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Experimental study for the evaluation of creep in concrete through thermal measurements

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Abstract

This investigation, conducted at the Non-Destructive Testing Laboratory at the Politecnico di Torino, made it possible to establish an experimental relationship between specific creep values measured in concrete test pieces obtained from different mixes and the decrease in temperature observed in identical test pieces at the end of low-intensity short-duration compressive tests.

This relationship is independent of type of mix and therefore has general validity: it can be used to make qualitative predictions about creep without having to perform long duration tests. It may lead to interesting developments in various applications, especially in the field of structural diagnosis.

Keywords: Temperature; Thermal analysis; Creep; Cycles; Concrete

1. Introduction

Earlier investigations concerning the variations in the mechanical properties of concrete subjected to low-intensity short-duration uniaxial compressive loading cycles [1] revealed a general increase in both the failure strength and the elastic modulus of the material, as well as a reduction in max. displacement at failure, all these phenomena being accompanied by a marked decrease in temperature.

The decrease in temperature, which seems to contradict Kelvin's law of thermoelasticity, reflects the chemical–physical transformations that take place inside the cement matrix under the effects of cyclic loading and bring about variations in the mechanical properties of concrete. Many investigations [2–5], conducted in recent years at the Non-Destructive Testing Laboratory of the Politecnico di Torino, have analysed this theme and provided significant methodological foundations for this study. In particular, it has been observed that:

- the decrease in temperature observed in undamaged test pieces subjected to uniaxial compressive loading cycles takes place both inside and on the surfaces of the test piece;
- the extent and evolution of the phenomenon does not depend on type of mix;
- the cooling effect cannot be ascribed to the evaporation of absorbed water, as verified through tests made on test pieces soaked in water and oven-dried;
- the decrease in temperature is a function of the applied load: it increases with increasing loading cycle amplitude and σ_{max}/σ_r ratio;
- the decrease in temperature also depends on load application frequency (it is greatest at 1 Hz);
- the phenomenon evolves as a function of the number of cycles performed: in low-intensity cyclic tests

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Nomenclature

Legend
σ_r [MPa] Failure stress during static compression test
σ_{max} [MPa] Max. stress reached during cyclic test
σ_{min} [MPa] Min. stress reached during cyclic test
f [Hz] Loading cycle frequency
n [–] Number of cycles
T [°C] Temperature
ΔT [°C] Temperature variation in test specimen during cyclic test with respect to unloaded specimen
ΔT^* [°C/MPa] Specific temperature variation (given by ΔT as a function of the applied load)
ϵ_f [μm/m] Creep strain
ϵ_f^* [μm/m MPa] Specific creep strain (given by ϵ_f as a function of the applied load)

(σ_{max}=20% σ_r), it seems to come to an end after approx. 3000–3600 cycles;
– on previously damaged test pieces, a low-intensity short-duration compressive loading cycle does not bring about a decrease in temperature, but rather an increase which is proportional to the severity of the damage.

These findings were used to define the parameters of the testing program.

Alongside the studies conducted on the variations in the mechanical behaviour of concrete subjected to cyclic loading tests and the relative thermal effects, other investigations [6,7] revealed an analogy between the creep strains observed in concrete test pieces under a constant uniaxial compressive load and the irreversible deformations that occur in identical test pieces under cyclic loading. This analogy suggests that both phenomena are governed by the same mechanism (save that under cyclic loading the strains develop much faster compared to the time it takes for creep phenomena to reach completion). Different experimental correlations between creep and the residual deformations caused by cyclic loading have therefore been proposed.

These results suggest that the creep strains occurring in concrete under sustained loading and the phenomena of reloading and cooling have common causes, to be ascribed precisely to the chemical–physical transformations that take place in the material, and which cyclic tests are able to

Table 1
Mix types

Mix	Cement proportion (CEM I 42,5 R) [kg/m^3]	Water/cement ratio	R_{ck} [MPa]	σ_r [MPa]
A	200	0.7	15	17.1
B	250	0.7	25	36.3
C	300	0.7	35	38.8

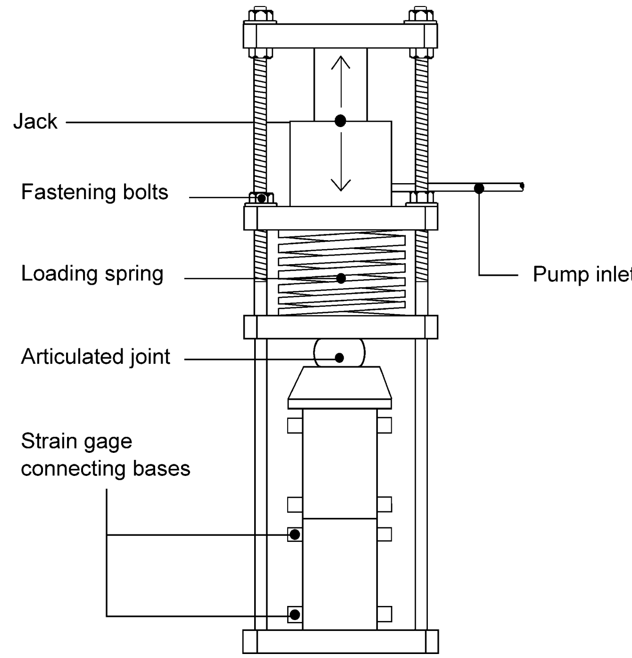

Fig. 1. Loading set-up during creep tests.

Fig. 2. Arrangement of the thermoresistors on the test piece.

Table 2
Names used in the tests

Static failure tests	Creep tests	Cyclic tests
SF [*Y*][*N*]	CR [days] [*Y*][*N*]	CYC [*Y*][*N*]

Y=type of mix; *N*=test piece number; days=duration of creep tests.

produce faster compared to static tests. Accordingly, an experimental correlation was sought between the specific creep strains observed in concrete specimens from different mixes subjected to sustained uniaxial loading and the decrease in temperature observed in identical test pieces at the end of low-intensity short-duration uniaxial compressive loading cycles. This relationship, having general validity in as much as it does not depend on type of mix, makes it possible to make qualitative predictions concerning creep without having to perform long duration tests.

2. Testing program

The tests were performed on cores drilled from three ordinary concrete slabs characterised by different cement proportions. Series of 12 test pieces were obtained from each slab, of which 2 were used for the mechanical characterisation of the mix through static failure tests, 6 were subjected to creep tests of different time durations and 4 were used in cyclic compressive tests. During the latter tests, temperature variations were monitored in order to correlate the degree of cooling measured at the end of the cyclic tests with the creep strains produced during the creep tests. The loads applied during the different tests were selected as a function of the mechanical strength of the test pieces; as for the cyclic tests, load level, time duration and frequency parameters were defined on the basis of the results obtained from Refs. [1–5].

2.1. Test pieces

To simulate as closely as possible the test pieces obtained from existing structures, cores were drilled from three square slabs made of ordinary concrete, with 100 cm long sides and 16 cm high, characterised by different cement proportions. At the time of core drilling, the concrete was 3 months old. From each slab, a total of 28 cores were produced, 60 mm in diameter and approx. 160 mm long. The ends of the cores were then sawn off to obtain cylinders of the desired size (approx. 120 mm long) with flat ends.

The mechanical properties of each mix are listed in Table 1, where R_{ck} stands for characteristic strength, as estimated through a static failure test performed on four cubes with sides measuring 16 cm, and σ_r is the average failure stress as determined through uniaxial static compressive tests performed in strain control on two cylinders.

2.2. Testing equipment

The testing set-up employed was as follows:

- 250 kN servo-controlled testing machine, for load control and strain control tests.
- Temperature sensors, consisting of platinum thermal resistors, with nominal resistance of 100 Ω at 0 °C, measuring 4×3.2 and 0.4 mm thick. These sensors were connected to a conditioning unit via a network of high precision resistors able to linearise their output signals and achieve a resolution of 0.004 °C.
- Conditioning and amplification system for temperature signals.
- Displacement measuring instruments, consisting of a removable mechanical strain gage (used in creep tests) and a pair of inductive bridge displacement transducers, with nominal travel of 10 mm (used in cyclic loading tests).

Table 3
Overview of the testing condition

Name	Description	Number of test pieces			Testing conditions	Values measured
		Mix A	Mix B	Mix C		
SF [*Y*][*N*]	Static failure test	2	2	2	Static compressive test in strain control, with piston speed of 0.0025 m/s	Load, displacement.
CR [28] [*Y*][*N*]	Creep test at 28 days	2	2	2	Compressive test under long-duration constant load. σ=40% σ_r; duration=28, 40 g, 60 days.	Load, displacement.
CR [40] [*Y*][*N*]	Creep test at 40 days	2	2	2		
CR [60] [*Y*][*N*]	Creep test at 60 days	2	2	2		
CYC [*Y*][*N*]	Cyclic test on undamaged test pieces	4	4	4	Cyclic compressive test. σ_{max}=20% σ_r; σ_{min}=10% σ_r; f=1 Hz; n=3600 cycles	Load, displacement, temperature.

– Data acquisition system, connected to an IBM processor.
– Metal frames for the execution of creep tests, fitted out as described below (see Section 2.4).

2.3. Static failure tests

Static compression tests were performed on the test pieces until failure in strain control with piston lowering rate of 0.0025 m/s. The post-failure stage was also recorded.

2.4. Creep tests

The results of creep tests of three different durations (28, 40 and 60 days) were analysed for each type of mix, using two cylinders for each test.

All test pieces were subjected to a load corresponding to 40% of their failure strength. The static load was applied with the aid of high stiffness metal frames made up of short slabs sliding along rails and loading springs, as illustrated schematically in Fig. 1. Two cylinders were placed end to end inside each frame. The load was applied by means of a jack connected to a hydraulic pump, equipped with a manometer previously calibrated under the servo-controlled testing machine: the hydraulic jack was placed above the spring, between two plates, of which the upper one was fixed and the lower moveable, so that when the piston expanded due to the effect of the loading the lower plate moved down and loaded the spring. Having reached the desired load level, the movement of the lower plate was stopped by means of fastening bolts and the pressure in the jack was released. The constraint thus applied to the spring ensured that the load remained constant over time.

Loaded frames were placed in an environment with controlled temperature and relative humidity (T=20 °C, R.H.=65%). An unloaded test piece was placed in the same environment to measure its swelling or shrinkage, if any. Shortening was measured by means of a removable mechanical strain gage applied to each cylinder along two diametrically opposed generatrices marked out with letters X and Y, with a reading base of 100 mm. Shortening was calculated as the average of the readings obtained on the X and Y sides. Creep curves were worked out as the difference between total strains and the sum of elastic strains and shrinkage, the latter having been measured on the unloaded test pieces.

2.5. Cyclic compressive tests

The tests were characterised by the following parameters:

– σ_{max}=20% σ_r;
– σ_{min}=10% σ_r;
– f=1 Hz;
– Number of cycles=3600 (1 h).

The load was applied according to a sinusoidal law.

The evolution of test piece temperature was measured by means of two platinum thermal resistors applied to the test piece surface at mid-height, on two diametrically opposed generatrices, as shown in Fig. 2. A layer of conductive paste was interposed between the test

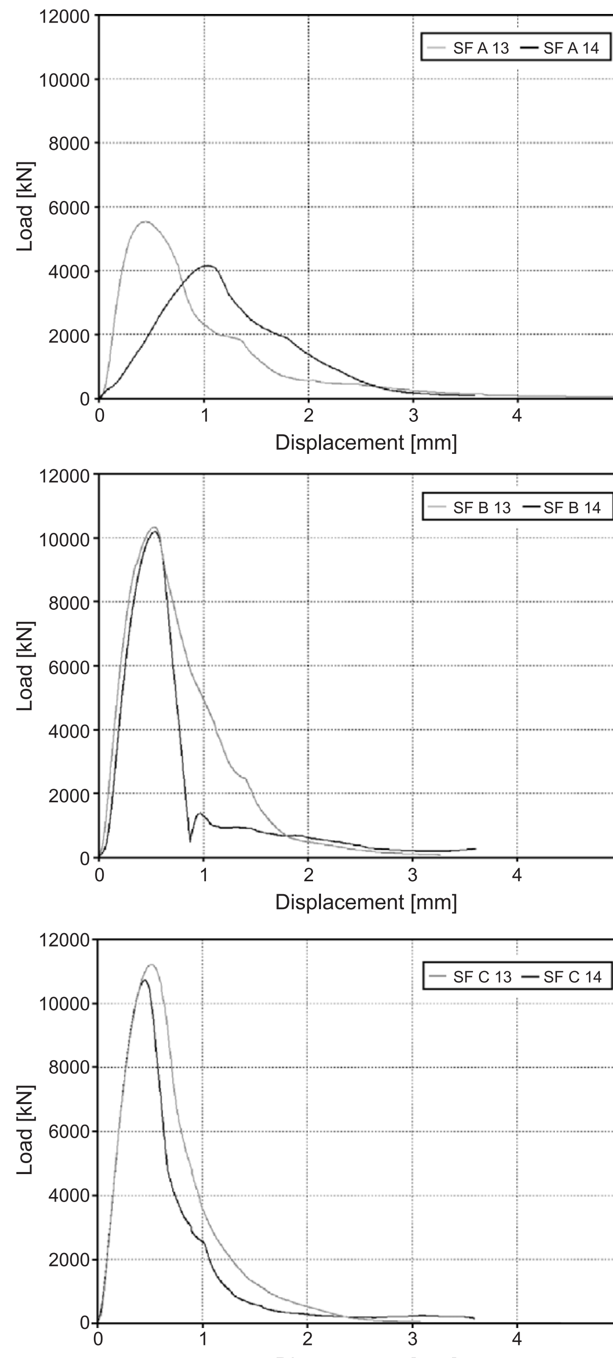

Fig. 3. Determination of the mechanical properties of the mixes.

piece and the sensors, for improved thermal coupling; moreover the probes were coated with a special mastic to minimise the confounding effect of the exterior environment. Such technical measures were adopted after a careful evaluation of the influence of the environment and the experimental apparatus itself, in order to take appropriate precautions and ensure substantially adiabatic test conditions. In particular, the effects of conduction–convection and radiation were taken into account by making use of different testing configurations: bare test pieces, only equipped with the aforementioned thermal protection at the point of application of the thermal resistors and test pieces covered with (a) a 3-cm-thick glass wool layer, (b) a 3-cm-thick glass wool layer+aluminium sheets and (c) aluminium sheets. For short duration tests, the four methods can be rated as approximately equivalent, given the low thermal conductivity of concrete and the absence of direct exposure to radiation sources, consequently the authors decided to adopt the first set-up,

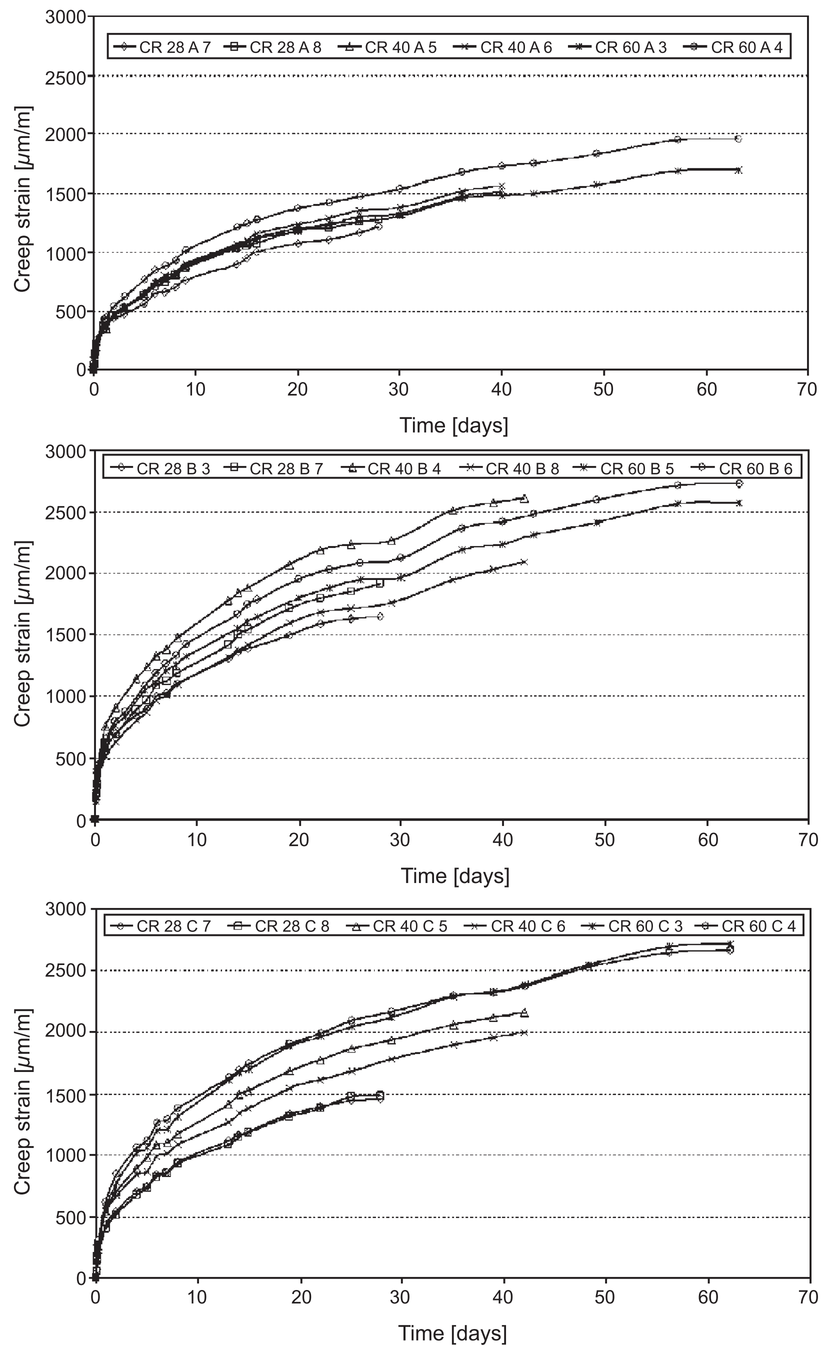

Fig. 4. Evolution of creep strains.

which was the simplest. Similarly, for short duration tests, the interference due to the testing machine can also be rated as negligible (while it has to be taken into account in long duration tests). Another thermal resistor was applied to an unloaded concrete specimen and ΔT curves were obtained on the basis of the difference between the temperature of the unloaded test piece and the temperature of loaded test pieces (as average over the readings of the two sensors).

During the cyclic tests, the dimensional variations of the tests pieces were also determined by means of displacement transducers.

2.6. Overview of the tests

The names used in the tests and an overview of the testing conditions are given in Tables 2 and 3.

3. Results

The mechanical properties of the test pieces as determined through static failure tests are shown in Fig. 3.

The measures taken on each series of test pieces subjected to creep are given in Fig 4.

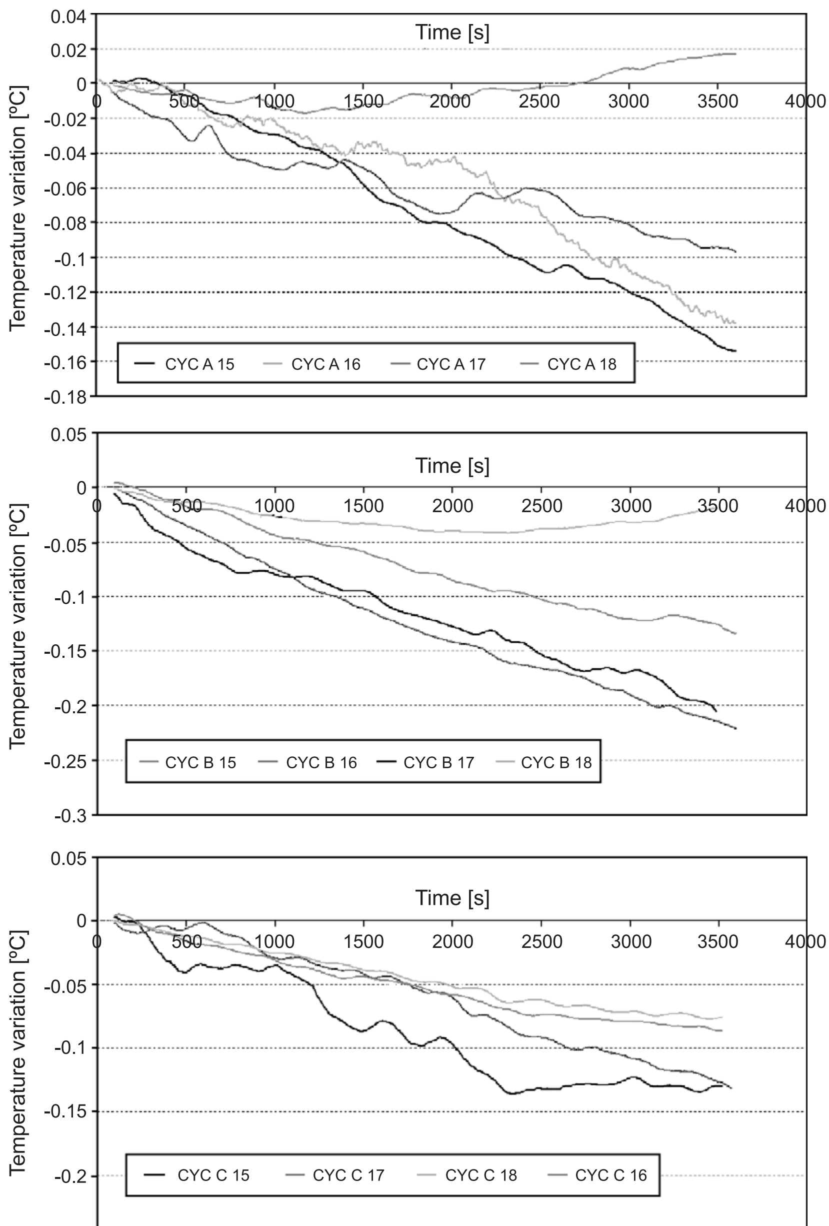

Fig. 5. Evolution of temperature variations during cyclic tests.

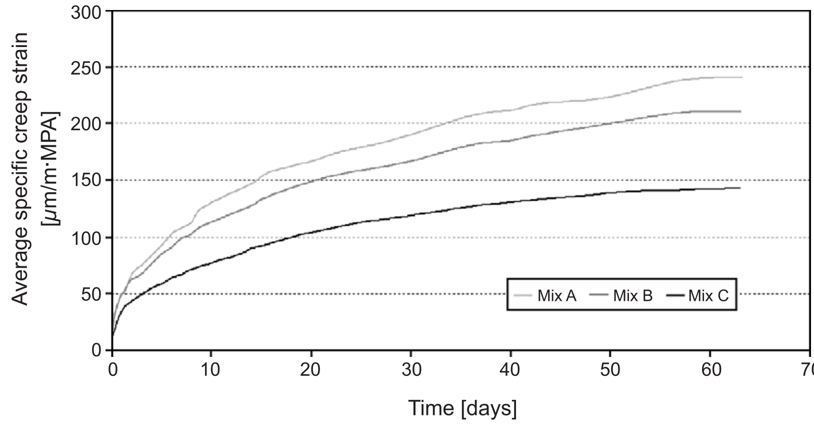

Fig. 6. Average specific creep curves for the different mixes.

Cyclic test results are summarised in Fig. 5, which shows the evolution of temperature variations observed during the tests.

4. Analysis of the results

The results of creep tests are summarised by the average specific strain curves (ϵ_f^*) shown in Fig. 6. They have been obtained by considering the average creep strain values observed in the test pieces of each series (this was done in order to take into account the influence of the various levels of creep as a whole) and dividing such strain values by the applied load, so as to make the results comparable (the three series having been subjected to a load corresponding to 40% of their strength, load levels were different for each mix type). It should be noted that the mixes with the lowest cement proportion displayed the highest specific strain.

The values obtained by monitoring temperature during cyclic tests are summarised through the average specific cooling curves (ΔT*) shown in Fig. 7. They have been determined as average over the readings taken on the test pieces of each series, which, in this case too, are given in non-dimensional form with respect to the applied load.

As widely documented in the literature, in cyclic tests strains evolve in time in the same way as in tests under sustained loading, with the difference that cyclic loading causes an acceleration of deformation phenomena, which take place faster. This similarity leads to believe that static creep test results and cyclic test results could be correlated. Since cyclic tests are also accompanied by thermal phenomena, then a possible correlation is sought in terms of specific cooling at the end of cycles vs. specific creep strain. In fact, from an analysis of the temperature variations recorded during cyclic tests it was found that all the test pieces underwent a decrease in temperature. Such a cooling effect could be interpreted on the basis of the first principle of thermodynamics: in substantially adiabatic conditions, the test piece absorbs work from the testing machine and hence, the internal energy of the latter must necessarily increase. Since temperature decreases, then the internal energy component associated with the material's chemical structure and cohesion must increase, in order to offset the cooling phenomenon. Therefore, one may suppose that cyclic loading could bring about endothermic reactions inside the cement matrix, e.g., a reduction in the distances between hydrated cement grains and the ensuing creation of new bonds, or a

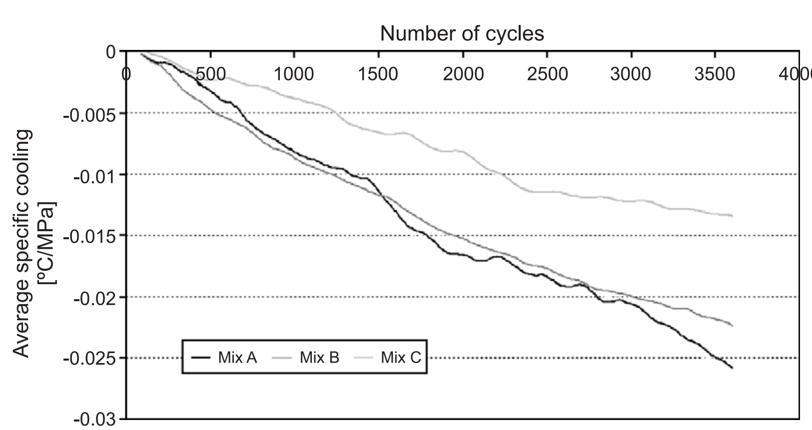

Fig. 7. Average specific cooling curves for the different mixes.

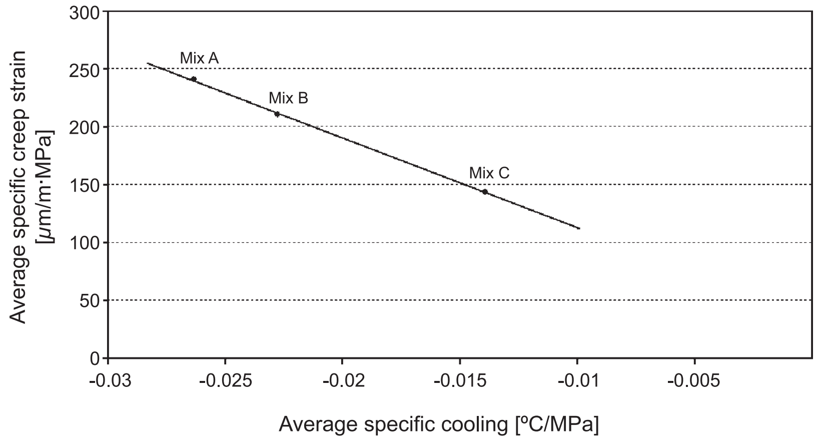

Fig. 8. Linear correlation between specific cooling and specific creep strain.

change in the microscopic structure similar to the one described by Powers in his thermodynamic theory of creep behaviour of concrete.

As a first attempt, the correlation between the specific reduction in temperature (ΔT^*) and the specific creep strain values (ϵ_f^*) is sought in a linear form: cooling and medium term creep were found to be directly proportional, as can be seen from Fig. 8. Since the tests were performed on different types of mix, the linearity law observed has general validity, i.e., it does not depend on cement proportions.

5. Conclusions

The values obtained by measuring the temperature of concrete test pieces produced from mixes with different cement proportions during cyclic uniaxial compression tests (with max. stress corresponding to 20% of the failure stress, 1 Hz frequency, and duration of 3600 cycles) confirmed a tendency of the material to cool.

By comparing the decrease in temperature observed in specimens from each mix at the end of the cyclic test with the degree of creep displayed by specimens subjected to medium duration static creep tests, it has been determined that the two variables could be correlated by a direct proportionality law. The three types of mix, in fact, display specific creep values which are linearly proportional to the specific cooling values. Since cement proportion is different for each type of mix, it may be inferred that the aforementioned correlation has general validity and applies to all types of concrete.

Hence, it is possible to make qualitative predictions about the degree of creep occurring in concrete in the medium run without having to perform long duration tests, by performing a cyclic compression test and measuring the variations in temperature: a greater decrease in the temperature of the concrete will reflect a greater propensity of the material to undergo creep strains. However, the proposed correlation must be considered as a first attempt to investigate this issue: it requires further in-depth studies and is presented with the purpose of stimulating future discussions.

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