MICROSTRUCTURE EVOLUTION OF CONCRETE UNDER LOW-FREQUENCY CYCLIC LOADING: DETERMINATION OF THE POROSITY VARIATIONS

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Generally structural concretes are subjected to variable and repeated loadings and are sometimes modelled by fatigue tests. In such cases the loading is cyclic and the frequency is high. Although these tests allow us to draw up Woelher curves and Goodmann diagrams they cannot strictly reproduce the behaviour of concrete in structures where the loading frequencies are much lower.

Consequently we are interested in the behaviour of concrete under low frequency (about one cycle per minute) cyclic loading and we have chosen to study the rheologic behaviour and material evolution-cracks, fractures, "consolidation"... - rather than the fatigue life.

KEYWORDS

Concrete, microconcrete, monoaxial compression, cyclic loading, low frequency, microcracks, porosity, consolidation.

INTRODUCTION

The results of partially prestressed structures tests (Pinglot and Pons, 1974) have shown that low-frequency cyclic loadings did not involve concrete fatigue after about a hundred thousand cycles. On the contrary, on condition that the maximum cyclic load does not exceed half of the rupture load, the ultimate bending moment of beams subjected to 10000 repeated loadings was always superior to the bending moment of beams submitted to progressive direct loading up to breaking point. Therefore it appears that low-cycle loading are not liable to damage or micro-crack the concrete but, on the contrary, to strengthen or consolidate it. This consolidation has been attributed to a decrease of porosity of the cement paste.

In order to study this behaviour more exactly we have investigated the behaviour of microconcrete subjected to monoaxial compression and low-cycle harmonic loading. These tests have been carried out to determine the influence of various parameters on the development of mechanical deformations and moduli (Pons and Maso, 1982, 1983).

These are the conclusions we may infer from these tests : the development, under cyclic loadings, of transverse and longitudinal deformations is very important in the beginning but, after, it notably slows. In addition, at the beginning of cyclic loadings, the development of longitudinal deformation is twice as pronounced as that of transverse deformation. This difference tends to lessen when the number of cycles increases. The structural explanation of this phenomenon is linked to the progressive closing of unsaturated pores : that is fast and preponderant in the loading direction. After the deformation development is linked to the oozing of the water from saturated pores induced by the energy liberated by the cyclic loadings. Transverse and longitudinal deformations follow a similar pattern. After cyclic loading we have noticed a linearization of stress/strain curves, the area between loading and unloading curves decreases and consequently there is a diminution of the energy used up by the internal friction. For maximal cyclic loads equal to 50 % of ultimate load there seems to be a "consolidation". There is an important increase of longitudinal deformation modulus and therefore a hardening or consolidation of the microconcrete. Consequently in so far as the maximal cyclic load does not exceed 80 % of the ultimate load in direct loading conditions, there is, under the cyclic loading, a decrease of test piece volume and the residual transverse deformation is lower than the longitudinal deformation. After being subjected to 10000 cyclic loadings, the microconcrete does not seem to show important damage.

All these phenomenons are linked to the presence of unsaturated pores, microcracks and free-water. Apart from the strictly mechanical point of view, we think that it might be very interesting to study the structural evolution of the concrete under low-cycle harmonic loading. The first research, that we relate in detail further on, describes the changes in the porosity.

EXPERIMENTAL METHOD

Specimens

The concrete is cast in cylindrical moulds (section : 200 cm^2, length : 32 cm). Their sizes allow us to core out 12 test pieces for porosity measurements. The composition of the concrete used in these tests is the same as that used for our beam tests (Pinglot and Pons, 1974). The cement mix is 350 kg/m^3, the water/cement ratio 0,5. The aggregates are crushed calcite gravel (maximum size 12,5 mm, minimum 0,08). The nominal 28 day compressive strength is 41 MPa -range ± 5 %.

We have manufactured 3 sets, each having 6 test pieces. In each set 4 test pieces were submitted to direct ultimate loading, so we were sure of the batch conformity, another was submitted to 10000 cyclic loadings, and the last one, the reference test piece, was directly loaded at the same load as the maximal cyclic load.

Loadings and Measurements

After a 28 day curing period the test pieces are subjected to direct or cyclic monoaxial compression.

The direct loading is carried out up to 50 % of the ultimate load, the loading rate is 0,33 MPa/s.

The main features of the low-cycle harmonic loading are : 2 cycles per minute frequency, minimal cyclic load equal to 25 % of ultimate load, maximal cyclic load equal to 50 % of ultimate load (stress-range is σ_m = 10 MPa, σ_M = 20 MPa).

Longitudinal deformations have been mesured, for a reference length of 100 mm, by 3 displacement transducers on the longitudinal generatrix at 120° intervals. Transverse deformations have been measured by 3 strain gauges mounted circumferentially 120° apart and at mid height.

Determination of the Microstructure Porosity

Our object is to study, on one hand, the total porosity variations, and on the other hand, the size distribution of the pores and microcracks.

The total or absolute porosity is $n = (\gamma_r - \gamma_a)/\gamma_r$ with γ_a apparent density and γ_r real density deduced from weighing of the test piece after grinding.

The size or volumic distribution of porosity is determined by mercury pressure penetration. Such a procedure allows the determination of surface pores, its results depend on the possible orientation of pores or microcracks. In order to bring to the fore a preferential orientation of pores, linked to the working, we have carried out a bi-directional coring of the test cylinders. We obtain in each test piece 6 cores (Ø = 20 mm, h = 50 mm) oriented in a parallel direction to loading and 6 orthogonal.

We used a mercury pressure penetration porosimeter. The range of pore radius was from 75 - 7540 Å. For macropores having a radius more than 7540 Å we used a mercury dilatometer.

SIZE VARIATION STUDIES : BEFORE AND AFTER CYCLIC-LOADING BEHAVIOUR

Longitudinal Deformation ε_1

Its development is shown by Fig. 1

At the maximal load, the deformation increase between the first and the 10000th loading cycle is 41 %. The microconcrete tests (Pons and Maso, 1982) have shown a 39 % increase. Thus the development is similar and the observations are the same : for tests carried out to a maximal cyclic load equal to 50 % ultimate load, after 10000 loading cycles, there are an apparent "accomodation" (hysteresis loop stabilization), a diminution of the energy used up by the internal friction, and, also, a linearization of stress/strain curves. The secant longitudinal deformation modulus after N cycles E_σ^n is given us by the relation, for all of stress/strain curve points, $\sigma = E_\sigma^n \times \varepsilon_1$, the origin being the one of the studied cycle. The Table I shows the E_σ^n evolution beetween the 1st and the 10000 th cyclic-loading.

We noticed that, for stress range superior to $0,375\,\sigma_R$, E_σ^n increase is very perceptible. Thus there is a strengthening or consolidation of concrete. The E_σ^{10000} constant value shows the stress/strain curve linearization. Comparing with microconcrete tests (Pons and Maso, 1982) we found that the longitudinal deformation moduli are more important and, on the contrary, their development under cyclic loading is lower, which is consistent (for microconcrete E_σ^1 = 18000 MPa and ΔE_σ = 15 % with $\sigma = 0,5\,\sigma_R$).

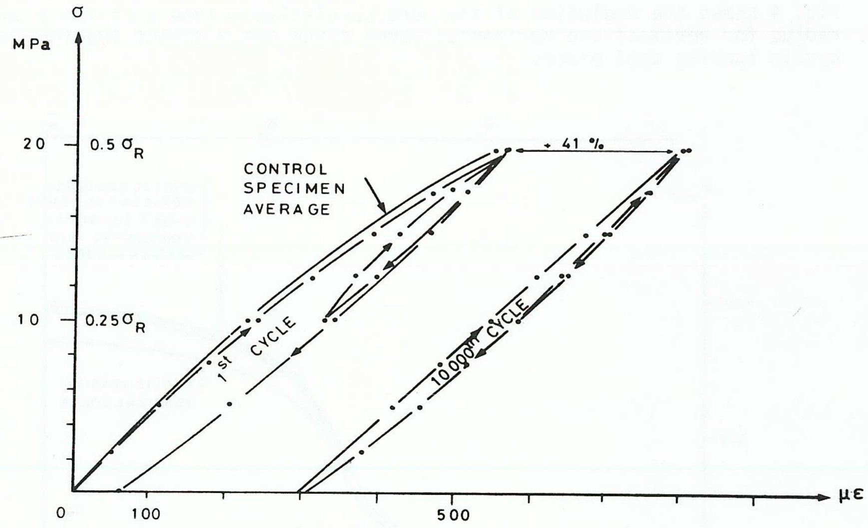

Fig. 1. Development of longitudinal deformation

TABLE 1

	$E^n_\sigma \iff \sigma = E^n_\sigma \times \varepsilon_1$		
σ	E^1_σ 1st cycle	E^{10000}_σ	ΔE_σ %
0,25 σ_R	40 800	40 300	0
0,375 σ_R	38 100	40 000	5
0,50 σ_R	35 900	40 200	12

σ : Applied stress (MPa)

σ_R : ultimate stress (MPa)

Transversal Deformation ε_2

The development of the transversal deformation ε_2 is smaller but its behaviour is similar. At the maximal cyclic load, there is a 21 % increase. For the microconcretes it is about 15 %. The transversal deformation modulus $\nu(\sigma)$, (given by the relation $\varepsilon_2 = \nu(\sigma) \times \varepsilon_1$, the origin is the one of studied cycle), is almost constant between the 1st and the 10000th cycle : $\nu(\sigma)$ # 0,25.

As for the residual deformation after cycling, the modulus of the permanent transverse deformation is $\nu(\sigma) = 0{,}17$. There is a longitudinal shortening that is not matched by an increase of a transverse deformation. There is an important volumetric decrease.

To conclude, comparing the concrete and microconcrete behaviour underlines similar phenomena but they have not the same development. Before cyclic loading the concrete is stiffer than the microconcrete (the longitudinal deformation modulus is upper) ; both show increases in stiffness after cyclic loading but the increase is greater for the microconcrete than for the concrete.

STRUCTURAL MODIFICATIONS : POROSITY VARIATION

Total or Absolute Porosity

The total porosity (average of porosity measures carried out with 12 cores in each test piece) is equal to 10,22 % for the direct loading test pieces and to 9,82 % for the cyclic loading. Thus we find that the porosity of test pieces subjected to 10000 cyclic-loadings is inferior to that of the direct loading test pieces by about 4 %.

Thus there is a microstructure consolidation involving, for the mechanical point of view, an increase of longitudinal deformation modulus.

Pore Size Distribution - Global Distribution

First, we examine the porosity distribution independently of the test piece coring orientation. Fig. 2 shows the cumulative volume of less 7540 A° radius pores as a function of pore radius. Logically we find again that the pore cumulative volume of the cyclic-loaded test-pieces is lower than that of direct loaded test pieces. The difference begins for pore radii superior to 251 A°. On the other hand we observe that the radius of the majority of pores is included between 251 and 754 A°. Finally as the curve is, at its origin, tangential to x-axis, we can say that the volume of pores of less than 75,4 Å radius, is negligible.

The volumetric distribution of these pores ΔV as a function of the pore radius R is shown by Fig. 3. We observe distinctly that the pore volume decrease mainly has an effect in the 188 to 754 A° radius range. As for the porosity investigated by mercury pressure lower than the atmospheric, in any case the tests show it is negligible. Its total volume is equal to 2 % of the total pore volume. We cannot make an inference from so small variations but we can assert that there are not, after the cyclic loading, macrocracks in the concrete.

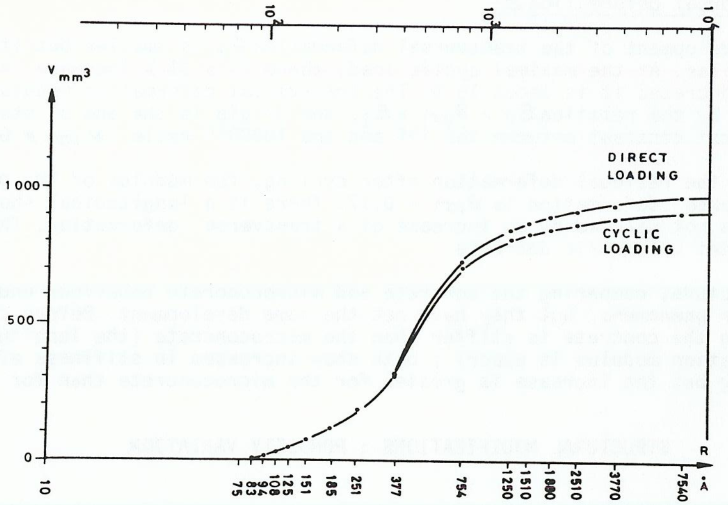

Fig. 2. Cumulative pore volume as a function of pore radius

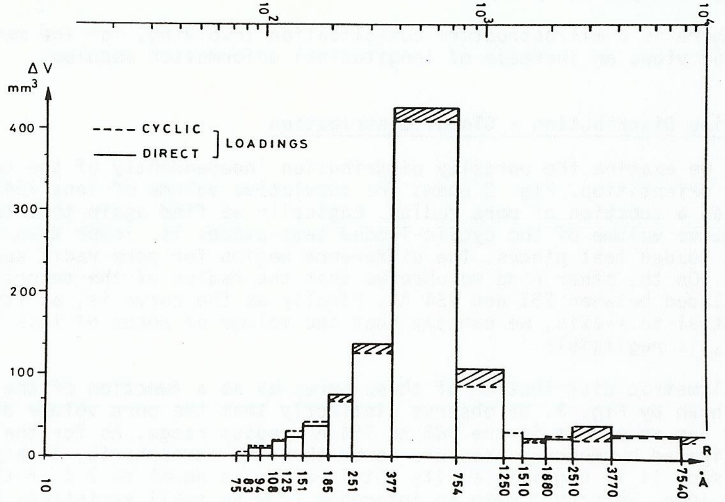

Fig. 3. Volumetric distribution of pore as function of pore radius

Oriented Distribution of the Porosity

Fig. 4 shows the evolution of the pore cumulative volume as a function of pore radius for vertical and horizontal cores taken out 3 direct loading and 3 cyclic loading test pieces.

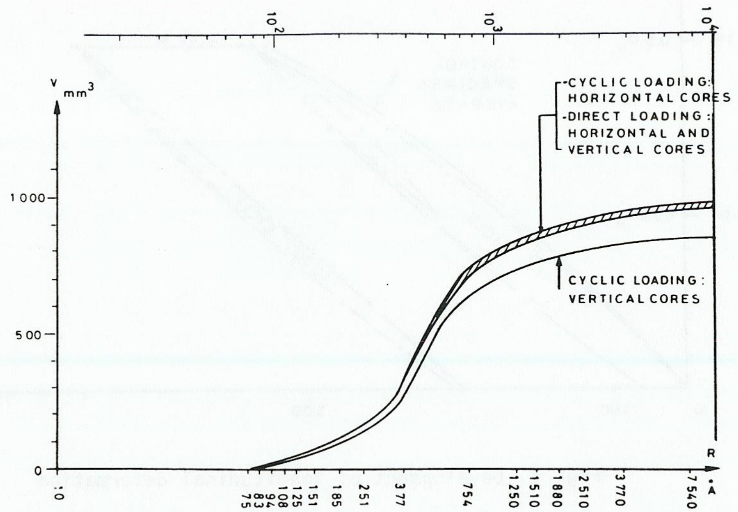

Fig. 4. Pore cumulative volume as a function of pore radius - Coring orientation influence

We find that the vertical cores of the cyclic loading test pieces show a pore volume decrease, so, their consolidation is better.

The explanation of these results is that the mercury penetration porosimeter only detects the surface pores. So if pores and microcracks have a preferential orientation the coring direction will have a great consequence.

In its initial state the concrete porosity (pores, microcracks) almost is homogeneous and isotropic. After the cyclic loading we note that the cores which are parallel to the loading direction and which cross more microcracks than vertical cores have a more important porosity decrease. Consequently these are the microcracks, which are oriented orthogonaly to the loading direction, that are closing. As for the horizontal cores, after cyclic loading, the porosity is unchanged though the total porosity decreases. We suppose there are coming out some microcracks which are parallel to loading direction.

In conclusion, as we have supposed in a previous publication (Pons and Maso, 1982), the pores and microcracks whose the orientation is orthogonal to the loading direction are closing first.

Comparing Total and Emerging Porosity

The total porosity decrease, after cyclic loading, was 0,4 % of core total volume. The surface porosity, detected by the mercury penetration porosimeter, was 0,36 %. We ascertain that the volume decrease of the porosity is caused almost entirely by the decrease of surface porosity.

It is especially, as we have assumed in a previous publication the possibility of water exchange between the test piece and the surrounding air that governs the concrete behaviour.

CONCLUDING REMARKS

The monoaxial compression and low-cycle harmonic loading does not involve, for the tested concretes and microconcretes, fatigue of the behaviour.

We note a concrete consolidation that is shown by an important increase of its longitudinal deformation modulus. Moreover comparing concretes and microconcretes underlines a similar behaviour. However the concretes have a superior rigidity -more important longitudinal deformation moduli- and, logically, creep slower under the cyclic-loading. In the experimental loading range ($\sigma m = 0{,}25\,\sigma_R$ $\sigma_M = 0{,}50\,\sigma_R$) the porosity measurements corroborate the external observations : there are neither damaging nor microcrack enlargement in the material since, after cyclic loading, the porosity decreases. Moreover there is no increase in the number of pores whose diameters are the most important, on the contrary, for the most numerous divisions, there is a translation towards the lower diameters. Studying the pore orientation shows that there is a preferential closing of the pores and microcracks whose larger size is orthogonal to the loading direction. These porosity variations are caused by the closing of the connected pores and microcracks. They are linked to the displacement possibilities of free water in concrete matrix.

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