APPLYING FRACTURE MECHANICS TO CONCRETE: STRENGTH IS NOT ENOUGH WHEN CONCRETE GOES INTO HAMMERED PILES

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This contribution provides an example of an application of Fracture Mechanics concepts to a practical concrete problem. Reinforced concrete piles made with two concretes having the same standard mechanical properties (compressive and tensile strength and elastic modulus) behaved in a different way; one set of piles was more brittle than the other. Fracture mechanics concepts provided some clues for solving this problem by disclosing the relevant parameter, the fracture energy G_F and by suggesting procedures to improve its value.

INTRODUCTION

Although reinforced concrete piles have proved their ability to take a great amount of punishment without structural damage, sometimes fracture occurs during hammering. This paper presents an example of pile damage during driving and how this problem was analyzed using Fracture Mechanics concepts applied to concrete. A Company producing concrete piling, found that the piles coming from one of their two pile precast factories (Factory A) occasionally showed brittle behaviour when being hammered. The design of the reinforced piles was the same as that of the other factory (Factory B). Figure 1 shows a typical section of these piles, whose length is usually 12 m.

Concrete mixes were nominally identical for both factories, but the aggregates came from different quarries. The mechanical properties of both concretes, as measured through tensile and compressive stresses, and Young modulus, were almost the same or even better for concrete from factory A. No classical approach could explain the different behaviour of the two concretes, since the conventional strengths of the *brittle* concrete A were never below those or the *well behaved* concrete B.

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Looking for fracture parameters, the specific fracture energy G_F was measured in both concretes. It turned out that G_F and the characteristic length were much lower for concrete A than for concrete B, so that the theoretical brittleness correlated well with the observed brittleness. Such measurements and some actions undertaken to improve concrete A are described in detail in the next sections.

CONCRETE PILE PROPERTIES

Strong concrete is usually required for piles. The mix design of both concretes A and B, was the same—as already mentioned—and is shown in Table 1.

TABLE 1 - Proportional mixing of concrete, A and B, by weight

Cement	Coarse aggregate	Fine aggregate	Water
1	2.64	2.46	0.43

Cement content 390 kg/m^3.

The cement was a rapid-hardening Portland (ASTM type III). Natural rounded aggregates, classified as siliceous, were used for concrete B and crushed dolomitic aggregates were used for concrete A. In both concretes, maximum aggregate size was 25 mm. Also 4.2 kg/m^3 of superplasticizer *Fluinel* ® was added to the mixes.

Mechanical properties were measured from cylindrical specimens of 300 mm length and 150 mm diameter, according the ASTM standards: Compressive Strength (C.39), Tensile Strength (C.496) and Modulus of Elasticity (C.469). Average results of three samples 28 days, are shown in Table 2.

The specific fracture energy G_F was measured according the procedure proposed by RILEM TC 50 [1], and taking into account additional refinements suggested by the authors [2, 3, 4]. Test specimens were notched beams of 100 x 100 x 850 mm.

Testing was performed in a 100 kN servohydraulic testing machine INSTRON 8501, run in actuator position control mode. Loads were measured with a 5 kN load cell with a resolution of 5 N and 0.5 percent accuracy.

TABLE 2 - Concrete properties (28 days)

Concrete Type	Compressive Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)
A	57.5	5.7	48
B	43.5	4.5	36

Deflection was measured as the relative displacement of the control loading head and the line defined by the points on the upper surface of the specimen located on the verticals of the lower supports. The displacement was measured by an extensometer of accuracy better than 5 µm. In all tests, weight compensation was used.

The mean load-displacement curves are shown in Figure 2.

Table 3 summarizes the experimental results of the specific fracture energy G_F, as well as the computed values of the characteristic size [5],

$$l_{ch} = \frac{G_F E}{f_t^2} \qquad (1)$$

where E is the elastic modulus and f_t the tensile strength.

TABLE 3 - Concrete fracture properties

Concrete Type	G_F (J/m^2)	$G_{F,average}$ (J/m^2)	l_{ch} (mm)
A	102, 104	103	152
B	130, 153, 169	151	268

Fracture energy results clearly show that concrete B is tougher than concrete A— even though the standard properties are almost the same—a fact that probably is at the root of the superior performance of concrete B during hammering.

Several parameters have been proposed to characterize the brittleness of concrete structures. A useful one is the brittleness number [6]:

$$B = \frac{L}{l_{ch}} \qquad (2)$$

where L is a characteristic dimension of the structure. A higher brittleness number indicates increased brittleness. However, this number has not an absolute meaning, because the structural dimension L is open to choice. It is useful only when comparing geometrically similar structures. Since the piles from the two factories are geometrically identical, one can in principle determine the relative brittleness of the two concretes to be 1.8. Hence concrete A may be estimated to be nearly twice as brittle as concrete B, which again supports the observed field behaviour (For this to be exact, the two concretes should display a softening curve with exactly the same shape. This is probably not so, but the existing experience with other concretes tends to show that the difference must be slight).

A fractographic analysis of the broken samples revealed that, for concrete B, most of the aggregates were debonded, while for concrete A they were broken.

IMPROVING CONCRETE TOUGHNESS

The fractographic evidence suggests that the low toughness values of concrete A as compared with concrete B are due to its weaker aggregates. Toughness of concrete A can be improved in either of two ways: by improving the strength of aggregates,avoiding aggregate fracture and forcing the crack to bend round the aggregates, or by improving the toughness of the cementitious matrix.

The second solution was selected for economic reasons, and the matrix toughness was improved by fibre reinforcement. Polipropilene fibres (Concrefib®)) of 40 mm length were used. Concrete mix and curing procedures were as previously described. For comparison purposes another set of samples similar to concrete A, henceforth called A2 were also tested.

The load-displacement curves corresponding to the RILEM tests are shown in Figures 3 and 4 for some representative samples. It is worth noticing the large tail due to fibre reinforcement in the P-δ curves for FRC. Table 4 summarizes the main mechanical properties.

TABLE 4 - Mechanical properties of reinforced and A2 concretes

Concrete Type	Compressive Strength (MPa)*	Tensile Strength (MPa)	Elastic Modulus (GPa)	G_F (J/m^2)	lch (mm)
Fibre Reinforced	59.4	5.0	45	157	283
A2	57.7	5.0	40	101	162

*28 days

The specific fracture energy for fibre reinforced concrete is the average value of four measurements (115, 144, 169 and 137 J/m^2), and the corresponding value for A2 the average value of three tests (92, 101 and 123 J/m^2). The fractographic analysis of broken samples revealed that the majority of the aggregates were broken, a result expected from previous tests with concrete A.

The increased toughness of fibre reinforced concrete, similar to that of concrete B, suggested the possibility of using it for piles, even though the aggregates were still weak. Further tests on piles made with FRC showed good performance during hammering and, at present, sufficient experience has been accumulated to permit safe and economic utilisation of these fibre reinforced concrete piles.

FINAL COMMENTS

This research has shown quantitatively—that concrete A is more brittle than concrete B and fibre reinforced concrete. Hence, under the same circumstances, piles made with concrete A should exhibit more brittle behaviour than piles made with the other concretes.

There is still some controversy on the measurement of *absolute* values of G_F because the results may depend on the specimen size [2, 3, 4] and on the measurement procedure (RILEM, Bazant, Shah, etc.) [7]. Sometimes, it is not necessary to reach an agreement about this point to solve the problem. This is an example where the absolute value of G_F is not needed, only relative values are of interest; an increase of 50 percent in G_F is all that was needed to drive the concrete to safe grounds.

Fracture Mechanics concepts provided a procedure for solving this problem; after pointing to the *relevant parameters*—specific fracture energy G_F and brittleness number—, this technique offered a way to *quantify* this properties and finally suggested procedures to *improve* them up to values that previous experience had shown acceptable.

ACKNOWLEDGEMENTS

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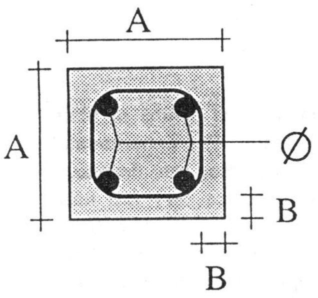

A = 235, 270 or 300 mm
B = 25 mm
Ø = 12 or 20 mm

Figure 1. Cross-section of concrete piles

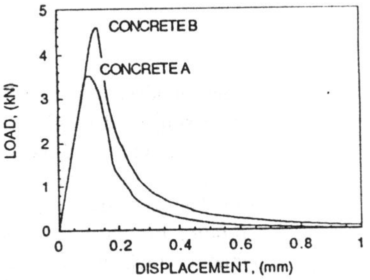

Figure 2. Load-displacement curves for concrete A and for concrete B.

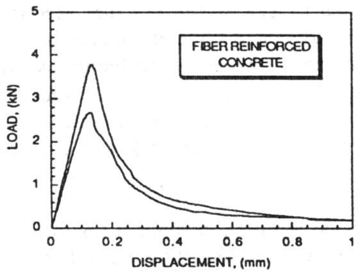

Figure 3. Load-displacement curve for fibre reinforced concrete

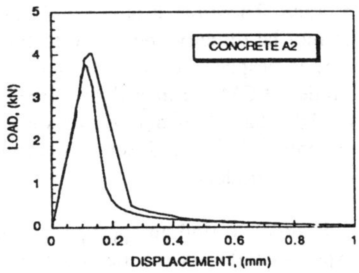

Figure 4. Load-displacement curve for concrete A2.