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APPLICATION OF ACOUSTIC METHODS TO ASSESSMENT OF CONCRETE HUMIDITY INFLUENCE ON THE PROCESS OF CONCRETE DESTRUCTION

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Owing to application of acoustic research methods, i.e. the ultrasound and the acoustic emission methods, it was pointed out in the paper that concrete humidity is of an essential influence on the process of concrete destruction. It was also proved that the totting sum of the acoustic emission recorded during the process of destruction of concrete is clearly determined by bulk humidity of the material under investigation.

The examination results submitted here refer to plain concrete subjected to an influence of innediate loads during tests of compressing it quasi-axially and stretching according to Brazilian method.

Poprzez zastosowanie akustycznych metod badawczych to znaczy metody ultradźwiękowej i emisji akustycznej, wykazano w pracy, że wilgotność betonu wpływa w istotny sposób na przebieg jego niszczenia. Wykazano także, że rejestrowana podczas procesu niszczenia betonu suma zliczeń emisji akustycznej jst wyraźnie uzależniona od wilgotności masowej badanego materiału.

Prezentowane wyniki badań dotyczą betonu zwykłego o różnej wilgotności masowej, poddanego działaniu obciążeń doraźnych w próbie ściskania quasi-osiowego oraz rozciągania metodą brazylijską.

1. Introduction

Presence of water in a capillary-porous material, as is concrete, shapes its building and functional properties both at the stage of its forming and during its exploitation. Water is introduced to concrete at the technological stage and partly remains in it while its curing, hardening and utilizing. The other source is humidity concrete acquires and which results from sorption processes or capillary pull-up from the surrounding. Depending on how concrete constructions are exploited, the capillary flow of water may take place within a relatively broad range of concrete humidity, i.e. from sorption humidity as far as till a full saturation state [6].

Since constructions made of concrete, depending on the assignment work in various humidity conditions, it is essential to determine the influence of the material's humidity on the course of its destruction caused by a load. The fact that humidity plays an important role in the destruction of loaded concrete was emphasized in, among others, the papers of [10, 11, 12].

However, exhaustive empirical data in this scope, have not yet been obtained.

It is also important to determine the influence of humidity concrete contains on acoustically-measured parameters, especially those obtained owing to the emission method, which serve as the basis for determining the scale or the course of load-caused destruction of this material. The problem should be recognized as crucial as, among others, since 1981 the acoustic emission method has found wider and wider application to studies on concrete in our country [3, 4, 5].

In order to explain the above issues, the investigations were carried out for various bulk humidity concretes subjected to Brazilian method quasi-axial compression. A wide range of the concrete's bulk humidity was achieved by its appropriate storage which rendered it possible for the material to remain in a dry state, a state of maximal sorption humidity and a state of full saturation. The ultrasound and acoustic emission methods were made use of as the investigation techniques.

2. Description of the investigations

The investigations referred to normal concrete of the compression resistance comprised within the B20-class, widely applied to concrete constructions.

The investigations were accomplished after a 90-day curing on samples $100 \times 100 \times 100$ mm and $150 \times 150 \times 150$ mm in size, made of a concrete mix, the formula of which was, in terms of 1 m^3, as follows:

– portland cement "35", coming from The Groszowice Cement Plant	– 320 kg,
– natural gravel "Proszowice"	– 1188 kg,
– river sand "Wrocław"	– 716 kg,
– municipal water	– 177 l.

Depending on the way of storage of the samples, various bulk humidity concrete was obtained at the moment of examination, i.e.:

– concrete of bulk humidity $W_m = 0{,}00\%$	– the samples had been stored for 86 days in a climatic chamber at a temperature of +18°C (±1°C) and relative air humidity of ca 95%, and then dried at a temperature of 105°C to reach constant weight (dry state).
– concrete of bulk humidity $W_m = 2{,}28\%$	– the samples had been stored for 28 days in a climatic chamber at a temperature of +18°C (±1°C) and relative air humidity of ca 95%, and then, till the 90th day, in the laboratory at a temperature of +18°C (±3°C) and relative air humidity of ca 65% (sorption humidity state).
– concrete of bulk humidity $W_m = 2{,}56\%$	– the samples had been stored for 90 days in a climatic chamber at a temperature of +18°C (±1°C) and relative air humidity of ca 95% (maximal sorption humidity state).

– concrete of bulk humidity $W_m = 5{,}84\%$ – the samples had been stored for 86 days in a climatic chamber at a temperature of $+18°C$ ($\pm 1°C$) and relative air humidity of ca 95%, and then water-saturated to reach a full saturation state.

Depending on bulk humidity of the concrete, the samples were divided into 4 groups and named series. The following series denotations were accepted:
– the "As" – series, $W_m = 0{,}00\%$;
– the "Ap" – series, $W_m = 2{,}28\%$;
– the "Ak" – series, $W_m = 2{,}56\%$;
– the "Aw" – series, $W_m = 5{,}84\%$.

The accomplished investigations employed the ultrasound and the acoustic emission methods, the samples being compressed quasi-axially and subjected to tension according to Brazilian method. The axial compression was accomplished having withdrawn the friction at the contact spots of the samples' surfaces and the tester's pressure plates. To achieve this, the surfaces has been grinded and then lubricated with cup grease.

The testing stand comprised the following elements:
– Instron 1126 – type tester,
– American, made by Acoustic Emission firm, acoustic emission measurement set,
– acoustic emission detector, AC175-model, of resonance frequency of 175 kHz;
– two-channel X Y_1 Y_2 – recorder manufactured by a Japanese firm Riken Denshi;
– Polish-made ultrasound testing set, Unipan 541-type;
– ultrasound heads of frequency of 500 kHz.

While testing the $100 \times 100 \times 100$ mm concrete samples, the totting sum of the acoustic emission, effective voltage of the acoustic emission, RMS, as well as the transition time of longitudinal ultrasound waves along the direction perpendicular to that of the force action were recorded as a function of stress increment. The

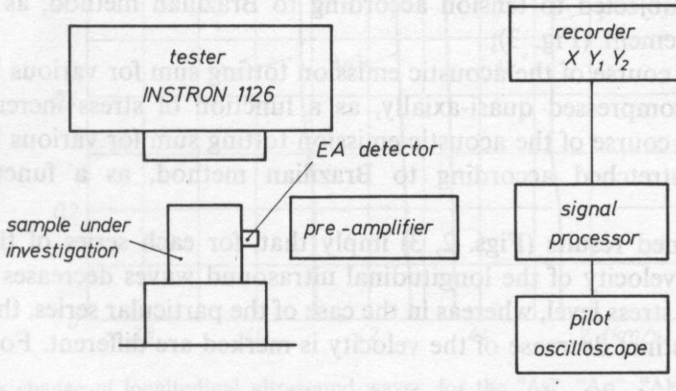

FIG. 1. A diagram of the research stand to measure the acoustic emission.

investigation were carried on at the air temperature of 20°C (±2°C) and relative air humidity of 55% (±5%).

3. Investigation results and their analysis

On the grounds of the classical resistance examinations of the concrete in question, having tested the samples 150×150×150 mm in size, mean compression and tension resistances after a 90-day curing were determined. The obtained results have been displayed in Table 1.

Table 1. Mean compresion and stretching resistances of concrete, determined on 150×150×150 mm samples after a 90-day curing

Concrete series denotation	Concrete humidity	Bulk humidity of concrete W_m [%]	Mean compression resistance $\bar{R}$ [MPa]	Mean stretching resistance $\bar{R}_r$ [MPa]	Softening co-efficient while compre-ssing [−]
1	2	3	4	5	6
"As"	dry state	0,00	31,50	1,97	1,00
"Ap"	damp state	2,28	27,00	2,30	0,86
"Ak"	damp state	2,56	27,30	2,40	0,87
"Aw"	water-satura-ted state	5,84	23,49	2,64	0,75

According to the investigation results obtained with the help of the ultrasound and the acoustic emission methods, the following relationships were determined:
– a velocity change of the longitudinal ultrasound waves for various bulk humidity concrete compressed quasi-axially, as a function of stress increment (Fig. 2);
– a velocity change of the longitudinal ultrasound waves for various bulk humidity concrete subjected to tension according to Brazilian method, as a function of stress increment (Fig. 3);
– variability course of the acoustic emission totting sum for various bulk humidity concrete compressed quasi-axially, as a function of stress increment (Fig. 4);
– variability course of the acoustic emission totting sum for various bulk humidity concrete stretched according to Brazilian method, as a function of stress increment.

The obtained results (Figs. 2, 3) imply that, for each series of the concrete in question, the velocity of the longitudinal ultrasound waves decreases together with an increase of stress level, whereas in the case of the particular series, the stress values at which a distinct decrease of the velocity is merked are different. For instance, the tension test for the "Aw" – series displays the phenomenon at the level of 0.9 $\frac{\sigma}{R}$, for

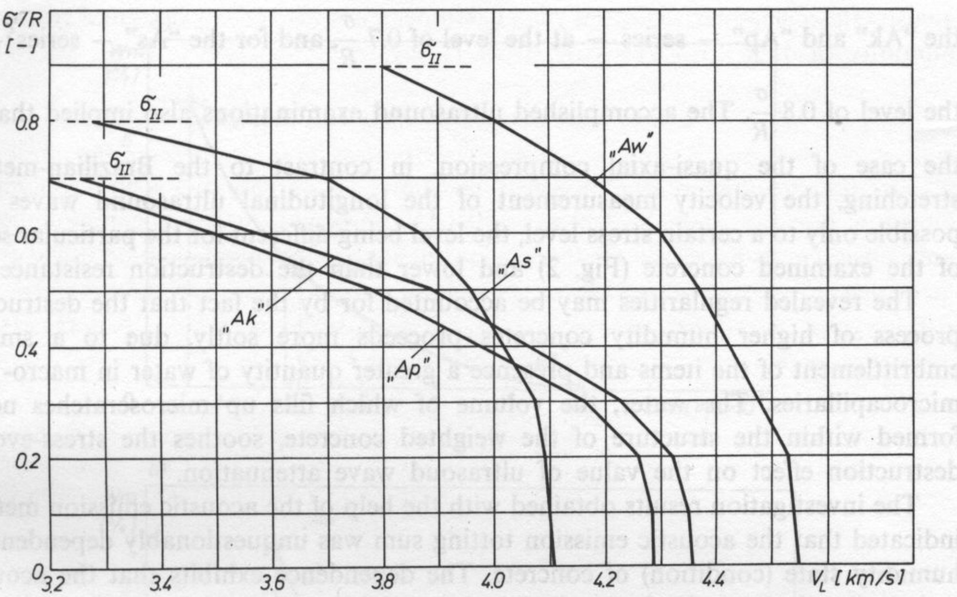

FIG. 2. Velocity change of longitudinal ultrasound waves, for the "As", "Ap", "Ak" and "Aw"-series concrete compressed quasi-axially, as a function of stress increment.

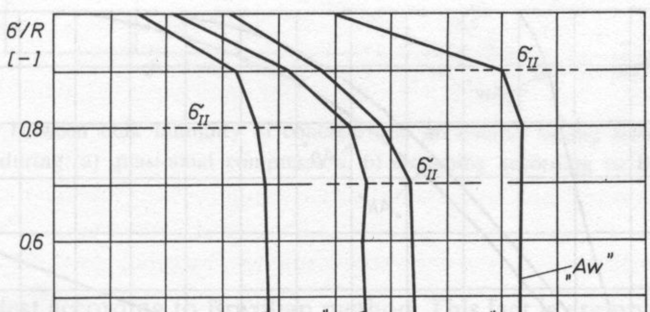

FIG. 3. Velocity change of longitudinal ultrasound waves, for the "As","Ap", "Ak" and "Aw", series concrete stretched according to Brazilian method, as a function of stress increment.

the "Ak" and "Ap" – series – at the level of $0.7\,\frac{\sigma}{R}$, and for the "As" – series – at the level of $0.8\,\frac{\sigma}{R}$. The accomplished ultrasound examinations also implied that, in the case of the quasi-axial compression, in contrast to the Brazilian-method stretching, the velocity measurement of the longitudinal ultrasound waves was possible only to a certain stress level, the level being different for the particular series of the examined concrete (Fig. 2) and lower than the destruction resistance.

The revealed regularities may be accounted for by the fact that the destruction process of higher humidity concretes proceeds more softly, due to a smaller embrittlement of the items and presence a greater quantity of water in macro- and microcapillaries. The water, the volume of which fills up microscratches newly formed within the structure of the weighted concrete, soothes the stress-evoked destruction effect on the value of ultrasoud wave attenuation.

The investigation results obtained with the help of the acoustic emission method indicated that the acoustic emission totting sum was unquestionably dependent on humidity state (condition) of concrete. The dependence exhibits that the acoustic emission totting sum, at the particular stages of destruction, is the smaller the more humid is the concrete, as was presented in Fig. 4 for a quasi-axial compression test. It is also worth mentioning that the acoustic emission totting sum of the examined concrete series is markedly greater in the quasi-axial compression test as compared

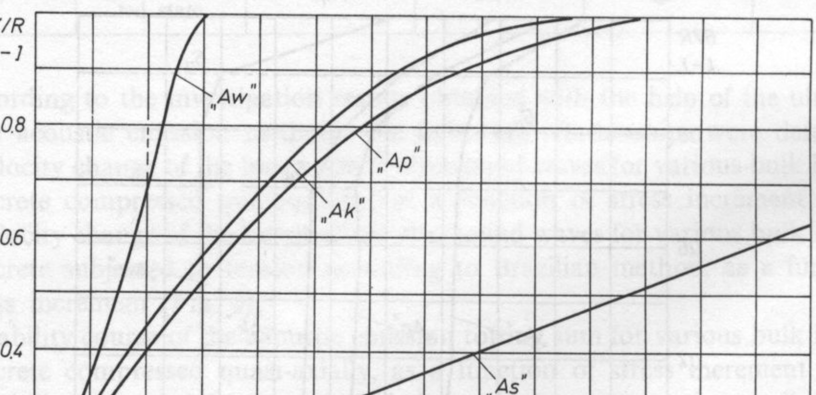

FIG. 4. Variability course of the acoustic emission totting sum, for the "As", "Ap", "Ak" and "Aw"-series concrete compressed quasi-axially, as a function of stress increment.

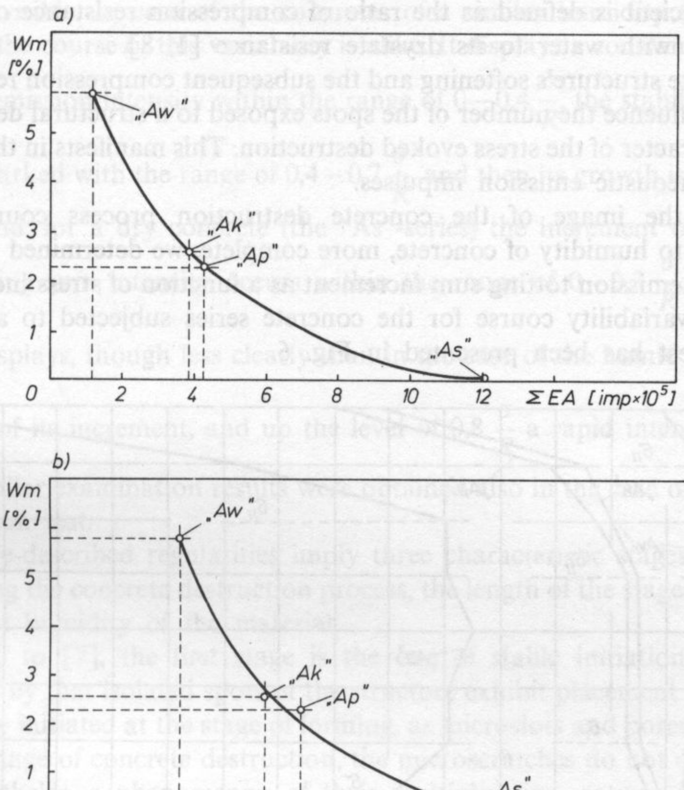

FIG. 5. Relationship between bulk humidity of concrete and an overall totting sum of the acoustic emission occurring during: a) quasi-axial compression, b) stretching according to Brazilian method.

with the tension test according to Brazilian method. This fact is exemplified in Fig. 5, which displays the relationship between bulk humidity of the examined concrete and the overall totting sum of the acoustic emission occuring during quasi-axial compression (Fig. 5a) and stretching according to Brazilian method (Fig. 5b).

Concrete humidity appears to have an influence on the value of the acoustic emission totting sum, the emission occuring during concrete destruction. The influence is associated with a weakening of connections between the structural lattice crystals. The weakening results from the fact that the connections, as the material's humidity increases, are partially dissolved causing a gradual decrease of the concrete's compression resistance [1]. In the case of the examined concrete series, there was also observed a decrease of this resistance, characterized by the walues of the softening coefficient, drawn up in Table 1. It is worth mentioning that the softening coefficient is defined as the ratio of compression resistance of a concrete fully saturated with water to its drystate resistance [1, 8].

The concrete structure's softening and the subsequent compression resistance loss immediately influence the number of the spots exposed to a structural destruction, as well as the character of the stress evoked destruction. This manifests in the number of the recorded acoustic emission impulses.

To make the image of the concrete destruction process course changes, corresponding to humidity of concrete, more complete, we determined the intensity of the acoustic emission totting sum increment as a function of stress increment. For instance, this variability course for the concrete series subjected to a quasi-axial compression test has been presented in Fig. 6.

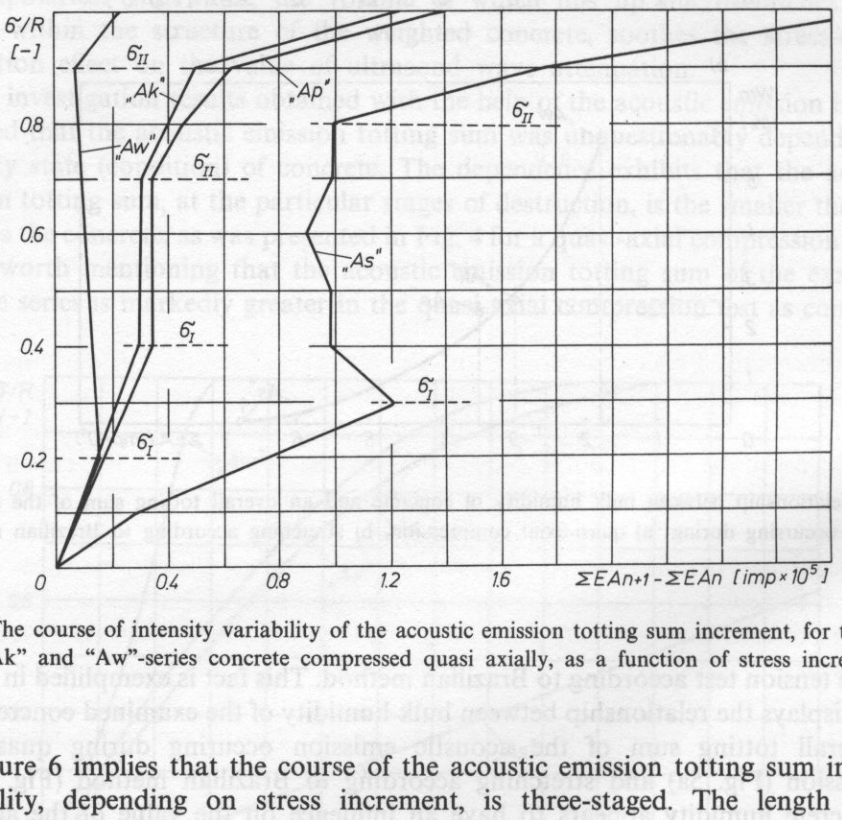

FIG. 6. The course of intensity variability of the acoustic emission totting sum increment, for the "As", "Ap", "Ak" and "Aw"-series concrete compressed quasi axially, as a function of stress increment.

Figure 6 implies that the course of the acoustic emission totting sum intensity variability, depending on stress increment, is three-staged. The length of the particular stages, however, varies with respect to an examined series and depends on the concrete's bulk humidity.

Thus, for water-saturated concrete (the "Aw"-series), the range of $0-0{,}2\ \frac{\sigma}{R}$ displays a constant increment of the acoustic emission totting sum, the range of $0{,}2-0{,}9\ \frac{\sigma}{R}$ exhibits stabilizing of its increment, and above $0{,}9\ \frac{\sigma}{R}$ its repeated increment is visible. In case of the concretes of a similar humidity (the "Ak" and "Ap"-series), the course of this variability is alike. It displays a constant increment of the acoustic emission intensity within the range of $0-0{,}4\ \frac{\sigma}{R}$, the stabilization of this intensity is marked with the range of $0{,}4-0{,}7\ \frac{\sigma}{R}$, and then its growth is observed. On the other hand, for a dry concrete (the "As"-series) the increment of the acoustic emission totting sum intensity occurs within the range of $0-0{,}3\ \frac{\sigma}{R}$; the range of $0{,}3-0{,}8\ \frac{\sigma}{R}$ displays, though less clearly than in the case of the humid concretes, the stabilization of its increment, and up the level of $0{,}8\ \frac{\sigma}{R}$ a rapid intensity growth is observed. Similar examination results were obtained also in the case of the Brazilian method tension test.

The above-described regularities imply three characteristic stages to be distinguished during the concrete destruction process, the length of the stages undoubtedly depending on humidity of the material.

According to [7], the first stage is the one of stable initiation of scratches, characterized by that isolated spots of the structure exhibit placement of microscratches that were initiated at the stage of forming, as microslots and pores. It is peculiar that, at this stage of concrete destruction, the microscratches do not develop. There occurs, nevertheles, a phenomenon of their multiplication, as was proved by the studies of the present paper's authors (Figs 2, 3 and 6), which is indicated by a slight velocity drop of the longitudinal ultrasound waves and a constant increment of the acoustic emission totting sum intensity. An increase of the load makes the concrete destruction process enter the stage of stable propagation of the scratches, during which occur propagation of the microscratches formed at the first stage as well as formation of new, stable microscratches – resulting from either the destruction of adhesion between the aggregate grains and the slurry or the one of the slurry itself. [7]. This state is indicated by a considerable attenuation of the ultrasound waves and a stabilization of the acoustic emission totting sum intensity increment. Provided there is a further increase of the load, the concrete destruction process enters the stage of catastrophic destruction. The stage exhibits formation of distinct, wide scratches spreading out unstably to reach a total destruction of the material. The phenomenon, as was pointed out by the investigations is particularly visible in the quasi-axial compression test and marked by a total loss of measurability of the longitudinal ultrasound wave velocities, and also by a rapid increment of the acoustic emission totting sum intensity.

The boundaries between the particular stages of concrete destruction are determined by the critical stresses, σ_{I} and σ_{II}, which according to, among others, [2, 11] are identified with fatique and long-term resistances of concrete, respectively.

Values of these stresses, which characterize the qualitative changes occuring in the structure of the examined material as the load increases, were determined for the particular series of the concrete under investigation with the help of the ultrasound and the acoustic emission methods, according to the criteria provided in [3]. Then the values were plotted in Figs 2, 3 and 6. Additionally, Fig. 7 submits a matching to

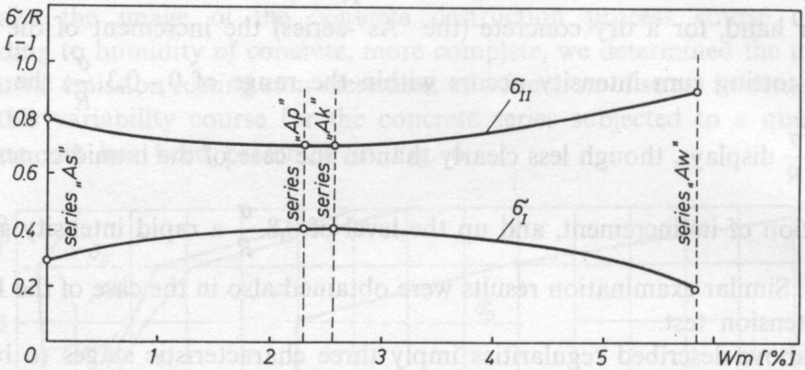

FIG. 7. Variability course of the critical stresses' values, σ_{I} and σ_{II} in relation to bulk humidity of concrete.

show the variability course of the critical stresses, σ_{I} and σ_{II}, in relation to humidity of a concrete under investigation. An analysis of Fig. 7 implies that concrete humidity is of a crucial influence on these stresses' values. Hence, as humidity of a concrete increases, the values of the critical stresses, σ_{I}, initially grow and then, down the bulk humidity value of ca 2,60%, decrease. For the critical stresses, σ_{II}, the relationship is reverse.

It need be noted that the accomplished studies pointed out a great usefulness of the acoustic emission method when determinig the critical stresses' values, σ_{I} and σ_{II} of a concrete, the values distinguishing between the particular stages of concrete destruction. Hitherto, the stresses have been determined on the grounds of knowing the variability course of strain characteristics obtained due to measurements of longitudinal and cross-sectional strains of concrete [2].

5. Summary

The application of acoustic research methods, i.e. the ultrasound and the acoustic emission ones, has proved concrete humidity to have a substantial influence on the process of destruction of concrete. The results obtained owing to these methods, and especially those of the acoustic emission method, clearly prove that three characteristic stages are distinguishable during the concrete destruction process, and that the duration of the stages unquestionably depends on humidity of concrete. It has also been pointed out that the values of the critical stresses, σ_{I} and σ_{II}, constituting boundaries between the particular concrete destruction stages are related to humidity of the material in question.

The valus of the critical stresses, σ_I, have been stated to grow initially as concrete humidity increases, from 0,3 to 0,4 $\frac{\sigma}{R}$ and then, starting from bulk humidity of ca 2,60%, to decrease to 0,2 $\frac{\sigma}{R}$. For the critical stresses, σ_{II}, the relationship is reverse, yet initially the values decrease from 0,8 to 0,7 $\frac{\sigma}{R}$ and then grow to 0,9 $\frac{\sigma}{R}$. The occurrence of differences in the course of the process of concrete destruction, the differences being connected with concrete humidity, is also evidenced by differences in totting sum quantities of the acoustic emission recorded during the process of destruction of concrete.

It has also been revealed that the acoustic emission totting sum, the emission being recorded during the destruction process, depends substantially on bulk humidity of the material under investigation. The sum is the smaller the greater bulk humidity of the concrete. The fact need be taken into account when interpreting the results of studies on concrete obtained with the help of the acoustic emission method.

References

[1] Г. Д. Цискрели, *О растяженности армированных бетонов*, Бетон и железобетон, 3, 124–127, (1963).

[2] K. Flaga, K. Furtak, *Wpływ rodzaju kruszywa na poziomy naprężeń krytycznych w betonie ściskanym*, Arch. Inż. Ląd., **26**, 4, 653–666. (1982).

[3] J. Hoła, A. Moczko, *Analiza procesu niszczenia wybranych struktur betonowych przy wykorzystaniu metody ultradźwiękowej i emisji akustycznej*, Praca doktorska, PWr, Wrocław, (1984).

[4] J. Hoła, A. Moczko, J. Pyszniak, *Wpływ wilgotności i naprężeń w betonie ściskanym na jego emisję akustyczną*, XXX Konferencja Naukowa KILiW PAN, Krynica, 3, 175–180. (1984).

[5] J. Hoła, A. Moczko, J. Pyszniak, *Możliwości wykorzystania metody emisji akustycznej w badaniach betonu.* Przegląd budowlany 11, 477–479. (1988).

[6] M. Leśniewska, A. Pogorzelski, *Wpływ porowatej struktury materiałów budowlanych na ruch kapilarny wody*, Arch. Inż. Ląd. **27**, 1, 123–140. (1981).

[7] K. Newman, J. B. Newman, *Failure theories and design criteria for plain concrete.* Civil Engineering Materials Conference: Structure Solid Mechanice and Engineering Design. Procceedings of the Sauthampton, ref. 83, (1969).

[8] J. Pyszniak, *Wpływ wilgotności betonu na ocenę jego wytrzymałości i prędkości fal ultradźwiękowych.* Praca doktorska, PWr, Wrocław. (1963).

[9] П. А. Ребиндер, *Физико-химическая механика как основа закрепления грунтов в дорожном строительстве и производстве строительных материалов на основе грунтов*, Труды совещания по теорителеским основам техники грунтов, МГУ, Москва, (1961).

[10] H. Rüsch, *Physikalische Fragen der Betonprüfung*, Zement – Kalk – Gips, **12**, 1, 1–9, (1959).

[11] S. P. Shah, S. Chandra, *Critical stress volume change and microcracking of concrete.* ACJ Journal, **65**, 9, 770–781, (1968).

[12] P. H. Wittmann, *The structure of hardened cemente paste. A basic for a better understanding of the materials properties.* Proceedings of a Conference held at University of Sheffield, Cement and Concrete Association, London, 96–117. (1976).

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