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TOUGHNESS OF OLD PLAIN CONCRETES

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Abstract

The mechanical behaviour of different plain concrete specimens was evaluated a month after casting and several years later (20 and 26), under the same testing conditions. Four concrete mixes were considered, with the same type and content of cement and aggregate, but with different aggregate gradings and water to cement ratios. All the specimens had the same curing since their casting. Compression tests employed cycles of axial deformation of increasing amplitude. The ratio between the energy required to reach collapse and the peak resistance was used as toughness index. Monotonic direct tensile tests were carried out on notched cylindrical specimens and the “characteristic length” was used as toughness parameter. The results show that the aged specimens have a considerably lower toughness, both in compression and in tension tests. Therefore when the post-peak "ductility" and concrete toughness become important, e.g. for redistribution of local peak stresses, propagation of cracks in massive concrete or resistance under extreme conditions, a design criteria referring to the expected long term concrete toughness should be used.

1 Introduction

Deterioration of concrete structures can result from a series of causes among which aggressive exposure conditions, unusual loading, inadequate design and poor construction practice, CEB (1989). In the present paper a sort of deterioration of plain concrete, due to simple ageing, is considered and discussed. It is related to the property that in earthquake engineering is named material ductility, and material toughness in fracture mechanics. In the following the term toughness will be referred to.

With regard to design criteria, most requirements concern the elastic strength of the structure, not its toughness. When these requirements are checked with reference to the nominal 28-days resistance, they result to be satisfied with higher margin when referenced to aged strength.

When the post-elastic behaviour become important (e.g. likelihood of propagation of an existing crack in massive concrete, resistance under extreme conditions and redistribution of local peak stresses) the design requirements have to concern toughness but, in this case, reference to the nominal 28-days toughness could be considered no more adequate. It is in fact well known that as the concrete compression strength increases the toughness tends to decrease, Siebel (1988).

However very few information exist on the long time variation of concrete toughness. The aim of this paper is just to give a quantitative measure of this variation after almost 30 years, based on both compression and tension tests. It could be very useful particularly in the evaluation of concrete structures prior to rehabilitation, as many failures taken place in rehabilitation projects seem to be ascribed to erroneous procedures and improper judgements, ACI (1993).

2 Experimental procedures

2.1 Materials

Four concrete mixes were designed using the same Portland Cement (corresponding to the present CEM I 42.5, according to the European Standard) at a content of 320 kg/m^3 and the same siliceous aggregate at a total content of 1870 kg/m^3. Two grading size distributions of the aggregates (Gravely-G and Sandy-S reported in Table I) and two water/cement ratios (0.57 and 0.72) were used.

A first complete series of concrete specimens was prepared in the year 1968 (series A: 20x20x80 cm prisms); a second partial series (only aggregates with G distribution and water/cement ratio of 0.57) was prepared in 1990 (series B: 20x20x80 cm prisms) and finally a third complete series was prepared in 1994 (series C: 20x20x20 cm cubes) using the same aggregates and very similar cements. Until testing they were cured under controlled temperature (about 20°C) and relative humidity (80%) conditions.

In table II the average compressive strength and modulus of elasticity of concretes after 1 month (ϕ 10 h 20 cm cores from cubes of series C) and after 26 years curing (ϕ 10 h 20 cm cores form prisms of series A) are reported. The density varied between 2350 and 2420 kg/m^3.

Table I Grading sizes of aggregates

Particle size range (mm)	G distribution (%)	S distribution (%)
0 - 1	16.4	24.6
1 - 4	16.4	21.6
4 - 8	9.2	13.6
8 - 16	28.4	19.6
16 - 32	29.6	20.6

Table II Mechanical properties

Aggregate distribution		G		S	
water/ cement		0.57	0.72	0.57	0.72
Comp. Str. (MPa)	1 month	35	26	32	29
	26 years	45	34	-	37
E (MPa)	1 month	32100	23000	29100	25800
	26 years	32800	29000	32800	32400

2.2 Toughness parameters

In order to evaluate the concrete toughness two main parameters were controlled both for young and old concretes.

The first was the energy to collapse evaluated on the basis of stress-strain diagram of specimens under cycles of compression stresses of increasing amplitude. More exactly this index was quantified as the ratio between the sum of the absorbed energy during cycles ($U_c = \sum \int \sigma \, d\varepsilon$ where the summation includes the cycles in which the peak of the stress σ_0 is reached and subsequent cycles till collapse) and the product $0.5*\sigma_0*\varepsilon_0$ where ε_0 is the strain corresponding to the peak stress σ_0. This ratio named normalised energy U_c is shown to carry the same information as quantity "ductility" currently used in earthquake engineering with reference to an elastic-perfectly-plastic material.

The second-one was the energy to collapse evaluated in a monotonic direct tensile test on notched cylindrical specimens and expressed as "characteristic length" $l_{ch} = G_F*E/f_t^2$, where G_F = fracture energy, E = elastic modulus and f_t = tensile strength. This parameter is widely used in fracture mechanics to quantify the concrete toughness and to fairly represent the likelihood of the crack propagation, Peterson (1981) and Hillerborg (1989). Other dimensionless parameters called brittleness numbers, Elfgren, (1989) and Gettu, Prat, Kazemi (1992), have also been proposed to characterise the brittleness of concrete structures. However these numbers have no absolute meaning as they are dependent on the characteristic dimension of the structure, that is open to choice, Elices, Guinea, Planas (1992).

3 Compression tests

At the time of compression testing, the concretes A were 20 years old while the concretes B only 1 month old. The tests were carried out on the 20x20x80 cm concrete prisms through a 150 ton hydraulic machine equipped with two spherical hinges to minimise accidental eccentricity.

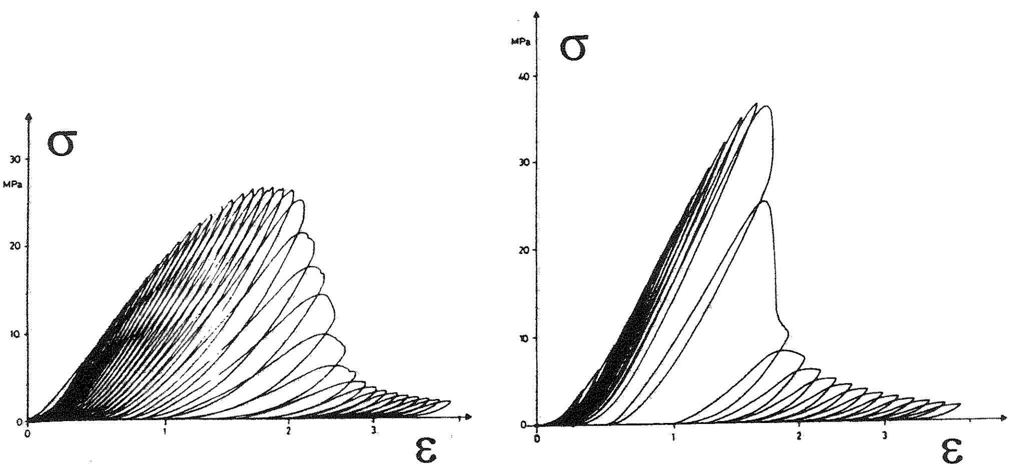

Fig.1. Stress-strain curves in cyclic compression tests for 1 month (left) and 20 years (right) aged concretes

The experimental equipment is described in a previous paper by Castellani, (1993). Fig.1 shows typical stress-strain diagrams for concrete prisms aged 1 month and 20 years.

After 20 years the concrete has higher strength but lower ductility than young concrete. The average value of the normalised energy U_c was 2.07 for the concretes aged 28 days and 1.29 for those aged 20 years. Generally the concrete toughness decreased by 30-50%. Detailed results are reported in the above mentioned paper by Castellani, (1993).

4 Tensile tests

At the time of tensile testing, the concretes of series A were 26 years aged while the concretes of series C were only 1 month old. Before testing, ϕ 10 h 20 cm cylinders were cored from the old concrete prisms and from the young concrete cubes.

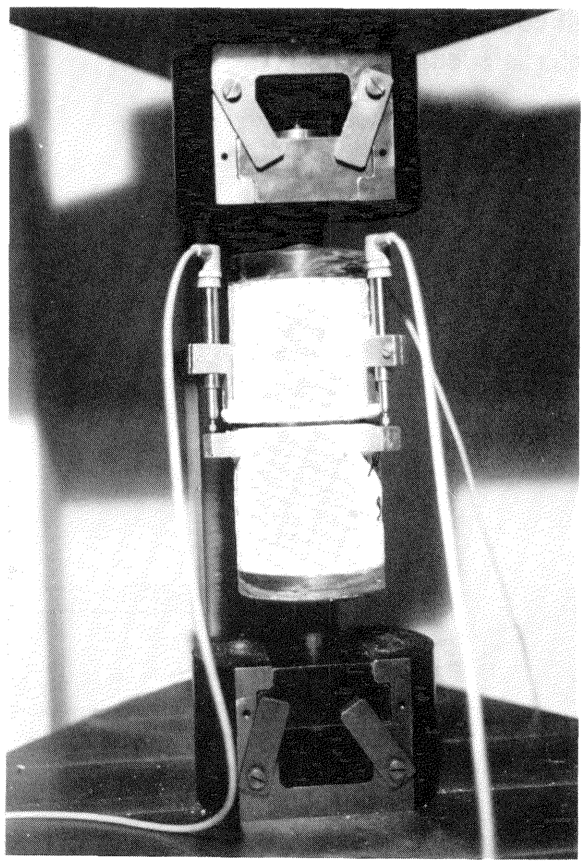

Fig. 2. Stable tensile tests on prenotched concrete cores

Each specimen was anularly prenotched (1cm) and then provided with three steel supports, glued at 120° intervals on the concrete surface, with displacement transducers (LVDT) to measure the Crack Mouth Opening Displacement (CMOD) (Fig. 2).

The specific fracture energy G_F was determined by stable direct tension tests on at least three prenotched cylindrical specimens for each type of concrete. The tests were carried out through a computer controlled machine (maximum load = 60 t), using the CMOD as feed back signal. The imposed displacement rate was 0.0025 μm/sec.

The diagrams of load versus CMOD, where CMOD is the average signal of the three transducers, were recorded. As an example they are reported in Fig. 3 for concrete specimens (G aggregate distribution and w/c=0.72) aged 1 month and 26 years respectively. As the area under the load-crack opening curve includes not only the amount of energy consumed by the fracture zone but also the amount of energy consumed by the material outside the fracture zone before the tensile strength is reached, this last small contribution was subtracted in the calculation of G_F values. They are reported for all concretes in table III, together with the tensile strengths (f_t) and the characteristic lengths (l_{ch}).

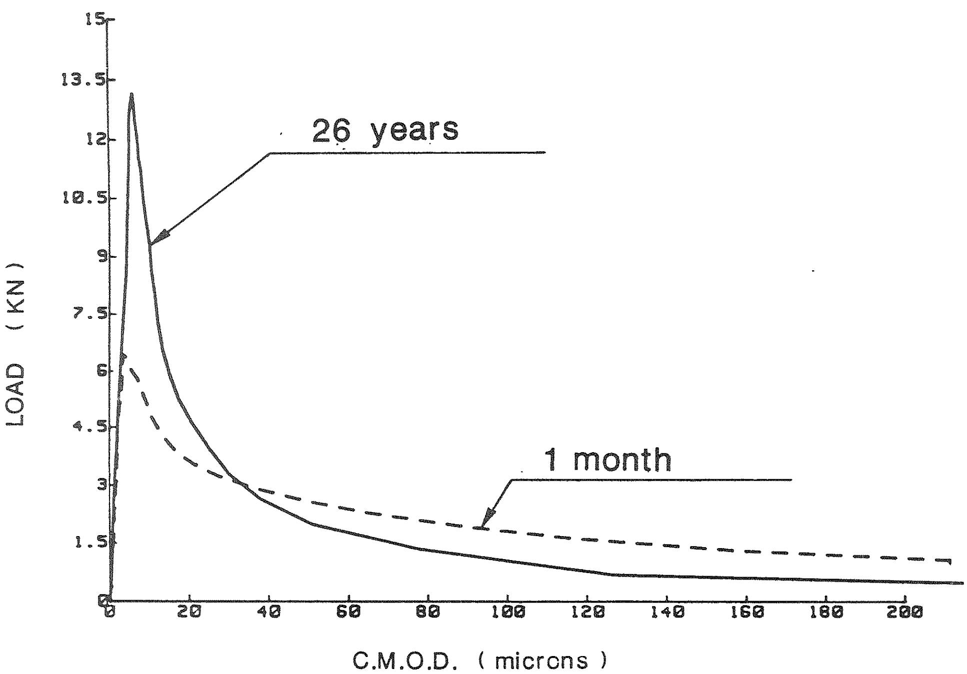

Fig. 3. Load-crack opening curves in stable direct tensile tests for 1 month and 26 years aged concretes

Table III Fracture mechanics parameters for direct tensile tests

Aggregate distribution		G		S	
water/ cement		0.57	0.72	0.57	0.72
f_t (MPa)	1 month	1.63 ± 0.21	1.10 ± 0.18	1.98 ± 0.24	1.51 ± 0.38
	26 years	2.30 ± 0.47	2.18 ± 0.48	2.21 ± 0.28	2.37 ± 0.70
G_F (N/m)	1 month	102.2 ± 30.9	103.7 ±15.3	112.3 ± 30.7	105.1 ± 24.4
	26 years	122.8 ± 56.5	85.2 ±21.3	100.9 ± 11.8	116.9 ± 30.9
l_{ch} (mm)	1 month	1305 ± 425	1963 ±341	797 ± 183	1294 ± 680
	26 years	727 ± 217	531 ± 147	689 ± 198	743 ± 346

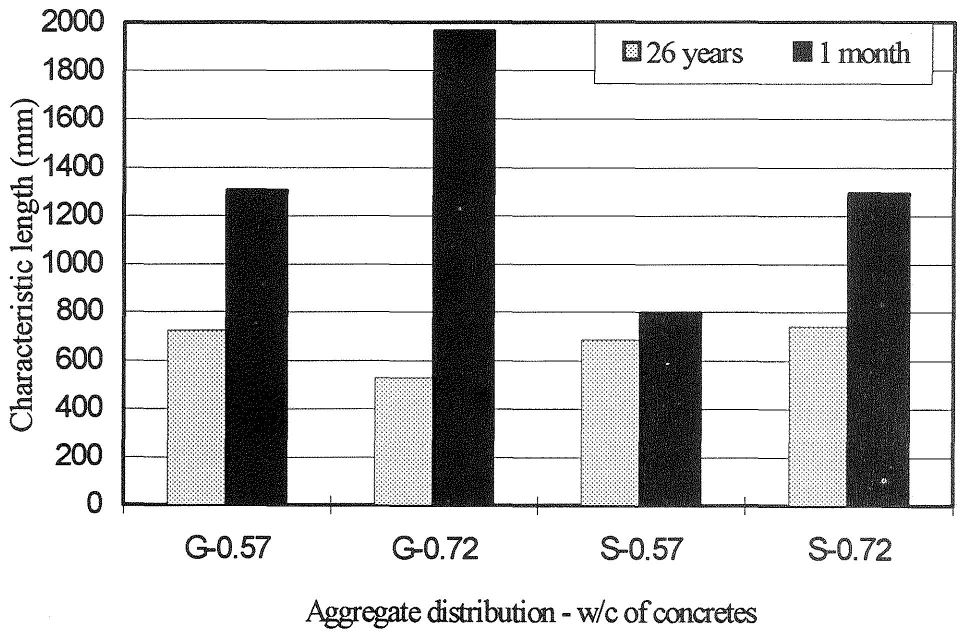

Fig.4. Characteristic lengths for 26 years and 1 month aged concretes

In spite of the wide dispersion of the results (coefficients of variation of about 30%), considerably lower values of characteristic lengths are observed for the 26 years aged concretes in comparison with the young ones, independently of the aggregate distributions and of the w/c in the concrete (Fig.4). The average values is about 1300 mm for concretes aged 28 days and about 650 mm for concretes aged 26 years.

The characteristic length values given in the technical literature for concrete greatly vary between about hundred to thousand millimetres, depending on the concrete mix design and in particularly on the type of aggregates, cementitious matrix and aggregate/cementitious matrix interlock.

Values of 150-200 mm have been measured for high strength concretes, Berra, Ferrara (1990) and Konig, Remmel (1992), while normal concretes show generally higher characteristic lengths. Values as high as 2300 - 2400 mm have been also reported, Blaschke, Mehlhorn (1992).

The lower is the characteristic length the lower is the toughness of the concrete and then the higher is its fragility. Therefore the values of this fracture parameter obtained in this research confirm that the concrete toughness decreases with age and show that after 26 years it can be reduced even by one half.

5 Conclusions

Retrofitting of structural adequacy of existing constructions to prescribed loading conditions is generally based on the measure of the compressive strength of the concrete, which may be more favourable than expected, and on the assumption that the concrete toughness - if required - has remained constant, or even has improved in proportion to the strength.

The results of the present research suggest that such formulations should be revisited to take account of the reduced toughness of concrete with increasing age, namely to check whether the higher strength can compensate the reduced toughness.

In particular, the experimental tests of this study, carried out on different types of concretes at 1 month and after several years of curing, showed that:

- After 20 years the concrete has higher compressive strength but lower toughness than young concrete. The concrete toughness, evaluated on the basis of stress-strain diagrams of specimens under cycles of compression stresses, decreased by 30-50%.

- The energy to collapse, evaluated after 26 years in a monotonic direct tensile test on prenotched cylindrical specimens and expressed as “characteristic length“, decreased by even 50%.

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