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A thin-wall cement paste cylinder for creep tests at variable humidity or temperature

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Production of cement paste cylindrical specimens developed for creep tests at variable humidities and/or temperatures is described. The wall thickness is only 0.75 mm, which is required so that an equilibrium humidity distribution can be achieved in a short time with the result that the material parameters may be obtained directly by experiment.

INTRODUCTION

With the present knowledge it is impossible to predict satisfactorily the stresses and strains in concrete under long-time loads if the concrete is exposed to variable humidities or temperatures. The reasons are two. First, the stress-strain relationship under these conditions must be based on understanding of the creep mechanism, and its thermodynamics in particular. The basic theory has already been developed [1], but the numerical values of material parameters are not yet known. Secondly, the massive concrete specimens, which have invariably been used in the past, do not reach uniform humidity distribution even after decades, as recent analyses of drying indicate [5]. If the microcracking due to non-uniform humidity is negligible, the material parameters in the stress-strain relations can be determined from such data analytically, using methods of optimization and control theory. However, the procedure is complex and introduces additional error.

Therefore, a direct experimental determination of the material parameters is highly desirable. For this purpose the specimen must be as thin as possible, so that a uniform humidity distribution may be achieved in a short time. This need has been recognized by Torroja and de la Peña [2] who used cylindrical cement mortar specimens of 2 mm wall thickness. They used a steel outside mold, split longitudinally in two pieces. A layer of cement paste was spread on the mold and the interior surface was formed by a rotating straight edge. The main point in their technique was the absence of interior mandrel, which was made possible by good adhesion of paste to steel and a low water-cement ratio (0.34). But with this technique the normal water-cement ratios cannot be used, and maintaining a uniform wall thickness is also problematic. Specimens of thickness 2.5 mm have been produced (in a plexiglas mold with a teflon mandrel) by Mullen and Dolch [3] and somewhat thicker ones were used by Jessop [4]. Hollow cylinders with thicker walls have been used quite frequently, especially for torsion tests.

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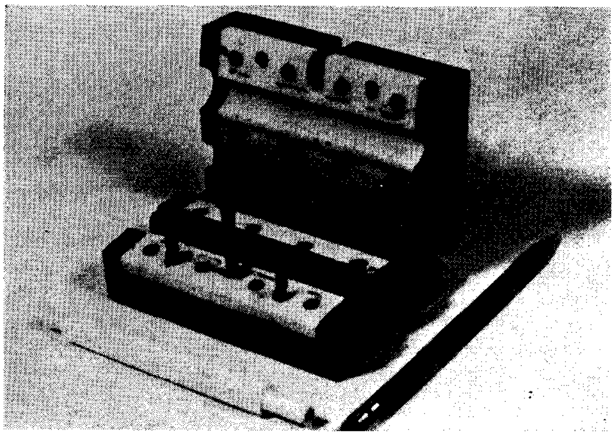

Fig. 1. — Photograph showing the mold in an open position, the mandrel and the specimen ready to be removed.

However, on the basis of recent studies of drying [5], it has been calculated that the specimen must be less than 1 mm thick in order to achieve a nearly uniform humidity distribution within less than a day. Such a specimen can be made, of course, only of cement paste. However, extrapolation of the data to concrete is possible because the effect of aggregate upon creep is reasonably understood.

For minimum wall thickness, a cylindrical shape is the most favorable one because it gives the highest local buckling strength of wall. This paper describes the production of a specimen with a wall thickness of 0.75 mm.

SPECIMEN MANUFACTURE

The mold for casting the specimens is made of teflon reinforced by aluminum, as is shown in figures 1 and 2. Cement paste of water-cement ratio 0.45 (made of 20 grams of Portland Cement 20687, ASTM Type I) is mixed under vacuum, to avoid entrainment of air, and is then carefully spread on the lower part of the open mold, trying to avoid entrapping air bubbles (by spreading the paste from one point, and piercing). The teflon mandrel is then pressed lightly into the paste, more paste is spread on top of the mandrel and the top half of the mold is closed and gradually tightened by the screw while the mold is on a shaking table. The excess paste squeezed out is then washed away gently, the mold is wrapped in a dripping wet cloth and put in a plastic bag. In this state the specimen is cured for 24 hours at 25 °C, after which the specimen is removed from the mold. This is a delicate procedure which is accomplished as follows.

First the closed mold with specimen is cooled with tap water for one minute and then is submerged in ice water for three minutes. Ice water is then passed through the mandrel for two minutes. After a slight loosening of the screw which is compressing the mold, the mandrel is removed by pulling on one end of the mandrel. The cooling and the Poisson's effect caused by pulling the mandrel allow the mandrel to be removed easily. Then the mold is pried open after which the specimen is gently rolled out of the other half of the mold. The specimen is then wrapped in a wet dripping cloth that has been in the ice water. The specimen in a cloth is then set out at room tem-

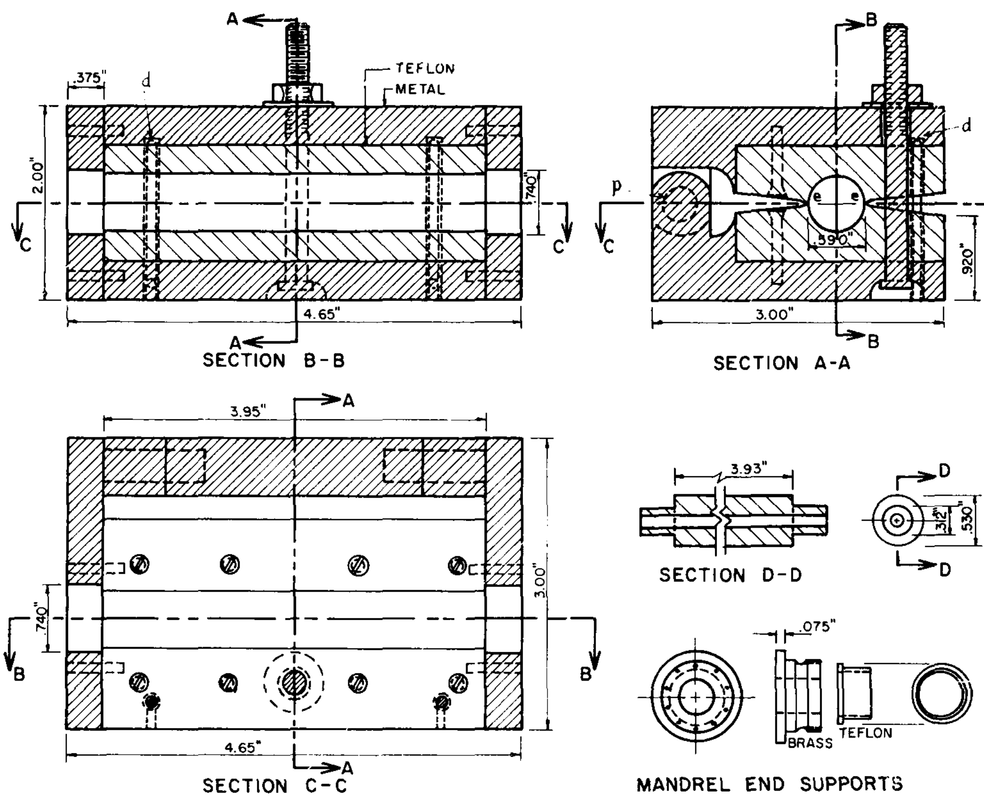

Fig. 2. — Cross sections of the mold (Dimensions in inches, 1 inch = 2.54 cm).

perature for several minutes. The specimen is then placed in lime water at 25 °C for 27 days. (The lime water is necessary to prevent carbonation.) All of these steps must be carefully implemented so that cracking of the specimen does not occur due to air drying, rough handling, or sudden changes in temperature. Approximately one of thirty specimens develop cracks and about one of ten specimens have some bubbles in them; the bubbles are usually so small that the specimen is still usable. After the 27 days in lime water the specimens are stored under lime water in a refrigerator at 2 °C until they are tested. To obtain perfect ends of specimens, part of the original length is cut and the end is ground to achieve flat surface.

STRAIN MEASUREMENT AND PRELIMINARY RESULTS

Preliminary data were collected under two different conditions for the specimens. A wet specimen (i.e. wrapped in a dripping wet cloth) was tested in static compression at 22 °C after 28 days in lime water. The compressive strength was 390 kp/cm² and the Young's initial tangent modulus was 194,000 kp/cm². The stress-strain curve was curved as is typical of thick cement paste specimens. A specimen stored at ambient temperature of 24 °C, and humidity of 50 %, for 6 weeks had a compressive strength of 490 kp/cm² and a compressive modulus of 243,000 kp/cm², and its stress-strain curve was perfectly linear to failure and perfectly reversible at first unloading and first reloading.

The axial creep and shrinkage strains are large enough to be measured by dial gages. Because of relative fragility of the specimens, the gages cannot easily be attached to the specimen itself (at points far enough from the loading platens to avoid end restraints). Thus, the strain is more conveniently measured between sufficiently rigid steel platens which introduce the load into the specimen.

For the cases of cyclic loading, and also to increase sensitivity, it is more convenient to use electrical resistance strain gages. These cannot be glued to the specimen surface because, for one reason, moisture exchange with the environment would be hindered. Therefore, a strain sensor was developed, consisting of two light portal-shaped (or C - shaped) metallic frames whose ends are attached to the loading platens. The frame is being bent as the specimen deforms and the maximum normal bending strains are measured by two minute resistance strain gages glued to the metal surfaces and waterproofed to minimize the effects of moisture upon the gages. Using a portal frame of cross section 1.6 × 3.2 mm, span 100 mm, and length of the arms (perpendicular to specimen axis) 35 mm, the maximum bending strain in the frame is about 28 times less than the axial strain of the specimen. But the sensitivity still equals about 10^{-6} in specimen strain which is about 25 times better than with the dial gages because the electrical resistance gages themselves are much more sensitive. With the cross section used, the rigidity of the frame sensor is about 1,700 times less than that of the specimen

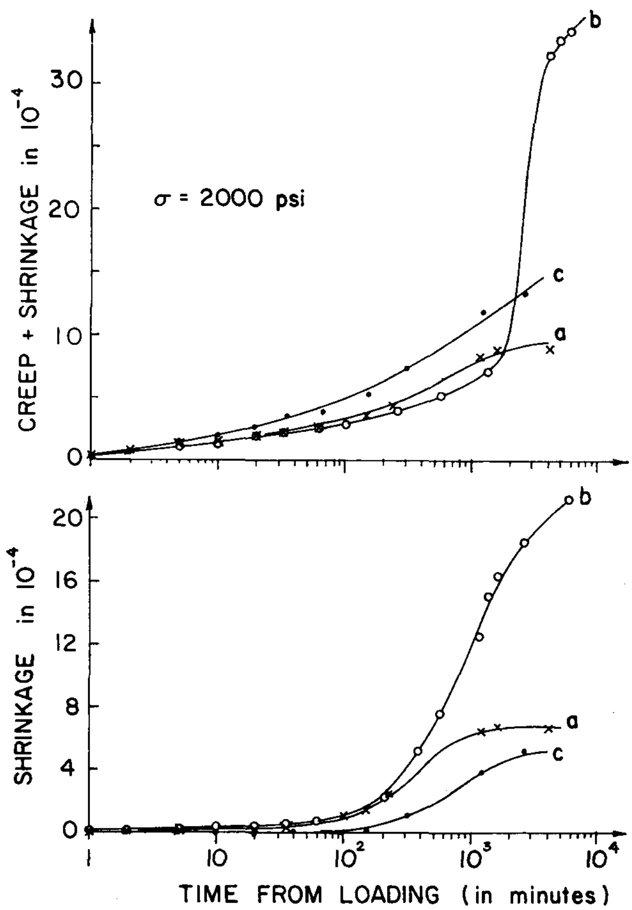

Fig. 3. — Short time axial creep under axial stress 2000 psi (141 kp/cm²) and shrinkage at 38 °C for three different environment histories :

a) constant 99 % relative humidity; *b*) drop from 99 % to 75 % within a day (linear variation with time) and load applied at the beginning of the drop; *c*) same as b, but load applied after 1 day, at the moment when 75 % humidity was reached. Strains were obtained by dial gages. The instantaneous strains corresponding to loading applied over a 2 min. period were 12.28, 9.98 and 12.11.

(in instantaneous deformation), which is sufficiently small. However, a random zero drift of these gages seems to be too large for long test periods (1).

All testing is done in a chamber with program controlled temperature and relative humidity. For the results are to be relevant for actual size concrete structures, the air is circulated through a CO_2 - removing filter.

Figure 3 shows preliminary results from a few creep tests in various atmospheres at 38 °C. Curve *b* clearly shows a marked acceleration of creep by drying (drying creep effect). It is noteworthy that shrinkage curve *b* begins to rise substantially only after the specimen should have dried [5] to uniform

(1) As far as gage stability is concerned, an unbonded resistance wire gage would be better. It was considered to place a wire inside the specimen along its axis, stretched between two cross beams anchored into the specimen. But the shrinkage can be larger than the highest possible strain due to tension of the wire, so that adjustments of wire strain during the test by a set screw would be necessary. This appeared to be too inconvenient.

pore humidity. Thus shrinkage is thus largely delayed with regard to drying. For explanation it must be assumed that shrinkage is due to a change in disjoining pressure in hindered adsorbed layers, which is delayed, rather than surface tension in the pores, which is simultaneous. It should be also noted that some of the shrinkage could represent delayed thermal contraction because temperature was raised from 2 °C to 38 °C only 1 day before loading.

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APPENDIX - DISCUSSION OF MOLD DESIGN

Teflon has been used because of its very small adhesion to cement paste. But even more important is its thermal expansion coefficient (62×10^{-6} per °C, average between 25° and 0 °C), which exceeds that of cement paste about 15 times. Thanks to the difference in thermal dilatation coefficients, the mandrel can be made loose in the specimen by cooling. (This is also somewhat helped by keeping the specimen at room temperature.) Theoretically, the gap produced by cooling between the mandrel and the specimen is about 0.0025 mm. For successful removal of specimen from the mandrel, the maximum deviation of the mandrel shape from the exact cylinder must be less than this value, or the specimen would crack. The breakage of bond with cement paste is also induced by longitudinal thermal contraction of the mandrel. Pulling the mandrel out also helps in this regard because the Poisson effect causes the diameter of the mandrel to contract near the pulled end. (Note that pushing the mandrel out of the specimen would be impossible because the diameter would increase at the pushed end due to the Poisson effect.)

Thermal contraction of teflon also enables unmolding of the specimen on the exterior surface. Namely, because of the fixation of teflon parts on the aluminum case (fig. 2) whose thermal contraction is many times less, cooling results in an increase rather than a decrease of the diameter of the hole in the mold. Encasement of teflon parts in aluminum is also needed to give sufficient rigidity to the mold.

The closing of mold by the screw probably creates considerable pressure in the paste to overcome its viscous resistance. (In this regard the production method is similar to pressure molding of plastics.) All parts which are supposed to come in contact by squeezing out the cement paste may have only a very small contact area (or damaging pressure would build up). Therefore edges shown in figure 1 are provided where the two teflon parts come in contact. For the same reason the end washers are either loose in the mold or are provided with grooves to make all contact areas small. The precise distance of the opposite sides of mold on closing is guaranteed by contact of steel rods (*d* in fig. 2) which are not touched by the paste. The pivot (*p* in fig. 2) gives reliable guidance during the closing of the mold. Pressures on molding can deform teflon parts plastically, e.g. decrease the diameter of mandrel near the ends, in which case replacement is necessary.

A number of other alternatives has been tried before a successful design has been reached. For instance, to achieve good bending rigidity, the mandrel was at first reinforced by a hollow steel core. But then longitudinal contraction of diameter is about half the value without the core. Consequently, double precision is needed in machining the mandrel. However, high bending rigidity was found to be unnecessary. Another mandrel was produced of metal, with a hollow cross section consisting of various wedge-shaped pieces which all could be successively pushed toward (and subsequently along) the axis of the cylinder. But cement paste under pressure was penetrating into this mandrel, and in spite of teflon spray unmolding appeared to be impossible. It was also contemplated to use for unmolding the Poisson effect (instead of differential thermal contraction), by precompressing the hollow mandrel longitudinally before casting the specimen and keeping it so until unmolding. However, no convenient arrangement was found which would guarantee straightness of the slender precompressed mandrel and avoid change of its dimensions due to creep.

Another method which was tried was to stretch the teflon mandrel causing a lateral Poisson contraction before pulling the mandrel from the specimen. However, the tensile strength of the teflon, as well as the lateral contraction, was too low, and the creep strains of mandrel were too high to permit the use of this method. It was also tried to place the cement paste into the closed mold while pushing the mandrel into the cylindrical hole in the form longitudinally. But this always led to large voids in the wall of specimen. Casting the specimen into a mold which spins to provide centrifugal force that would keep the paste on the wall was also considered, but rejected because the water-cement ratio could not be controlled.

Il should be noted that casting of a specimen of water-cement ratio 0.35 with the mold described here appeared to be impossible. The mold could not be closed, apparently because the viscosity of paste was too high.

A method which was used with some success for a while was to first remove the specimen from the mold and then pull the mandrel from the specimen. All of the cooling and handling procedures were the same as in the presently used method. The major difficulty with this procedure was the cracking of the ends of the specimen in about 1 out of 5 specimens.