Fracture Mechanics of Concrete Structures
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TENSILE FAILURE OF NORMAL CONCRETE AND STEEL FIBRE REINFORCED CONCRETE AT HIGH STRAIN RATES

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Abstract
It is well known that the tensile strength of most materials is dependent on the strain rate, increasing with higher strain rates. During the last two decades new types of cement based materials have been invented with very high strength and very high ductility. The mechanical properties of this kind of materials have hitherto not been investigated at high strain rates. One of the most efficient ways to test concrete at high strain rates is by using the Hopkinson bar bundle where precise measurements can be performed at strain rates as high as 20 s^{-1}. In this work four very different kinds of concrete have been tested at high strain rates using a Hopkinson bar. It is shown that the tensile strength and the ductility of the four types of concrete are highly dependent on the strain rate.
Key words: High strain rates, High strength concrete, Hopkinson bar.

1 Introduction

The variety of structures which are subjected to loading at medium and high rates is vast e.g. housings (gas explosions), pavements (traffic load), bridges and road barriers (impact loads from ship and cars), power plants (explosive and impact loading).

In order to use the new designing tools like fracture mechanics it is necessary to obtain information about the mechanical properties of concrete materials at different strain rates. The introduction of highly sophisticated experimental techniques, like the Hopkinson bar bundle, Albertini et al. (1996a), Albertini et al. (1996b), Cadoni et al. (1995), has now made it possible to precisely characterise concrete materials at high strain rates.

2 Experiments

2.1 Materials

The experimental program outlined here consists of 12 experiments including four different materials (a normal strength concrete and three high strength steel fibre reinforced concrete) tested at high strain rates. Different static characteristics of the four types of concrete are shown in table 1. For a amore detailed description of S5 and D4 confer to, Aalborg Portland (1995). At the moment not all static data are available for Flex Binder.

Table 1. Characteristics of the four types of concrete.

Type	Maximum Aggregate size [mm]	Compressiv e strength	Tensile Strength	Bending Fracture Energy
Normal	10	45.18	1.84	0.068
Flex Binder	-	230	-	-
Ducorit D4	4	182.8	12.51	14.96
Ducorit S5	5	110.5	113.1	8.66

2.2 Testing equipment and procedure

The test rig consists of five parts connected in a serial system. A pre-loading bar, a blocking device, an aluminium bar (the incident bar) with a cross section of 60 mm by 60 mm and a length of 2.2 m, then follows the specimen. Finally another aluminium bar, identical to the first one (the transmission bar). Before an experiment the specimen is glued in between the two aluminium bars.

The two aluminium bars are instrumented with a four strain gages. The two strain gages placed on each bar are located 800 mm and 1700 mm from the specimen, see figure 1.

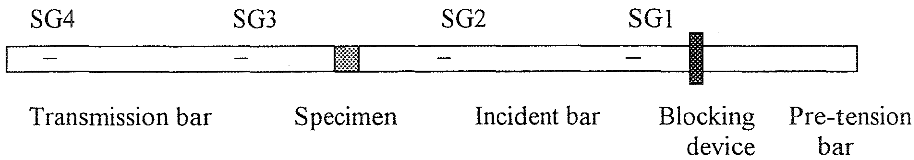

Fig. 1. Schematics of test set-up.

During an experiment the pre-loading bar is initially pulled in tension in the elastic range, while the two aluminium bars and the specimen are unloaded. This can be done by activation of the blocking device. The elastic energy stored in the pre-tensioned bar is then suddenly released, as a brittle fracture occurs of a notched bolt in the blocking device. This generates a tensile pulse, which propagates along the incident bar loads the specimen and propagates along the transmission bar. During the entire tests the pre-loading bar and the two aluminium bars will stay in the elastic range. The concrete specimen on the other hand will fracture.

The tests have been carried out using a Nicolet device for the data acquisition. The system is designed to provide high precision 12 bit waveform acquisition and analysis capabilities with a maximum sampling frequency of 1 MHz, which is utilised in this investigation. The data acquisition system receives the signals from a VISHAY 2400 System amplifier. All the signals are subsequently recorded on a personal computer.

3. Hopkinson bar theory

The application of the uniaxial wave propagation theory of elastic stress waves along bars having small transverse dimension with respect to the wavelength of the applied stress pulse allows the calculation of the following quantities:

1. The history and amplitude *F(t)* of the loading pulse generated by the pre-tensioned bar and propagated towards the specimen along the incident bar (or the input bar)

$$F(t) = A_I E_I \varepsilon_I (t) \tag{1}$$

where t is the time, A_I is the cross sectional area of the incident bar, E_I is the modulus of elasticity of the incident bar and ε_I is the elastic strain in the incident bar caused by the incident pulse.

2. The history and amplitude of the loading process at both ends connected to the specimen of the incident and transmission bars:

$$R_{INPUT} = E_I A_I [\varepsilon_I (t) + \varepsilon_R (t)] \tag{2}$$

$$R_{OUTPUT} = E_o A_o \varepsilon_T (t) \tag{3}$$

Where A_o is the cross sectional area of the transmission bar, E_o is the modulus of elasticity of the transmission bar, ε_R is the elastic strain of the incident bar caused by the reflected pulse and ε_T is the elastic strain of the transmission bar caused by the transmitted pulse.

3. Displacement history and amplitude $S(t)$ at both ends, connected to the specimen, of the incident and transmission bars:

$$S_{INPUT} = C_0 \int_0^t [\varepsilon_I - \varepsilon_R (t)] dt \tag{4}$$

$$S_{OUTPUT} = C_0 \int_0^t \varepsilon_T (t) dt \tag{5}$$

Where C_0 the elastic wave velocity in the aluminium bars. The modified Hopkinson bar used in this investigation satisfies the conditions of applicability of the elastic wave propagation theory because the wavelength (1.5 m) is much larger than the transversal length of the bar (0.06 m). The modified Hopkinson bar test set-up can therefore be considered as a transducer system, which allows measurement of the load displacement characteristics of the specimen.

4. Fracture parameters

The load displacement curves obtained from the nine experiments are converted into stress strain curves by dividing by the length of the specimen. The obtained stress strain curves are shown in figure 2 - 5. In this investigation two fracture parameters have been calculated from the measured load-displacement curves, the uniaxial tensile strength and the

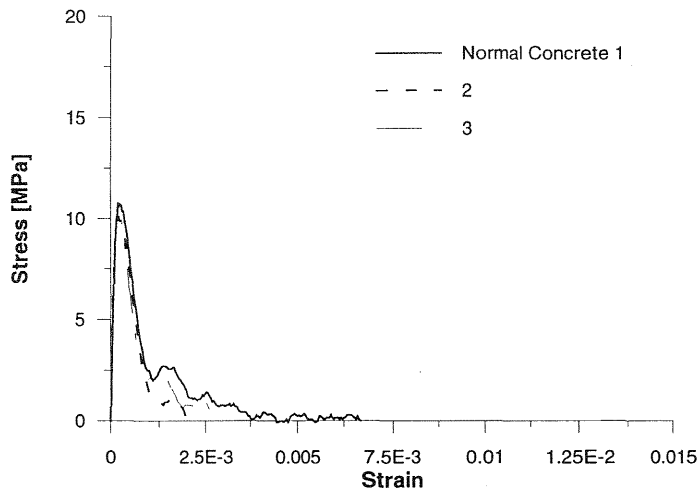

Fig. 2. Stress- strain relationship for normal concrete

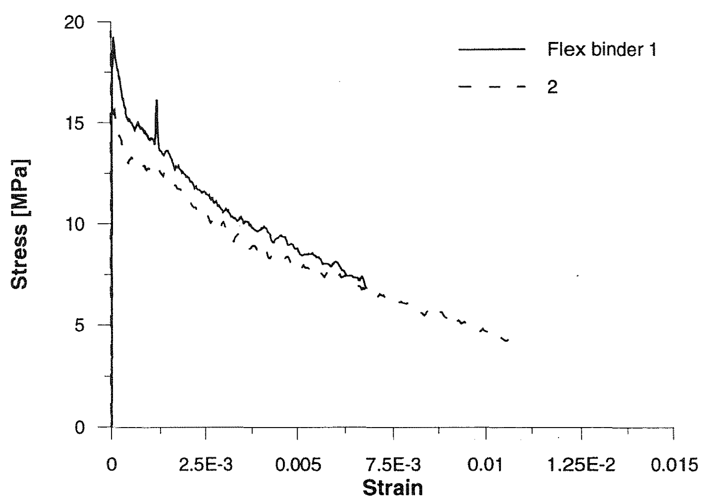

Fig. 3. Stress – strain relationship for Flex Binder.

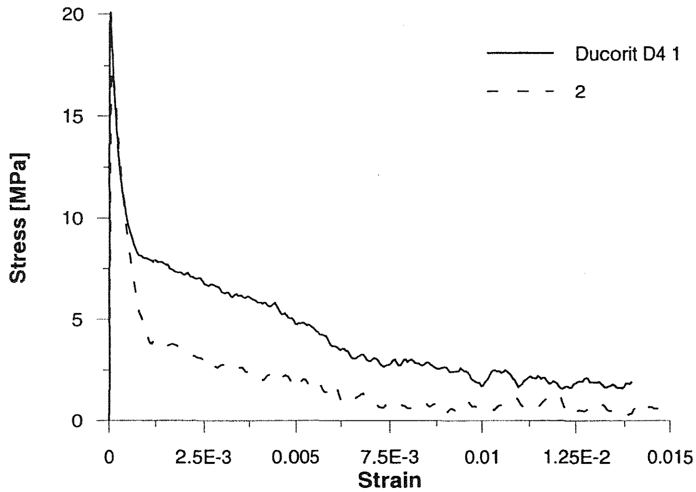

Fig. 4. Stress - strain relationship for Ducorit D4

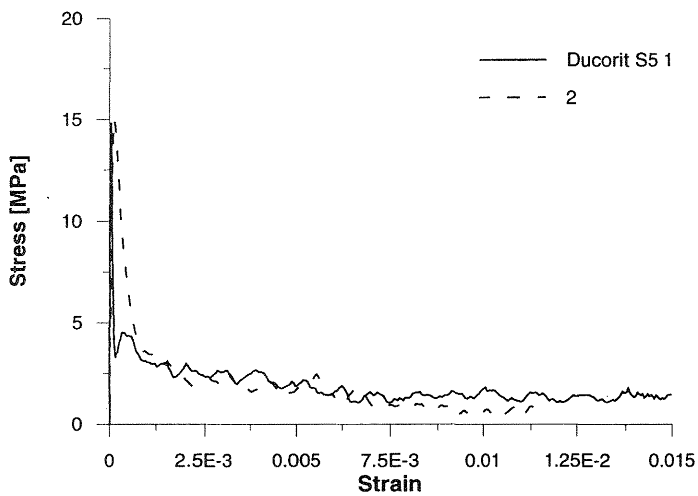

Fig. 5. Stress – strain relationship for Ducorit S5

fracture energy It is seen that there is a high degree of reproducibility of the tests.

4.1 The uniaxial tensile strength

The uniaxial tensile strength is assumed to be the maximum stress measured during the loading process. The tensile strengths obtained from the nine tests are shown in table 1.

4.2 The specific fracture energy

The specific fracture energy is calculated as the area under the load displacement curve (the elastic part of the deformation have been subtracted).

Table 2. Fracture parameters obtained from tests.

Specimen	Tensile Strength [MPa]	Fracture Energy [N/mm]
Flex binder 1	18.992	6.342
Flex binder 2	18.563	5.489
D4 1	17.053	2.264
D4 2	18.346	3.588
S5 1	14.771	1.716
S5 2	15.222	2.191
Normal Concrete 1	10.74	0.40
Normal Concrete 2	10.10	0.36
Normal Concrete 3	10.60	0.33

It is seen that the fracture energy of the normal concrete has increased compared to the static value, whereas this is not the case for the high performance concrete. This is probably due to the fact that the fracture energy for the static experiments are determined on beams in three point bending, were a significant amount of energy dissipates in zones away from the fracture zone.

5. Conclusions

A series of experiments with four types of concrete and at two different loading rates has been conducted. It is shown that both for normal concrete and high performance concrete there is a significant influence of the loading rate on the mechanical materials parameters. The tensile strength is seen to be increasing while there is not a clear picture regarding the energy absorption.

6 Acknowledgement

The production and delivery of the high performance concrete specimens by Densit A/S, Aalborg, Denmark, is highly appreciated.

7 References

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