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VARIATIONS IN THE MECHANICAL PROPERTIES OF CONCRETE SUBJECTED TO LOW CYCLIC LOADS

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ABSTRACT

This paper analyses the changes occurring in the mechanical properties of concrete subjected to uniaxial compression loading cycles having low intensity and short duration. The concrete was seen to undergo strain hardening and an increase in stiffness due to the effects of dynamic loading, as revealed by an increase in the material's failure load and modulus of elasticity. In poor quality concrete, a shift from ductile to brittle failure was observed. © *1997 Elsevier Science Ltd*

Introduction

When materials are subjected to cyclic loading they are generally seen to undergo a progressive deterioration of their mechanical properties. Some authors instead have witnessed an increase in the static compressive strength of concrete subjected to a limited number of low intensity compressive cycles. Bennet and Muir [1] found that the static compressive strength of specimens subjected to preliminary cyclic loading was from 1 to 20% higher than that specimens not previously subjected to loading, whilst according to Mehemel and Kern [2] this improvement, on average, comes to 10%. They ascribed this phenomenon to a fall in the tensile stress singularities developing in the material and the redistribution of stresses arising from the creep induced by cyclic loads. From a series of short duration dynamic and static compressive tests of considerable intensity (90% and 95% of mean compressive strength), Award and Hilsdorf [3] observed an increase in concrete static strength compared to specimens not previously subjected to loading, as well as an increase in fatigue strength, both of them inversely proportional to the number of loading cycles performed up to 20%-30% of fatigue life.

The aim of the experimental investigation described in this paper, which was carried out on cylindrical concrete specimens obtained by core drilling, was to observe the strain hardening of the material for a limited number of low intensity cycles, and to study the changes taking place in concrete following dynamic loading. In addition to the variations in failure load, the testing program also made it possible to analyse the variations in total fracture energy and the variations in the stress-strain curves occurring in concrete specimens of different quality.

Testing Set-up and Procedure

The procedure adopted was as follows: some of the specimens were subjected to a preliminary cyclic compressive loading of an intensity equal to 10% and 20% of the failure load; after that, such specimens were tested till failure through a uniaxial static compressive test by applying the load in the same direction as in the previous tests. The values of the mechanical properties worked out from the static compressive tests for the specimens subjected to cyclic loading were compared with those obtained on similar specimens not subjected to the preliminary loading cycles.

Dynamic and static compressive tests were performed by means of a 250 kN testing machine fitted out with a system for the measurement of the load and piston stroke and equipped with an electronic device in order to control the piston displacement rate.

Two different types of concrete were used to assess the variations in these phenomena in relation to concrete quality: the concrete with poorer mechanical properties is referred to as mix I and the one possessing higher strength is referred to as mix II. Cylindrical test pieces obtained by core drilling, 45.5 mm in diameter and 140 mm long, were used: the two ends on which are applied the machine plates have been carefully levelled. The composition and mechanical characteristics of the mixes used are listed in Table 1, where Rcm indicates tensile stress at failure in cube specimens.

Some of the specimens were subjected, for about two hours, to compressive loading cycles at a frequency of 1 Hz with a sinusoidal load varying between a maximum corresponding to 20% of the failure load (5.2 kN for mix I concrete and 19.2 kN for mix II) and a minimum of 2% of the failure load. During the tests, the evolution of temperatures was also measured by means of resistors [4] with 0.001°C sensitivity arranged on the sides of the test pieces (Fig. 1). Other specimens were subjected to cyclic loading corresponding to 10% of the failure load in order to monitor the variations occurring in the mechanical behaviour of the material under lower intensity dynamic loading. Comparatives tests lasting 30 minutes (1800 cycles) were also conducted to study the time influence on the material's strain hardening.

The specimens subjected to compressive loading cycles were then tested till failure through static compressive tests carried out in controlled strain conditions.

TABLE 1

Composition and Strength of the Concrete Mixes

Type		**I**	**II**
Cement 42.5 R	[kg/m^3]	200	400
Sand 0 to 4 mm	[kg/m^3]	991	789
Aggregate 5 to 8 mm	[kg/m^3]	1169	1142
W/C	-	0.70	0.40
R_{cm}	[N/mm^2]	16	59

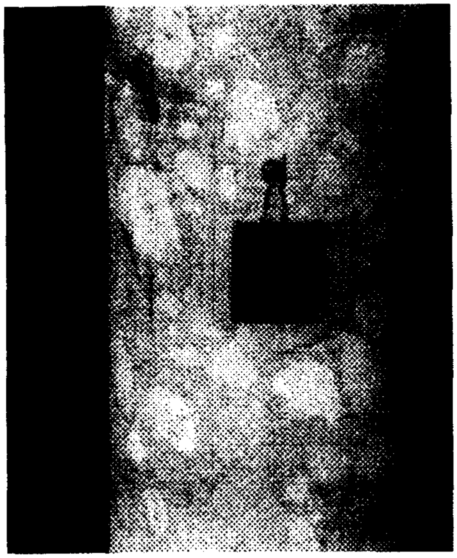

FIG. 1.
Arrangement of resistors.

In order to compare the results, specimens not previously subjected to dynamic loading were then tested in similar conditions.

The static compressive tests were carried out in controlled strain conditions with a testing machine piston feed rate of $5 \cdot 10^{-6}$ m/s; this made it possible to work out specimen strength during the stage following maximum failure load.

Table 2 shows the break down of the concrete specimens over the different types of test.

Test Results and Discussion

Load-displacement curves were plotted for the specimens manufactured with mix I in the three loading configurations envisaged: no preliminary cyclic loading (Fig. 2a), preliminary cyclic loading at 20 % of R_{cm} (Fig. 2b), and at 10 % of R_{cm} (Fig. 2c).

TABLE 2

Static Testing Programme: Number of Specimens

Type of pre-loading	I	II
not pre-loaded	5	5
2 h cyclic loading 20 % of R_{cm} with meas. of temperature	5	5
2 h cyclic test, 10 % of R_{cm}	3	2
0.5 h cyclic test, 10 % of R_{cm}	2	3

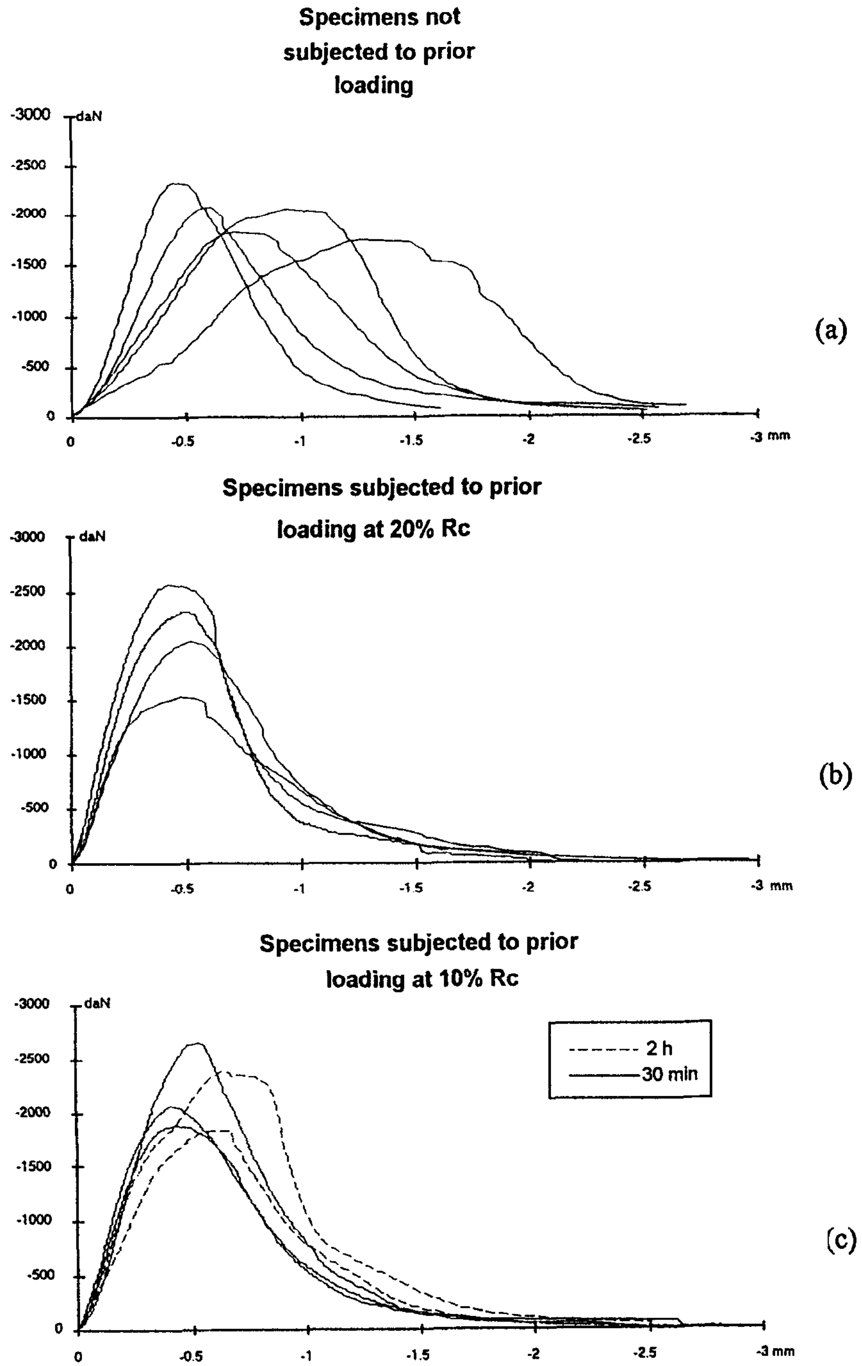

FIG. 2.
Load-displacement curves for mix I specimens.

TABLE 3

Failure Stress and Total Fracture Energy for Mix I Specimens

type of test	σ_R [N/mm^2]	s_σ [N/mm^2]	W_{tot} [J]	s_W [J]	No. of tests
no pre-loading	12.4	1.407	18.9	4.072	5
pre-load. 20 % R_C	13.6	2.742	17.5	3.956	5
pre-load. 10 % R_C	13.3	2.149	16.9	2.624	5
total pre-load.	13.45	2.329	17.2	3.184	10

The behaviour of mix I concrete is ductile (Fig. 2a): failure is not followed by a sudden decrease in compressive strength, but rather by a substained softening stage. Figs. 2b and 2c show that the specimens previously tested at 20% and 10%, respectively, exhibited a brittle behaviour instead: following failure, compressive strength is seen to drop almost immediately. These variations are given in quantitative terms in Table 3, where:

σ_R = tensile stress at failure in cylindrical specimens;
s_σ = standard deviation of tensile stress;
W_{tot} = total fracture energy, determined from the load-displacement curve integral;
s_W = standard deviation of total fracture energy.

Mix II specimens not previously subjected to cyclic loading (Fig. 3a) already display a brittle behaviour. The effect of the decrease in strength that occurs following failure is maintained, but substantially there is no appreciable further reduction in strength in the specimens subjected to prior loading at 20% (Fig. 3b) and 10% (Fig. 3c).

Table 4 lists the values of total fracture energy and failure stress for mix II specimens.

Significant indications on material properties may be obtained from the analysis of the apparent axial rigidity K_a (calculated on the basis of the displacement of machine plates), displacement at failure s and the determination of the centroids X_g, Y_g of the load-displacement curves of Figures 2 and 3, which are represented in schematic form in Figure 4.

It should be kept in mind that the apparent axial rigidity K_a of the specimen, also includes machine strains and crushing strains between plates and specimen. Since the purpose of the research is the investigation on variations in behaviour between specimens subjected and not subjected to preliminary loading cycles, it was not deemed necessary to evaluate the effective elastic modulus.

By comparing the values obtained for specimens not subjected and subjected to prior loading cycles, it is possible to infer additional information on the type of transformation that has taken place in the concrete, as illustrated in Table 5, where are reported also the failure load F_{max}.

Displacement at failure s is taken to be the value measured at the apex of the load-displacement curve; when this value is represented by a straight line running parallel to the displacement axis, the starting point of the descending branch is taken into account instead.

The specimens subjected to preliminary loading cycles (solid line curve in Figure 4) have a different load-displacement curve and exhibit a higher failure load and lower strains compared to the specimens not subjected to preliminary loading (dashed curve in Figure 4). This

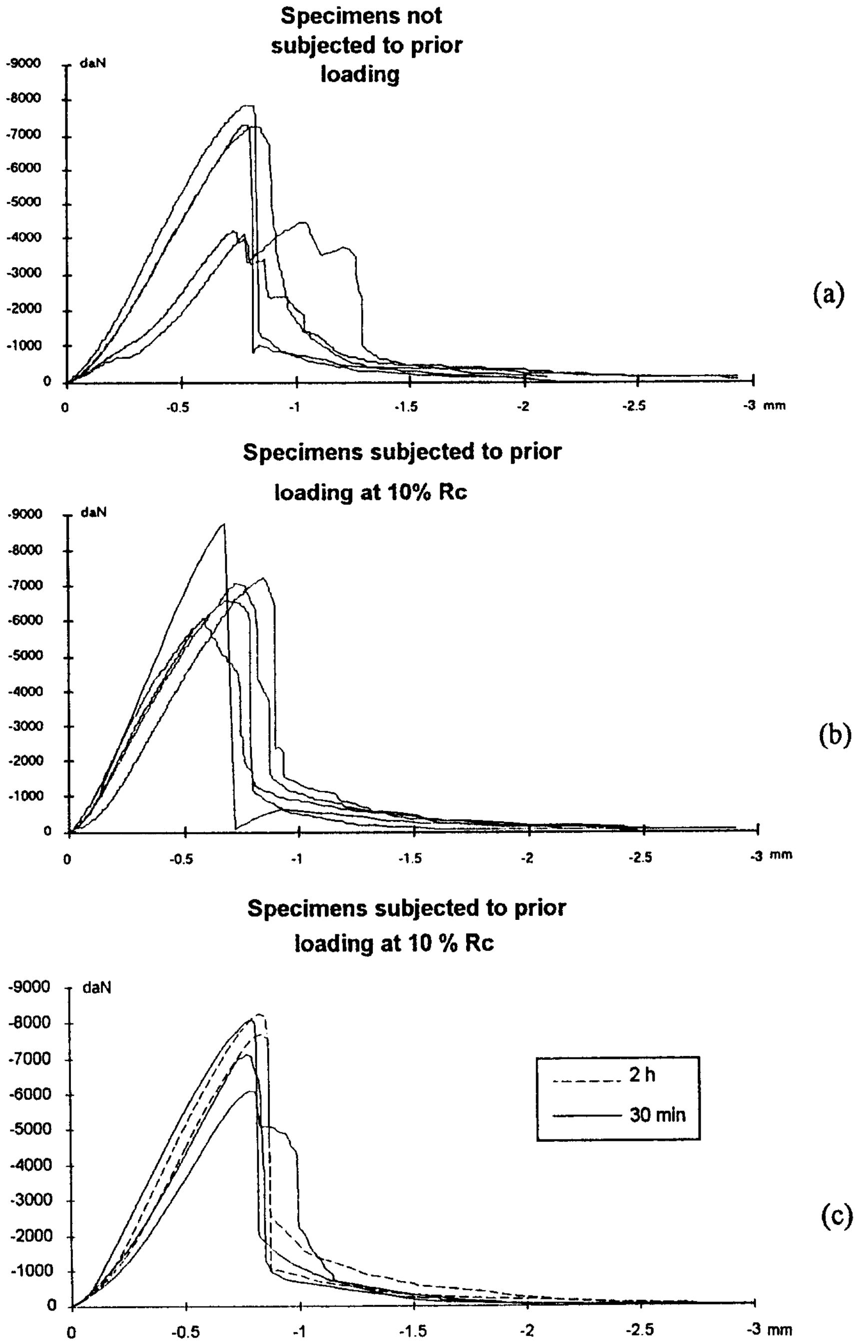

FIG. 3.
Load-displacement curves for mix II specimens.

TABLE 4

Failure Stress and Total Fracture Energy for Mix II Specimens

type of test	σ_R [N/mm^2]	s_σ [N/mm^2]	W_{tot} [J]	s_W [J]	No. of tests
not pre-loaded	38.3	10.676	36.2	4.711	5
pre-loaded 20 % R_C	42.1	6.947	39.1	4.044	5
pre-loaded 10 % R_C	45.8	5.362	39.9	5.063	5
total pre-loaded	43.8	6.28	39.4	4.315	10

is also borne out by the variation in the X_g, Y_g positions of the centroids of the two curves: whilst non pre-loaded specimens display a failure diagram which closely resembles the dashed curve, cyclic loading modifies the specimens so that their failure diagram becomes similar to the curve represented by a solid line.

In order to define these changes in quantitative terms, let us introduce the following parameters, ***r***, ***c*** and ***p***, by denoting the values of the quantities involved before and after the cyclic test with subscript 1 and subscript 2, respectively:

- r = $\dfrac{F_{max\ 2}}{F_{max\ 1}}$ ratio between failure loads;

- c = $\dfrac{\eta_1}{\eta_2}$ ratio between displacements at failure;

- p = $\dfrac{K_{a2}}{K_{a1}}$ ratio between apparent axial rigidity.

For the tests at 20 % R_{cm} we get the following values:

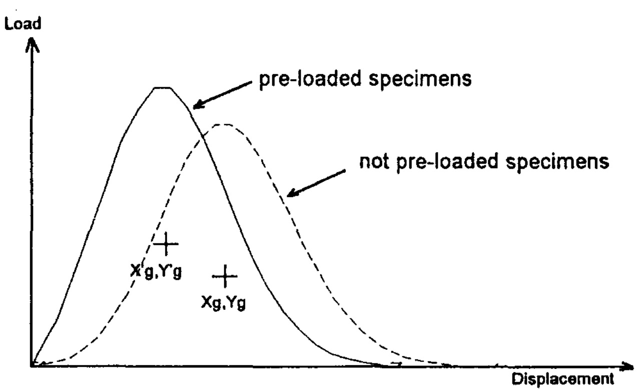

FIG. 4.
Centroid of the load-displacement curve for mixes compacted to a different extent.

TABLE 5

Mechanical Properties of the Specimens Before and After Cyclic Loading

Test	X_g [mm]	Y_g [N]	s [mm]	F_{max} [N]	K_a [N/mm^2]
Mix I					
not pre-loaded	0.892	7778	0.791	20110	3605
pre-loaded 20% R_C	0.665	8037	0.463	22150	6731
Mix II					
not pre-loaded	0.787	20581	0.822	62360	8699
pre-loaded 20% R_C	0.696	21359	0.719	71307	10636

Mix I	Mix II
r = 1.101	r =1.143
c = 1.709	c = 1,142
p = 1.867	p = 1.223

Failure load F_{max} and hence stress at failure are seen to increase on average in shifting from concrete specimens not subjected to prior loading to concrete specimens subjected to cyclic compressive loading beforehand.

In mix I specimens, the increase in failure stress is about 10%, while in mix II concrete it comes to about 14%. As for the parameters defining deformability, it should be noted that the increase in displacement at failure, η, is about 70% for mix I and about 14% for mix II. The increase in apparent axial rigidity is about 86% and 22%, respectively.

The comparison of the variation of parameters *c* and ***p*** for the two different mixes demonstrates that the inclusion of the crushing and machine strains is irrelevant for the analysis of the changes of mechanical proprierties.

Thus we find that dynamic loading reduces pore space in the concrete so that in the subsequent static compressive tests deformability is hindered by improved material compaction.
In concrete which is more closely compacted to begin with, strain hardening takes place all the same as is reflected in an increase in maximum load and reduced deformability, even though this phenomenon is much more evident in less tightly compacted concrete.

In mix I concrete, on account of the improvement of mechanical properties of the material, we should expect *total fracture energy* W_{tot} to increase, like compressive strength, but in actual fact it is seen to decrease. This is only an apparent contradiction and explanation for this lies in the fact that concrete has shifted to a different failure mode, ductile failure having been replaced by brittle failure. Consequently, the uniaxial failure test is not able to measure the actual variations in the material's interior energy.

This is confirmed by the observation of standard deviation values relating to specimen failure stresses: such values should also decrease as we go from non previously loaded to previously loaded concrete since the compacting process taking place during cyclic loading should make the concrete more homogenous. Standard deviation values are seen to increase instead, because of the shift to brittle failure which is characterised by a greater scatter in the results.

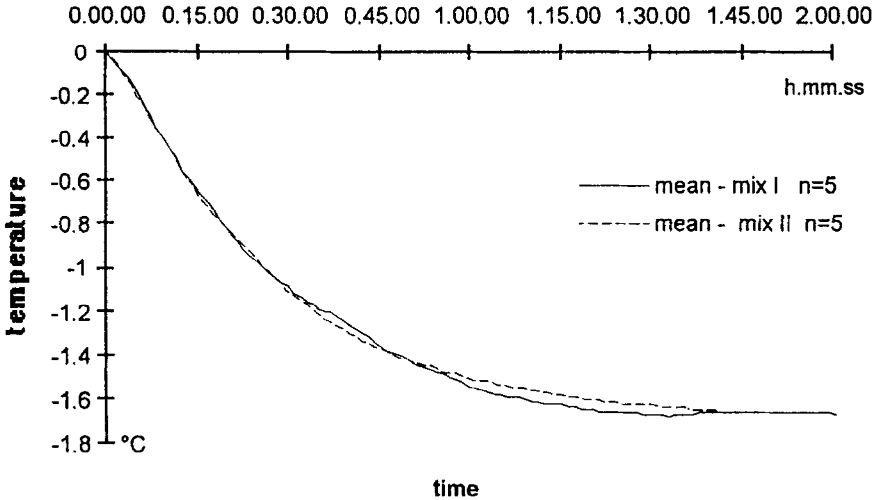

FIG. 5.
Evolution of temperature during cyclic compressive tests at 20% R_{cm}.

In mix II specimens, total fracture energy is higher in non pre-loaded specimens compared to those that have been subjected to cyclic loading. Since the failure mode is the same, this means that the strength of the material has been enhanced by dynamic loading. The energy supplied by the cyclic loading adds mostly to the material's elastic energy: this is reflected in a parallel increase in maximum failure load. The increase in total fracture energy comes to about 10%.

The evolution of temperature values, as measured during cyclic compressive loading is evidence of the fact that energy is being absorbed by the concrete. In Figure 5, the mean temperature value as determined on 5 specimens manufactured from mix I is shown as a solid line and the mean over 5 mix II specimens is represented by a dotted line. The 10 specimens had all been previously subjected to dynamic loading at 20% of the failure load.

Regardless of mix type, a decrease in temperature is observed during preliminary dynamic loading, which shows that the energy transferred to the concrete by the testing machine is not dissipated in the form of heat, and the concrete absorbs a further amount of energy from the environment.

Conclusions

Low intensity (10-20%) and short duration (7200 cycles at 1 Hz) cyclic loading compacts the material which, consequently, displays a 10% to 15% increase in failure load and reduced deformability (of 86% or 22%, depending on type of mix).

The material, as modified by preliminary dynamic loading, is more homogenous and is characterised by a stiffer behaviour. Failure shifts from ductile to brittle behaviour, as is clearly demonstrated in mix I specimens.

During the loading cycles, the concrete acquires energy resulting in improved compaction of the material.

Improved compaction is observed for both loading levels (20% and 10% of the failure load); it can be already observed after 1800 cycles, but it is particularly evident after a greater number of cycles.

During cyclic loading all the specimens have absorbed energy. The resistors located to the sides of any specimen reveal a fall in temperature of about 1.5°C (a phenomenon seemingly conflicting with the expected behaviour of a material characterised by marked hysteresis cycle and the concomitant dissipation phenomena; it is now being investigated further).

The energy stored up in the specimen during the cyclic loading partly produces strain hardening of the material and partly increases the failure load in consequence of changes to the concrete matrix: an interpretation has been formulated in [5].

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