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Experimental and Theoretical Studies of the Peculiarities of Concrete Behavior in Time and the Concrete Limit Characteristics from the Standpoint of Creep Adsorption Theory

Merab Lordkipanidze [α], Olgha Giorgishvili [σ], Iuri Salukvadze [ρ], Nika Botchorishvili [Ѡ] & Aleksandre Tatanashvili [¥]

Abstract- Based on the experimental and theoretical studies from the standpoint of the adsorption theory of creep, the authors show the peculiarities of the concrete behavior in time and propose a universal graph of the limit characteristics of concrete, including: the limits of strength, elastic deformation, linear creep, endurance.

It is established that the limit strength value R changes in time and depends on the velocity of load application, while the elastic deformation limit is a constant value and does not depend on the age of concrete and the load application velocity.

The maximal limit deformation of concrete of any composition is a constant value under repeated loads as well as under the constant load.

The breaking of concrete in time occurs due to the combined action of external forces, which is expressed in terms of the trapezoid area, and due to an additional effect of the wedging action of water which is equal to the triangle area.

According to the theory on the nature of concrete creep, the cause of the creep in the region of elastic deformation is the influence of water adsorption, which shows itself in its wedging action on the reversible micro cracks of concrete, i.e. the creep in the elastic deformation region is completely reversible, and the wedging action of water can be regarded as an additional stress to the stress due to load.

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I. Introduction

According to the theory on the nature of concrete creep, the cause of the creep in the region of elastic deformation is the influence of water adsorption, which shows itself in its wedging action on the reversible micro cracks of concrete, i.e. the creep in the elastic deformation region is completely reversible, and the wedging action of water can be regarded as an additional stress to the stress due to load [1], [2].

The action of adsorbed layers of water reduces to their two-dimensional migration over the surfaces of micro cracks which are under the action of two-dimensional pressure in the mouths of further water motion, thereby leading (in constant external conditions) to the increase of deformation. The effect of this pressure is equivalent to the increase of external force F by the value $\Delta F \approx \sigma\_0-\sigma\_V$ which replaces the action of adsorbed layers which are its mechanical equivalent [3]. Quite a lot of works are devoted to the investigation of problems concerning the mechanical characteristics of concrete, see e.g. [1], [2], [3].

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II. Materials and Methods

The results of the studies carried out in this connection and confirmed by experimental data are presented in Fig. 1 in the form of a theoretical graph.

A concrete prism is subjected to axial compression or tension and its deformations expressed in terms of the coordinates σ, ε with the origin at the point 0^1 are measured. After recording the moment of concrete deformation origination at the point 0, a minimal breaking load is instantly applied to the prism. We fix D and N. Readings are taken starting not from 0^1 but from 0 which is the real origin of the coordinates since concrete begins to work from this point. Connecting 0 with N we get the triangle 0DN which expresses the strength characteristic showing the capacity of concrete of every composition and age for work. 0D corresponds to the actual concrete ultimate strength R which is the maximal stress under the minimal, instantly breaking load instantly applied to the area of the working cross-section of the concrete element. Therefore R is the well-defined strength characteristic that fixes the increase of strength depending on a degree of the restraint of tensile deformation of concrete since no irreversible micro cracks might have developed in concrete by the moment of its instant breaking. The limit deformation $\varepsilon_{\text{пр}}$corresponding to R has the following inherent peculiarity: $\varepsilon_{\text{пр}}$ is constant, not depending on the age of concrete. ON expresses the rectilinear line between the coordinates σ and ε the tangent of whose angle of slope to the abscissa axis is the concrete elasticity modulus.

These facts indicate the following: 1) the concrete works by Hooke's law until it reaches R and its elasticity modulus is a constant value not depending on a degree of concrete tension; 2) irreversible micro cracks appear and develop in concrete only after it reaches R; 3) in the presence of surface-active substances there is no weakening of the cohesion between particles takes place in the elastic deformation region; 4) the limit of concrete elastic deformation is R; 5) the breaking of concrete occurs in two ways: if the creep deformation is non-damping, then concrete breaks on reaching R and, simultaneously, it breaks for the corresponding $\varepsilon_{пр}$in the conditions of increased loading. Below we give the physical interpretation of these two cases of concrete failure.

Let us draw the vertical line through N normally to the abscissa axis. For the tested concrete with the every index, independently of the concrete age the vertical line, which with time grows up to N, limits all ultimate deformations irrespective of a loading mode (loading conditions).

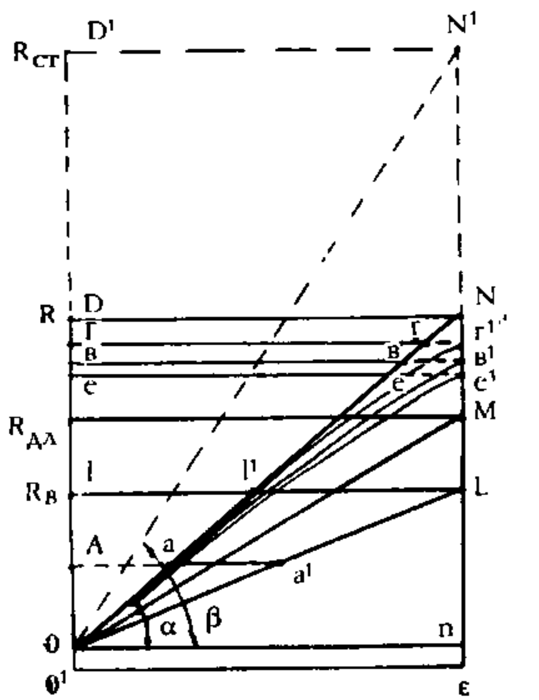

Fig. 1: Universal theoretical graph of the concrete limit characteristics

As different from the central tension of concrete, for axial compression we observe the restraint of tensile deformation caused by the friction of the concrete end faces against the cheeks of the press. Thus, if the friction is removed, the refraction points of the curves 0e^1, 0b^1 and 0r^1 on σ, ε (Fig.1) of both concrete specimens will lie on the vertical line Nn and will simultaneously fix the end points (e^1,b^1,r^1) of maximal limit deformations and the moment of concrete breaking. They will lie higher with an increase of the velocity of concrete loading. If the loads corresponding to the refraction points e^1, b^1 and r^1 are instantly applied to the concrete prisms, then on the straight line 0N we instantly obtain the points e, b and r which fix elastic limit deformations due to load application. However the breaking does not occur until the initial creep at these points reaches the corresponding points e^1,b^1,r^1 , i.e. until the total limit deformation reaches the vertical line Nn and becomes equal to the deformation DN and as elastic as the latter.

Thus the breaking of concrete occurs only after concrete reaches R and $\varepsilon_{пр.}$ However this happens only in the case of non-damping creep of concrete, i.e. after the ultimate strength is reached, it is immediately followed by additional stress. All this indicates that in the elastic deformation region, the concrete works by Hooke's law. The curvilinear lines are obtained because not deformations due to loading are plotted on the abscissa axis but total deformations produced in particular by additional stress which is not plotted on the ordinate axis.

From the above-said it follows that creep deformation increases with time and at the level of the point M becomes maximally limiting. If above the point M the creep deformation was non-damping, at the point M it subsides and below the point decreases in direct proportion to the load by the straight line OM. At the level of the point M, simultaneously with achieving maximal limit creep deformation and therefore simultaneously with deformation damping, the strength of concrete stops growing in time and, with achieving R and $\varepsilon_{пр}$, because of the damped creep there will be no additional stress and concrete will not break. Therefore in our experiments the breaking of concrete occurs not with achieving R and $\varepsilon_{пр}$but after if the load increases.

The strength characteristic of concrete longevity at the considered point M of its stress-strained state is the limit of durable resistance of concrete, which is the limit stress under load and for which no breaking occurs and at the same time such factors are achieved as creep deformation damping, maximal limit value of creep deformation, termination of concrete strength growth in time, and the concrete actual limit strength R. However the difference $R_{ст}$-$R_{дл}$ is spent on the creep of concrete. Therefore the most important task of increasing the useful strength needed for maintaining the carrying capacity of concrete is to decrease the creep deformation of concrete.

The limit characteristic of concrete longevity is the fatigue (endurance) limit $R_{в}$ which is the maximal stress of concrete subjected to the action of repeated loads under which the creep gets damped. R and its corresponding $\varepsilon_{пр}$ are achieved, while the breaking does not occur. If by applying repeated loads to concrete of any age we quickly achieve the maximal ultimate deformation, but will continue to apply repeated loads, then, with time, the concrete age and strength/increase. In order to keep the maximal deformation constant since it tends to decrease it is necessary to increase the repeated load until the moment at which the concrete strength stops to grow. In that case we achieve $R_{ст}$ and $R_в=R_{дл}$. Therefore, under both repeated and constant loads, the maximal limit deformation of concrete is a constant value and does not depend on the concrete age.

To conclude, it should be emphasized that the peculiarities of the work of concrete in time and its limit characteristics obtained theoretically (Figure 1) are completely confirmed by experimental data (Figure 2).

III. Experimental Confirmation of the Diagram of the Concrete State under Free Axial Compression and Tension

Proceeding from the principles of the adsorption theory of the nature of linear creep of rigid bodies, we performed experimental studies of the limit strength and deformation characteristics of concrete under free axial compression and central tension.

The concrete specimens were prisms of 10×10×40 cm and cubes of 10×10×10 cm. The consumption of materials per 1 kg//m^3 was: cement M4000 – 320, gravel – 1180, sand – 650, water – 180 (2330 kg//m^3), vibration duration was 20 s, humidity 90%, temperature 20^{0}C.

The molds were removed from the specimens two days after manufacturing and then stored in the test room with normal thermal conditions.

We described in detail only the experiments with the specimens of three-month age since the specimens of 9 and 16 months of age were tested analogously (Figure 2).

The 10×10×40 cm concrete prisms were tested for axial compression on the press H-50. Friction between the end faces of the prism and the plate of the press was removed by applying paraffin to the prism end faces.

Longitudinal deformations were measured by resistance sensors with 50 mm base which were glued to the middle part of two opposite faces of the prisms. Readings of the sensors were recorded by two instruments with a scale division 10^{-5}.

The concrete was found to develop no deformation until the application of a certain amount of load (300 H in the considered case). This value was taken as the real origin (0) of the coordinates ρ, ε (Figure 2,a). Further, an instant maximal breaking load was applied with a velocity of 15.0 MPa/s. At the time of specimen breaking, we simultaneously fixed the breaking load by manometer readings, and the limit deformation by two measuring instruments.

OD, the value of the real strength limit R=25.0 MPa was plotted on the ordinate axis, while DN, the value of limit deformation (shortening) of concrete $\varepsilon=104\times10^{-5}$ was plotted on the horizontal line. The vertical line Nn was drawn from the point D to the intersection with the abscissa axis. The point N was connected with the real origin 0. In this manner, using experimental data obtained by testing only one concrete specimen, we estimated the real strength limit, the corresponding limit elastic deformation $\varepsilon_{пр}$ and the straight line ON showing the relationship between concrete stresses and deformations and the tangent of whose angle of slope to the abscissa axis is the elasticity modulus of concrete. It is also important to note the obtained area of the triangle ODN represented the behavior of concrete at the time of its breaking.

Next we determined in a usual manner the limit strength and the limit deformation, i.e. at the load application velocity of 0.2 MPa/s. We constructed the stress-strain curve. As a result the strength limit was found to be equal to R'=21.6 MPa and the limit compression to $\varepsilon=108\text{x}10^{-5}$. It is specific to note that the point of refraction of the curve Γ' at the moment of breaking happened to lie on the vertical line Nn. Next we tested the experimental twin specimen to which we applied the breaking load R'=21.6 MPa. In this case the limit elastic deformation was $\varepsilon=90\times10^{-5}$, whose end point turned out to lie on the straight line of the elasticity modulus of concrete $\varepsilon=90\text{x}10^{-5}$. Further, the process of deformation continued in time and its end point Γ' reached the vertical line Nn at the moment of breaking

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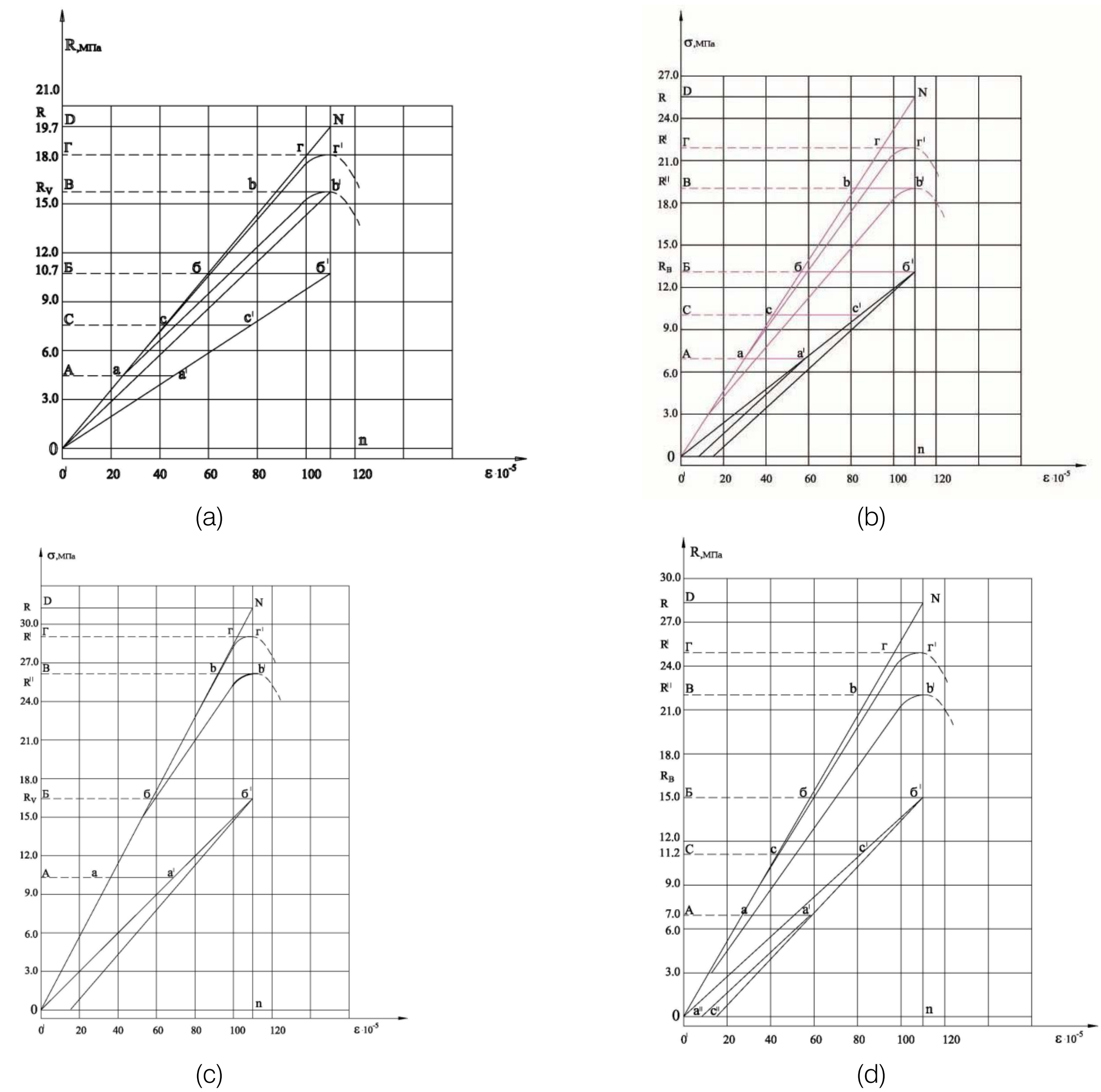

Fig. 2: Experimental justification of the universal graph of compression of concrete at the age of 1 month (a), 3 months (b), 9 months (c) and 16 months (d)

For a more complete understanding of the nature of limit characteristics of concrete, an experiment was run with the application of compressive breaking load at a much slower velocity, namely v=0.005 MPa/s and the stress-strain curve was constructed. The limit strength was R''=19.6 Mpa, while the end point of limit deformation (ε=110x10^{-5}) coincided with the refraction point of the diagram and turned out also to lie on the vertical line Nn, which testifies to the fact that its value is equal to the instant maximal elastic deformation. When the instantly breaking load was applied to R''=19.6 the end point of elastic deformation reached the the elasticity modulus line, while the total deformation (elastic deformation in time) reached the vertical line Nn and coincided with the refraction point of this curve.

The curves OBbb', OCcc', Oaaa shown in Fig. 2 denote the limit of the fatigue (endurance) behavior of concrete under repeated static loads.

The theoretical principles of the universal graph of the limit characteristics of concrete and the peculiarities of its work were fully confirmed in the case of central tension as well (Figure 3).

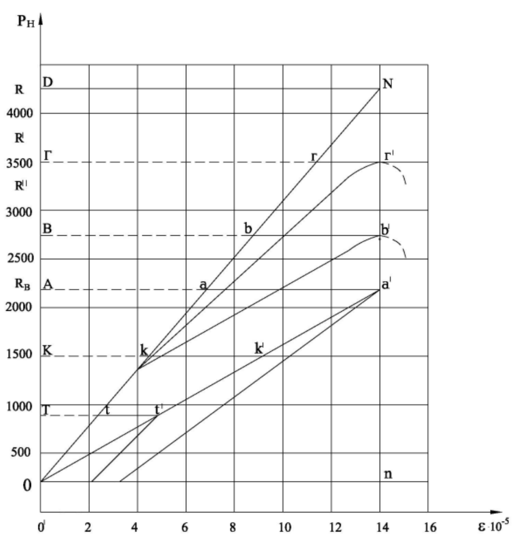

Fig. 3: Experimental justification of the universal graph for the central tension of concrete

IV. Conclusion

The analysis of the above graphs allows us to make the following conclusions:

1) The limits of structural changes of concrete are the real strength limit which is the maximal stress obtained by dividing the instantly applied load by the area of the working cross-section of a concrete element and the corresponding limit elastic deformation.
2) The concrete strength (R) changes with time and depends on the velocity of load application, while the limit deformation $\varepsilon_{\text{пред}}$, being wholly elastic, has its inherent peculiarity: for the concrete of any composition and any degree of its restraint the value $\varepsilon_{\text{пред}}$ is constant and does not depend on the age of concrete and the velocity of load application.
3) The law of concrete of concrete strength change in time is of the same character as the law of an instant change of the concrete modulus of elasticity since $\varepsilon_{\text{пр}}$ =const and R=εF, which is confirmed by the experiment.
4) Any failure occurs when concrete achieves the real strength limit and the real elastic deformation $\varepsilon_{\text{пр}}$. In this connection concrete performs the work equal to the area of the triangle 0Nn in Figure 2. With the decrease of the load application velocity the concrete strength R' decreases too. Experiments with dry, air-dried and water-saturated concrete showed that the additional stress is produced by the wedging action of water or, which is the same, by sorption load. In [4] it is stated that for calcium hydro silicates and Portland cement materials the sorption load of any value, including the maximal one, acts like mechanical load. Therefore the failure of concrete in time occurs under the total work of the external force which is expressed as the area of the trapezoid OB b'n, and also under the additional work of the wedging action of water equal to the area of the triangle BB'N, the combination of these both factors being equal to the area of the rectangle 0Nn.

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