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BEHAVIOR OF PREDRIED MATURE CONCRETE BEAMS SUBJECT TO PARTIAL WETTING AND DRYING CYCLES

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Abstract. The presented research focuses on the behavior of predried concrete beams with 2.5 m span subjected to cycles of nonsymmetric wetting and drying. Wetting is induced by partially immersing the specimens in a water basin. The submerged portion of the specimens was relatively low (1/5 to 1/10 of their height) leading to a highly nonuniform and nonsymmetric distribution of eigenstrains due to concrete swelling. Unlike conventional experiments on the volume changes of concrete, the measured quantity is not the axial deformation but the vertical displacement instead. This paper presents the experimental data obtained within two wetting and drying cycles, running over 1 year.

Keywords: Concrete, wetting cycles, shrinkage, swelling.

1. Introduction

Despite the relatively high number of studies on concrete creep and shrinkage, both phenomena and their origins have not been comprehensively described and satisfactorily explained. The situation is complicated by numerous factors influencing both creep and shrinkage.

It is well known that concrete drying (or moisture changes) has a crucial impact on the evolution of drying shrinkage and drying creep (so-called Pickett effect [1]). The absolute majority of experiments keeps the relative humidity constant over the whole test duration [2]. In contrast to this, the real concrete structures experience natural ambient conditions which are subject to annual cycles and daily fluctuations. Furthermore, in the case of rain, some concrete members can encounter a direct contact with water.

The number of studies on the time-dependent behavior of concrete under cyclic ambient conditions is rather limited, e.g. [3–5] or [6, 7] but the latter deals only with high-strength concretes. A common feature of these experiments is that the entire surface of the specimens is subject to moisture changes and the typically measured quantity is the axial deformation. The only exception is the study of Hansen [4] who examined the curvature caused by bending under variable relative humidity which was varied between 50% a 70%. In experiments, typically, moisture changes are imposed by changing the level of relative humidity, only very rarely by immersing the specimens directly into a water.

To our best knowledge, so far, not a single study has examined the response of concrete specimens subjected to nonsymmetric wetting and drying cycles in which the specimens experience direct contact with water. Indeed, the objective of the present research conducted at CTU in Prague is to fill this existing gap. Within the experimental part of the research described in the present paper, the predried ordinary-strength concrete beams with 2.5 m span and 3 different heights are subject to partial soaking on their bottom surface followed by uniform drying. With approximately 3.5 months on average, the beams have experienced 2 wetting and drying cycles during the first 14 months of the experiment.

2. Materials and methods

All specimens in that study were prepared from an ordinary structural concrete C30/37. The composition is listed in Tab. 1 and the basic strength characteristics determined at the age of 27 days are summarized in Tab. 2.

Ingredients	Qtty [kg/m^3]
Cement CEM II/B-S 32.5R	379
Water	185
Aggregates (fine 822, coarse 969)	1791
Superplasticizer Sika BV4	1.9

Table 1. Concrete composition.

Property	Unit	Value
Compressive strength, f_c	[MPa]	36.8 ± 1.4
Young's modulus, E	[GPa]	30.3 ± 0.3
Tensile strength, f_t	[MPa]	3.38 ± 0.45
Fracture energy, G_f	[N/m]	150 ± 21

Table 2. Concrete mechanical properties at the age of 27 days.

The core of the present experimental program is represented by a set of 5 simply supported concrete beams (see Fig. 1) with a constant width of 100 mm and cross-sections 100×100 mm (3 specimens), 100×150 mm and 100 × 200 mm (1 specimen each) and a uniform span of 2.5 m subject to non-symmetric wetting and drying

Figure 1. A complete set of 5 concrete beams with 3 sets of 5 displacement sensors above the supports and at the midspan. External loading at $L/5$ with a pair of 15-kg weights.

cycles. The beams were prepared from a spare backup specimens from a preceding experimental project on shrinkage-induced deformations of concrete beams subjected to nonsymmetric drying, whose details and first results can be found in [8].

The specimens were demolded after 34 days of moist curing. Afterwards, the beams were kept approx. 1 year in a large laboratory hall next to the main set of specimens. The ambient conditions were not controlled and thus were susceptible to both annual and daily changes. However, on average the conditions were very close to the standard laboratory environment with relative humidity $h_{\mathrm{env}} = 50\%$ and $T = 20°\mathrm{C}$. The specimens were stored horizontally; the orientation of the cross-section was identical to the casting position and perpendicular to the final loading direction.

Figure 2. Companion specimens for supplementary measurement of weight loss/gain during drying and wetting cycles.

The original length of the specimens with 100×150 mm and 100×200 mm cross-section was 3.0 m. To unify their length with the three specimens $100 \times 100 \times 2700$ mm, these beams were at the age of 386 days trimmed to 2.6 m and soon afterwards (age 403 days) the beams were set to their destined position to minimize the overlap of the short-term creep deformation caused by self-weight with the effect of the prescribed ambient conditions. In addition to this, one specimen with 100×100 mm cross-section was loaded by a couple of 15-kg weights placed $L/5 = 0.5$ m from the supports (see Fig. 1). To examine the change in stiffness due to the moisture changes, 14 days after the start of the first wetting cycle, this specimen was unloaded and the external weights were moved to the neighbouring specimen of the same size. In the Figures presented in Section 3, this is marked by a black dashed line labelled "S".

Phase	Duration [days]	Age of concrete [days]
Moist curing	34	0 – 34
Pre-drying	375	34 – 408
Wetting 1	84	408 – 493
Drying 1	132	493 – 625
Wetting 2	113	625 – 738
Drying 2	112	738 – 850
Wetting 3		850 –

Table 3. Phases of the experimental program.

Another set of 5 companion specimens was prepared from the sawn-off parts. These 200 mm long prisms served to monitor the weight changes due to drying and wetting cycles (see Fig. 2). Similarly to the beams, there are 3 specimens with $H = 100$ mm and one of each $H = 150$ mm and 200 mm.

The first wetting cycle started at the age of 409 days, one week after the loading by the beams' self-weight. The space underneath the beams was filled with water such that the lower part of the beams (20 mm high) became immersed, see Fig. 3. The procedure was similar in the case of the companion specimens, only the water level was 5 mm higher, i.e. 25 mm (see Fig. 4). The first wetting phase took 84 days, after which the water was drained.

The length of the individual phases was not uniform and was not prescheduled in advance. The transition

Figure 3. Detail of concrete beams at the left support soon after the onset of wetting. Cyan line indicates water level and 20 mm immersed depth.

Figure 5. Detail of the displacement sensors installed at the midspan.

Figure 4. 5 companion specimens in a water basin subject to wetting (water level 25 mm).

between the phases was chosen with respect to the rate of the moisture mass loss. The other factor was the availability of staff to conduct regular measurements. The duration of the phases is summarized in Tab. 3.

The beams were equipped with 15 potentiometric linear transducers with an internal spring return (MMR10-12, effective stroke 12.7 mm) installed at the midspan and at the supports to compensate for their potential movements. The sensors were mounted to a steel frame which was anchored to the floor, see Figs. 1 and 5. The automatic reading was done every 30 minutes and more frequently, every 2 minutes, at the beginning of the drying/wetting cycle. The weight changes of the companion prismatic specimens were monitored manually using laboratory balance Kern & Sohn GmbH 572-55 with weighing capacity 20 kg and precision 0.05 g. At the beginning of each drying/wetting cycle, when the rates of weight changes were the highest, the measurement was conducted twice a day. The measuring frequency was decreasing with the rate of mass change until it reached the weekly period.

3. Results and discussion

The loading by self-weight of the beams was accompanied by their instantaneous deflection, which, owing to the adopted experimental setup, could not have been monitored. Furthermore, as shown later, the magnitude of this deflection is negligible in contrast to the deformation caused by the changes in ambient conditions. The creep deformation due to self-weight which occurred during the first week and prior to wetting were measured, but, because of their small magnitude (high concrete maturity, predried state, and small loading effect) are not presented here.

The deflection presented in the following Figures can be completely attributed to the deformations caused by nonuniformly distributed eigenstrains produced by swelling and shrinkage, and partially deflection associated with transient creep (linked to moisture changes) and microcracking. The origin of the time scale corresponds to the beginning of the first wetting. Additionally, the individual cycles are marked by vertical dashed lines: blue and labelled “W” stands for wetting, and red, “D”, for drying.

The beginning of the **first wetting cycle** is accompanied by concrete swelling in the immersed region leading to positive curvature and positive (downward) deflection. The behavior during the first two hours after the onset of wetting is presented in Fig. 6. The height of the immersed region is the same for all three specimen heights. Therefore, the initial deflection should decrease with increasing height and restraining bending stiffness, which nicely agrees with the measurements.

The initial evolution of the vertical deflection is very interesting. In all three cases, the deflection rate is almost constant during the first 30 minutes. Afterwards, the rate gradually decreases, such as in the case of larger specimens ($H = 150$ mm in red color and $H = 200$ mm in blue color) or suddenly stops like in the case of the specimens with $H = 100$ mm (shown in greyscale). For all three heights, the evolution of deflection has a characteristic plateau which is for $H = 100$ mm between ≈ 10 and 40 minutes. In the case of larger specimens, the presence of the plateau is not so striking and it is reached later, ≈ 0.5–2.5 hours ($H = 150$ mm) and ≈ 0.7–6 hours ($H = 200$ mm), see Fig. 7 with time in the log-scale. The corresponding deflection is ≈ 0.45 mm for $H = 100$ mm and 0.32 mm for the other two cases.

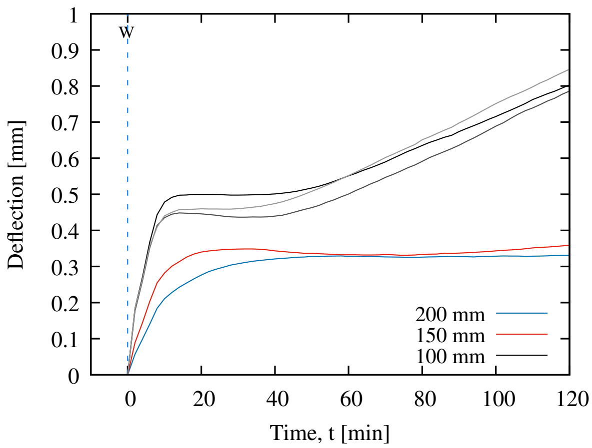

FIGURE 6. Vertical deflection at the midspan of the beams during the first 2 hours of the first wetting cycle.

The same value of vertical deflection of $H = 150$ and 200 mm several hours after loading needs to be interpreted with caution. As shown in Fig. 8, the prism with $H = 150$ mm imbibes considerably less water than the other specimens. This material inhomogeneity might be responsible for the smaller swelling strain and thus different structural response.

The first few hours after wetting the behavior of the beams is very complex. Most probably, it is a result of two competing processes: concrete swelling, which triggers the deflection, and relaxation of the generated stresses caused by a high moisture rate. In addition to this, the region of the swelling concrete is gradually increasing and the distributions of moisture and stresses over the height become less nonlinear.

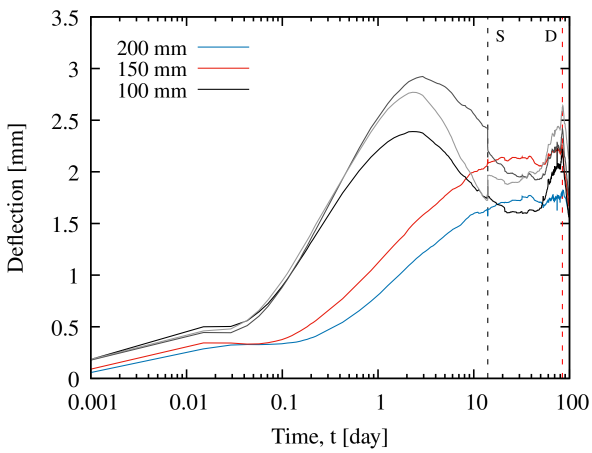

FIGURE 7. Vertical deflection at the midspan of the beams, time t in log-scale is measured from the onset of wetting.

The highest deflection, between 2.5 and 3.0 mm, is reached in $H = 100$ mm after 2–3 days of wetting. Except for a small difference in the deflection, the behavior of beams $H = 150$ mm and $H = 200$ mm in the second half of the first wetting cycle is very similar (see Fig. 7). The fluctuations in deflection can be attributed to the combination of changing ambient conditions as well as to the water level in the basin. (Note also the apparent oscillations of the mass in Fig. 8 in this period when the overall equilibrium was disturbed by inaccurate refilling the content of evaporated or imbibed water.)

It can be stated that the deflections at the end of the first wetting cycle are very similar except for the beam with $H = 200$ mm whose deflection is approximately 20% less than in the other cases, see Fig. 10. The change in deflection at $t = 14$ days caused by external weight removal or loading is almost identical (see Fig. 7). In this wetting cycle, there are no other consequences of the external loading.

The **first drying cycle** results in an almost identical evolution of moisture loss in all the specimens, see Fig. 8. Additionally, the development of vertical deflection of all beams is very similar and, at the end of the drying cycle, is around 1 mm (see Fig. 10). The exception is the specimen with external loads whose deflection recovers considerably less.

At the beginning of the **second wetting cycle**, in all cases, the total deflection becomes considerably larger than what it was at the end of the first wetting. The highest increase is in the case of the smallest specimens, $H = 100$ mm, which exhibit similar behavior to the first wetting (sharp increase followed by a decrease but now at slower rates). Additionally, in the second wetting cycle, the differences between the beams of different sizes tend to propagate.

The highest deflection of all belongs to the specimen with external weights; the difference has prominently arisen already during the first drying cycle. The phenomenon responsible for this behavior might be the drying creep at the bottom surface. Figure 8 shows that for $H = 150$ mm and $H = 200$ mm, the mass gain in the second wetting cycle is considerably less than in the first wetting. This suggests that at the beginning of this experiment, the concrete specimens were not in equilibrium with the ambient conditions. This might be one of the reasons responsible for the different behavior of the beams.

The mass change in the second and at the beginning of the **third wetting cycle** is very similar, both in terms of evolution as well as the measured values. Drying was terminated when the moisture content was still 30 g above the initial value, but it needs to be born in mind that the average ambient humidity (see Fig. 9) was higher than during predrying ($h_{\mathrm{env}} = 0.5$). In contrast to this, the differences between the individual beams tend to increase during the second drying and the third wetting, which is now in progress. The decrease in deflection of $H = 100$ mm beams at the beginning of wetting has vanished in the third cycle.

4. CONCLUSIONS

This paper presents original experimental data on predried concrete beams subject to wetting and dry-

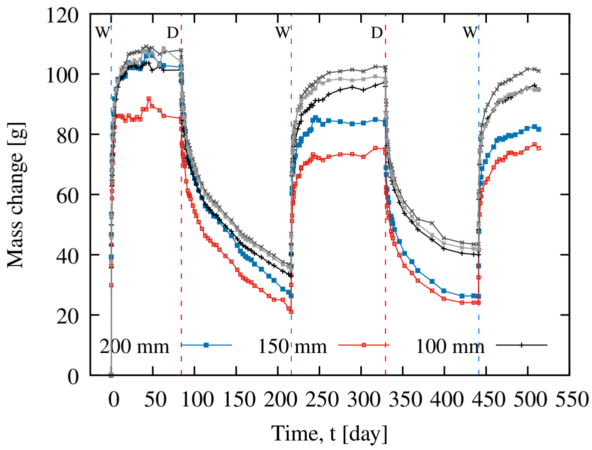

Figure 8. Total mass increase of companion specimens subject to wetting and drying cycles. The specimens had uniform length $L = 200$ mm and breadth $B = 100$ mm but different height $H = 100, 150$ and 200 mm.

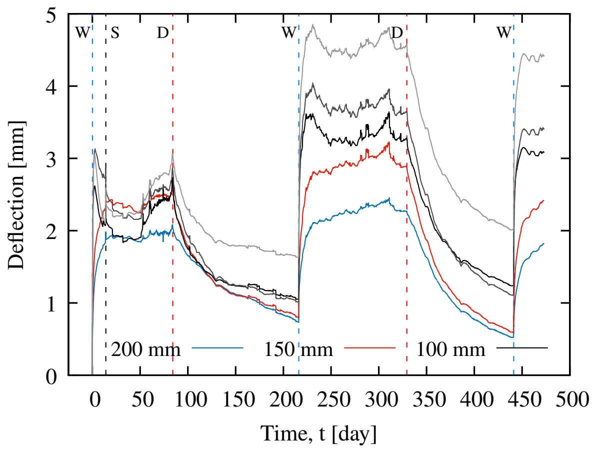

Figure 10. Development of vertical deflection of the concrete beams with height 100, 150 and 200 mm and span 2.5 m subject to cycles of wetting (W) and drying (D) which are marked by vertical dashed lines. "S" corresponds to the instant when the external weights were switched between two beams with $H = 100$ mm.

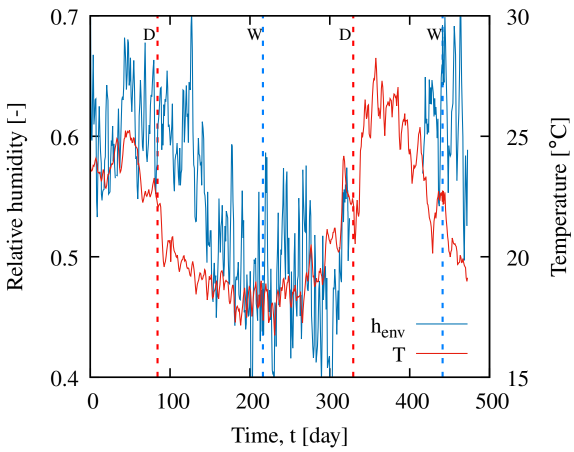

Figure 9. Evolution of the ambient conditions during the experiment.

ing cycles. In contrast to the experiments in the literature, which are scarce, wetting is nonsymmetric which causes high values of curvature.

Consistency of the measured data is supported by similarities in the observed trends. However, despite quite similar behavior in the first wetting and drying cycle, further cycling tends to split the response of the beams with different sizes. The behavior in the initial stage of the wetting period is extremely complex and with cycling undergoes changes.

In the next part of this research, mathematical modeling will be used to further analyze and better understand the complicated phenomena. The calibration will be adopted from previous research [8] which will enable efficient identification of the behavior related to concrete swelling.

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