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CHARACTER OF STRESS FAILURE OF HIGH-STRENGTH CONCRETE DETERMINED BY ACOUSTIC EMISSION METHOD

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ABSTRACT

This paper presents results of investigations into the failure of high-strength concrete under compression carried out by means of the acoustic emission (AE) method. A number of such concretes, differing in their composition and compression strength were investigated. Several AE parameters, including AE events, AE counts, the rate of counts and the AE signal RMS value, were recorded simultaneously. On this basis it has been established that the failure of the tested concretes is a three-stage process. The initiating and critical stress values which delimit the particular stages in the process of failure have been determined. It has been found that these values depend on the compression strength of the investigated concretes and they increase with it. The obtained results are of both theoretical and practical importance.

INTRODUCTION

It is thought that the failure of high-strength concrete is more sudden than that of plain concrete. In classic strength investigations the failure of high-strength concrete is described as explosive. It is not fully explained if and to what degree this explosive failure is signalled by the concrete before it occurs. It has not been established conclusively if, similarly as in plain concrete, three qualitatively different stages: a stage of the stable initiation of microcracks, a stage of the stable propagation of microcracks and a stage of catastrophic failure are distinguishable in the failure of high-strength concrete [1]. It has not been determined what values initiating stress σ_i and critical stress σ_{cr}, which are the conventional stress levels delimiting the above stages of failure, take on. These problems have been tackled by only a few researchers, e.g. [2, 3, 4].
One should mention here the role ascribed to initiating stress σ_i and critical stress σ_{cr}. As it was said before, these two kinds of stress delimit the particular stages in the failure of concrete. Initiating stress is regarded as marking the upper limit of the elastic work of concrete under a short-time load and it reaches a similar value as that of fatigue strength. Whereas critical stress is identified with long-time strength of concrete [5,6, 7, 8]. It is essential to know the values of these stresses to assess the durability and safety of particularly those concrete structures which are loaded repeatedly or are subjected to overloads. Since structures made of high-strength concrete are no exception in this respect, the problems dealt with in this paper are important from both the theoretical and practical points of view.

DESCRIPTION OF STUDIES

Four high-strength concretes made of crushed 2-16 mm basaltic aggregate, washed sand with the grading of 0-2 mm and Portland cement 45 without mineral additives were investigated.

Such a composition of the aggregate was used which ensured the maximum density of the concretes. The initial concrete, designated by 0, was modified with a superplasticizer, and with a combination of superplasticizer and silica fume, so as to obtain ever higher values of compression strength. The composition of the tested concretes is given in table 1. Table 2 gives, among other things, compression strength and tensile strength values for the investigated concretes, obtained using 150×150×150 mm specimens after 28 and 90 days of curing. As it follows from the table, all the investigated concretes meet, after 28 days of curing, the minimum strength standard of 60 MPa for high-strength concrete [9, 10, 11].

TABLE 1

COMPOSITION OF TESTED HIGH-STRENGTH CONCRETE

Concrete designation	Constituents in kg/m^3					$\frac{W}{C+SF}$
	Cement	Aggregate	Water	Super plasticizer	Silica fume	
0	450	2033	180	-	-	0.400
1	450	2085	146	9.00	-	0.324
2	450	2096	140	11.25	13.50	0.302
3	450	2069	140	13.50	31.50	0.291

TABLE 2

COMPRESSION AND TENSILE STRENGTH VALUES DETERMINED FOR 150×150×150 mm CONCRETE SAMPLES AFTER 28 AND 29 DAYS OF CURING

Concrete desig-nation	Mean compression strength after 28 days f_{cm} [MPa]	Mean splitting tensile strength after **28** days $f_{ctm,sp,28}$ [MPa]	Mean compression strength after 90 days $f_{cm,90}$ [MPa]	Minimum compression strength after 90 days $f_{cmin,90}$ [MPa]	Maximum compression strength after 90 days $f_{cmax,90}$[MPa]	Mean splitting tensile strength after 90 days $f_{ctm,sp,90}$ [MPa]
0	65.10 2.54%	3.85 10.95%	68.00 2.68%	65.00	70.30	4.00 11.50%
1	86.20 4.02%	6.20 10.11%	88.70 4.23%	84.40	92.80	6.50 8.53%
2	95.60 3.41%	6.70 9.03%	98.90 3,22%	95.20	101.10	6.80 8.92%
3	105.0 4.75%	6.60 10.18	110.30 4.70%	100.10	116.80	6.70 10.82%
Note: variati	n **coefficient values** are **given** below **the line.**					

The acoustic emission method was applied to study the course of failure, caused by axial compression, in concretes after 90 days of curing, using 50×50×100 mm specimens cut out from larger sample elements. Twelve specimens of each concrete were tested.

ANALYSIS OF TEST RESULTS

Fig. 1 shows the AE counts recorded during the compression of the investigated concretes versus failure time. As one can see the values of this AE parameter are minimal at the initial phase and the intermediate phase of loading. This indicates that very few cracks appear in the structure. Only at the final stage of loading, the AE counts increase rapidly, indicating very intensive formation and development of cracks. If the compression strength test results given in table 2 and the data presented in fig. 1 are put together, an interesting observation can be made: the AE counts recorded during the whole process of failure decrease as compression strength increases.

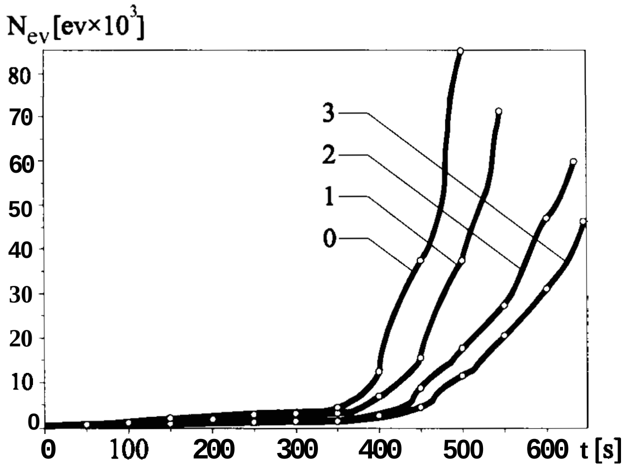

Figure 1: AE events recorded during compression of tested high-strength concretes versus failure time

This fact seems to corroborate the literature findings that silica fume improves the homogeneity of the structure of concrete and reduces structural defects [9, 10, 11, 12].

Fig. 2 shows exemplary AE counts-rate measurements for concretes 0, 1 and 3. Three stages can be distinguished in the trace of this AE parameter as a function of failure time. At the initial stage of loading the rate of AE counts is slightly higher than at a later stage.

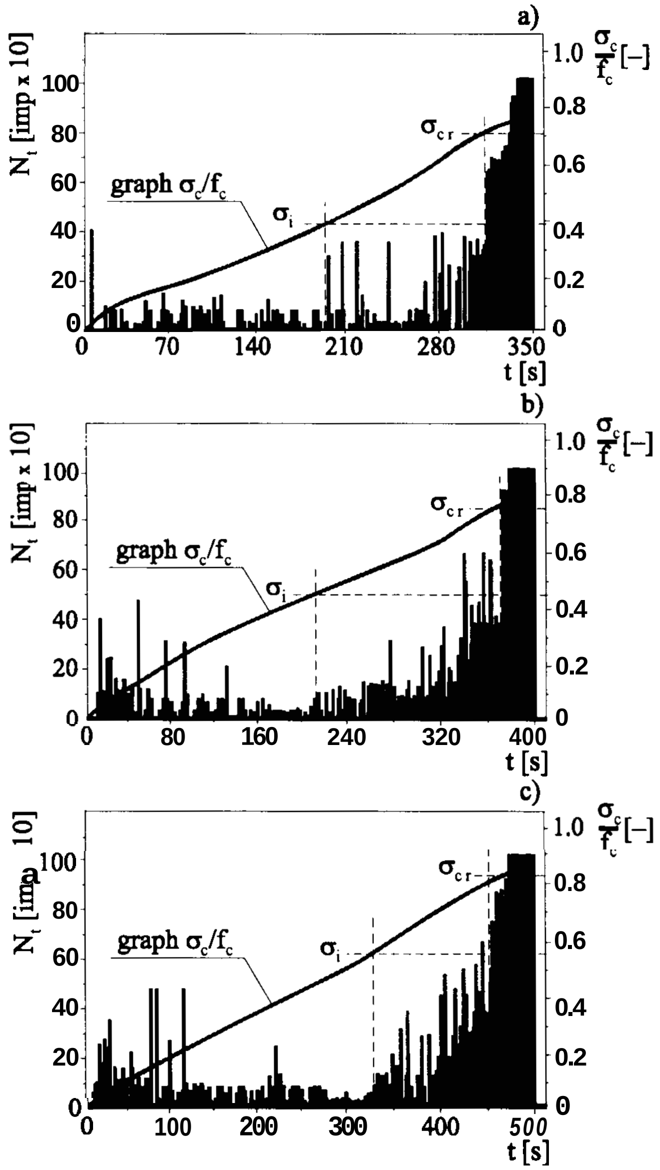

Figure 2: AE counts rate at initial and intermediate stages of loading with plotted graph of relative compressive stress value σ_c/f_c versus failure time: a) in concrete 0, b) in concrete 1, c) in concrete 3

This is probably due to slight apparent emission. As the load increases further, the rate of AE counts decreases and stabilizes. One can say that the loaded concretes have “quieted down” acoustically. Then the rate of counts begins to increase moderately. As the load enters the final stage, the rate of counts begins to increase rapidly until the material fails. Fig. 2 shows also graphs of the relative compressive stress increment during the failure of the tested concretes with marked levels at which the rate of AE counts respectively stabilizes and increases sharply.

The AE counts were recorded also in the compressed concretes and their rate versus relative increment in compressive stress was determined using the relation given in [4]. The rate for concretes 0 and 3 is shown in fig. 3. As one can see, the rate of AE counts increases rapidly at the final stage of loading whereas at the earlier stages the rate increments are slight.

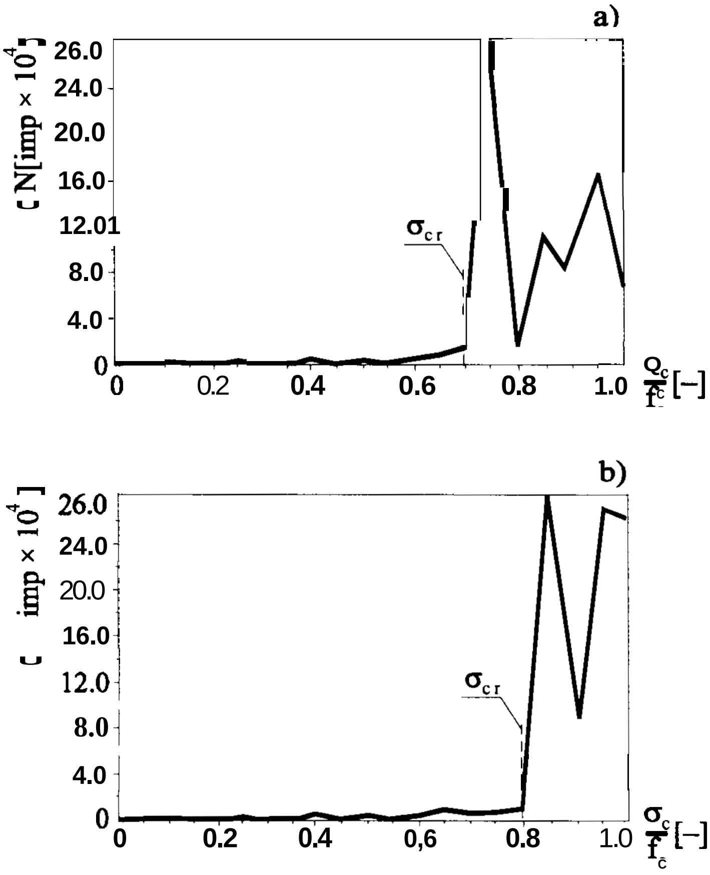

Figure 3: AE counts increment rate versus relative compressive stress value:
a) in concrete 0, b) in concrete **3**

Also the recorded AE signal RMS values versus the increment in relative compressive stress, shown for concretes 0 and 3 in fig. 4, were analyzed.

Similarly as in the case of the rate of AE counts, three stages can be distinguished in the trace of this parameter. At the initial stage of loading the *AE* signal RMS value is low and stable. As the load increases this value increases moderately. At the final stage of loading it increases sharply until the concrete fails.

If follows from the results shown in figs 1-4 that the values of the AE parameters recorded during the failure of concrete increase sharply at the final stage of loading. The stress level at which the sharp increase begins is not the same in all the tested concretes. It is determined by the compression strength and it rises with it. This means that the tested high-strength concretes do not fail suddenly – their failure is signalled by rapidly increasing acoustic activity. Also the amplitudes of acoustic pulses are larger in concretes with higher compression strength – as evidenced by the images of the pulses recorded during the failure of the concretes (two such images are shown in fig. 5) and by their amplitude-frequency distributions.

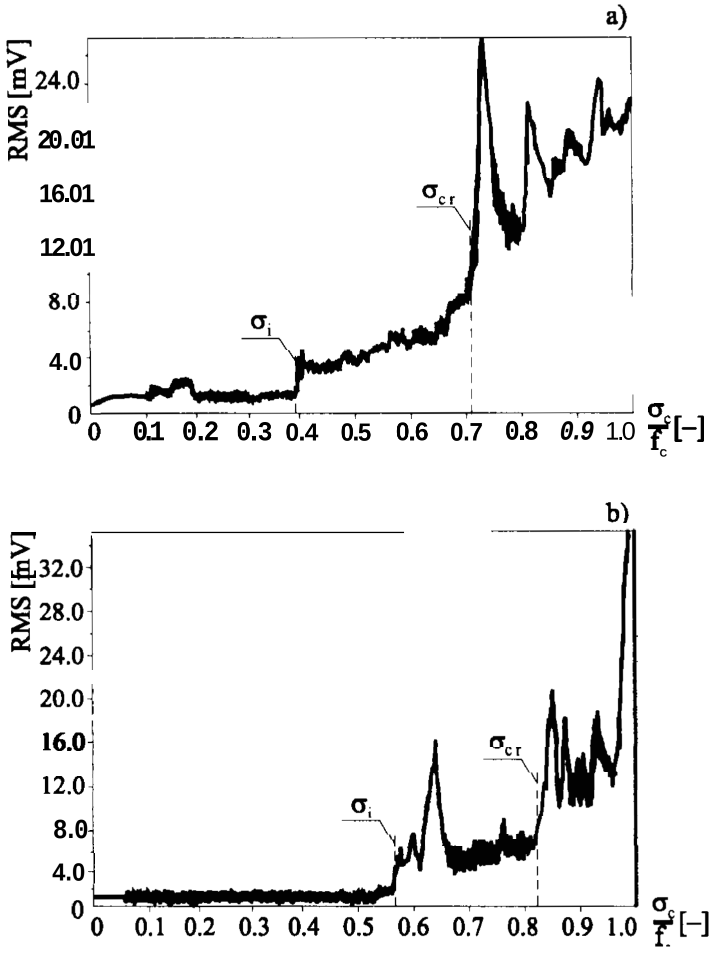

Figure 4: Recording of AE signal RMS value versus increment of relative compressive stress σ_c/f_c: a) in concrete 0, b) in concrete 3

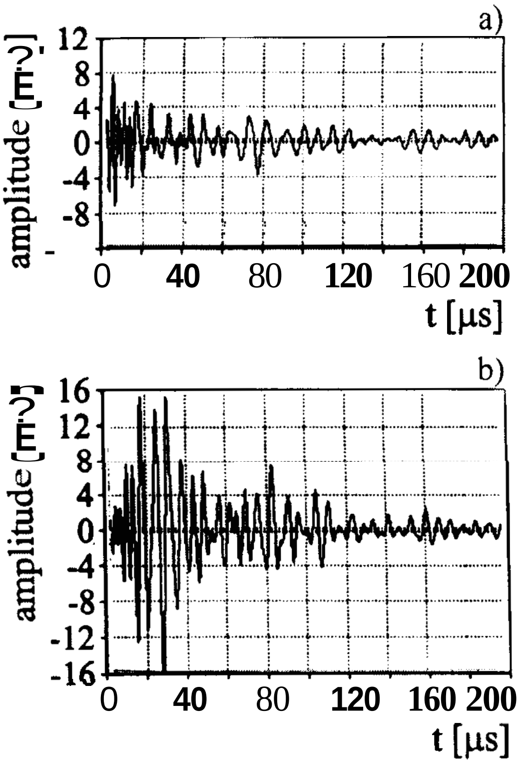

Figure 5: Sample images of acoustic pulses recorded during compression of concrete 0 and 3:
a) concrete 0 – relative stress level close to about 0.75 σ_c/f_c;
b) concrete 3 – relative stress level close to about 0.8 5σ_c/f_c.

The obtained results corroborate the thesis that the failure of high-strength concrete is not a continuous but multistage process. In the authors' opinion, the three-stage traces of the AE counts rate and the AE signal RMS value indicate clearly that the failure of high-strength concrete is a three-stage process. It should be noted here that it is harder to distinguish the phase of the stable initiation of microcracks from the phase of the stable propagation of microcracks in high-strength concretes than in plain concretes. This is due to the fact that much fewer cracks appear and develop at these stages of failure in high-strength concretes.

The initiating stress (σ_i) level and the critical stress (σ_{cr}) level which delimit the stages of failure in the tested high-strength concretes were determined. Stress σ_i occurs at the level at which the stable and low rates of AE counts and the AE signal RMS values start to increase gradually. Stress σ_{cr} occurs at the level at which all the recorded AE parameters start to increase sharply. The respective stress levels are marked in figs 2, 3 and 4 and their mean relative values calculated on the basis of the relative values of all the parameters recorded during failure are given in table 3.

TABLE **3**

MEAN RELATIVE VALUES OF STRESSES σ_i and σ_{cr}
DETERMINED FOR TESTED HIGH-STRENGTH CONCRETES

Concrete designation	Mean values	
	σ_i[-]	σ_{cr} [-]
0	0.39 4.1%	0.72 4.3%
1	0.45 4.6%	0.76 5.0%
2	0.52 4.8%	0.80 4.7%
3	0.56 4.3%	0.83 4.8%

Note: variation coefficient values are given below the line.

It follows from table 3 that the mean values of both initiating stress σ_i and critical stress σ_{cr} are the higher, the higher the compression strength of the high-strength concretes. One should note the high initiating stress values in concretes **2** and 3 with silica fume. This means that the latter concretes have much higher fatigue strength than both plain concrete and the other tested concretes. It is somewhat surprising that the critical stress values in the concretes with silica fume are not much higher than the ones which usually occur in plain concrete. According to the literature, the stage of catastrophic failure of the tested high-strength concretes should have begun at a much higher stress level.

CONCLUSIONS

1 In the light of the results yielded by the AE investigations it appears that the failure of the tested high-strength concretes under compression is a three-stage process. But in this case it is much more difficult than in plain concrete to distinguish the stage of the stable initiation of microcracks from the stage of the stable propagation of microcracks. This is probably due to the fact that few microcracks appear and develop in these stages of failure of high-strength concrete. The stage of catastrophic failure leading to an explosive failure is very distinct, manifesting itself in the rapidly increasing values of all the recorded AE parameters. The explosive failure effect is more pronounced in concretes with higher compression strength.

2 It has been found that initiating and critical stress values in the tested high-strength concretes depend on compression strength. Clearly, the highest values of initiating stress were recorded for concretes 2 and 3 which contained silica fume. This finding is important for the durability and safety of structures made of high-strength concrete in which fatigue strength plays a critical role. The highest values of critical stress were also recorded for concretes 2 and **3,** but they were not significantly higher than the ones usually

measured in plain concrete. This means that the tested high-strength concretes signal quite early their failure. This finding is important from the point of view of the safety of concrete structures which are subject to overloads.

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