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DETERMINATION OF INITIATING AND CRITICAL STRESS LEVELS IN COMPRESSED PLAIN AND HIGH-STRENGTH CONCRETE BY ACOUSTIC METHODS

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New criteria suitable for determining the levels of initiating stress σ_{i} and critical stress σ_{cr} in plain and high-strength concrete under compression by acoustic materials testing methods have been established. Also the criteria known from the literature on the subject have been verified. On the basis of the author's own research results obtained by the ultrasonic method and the acoustic emission (AE) method the limits of the applicability of the two above methods have been determined. The new criteria, classified according to their suitability for plain concrete or high-strength concrete, have been defined using such descriptors as: the velocity of longitudinal ultrasonic waves, AE counts, the rate of AE counts, the energy of short AE impulses and the RMS value of AE.

1. Introduction

Initiating stress σ_{i} and critical stress σ_{cr} should be treated as certain stress levels in concrete subjected to loading which delimit qualitatively different stages in the damage to its structure. Three such stages can be distinguished in the course of the failure of concrete under compression. According to [1] they are: the stable initiation of microcracks, the stable development and propagation of the microcracks and the unstable propagation of the microcracks. The validation of the above can be found in many papers, especially monographs [2–9]. It should be noted here that the multistage character of the failure of concrete subjected to compression has not been confirmed by researchers who favour the Palmgren–Miner theory of damage accumulation as expounded, for example, in [10].

Initiating stress σ_{i} and critical stress σ_{cr} levels are not the same in all the concretes subjected to compression. Several technological and service conditions have a bearing on the above stress levels [7–9, 11–18]. The considered stress levels are regarded to be two fatigue characteristics which give us a clue as to the susceptibility of compressed concrete to signalled or not signalled cracking. Furthermore, research has indicated that the level of stress σ_{i} in compressed concrete can be regarded as equal to the safe fatigue life [19] and that of stress σ_{cr} — as equal to the long-lasting fatigue strength [20, 21].

In order to determine levels σ_{i} and σ_{cr} it is necessary to trace the failure of concrete in the whole range of loading. For this purpose indirect methods have been used with much success. These include: the strain measurement method, the ultrasonic method and the acoustic emission (AE) method. As regards the strain measurement method, the criteria for determining the considered stress levels in compressed plain concrete have been defined and they can be found in the literature on the subject [7, 11, 12, 22, 23]. But they have been shown to be unsuitable for determining levels of critical stress σ_{cr} in compressed high-strength concrete [18, 24]. Practically no descriptions of such criteria for determining levels of stress σ_{i} and stress σ_{cr} on the basis of results obtained by acoustic methods can be found. This is probably due to the continuous improvements made in measuring equipment which open up new research possibilities. Another factor here is the introduction of all kinds of additives and admixtures into concrete which affect the strength characteristics (broadly understood) of this material.

Since the ultrasonic method and the AE method have been used more and more frequently to investigate the failure of compressed concrete, both plain and high-strength one, the author of the present paper deemed it proper to assess the usefulness of these methods and the suitability of their criteria for the determination of levels of stress σ_{i} and stress σ_{cr}. The assessment is based on the author's own experimental results.

2. Ultrasonic method

The descriptors used in the ultrasonic method to describe the failure of compressed concrete and to determine the levels of stress σ_{i} and stress σ_{cr} are the time of passage or the velocity of propagation of a longitudinal ultrasonic wave perpendicularly to the direction in which the load acts. Experimental research has shown that the values of these descriptors are causally linked to the course of failure.

In papers [12, 25], among others, it is suggested that the level of stress σ_{i} in concrete should be the level at which a longitudinal ultrasonic wave propagated perpendicularly to the direction of compressive load passes through the concrete in the shortest time. The level of stress σ_{cr} is assumed to be the stress level at which this wave's time of passage reaches again initial value t_0. This is illustrated in Fig. 1.

The above criteria have been found to be inapplicable to plain concrete with average or increased compression strength or to high-strength concrete [14–16, 18]. It cannot be ruled out that they are applicable to plain concrete with very low compression strength.

It has also been found that it is not possible to establish a definite criterion for determining levels of stress σ_{i} in concretes belonging, by reason of their compression strength and deformability, to plain concretes. Such a criterion can, however, be established for stress σ_{cr}: it is the vanishment of the possibility of measuring the velocity of a longitudinal wave propagated perpendicularly to the direction in which the load acts, as illustrated by curve 1 in Fig. 2. The criteria established for high-strength concretes are represented by curve 2 in Fig. 2 [18].

The stress level above which a marked decrease in the longitudinal ultrasonic wave's velocity occurs (it becomes apparent that there is no linear relationship between the velocity and the compressive stress) in concretes of this kind is the level of stress σ_{i}. The stress level at which the possibility of measuring the wave's velocity vanishes is that of stress σ_{cr}.

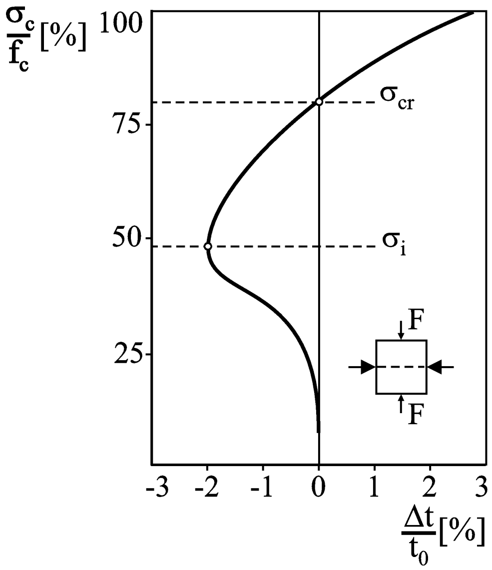

Fig. 1. Criteria for determining levels of stresses σ_i and σ_{cr} in compressed concrete by ultrasonic method [12, 25].

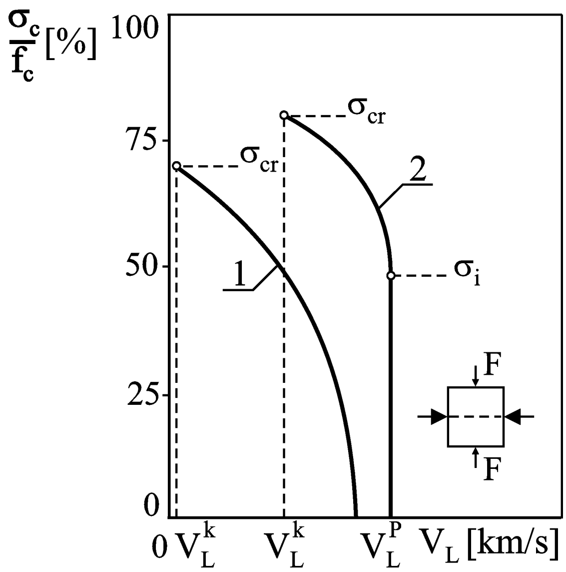

Fig. 2. Criteria established by the author for determining levels of stresses σ_i and σ_{cr} in compressed plain concrete (1) [14, 16] and high-strength concrete (2) [18].

3. Acoustic emission method

The descriptor which has been used with success to determine the levels of initiating stress σ_i and critical stress σ_{cr} in compressed plain concrete is AE counts [14–17, 26–28].

As it follows from source work [26], AE counts in concrete subjected to compression should be measured as a function of, for example, stress increment. Then the rate of AE counts, also as a function of stress increment, is determined. This can be written as [27]:

$$\mathrm{IN} = \sum N_{n+1} - \sum N_n \,, \tag{1}$$

where IN — a rate of AE counts, $\sum N_{n+1}$ — AE counts recorded for stress levels $n+1$, $\sum N_n$ — AE counts recorded for stress levels n.

Stress intervals in which the rate of AE counts is determined can be as large as, for example, $0.05\sigma_c/f_c$. A sample course of the rate of AE counts determined in this way is shown in Fig. 3. Three stages can be distinguished in it: a stage of steady increment of AE counts, a stage of stable increment of AE counts and a stage of rapid increment of AE counts.

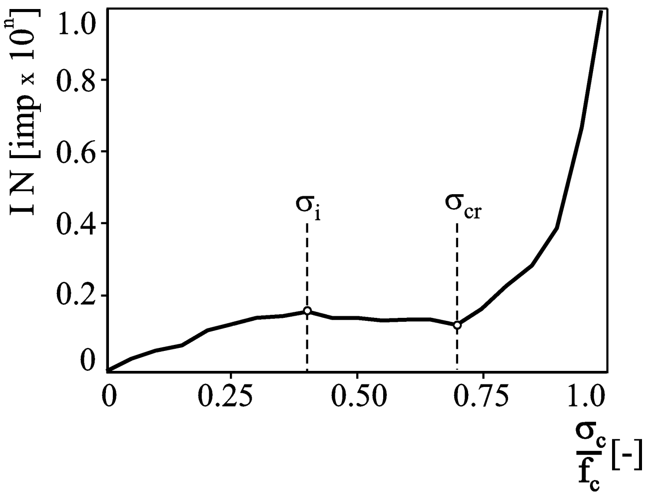

Fig. 3. Determination of levels of stresses σ_i and σ_cr in compressed plain concrete on basis of measured AE counts [14–17, 26, 27].

Knowing the rates of AE counts as a function of compressive stress, levels of stresses σ_i and σ_cr can be read directly from the plotted graph. To increase the accuracy of reading the above stress levels, the stress intervals in which the rate of AE counts is determined can be narrowed locally to, for example, $0.025\sigma_c/f_c$. As Fig. 3 shows, the stress level at which the stage of steady increment of AE counts and that of stable increment of AE counts are clearly delimited corresponds to the level of stress σ_i. At the level of stress σ_cr the stage of stable increment of AE counts and that of rapid increment of AE counts can be clearly distinguished. This way of determining the considered stress levels can be called graphic.

Knowing the rate of AE counts as a function of compressive stress increment, the levels of stresses σ_i and σ_cr in concrete can be determined also by statistical methods. Then it should be assumed that a specified rate of AE counts is a function of acoustic impulses in a certain time interval corresponding to a certain increment in compressive stress. The points of inflexion of this function occur at the places at which the stages of steady, stable, and stable and rapid increment in the number of the impulses become delimited. By determining these points we determine the levels of stresses σ_{i} and σ_{cr}. This represents a criterion for determining the above stresses. Then it is enough to assume the following model:

$$Y = f(x) + \varepsilon, \tag{2}$$

where $Y = (Y_1, ..., Y_n)^t$ — (a dependent variable) observed changes in the rate of AE counts (IN); $x = (x_1, ..., x_n)^t$ — (an independent variable) relative stress in compressed concrete (σ_c/f_c); $\varepsilon = (\varepsilon_1, ..., \varepsilon_n)$ — such a random vector having dimension n (measuring errors) that ε_1 has distribution $N(O, \sigma^2)\sigma <\propto$ for $i = 1, ..., n$; n — a number of observations.

Since the aim of the statistical analysis is to determine the points of inflexion of the function, it is not possible to apply the least squares method to the whole observation area. Thus this domain of function $f(x)$ should be divided into three intervals in which, we surmise, the function has three different forms. The author has determined experimentally that the regression curves can be estimated by the least squares method, assuming model form $Y = ax + b$ for intervals I and II and model form $Y = \exp(ax + b)$ or $Y = ax + b$ for interval III. Eventually, a model better fitted to the data (for which coefficient R^2 will have a higher value) should be assumed for interval III. Ultimately, the value of stress σ_{i} is obtained as the intersection of the estimated curves in intervals I and II and the value of stress σ_{cr} — as the intersection of the estimated curves in intervals II and III, as illustrated in Fig. 4.

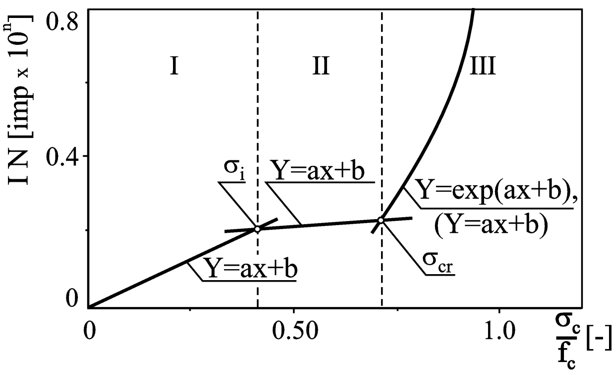

Fig. 4. Determination of points of inflexion of AE counts rate function by statistical methods for compressed plain concrete.

It follows from [18] that the rate of AE counts is less useful for the determination of the considered stresses in high-strength concrete since the number of AE counts recorded during the initial stage and the intermediate stage of loading in this case is small. And small increments in AE counts per unit of length make it difficult to determine the level of initiating stress σ_{i}. But, as Fig. 5 shows, it is possible to determine the level of critical stress σ_{cr} corresponding to the level of compressive stress at which AE counts begin to increase rapidly.

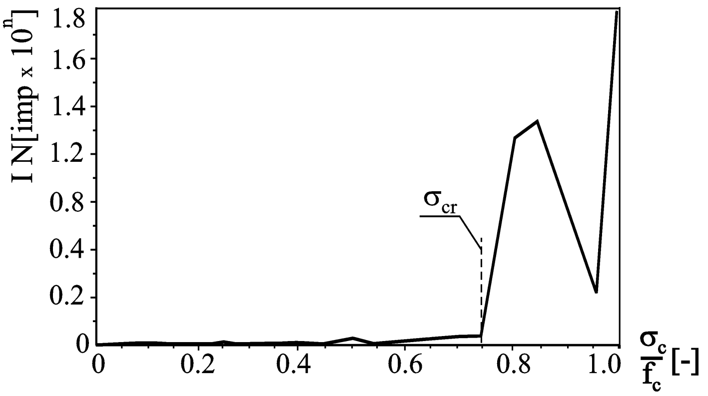

Fig. 5. Determination of critical stress σ_{cr} in compressed high-strength concrete based on measurements of AE counts [18].

The AE method allows one to determine levels of stresses σ_{i} and σ_{cr} in compressed concrete on the basis of other than AE counts descriptors. One can use the rate of AE counts, the energy of short AE impulses or the RMS value of the AE signal for this purpose [18]. Below it is described how to do it for high-strength concrete.

As regards the rate of AE counts and the energy of short AE counts, they should be measured as a function of failure time. Also a graph of absolute or relative compressive stress versus failure time should drawn. The AE signal's RMS value should be measured as a function of, for example, relative compressive stress. Figures 6, 7 and 8 show typical traces, with distinguishable three stages, of the above AE descriptors in high-strength concrete subjected to compression. Figures 6 and 7 include an exemplary graph of compressive stress, denoted by σ_c/f_c, versus failure time.

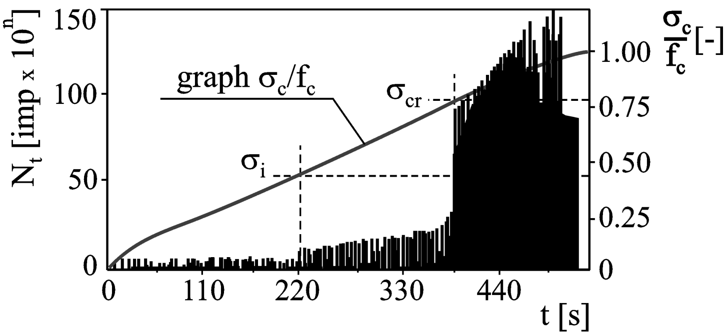

Fig. 6. Determination of levels of stress σ_{i} and σ_{cr} in compressed high-strength concrete based on measurements of AE counts rate [18].

As one can see in Figs. 6, 7 and 8, the values of all the above AE descriptors are low initially. Then a the rate of AE counts and the energy of short AE impulses increase moderately and the AE signal's RMS value increases quite sharply. In the final stage the increases are rapid and in the case of the AE signal's RMS value, the increase is very

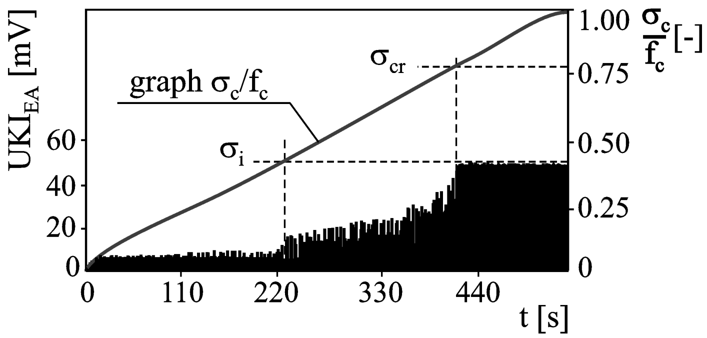

Fig. 7. Determination of levels of stress σ_{i} and σ_{cr} in compressed high-strength concrete based on measurements of energy of short AE impulses [18].

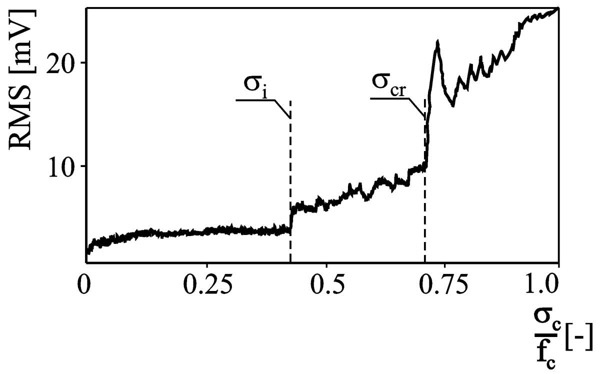

Fig. 8. Determination of levels of stress σ_{i} and σ_{cr} in compressed high-strength concrete based on measurements of AE signal's RMS value [18].

sharp. To establish the levels of stresses σ_{i} and σ_{cr}, the failure time after which the rate of AE counts and the energy of short AE impulses start to increase, first moderately and then rapidly, should be determined. By plotting the determined times on the graph of σ_c/f_c versus failure time one can establish the considered stress levels. In the case of the AE signal's RMS value one should locate the points at which moderately sharp and very sharp increase in the value of this descriptor occurs. These points, plotted on the axis of relative compressive stress σ_c/f_c, indicate the sought levels of stress σ_{i} and σ_{cr}.

4. Conclusions

1. The criteria for determining the levels of initiating stress σ_{i} and critical stress σ_{cr}, which divide the qualitatively different stages in the course of failure of concrete subjected to compression, found in the literature are based mainly on the experimental results obtained by the strain measurement method. Very few such criteria are available for acoustic methods which have been applied more and more frequently — especially the acoustic emission method — to investigate the failure of concrete. Furthermore, not

all of the literature criteria based on experimental results obtained by acoustic methods are useful for either plain or high-strength concrete. This problem has been addressed by the author of the present paper on the basis of his own experimental results.

2. In the case of the ultrasonic method it is impossible to establish a definite criterion which would enable the determination of stress σ_{i} levels in plain concrete under compression. It is possible, however, to establish such a criterion for stress σ_{cr} in this kind of concrete. Whereas in the case of compressed high-strength concrete the ultrasonic method is suitable for the determination of both stress σ_{i} and stress σ_{cr}.

3. As regards the AE method it is possible to establish definite criteria enabling the determination of the levels of stresses σ_{i} and σ_{cr} in plain concrete subjected to compression. It is enough to use AE counts for this purpose. Whereas the usefulness of this AE descriptor for the determination of the levels of stress σ_{i} in high-strength concrete is problematic due to the fact that the number of AE counts recorded in the initial stage and in the intermediate stage of loading this kind of concrete is small. Apart from AE counts, other AE descriptors, such as the rate of AE counts, the energy of short AE impulses and the AE signal's RMS value, can be used successfully to determine the levels of both initiating stress σ_{i} and critical stress σ_{cr}.

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