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INFLUENCE OF STEAM CURING ON HIGH-CYCLIC BEHAVIOUR OF PRESTRESSED CONCRETE BRIDGE ELEMENTS

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Abstract. The paper discusses the influence of curing conditions (steam and normal curing) on high-cyclic creep and fatigue strength of reinforced concrete bridge elements. The present analysis is based on experimental investigation performed by the first author: 46 plain concrete prisms and 13 prestressed concrete beams were subjected to the high-cycle loading (up to four million cycles). A comparative regression analysis of the fatigue strength of compressive concrete, in terms of a number of load cycles for given max stress level (*S-N* relationship) has been performed. The analysis has shown that curing conditions had no significant effect on the *S-N* relationship. On the contrary, curing conditions have significantly influenced the cyclic creep of compressive concrete. On average, the steam cured members had from 30 up to 80% larger deformations than the specimens cured under normal conditions. The difference was larger for higher numbers of loading cycles.

Keywords: curing conditions, fatigue testing, cyclic creep, prestressed concrete bridges.

1. Introduction

The design of a structural member is based on two criteria: strength and serviceability. As a result of the extensive research work carried out in different countries, the ultimate load behaviour of flexural members is now quite well understood. Due to the use of refined ultimate state theories, as well as higher strength concrete and reinforcement, resulting in longer spans and smaller depths of structures, deformations are often the governing design criterion. Insufficient up to date information on long-term behaviour, e.g. influence of the cyclic loading on the properties of concrete, usually met in practice, has caused a growing interest in the deformational analysis of prestressed concrete (PC) members. Namely, designs of bridges, oceanic structures or railway ties etc. necessitate evaluating the loading, accompanied by a huge number of cycles.

Bridge elements usually are subjected to cyclic loads during the period of maintenance. The fatigue life of the bridge elements is of the order of 10^3–10^7 cycles for high-cycle fatigue case (Hsu 1981). Nowak *et al.* (2000) found that shrinkage strains in accomplice with tensile fatigue of concrete induced cracking in concrete slabs in two existing haunched steel-girder bridges in Michigan. The effect of cyclic loading on cracking behaviour of bridge elements could be an important consideration in the serviceability of reinforced concrete members, especially in terms of corrosion of reinforcing steel and appearance (Juozapaitis *et al.* 2006). The increase in crack width due to repetitive loading can vary between 100 and 200% over several years (ACI Committee 224 2001). While there is a large scatter in the data, information obtained from fatigue tests with up to 1 million cycles indicate that a doubling of crack width with time can be expected (Rehm, Eligehausen 1979). The increase in the rate of crack width development under cyclic loading has been reported by different investigators (Rehm, Eligehausen 1979).

Fatigue of concrete is a progressive process of micro-crack initiation and propagation leading to macro-cracks which can grow and determine the remaining fatigue life by causing stress to increase until failure occurs. Fatigue fracture occurs at stress levels, which are significantly less the static fracture strength limit of concrete. Studies of the stress-strain behaviour of concrete under cyclic compressive load (ACI Committee 224 2001) indicated the concrete undergoes rapid deterioration once the peak stress exceeds 70% of the short-term compressive strength of the concrete due to cyclic creep.

The current investigation employs the experimental studies carried out by the first author (Дулинскас 1973). The article analyses influence of the curing conditions on strength and deformations of PC beams and prisms subjected to high-cyclic loading.

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2. Background

During the last few years the concrete fatigue phenomenon has once again gained interest, especially for railway bridges due to more slender structures, higher traffic speeds and higher axle loads (Carpinteri *et al.* 2004; Dulinskas *et al.* 2007; Gribniak *et al.* 2007, 2008; Kaklauskas 2004). In Sweden, for example, the increased axle loads on the existing railway lines have caused problems with the bridges since it has led to a change of the conditions for the bridges compared to the ones when they were built (Thun 2006).

Fatigue of materials was initially investigated for steel. The first study of metal fatigue was performed around 1829 by the German engineer Albert. For concrete the fatigue phenomenon was observed rather late. The first fatigue curve for concrete cubes in compression was published by Van Ornum in 1903, who found that concrete had fatigue strength about 55% of its static ultimate strength for a life of 7000 cycles. Hsu (1981) reported that development of highway systems in the 1920s led to further interest in the fatigue of concrete, since the concrete pavements used for highways are subjected to millions of load cycles from axle loads of cars and trucks.

The most basic information about the fatigue behaviour of concrete specimens is represented by its *S-N* curve (or *Wöhler*'s diagram), which provides number of load cycles *N* for given max stress level *S*:

$$S = \frac{\sigma_{c,\max}}{f_{cm}}, \tag{1}$$

where $\sigma_{c,\max}$ – max compressive stress of a cycle; f_{cm} is the mean value of compressive strength of concrete.

Aas-Jakobsen (1970) examined the influence of the min stress of a cycle, $\sigma_{c,\min}$, on the fatigue strength. He showed that the relationship between S and $S_{\min} = \frac{\sigma_{c,\max}}{f_{cm}}$ is linear for fatigue failure at 2×10^6 load cycles. If R is defined as the ratio between the max and min stress, $\frac{\sigma_{c,\max}}{\sigma_{c,\min}}$, then the relationship between S and R should be also linear:

$$S = 1 - 0.064 \times (1-R) \times \lg N. \tag{2}$$

Tepfers and Kutti (1979) modified the above Eq as follows:

$$S = 1 - 0.085 \times (1-R) \times \lg N. \tag{3}$$

It has been pointed out that both above Eqs (2) and (3) assume constant amplitude *R* (Tepfers, Kutti 1979). Hsu (1981) proposed *S-N-T* conception for solving fatigue problem. In this approach parameter *T* reflects the period of the cyclic loading. Stemland *et al.* (1990) have developed a model to predict the relation between S, $S_{\min}$ and N:

$$\lg N = \begin{cases} X, & X \le 6, \\ \dfrac{X}{1-0.2\times(X-6)}, & X > 6; \end{cases}$$
$$X = \left(12 + 16S_{\min} + 8S_{\min}^2\right) \times (1-S). \tag{4}$$

It should be noted, that the fatigue model adopted in *CEB-FIB Model Code 1990* is based on the above approach. More comprehensive review of the fatigue failure models is reported by Kim and Mc Cullogh (2002).

Other important issue is that fatigue test's results are highly scattered and appropriate number of the tests is needed to obtain statistically meaningful results (Dulinskas *et al.* 2007). This is particularly true for concrete, a material which structure and fabrication process are such that relatively large standard deviations are observed in its mechanical properties. Hordijk and Reinhardt (1993) studied the fatigue behaviour of plain concrete and concluded that the propagation of cracks leads to failure of concrete, although the exact mechanism is not clear.

Factors like the range of loading, rate of loading, eccentricity of loading, loading history, material properties, and environmental conditions influence fatigue strength. The performance of reinforced concrete members also depends on the composite action between steel and concrete (Kaklauskas *et al.* 2008; Khalfallah 2008). Carpinteri *et al.* (2004) showed that by distributing the same area of reinforcement among a multiple number of layers, the energy dissipation capacity of the beam as well as its fatigue life significantly increase.

3. Fatigue tests

The tests under static and high-cyclic loading were performed with two types of specimens: plane concrete prisms subjected to compression and PC beams subjected to four-point bending. Age of the beams at testing ranged from 110 to 135 days. Prestressing was such that beams under loading virtually had not tensile stresses in their cross-section. Testing was aimed at determining the behaviour of compressive concrete subjected to the cyclic load. The specimens of the first series (7 beams and 35 prisms) were hardening under the normal conditions (normal-cured) and the specimens of the second series (9 beams and 19 prisms) were steam-cured. Heat treatment lasted for 7 hours at 80 °C temperature with the initial 20 degrees per hour temperature increase. The concrete mix proportion 1:1.42:1.99 with water-to-cement ratio 0.35 was the same for all experimental specimens.

The dimensions of the prisms subjected to compressive loading were 71 × 71 × 280 mm and 100 × 100 × 400 mm. The dimensions of the beams and the scheme of application of loads are presented in Fig. 1.

The high-strength wire of 5 mm in diameter was employed as reinforcement for PC beams. Prestressing the bottom and the top reinforcement was performed respectively at the level of 49 and 65% of their yield limit. In order to determine the physical and mechanical properties of each series of beams, the samples of reinforcement and concrete were tested. The obtained properties are given in Table 1. Three beams of each series were tested under the static load in order to establish their ultimate load-carrying capacity.

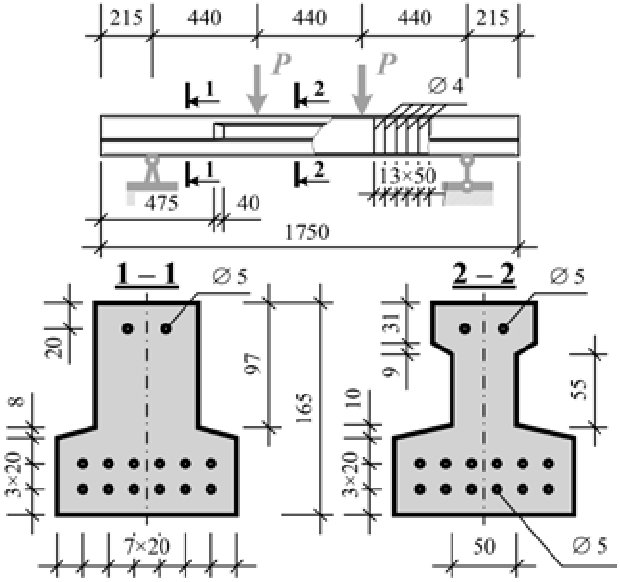

Fig. 1. Loading scheme and dimensions of PC beams

Table 1. Characteristics of the specimens

Explanation	Normal-cured			Steam-cured		
	N	*m*	δ	*N*	*m*	δ
Cube strength (150 mm), MPa	17	54.54	4.1%	15	40.80	5.8%
Prism strength (71 mm), MPa	9	48.00	4.5%	13	38.50	5.2%
Initial tangent modulus, GPa	9	32.57	4.2%	13	28.25	5.4%

	N	*m*	δ
Reinforcement steel strength, GPa	11	1.55	1.0%
Modulus of elasticity of steel, GPa	10	191.5	5.5%

Note: *N* – number of samples; *m* – mean value; δ – coefficient of variation.

The experimental set-ups of the prisms and the beams are shown in Figs 2 and 3. The cyclic loading (up to four million cycles) was subjected to 46 plain concrete prisms and 13 prestressed concrete beams. The load of a sinusoidal waveform of a frequency 10–11 Hz was taken in the tests. Each prism and beam was tested under cyclic loading of constant amplitude, *R*, but different specimens had different load intensities. The value of the stress level *S* varied from 0.57 to 0.68 (Eq (1)). A similar parameter referring to the beams and relating to the max value of the bending moment to the ultimate one ranged from 0.5 to 0.7. One-stage constant amplitude *R*, both for the prisms and the beams, was taken to be 0.33.

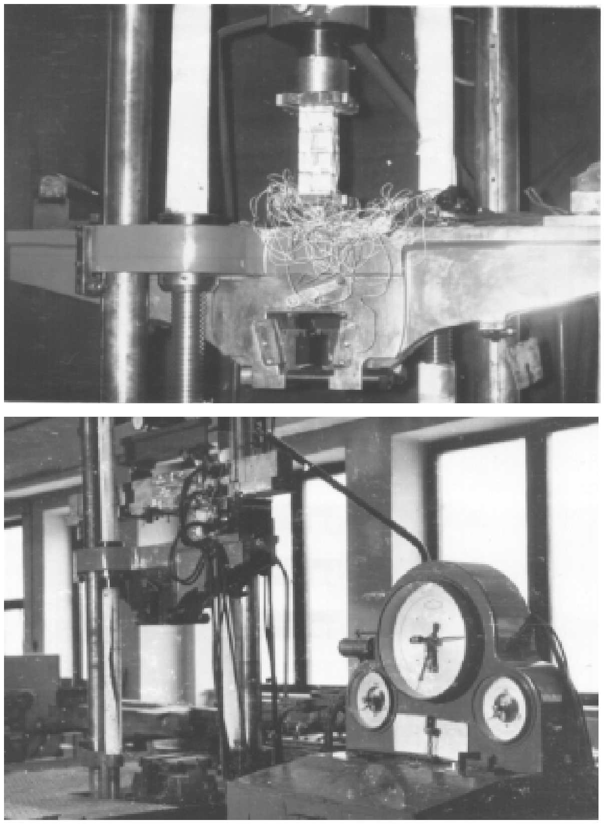

Fig. 2. Experimental set-up of the prisms and the beams (Дулинскас 1973)

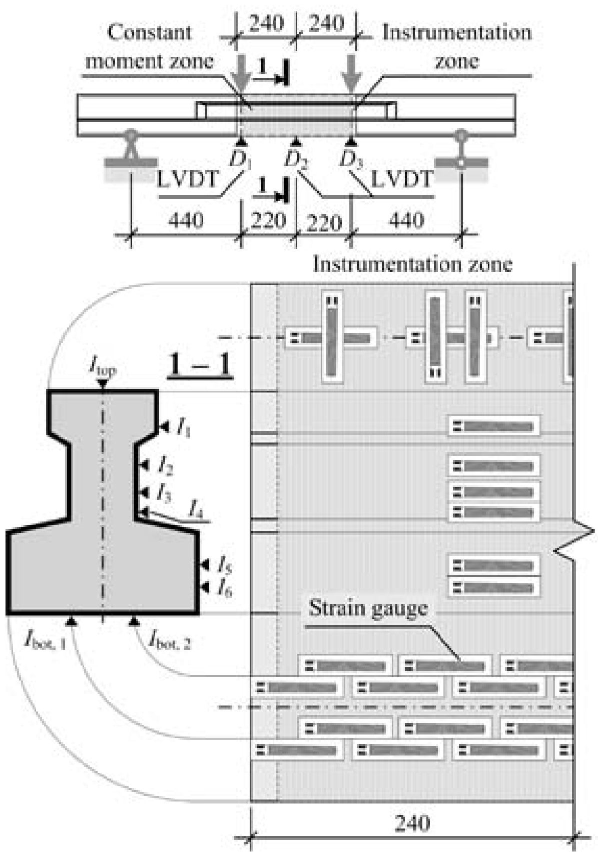

Fig. 3. Beam instrumentation

Fig. 3 shows instrumentation of the test beams. The strains were measured by means of 51.5 mm strain gauges glued on concretes surface at different levels of the pure bending zone. The vertical displacements of the controlled sections were measured applying displacement transducers (LVDT) (Fig. 3).

4. Fatigue test results and their analysis

This section discusses the results of investigation on the influence of curing conditions on the high-cycle fatigue strength and cyclic creep of compressive concrete. Data of both tests, i.e. on prisms and beams, were employed. As noted before, influence of the tensile concrete was eliminated by assuring compression in most part of the cross-section of the beams.

4.1. Fatigue strength of compressive concrete

As discussed in Section 2, results of the fatigue test often are plotted in terms of a number of load cycles for given max stress level (*S-N* curve or *Wöhler*'s diagram). Experimental points and fatigue predictions made using the relationships discussed in Section 2 (Eqs (3) and (4)) in Fig. 4.

Due to small amount of test data (Fig. 4), it is not possible to make statistically meaningful conclusions of influence of the curing conditions on fatigue strength of the experimental specimens. Therefore, results of the tests of compressive concrete prisms reported by Ople and Hulsbos (1966) and Holmen (1979) were also included in the analysis. Thus a statistical analysis of the fatigue behaviour of compressive concrete has been performed using 63 experimental points from the high-cycle (10^4–10^7 cycles) fatigue interval. A regression line with 95% confidence limits derived for all experimental points are shown in Fig. 5. It should be noted that the derived regression line has approached the relationship proposed by Stemland *et al.* (1990) (Fig. 4).

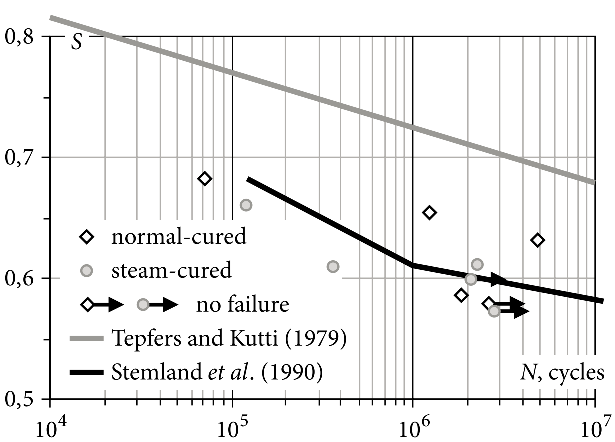

Fig. 4. The *Wöhler*'s diagram of compressive specimens cured under different conditions

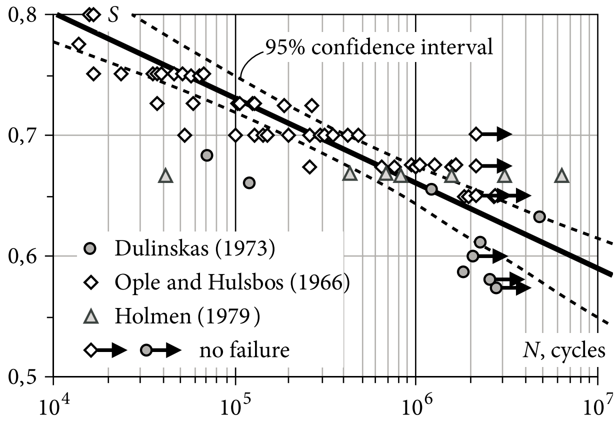

Fig. 5. The *Wöhler*'s diagram with 95% confidence limits, based on the experimental results reported by Dulinskas (Дулинскас 1973), Ople and Hulsbos (1966), and Holmen (1979)

The influence of curing conditions on the fatigue strength of compressive specimens was investigated using a comparative regression analysis. Regression Eqs have been derived for each of two sets of data: 1) all experimental points and 2) test data of specimens cured under normal conditions. The obtained regression Eqs are presented in Table 2. In order to decide whether the curing conditions have significant influence on fatigue strength, statistical hypothesis about the equivalence above Eqs has been checked out. Two hypotheses have been formulated: 1) the *null hypothesis*, H_0, assuming of equivalence of the Eqs; 2) the *alternative hypothesis*, H_1, stating that the Eqs are different. In a two-tiled test, the *null hypothesis* was accepted with 10% significance level. The latter value defines a probability of rejecting hypothesis H_0, when in fact it is true. In a statistical sense, curing conditions had no significant effect on the *S-N* curve. In practical terms, the coefficient of determination r^2 (Table 2) indicates that a number of loading cycles makes around 60% impact on variation of the fatigue strength, whereas such factors as mix composition, age of specimens, sort of loading, humidity etc. are responsible for the remaining 40% variation.

Table 2. Results of the regression analysis

Series of samples	Regression Eq	Coefficient of determination
All specimens	$\lg(N) = 15.36 - 14.16S$	$r^2 = 59\%$
Normal-cured	$\lg(N) = 16.55 - 15.80S$	$r^2 = 64\%$

4.2. Cyclic creep of compressive concrete

Deformations of compressive concrete under cyclic loading were investigated experimentally by testing prisms and PC beams. In order to perform comparison for different specimens, the test deformations (strains, curvatures, etc.) were divided by the factor *S* (Eq (1)):

$$\varepsilon' = \frac{\varepsilon_{obs}}{S}, \quad \kappa' = \frac{\kappa_{obs}}{S}; \tag{5}$$

where ε' and κ' – the *relative* strain and curvature, respectively; ε_{obs} and κ_{obs} – observed deformations and curvatures, respectively.

The analysis has shown, that, on the contrary, to the fatigue strength investigations, influence of curing conditions had a significant effect on cyclic creep. The graphs of the *relative* strains of compressive concrete vs a number of load cycles, *N*, derived from experimental data of prisms are given in Fig. 6. This figure shows that the steam-cured prisms had, on average, from 30 up to 80% larger strains than the specimens cured under natural conditions. The difference was larger for higher numbers of loading cycles. Similar results have been obtained for the beams. The *relative* curvatures of beams, depending on a number of load cycles and the curing conditions of concrete and the number of load cycles, are shown in Fig. 7. As expected, in support to the results on prisms, the *relative* curvatures of steam-cured beams were significantly larger in respect to beams hardened under natural conditions.

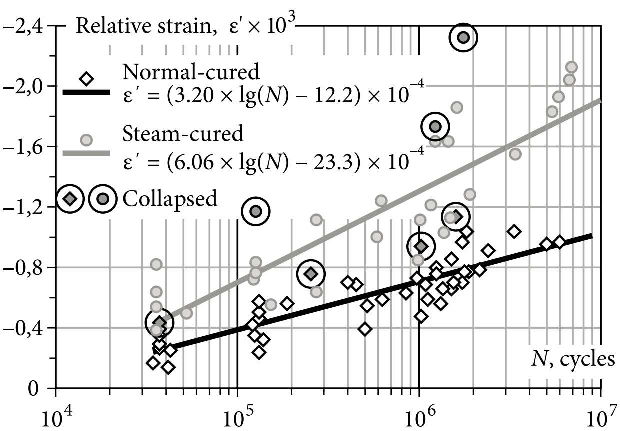

Fig. 6. Compressive strains induced by the cyclic creep

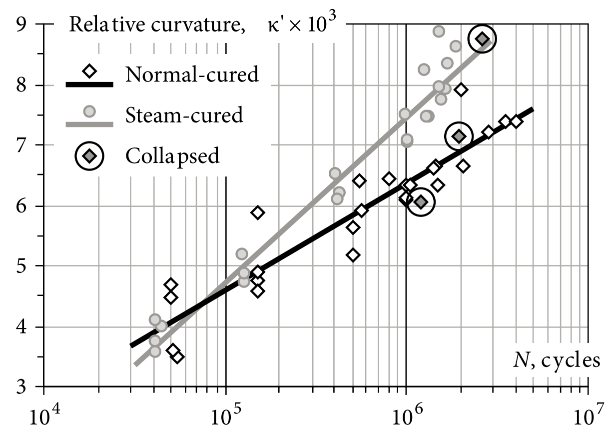

Fig. 7. Increment of curvature of the experimental beams due to cyclic loading and curing conditions

The *relative* strain distribution within the section of a selected beam for different loading cycles is shown in Fig. 8 (indicators I_k, $k = 1\dots6$, were placed as shown in Fig. 3).

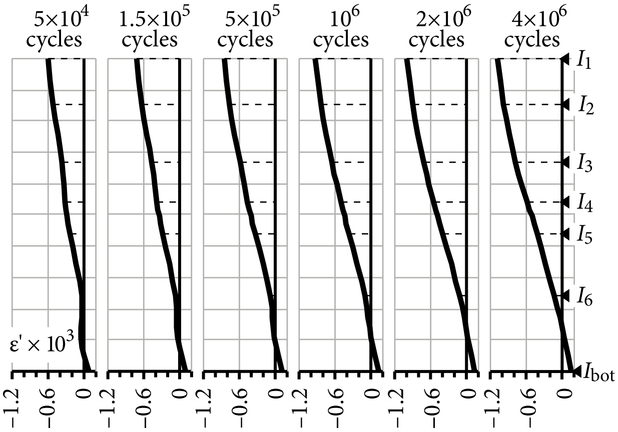

Fig. 8. The distribution of *relative* strains across the section of experimental PC beam at max loading level corresponding to 60% of the ultimate moment

Fig. 8 validates the hypothesis of linear strain distribution within the section depth for case of cyclic loading. As most of the beam's section is free of tension, the regression Eqs obtained from prism tests (Table 2) are applicable to the beam analysis.

5. Conclusions

This paper presents investigation on the influence of curing conditions on the high-cycle fatigue behaviour of concrete bridge elements. The fatigue strength of prestressed concrete beams and high-cycle creep of compressive concrete members has been analysed. Conclusions are based on fatigue tests performed on 16 prestressed beams and 54 prisms cured at different conditions. The specimens of the first series (7 beams and 35 prisms) hardened under the normal conditions and the specimens of the second series (9 beams and 19 prisms) were steam-cured. Fatigue data reported in the literature were also included into a comparative regression analysis. The following conclusions can be drawn:

- It has been shown that the number of loading cycles makes around 60% impact on variation of the fatigue strength, whereas such factors as mix composition, age of specimens, sort of loading, humidity etc. are responsible for the remaining 40% variation.
- The regression analysis has shown that curing conditions had no significant effect on the *S*-*N* relation (*N* – the number of load cycles for given max stress level *S*).
- On the contrary to the above, the influence of curing conditions had a significant effect on cyclic creep of tested specimens. On average, the steam cured prisms had from 30 up to 80% larger compressive creep strains than the specimens cured under natural conditions. The difference was larger for higher numbers of loading cycles. Qualitatively similar results were obtained for the test beams.

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