ARCHIVES OF ACOUSTICS
24, 2, 233–244 (1999)

ACOUSTIC-EMISSION INVESTIGATION OF FAILURE OF HIGH-STRENGTH CONCRETE

J. HOŁA

Institute for Building Engineering
Wrocław University of Technology
(50-370 Wrocław, Wybrzeże Wyspiańskiego 27, Poland)

This paper presents results of acoustic-emission investigations of the failure of high-strength concrete. Concretes differing in their composition and compressive strength were tested. Several acoustic emission (AE) parameters were recorded as a function of failure time. It has been shown that the failure of such concretes is signalled, starting from a certain stress level, by visibly intensifying acoustic activity. An analysis of the AE measurements has shown that the failure of the tested high-strength concretes is not continual but multistage. Stress values which delimit these stages have been determined.

1. Introduction

High-strength concrete, in comparison with plain concrete, is characterized by very high compressive strength and a rapid increase of this strength at the initial stage of hardening. Its minimum compressive strength amounts to 60 MPa after 28 days of hardening [1, 2, 3]. This high strength is obtained by using aggregate and cement of proper quality and a small quantity of make-up water and modifying the structure with appropriate additives and chemical admixtures. Such concrete has been used increasingly more often in building practice to make concrete and reinforced concrete structural components, such as monolithic and prefabricated framework members employed in tall buildings and building structures, which work under heavy loads [3, 4, 5].

The stress pattern in the structure of loaded high-strength concrete is considered to be more uniform than that in plain concrete [2, 3, 6]. As a result, stress concentrations in the former are reduced. The size of defects which appear during the production stage is reduced due to a superplasticizer admixture and an addition of very fine particles of microsilica. The variation in porosity also is reduced and the interfacial transition zone becomes more consolidated. The difference between the rigidity of the aggregate and that of the cement mortar is smaller. As a result, fewer microcracks appear in the structure of loaded high-strength concrete whereby the crack resistance of this material increases but at the same time a fracture is more sudden [2, 3]. It is not clear if there is any warning sign of this sudden fracture. It is known only that during standard strength tests high-strength concrete fails in an "explosive" way. It is not clear either if, similarly as in plain concrete, the failure of this concrete is a multistage process and what the stress, i.e. initiating stress σ_i and critical stress σ_{cr}, levels delimiting the particular stages are. Papers [7, 8] deal with the investigation of the failure of concrete possessing high compressive strength but not exceeding 60 MPa. Taking into account the findings presented in papers [9, 10, 11, 12, 13, 14, 15 and 16], it can be assumed that the above kinds of stress delimit the particular stages in the failure of concrete. It is accepted that the initiating stress marks the upper limit of the elastic zone of concrete work under short-time loads and it assumes a similar value as that of the fatigue strength of the concrete. The critical stress is identified with the long-term strength of concrete. It is essential to know the values of these stresses in order to assess properly the durability and safety of, especially, concrete structures subjected to repeated loading or overloads. Since structures made of high-strength concrete are not an exception to this, the problems touched upon in this paper are important both for theory and practice.

2. Description of tests

Four high-strength concretes, made from crushed 2 – 16 mm basalt aggregate, washed 0 – 2 mm sand and Portland cement 45, were tested. Concrete composition designated as "0", which was first modified with a superplasticizer and then with a superplasticizer and micro silica to obtain ever higher values of compressive strength, was taken to be the initial composition. Table 1 summarizes the basic data on the tested concretes and Fig. 1 shows the increase in their compressive strength in time.

Table 1. Basic data on tested high-strength concretes.

Concrete designation	Components in kg/m³					Average compressive strength sfter 28 days [MPa]
	Cement	Aggregate	Water	Super-plasticizer	Micro-silica	
"0"	450	2033	180	–	–	65
"1"	450	2085	146	9.00	–	86
"2"	450	2096	140	11.25	13.50	95
"3"	450	2069	140	13.50	31.50	105

The failure of the concretes was investigated, after 90 days of curing, by subjecting 50 × 50 × 100 mm specimens cut out from larger elements to axial compression. There were 12 specimens in each batch of concrete. The acoustic emission technique was used. A diagram of the AE measuring position is shown in Fig. 2. The sum and rate of AE count, the sum of events and the short pulse energy were recorded versus failure time and stored in the computer's memory. The ultrasonic technique was used as an ancillary. In this case, changes in the velocity of longitudinal ultrasonic waves versus the stress increment were examined perpendicular to the direction of compression in 150 × 150 × 150 mm specimens.

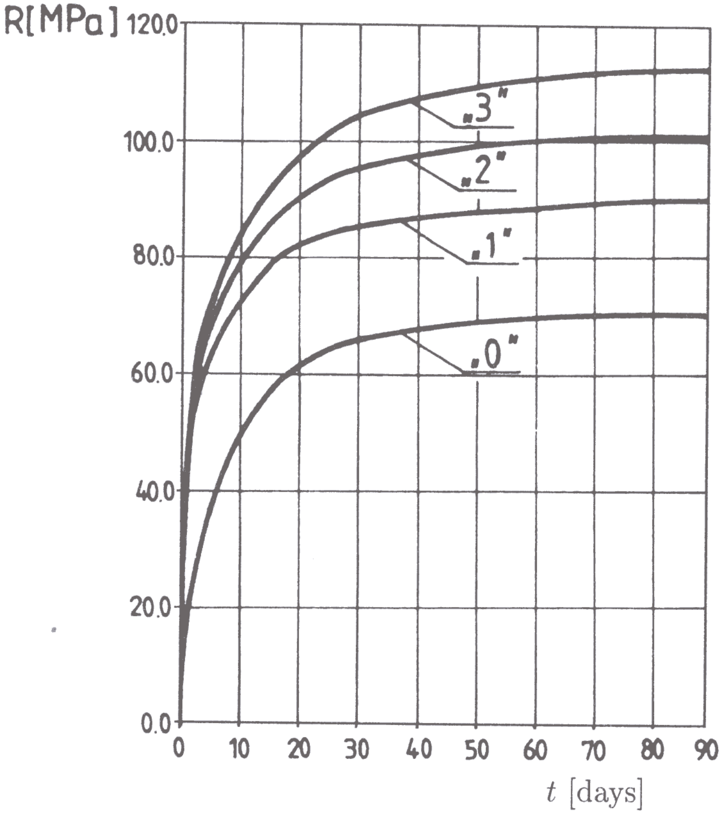

Fig. 1. Increase of compressive strength in time for tested high-strength concretes.

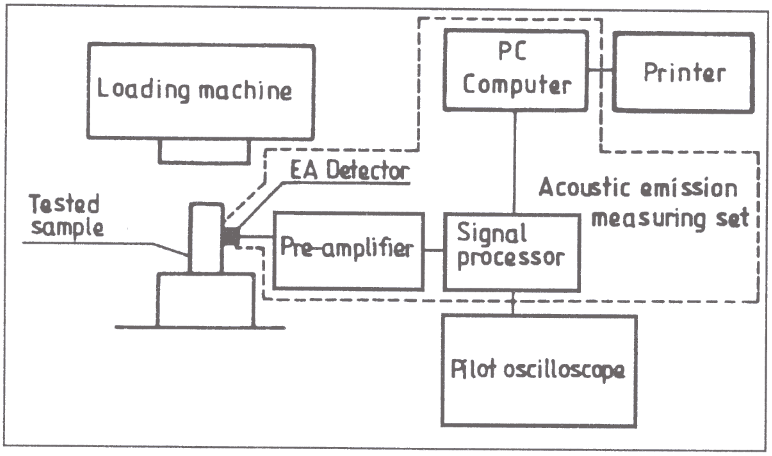

Fig. 2. Diagram of AE measuring position.

3. Test results and their analysis

The averaged AE counts recorded during the compression of the concrete specimens are presented as a function of failure time in Fig. 3. Figures 4, 5 and 6 show the rate of AE counts versus failure time for concretes "0", "1" and "3". It follows from the figures

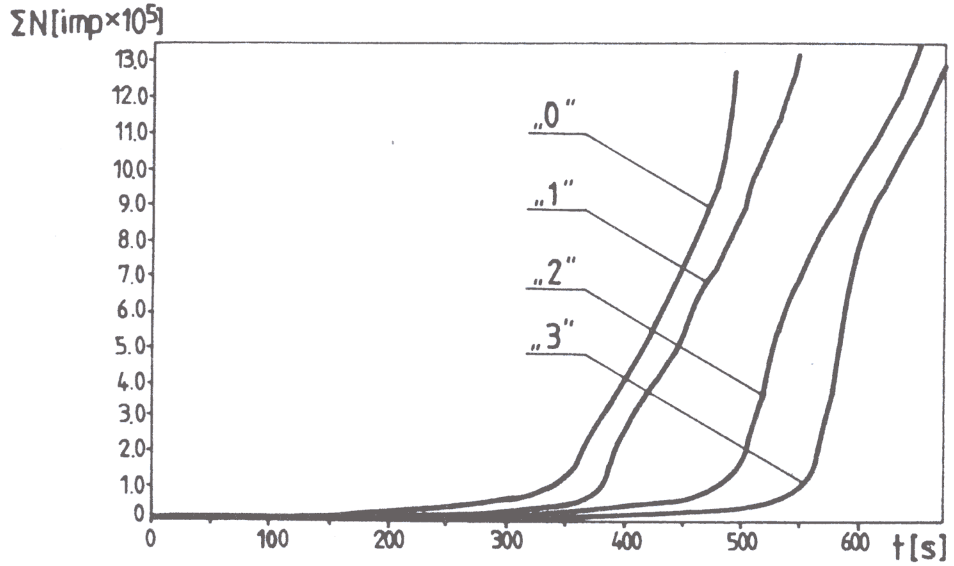

Fig. 3. AE counts vs. failure time determined during compression of high-strength concretes "0", "1", "2" and "3".

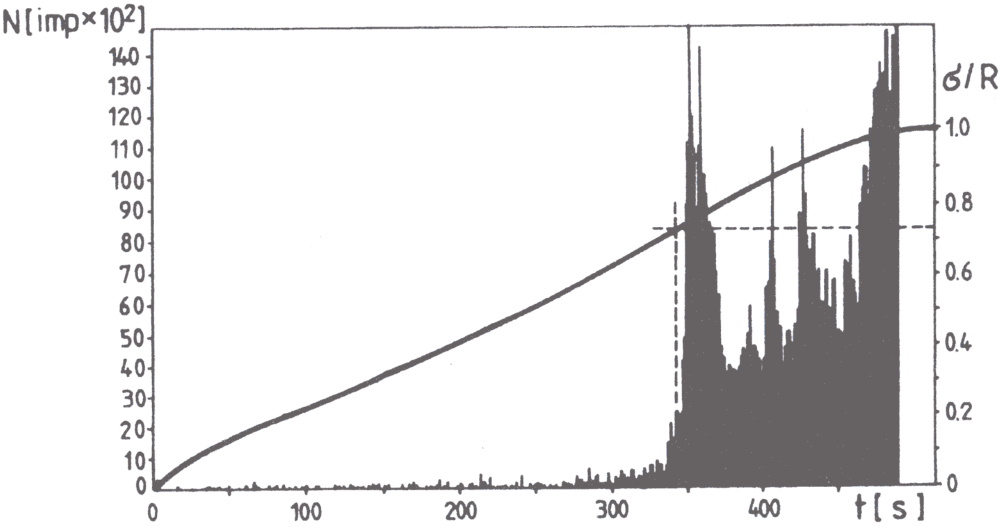

Fig. 4. AE counts rate vs. failure time for concrete "0".

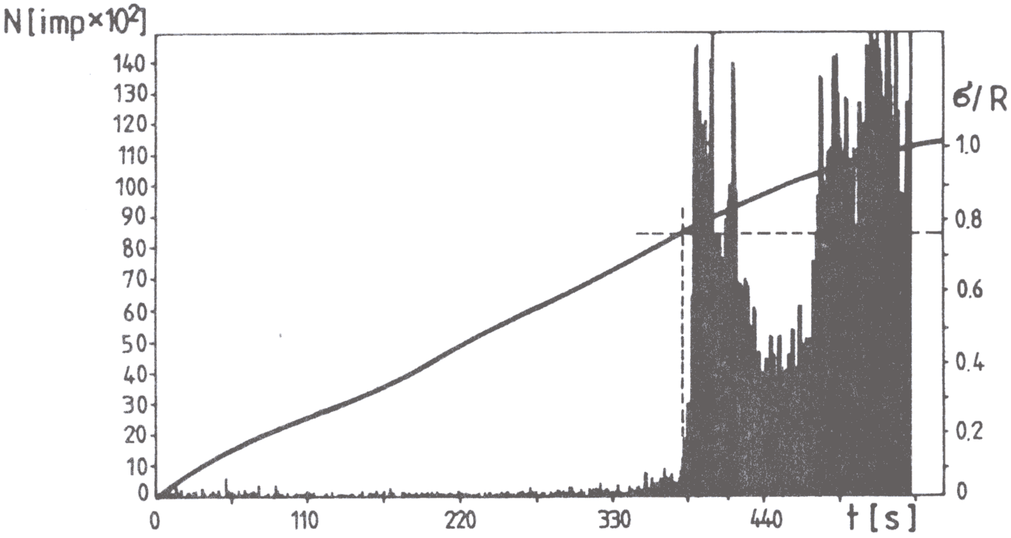

Fig. 5. AE counts rate vs. failure time for concrete "1".

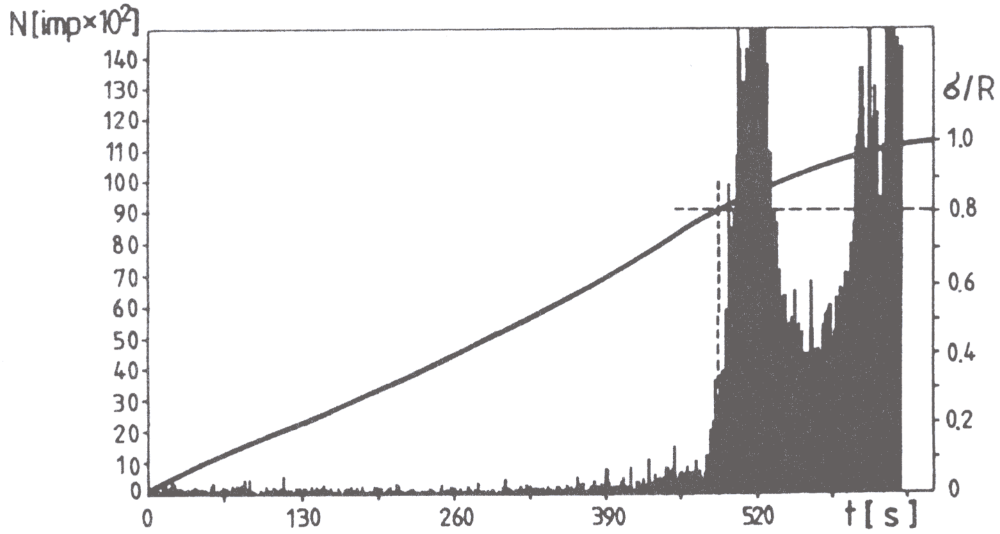

Fig. 6. AE counts rate vs. failure time for concrete "3".

that the acoustic activity of the tested concretes remains slight for some time after the commencement of loading. This indicates that few microcracks appear at the initial and intermediate stages of loading. It is only at the final stage of loading that the values of the measured AE parameters increase rapidly, which indicates that microcracks appear and develop at a very fast rate. Similar observations were made by the authors of paper [8] during the testing of high-strength concretes. It follows from the auxiliary diagrams in Figs. 4, 5 and 6, illustrating a relative increase in stress versus time, that the stress level above which the acoustic activity of the tested high-strength concretes increases rapidly is in the interval of $0.7-0.8\,\sigma/\mathrm{R}$. In concrete "0", this level is close to $0.7\,\sigma/\mathrm{R}$ and it is close to $0.8\,\sigma/\mathrm{R}$ in concrete "3". On this basis it can be concluded that the failure of the high-strength concretes does not occur suddenly. It is signalled by rapidly increasing acoustic activity. The obtained results indicate also that the failure of these concretes is not continual. This is confirmed by the variation of AE counts increment shown versus stress increment for concrete "0" and "1" in Figs. 7 and 8.

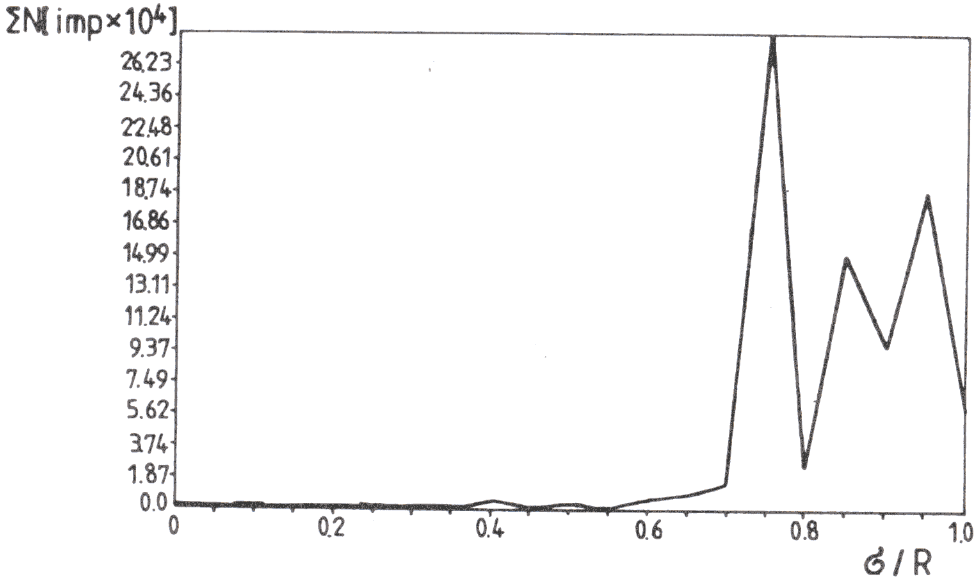

Fig. 7. AE counts increment vs. stress increment for concrete "0".

The test results were analyzed closely to determine if the failure of the concretes is a two-stage or, as in plain concrete, three-stage process. For this purpose, the accuracy of reading of AE counts rate during the initial and intermediate stages of loading was increased by changing the scale on the X-axis and the Y-axis. The obtained results are shown for concrete "0", "1" and "3" in Fig. 9. The figure shows that at the initial stage of loading the count rate is slightly faster than in the period which follows. This is clearly associated with apparent emission. As the loading continues, the AE counts rate decreases and stabilizes. One can say that the loaded concretes have "quietened down". At the intermediate stage the count rate begins to grow steadily. When the loading enters the final stage, the AE counts rate goes up sharply and continues to increase rapidly until the concrete fails totally. The stress levels which delimit these stages are marked in Fig. 9. The results of the investigations indicate that the failure of the high-strength concretes is a multistage process. These findings have been verified, although less firmly, by the measurements of the energy of short AE pulses, shown for concrete "0", "1" and "3" in Fig. 10. It is significant that the stress level at which stabilization ends and a steady increase of both the counts rate and the AE short signals energy begins is close

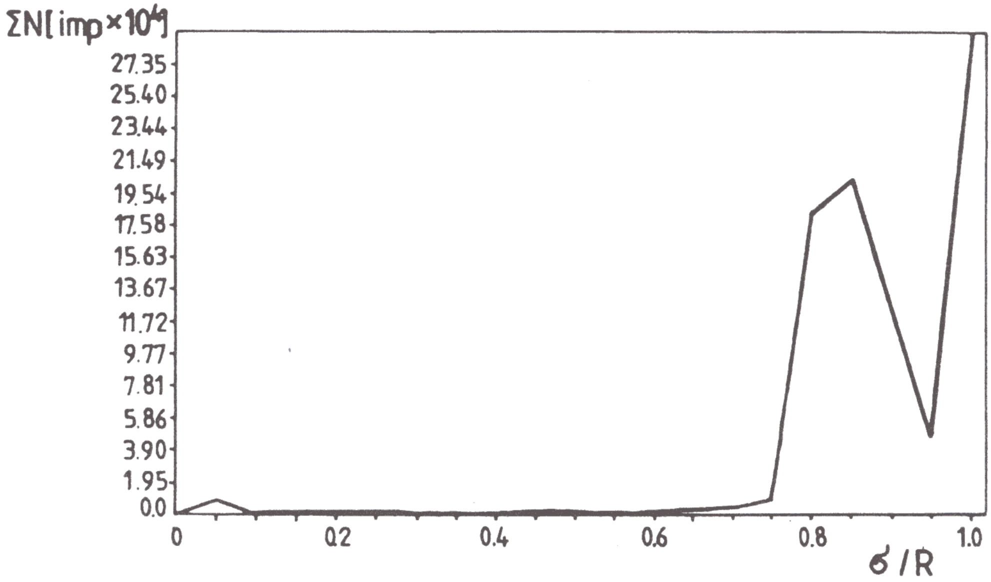

Fig. 8. AE counts increment vs. stress increment for concrete "1".

to the stress level at which also a decrease in the velocity of longitudinal ultrasonic waves is observed. Changes in the latter velocity during the compression of the high-strength concretes are shown in Fig. 11. Taking the above observations and the criteria given in [13, 15] into account, it can be assumed with a high probability that this level corresponds to initiating stress σ_i. The stress level at which the values of the measured AE parameters increase rapidly corresponds to the level at which it becomes impossible to measure the velocity of longitudinal ultrasonic waves in high-strength concretes. According to the criteria defined in [13, 14], this level corresponds to critical stress σ_{cr}. The averaged values of initiating and critical stresses in the tested concretes have been compiled in Table 2. It should be mentioned that the compressive force versus failure time data stored in the computer's memory turned out to be very useful for the determination of the stresses. It follows from Table 2 that both initiating and critical stress values are the higher, the higher the compressive strength of the tested concretes. They are

Table 2. Initiating and critical stress values determined for high-strength concretes by acoustic emission technique.

Concrete designation	Initiating stress σ_i	Critical stress σ_{cr}
"0"	0.40	0.73
"1"	0.45	0.76
"2"	0.52	0.80
"3"	0.54	0.82

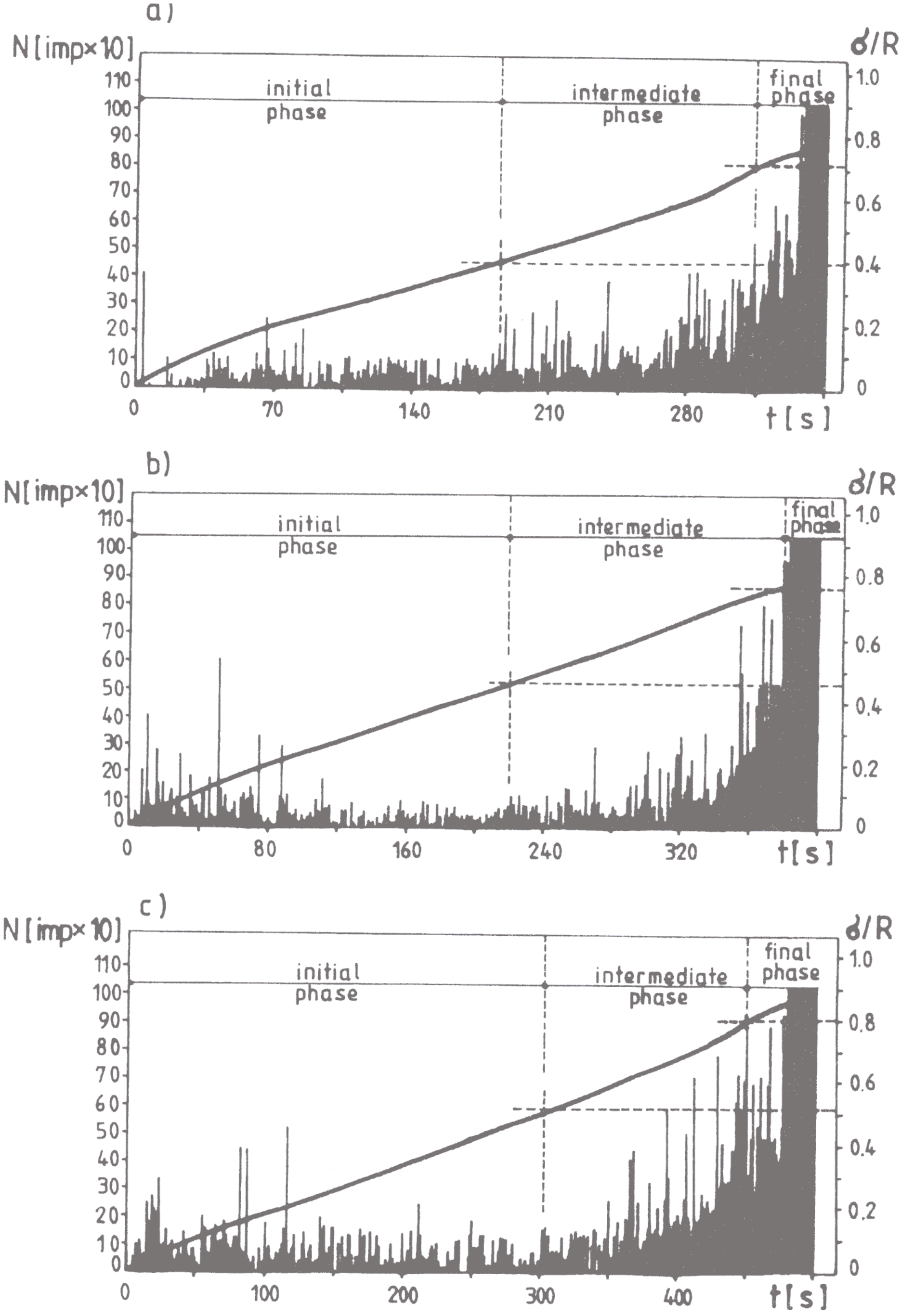

Fig. 9. AE counts rate at initial and intermediate stages of loading for: a) concrete "0", b) concrete "1", c) concrete "3".

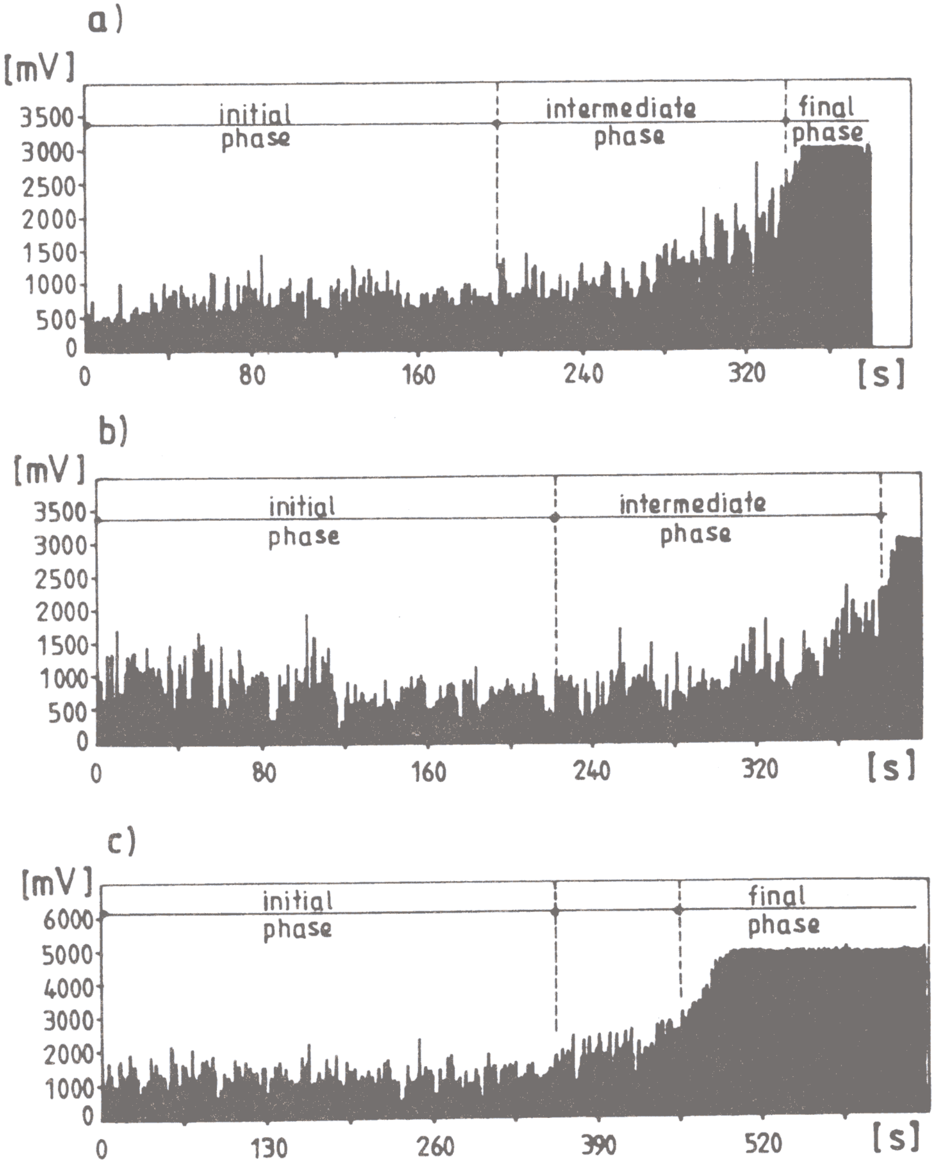

Fig. 10. Measurements of AE short pulses energy in: a) concrete "0", b) concrete "1", c) concrete "3".

highest in the high-strength concretes which contain microsilica. This may be due to the positive effect of microsilica on the structure of concrete. As mentioned previously, micro silica causes, among other things, the compaction of the structure in the interfacial transition zone between the aggregate and the cement paste [17, 18]. It contributes to a reduction in both the size of the portlandite crystals and the degree of their orientation relative to the aggregate grains [17, 18]. It also brings about a reduction in the size

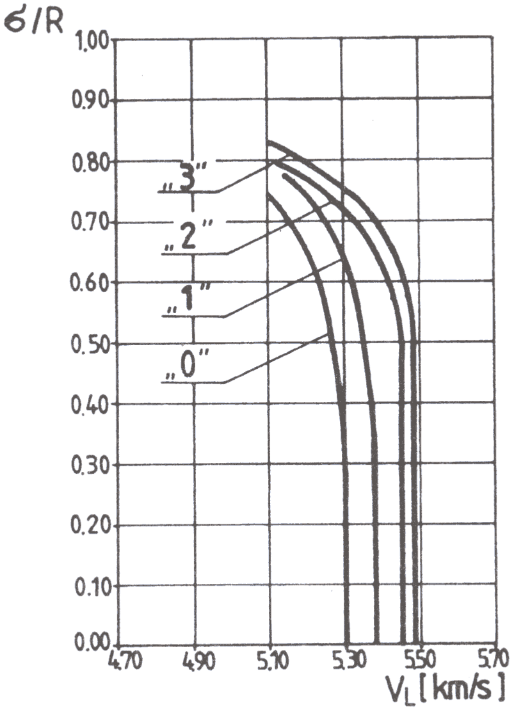

Fig. 11. Changes in velocity of longitudinal ultrasonic waves in compressed high-strength concretes "0", "1", "2" and "3" vs. stress increment.

of the largest pores and their partial closing not only in the interfacial transition zone but in the whole cement paste volume as well [19]. As a result, the size of defects which appear in the structure of high-strength concrete at the production stage decreases. Thus microcracks appear and develop in high-strength concretes at higher stress levels than in plain concrete, as manifested by higher values of initiating and critical stresses.

4. Conclusions

It has been determined by applying the acoustic emission technique that the acoustic activity of the tested high-strength concretes is very low at the initial and intermediate stages of loading. This indicates that very few microcracks appear during this time. A rapid increase in this activity, indicating intensive microcracking, occurs only at the final stage of loading. On the basis of the obtained results it can be concluded that the failure of high-strength concrete is not sudden and it is preceded by warning signs. The stress level at which the warning signs are very clear depends on the compressive strength of concrete and for the tested concretes it is in the interval of $0.7-0.8\,\sigma/\mathrm{R}$.

An analysis of the AE counts rate and the AE short pulses energy recorded as a function of failure time has shown that these relationships do not have continual character. At the initial stage of loading the values of the parameters, after their slight initial increase due to apparent emission, decrease and stabilize. Then there follows a steady increase in the values of the measured AE parameters, which becomes rapid at the final stage of loading. On this basis it can be concluded that the failure of the tested high-strength concretes is not a continual but multistage process. This has been confirmed by results of ultrasonic tests. The limits of the particular stages are initiating stress σ_i and critical stress σ_{cr}. It has been determined that the values of initiating stress in the tested high-strength concretes are within the interval of $0.40 - 0.54\,\sigma/\mathrm{R}$. The values of critical stress are in the interval of $0.73 - 0.82\,\sigma/\mathrm{R}$. It is symptomatic that the values of the two kinds of stress are the higher, the higher the compressive strength of the tested high-strength concretes. The highest values are recorded for concretes which contain an microsilica addition.

References

[1] J. Mikoś, *Technology of high strength concretes* [in Polish], Przegląd Budowlany, 8-9, 355–358 (1992).

[2] L. Kucharska and A.M. Brandt, *Composition, production and mechanical properties of high-strength concretes* [in Polish], Inżynieria i Budownictwo, 9, 356–360 (1993).

[3] J. Jasiczak and P. Mikołajczyk, *Technology of concrete modified by admixtures and additives. Domestic and foreign tendencies* [in Polish], Poznań 1997.

[4] R. Kowalczyk, *Application of high strength concrete in high buildings* [in Polish], Inżynieria i Budownictwo, 9, 366–369 (1993).

[5] K. Flaga, *Reflection about application of high-grade concrete in Poland* [in Polish], Przegląd Budowlany, 6, 4–7 (1995).

[6] L. Kucharska, *Forming of the structure of high-efficient concretes, the role of additions and admixtures* [in Polish], Przegląd Budowlany, 8-9, 351–354 (1992).

[7] M.M. Smadi and F.O. Slate, *Microcracking of high and normal strength concrete under short- and long-term loadings*, ACI J., **86**, 3, 117–127 (1989).

[8] J. Mierzwa, K. Pogan and Z. Ranachowski, *The correlation between the generated acoustic emission and the compressive and static strength in plain and high strength concrete*, Archives of Acoustics, **22**, 3, 333–342 (1997).

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

[10] K. Newmann and I.B. Newmann, *Failure theories and design criteria for plain concrete. Structures, solid mechanics and engineering design*, Proc. Southampton, 1969, Civ. Eng. Mat. Conf., 963–995, London 1971.

[11] A.M. Brandt *et al.*, *Cracking and failure mechanism in concrete-like composites* [in Polish], [in:] Mechanical Properties and Structures of Concrete Composites, Polish Academy of Sciences, Ossolineum, 163–209, 1974.

[12] Z. Ranachowski, *Application of acoustic emission method to determine the limit of proportionality and the static strength in concrete*, [in:] Brittle Matrix Composites 3, A.M. Brandt and I.H. Marshall [Eds.], Elservier Applied Science Publishers, London and New York, 234–239, 1991.

[13] J. Hoła, *Effect of aggregate grading on the stress degradation of compressed concrete*, Archives of Civil Engineering, 1–2, 85–101 (1992).

[14] K. Flaga, *The influence of the stresses on the stress destruction and the strength parameters of concrete. Analytical models and new concepts in mechanics of structural concrete*, Published by the Białystok University of Technology, Białystok, 55–77, 1993.

[15] J. Hoła, *Acoustic emission in concrete: Acoustic emission sources, application, methods* [in Polish], J. Malecki and J. Ranachowski [Eds.], Institute of Fundamental Technological Research, Polish Academy of Sciences, Biuro Pascal, Publishers, Warsaw, 223–240, 1994.

[16] P. Stroeven and A. Moczko, *Assessment of damage evolution stages in cementitious composites by acoustic emission technique*, 2nd International Conf. on Nondestructive Testing of Concrete in the Infrastructure, Nashville, 12–14, 1996.

[17] J. Piasta and W. Piasta, *Aggregates v. high strength concretes* [in Polish], Przegląd Budowlany, 8-9, 361–363 (1992).

[18] Cz. Wolska-Kotańska, *Utilization of a silica dustdirective tendency in world building industry* [in Polish], Przegląd Budowlany, 2, 19–21 (1995).

[19] A.M. Brandt, *Influence of the interfacial transition zone (ITZ) on the mechanical properties of high performance concretes (HPC)* [in Polish], [in:] Zagadnienia materiałowe w Inżynierii Lądowej MATBUD'98, Kraków-Mogilany, 21–30, 1998.