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STUDIES OF FAILURE OF HIGH-STRENGTH CONCRETE

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This paper presents results of studies, conducted by means of the acoustic emission technique and strain measurements, of the failure of high-quality concrete. Several concretes differing in their composition and compression strength were tested. It has been determined that the failure of high-strength concrete can be regarded as a three-stage process. The values of the stresses initiating the stable development of microcracks and those of the critical stresses after which the unstable development and propagation of microcracks begin were determined. It has been established that the values of these stresses for the tested concretes depend on compression strength and they increase with this strength. The obtained results are of significance to both the theory and practice.

1. INTRODUCTION

High-strength concrete has the compression strength of over 60 MPa [1, 2, 3, 4]. Its use in building practice has been increasing steadily [4, 5, 6, 7]. Concrete can acquire such high strength if aggregate and cement of suitable quality and a small quantity of water are used and the concrete mix components are matched well. By adding some plasticizer and microfiller to such a composition, strength far exceeding the minimum value of 60 MPa required of high-strength concretes can be obtained [1, 2, 3, 4, 7, 8, 9, 10, 11].

Research aimed at improving the durability of concrete, conducted for many years, has shown that a small amount of microfiller - silica dust - introduced into concrete improves substantially the homogeneity of its structure. This improvement is partly due to the greater consolidation of the hardened concrete, the enlarged interfacial transition zone, the considerable reduction of the air pores formed as a result of the evaporation of the water that did not take part in the hydration of the cement, the reduction of capillary pores as well as the size and number of shrinkage cracks which appear during hardening, and the reduced difference in rigidity between the aggregate and the cement mortar [2, 3, 4, 8, 9, 10, 12]. Therefore stress concentrations are considerably reduced and fewer cracks appear in the structure of high-strength concrete. Consequently, this concrete behaves under a load differently that ordinary concrete.

High-strength concrete is considered to fracture more rapidly than ordinary concrete [2, 3, 4]. It should be noted that the failure of high strength concrete observed during conventional strength tests is referred to as explosive failure. It is not explained if there is any warning sign of this rapid cracking. It is not clear whether three characteristic stages can be distinguished in the failure of high-strength concrete as it can be done in the case of ordinary concrete. The three stages are: the stable initiation of microcracks, the stable propagation of microcracks, and the unstable propagation of microcracks – referred to as catastrophic failure [13]. It is not certain if the criteria applied to ordinary concrete to determine the level of initiating stress σ_i and that of critical stress σ_{cr}, which delimit the failure stages, are applicable to the same extent to high strength concrete [13, 14, 15, 16, 17, 18]. It is not known how high the values of these stresses are in high-strength concrete. So far these problems have been addressed only by a few researchers. For example in [19], it has been shown that the failure of concrete characterized by increased compression strength and that of ordinary concrete is similar but initiating and critical stress values are higher in the former concrete. No such conclusions can be found in [20] since the authors were unable to determine the level of initiating stress in the tested high-strength concrete specimens. Whereas in [21] it has been established that the strain-stress relationship is linear up to a very high level of effort and the increase in microdamage which signals the approaching failure is observed at a higher effort than in ordinary concrete. This suggests that the level of critical stress is higher in high-strength concrete than in ordinary concrete.

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 [12, 13, 15, 21, 22, 23, 24, 25, 27]. 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.

2. 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 microsilica, so as to obtain ever higher values of compression strength. The composition of the tested concretes is given in Table 1. The basic properties of the hardened concretes are described in Table 2.

Table 1. Composition of tested high-strength concrete.

Concrete designation	Constituents in kg/m^3					$\frac{W}{C + M_{silic}}$
	Cement	Aggregate	Water	Super plasticizer	Microsilica	
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. Basic properties of hardened high-strength concrete after 90 days of curing.

Concrete designation	Volumetric density [kg/m^3]	Density [kg/m^3]	Porosity [%]	Absorbability [%]	Compression strength after 28 days [MPa]
0	2581	2833	8.90	2.31	65
1	2618	2838	7.70	1.55	86
2	2642	2852	7.36	1.53	95
3	2624	2854	8.06	1.13	105

Figure 1 shows the increase of compression strength in time, determined for 150 × 150 × 150 mm specimens after 3, 7, 28 and 90 days. Until then the specimens were cured in a climatic chamber at the air temperature of 18 °C (±1°C) and the air relative humidity of approx. 95%. The specimens were subjected to compression in such a way that there was no friction at the contact between the specimen's surface and the tester's clamps. To eliminate friction, the appropriate surfaces were ground and then lubricated with cup grease, similarly as in [17]. The failure of concrete caused by axial compression was investigated for the concrete which was cured for 90 days. The acoustic emission (AE) technique and strain measurements were used in the investigations. The set-up configuration is shown in Fig. 2. The AE investigations were conducted on 50 × 50 × 100 mm specimens cut out from larger elements. 12 specimens were tested for each kind of concrete. Two independent acoustic emission measuring sets: a multi-gauge set

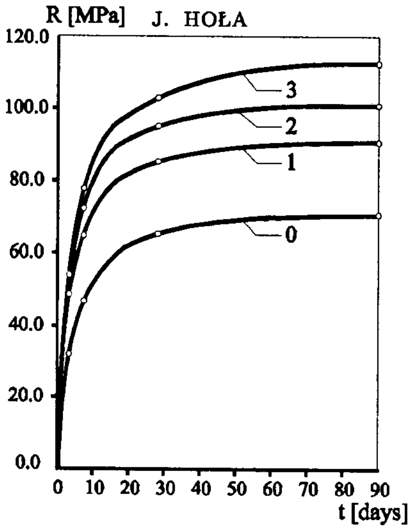

FIG. 1. Compression strength increment in time for tested concretes.

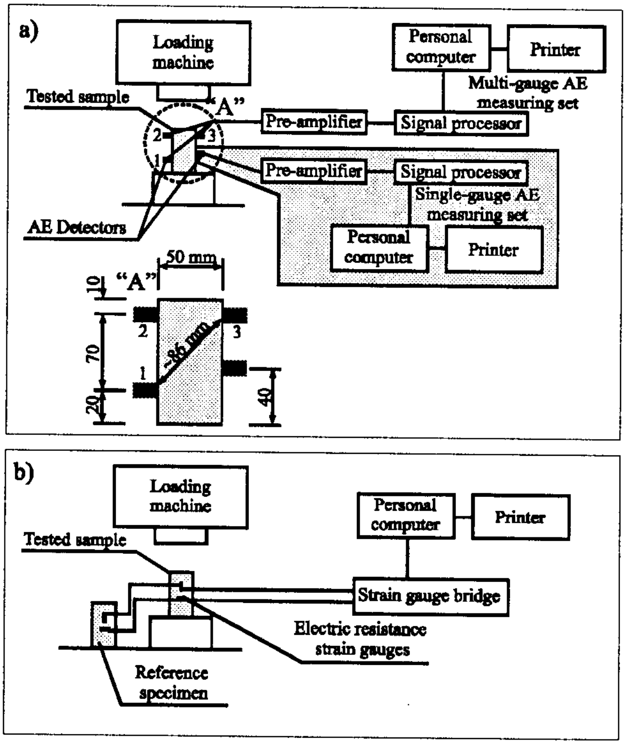

FIG. 2. Configuration of set-up for measuring: a) acoustic emission in concrete, b) strains in concrete.

and a single-gauge set were used. The multi-gauge set enabled the recording of the signal RMS (root-mean-square) value [28] and the number and location of events along the way between gauges 1-2, 1-3 and 2-3. The single-gauge set enabled the recording of the number and rate of AE counts. Longitudinal and transverse strains were measured in six 350 mm high, 113 mm in diameter cylindrical specimens for each tested concrete. Electric resistance wire strain gauges RL 300/50 stuck on at half of the specimen height and an automatic extensometer bridge were used for this purpose. The measurements were recorded by a computer.

3. Results of studies and their analysis

The following relationships have been established on the basis of the acoustic emission and strain measurement investigations for the concretes subjected to compression:

- the variation of AE counts sum as a function of failure time (Fig. 3),

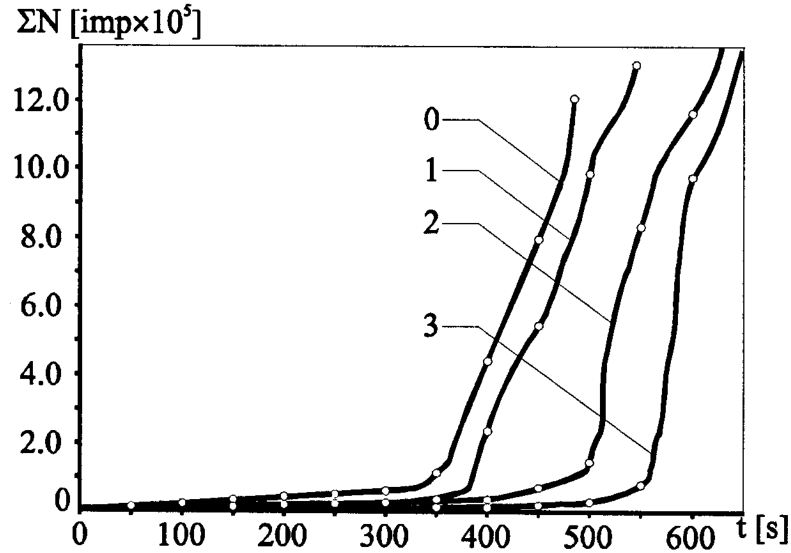

FIG. 3. AE counts sum, recorded during compression of high-strength concrete, as function of time.

- the variation of AE events sum as a function of failure time (Fig. 4),
- AE counts rate as a function of failure time (Fig. 6),
- AE RMS (root-mean-square) value as a function of relative stress increment σ/R (Fig. 9),

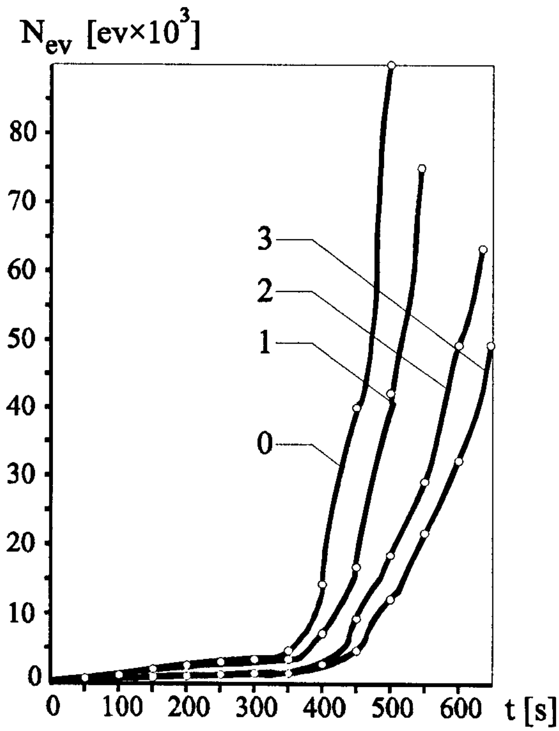

FIG. 4. *AE events sum as function of time, recorded during compression of high-strength* concrete 0, 1, 2 and 3.

• the location of AE events in specimens as a function of events amplitude (Fig. 10),

• the variation of longitudinal and transverse strains as a function of relative stress increment σ/R (Fig. 11).

The results, presented in Figs 3 and 4, obtained by means of the acoustic emission technique indicate that the pattern of the variation of the AE counts sum and the AE events sum during failure is similar for all the tested concretes. Characteristically, the values of the AE parameters recorded during the initial stage and the intermediate stage of loading are negligible. The negligible acoustic activity of the tested high-strength concretes in comparison with the considerable effort indicates that very few microcracks develop. Only at the final stage of loading, the values of the measured AE parameters increase rapidly, which is a sign of the very intensive development and propagation of cracks. Figure 5 provides interesting information. The events sum recorded during the entire failure for the tested concretes decreases, whereas the total counts sum increases as the compression strength increases. It seems that the fact that a smaller number of events was recorded in the high-strength concretes corroborates the

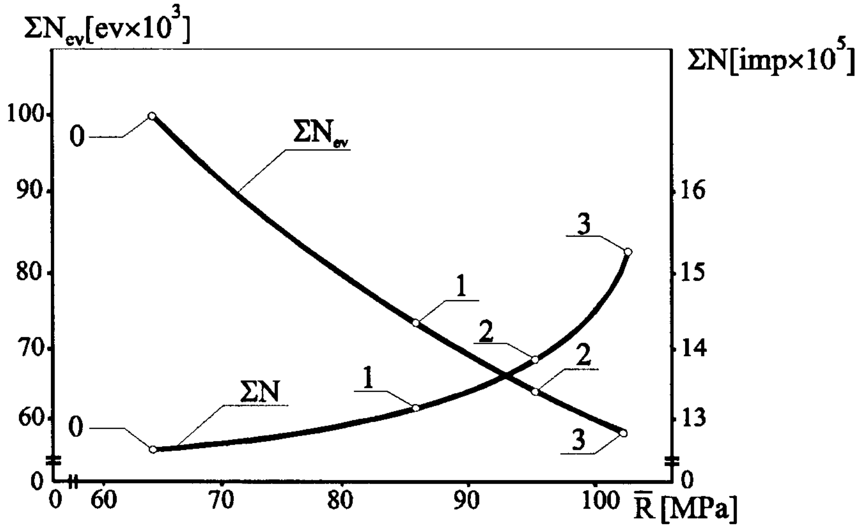

FIG. 5. Total events sum and total counts sum versus compression strength of tested high-strength concretes.

observations found in the literature, according to which microsilica contributes to the improvement of the homogeneity of the structure and to the reduction structural defects [2, 3, 4, 8, 9, 10, 11]. It has been established that the number of acoustic events correlates very well with the real number of events occurring in the structure of a material under a load [28]. Whereas the AE counts sum is correlated with the number of such events to a lesser degree. The sum depends to a large degree on the values of the amplitudes of the acoustic pulses emitted from the failing material [28]. The counts sum versus strength relationship shown in Fig. 5 suggests that high-strength concrete when failing, emits stronger acoustic pulses characterized by greater amplitudes. A similar counts sum-compression strength relationship was established in [20]. Figure 6 shows exemplary measurements of the AE counts rate versus failure time. The results indicate a rapid increase in the rate during the final stage of loading. One can use the diagrams of the relative stress increment during failure, included in Fig. 6, to read out the stress level from which the counts rate increases sharply. This level is not the same for all the tested concretes. For example, it is close to 0.7 σ/R in concrete 0 and to 0.8 σ/R in concrete 3. The results indicate that the tested concretes do not fail suddenly. Their failure is signalled clearly by the rapidly intensifying acoustic activity, starting from the level given above. The results suggest also that the failure of the concretes is not continual. A stage of catastrophic failure can be distinguished clearly in it. This is corroborated by the variation of AE counts sum increment rate versus relative stress increment σ/R. This rate was calculated using relation (3.1), [18]:

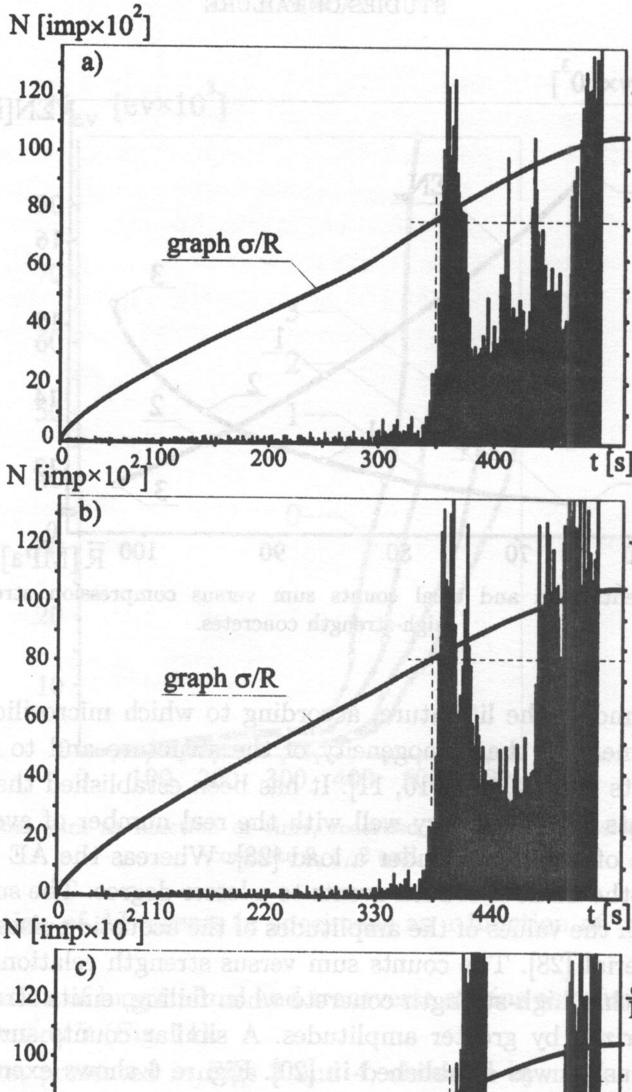

FIG. 6. AE counts rate N versus time and graph showing relative stress increment σ/R during failure for: a) concrete 0, b) concrete 1, c) concrete 3.

$$\text{IN} = \sum \text{N}_{n+1} - \sum \text{N}_n$$

where: IN – AE counts sum increment rate, $\sum N_{n+1}$ – the AE counts sum recorded for stress level "n+1", $\sum N_n$ – the AE counts sum recorded for stress level n. The rate for concrete 0, 1 and 3 is shown in Fig. 7.

To determine whether the failure of the high-strength concretes is a three-stage process, similarly as that of ordinary concrete, the obtained results were subjected to further analysis. The accuracy of reading the AE counts sum increment rate in the range covering the initial stage and the intermediate stage of loading was increased. Unfortunately, the very small increments of this sum per unit of stress made it impossible to obtain more detailed information than the one presented in Fig. 7. It should be explained here that three distinct stages can be distinguished in the course of the AE counts sum rate in ordinary concrete, which correspond to the three stages in the failure of the concrete, and the values of the initiating and critical stresses which delimit the stages can be calculated [17, 18, 25, 26]. Also the accuracy of reading the AE counts rate during the initial stage and the intermediate stage of loading was increased. Typical results for concrete 0, 1 and 3 are presented in Fig. 8. The figure shows that the counts rate at the initial stage of loading is slightly higher than later. This is undoubtedly due to apparent emission. As the loading proceeds, the rate of AE counts decreases and stabilizes. Therefore one can say that the loaded concrete has "quieted down acoustically". Then the counts rate starts increasing steadily. As the loading enters the final stage, a rapid increase in the AE counts rate takes place and continues until the concrete fails completely. Figure 8 includes diagrams of the relative stress increment during failure, with marked lengths of the particular stages of loading and the stress levels which delimit them. The stress levels are not the same for all the tested concretes. The observed three-stage course of the AE counts rate suggests that the failure of the tested high-strength concretes is a three-stage process. The lengths of the particular stages of failure correspond to the lengths of the stages in the course of the AE counts rate. Also the recordings of the AE signal RMS value, examples of which are shown for concrete 0 and 3 in Fig. 9, were examined. The examination revealed three distinct stages in the course of this parameter as a function of relative stress increment. Similarly as in the case of the counts rate, the AE RMS value is low and stabilized at the initial stage. As the load increases, so does the value of this parameter. Figure 9 shows that the increase in the AE signal RMS value is stepwise at the relative stress (σ/R) level of about 0.4. This stepwise increase is observed in concrete 3 at the level of 0.56 σ/R and it is much more pronounced than in concrete 0. Another rapid increase in the value of this parameter takes place in several jumps at the final stage of loading of the concretes. These data indicate that the failure of the high-strength concretes is a three-stage process. One should notice here the dis-

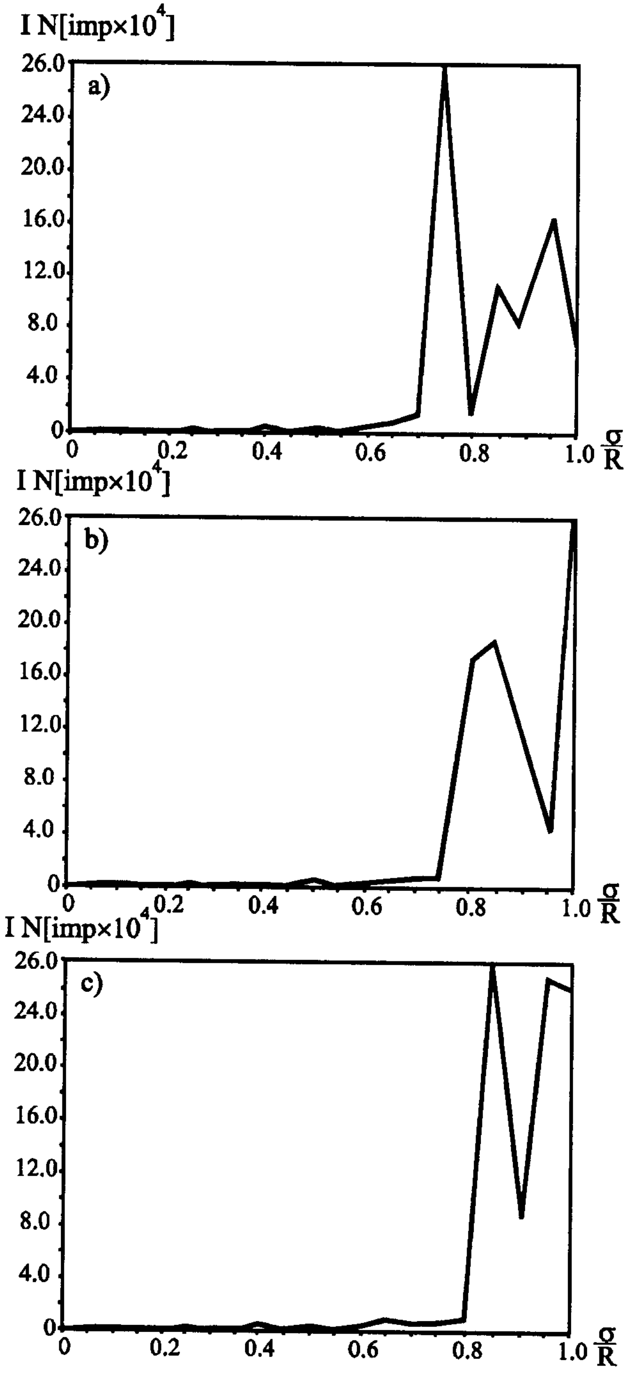

FIG. 7. AE counts sum increment versus relative compressive stress increment σ/R for: a) concrete 0, b) concrete 1, c) concrete 3.

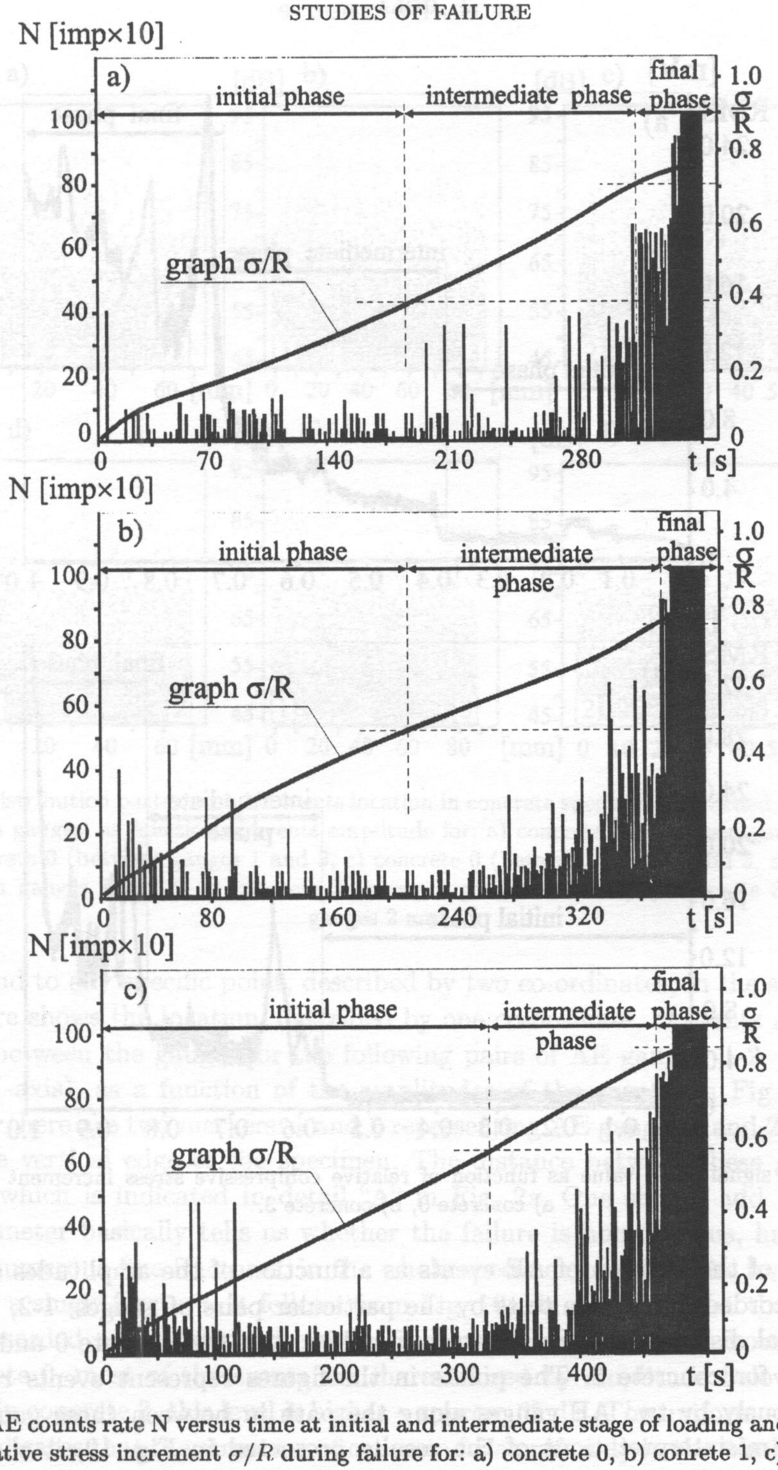

FIG. 8. AE counts rate N versus time at initial and intermediate stage of loading and graph showing relative stress increment σ/R during failure for: a) concrete 0, b) conrete 1, c) concrete 3.

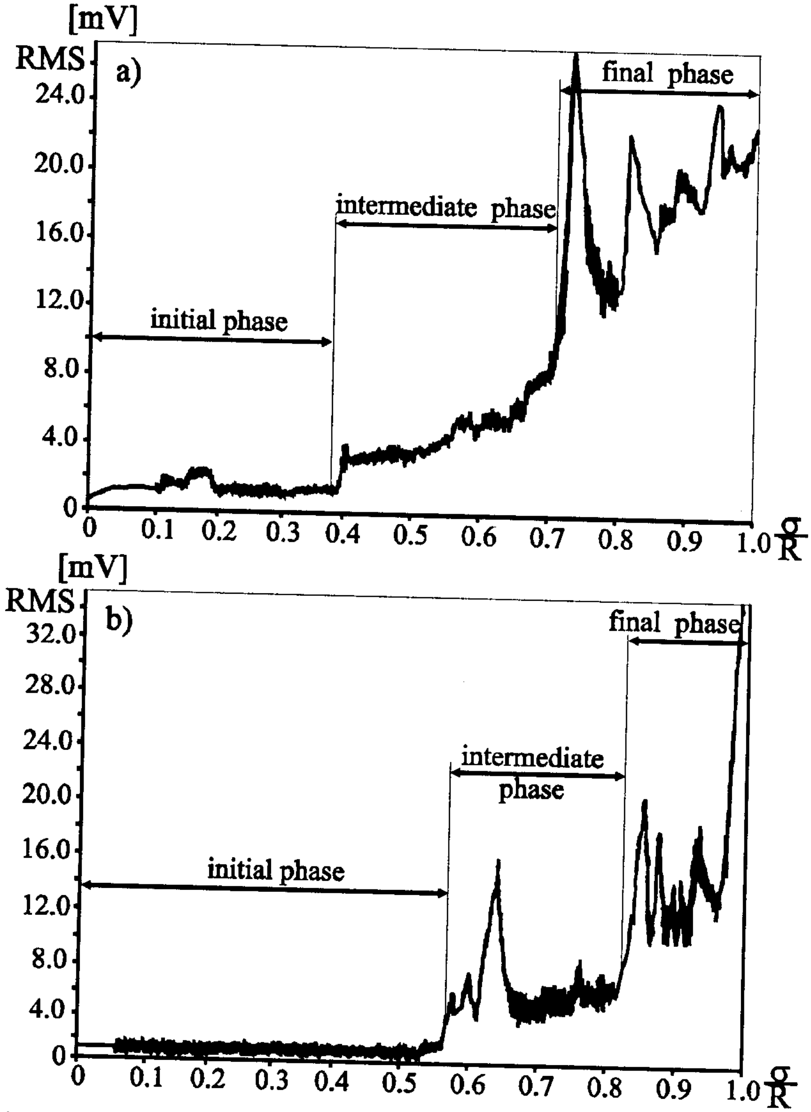

FIG. 9. AE signal RMS value as function of relative compressive stress increment σ/R for: a) concrete 0, b) concrete 3.

tributions of the location of AE events as a function of the amplitudes of these events, recorded during the tests by the particular pairs of gauges: 1-2, 1-3 and 2-3. Typical distributions are shown in Fig. 10 a, b, c for concrete 0 and in Fig. 10 d, e, f for concrete 3. The points in the figures represent events recorded simultaneously by two AE gauges along the path in between these gauges. To avoid any misinterpretations of the results presented in Fig. 10, it should be explained that the events recorded simultaneously by the two gauges do not cor-

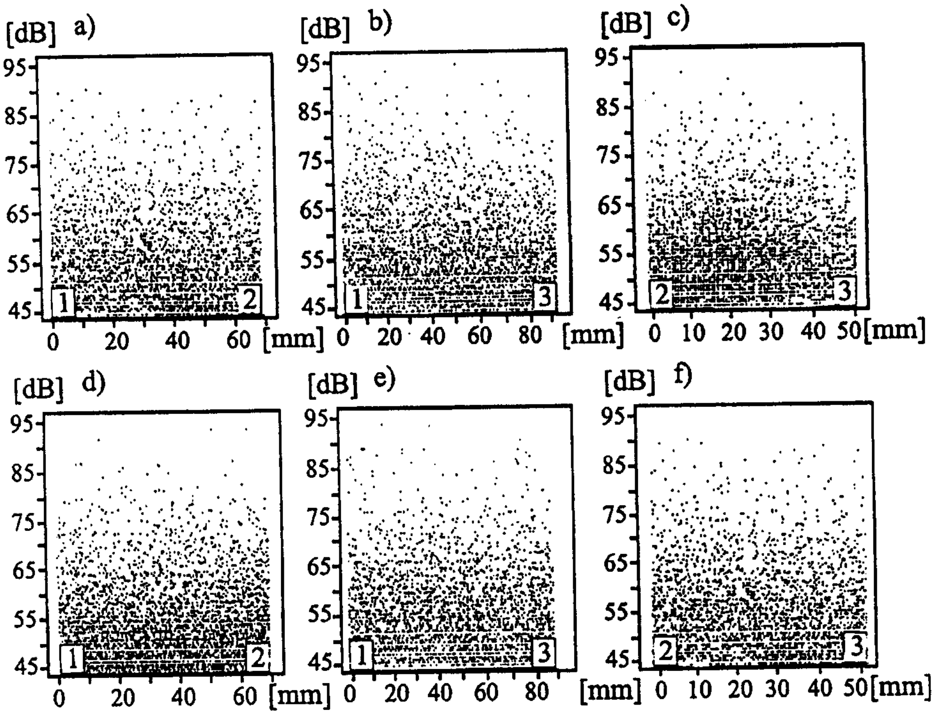

FIG. 10. Distribution patterns of AE events location in concrete specimens, recorded along path in between gauges, as function of events amplitude for: a) concrete 0 – between gauges 1 and 2, b) concrete 0 (between gauges 1 and 3, c) concrete 0 (between gauges 2 and 3, d) concrete 3 (between gauges 1 and 2, e) concrete 3 (between gauges 1 and 3, f) concrete 3 (between gauges 2 and 3.

correspond to any specific point, described by two co-ordinates, in the specimen. The figure shows the location, described by one co-ordinate, of events along the path in between the gauges for the following pairs of AE gauges: 1-2, 1-3 or 2-3 (the X-axis), as a function of the amplitudes of the events. In Fig. 10a, for example, there are two markers: 1 and 2 representing AE gauges 1 and 2 situated along the vertical edge of the specimen. The distance between these gauges is 70 mm, which is indicated in detail "A" in Fig. 2a. One should add that this AE parameter basically tells us whether the failure is homogenous, having the form of numerous fine fractures, in the whole specimen or it has the form of, for instance, a single fracture. It follows from Fig. 10a, b, c, d, e, f that the spacing of the recorded events along the paths in between the gauges is homogenous. In concrete 0, most of the events are characterized by amplitude below 55 dB, whereas in concrete 3, this level is higher – approx. 65 dB. The uniform spacing of events indicates that the structure of concrete fails uniformly in the whole volume of the tested concretes. This proves that the cause of the stepwise changes in the signal RMS value and the rapid stepwise increase in the value of the AE counts rate at the final stage of loading is not a single large fracture. The data indicate that this is an effect of many small cracks developing simultaneously in the structure once the concrete reaches an appropriately high level of effort. Moreover, the absence of marked concentration of AE events in the surface region (areas where gauges 1 and 2 are located) of the specimen being in direct contact with the testing machine's clamps proves that friction was eliminated.

In addition, the longitudinal and transverse strains in the concretes were measured as a function of stress increment. The measurement of these strains, in the case of ordinary concrete, constitutes a basis for the assessment of failure and the calculation of initiating and critical stresses. The criteria applied to the determination of these stresses on the basis of the measured strains can be found in [15, 17]. The results shown in Fig.11, similarly as those obtained in [9], prove that the strain-stress relationship is linear up to a relatively high level of effort of the tested high-strength concretes. For example in concretes 2 and 3, which contain microsilica and are characterized by the highest compression strength values, this linearity extends to the level of 0.7 σ/R. Therefore it is impossible, as Fig. 12 shows, to determine the stress levels at which the maxima of unit dilatational strain and those of the coefficient of transverse expansion occur in the tested concretes. This does not mean that no initiating stress occurs in the high-strength concretes but merely implies that the criteria applied to the determination of this stress in ordinary concrete are useless in the case of high-strength concrete. Nevertheless, it is possible to determine the stress levels at which the maximum of the global volumetric strain values occurs and the levels at which the volumetric strain decreases to zero again. The obtained results contradict the idea of the continual failure of the high-strength concretes and indicate a level of critical stress in them.

In the author's opinion, the failure of high-strength concrete can be regarded, in the light of the obtained results, as a three-stage process. It should be noted that it is much more difficult to distinguish the stage of the stable initiation of microcracks from the stage of the stable propagation of microcracks in high-strength concrete than in ordinary concrete. This is due to the much smaller number of microcracks which appear and develop during these stages of failure in high-strength concrete. As it was mentioned before, this is a positive result of an improvement in the homogeneity of the structure of this concrete and a considerable reduction in the number of structural defects.

The levels of initiating stress and critical stress which delimit the particular stages of failure of the tested high-strength concretes were determined. It was assumed that an initiating stress occurs at a level at which the stabilized low values of the AE counts rate and of the signal RMS value begin to increase steadily. The obtained results are presented in Table 3.

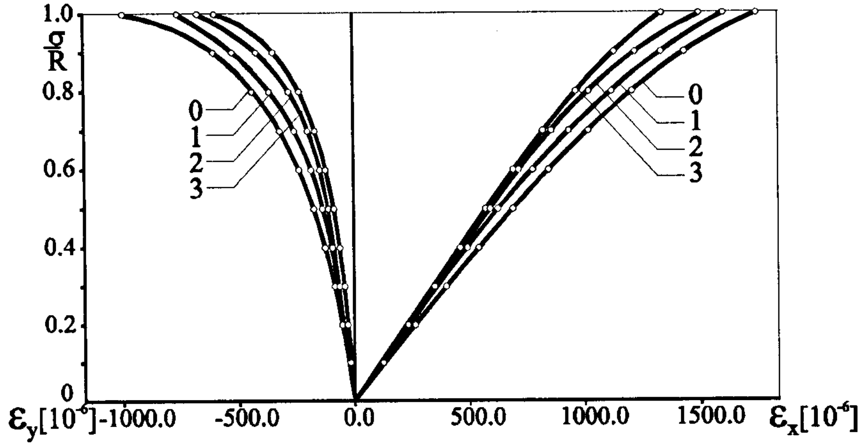

FIG. 11. Longitudinal and transverse stresses in high-strength concretes as function of relative compressive stress increment.

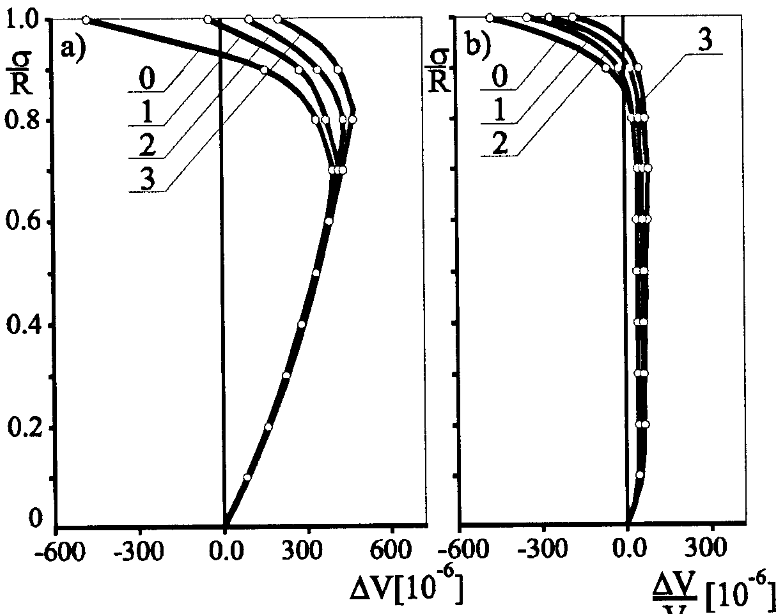

FIG. 12. Changes in strain curves as function of relative compressive stress for tested high-strength concretes a) total volumetric strain, b) unit volumetric strain.

Table 3. Values of initiating σ_i and critical σ_{cr} stress determined for tested high-strength concrete by acoustic emission technique and strain measurements.

Concrete designation	Measurement method			
	Acoustic emission technique		Strain measurement	
	σ_i	σ_{cr}	σ_i	σ_{cr}
0	0.40	0.73	–	0.75
1	0.45	0.76	–	0.78
2	0.52	0.80	–	0.83
3	0.56	0.82	–	0.85

It follows from Table 3 that the values of both the initiating stress and critical stress are the higher, the greater is the compression strength of the tested high-strength concretes. One should note the high values of initiating stress σ_i in the concretes with a microsilica additive. This means that the fatigue strength of these concretes is much greater in comparison with the fatigue strength of ordinary concrete and that of the other concretes tested. It is somewhat surprising that the values of critical stress σ_{cr} determined for the concretes with a microsilica additive are not significantly higher than those which usually occur in ordinary concrete [14, 15, 16, 17, 18, 23, 24]. On the basis of literature data one could rather expect that the stage of catastrophic failure of the high-strength concretes would begin at a much higher level of stress.

4. Conclusions

1. In the light of the results of the studies carried out by means of the acoustic emission technique and strain measurements, the failure of the tested high-strength concretes can be regarded as a three-stage process. It has been found that it is difficult to distinguish the stage of the stable initiation of microcracks from the stage of the stable propagation of microcracks in the failure of these concretes. It has been shown that the acoustic activity of the concretes is very low and the longitudinal and transverse stress-strain relationship is almost linear in the stress range covering the two stages. This is undoubtedly due to the small number of microcracks which appear and develop at these stages of failure. The stage of catastrophic failure stands out in this process. This is reflected in the rapidly increasing values of all the recorded AE parameters and in the evidently nonlinear strain-stress relationship.

2. The high-value initiating stress σ_i which marks the boundary between the stage of stable initiation and the stage of stable propagation was determined by

means of the acoustic emission technique. The measurement of the rate of AE counts rate as a function of failure time and the measurement of the signal RMS value as a function of relative stress increment were very helpful in this. Whereas the rate of AE counts sum increment as a function relative stress increment turned out to be unhelpful. The high-value critical stress σ_{cr} which marks the boundary between the stage of stable propagation and the stage of catastrophic failure was determined by applying the two research methods. In this case, the criteria applied to the determination of critical stress values in ordinary concrete turned out to be helpful.

3. 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 the microsilica additive. 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 ordinary 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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