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ROLE OF THERMAL TREATMENT IN STRESS FAILURE OF CONCRETE DIFFERING IN ITS AGGREGATE GRAIN COMPOSITION

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Results of tests aimed at determining the influence of heat treatment on the stress failure of concrete differing significantly in its aggregate grading are presented. Seven batches of concrete, having similar compressive strengths but differing radically in their grain composition, were tested. The specimens were subjected to heat treatment in low-pressure steam in an identical temperature-time cycle. It has been shown that the course of destruction of the specimens made from different mixes is determined by heat treatment, no matter what is the fine aggregate content in the concrete. This is demonstrated above all by the values of initiating stress σ_i and critical stress σ_{cr} determined in the tested mixes and compared with the values of these stresses in the analogous but normally cured concrete mixes.

1. INTRODUCTION

The heat treatment of concrete in low-pressure steam is one of the technological factors that affect the process of destruction of this material under the action of external load. This view is shared by many researchers. So far research in this problem has focused on the variation of the temperature and time parameters of the treatment and the evaluation of their influence on the process of destruction of concrete. In tests that were conducted, the composition of concrete was kept constant [1, 2]. However, there are very few studies that try to determine what influence the heat treatment has on the stress failure of concrete differing significantly in its aggregate grading. This problem was alluded to in [3]. As it is known from practice, prefabricated concrete units are made of concrete mixes with small, increased and large fine aggregate fractions.

In the opinion of the author of this paper, this problem needs to be investigated more fully through experimentation, particularly as concerns the values of the initiating stress σ_i and critical stress σ_{cr} in such concrete. One should notice here that the above stresses represent certain apparent levels of stress in the loaded concrete and once they are reached, characteristic phenomena occur in the structure of the material, resulting in the initiation and propagation of microcracks. These stress levels are closely associated with the destruction of the structure of concrete since they delimit the particular stages of this destruction, i.e. the stage of stable initiation, the stage of stable propagation and the stage of unstable propagation [4, 5, 6, 12].

It is commonly believed that the permanent development of microcracks in the structure of the loaded concrete starts at initiating stress level σ_i. This initiating stress constitutes the upper limit of elastic work of concrete under short-time loads and the limit of linear creep under long-time loads [1, 5, 7, 8]. This stress is also identified with the safe fatigue life of concrete [1, 5, 6]. It is also believed that critical stress σ_{cr} initiates the unstable propagation of microcracks in the structure of concrete. This stress is identified with the limit of nonlinear creep under a long-time load and the long-term strength of concrete [1, 4, 7].

A deeper knowledge of the considered problem would have a value not only for the theory. For some time now, systematic attempts have been made to use the concepts of initiating stress σ_i and critical stress σ_{cr} for the estimation of the fatigue strength level of concrete [1, 8]. It is also proposed to assume values of allowable stress in concrete depending on the initiating stress and the critical stress, which may be of great significance, especially for the calculation of bridge structures [8, 9, 10]. Generally, the trend is towards the utilization of the knowledge of σ_i and σ_{cr} stress values in concrete at the design stage in order to prevent too great stresses, which might cause fatigue cracking or the deterioration of the service properties of newly designed concrete structures, particularly bridges. It is believed that the damage of many existing bridge structures was caused mainly by fatigue cracking [8].

To study the problem, tests were carried out on several batches of concrete of similar ultimate compressive strength, but differing in its aggregate grading, and cured in the same heat treatment conditions. The rounded aggregate's grading in the particular mixes was varied by changing the sand fraction from 25 to 100 % in relation to the whole aggregate. The concrete was subjected to short-time loads, using a quasi-axial compression test. Acoustic emission was employed as the research technique. The obtained results have been presented against the background of previous tests on analogous concrete but cured normally [11].

2. DESCRIPTION OF TESTS

Seven batches of concrete of similar ultimate compressive strength, falling under grade B25, cured in heat treatment conditions were tested. The particular batches of concrete, designated in this paper by letters from AN to GN, differed in their aggregate grading. The differences in the composition between the batches of concrete were achieved by varying the sand fraction from 25 to 100 % in proportion to the total aggregate. The aggregate grading curves for the prepared aggregates are shown in Fig. 1. The tests were carried out on 100 × 100 × 100 mm cube specimens after 90 days of curing. There were 12 specimens in each batch of concrete. The specimens in the particular batches were made of concrete mixes whose composition per 1 m^3 is given in Table 1. The values of selected material parameters characterizing the tested batches of concrete, calculated on the basis of the number of components used, have been compiled in Table 2.

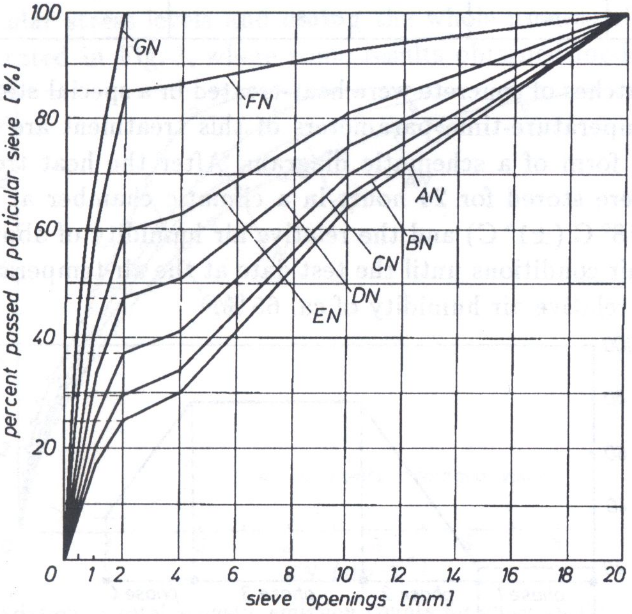

FIG. 1. Aggregate grading curves for tested concrete mixes.

Table 1. Composition of concrete mixes.

Designation of mix	Components			
	Portland cement "35" (kg/m^3)	Natural gravel (kg/m^3)	River sand (kg/m^3)	Water (l/m^3)
AN	294.2	1438.8	479.6	163.4
BN	305.7	1340.1	574.3	169.9
CN	321.5	1185.3	711.2	178.6
DN	334.5	958.6	867.3	185.7
EN	350.1	697.0	1045.4	194.5
FN	420.0	249.0	1427.7	231.0
GN	469.0	–	1480.0	257.0

Table 2. Values of selected material parameters characterizing tested concrete mixes.

Mix symbol	Type of parameter		
	Sand point (%)	Overall interior surface aggregate per 1 m^3 of mix F_k (m^2)	Thickness of mortar covering coarse aggregate ϱ (μm)
AN	25	3755	746.8
BN	30	4340	885.9
CN	37.5	5180	1137.3
DN	47.5	6116	1585.9
EN	60	7186	2467.0
FN	85	8763	9571.9
GN	100	9768	–

All the batches of concrete were heat-treated in a special steaming chamber. The temperature-time parameters of this treatment are presented in Fig. 2 in the form of a schematic diagram. After the heat treatment, the specimens were stored for 24 hours in a climatic chamber at the air temperature of 18° C (±1° C) and the relative air humidity of about 95 %, and then in dry-air conditions until the test date at the air temperature of 18° C (±3° C) and relative air humidity of ca. 65 %.

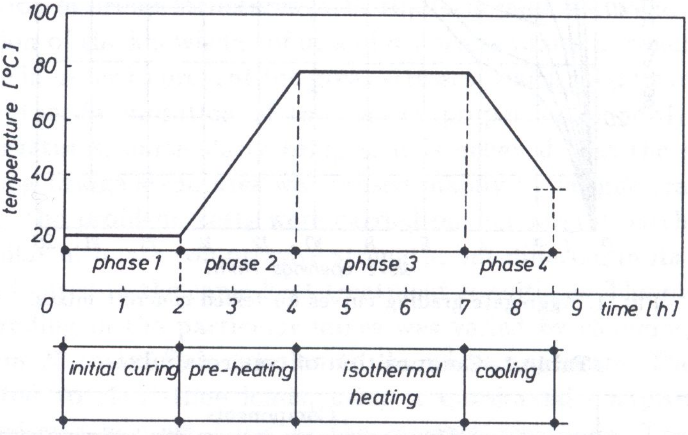

FIG. 2. Schematic diagram of the heat treatment of concrete.

Acoustic emission was employed as the research method for the quasi-axial compression test. The specimens were compressed in such a way that there was no friction at the contact between them and the pressure plates of the testing machine. For this purpose, the specimens' surface was ground, and then lubricated with cup grease. During the tests on the concrete specimens, the total counts of acoustic emission and its effective voltage were recorded. The test configuration for measuring of the acoustic emission consisted of the same components as in [2]. The tests were conducted at the air temperature of 20° C (±3° C) and the relative air humidity of about 55%.

3. TEST RESULTS AND THEIR ANALYSIS

The results obtained by the acoustic emission method have shown that the variation of total acoustic emission counts $\sum N$ as a function of stress increment σ/R is similar for all the tested batches of heat-treated concrete. There are, however, visible differences in the magnitude of this sum, both at the particular stress levels and during the whole process of destruction. This is illustrated in Fig. 3, where some results obtained for four from the seven tested batches of concrete are presented. It follows from this figure that the higher the coarse aggregate content in the heat-treated concrete, the larger the total of acoustic emission counts. There is also a close relationship between the total of acoustic emission counts recorded during the whole process of destruction of the tested batches of the heat-treated concrete and the material parameters that characterize the concrete. This observation is illustrated by Figs. 4 and 5, in which curves *1* represent the relationship between this total and overall internal surface of the aggregate F_k and effective thickness of the mortar coating of concrete ϱ, respectively. For comparison, Figs. 4 and 5 show this relationship in the form of curves *2* which represent

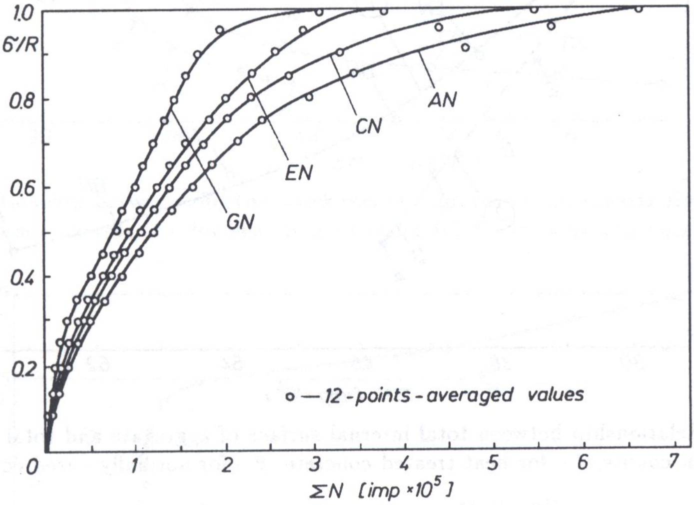

FIG. 3. Variation of total acoustic emission counts for quasi-axially compressed heat-treated concrete mixes AN, CN, EN and GN as function of stress increment.

the results obtained from tests on analogous seven batches of concrete, designated by letters from A to G, but cured normally. By comparing the two relationships presented both in Figs. 4 and 5, one can see clearly that the total of acoustic emission counts is always larger in the heat-treated concrete. Moreover, the smaller the total internal surface of the aggregate and the smaller the effective thickness of the mortar coating of coarse aggregate, the larger the difference in the total of acoustic emission counts between the thermally treated concrete and the analogous but normally cured one.

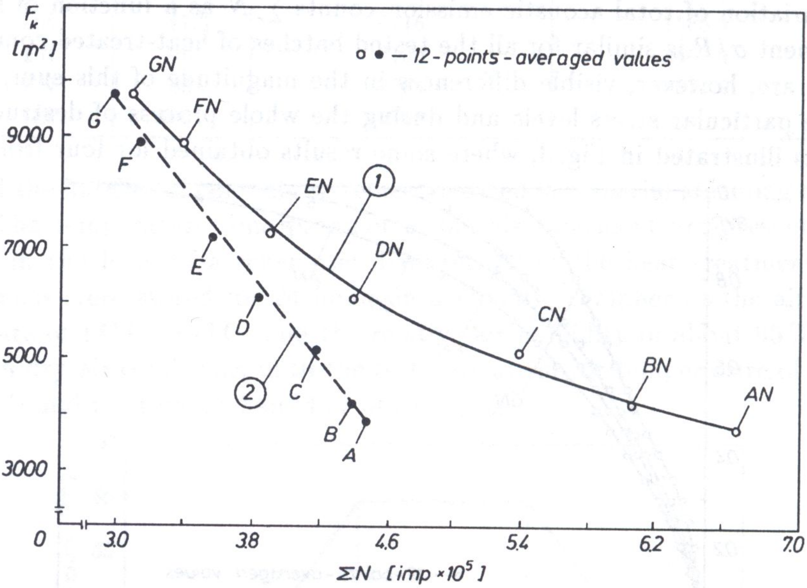

FIG. 4. Relationship between total internal surface of aggregate and total acoustic emission counts; *1* – for heat-treated concrete, *2* – for normally cured concrete.

The regularities in the recorded total of acoustic emission counts shown in Figs. 3, 4 and 5 are due to, among other things, the fact that an increase in the amount of coarse aggregate in concrete has an effect on both the number and the size of microcracks that develop during the loading of the concrete. These microcracks appear especially at the contact between this aggregate and the mortar which surrounds it [11, 12, 13]. In turn, the products of cement hydration formed at an elevated temperature have a more coarse-grained structure than when they are formed at the normal temperature. Not without significance are temperature and humidity gradients resulting in volume and shrinkage cracks [2, 8]. This means that heat treatment results in a more heterogeneous structure of concrete than the structure of concrete cured normally. More heterogeneous, i.e. containing more potential spots which constitute sources of acoustic emission. In the light of the obtained results, the degree of this heterogeneity increases as the content of coarse aggregate in concrete increases.

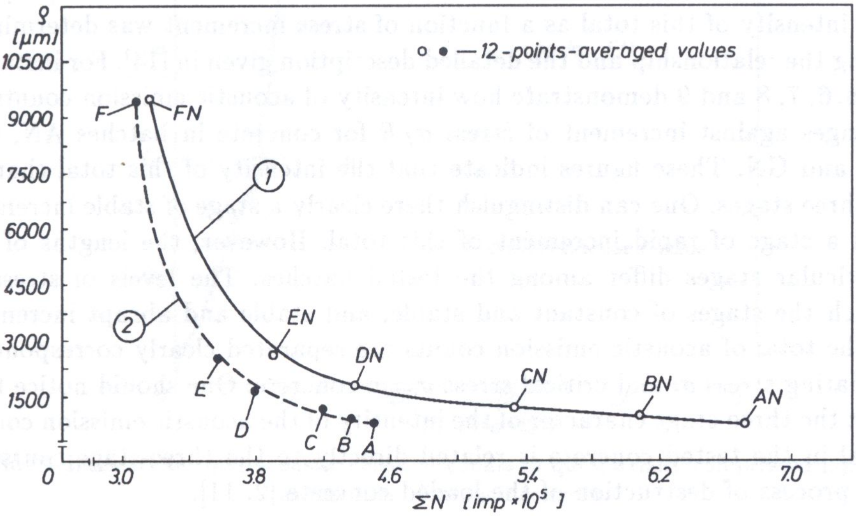

FIG. 5. Relationship between effective thickness of aggregate's mortar covering and total acoustic emission counts; *1* – for heat-treated concrete, *2* – for normally cured concrete.

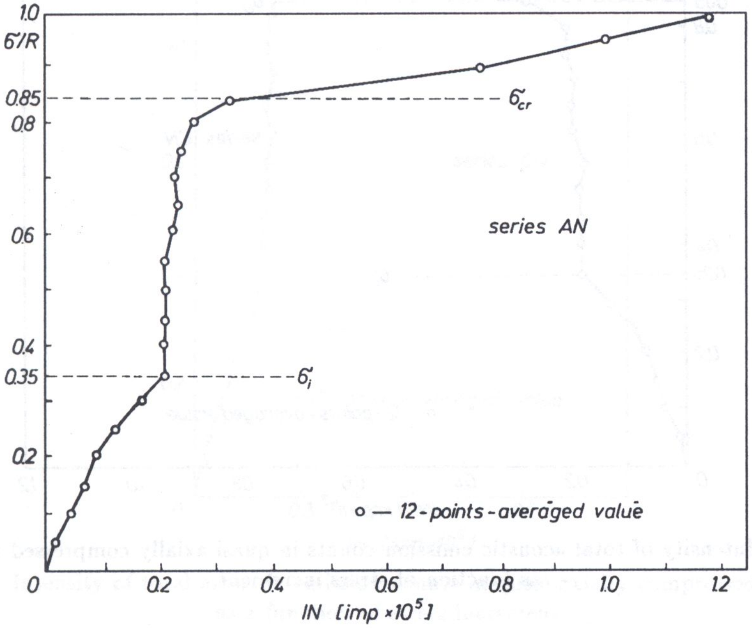

FIG. 6. Intensity of total acoustic emission counts in quasi-axially compressed mix AN as function of stress increment.

To provide a more comprehensive picture of the variations in the pattern of destruction of the tested batches of heat-treated concrete, the values of initiating stress σ_i and critical stress σ_{cr} in them were determined on the basis of the recorded total of acoustic emission counts. For this purpose, the intensity of this total as a function of stress increment was determined, using the relationship and the detailed description given in [14]. For instance, Figs. 6, 7, 8 and 9 demonstrate how intensity of acoustic emission counts IN changes against increment of stress σ/R for concrete in batches AN, CN, EN and GN. These figures indicate that the intensity of this total changes in three stages. One can distinguish there clearly a stage of stable increment and a stage of rapid increment of this total. However, the lengths of the particular stages differ among the tested batches. The levels of stress at which the stages of constant and stable, and stable and abrupt increment of the total of acoustic emission counts are separated clearly correspond to initiating stress σ_i and critical stress σ_{cr} in concrete. One should notice here that the three-stage character of the intensity of the acoustic emission counts total in the tested concrete is related directly to the three-stage course of the process of destruction of the loaded concrete [2, 11].

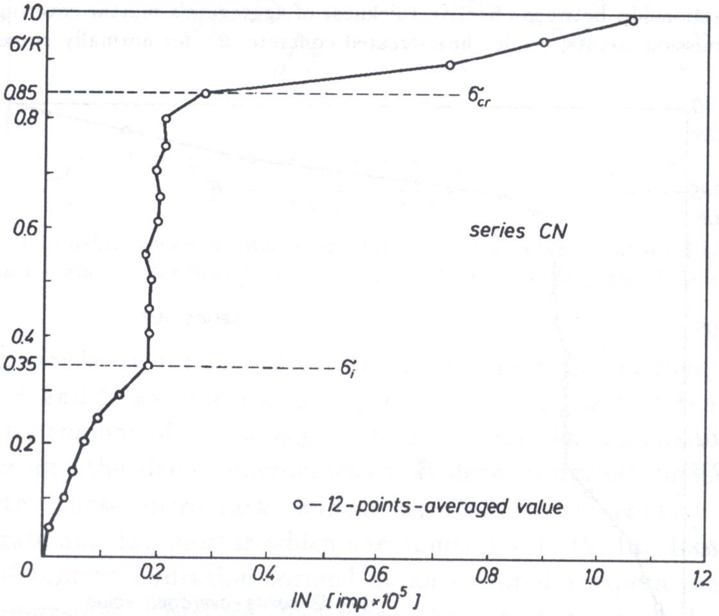

FIG. 7. Intensity of total acoustic emission counts in quasi-axially compressed mix CN as function of stress increment.

Curves *1* in Fig. 10 show how the values of initiating stress σ_i and critical stress σ_{cr} change, depending on the total internal surface of the aggregate

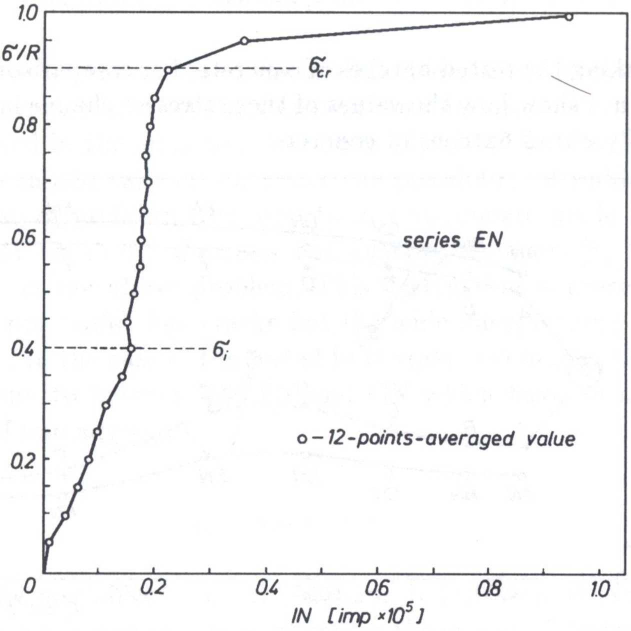

FIG. 8. Intensity of total acoustic emission counts in quasi-axially compressed mix EN as function of stress increment.

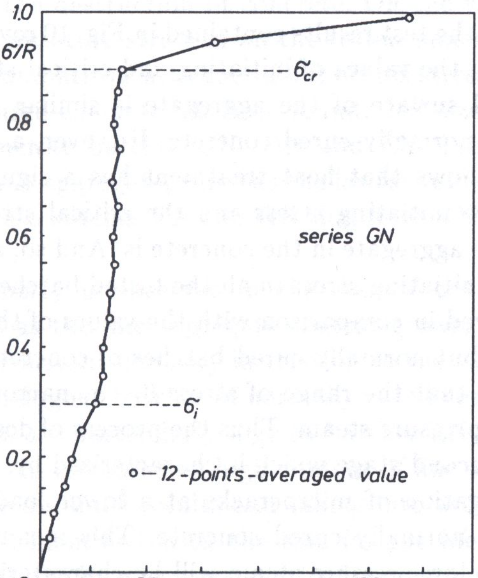

FIG. 9. Intensity of total acoustic emission counts in quasi-axially compressed mix GN as a function of stress increment.

used for making the tested batches of concrete. For comparison's sake, curves *2* in this figure show how the values of these stresses change in the analogous but normally cured batches of concrete.

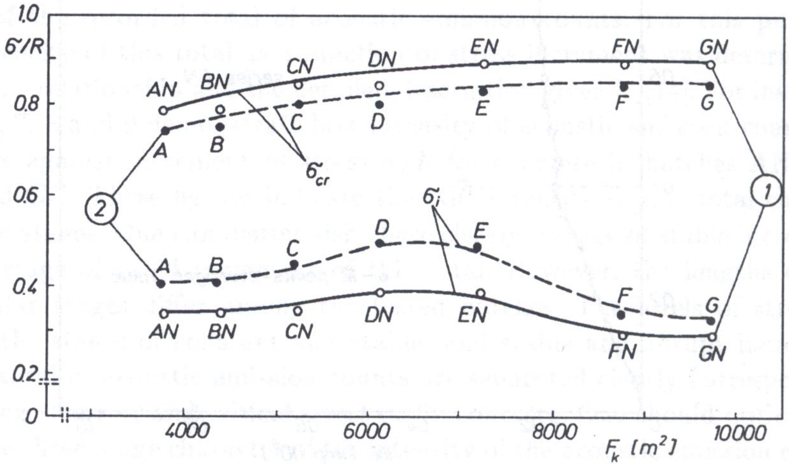

FIG. 10. Variability of initiating stress σ_i and critical stress σ_{cr} depending on total internal surface of aggregate; *1* – for heat-treated concrete, *2* – for normally cured concrete.

An analysis of the test results contained in Fig. 10 reveals that the pattern of the variation in the values of initiating and critical stresses depending on the total internal surface of the aggregate is similar for the heat-treated concrete and the normally cured concrete. However, a comparison between curves *1* and *2* shows that heat treatment has a significant effect on the values of both the initiating stress and the critical stress, no matter what the content of fine aggregate in the concrete is. And so, a marked decrease in the values of the initiating stress in all the tested batches of the heat-treated concrete is observed in comparison with the values of this stress determined in the analogous but normally cured batches of concrete.

This indicates that the range of stress $0 - \sigma_i$ narrows in concrete heat-treated with low-pressure steam. Thus the process of destruction of this concrete enters the second stage which is characterized by, among other things, the stable propagation of microcracks at a lower loading of the material in comparison to normally cured concrete. This means also that concrete heat-treated with low-pressure steam will be characterized by lower fatigue strength than the normally cured concrete, no matter what aggregate grading was used.

In the case of the critical stress, a reverse tendency was observed, i.e. as a result of the heat treatment the values of this stress increased as the fine aggregate content increased. Moreover, a comparison between curves *1* and *2* in Fig. 10 shows that the values of the critical stress in the heat-treated concrete batches increase by a constant quantity in relation to the values of this stress determined in the analogous but normally cured batches of concrete. Therefore, one should take into account the possibility of sudden destruction in the case of prefabricated structural components made of concrete characterized by high critical stress. The authors of papers [8, 15, 16] hold a similar view on the above problem. This destruction is preceded by the appearance of not "safe" fine cracks but the wide ones, leading to immediate destruction. In the case of the tested heat-treated concrete, this problem applies especially to batches EN, FN and GN which have an increased or high content of fine aggregate.

4. CONCLUSIONS

By using the method of acoustic emission it has been shown that heat treatment with low-pressure steam influences the course of destruction of all the tested mixes of compressed concrete. The determining factors here are mainly the values of initiating stress σ_i and critical stress σ_{cr} that delimit the particular stages of the destruction of concrete. On the whole, a reduction in the values of the initiating stress in all the tested mixes of the thermally treated concrete in comparison with the values of this stress in the analogous mixes of normally cured concrete has been found. The size of this reduction is the largest in concrete batches CN, DN and EN, i.e. the ones with a medium content of fine aggregate, whereas the lowest values of the initiating stress occur in concrete batches FN and GN that have a high content of fine aggregate.

The reverse tendency is observed in the case of critical stress σ_{cr}. It has been found that as the fine aggregate content grows, the values of this stress increase by a constant quantity in relation to the values of this stress determined in the analogous batches of normally cured concrete. The values of the buckling stress are particularly high in batches EN, FN and GN that are characterized by an increased or high content of fine aggregate.

In the light of the obtained results and taking into account the fact that initiating stress σ_i is identified with the safe fatigue life of concrete, and critical stress σ_{cr} with the long-term strength of concrete, it seems advisable to broaden the strength characteristic of concrete by including the values of these stresses. By doing so, the durability and safety, especially of components and structures designed to be made from concrete heat-treated in low-pressure steam and those which are subjected to variable loads or overloaded, will be increased significantly.

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