CEB
27 th PLENARY SESSION
PARIS SEPTEMBER 1990

COMITÉ EURO-INTERNATIONAL DU BÉTON
CONTRIBUTION OF THE POLISH NATIONAL GROUP

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THE INFLUENCE OF ENVIRONMENT HUMIDITY AND THE WATER CONTENT IN THE CONCRETE MIX ON THE DEVELOPMENT OF SHRINKAGE STRESSES

1. Introduction

The relative humidity of air and the water-cement ratio of the concrete mix belong to the most important technological factors affecting the development of shrinkage stresses in concrete [1,4,6,7,8]. Technical literature does not indicate any extensive research aiming at a quantitative explanation of the determined relations. Only simplified tests have been carried out so far, the results of which lead to rather contradicting conclusions[1,2,4,6,8]or indicate the complex character of the effects exerted by all the mentioned factors[4,6]. This induced the author of the present paper to undertake investigations in this field. CEB-FIP Model Code 1990(Bull.190) renders a method of determining the values of shrinkage strains; it does not contain, however, any information on shrinkage stresses calculation. In author's paper it has been proved that technological factors which have been considered have different influence on the shrinkage stresses than on the development of shrinkage it self.

2. The aim, the scope and a description of the tests

It was the aim of the author's own tests to investigate the development of shrinkage stresses in concrete while curing, and to determine their correlation with shrinkage strains at various values of the two most important technological factors. Knowledge concerning the development of shrinkage stresses in actual concrete with a given curve of the development of tensile strengths provides essential information, making it possible to evaluate quantitatively the resistance of concrete to shrinkage cracking, not only basing on the moment of the occurrence of

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the first crack, but also on the ratio of tensile strength to shrinkage stresses. This ratio expresses the margin of safety against cracking and may serve as a quantitative "measure of quality", as far as the resistance to cracking is concerned [10].

The subject matter taken up in the present paper has been restricted to bar-shaped concrete elements and curing without any freedom of deformation. The choice of just such an element was dictated by the simplified assumption that the field of shrinkage deformation was homogeneous over the entire cross-section of the sample. The element was deprived of its freedom of deformation by providing both its ends with external constraints in the shape of coaxial pivot bearings. Such an idealized experimental model relates, however, to cases really applied in concrete structures and makes it possible to check the resistance against shrinkage cracking of this material in nearly extreme conditions.

The decisive aim of these researches was to determine the influence of the relative humidity of air α and the water content in the mix ω upon the development of shrinkage stresses σ_{bs} and the time of the occurrence of cracks t_z.

The tests comprised

- the development of free concrete shrinkage in time $\varepsilon_s(t,\alpha,\omega)$,
- the development of shrinkage stresses $\sigma_{bs}(t,\alpha,\omega)$ or $\sigma_{bs}(\varepsilon_s,\alpha,\omega)$,
- the tensile strength $f_{ct}(t)$,
- the compressive strength after 28 days f_{cu}.

These tests were planned to be carried out at three levels of humidity α and three levels of mix-water content (expressed by the water-cement ratio $\omega = w/c$, the content of cement being constant). As such experiments require much time, the programme comprised only five cases, as shown in Fig.1.

Each case comprised 12 samples for the testing of σ_{bs} as well as 8 samples to determine the value of ε_s. All of them were made of five mixes: of each mix additionally five cubes 150x150 mm were formed to determine the value of f_{cu}. The samples were grouped stochastically.

The composition of the concrete mixture for $\omega_1 = 0{,}55$ was as follows: 243 kg Portland cement "35", 2084 kg sand-gravel mix, 134 l water. In the case of $\omega_2 = 0{,}70$ and $\omega_3 = 0{,}85$ the content of water and aggregate was appropriately changed. The samples were taken out of the moulds after 24 hours and then stored and tested at a temperature of 20±1° C. All the samples used for the checking of their strength were stored at a humidity of $\alpha_3 = 85\%$.

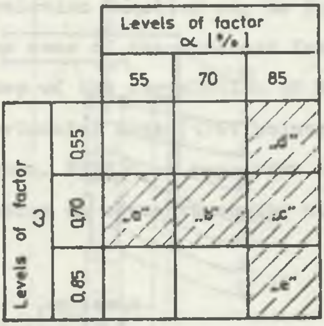

Fig.1. Test programme

With the exception of f_{cu}, the experimental elements were provided with caps as shown in Fig.2. As the cross-sections were rather small and the time of testing comparatively long, the effect of the not uniform drying of the respective parts of the sample was neglected. Deformations were measured by means of frames, rods and dial gauge (1 μm) mounted on the samples, on a basis 400 mm long. In order to model the behaviour of a sample deprived of its freedom of deformation (mounted at both ends), specially constructed gravitational tension creep-testing machines were used (Fig.3). The samples were successively loaded twice the day, so that a constant length of the measuring base might be secured. Thus, shrinkage deformations (contractions of the sample) were compensated by lengthening it, these extensions being brought about by external loads. The known value of the force exerted on the sample facilitated the calculation of the mean value of shrinkage stresses in the cross-section of the sample.

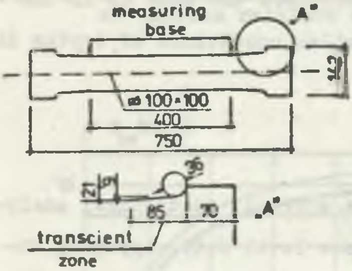

Fig.2. Geometry of the samples

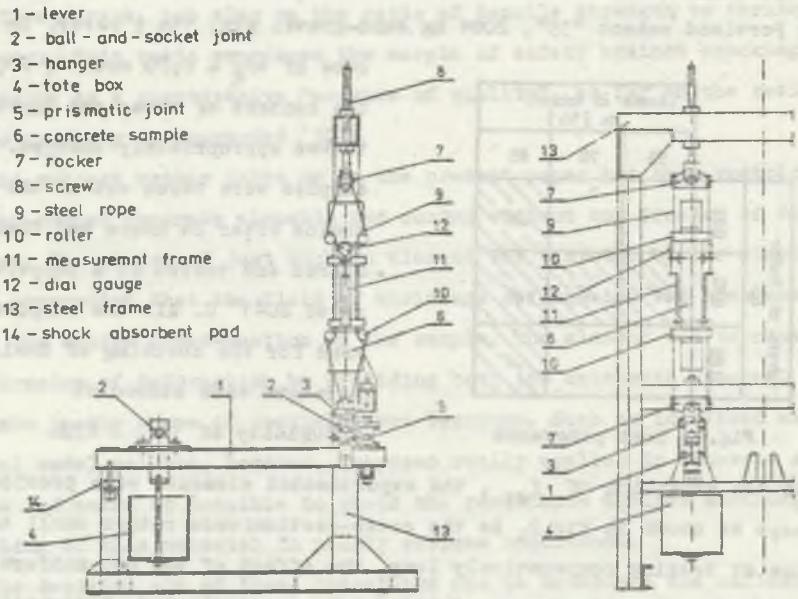

Fig.3. Schematic diagram of a multi-stand creep-testing machine

The shape of the samples used for measuring the free shrinkage of concrete and their distribution in the laboratory were the same as in the case of loaded elements, which warranted similar conditions of drying in both groups of concrete samples.

3. Analysis of the test results

Before the processing of test results was started, statistical analyses were to be carried out on the significance level 0,05. Applying variance analysis for f_{cu} , it was found that the experimental material constitutes a homogeneous set. It was also checked (by means of Dixon´s test) whether the extreme values of the obtained results were not subject to gross errors. According to the purpose of this research work most complete information about the investigated relations was to be aimed at. Mathematically this problem was reduced to the search for a function of statistically reliable responses. The applied analysis of variance and regression has made it possible to evaluate the degree of the scattering of data and their suitability, the contribution of the respective components, but also to omit inessential expressions. Detailed results of the correlation function may be found in [10] , and in the diagrams provided below some of the obtained functions are illustrated (together with the values of the correlation of R and the test F). As there are so many experimental data (1761 points), they have not been plotted into the diagram. Figs.4, 5 represent curves of the development of shrinkage stresses in elements curing without freedom of deformation. The influence

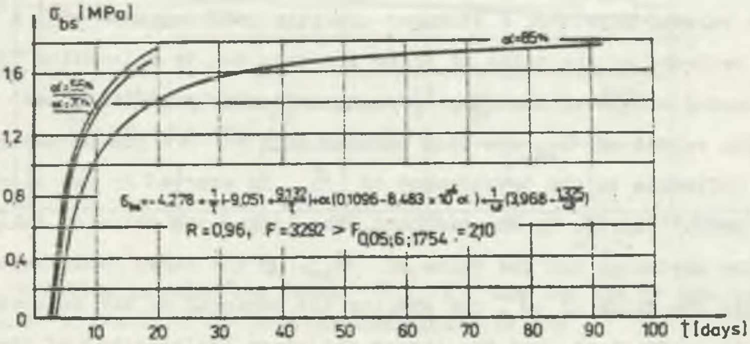

Fig.4. The development of shrinkage stresses in concrete (ω = 0,70) at various relative air humidities

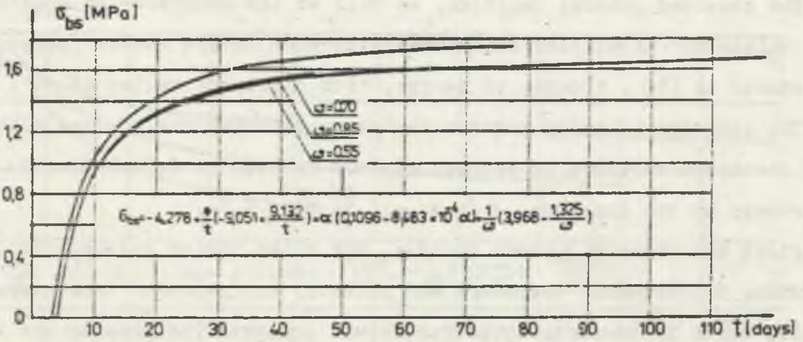

Fig.5. The development of shrinkage stresses in concretes with varying mix-water contents at a relative air humidity of α = 85%

of air humidity α on the development of shrinkage stresses is not the same as on the development of the shrinkage itself. There is no direct depenpendence saying that the smaller the value of α , the larger the σ_{bs} , because humidity affects not only the shrinkage, but also the tensile strength of concrete and its susceptibility to stress relaxation [4]. Lower humidity, e.g., is accompanied by a greater shrinkage, a slightly smaller actual tensile strength, and thus also a smaller value of the strain coefficient and a larger creep of the concrete [3]. Therefore, an increase of shrinkage results in an increase of shrinkage stresses, whereas the reduction of the strain coefficient leads to a drop of their values. Moreover, a stronger creeping goes together with a considerable decrease of the value of these stresses due to relaxation [3]. This reducing effect of humidity becomes particularly evident when $\alpha =$ $= 55\%$; the values of σ_{bs} are then smaller than at $\alpha = 70\%$. A similarly complex influence on the development of σ_{bs} is exerted by the water--cement ratio (Fig.5). On the one hand, the larger the value of ω, the greater the shrinkage and the value of σ_{bs}. On the other hand, however, the larger the value of ω , the smaller the strength of the concrete and the strain coefficient, and the larger the creep (relaxation) of the concrete [4], i.e. the smaller the value of shrinkage stresses. This reducing effect becomes visible particularly when $\omega = 0,85$. In this kind of concrete the stresses are smaller than the value of σ_{bs} at $\omega = 0,70$.

The observed general relation, as well as the occurence of unfavourable values of ω display some similarity with cement mortar (compo), discussed in [6] , though, of course, with different values of ω .

The relation existing between shrinkage deformations of free elements and shrinkage stresses in samples without freedom of deformation is expressed by the function $\phi(t, \alpha, \omega)$ in Figs.6,7 .

First the value of ϕ grows rapidly, but after having reached its maximum, it gradually decreases and probably approximates some constant value, which is characteristic for mature concrete.The greater the humidity α ,the greater is the extreme value of $\phi(t)$ (Fig.6) for concrete with the water-cement index $\omega = 0,70$. It seems that in the case of aged concrete the values of $\phi(t)$ for various humidities α do not differ very much from each other, and may even be quite the same.

In the case of concretes with varying amounts of mix-water the values of $\phi(t)$ are larger for smaller w/c , the extreme values being almost identical (Fig.7).

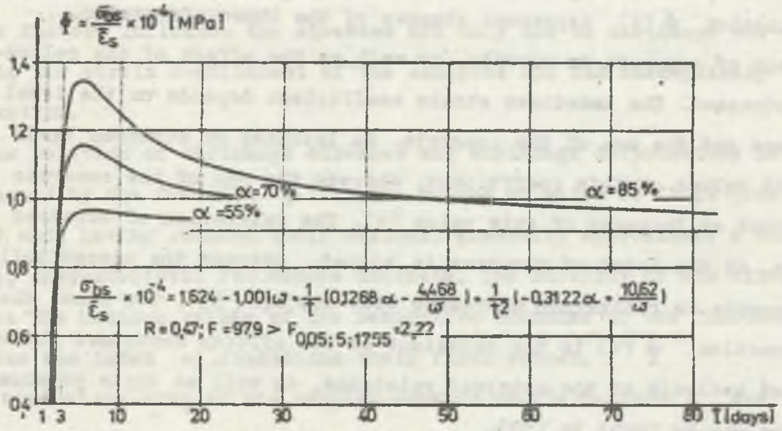

Fig.6. Relation between the ratio $\sigma_{bs}/\bar{\varepsilon}_s$ and the age of the concrete at $\omega = 0{,}70$ and various humiditees of air

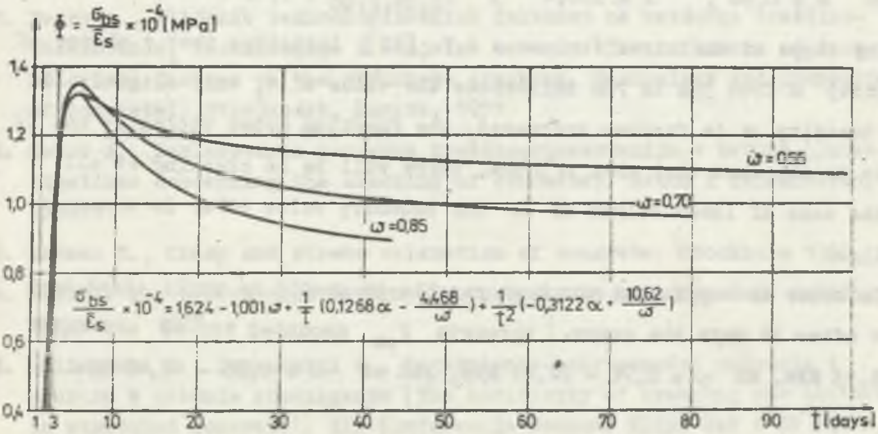

Fig.7. Values of the ratio $\sigma_{bs}/\bar{\varepsilon}_s$ for concretes with various water-cement ratios at $\alpha = 85\%$

The function $\phi(t)$, in [10] called the "rheological strain coefficient" of concrete in tension makes it possible to calculate the shrinkage stresses at any time t_1, basing on free shrinkage deformations ε_s and making use of the relation

$$\sigma_{bs1} = \phi_1 \cdot \varepsilon_{s1} .$$

The function $\phi(t)$ expresses changes of the immediate strain coefficient of concrete in tension, as well as the effect of the relaxation of stresses. The immediate strain coefficient depends on the level of stresses and the age of the concrete. An increase of stresses leads to reduced values of this coefficient, whereas the age of the concrete brings about an increase of this value [4]. The relaxation of stresses is larger, at the level of stresses is higher whereas the susceptibility of concrete to relaxation decreases with its age [3] . The final shape of the function $\phi(t)$ is the resultant of the effects mentioned above. A detailed analysis of the obtained relations, as well as their physical motivation may be found in [10].

The interdependence existing between the time of crackingof elements curing without freedom of determination and the factors α and ω is expressed by the function:

$$t_z \text{ (days)} = 227{,}5 - \frac{600.5}{\alpha - 90} - 329{,}6\,\omega \quad ,$$

where $R = 0{,}96$, $F = 356{,}4 > F_{0,05;2;60} = 3{,}15$.

The shape of the curve for $\omega = 0{,}7$ [10] indicates that a change of humidity α from 55% to 70% influences the value of t_z only slightly. If the humidity α is further increased, the function grows violently and it is to be supposed that when $\alpha \gg 90\%$, there will be no cracking at all. In the case of lower values of ω the boundary value of α is somewhat smaller.

In order to supplement the test results it should be still added here that after 28 days the compr. strength f_{cu} amounted to: at $\omega = 0{,}55$ - 26,13 MPa, at $\omega = 0{,}70$ - 22,81 MPa, and at $\omega = 0{,}85$ - 18,47 MPa.

4. Conclusions

The interdependence of shrinkage stresses and the factors α and ω, determined in this paper, is of a rather complex character. There is no simple relation which would say that the lower the humidity α or the higher the indeks ω, the greater are the shrinkage stresses, because these factors influence the stresses not only due to shrinkage but also due to the strain coefficient of the concrete and its susceptibity to relaxation.

The relation of shrinkage stresses and shrinkage deformations is expressed by the function $\phi(t)$, the values of which at first grow rapidly and, having reached their maximum, gradually approximate a constant value, characteristic for mature concrete. The humidity of air differentiates the maximum values of the respective branches of the function, whereas the index ω conditions their final values.

The time of cracking of the samples depends on the factors α and ω. A distinct influence of humidity is to be observed at $\alpha > 70\%$. As soon as this value has been reached, the values of t_z begin to increase violently. It is to be supposed that at $\alpha \geq 90\%$ and $\omega \leq 0{,}70$, the samples will not be subjected to cracking at all.

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WPŁYW WILGOTNOŚCI ŚRODOWISKA ORAZ ZAWARTOŚCI WODY ZAROBOWEJ W BETONIE NA ROZWÓJ NAPRĘŻEŃ SKURCZOWYCH

Streszczenie

Przeprowadzono badania na elementach betonowych dojrzewających bez swobody odkształceń. Poznano wpływ wilgotności względnej powietrza i zawartości wody zarobowej w mieszance na rozwój naprężeń skurczowych i czas pojawienia się rysy. Określono statystyczne związki między odkształceniami i naprężeniami skurczowymi, przy różnych poziomach uwzględnionych w badaniach czynników. Wskazano taki obszar utworzony z tych czynników, kiedy zarysowanie betonu nie występuje.

ВЛИЯНИЕ ВЛАЖНОСТИ ОКРУЖАЮЩЕЙ СРЕДЫ И СОДЕРЖАНИЯ ВОДЫ ЗАТВОРЕНИЯ В БЕТОНЕ НА РАЗВИТИЕ УСАДОЧНЫХ НАПРЯЖЕНИЙ

Резюме

Проведены испытания бетонных образцов, твердеющих без свободной деформации. Исследовалось влияние относительной влажности воздуха и содержания воды затворения в смеси на развитие усадочных напряжений и появление трещины. Определены статистические зависимости между деформациями и напряжениями (усадочными) при различных значениях факторов, принятых во внимание в исследованиях. Представлена такая область, в которой при существующих факторах не появляется на бетоне трещина.