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ON THE POSSIBILITY OF EXPERIMENTAL INVESTIGATION OF SHRINKAGE IN CONCRETE

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1. Introduction

Shrinkage and swelling deformability are very important attributes of concrete and have some effects even when no external load is imposed on the structure. Intensity of these processes depends upon a number of factors, and the most important of them are hygrothermal conditions of the environment.

Researches on shrinkage are carried on since more than fifty years. At the very beginning all the deformations of long duration were treated as a complex, and shrinkage and flow of concrete were not distinguished.

First modern researches were conducted by Allan [2], Dutron, Menzel [13], and Carlson [8].

The measurement of shrinkage of concrete is usually conducted on the surface - by the means of the mechanical strain gauges. The aim of the reported work is to show a possibility of application of electrical resistance strain gauges for inner measurements. In these measurements strain will be obtained not in one direction only, but in the form of all six components of the strain tensor. There is a possibility to compare such experimental data with the results of a theoretical approach.

2. Shrinkage of concrete

Shrinkage of concrete is a consequence of structural variations being caused mainly by the changes in the humidity of capillars and other voids inside concrete element. Known are also other reasons of shrinkage - for example carbonation processes.

In this contribution the setting of concrete, which is also connected with a sort of shrinkage, is not taken into account. Also there will be no distinction between moisture shrinkage and carbonation shrinkage - for both the components together accepted will be the term - drying shrinkage.

The magnitude of shrinkage depends on many factors - e.g. quality and amount of cement, water-cement ratio, composition and type of aggregates, age of concrete, hygrothermal conditions.

There is no complete explanation of the process of shrinkage, based on the microstructure of cement paste. Some informations may be found in the monograph by Bukowski [7] and the microstructure of cement paste is shortly described by Brunauer [6].

Shrinkage experiments usually consist of measurements of the linear, longitudinal deformation of small specimens, kept in well known conditions. Recorded are mainly temperature and humidity.

This kind of investigation allows to conclude that drying shrinkage is linearily dependent upon the humidity of material.

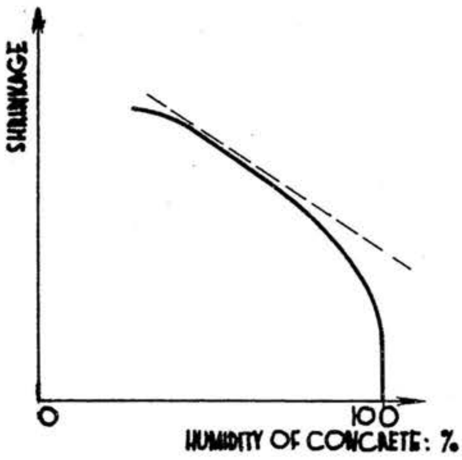
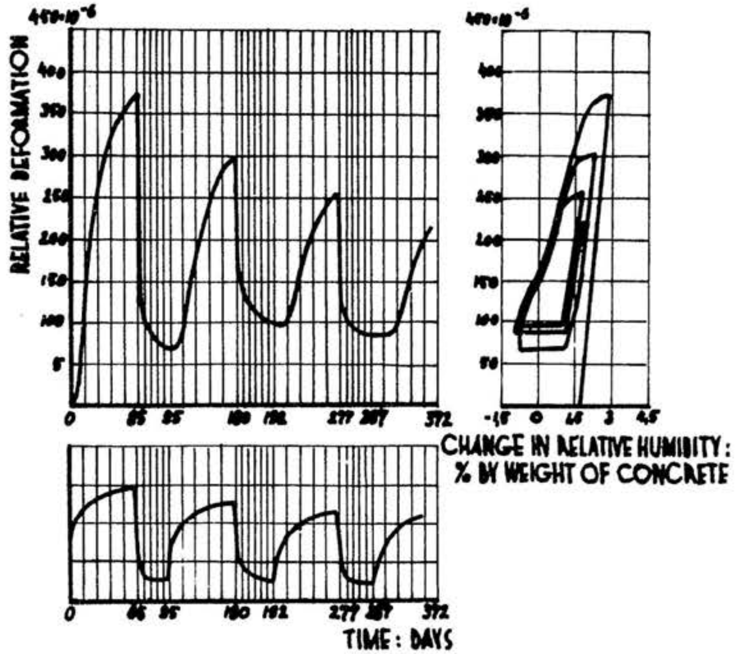


fig. 1

L´Hermite [10] presents the typical diagram /fig. 1/ where the said correlation is linear, with the exception of a region around the point of maximum humidity. This region corresponds to the very beginning of drying /the drying begins when specimen is visibly wet on the surface; in this moment it is not followed by any volume changes; cf. three stages of drying in the work by Newman [15] / and besides this region is rather small for old concrete.

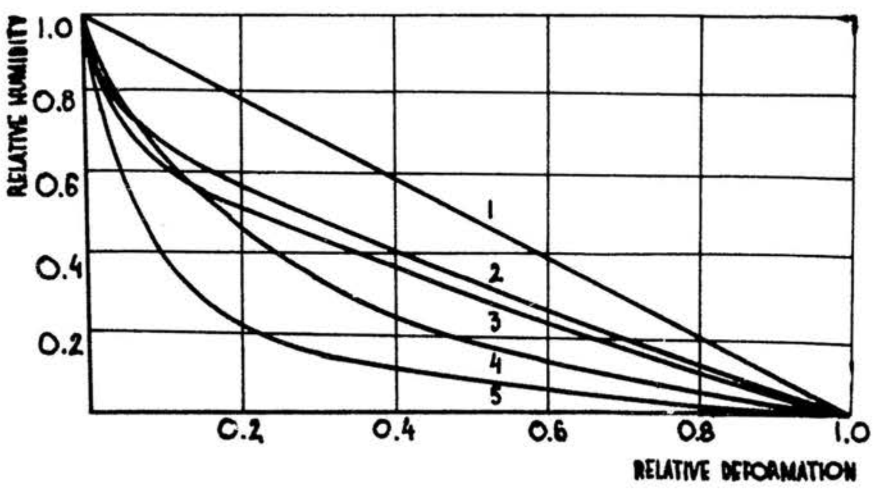
The diagram of similar character /fig. 2/ was obtained by Aleksandrovskij [1]. The specimen was dryied and humidified in line. In drying the relation is linear and this is a regularity in proceeding cycles. The relation discussed is linear at least for the ordinary constructional concrete. For the other concretes it may be of more complicated character, as it is shown on the diagram /fig. 3/ taken from the paper by Emielianov [9]. On the diagram numbers 2 to 5 correspond to light-weight concrete and number 1 stands for constructional concrete.

The conclusion, that the dependence between humidity and



RELATIVE DEFORMATION
CHANGE IN RELATIVE HUMIDITY : % BY WEIGHT OF CONCRETE
TIME : DAYS

fig. 2



RELATIVE HUMIDITY
RELATIVE DEFORMATION

fig. 3

shrinkage of concrete is linear, or that at least it is known, is one of the basic assumptions for the proposed method of a theoretical analysis.

In the case when the dependence is linear we can determine experimentally a coefficient called the coefficient of shrinkage /λ/. According to the Russian Building Code for example, it may be assumed as a constant $3.10^{-2} \frac{mm/mm}{g/g}$. Of course it may differ with many factors.

3. A method proposed for theoretical analysis of the shrinkage deformation

Like other effects concerning the whole volume of the body /e.g. - the thermal deformation/, shrinkage is never restricted to only one direction, as it is often approximately assumed.

Deformation of the drying element may be considered as a sum of free strain caused by the moisture changes, and of certain additional strain caused by the shrinkage stresses. In the absolute notation we can write it as follows:

$$\underline{\varepsilon} = \underset{o}{\varepsilon} + \underset{r}{\varepsilon} \qquad /3.1/$$

The first component of this sum is a tensor of the free strain. It corresponds to the pure volumetric strain state, i.e. - in any representation its diagonal components only differ from zero:

$$\underset{o}{\varepsilon} \equiv [\varepsilon_{ij}] = \begin{bmatrix} \underset{o}{\varepsilon} & 0 & 0 \\ 0 & \underset{o}{\varepsilon} & 0 \\ 0 & 0 & \underset{o}{\varepsilon} \end{bmatrix} \qquad /3.2/$$

These components we can imagine as the relative shortening of the edges of an infinitesimal concrete cube, which was taken from the initial and placed in the given humidity. First component of /3.1/ is therefore a tensor function of position inside element and of time. According to what was said above, and what is evident on the base of experiments, it may be assumed as a linear function of the humidity contents at a considered point. The components in /3.2/ have therefore form:

$$\underset{o}{\varepsilon} = \underset{o}{\varepsilon}(x_1, x_2, x_3, t) = \lambda\left[\omega(x_1, x_2, x_3, t) - \omega_\infty\right]$$

where: ω_∞ - is some fictive humidity /in g/g/ that will be reached by a specimen kept in the given humidity, after infinitely long time;

ω - humidity in the given point; time t is measured from the moment when the diffusion process began;

λ - above mentioned coefficient of shrinkage.

First step to solve the problem is the determination of the function describing distribution of the humidity inside an element /humidity field/. This function is sought as the solution of a well known diffusion equation:

$$\frac{\partial \omega}{\partial t} = K\left(\frac{\partial^2 \omega}{\partial x_1^2} + \frac{\partial^2 \omega}{\partial x_2^2} + \frac{\partial^2 \omega}{\partial x_3^2}\right)$$

where K is a diffusion coefficient /m^2/hour/.

The solution must satisfy some boundry conditions being dependent on the element's shape and on the curing conditions of a specimen. Coefficient K and the other coefficient that rules the rate of external evaporation /so called surface vector - in m/hour/, were examined by many authors e.g. Aleksandrovskij [1] and Murata [14]. Before the theoretical analysis of shrinkage both coefficients ought to be determined separately for every experiment that is to be compared with the theoretical solution. Unfortunately the known to author methods of determining of these coefficients are neither very simple nor well motivated.

After $\underset{o}{\varepsilon}$ is found in the described way, the actual state of strain must be determined. It is generally understood that only linear distribution of pure volumetric strain allows the deformation state free from stresses of the shrinkage origin. Such a distribution may be written according to formula:

$$\underset{o}{\varepsilon} = a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4$$

where $a_i = a_i(t)$; $i=1,2,3,4$ are functions of time only.

In any other case, new formed stresses will result in change of strain field, and the second component in /3.1/ will not be zero. This additional strain tensor may be described /in the same representation as /3.2// as follows:

$$\underset{\sigma}{\varepsilon} = [\varepsilon_{ij}] = \begin{bmatrix} \underset{\sigma}{\varepsilon}_{11} & \underset{\sigma}{\varepsilon}_{12} & \underset{\sigma}{\varepsilon}_{13} \\ \underset{\sigma}{\varepsilon}_{21} & \underset{\sigma}{\varepsilon}_{22} & \underset{\sigma}{\varepsilon}_{23} \\ \underset{\sigma}{\varepsilon}_{31} & \underset{\sigma}{\varepsilon}_{32} & \underset{\sigma}{\varepsilon}_{33} \end{bmatrix}$$

This unknown component of the actual strain tensor must be determined in such a way that the compatibility equation could be fulfilled by the sum /3.1/. For the small deformations, and in index notation, compatibility equations are:

$$\frac{\partial^2 \varepsilon_{ij}}{\partial x_k \partial x_l} + \frac{\partial^2 \varepsilon_{kl}}{\partial x_i \partial x_j} = \frac{\partial^2 \varepsilon_{ik}}{\partial x_j \partial x_l} + \frac{\partial^2 \varepsilon_{jl}}{\partial x_i \partial x_k}\ ; \ (i,j,k,l = 1,2,3)$$

where x_i; $i=1,2,3$ are cartesian coordinates, and ε_{ij} are the components of the actual strain tensor, described by the sum /3.1/, i.e. the components of the tensor:

$$\varepsilon = [\varepsilon_{ij}] = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix}$$

When solving practical problem, proper boundry conditions must be formulated. If these conditions contain stress fields, some constitutive equation /a characteristic for given material, functional relation describing how stress field depends on strain field/ must be assumed. As the first approximation accepted may be an assumption of classical elasticity.

The described theoretical treatment is analogous to the methods applied in thermoelasticity and leads to the theoretically determined field of strain that can next be compared with the result of experiments.

Such a theoretical analysis with experimental verification of results will make a base for calculation of shrinkage deformations in concrete bodies, or at least it will allow the improvement of the theory itself.

The first analysis of deformation of drying concrete elements of several shapes, with the use of the diffusion equation, was done by Pickett in 1946 [16].

4. Experimental measurement of shrinkage strain in concrete

As it was mentioned above, the theoretical analysis must be experimentally verified.

Generally known measuring methods used in concrete investigations are limited to the measurement of the mutual displacement of certain points of an element, or to the measurement of surface deformations.

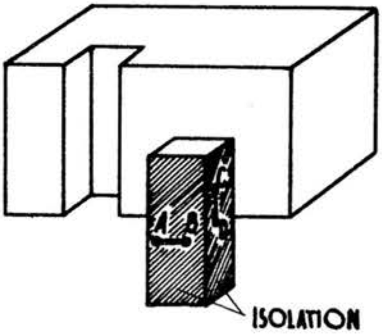


fig. 4

In 1937 Carlson [8] tried to investigate deformation inside concrete element by the means of the surface measurements. After isolating lateral surfaces of a concrete specimen against moisture movement /rectangular parallelepiped on fig. 4/ he assumed that the specimen is in the same condition as it would be cut out from the infinitely large slab, drying on the upward and downward surfaces. The moisture-proof layer consisted of copper foil.

It is possible to measure the surface deformations on the lateral surfaces, for example on bases A-B or C-D, and to treat them as being representative for the inner slab deformations.

Although the scheme is likely to be good for diffusion processes, it is not the same for the investigation of deformation state. The specimen and the block inside the plate has quite different boundry conditions.

During last twenty years some measuring methods based on the use of electrical resistance strain gauges were developed. It allowed to produce and to test some gauges for inner measurements in the concrete. The subject was studied by Carlson, Hondros, Pimienov and many others [11].

In the Institute of the Basic Technical Problems in Warsaw,

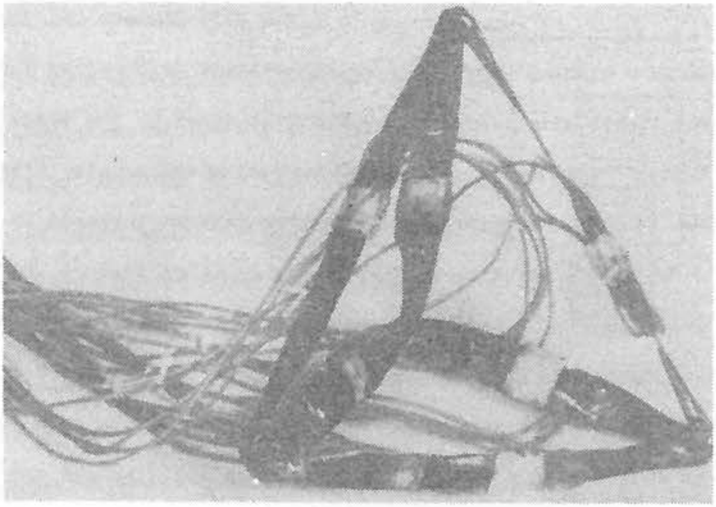


fig. 5

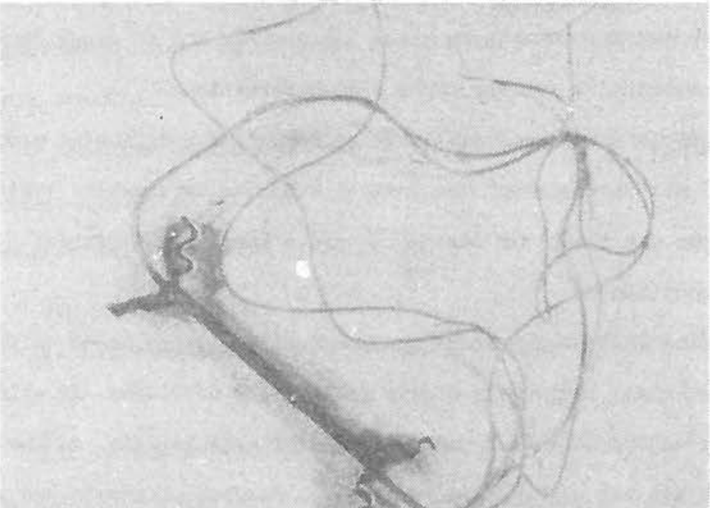


fig. 6

two such devices were prepared and tested in last years.

The device shown on fig. 5 was designed for measurement of six strain components at inner point of concrete element [4], [5]. Six thin copper strips are equiped with electrical resistance strain gauges, adequately fixed and waterproofed. The lengths of edges are 7 and 10 cm. approx. With the help of thin tension members /e.g. nylon strings/ the device may be placed at a selected point within form for concrete. After casting we obtain an element with the measurement device inside. It is assumed that this device gives an information about six components of strain tensor, in the point being the centre of gravity of the tetrahedron. Three components of linear strain are obtained directly and three angular components of strain may be found with the help of simple calculation [17].

The second gauge /fig. 6/ was designed as a copper foil box 1 x 1 x 8 cm approx. and it makes possible the measurement of one component of the strain tensor. The strain is measured by the means of two electrical resistance strain gauges glued and waterproofed inside the box. The whiskers assure the bond between the device and the concrete.

These two devices, as well as the others not mentioned here, were designed mainly for the observation of strain states of short duration. As the electrical resistance measurement methods developed, and as the component materials were improved, it become possible to use them for observation of the strain states of long duration. Beyer and Lebow [3] and Kubota and Sakane [12] may be an example of the investigation on the subject. The problem of measurement of the strain state of long duration was started also at the Institute of the

Basic Technical Problems in Warsaw.

Both devices described above were specially prepared. As for the long time observation waterproofing of a gauge is of great importance, all the materials were choosen very carefully.

The first /spatial/ device was constructed with the use of Saunders-Roe electrical resistance strain gauges /length of the base less than 0.63 cm, resistance about 80 ohm/, and with Araldite Strain Gauge Cement as waterproof cover and mechanical shield.

The second device was constructed with the use of the Polish production resistance strain gauges RL-120 /length of the base 1.5 cm, resistance 120 ohm/, and micromolecular wax as the waterproof agent.

The Wheatstone bridge and the connection box were of the Polish production /type T-2/. The additional set of constant resistances was choosen and connected to the bridge for zero drift control, and for the correction of the readings. Such a control set is not necessary for more precise apparatuses, e.g. for Hottinger Baldwin Bridge type MK.

5. The results of the measurements

Both the described measuring devices were placed in concrete cylinders: Ø 16 x 16 and Ø 16 x 50 cm, in a way shown on fig. 7. Specimens were fabricated of constructional concrete with the compressive strength of about 350 kG/cm^2. After taking into consideration the size of the devices, the aggregate diameter was limited to 2 cm.

One specimen of each type contained the compensation gauges - the compensation was of the 1 - 1 type.

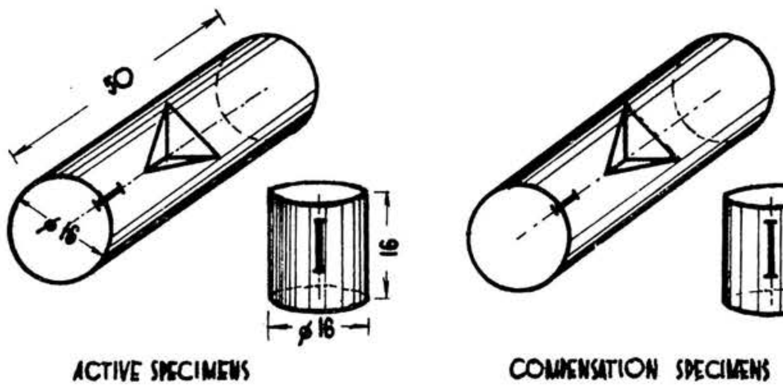


fig. 7

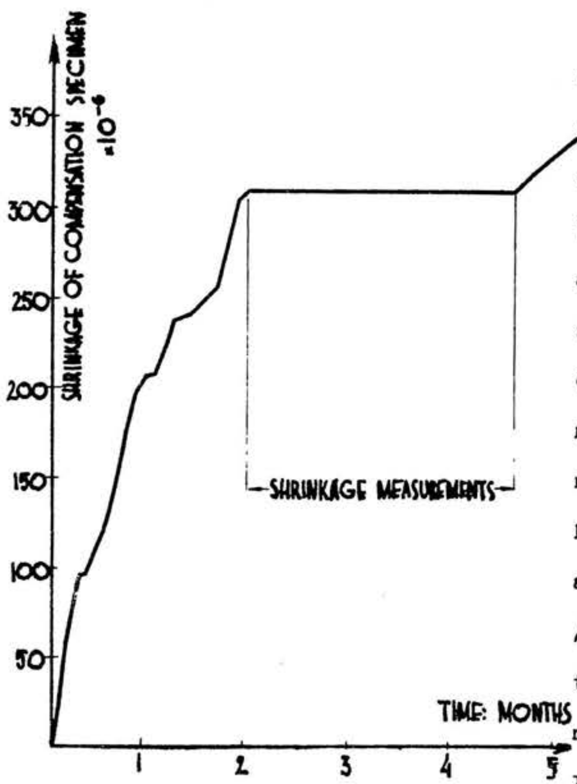


fig. 8

After fabrication one set of specimens /active specimens/ was kept in constant humidity of about 100% RH /in poliethylen bags and wet rags/. The other set was dried in room humidity. After some preparational readings, active specimens were taken out from the humidity 100% RH and placed also in the room humidity /about 75 % RH/. In the same time the compensation specimens were wraped in the poliethylen foil, to stop the process of their drying.

In fact, the longitudinal strain of the bigger cylinder, measured on its surface by the means of the Demec dial gauge, was constant in the time of observation /"shrinkage measurements" - on fig. 8/.

The measurements were continued by about three months, and as the main result the diagrams shown on fig. 9 and fig. 10 were obtained.

On fig. 9 shown is longuitudinal strain measured in three different points inside cylinders. Curves A and B correspond to the cylinder ∅ 16 x 50 cm, curve C to cylinder ∅ 16 x 16 cm.

The reason of the differences between A, B and C is probabely in the shape and in the drying conditions of specimens. Complete explanation needs full calculation,prepared on the base of the previously described assumptions.

Linear components of the strain tensor are shown on fig. 10.

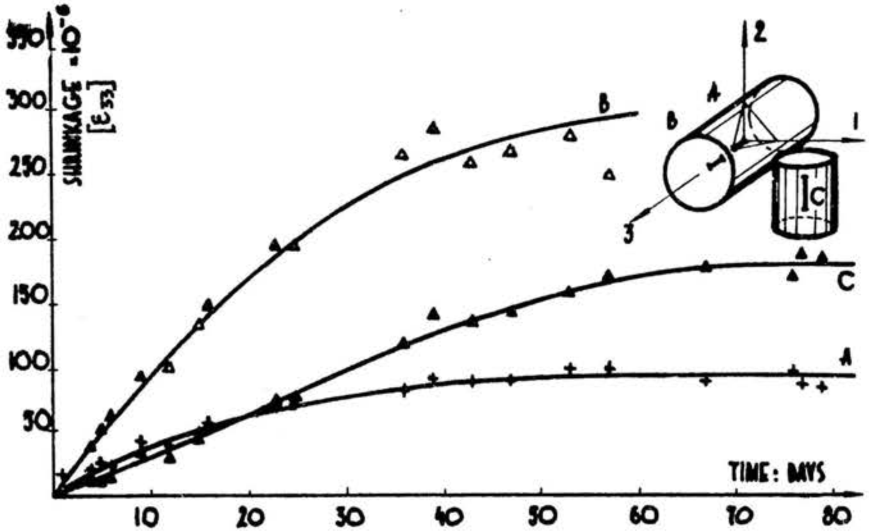


fig. 9

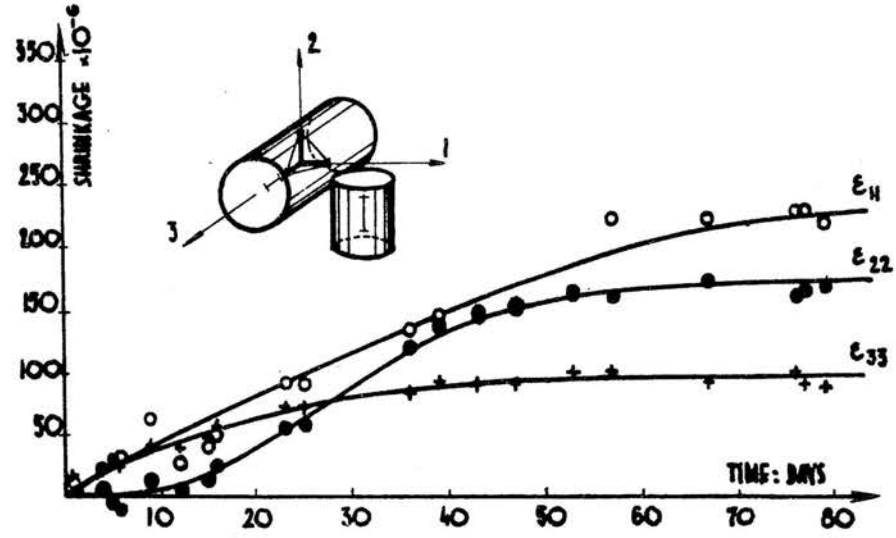

SHRINKAGE ×10⁻⁶
350
300
250
200
150
100
50
TIME: DAYS
10
20
30
40
50
60
70
80
ε_11
ε_22
ε_33
1
2
3

fig. 10

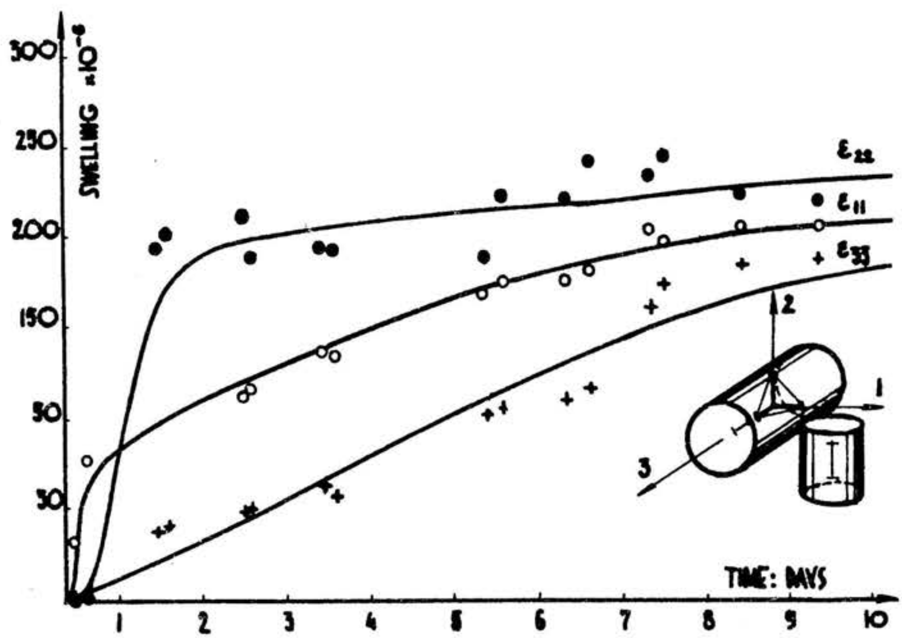

SWELLING ×10⁻⁶
300
250
200
150
50
TIME: DAYS
1
2
3
4
5
6
7
8
9
10
ε_22
ε_11
ε_33
1
2
3

fig. 11

There is an assumption that this measurement concerns the central point of the cylinder, although strain is actually measured in points around the centre. Indexes are used according to the drawing. It is possible to see the difference between the radial and longuitudinal strain components.

The diagram of the angular components of strain, that can also be measured with the same device, is not shown here. The changes of the strain were not great enough, i.e. practically they were of the order of the measurement accuracy. Possibly it was caused by small angular deformation in the obtained experimental scheme. In some cases angular components need perhaps greater accuracy of the measuring device.

The same set of specimens was used to measure the swelling strain. Both active and compensation specimens were dried at 60 % RH and then one of them was put into the humidity of about 100 % RH.

Linear components of the strain tensor, obtained in this experiment, are shown on fig. 11. As the rate of absorption of moisture is many time higher than the rate of drying, the time scale was changed. It is possible to notice the same regularity as on the fig. 10 - that the axial strain component is smaller in the comparison with the radial ones.

In all these experiments readings were done with the accuracy $\pm 10 \times 10^{-6}$ /10 microstrains/.

6. Concluding remarks

All the presented experiments were mainly of the introductory character and they were not done to make a base for a proof of a theoretical treatment. The material coefficients were not experimentally evaluated, and the boundary conditions were not precisely choosen. For the same reason no calculation of the strain inside drying cylinder was prepared. In the continuation of the research, another seria of experiments is to create a base for the verification of the theory.

The measurements prove full aplicability of the electrical resistance strain gauges for the observation of shrinkage deformation in concrete.

The experiment of this type needs a very high accuracy and care in preparation of materials and in operation of the devices. It allows to measure not only the shrinkage but also other deformations of concrete, like swelling, flow etc.

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