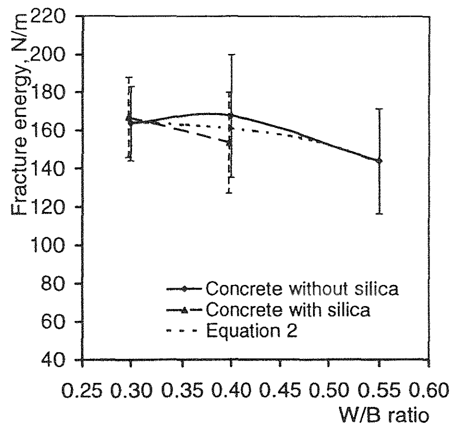

Fig. 5 The influence of W/B ratio on fracture energy of concrete

Disregarding concrete containing gneiss, the fracture energy increases with decreasing W/B ratio when silica fume is included, Table 2. For concretes with 0.4 W/B ratio the addition of the silica fume has a negative effect on the fracture energy except for concrete made of quartzite H. For concretes with 0.3 W/B ratio the addition of the silica fume has a negative effect on the fracture energy in 50% of cases.

Figure 5 shows the variation of the fracture energy with W/B ratio. The data in the figure corresponds to the mean value of all the fracture energy tests irrespective of the type of aggregate. Furthermore, the figure shows a mathematical function, equation 2, fitted to all results irrespective of the content of the silica fume and the type of aggregate.

$$G_F = 166 \cdot (1 - e^{10(W/B - 0.75)}) \qquad N/m \qquad 0.30 \le W/B \le 0.55 \tag{2}$$

In handbooks and design codes the fracture energy is normally expressed as a function of the compressive strength. Figure 6 shows the results of the fracture energy tests as a function of compressive strength. As can be observed, the compressive strength is not an appropriate parameter to express the fracture energy of the concrete. The figure also shows also a mathematical function, equation 3, fitted to the test results. The values ±15 are the limits of the 95% confidence intervals of the function. Furthermore, the figure shows the fracture energy as a function of compressive strength according to the CEB-FIP's Model Code 1990. It should be noted that the cylinder compressive strength of CEB has been converted to the cube compressive strength by using the multiplication factors 1.05x1.35.

$$G_F = 168 \cdot (1 - e^{-0.035 f_{cc}}) \pm 15 \qquad N/m \qquad 50 \le f_{cc} \le 140\ MPa \tag{3}$$

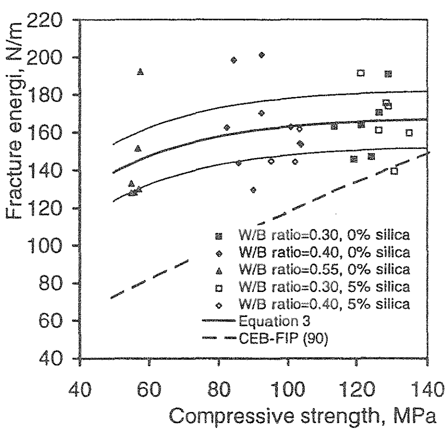

Fig. 6 Fracture energy as a function of compressive strength

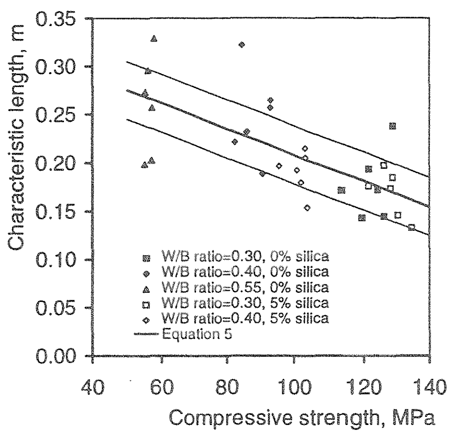

Fig. 7 Characteristic length as a function of compressive strength

The brittleness of concrete can be expressed by its characteristic length l_{ch} (m), Petersson (1981).

$$l_{ch} = \frac{E \cdot G_F}{f_t} \tag{4}$$

E, G_F and f_t are modulus of elasticity, fracture energy and uniaxial tensile strength respectively. However, in this investigation f_t has been equated to f_{cts}.

As far as the effects of the W/B ratio 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 with increasing strength, Figure 7. The figure also shows a mathematical function, equation 5, fitted to the test results.

$$l_{ch} = (-1.34 \cdot 10^{-3} \cdot f_{cc} + 0.34) \pm 0.03 \quad m \quad 50 \leq f_{cc} \leq 140 \; MPa \tag{5}$$

4.3 Flexural and net flexural strength

Both flexural and net flexural strength increase with decreasing W/B ratio. The influence of the coarse aggregates on these parameters is the same as in the case of the splitting tensile strength. Figure 8 shows the flexural and the net flexural strength as functions of the compressive strength. As can be observed the difference between the flexural and net flexural strength increases with increasing strength. The results indicate that the crack sensitivity of the concrete increases with increasing strength.

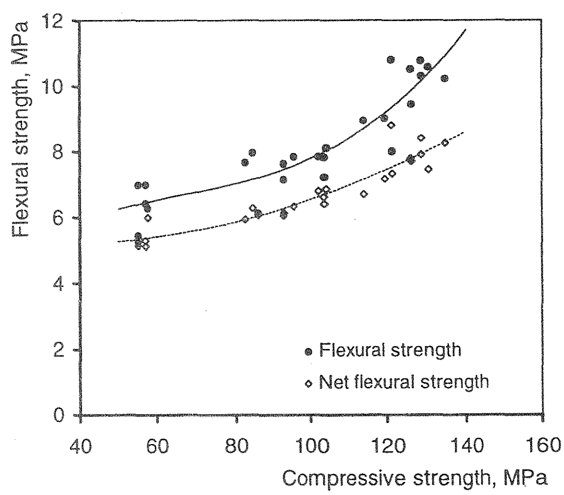

Fig. 8 The flexural and the net flexural strength as functions of the compressive strength

5 Conclusions

The types of coarse aggregate used in this investigation have little effect on the compressive strength of concrete. Furthermore no significant correlations between any of the fracture mechanical properties of the aggregates and the compressive strength of concrete have been observed.

The results show that both splitting tensile strength and modulus of elasticity of the concrete are influenced by the splitting tensile and modulus of elasticity of the aggregates.

The tests show that the type of aggregate has a considerable effect on the fracture energy when it is expressed as a function of the W/B ratio. Depending on the type of the aggregate the fracture energy may increase, or decrease by decreasing W/B ratio, or assume a maximum value in the intermediate range of the W/B ratio.

According to the results the brittleness and the crack sensitivity of the concrete increase with increasing strength of the concrete.

Acknowledgements

This investigation was a part of the Swedish national project dealing with high-performance concrete. This investigation has been conducted with the aid of financial support from Cementa, Elkem, Euroc Beton, NCC Bygg, SKANSKA, Strängbetong, The Swedish Council for Building Research (BFR) and Swedish National Board for Industrial and Technical Development (NUTEK). The project was conducted at the Division of Building Materials, Lund Institute of Technonlogy, Sweden.

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