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# FRACTURE PROPERTIES OF HIGH STRENGTH CONCRETE WITH VARYING SILICA FUME CONTENT AND AGGREGATES

F.P. Zhou, B.I.G. Barr and F.D. Lydon
School of Engineering, Division of Civil Engineering,
University of Wales College of Cardiff, Cardiff, CF2 1YF, U.K.

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## ABSTRACT

The paper reports on a fracture mechanics study of high strength concrete (water-binder ratios of 0.32 and 0.23) with compressive strength in the range 80 to 115 MPa. Silica fume contents of 10% and 15% cement replacement were used in conjuction with 10 mm gravel, 10 mm crushed limestone and 20 mm crushed limestone. In each case, compressive strength, splitting tensile strength, flexural strength, fracture energy , Young's Modulus, $K_{IC}$ and $CTOD_C$ were determined. Increasing the silica fume content from 10% to 15% is more significant for concretes with higher water-binder ratio. 20 mm crushed limestone produces higher compressive strength than 10 mm crushed limestone and gravel. The fracture energy increases with increasing aggregate size and stiffness and $K_{IC}$ increases with increasing compressive strength. The characteristic length is shown to be a good measure of brittleness of high strength concrete.

## Introduction

During the last two decades concrete technology has been undergoing rapid development. Concrete with strength in excess of 100 MPa can be produced readily with ordinary cement and aggregates [1] and [2]. Apart from strength, other properties, e.g. durability, have also improved due to the developments in concrete technology.

Unfortunately, high strength concrete tends to be more brittle than normal strength concrete. The ascending part of the stress-strain curve becomes steeper with increase of strength. Although the tensile strength increases for high strength concrete, the ratio between tensile strength and compressive strength changes from approximately 10% for normal strength concrete to approximately 5% for high strength concrete. Concrete is a quasi-brittle material and classical linear fracture mechanics is not directly applicable, even for high strength concrete. Thus, different non-linear fracture mechanics models have been proposed to tackle the fracture of concrete. Among the models developed, the Fictitious Crack Model of Hilllerborg et al [3] and the Two-Parameter Model of Shah and his co-workers [4] and [5] represent two different approaches. The material properties used in the former model are tensile strength, fracture energy and modulus of elasticity. In the latter model, the critical stress intensity factor ($K_{IC}$) and the critical crack tip opening displacement ($CTOD_C$) are the material parameters.

The paper reports on an experimental study to determine the fracture properties of high strength concrete containing 10% and 15% of silica fume (as cement replacement) and two types of coarse aggregates. The fracture properties determined are the fracture energy, the critical stress intensity factor and the $CTOD_C$. An attempt to characterise the brittleness of the high strength concrete is also reported.

## Experimental Details

*Materials and specimen preparation*

Information regarding the materials used in the study is summarised in Table 1 which gives details of the concrete mixes used in the experimental work. Silica fume is usually added to high strength concrete mixes to improve the quality of the cement phase and the aggregate/matrix bond. In this study two values of silica fume content were used i.e. 10% and 15% of the total binder content. The silica fume was supplied in a slurry form (50% water solution). Two types of coarse aggregates were used in the study. In the case of crushed limestone, two maximum sizes of 10 mm and 20 mm were used, whereas in the case of gravel only 10 mm aggregate size was used.

Table 1 shows that two main grades of concrete (W/(C+SF) = 0.32 and 0.23) were used in the study. The cement used was Ordinary Portland cement with either 10% or

TABLE 1 Details of concrete mixes

| No. | W/(C+SF) | SF/(C+SF) | Aggregate type | Aggregate size (mm) | Mix Proportion (C+SF):S:A:W (kg/m3) |
|---|---|---|---|---|---|
| M3210 | 0.32 | 10% | limestone | 10 | 454:660:1105:145 |
| M3215 | 0.32 | 15% | limestone | 10 | 454:660:1105:145 |
| M2310 | 0.23 | 10% | limestone | 10 | 547:660:1105:126 |
| M2315 | 0.23 | 15% | limestone | 10 | 547:660:1105:126 |
| S3210 | 0.32 | 10% | limestone | 20 | 454:660:1105:145 |
| S3215 | 0.32 | 15% | limestone | 20 | 454:660:1105:145 |
| S2310 | 0.23 | 10% | limestone | 20 | 547:660:1105:126 |
| S2315 | 0.23 | 15% | limestone | 20 | 547:660:1105:126 |
| G3210 | 0.32 | 10% | gravel | 10 | 454:660:1105:145 |
| G3215 | 0.32 | 15% | gravel | 10 | 454:660:1105:145 |
| G2310 | 0.23 | 10% | gravel | 10 | 547:660:1105:126 |
| G2315 | 0.23 | 15% | gravel | 10 | 547:660:1105:126 |

15% being replaced by silica fume. The superplasticizer used was Conplast 430, which is of the sulphated naphthalene formaldehyde condensate type, supplied in a 40% water solution.

Three standard 100*100*500 mm beams were cast for each mix. The beams were demoulded after one day and stored in a water tank until tested at 91 days. A 50 mm deep notch was introduced in the centre of each beam by a diamond saw and clip-gauge holders were glued on the surfaces adjacent to the notch mouth. These preparations were carried out on the beams on the day prior to the testing and some partial drying of the test specimens was inevitable and unavoidable.

*Testing Procedures*

Each beam was first tested in three-point bending to determine the fracture energy, Young's modulus, $K_{Ic}$ and $CTOD_C$. Then the two halves were used to determine compressive strength and splitting tensile strength.

Fracture energy, $K_{Ic}$ and $CTOD_C$ were determined according to RILEM recommendations by means of three-point bend tests on notched beams (Fig.1 ). The size of beams used in the present study was slightly different to that given in RILEM recommendations since the length of the beams was reduced from 840 mm to 500 mm. In each test, the crack mouth opening displacement (CMOD) was used as a feed-back control variable to obtain stable tests. Deflections were measured by means of an LVDT transducer. In each test the specimen was loaded progressively and a loading-reloading cycle was performed when the load decreased in the post-peak area to about 95% of the maximum load. Thereafter loading continued until the specimen broke into two halves.

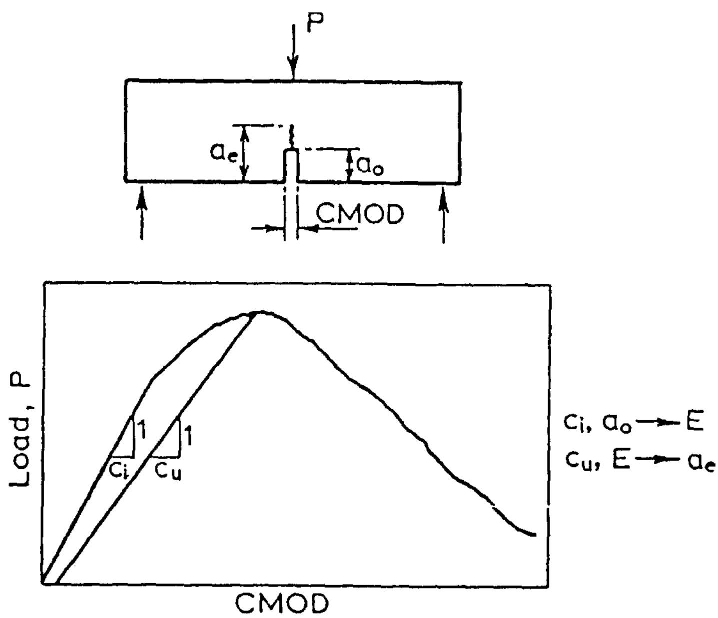


Fig.1 Schematic illustration of test for determination of fracture energy, Young's modulus, $K_{Ic}$ and $CTOD_C$

## Theory

The fracture energy can be determined directly from the area under the load-deflection curve.

Following the proposals of RILEM Technical Committee 89-FMT [6], the modulus of elasticity can be derived as follows:

$$E = 6Sa_0 V_1(a_0/d)/(C_i bd^2)$$

where S, b, d and $a_0$ are span, thickness, height and initial notch depth respectively and $C_i$ is the initial compliance as illustrated in Fig. 1. $V_1$ is a geometrical function of the ratio $a_0/d$ or $\alpha$ and is given by:

$$V_1(\alpha) = 0.76 - 2.28\alpha + 3.87\alpha^2 - 2.04\alpha^3 + 0.66/(1-\alpha)^2$$

The critical stress intensity factor $K_{Ic}$, is given by:

$$K_{Ic} = 3(P_{max} + 0.5W_0 S/L)S(\pi a_c)^{1/2} F(a_c/d)/2bd^2$$

and where $W_0$ and L are the self-weight and length of beam respectively, $P_{max}$ is the maximum load, and $a_c$ is the critical crack length which is determined by iteration from:

$$a_c = EC_u bd^2/6SV_1(a_c/d)$$

The geometrical function $F(a_c/d)$ or $F(\alpha)$ is given by:

$$F(\alpha) = 1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)/(\sqrt{\pi}(1+2\alpha)(1-\alpha)^{3/2})$$

and $C_u$ is the unloading compliance.

Finally, the critical crack trip opening displacement ($CTOD_c$) is given by:

$$CTOD_c = 6P_{max}Sa_c V_1(a_c/d)((1-a_0/d)^2 + (1.081 - 1.149a_c/d)(a_0/d - (a_0/d)^2))^{1/2}/(Ebd^2)$$

## Results and Discussions

The derived values of modulus of elasticity (E), critical stress intensity factor ($K_{Ic}$), and critical crack tip opening displacement ($CTOD_c$) are given Table 2. In addition the fracture toughness ($G_c = \frac{K_{Ic}^2}{E}$) and Q(=$\left(\frac{E*CTOD_c}{K_{Ic}}\right)^2$ ), a combined parameter proposed by Jenq and Shah [4] to measure brittleness, are also given in Table 2. (The application of fracture mechanisms to high strength concrete has been reported separately by Shah [7].

TABLE 2 Modulus of elasticity, $K_{IC}$, $CTOD_C$, Q and $G_C$ results

| No | $E(GPa)$ | $K_{IC}(MNm^{\frac{1}{2}})$ | $CTOD_c(10^{-6}m)$ | $Q(m)$ | $G_C(Nm/m^2)$ |
|---|---|---|---|---|---|
| M3210 | 30 | 0.77 | 19 | 0.55 | 19.8 |
| M3215 | 39 | 1.08 | 21 | 0.58 | 29.9 |
| M2310 | 38 | 1.16 | 22 | 0.52 | 35.4 |
| M2315 | 36 | 1.14 | 23 | 0.53 | 36.1 |
| S3210 | 36 | 0.93 | 19 | 0.54 | 24.0 |
| S3215 | 37 | 1.03 | 24 | 0.74 | 28.7 |
| S2310 | 39 | 1.18 | 23 | 0.58 | 35.7 |
| S2315 | 39 | 1.33 | 27 | 0.63 | 45.3 |
| G3210 | 34 | 1.03 | 23 | 0.58 | 31.2 |
| G3215 | 32 | 1.05 | 26 | 0.63 | 34.4 |
| G2310 | 36 | 1.21 | 27 | 0.64 | 40.7 |
| G2315 | 35 | 1.34 | 29 | 0.57 | 51.3 |

Table 3 summarises the results for compressive strength ($f_c$), splitting tensile strength ($f_{st}$), net flexural strength ($f_{fnet}$) fracture energy ($G_F$) and characteristic length ($\ell_{ch}$). The net flexural strength was determined $f_{fnet} = 3\ P_{max}\ S/2b(h\text{-}a)^2$ on the assumption that there is no notch sensitivity. The characteristic length is the measurement of brittleness proposed by Hillerborg [3] and is given by $\ell_{ch} = EG_F / f_{st}^2$.

TABLE 3 Compressive strength, splitting tensile strength, flexural strength and fracture energy of concrete at 91 days

| No. | $f_c$ (MPa) | $f_{st}$(MPa) | $f_{fnet}(MPa)$ | $G_F(Nm/m^2)$ | $l_{ch}(m)$ |
|---|---|---|---|---|---|
| M3210 | 81 | 3.4 | 4.5 | 82 | 0.21 |
| M3215 | 93 | 3.6 | 6.1 | 71 | 0.21 |
| M2310 | 103 | 4.9 | 6.8 | 61 | 0.12 |
| M2315 | 104 | 5.1 | 7.2 | 60 | 0.08 |
| S3210 | 91 | 3.0 | 5.4 | 73 | 0.29 |
| S3215 | 100 | 3.5 | 5.5 | 93 | 0.28 |
| S2310 | 115 | 4.2 | 7.4 | 75 | 0.17 |
| S2315 | 115 | 5.1 | 7.2 | 116 | 0.17 |
| G3210 | 85 | 3.4 | 4.9 | 114 | 0.33 |
| G3215 | 87 | 4.5 | 5.3 | 137 | 0.22 |
| G2310 | 102 | 5.1 | 6.8 | 105 | 0.15 |
| G2315 | 104 | 5.0 | 7.4 | 132 | 0.18 |

*Compressive Strength*

Compressive strengths for each aggregate type are depicted in the form of bar charts in Fig. 2. It is observed that the change of silica fume content from 10% to 15% does not affect the compressive strength for a water-binder ratio 0.23. All mixes were of medium/high workability and all test specimens were thoroughly vibrated on a table. Experience of this practice, with these materials, has confirmed that proper compaction has been attained and that observed differences between specimens with 10 and 15 percent silica fume are not, therefore, due to the compaction process. However, a small increase in compressive strength is observed for a water-binder ratio of 0.32, at least in the case of crushed limestone aggregate. Yogendran et al [8] have similarly reported that silica fume makes a greater contribution in enhancing the strength of low strength concrete than high strength concrete. Therefore the silica fume content may be reduced when producing concrete with a lower water-binder ratio.

Fig. 2 shows that the two 10 mm aggregates, i.e. gravel and crushed limestone, produce quite similar compressive strengths. This may be due to the bond between the mortar and the two aggregates being similar. Concrete with 20 mm crushed limestone aggregates gives greater strength than concrete with 10 mm aggregate size for both water-binder ratios used in the study. It is known that strength is reduced when the coarse aggregate size becomes too large or too small, but the optimum size of coarse aggregate is yet to be determined.

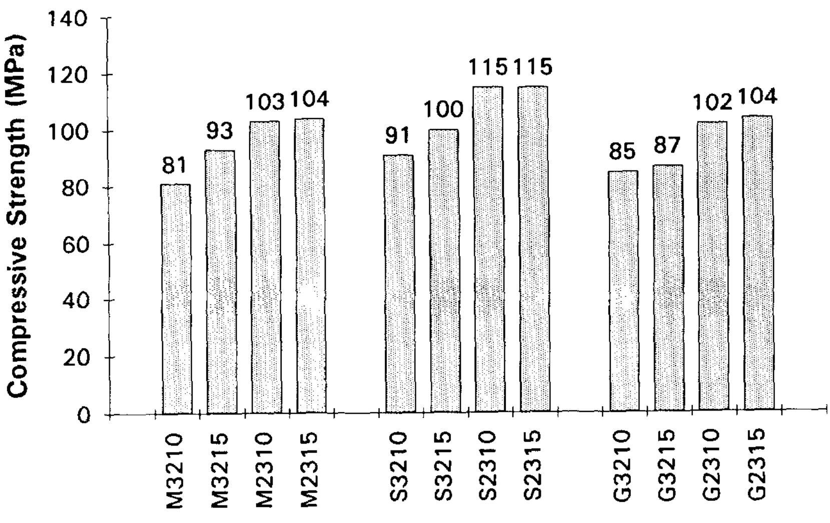


Fig. 2 Effects of silica fume and aggregate type and size on compressive strength. (M, S and G denote 10 mm, 20 mm crushed limestone and 10 mm gravel respectively).

*Fracture Energy*

Fig. 3 illustrates the effects of silica fume and aggregate type on the fracture energy. The fracture energy is observed to be higher for gravel than crushed limestone with the same size of aggregate, which is surprising. This could arise since the bond between the matix and the two aggregates is similar and hence the fracture energy of concrete with gravel will be higher due to the superior strength of the gravel itself. It is known that increasing aggregate size generally produces higher fracture energy for normal strength concrete. Fig. 3 shows that the same conclusion holds for high strength concrete. Clearly care should be taken in analysing the data since the size of the beams tested may be somewhat small for the 20 mm aggregate, bearing in mind that 50 mm deep notches were used in this study.

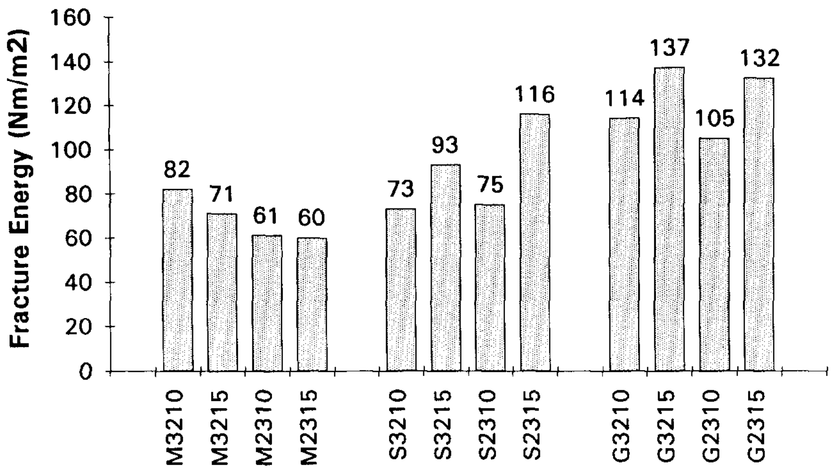


Fig. 3 Effect of silica fume content and aggregate type and size on fracture energy for different grades of concrete

The fracture energy of the gravel concrete and 20 mm crushed limestone aggregate concrete increases as the water-binder ratio decreases. However, the opposite effect is observed in the case of 10 mm crushed limestone aggregate where the fracture energy decreases as the water-binder ratio changes from 0.32 to 0.23. This may be due to to the improvement in the bond which results in fracture developing through aggregates rather than around the aggregates for this particular combination of size and type of aggregate.

*Fracture Toughness*

In classical fracture mechanics, the critical stress intensity factor is used to characterise the fracture toughness of materials. The experimental results for $K_{Ic}$ are

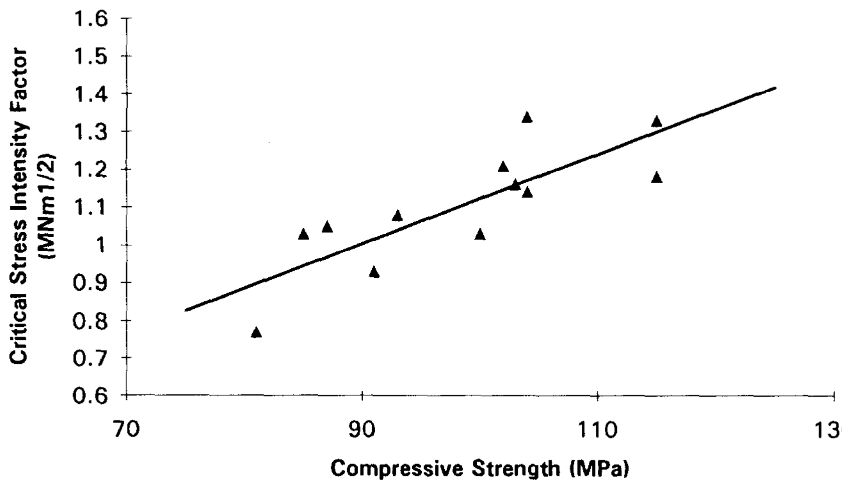


Fig. 4 Relationship between $K_{Ic}$ and compressive strength

presented in Table 2 and the variation of $K_{Ic}$ with the compressive strength is illustrated in Fig. 4 (where $K_{Ic} = 11.85 \times 10^{-3} f_c - 0.063$, r = 0.82 and 95% confidence limits = ± 0.22 $K_{Ic}$).

Fig. 4 shows that $K_{Ic}$ increases linearly with increasing compressive strength. These results are consistent with the observations by Shah [7] for normal strength concrete. Although increasing $K_{Ic}$ values means that the resistance to cracking is increasing, fracture behaviour actually becomes more brittle. Therefore $K_{Ic}$ may not be the most appropriate parameter for characterising the fracture of concrete. For concrete, another fracture parameters, $CTOD_c$, is needed according to the Two Parameter Model [4].

The increase of silica fume from 10% to 15% tends to give rise to higher $K_{Ic}$ values, except for the concrete with 10 mm crushed limestone and a water-binder ratio 0.23. Gravel seems to provide higher resistance to cracking than crushed limestone aggregate. Similarly, the fracture energy reported above was observed to be greater for the gravel mixes than for the equivalent crushed limestone aggregate mixes. These conclusions are suprising and require further detailed investigation.

*Material brittleness*

Various parameters have been proposed to characterise the brittleness of normal strength concrete. The characteristic length, $\ell_{ch} = \frac{E^*G_F}{f_t^2}$, proposed by Hillerborg in the Fictitious Crack Model [3], has been used to characterise brittleness of normal strength concrete, rock, glass as well as other materials. The smaller the value of $\ell_{ch}$, the more brittle is the material. Therefore $\ell_{ch}$ was evaluated in the present study and the results are presented in Table 3 and illustrated in Fig. 5 (where $\ell_{ch} = -3.84 \times 10^{-3} f_c + 0.58$, r = 0.59 and 95% confidence limits = ± 0.14 $\ell_{ch}$).

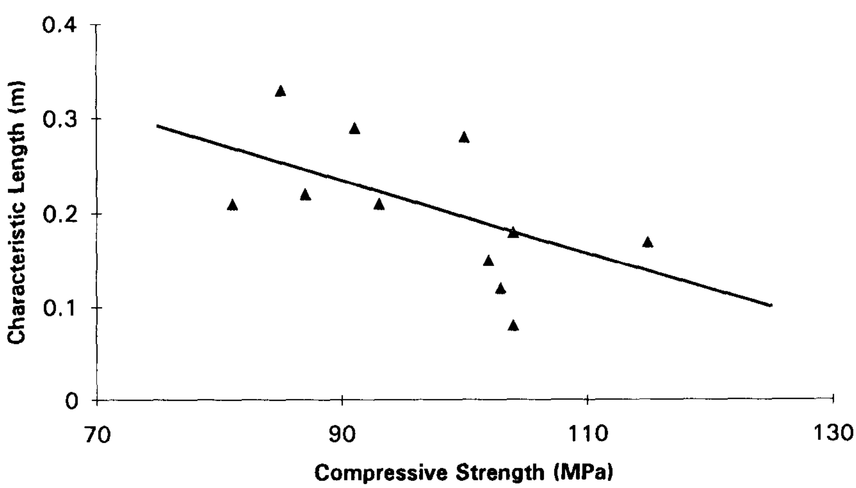


Fig. 5 Characteristic length and compressive strength

The value of characteristic length is reduced as the compressive strength increases (Fig. 5). As expected, concrete is more britlle when the water-binder ratio is reduced. The values obtained for $\ell_{ch}$ are consistent with the experimental results observed for the stress-strain curves of high strength concrete. Concrete containing gravel and 20 mm crushed limestone yield greater values of $\ell_{ch}$ than concrete with 10 mm crushed limestone aggregate. Thus the value of $\ell_{ch}$ depends on both the type and size of coarse aggregate used.

Another brittleness parameter, developed by Jenq and Shah [4], is the parameter Q which is given by $(E.CTOD_C/K_{IC})^2$. Values of Q are presented in Table 2. These results suggest that Q does not appear to be a good indication of material brittleness. The results gathered in this study show that $\ell_{ch}$ is a more appropriate indication of brittleness than Q.

*Tensile strength*

The splitting tensile strength increases with increasing compressive strength. However, in the case of high strength concrete the ratio of tensile to compresion strength is only of the order of 0.05, whereas in the case of normal strength concrete the ratio is of the order of 0.10. Note that the splitting tensile strengths were determined on dry half beams (following the bend tests) rather than via wet cylindrical test specimens. Thus the ratio of tensile to compressive strength may be somewhat lower than expected.

The flexural strengths were determined on notched beams rather than on unnotched beams. Consequently the flexural strengths are probably reduced. The ratio between flexural strength and splitting tensile strength varies in the range 1.3 to 1.7 in this study. (ACI recommedations suggest that the ratio should be in the range 1.4 to 1.6).

Fig. 6 shows the variation of flexural strength with splitting tensile strength. Fig. 6 also shows the theoretical relationship between flexural strength and splitting strength

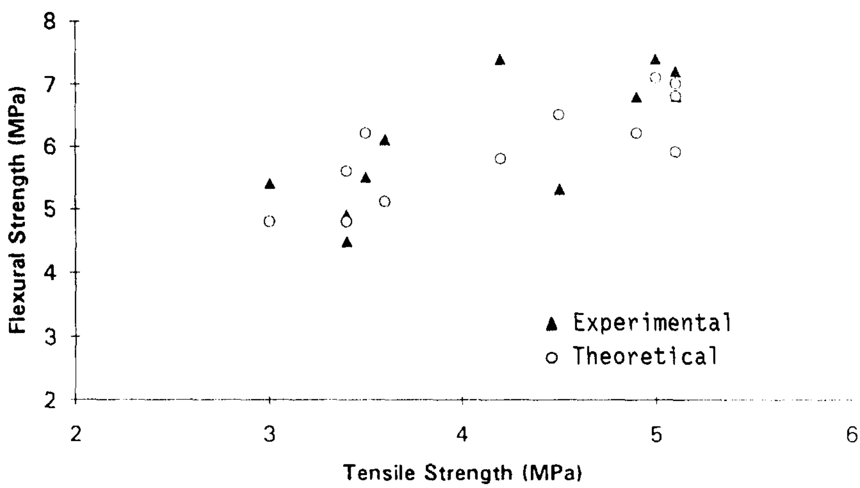


Fig. 6 Variation of net flexural strength with splitting tensile strength

(based on the Fictitious Crack Model [3].) Good correlation is observed between the tensile strength results obtained in this study and the results predicted by the Fictitious Crack Model. Assuming a relationship of the form $f_b = af_{st}^b$ for the results presented in Fig. 6 gives $f_b = 2.29f_{st}^{0.69}$ (95% confidence limits = ± 1.29 N/mm$^2$).

## Conclusions

A series of tests were carried out to study the strength and fracture properties of high strength concrete with varying silica fume content and coarse aggregates. The main conclusions which may be drawn from the study are as follows.

(1) With the materials used here, increasing the silica fume content from 10% to 15% cement replacement has more effect on compressive strength of concretes with higher water-binder ratio. Gravel and 10 mm crushed limestone aggregate produce concrete with similar compressive strengths. Increasing the size of the crushed limestone aggregate from 10 mm to 20 mm increases the compressive strength.

(2) The splitting tensile strength of high strength concrete is only of the order of 5% of its compressive strength. (The corresponding value for normal strength concrete is approximately 10%) The ratio between flexural tensile strength and splitting tensile strength is approxiamtely 1.5 for the high strength concrete used in this study. This ratio of 1.5 is in good agreement with the theoretical predictions given by the Fictitious Crack Model [3].

(3) The fracture energy increases with increasing aggregate size and with increasing aggregate stiffness.

(4) The critical intensity factor increases with increasing compressive strength.

(5) The characteristic length, $\ell_{ch}$, is shown to be a good increase of brittleness in high strength concrete.

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