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Behaviour and Durability of Concrete with Regards to Cycle and Time Dependent Effects

Comportement et durabilité du béton compte tenu des effets des cycles et du temps

Eigenschaften und Dauerhaftigkeit von Beton mit Rücksicht auf die von Perioden und Zeit abhängigen Effekte

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SUMMARY

The paper presents the main results of a research programme devoted to the problem of plain concrete subjected to cyclic stress, including both analytical and experimental investigations. Two mechanical approaches are proposed to allow for both cycle dependent and time dependent effects, the latter being more significant at high levels of loading. Based on the theory of damage, they provide a prediction of the durability of plain concrete subjected to cyclic loads. A constitutive law is proposed that accounts for the behaviour of concrete as observed during the tests up to failure point.

RÉSUMÉ

L'article présente les principaux résultats d'un programme de recherche portant sur le problème du béton soumis à des chargements cycliques, selon un double aspect analytique et expérimental. Deux approches mécaniques sont présentées pour rendre compte des effets des cycles et de ceux du temps, ces derniers étant réellement significatifs pour les niveaux élevés de chargement. Basées sur la théorie du dommage, elles fournissent une prédiction de la durabilité du béton soumis à des charges cycliques. Une formulation est ensuite proposée pour rendre compte du comportement du béton observé au cours des tests jusqu'à la rupture.

ZUSAMMENFASSUNG

Diese Arbeit präsentiert die Hauptergebnisse des Prüfungsprogrammes, das den Beton unter wiederholten Spannungen betrifft, mit sowohl analytischen wie auch experimentellen Prüfungen. Zwei mechanische Annäherungen werden präsentiert, um die von den Perioden und der Zeit abhängigen Effekte zu berücksichtigen. Der Einfluss der Zeit, besonders bei hohen Spannungen, wurde untersucht. Auf der Bruchtheorie basierend, ermöglichen sie, die Dauerhaftigkeit von Beton unter wiederholten Spannungen abzuschätzen. Eine konstitutive Gleichung wurde präsentiert, die das Verhalten des Betons, wie es bei der Prüfungen bis zu dem Bruchpunkt beobachtet wurde, berücksichtigt.

1. INTRODUCTION

During their service life, concrete structures can have to withstand accidental overloadings, which are likely to induce cyclic stresses. Such are the effects of seismic actions for example. For low levels of loading, the cyclic failure of concrete depends mainly on the extreme values of the loading stress. For maximum stress over 75% of the static strength, the influence of the cycle features (period, shape) is more obvious, and has been reported by several authors.

A reliable knowledge of the behaviour of their constitutive materials is required to predict the carrying ability of concrete structures subjected to variable loadings. The paper aims to present the main results of a research programme devoted to this specific problem. Test results are reported for 32 plain concrete samples subjected to cyclic compression, the maximum stress ranging between 65% and 90% of the static strength. Based on the test evidences, an analytic approach is proposed, that allows for both time dependant and cycle dependant damage. Then, the theory of damaging viscoplasticity is used to set up a constitutive law that accounts for the decrease of the longitudinal modulus and for the irrecoverable strain which develops up to failure point.

2. EXPERIMENTAL INVESTIGATIONS

Cylinders of diameter 8 cm and height 16 cm, made from ordinary concrete of broken granite gravel and Portland cement (strength class 35) were subjected to axial cyclic compression. The specimens were prepared in three batches from the same mixture, and stored under similar conditions. For all specimens, the age at testing time was about 7 months. A mechanical testing system (MTS) bed was used to conduct the tests. The axial load was transmitted to the sample ends through two steel plates. A spherical joint was used on the upper part of the press. The form of the loading cycle was sinusoidal. The cyclic load was adjusted for each sample, according to its actual compressive strength f_c, estimated from volumetric strain measurement at the beginning of the test [1]. The minimum stress σ_{min} was about equal to $0.1\,f_c$ for all samples. The maximum stress σ_{max} was chosen between $0.65\,f_c$ and $0.90\,f_c$. The tests were conducted up to failure point with a frequency of 10 Hz.

Table 1 : Summary of data for the cyclic tests.

sample †	f_c [MPa]	$\frac{\sigma_{max}}{f_c}$	$\frac{\sigma_{min}}{f_c}$	N_r [cycles]
24/3	*42.5	.90	.12	10
09/5	38.8	.87	.10	210
14/5	42.4	.85	.10	110
07/5	44.2	.85	.10	247
32/3	*42.5	.82	.12	130
19/3	*42.5	.81	.11	180
35/4	32.6	.80	.10	100
16/5	49.7	.80	.10	110
01/5	45.7	.80	.05	140
17/3	*42.5	.80	.10	190
18/3	*42.5	.80	.10	220
37/4	39.6	.80	.10	360
02/5	49.1	.80	.10	4130
39/4	28.1	.80	.10	9630
10/5	38.8	.80	.10	180500
06/5	*51.1	.78	.10	17468

sample †	f_c [MPa]	$\frac{\sigma_{max}}{f_c}$	$\frac{\sigma_{min}}{f_c}$	N_r [cycles]
03/5	39.7	.775	.10	30445
26/3	39.2	.75	.10	409
21/3	47.9	.75	.10	2950
31/3	29.5	.75	.10	6650
34/4	*39.6	.75	.09	16800
11/5	*51.1	.75	.09	19060
22/3	*42.5	.72	.10	4040
27/3	40.9	.70	.10	300
29/3	41.4	.70	.10	420
30/3	39.8	.70	.10	2610
28/3	41.8	.70	.10	70050
12/5	*51.1	.70	.09	231680
13/5	*51.1	.69	.08	216370
33/4	*39.6	.67	.09	761530
15/5	*51.1	.66	.08	661280
25/3	*42.5	.65	.08	93610

† *sample/batch numbers ;* * *mean value measured from six* $\Phi 8/16$ *cm cylinders.*

Two induction gauges 80 mm long were fixed opposite to each other on each cylinder. The level of the loading force, the longitudinal displacement given by the two gauges, the number of applied cycles and the loading frequency were monitored during the test. The density of measurement points was 10 per loading cycle. The data were recorded over 50 cycles for each 1000 cycles (each 350 cycles at the beginning and the end of the test duration).

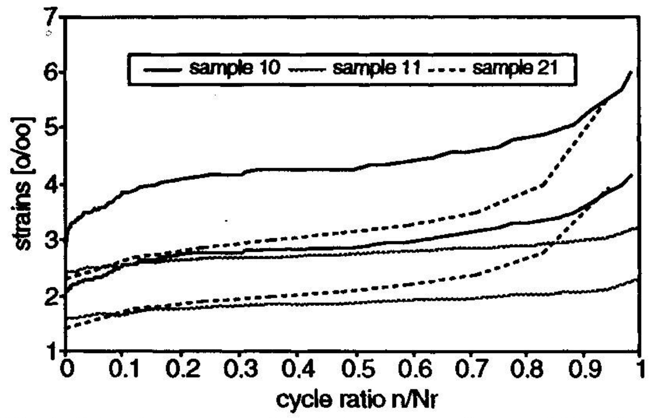

Fig.1 Maximum and minimum values of the longitudinal strains in terms of cycle ratio to failure.

Table 1 shows the ultimate compressive strength, the extreme levels of the cyclic stress and the number N_r of cycles at failure point for each sample. For most of the specimens, the measured longitudinal strains follow a S-shaped relationship in a strain *versus* cycle ratio to failure diagram. Typical curves are presented on Fig.1 for three samples (for each of them, the two curves show ϵ_{min} and ϵ_{max} corresponding to σ_{min} and σ_{max} respectively). Such curves suggest that the process of damage which leads to the failure is not only cycle dependant. The S-shape of the curves indicates the coexistence of creep damage which is a time related phenomenon depending on the stress level. As a matter of fact, the damage of plain concrete originates from the microcracks which develop during the loading. Authors have observed an increase of the microcracking in concrete samples subjected to either sustained or cylic high level loadings [2].

3. ANALYSIS OF DAMAGE IN PLAIN CONCRETE

3.1 Pure fatigue damage

Miner's law provides a simple way to allow for the rate of cycle dependant damage. In accordance with this law, the damage factor D_n accumulates in a linear way in terms of cycle ratio to failure :

$$dD_n = \frac{dn}{N_f} \quad \text{where} \quad dn = \frac{dt}{T} \qquad \Longleftrightarrow \qquad \dot{D}_n = \frac{1}{N_f T} \tag{1}$$

where T denotes the period of the loading cycle. The number N_f of cycles corresponding to pure fatigue failure can be derived from Aas-Jakobsen's formula :

$$\frac{\sigma_{max}}{f_c} = 1 - 0.0685 \left(1 - \frac{\sigma_{min}}{\sigma_{max}}\right) \log N_f \tag{2}$$

According to Tepfers and Kutti [3], this relationship applies for $\sigma_{max} \leq 0.75 f_c \div 0.80 f_c$.

3.2 Creep damage

For higher levels of loading, the number of cycles at failure proves to be more sensitive to the features of the cyclic stress (period, shape of the cycle). In the case of a static load maintained at a constant level, the process of damage causes the failure after a delay which depends on the level of loading. Rabotnov's law is a convenient way to express the rate of creep damage D_t at any time t. It can be written as follows :

$$\dot{D}_t(t) = \frac{\beta}{r+1} \left(\frac{\sigma}{f_c}\right)^k (1 - D_t)^{-r} \tag{3}$$

where β, k and r are material coefficients.

3.3 Total damage

One way to express that the behaviour of concrete is both cycle and time dependant is to assume the rate of total damage to be a linear combination of pure fatigue damage and creep damage :

$$\dot{D} = \phi_n \dot{D}_n + \phi_t \dot{D}_t \qquad \forall t \geq 0 \tag{4}$$

where ϕ_t and ϕ_n are two coupling coefficients. According to Eq.1 and Eq.3, the rate of pure fatigue damage keeps constant for identically repeated cycles, but the rate of creep damage at a given stress depends on the r value (constant rate for $r = 0$).

4. DURABILITY OF PLAIN CONCRETE UNDER CYCLIC LOADING

4.1 First method

Eq.3 can be easily integrated in the case of a constant stress σ. The failure is supposed to occur after a period of time t_u, corresponding to $D_t = 1$:

$$t_u(\sigma) = \frac{1}{\beta}\left(\frac{\sigma}{f_c}\right)^{-k} \tag{5}$$

The values of k and β coefficients have been calibrated from test results reported by Fouré [4] : $\beta = 3.058$, $k = 62.5$ [t_u *in sec.*].

One possible approach to account for a cyclic loading, is to assume $r = 0$ in Eq.3 and $\phi_n = 1$ in Eq.4. Under these conditions, the former equations yields :

$$\dot{D}(t) = \frac{1}{N_f T} + \frac{\phi_t}{t_{u(\sigma)}} \qquad \Longrightarrow \qquad D(t) = \frac{t}{N_f T} + \phi_t \int_0^t \frac{d\tau}{t_u(\sigma)} \tag{6}$$

keeping in mind that $t = nT$ (n : number of applied cycles). The failure is supposed to occur at cycle N_c, corresponding to $D = 1$. Hence :

$$\frac{1}{N_c} = \frac{1}{N_f} + \phi_t D_{t1} \qquad \text{where} \quad D_{t1} = \int_0^T \frac{dt}{t_u(\sigma)} \tag{7}$$

zone	σ_{max}	effect
A	$\leq 0.75\, f_c$	no
B	$0.75\, f_c \div 0.85\, f_c$	+
C	$\geq 0.85\, f_c$	+++

Table 2 : Influence of time on the cyclic strength of plain concrete.

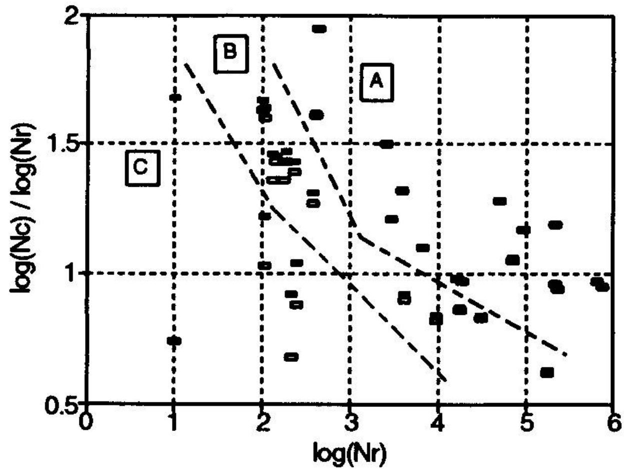

Fig.2 Comparison of computed values (Eq.7) with experimental figures (Table 1).

D_{t1} depends on the shape, the period and the level of the cyclic stress. In the case of a sinusoidal cycle, D_{t1} can be estimated as follows, s being any odd number ($s \geq 9$ for accuracy) :

$$D_{t1} = 0.469\,10^{-18} \left(\frac{\sigma_{max}}{f_c}\right)^{62,5} \frac{T}{s} \sum_{i=1}^{s} \left[1 + \frac{\sigma_{min}}{\sigma_{max}} + \left(1 - \frac{\sigma_{min}}{\sigma_{max}}\right) \sin \frac{2\, i\, \pi}{s}\right]^{62.5} \tag{8}$$

Theoretical values N_c, computed for $\phi_t = 0$ (▪) and $\phi_t = 5000$ (▫), are compared with test results on Fig.2. The influence of time depends on the upper level of the cyclic stress. For levels lower than 75% of the compressive static strength, the influence of time vanishes, in agreement with Tepfers and Kutti's conclusions [3].

4.2 Second method

An alternative approach consists to assume that the total damage is time dependant, whatever the level of loading is. This corresponds to $\phi_n = 0$ and $\phi_t = 1$ in Eq.4. Integrating that equation gives the total damage in terms of time. Keeping in mind that $t = n\,T$, the number of cycles at failure is obtained for $D = 1$:

$$D(t) = 1 - \left(1 - \beta\,\Gamma^{(k)}\,t\right)^{\frac{1}{r+1}} \quad \text{where} \quad \Gamma^{(k)} = \frac{1}{T}\int_0^T \left(\frac{\sigma(t)}{f_c}\right)^k dt \tag{9}$$

$$\text{hence :} \quad N_r = \frac{1}{\beta\,\Gamma^{(k)}\,T} \tag{10}$$

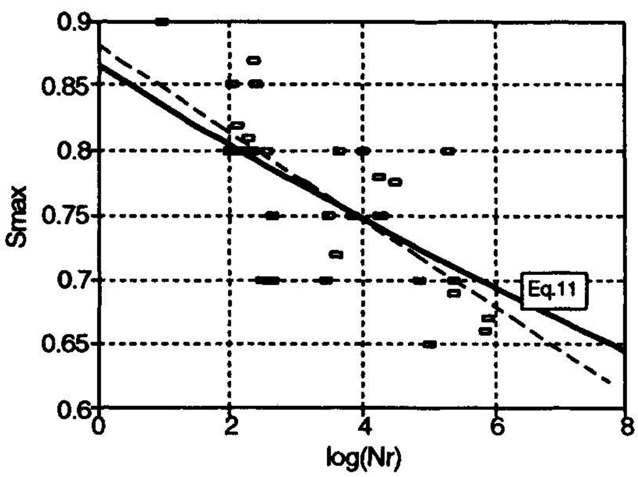

Fig.3 Representation of Eq.11 (solid line), compared with test results on a σ-N diagram.

According to Eq.10, the relationship between $\Gamma^{(k)}$ and N_r should be linear in a logarithmic scale. A linear regression, based on the mean square method, has been performed on our test results (assuming the slope to be equal to -1), in order to check this conclusion :

$$\log\Gamma^{(k)} = -\log N_r - 5.03$$

$$\iff \quad N_r = \frac{0.93\,10^{-5}}{\Gamma^{(k)}} \tag{11}$$

Expression (11) is compared with the regression line (dashed) calculated for σ_{max}/f_c in terms of $\log Nr$ for our test results on Fig.3.

5. BEHAVIOUR OF PLAIN CONCRETE UP TO CYCLIC FAILURE

The longitudinal strain has been recorded for each sample over the whole test duration. The data show a progressive decrease of the longitudinal modulus, along with the growing of a plastic strain during the test. The total strain can be expressed at any time as the sum of an elastic strain and a creep strain :

$$\epsilon(t) = \frac{\sigma(t)}{\left(1 - D(t)\right) E_o} + \epsilon_p(t) \tag{12}$$

where E_o is the initial value of the longitudinal modulus of elasticity. The expression of the damage factor $D(t)$ can be determined from Eq.3, assuming the existence of a possible initial damage D_o :

$$D(t) = 1 - \left[(1 - D_o)^{r+1} - \beta\,\Gamma^{(k)}\,t\right]^{\frac{1}{r+1}} \tag{13}$$

The creep strain ϵ_p is supposed to develop according to Norton's law. The influence of the state of damage on the creep rate is accounted for by considering the effective stress $\tilde{\sigma}$:

$$\dot{\epsilon}_p(t) = \left(\frac{\tilde{\sigma}(t)}{B}\right)^m \quad \text{where} \quad \tilde{\sigma}(t) = \frac{\sigma(t)}{(1 - D(t))} \tag{14}$$

where B and m are material coefficients. Integrating Eq.14, assuming the possible existence of an initial strain ϵ_o, yields :

$$\epsilon_p(t) = \epsilon_o + \left(\frac{B}{f_c}\right)^{-m} \Gamma^{(m)}\delta(t) \quad \text{where} \quad \delta(t) = \frac{1}{T}\int_0^t (1 - D(\tau))^{-m} d\tau \tag{15}$$

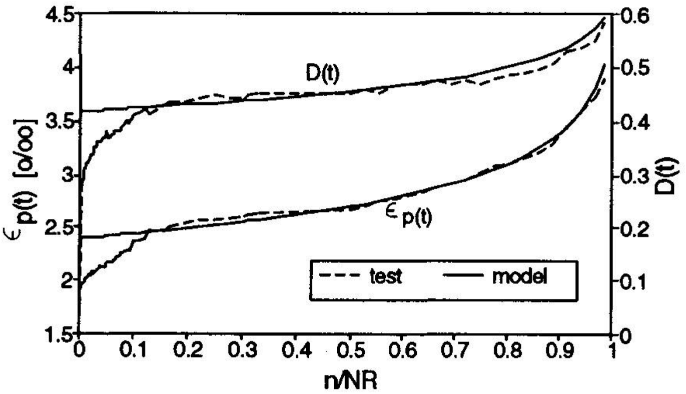

Fig.4 Theoretical and experimental values for $D(t)$ and $\epsilon_p(t)$

$$\text{and} \quad \Gamma^{(m)} = \frac{1}{T}\int_0^T \left(\frac{\sigma(t)}{f_c}\right)^m dt$$

Equations (12), (13) and (15) describe the constitutive law of plain concrete subjected to high level compressive loading. In order to check the validity of these expressions, it is necessary to estimate the values of D and ϵ_p from our test results. At cycle $n = t/T$:

$$D(t) = 1 - \frac{\sigma_{max} - \sigma_{min}}{E_o(\epsilon_{max} - \epsilon_{min})} \tag{16}$$

$$\epsilon_p(t) = \epsilon_{max} - \frac{\sigma_{max}}{(1 - D(t))\, E_o} \tag{17}$$

Fig.4 shows a comparison of the experimental figures corresponding to the sample 10, with the values predicted from Eq.13 and Eq.15 respectively.

6. CONCLUSION

The existence of a strain flow developing at a growing rate in terms of cycle ratio to failure, allows to assume that the process of fatigue damage is a time related phenomenon. Based on this assumption, two complementary approaches are proposed to account for the durability of plain concrete subjected to cyclic compressive stress. They both allow for the failure for low as well as high levels of loading. Assuming that the strain flow can be related to damaging viscoplasticity, it is possible to explain the cyclic behaviour of plain concrete as the result of a progessive decrease of the longitudinal modulus along with the growing of a creep strain in terms of the number of cycles. Based on this assumption, the behaviour of tested samples can be accounted for with a good accuracy.

7. REFERENCES

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