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FRACTURE ENERGY OF NORMAL STRENGTH CONCRETE, HIGH STRENGTH CONCRETE AND ULTRA HIGH STRENGTH ULTRA DUCTILE STEEL FIBRE REINFORCED CONCRETE

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Abstract

Usually, the composite material concrete is composed of cement, water, fine aggregate and gravel. By adding plasticisers and micro silica the strength can be increased and a material called high strength concrete can be obtained. At Aalborg Portland Cement Factory in Denmark a new material concept is developed where ultra high strength concrete with compressive strength as high as 300 MPa is obtained. The material is a cement-based material and is mixed and cured at room temperature. For three different cement-based materials the fracture energy is measured using the procedure recommended by RILEM. It is shown that the fracture energy for high strength concrete is almost the same as for normal strength concrete, whereas the fracture energy for the ultra high strength steel fibre reinforced concrete is several decades larger than for the high strength concrete.

1 Introduction

During the last seven decades concrete structures have been designed in almost the same way. Codes have been used and the calculation rules have been based on many years of experience both in practice and compared to laboratory experiments. Most of the rules are based on empirical formulas and, as long as certain limitations are fulfilled, sound concrete structures can be designed. However, during the last two decades new materials have been designed and if the conventional design methodology is used this can lead to disasters, Modéer (1993). Instead it is necessary to use more precise design methods such as fracture mechanics, Karihaloo (1995). By using this modern approach it has been possible to obtain huge economical benefits, Modéer (1993). Usually the composite material concrete is composed of cement, water, sand and gravel. By adding plasticisers and micro silica the strength can be increased and a material called high strength concrete can be obtained. At Aalborg Portland Cement Factory in Denmark a new material concept is developed where an ultra high strength ultra ductile steel fibre reinforced cement-based material with compressive strength as high as 300 MPa is obtained, Bache (1995). The material is a cement-based material and is mixed and cured at room temperature. The material has so far not been used in many structural systems, but is now gaining more interest in the Scandinavian countries where the material is used in both civil engineering structures and in the Norwegian part of the North Sea, Jensen (1995), Modéer (1995). This paper mainly deals with the determination of fracture parameters of the new material, and a comparison is made with two conventional types of concrete.

2 Experiments

For simplicity the three materials will in the following be named normal strength concrete (NSC), high strength concrete (HSC) and ultra high strength ultra ductile fibre reinforced concrete (UHS-FRC).

2.1 Materials

Three types of concrete are tested. In the following the materials are described. For all three materials the compressive strength was determined on 100 mm by 200 mm cylinders.

Table 1. Mix of the normal strength concrete

Contents	Amount
Cement	350 [kg/m^3]
Water	159 [kg/m^3]
Sand (0-4 mm)	901 [kg/m^3]
Gravel (4-8 mm)	900 [kg/m^3]
Air	50 [l/m^3]

Table 3. Mix of the ultra high strength ultra ductile steel fibre reinforced concrete giving 40 l

Contents	[kg/m^3]
Densit® binder	650
Water	102
Steel fibre [6% Vol]	324
Sand 0 -0.25 mm	113
Sand 0.25 mm - 1.0 mm	230
Sand 1.0 mm - 4.0 mm	461

2.1.1 Normal strength concrete

A normal strength concrete with max. aggregate size of 8 mm was used. The mix is shown in Table 1. The concrete was delivered from a commercial concrete manufacturer. The compressive strength is 50.43 MPa with a standard deviation of 2.45 MPa giving a coefficient of variation of 4.86 %.

2.1.2 High strength concrete

A high strength concrete with a max. aggregate size of 8 mm was used. The mix is shown in Table 2. The concrete was delivered from a commercial

Table 2. Mix of the high strength concrete

Contents	Amount
Cement	450 [kg/m^3]
Silica fume	35 [kg/m^3]
Water	141 [kg/m^3]
Plastiziser	1.7 [kg/m^3]
Super Plastiziser	12.1 [kg/m^3]
Sand (0-4 mm)	835 [kg/m^3]
Gravel (4-8 mm)	900 [kg/m^3]
Air	35 [l/m^3]

concrete manufacturer. The compressive strength is 93.6 MPa and a standard deviation of 3.08 MPa giving a coefficient of variation of 3.29 %.

2.1.3 Ultra high strength ultra ductile steel fibre reinforced concrete

An ultra high strength ultra ductile steel fibre reinforced concrete with a max. aggregate size of 4 mm and with steel fibres with thelength 12 mm and the diameter 0.4 mm was used. The mix is shown in Table 3.

The mean compressive strength is 166.5 with a standard deviation of 0.93 MPa giving a coefficient of variation of 0.56%.

2.2. Specimens

The standard RILEM specimen for determination of fracture energy with the dimension span 800 mm, depth 100 mm and thickness 100 mm is used. The specimens were cast in steel moulds. The day after testing the beams were demoulded and stored in water at 20°C until the day of testing. The day before testing a notch of half the beam depth was diamond saw cut in the beam. The normal strength concrete beams and the high strength concrete beams were kept wet until the moment of testing. The UHS-FRC beams were sealed in plastic after demoulding and kept sealed until the moment of testing. All experiments were repeated three times.

2.3 Testing equipment and procedure

The beams were subjected to three-point bending in a servo-controlled materials testing system. The beams were tested perpendicular to the casting direction. To measure the true beam deflection a reference bar was placed on either side of the beam, and the beam deflection was measured as the distance from the load point to the reference bar using two LVDTs with a base of 2.0 mm and a sensitivity of 5.0 V/mm. The piston displacement was measured using the built-in LVDT with a base of 5.0 mm and a sensitivity of 2.0 V/mm. The crack opening displacement was measured using a clip-gauge with a base of 2.0 mm and a sensitivity of 5.0 V/mm. The load was measured using a 10.0 kN load cell with a sensitivity of 1.0 V/kN. For the second and third UHS-FRC beams the beam displacements were measured using two LVDTs with a base of 20.0 mm and a sensitivity of 0.5 V/mm due to the large displacement of these specimens. The test set up is shown in figure 1. For the UHS-FRC the available piston displacement was however not enough to fracture the beams. When it was not longer possible to move the piston, an unloading was performed. Then steel sheets were inserted between the beam and the load cell and a reloading was then performed. This procedure was repeated until the beam was fractured.

All signals together with the time, *t*, were recorded using an analog to digital converter and an AT Personal Computer. The tests were controlled by a feedback signal that included contributions from both the piston displacement and the COD.

The feed back signal, δ, was created by analogy addition of the corresponding signals:

$$\delta = \delta_p + \alpha\delta_{COD} \tag{1}$$

where, δ_{COD}, is the crack opening displacement and, δ_p, is the piston displacement. The weight factor α varied was chosen as 3.0 for the normal and high strength concrete and 0.0 for the UHS-FRC beams.

The reference signal, a linear ramp, was generated using the same AT PC and a digital-to-analogy converter.

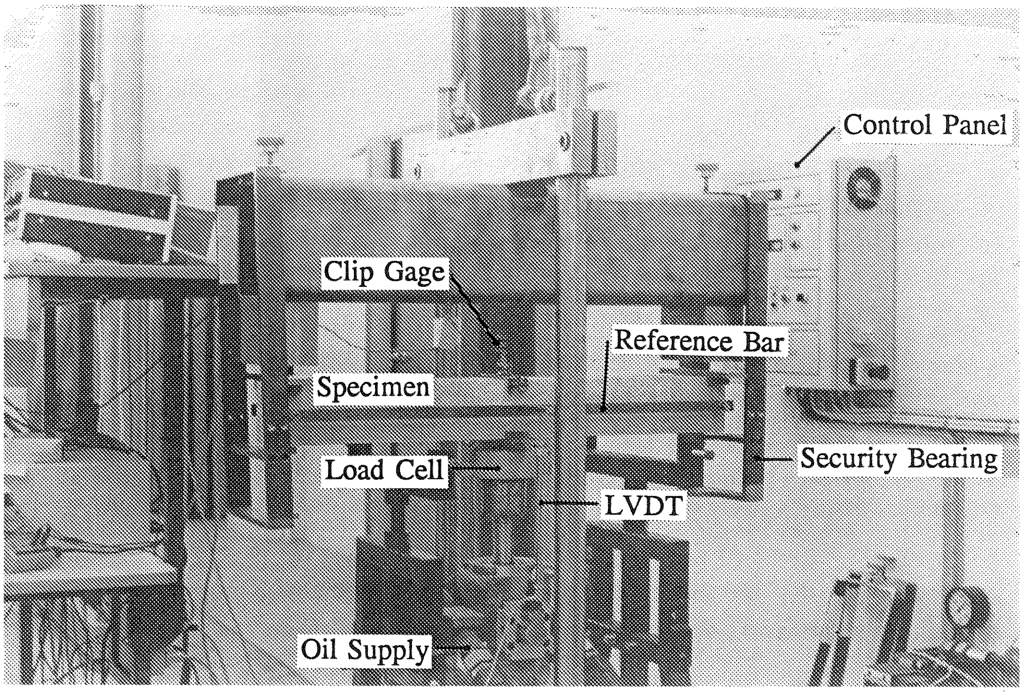

Figure 1. Photo of the test set up

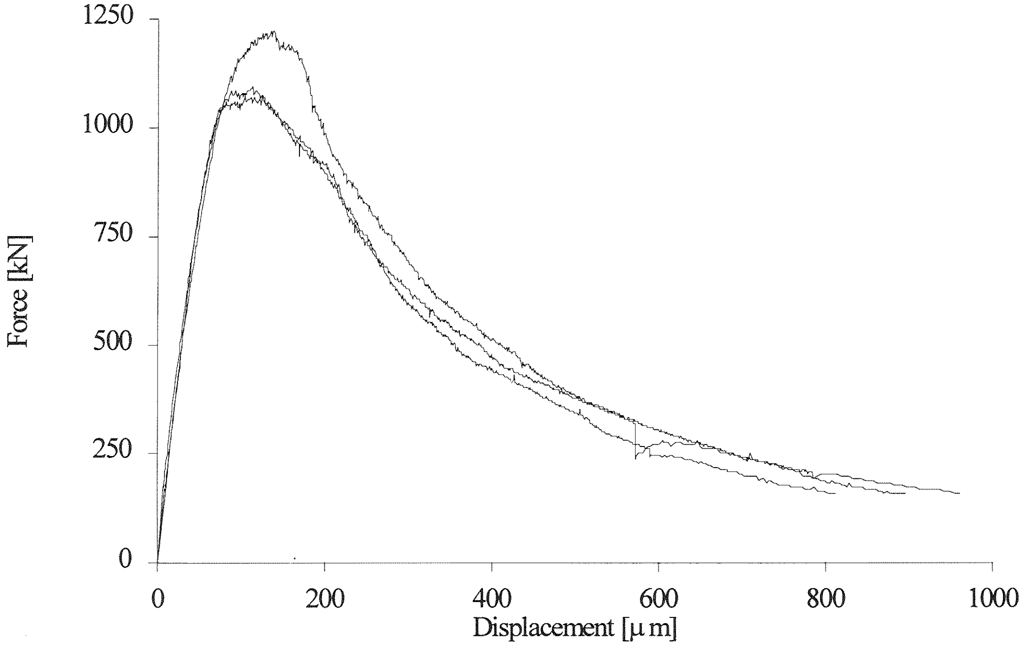

Figure 2. Load displacement curves for the normal strength concrete

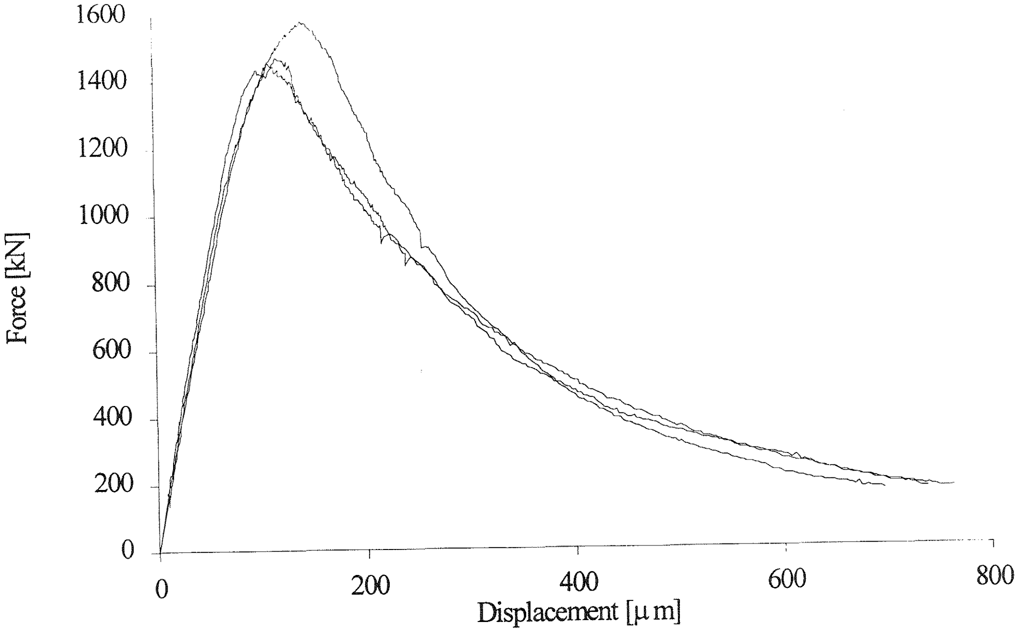

Figure 3. Load displacement curves for the high strength concrete

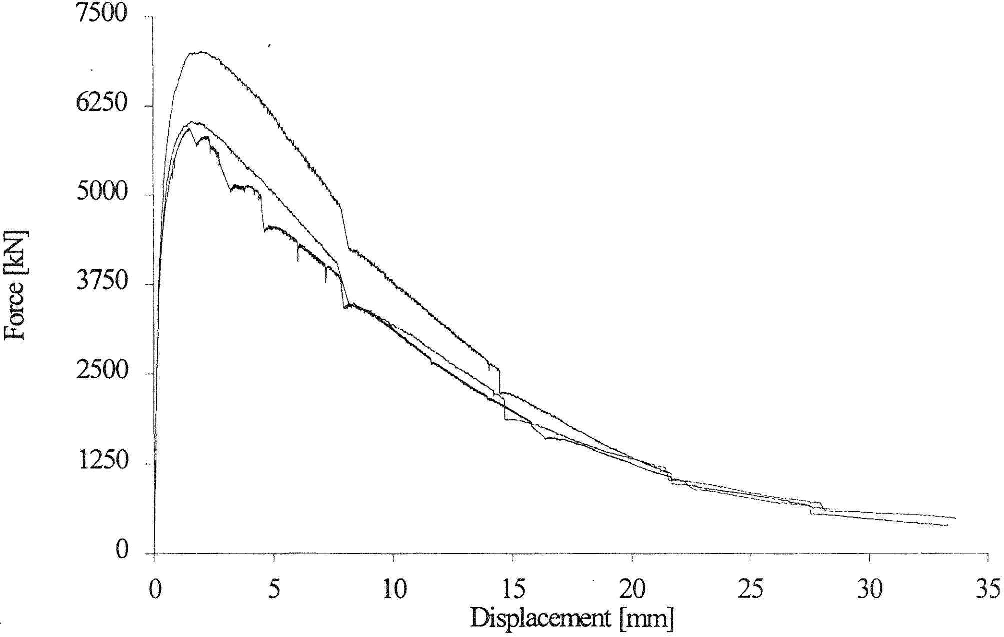

Figure 4. Load displacement curves for the ultra high strength ultra ductile steel fibre reinforced concrete

3 Fracture Parameter Results

Load-displacement curves for the three different materials are shown in figures 2-4, and in figure 5 one load-displacement curve for each of the three materials is shown for comparison.

Fracture parameters from three different models are calculated:

1 The bending tensile strength according to Bernoulli (modulus of rupture).
2 The critical stress intensity factor K_{Ic} according to LEFM.
3 The fracture energy according to the fictitious crack model.

In the following figures where the fracture parameters are presented the vertical lines show the minimum and the maximum value of the three repetitions.

3.1 The modulus of rupture

The modulus of rupture is calculated as the bending tensile strength of a Bernoulli-Euler beam

$$\sigma_m = \frac{3F_{\max} l}{2(d - a_i)^2 t} \tag{2}$$

where $F_{\max}$ is the peak load and d, t and a_i are the beam depth, thickness and notch depth, respectively. The bending tensile strengths for the three types of concrete are shown in figure 6.

3.2 The fracture toughness

The fracture toughness, K_c is calculated according to ASTM (1974):

$$K_c = \frac{3}{2} \frac{F_{\max} l \sqrt{a}}{bd^2} f\left(\frac{a}{d}\right) \tag{3}$$

where

$$\begin{aligned} f\left(\frac{a}{d}\right) &= 1.93 - 3.07\left(\frac{a}{d}\right) + 14.53\left(\frac{a}{d}\right)^2 \\ &\quad -25.11\left(\frac{a}{d}\right)^3 + 25.8\left(\frac{a}{d}\right)^4 \end{aligned} \tag{4}$$

The critical stress intensity factor for each beam is shown figure 7.

3.3 Fracture energy according to RILEM

According to the RILEM recommendation, RILEM TC-50 (1985), the fracture energy should be determined on a specimen with the dimensions: span = 800 mm, depth = 100 mm and thickness = 100 and an initial notch depth of a_i = 50 mm, the maximum aggregate size should not be larger than 16 mm.

Different areas are calculated in connection with the RILEM method. The experiments are usually ended before the load is decreased to zero. The experiment will therefore end at the load, F_1, and the corresponding displacement, δ_1, and the remaining area under the load-displacement curve must be estimated.

According to the Ulfkjær et al. (1995) and Petersson (1981) the descending branch in Phase III is described by

$$F = \left(\frac{\delta_c}{\delta}\right)^2 \tag{5}$$

the remaining contribution to the fracture energy, A_1, can then be determined by

$$A_1 = \frac{1}{t(d - a_i)} \int_{\delta_1}^{\infty} \frac{\delta_c^2}{\delta^2} d\delta \tag{6}$$

By applying the condition

$$F_1 = \left(\frac{\delta_c}{\delta_1}\right)^2 \tag{7}$$

the contant δ_c can be determined and the remaining fracture energy becomes

$$A_1 = \frac{F_1 \delta_1}{t(d - a_i)} \tag{8}$$

The mean value of the fracture energies (the sum of the area under the measured curve and the remaining area divided by the ligament) for each concrete is shown in figure 9.

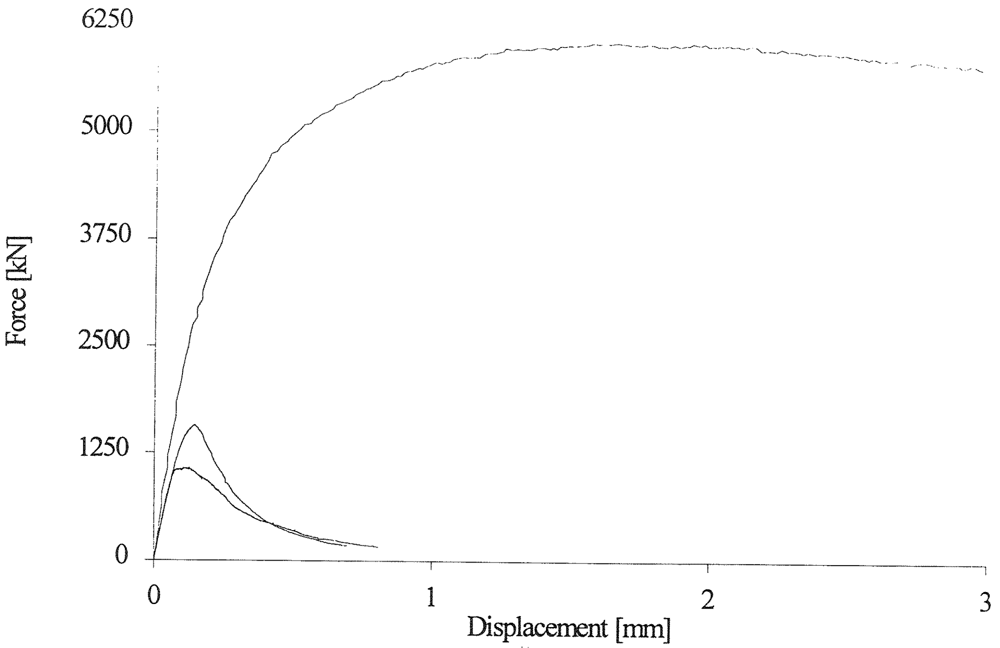

Figure 5. Load displacement curves for the normal strength concrete the high strength concrete and for the ultra high strength ultra ductile steel fibre reinforced concrete

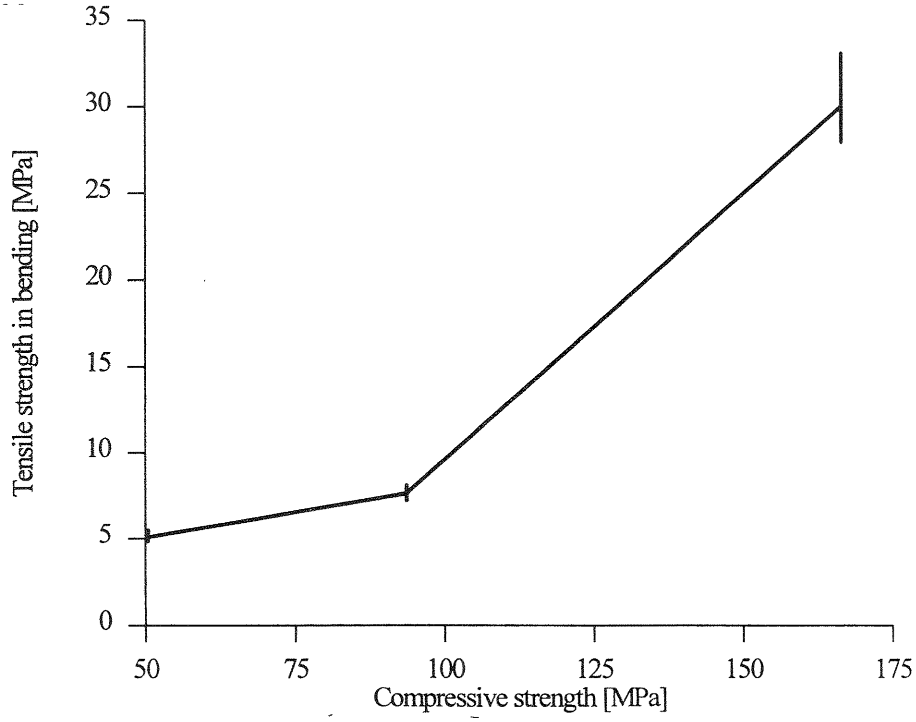

Figure 6. Bending tensile strength for the three materials

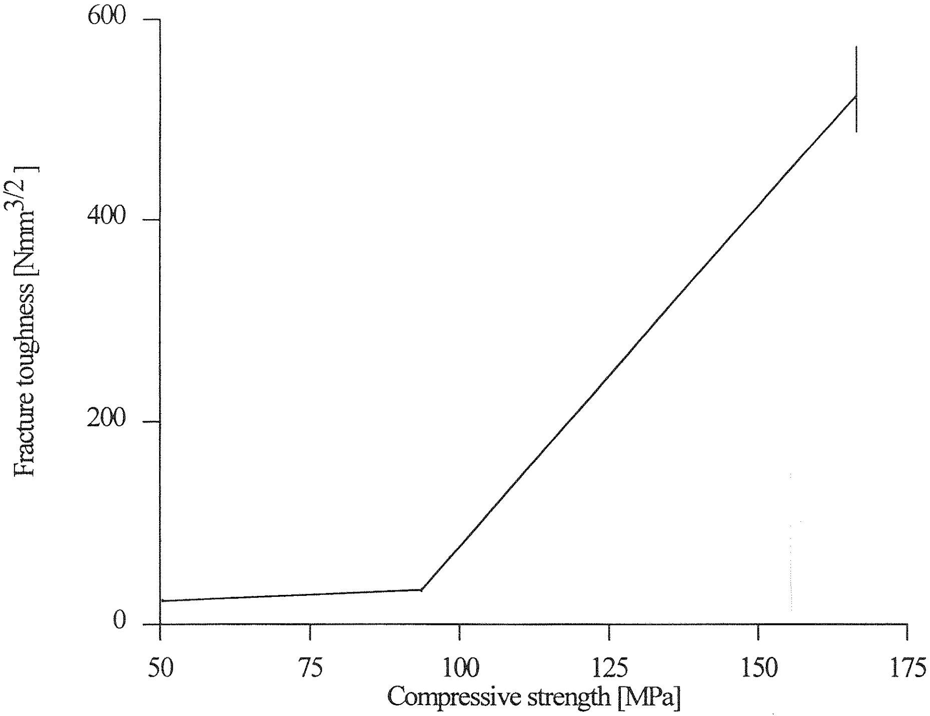

Figure 7. Fracture toughness for the three materials.

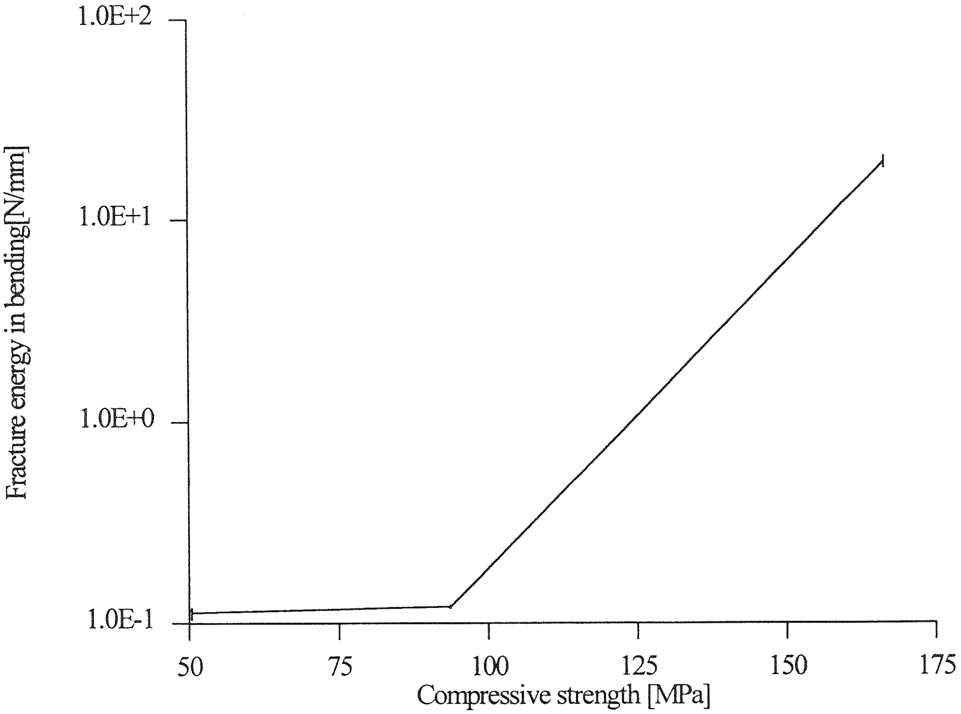

Figure 8. RILEM fracture energy for the three materials.

Table 4. Fracture parameters for the three parameters.

Test type		Mean	S.Dev	Coef. of Var.
Compressive strength	NSC	50.4 MPa	2.45 MPa	4.86 %
	HSC	93.6 MPa	3.08 MPa	3.29 %
	UHS-FRC	166.5 MPa	0.93 MPa	0.56 %
Bending Tensile Strength	NSC	5.08 MPa	0.36 MPa	7.02 %
	HSC	7.64 MPa	0.43 MPa	5.68 %
	UHS-FRC	30.0 MPa	2.72 MPa	9.11 %
Fracture Toughness	NSC	23.0 Nmm$^{3/2}$	1.60 Nmm$^{3/2}$	7.02 %
	HSC	33.3 Nmm$^{3/2}$	1.83 Nmm$^{3/2}$	5.49 %
	UHS-FRC	525.0 Nmm$^{3/2}$	44.5 Nmm$^{3/2}$	8.49 %
RILEM Fracture Energy	NSC	0.112 N/mm	0.755 N/mm	6.76 %
	HSC	0.120 N/mm	0.298 N/mm	2.49 %
	UHS-FRC	19.00 N/mm	1.30 N/mm	6.86 %

The fracture parameters are summarized in table 4. The compressive strength is seen to increase by a factor two between the NSC and the HSC and a factor three between the NSC and the UHS-FRC. The bending tensile strength is only increasing with a factor 1.5 between the NSC and the HSC and a factor six between the NSC and the UHS-FRC. For the fracture energy this effect is more pronounced since there is only a factor 1.1 between the NSC and the HSC and a factor 170 between the NSC and the UHS-FRC. Thus, the ductility is increased enormously by adding the steel fibres.

4 Conclusions

For three different cement-based materials the fracture energy is measured using the procedure recommended by RILEM. It is shown that the fracture energy for high strength concrete is almost the same as for normal strength concrete, whereas the fracture energy for the ultra high strength steel fibre reinforced concrete is 158 times higher than for the high strength concrete.

5 Acknowledgement

Hans Henrik Bache and Bendt Aarup of Aalborg Cement factory are highly acknowledged for providing the ultra high strength steel fibre reinforced concrete beams and for fruitful discusions.

6 References

ASTM (1974) E399-74: **Method of test for plane strain fracture toughness of metallic materials**.

Bache, H.H. (1995) Concrete and Concrete Technology in a Broad Perspec tive, in **Modern Design of Concrete Structures** (org. by J.P. Ulfkjær and Matz Modéer), Aalborg University, Aalborg, 1-47.

Jensen, B.S., Jensen, L.R.,Hansen, L.P. and Hansen, F.T. (1995) Connec tions in Precast Buildings using Ultra High-Strength Fibre Reinforced Concrete, in **Modern Design of Concrete Structures** (org. by J.P. Ulfkjær and Matz Modéer), Aalborg University, Aalborg, 63-75.

Hillerborg, A.(1985) Influence of Beam Size on Concrete Fracture Energy Determined According to a Draft RILEM Recommendation; **Report to RILEM TC50-FMC**. Rapport TVBN-3021, pp. 1-15.

Karihaloo, B. (1995) **Fracture Mechanics and Structural Concrete**, Longman Scientific and Technical, Essex.

Modéer, M. (1993), Offshore Concrete Platforms in Norway-Materials and Static Analysis, in ′**Fracture of Brittle Disordered Materials: Concrete, Rock and Ceramics**′ (eds. G. Baker and B. Karihaloo), Queensland, Australia.

Modéer, M.(1995) Modern Design in Practice,in **Modern Design of Concrete Structures** (org. J.P. Ulfkjær and Matz Modéer), Aalborg University, Aalborg, 145-154.

Petersson, P.E. (1981) Crack Growth and Development of Fracture Zones in Plain Concrete and Similar Materials, **Division of Building Materials, Lund Institute of Technology**, Report TVBM-1006, Lund, Sweden, pp. 1-174.

RILEM 50-FMC (1985), Determination of the Fracture Energy of Mortar and Concrete by Means of Three-Point Bend tests on notched beams, **Materials and Structures**, Vol. 18, No. 106, pp. 285-290.

Ulfkjær, J.P., Krenk, S. And Brincker, R. (1995) Analytical Model for Fictitious Crack Propagation in Concrete Beams, **Journal of Engineering Mechanics**, Vol. 121, No. 1, 7-15.