ENGINEERING TRANSACTIONS • *Enging. Trans.* • 40, 1, 25-36, 1992
Polish Academy of Sciences • Institute of Fundamental Technological Research

STUDIES ON THE EFFECT OF HEAT TREATMENT ON STRESS-PRODUCED FAILURE IN COMPRESSED CONCRETE

J. HOŁA (WROCŁAW)

This paper points out that the fracture process of plain concrete subjected to low-pressure steam heat treatment is different from that of the normally cured concrete. This was established by tests carried out by the methods of acoustic emission and strain measurements. The tests revealed that heat-treated concrete displays a considerably lower fatigue strength and a slightly higher long-term strength. This fact should be taken into account both in planning the cycles of heat treatment of concrete or in designing the prefabricated concrete structures, the safety of which largely depends on fatigue strength.

1. INTRODUCTION

The damage that takes place in concrete under stress depends upon a number of technological factors. These factors determine, among other things, dissimilarities and following them, the strength properties of concrete [14, 3]. They also accelerate the curing of concrete under thermal treatment, based on heat supply at the surface. What we mean here is concrete cured in low-pressure steam, a procedure widely used when manufacturing prefabricated concrete elements. During this procedure, the physico-chemical reactions intensify considerably. Thus, the material reaches the desired strength within a relatively short period, from a few to several hours, an essential goal of the contemporary technology of concrete. At the same time it should also be noted that, during the heat treatment of concrete in low-pressure steam, two essentially different phenomena occur in the stiffening of concrete: apart from the constructive quick hydration and formation of the cement stone, we also face the process of fracture. This process is connected with structural self-stresses appearing in concrete as a result of high temperature, humidity and pressure gradients [2, 5, 11, 1]. These stresses, also referred to as technological stresses, subsequently produce various structural defects in the concrete structure, notably volumetric and contraction microcracks, increased porosity and changes in the directions of capillaries. Hence, in numerous papers dealing with this topic it is found that the structure of concrete cured under conditions of low-pressure steam heat treatment is more exposed to cracking and other defects than the structure of concrete cured normally [2, 5, 9].

According to the above considerations, we are also justified in stating that the course of stress-produced damage in concrete subjected to low-pressure steam heat treatment will differ from that of normally cured concrete. This statement is also based on the fact that studies imply a greater susceptibility to cracking exhibited by prefabricated concrete structures. According to the author of this paper, the problem of the influence of the above-mentioned factor on the process of concrete failure has not been fully clarified experimentally as yet, as pointed out in [4, 7]. What is meant here is to find out, how it does affect the values of critical stresses, σ_{I} and σ_{II} in concrete. It is worth mentioning that the critical stresses denote certain accepted stress levels in concrete under load; if the levels are exceeded, certain characteristic phenomena occur in the material, e.g. the process of origination and propagation of cracks [14, 4, 8, 10, 13, 16]. According to [14, 10], critical stresses σ_{I} attain values similar to those of fatigue strength of concrete and can be defined as the lower boundary of damage in concrete. On the other hand, critical stresses σ_{II} are identified with long-term strength of concrete [14, 8, 13, 16]. It might appear advantageous to know the critical levels of stresses when, for instance, the values of safety coefficients for concrete, determined from the short-term strength test results [3].

In order to explain the problem under consideration, concrete specimens cured according to low-pressure steam treatment, were subjected to the quasi-axial compression test. The research techniques used were the acoustic emission method and, for comparison, the method of strain measurements.

2. DESCRIPTION OF THE TESTS

The tests were performed on normal concrete of B25-class compression strength, cured under the conditions of heat treatment. The tests were carried out after a 90-day curing, using block specimens of dimensions 100 × 100 × 100 mm, as well as cylindrical specimens 113 mm in diameter and

350 mm high, made of the concrete mix, of the following composition (per 1 m^3):

Portland cement "35" from Górażdże cement plant	321 kg,
Natural gravel "Proszowice"	1185 kg,
River sand "Wrocław"	711 kg,
Tap water	178 l.

There were four sample series made of this mix, three of which were subjected to heat treatment, infused in low-pressure steam, whereas the fourth series was cured normally – as the reference. Each of the series comprised 12 specimens of dimensions 100 × 100 × 100 mm, and 6 cylindrical specimens 113 mm in diameter and 350 mm in height.

The heat treatment of concrete was accomplished in a special infusion chamber, according to three thermal cycles. The variable parameters of the cycles were the lengths of the particular curing phases and the maximum temperature of heating. Figure 1 displays the schematic diagram of the heat treatment procedure, while in Table 1 the parameters characterizing the particular cycles are presented.

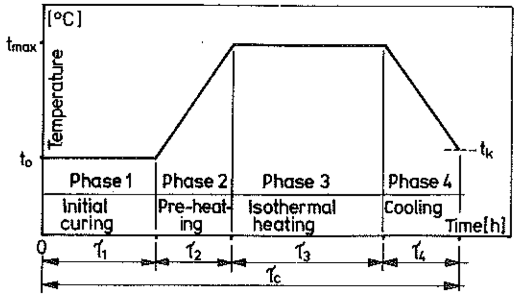

FIG. 1. Schematic diagram of the heat treatment process.

Table 1. Parameters characteristic for the cycles of heat treatment of concrete.

Cycle	Duration of a given phase [h]					Temperature [°C]		
	τ_1	τ_2	τ_3	τ_4	τ_c	t_0	t_{max}	t_k
Cycle 1	4.0	2.0	4.0	2.5	12.5	20	30	60
Cycle 2	2.0	2.0	3.0	1.5	8.5	20	80	30
Cycle 3	2.0	1.5	3.0	1.5	8.0	20	95	30

The following notations were accepted to characterize the concrete specimens:

N1 *series*	concrete heat-treated according to Cycle 1,
N2 *series*	concrete heat-treated according to Cycle 2,
N3 *series*	concrete heat-treated according to Cycle 3,
S1 *series*	concrete cured under normal conditions.

Curing and storage conditions for the particular concrete series were as follows:

N1 *series* – concrete heat-treated in low-pressure steam according to Cycle 1. After the treatment the samples were stored in a fog room for 24 hours, at the air temperature 18°C (± 1°C) and relative air humidity ca.95 %, and then – until the test date – in dry air conditions: the air temperature 18°C (± 3°C) and relative air humidity ca. 65 %.

N2 *series* – concrete heat-treated in low-pressure steam according to Cycle 2. Further procedure was as in the case of N1 series.

N3 *series* – concrete heat-treated in low-pressure steam according to Cycle 3. Further procedure was as in the case of N1 series.

S1 *series* – concrete stored, until the test date, in a fog room, the air temperature 18°C (± 1°C) and relative air humidity ca. 95 %.

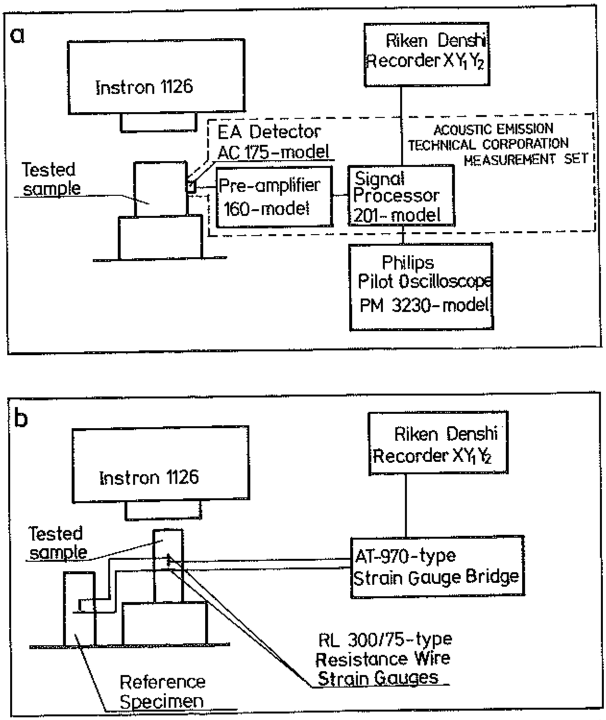

FIG. 2. Compression test configurations; a) measurement of acoustic emission, b) measurement of strain.

In the tests use was made of the acoustic emission method and, for comparison, of the method of strain measurements during the quasi-axial compression test. The specimens were compressed under friction-less contact conditions between the specimen and the testing machine pressure plates. To this end, these surfaces were ground and then lubricated with grease. The test stand unit for measuring the acoustic emission included the elements presented in Fig.2a; and that for strain measuring – in Fig.2b.

While testing the 100 × 100 × 100 mm specimens, recorded were the total acoustic emission counts and the effective voltage of the acoustic emission; considered as functions of the stress increment. On the other hand, in tests of the 113 mm in diameter and 350 mm in height cylindrical specimens, recorded were the longitudinal and transversal strains in concrete, also as functions of stress increment. The tests were carried out at the air temperature of 20°C (± 2°C) and relative humidity of ca. 55 %.

3. TEST RESULTS AND THEIR ANALYSIS

Test results of the acoustic emission showed that the total acoustic emission counts recorded during the entire process of destruction were distinctly higher when compared with the counts of the acoustic emission recorded in the normally cured concrete. This fact is illustrated in Fig.3, where displayed are the graphs of acoustic emission in the concrete series tested, as functions of the stress increments.

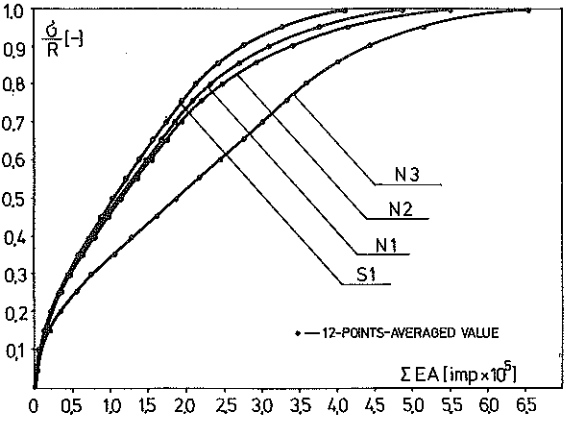

FIG. 3. Variation of total acoustic emission counts in S1, N1, N2 and N3 series for quasi-axially compressed concrete as a function of stress.

As to the thermally treated concrete, the total acoustic emission counts depend on the temperature of isothermal heating, i.e. the lower the heating temperature, the higher the counts. This is illustrated by the graph in Fig.4.

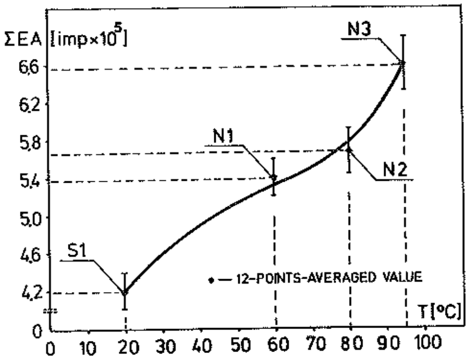

FIG. 4. Dependence of total acoustic emission counts on the temperature in concrete during isothermal heating.

We are justified to suppose that the character of the relationships shown in Figs.3 and 4 is the result of, among other things, the fact that cement hydration products tend, at higher temperature, to have a more coarse-crystalline structure than those in the case of products obtained at normal temperature. Significant also is a higher structural porosity of these products [15] and, as mentioned before, volumetric and contraction cracks due to temperature, humidity and pressure gradients. This means that during heat treatment the concrete structure obtained is more heterogeneous if compared with the structure of concrete cured normally; i.e., the structure obtained contains a greater number of potential spots that are sources of acoustic emission during the fracture process.

In order to expose the differences occurring in the fracture process of the concrete tested, the intensity of the total acoustic emission counts was determined as a function of stress. This function, for the particular concrete series, is shown in Figs. 5, 6, 7 and 8.

The figures imply that the intensity variation of the total acoustic emission counts is three-staged, depending on the stress increment. However, the lengths of the particular stages are different in different series tested. The results obtained prove that one can distinguish three characteristic stages displayed by the fracture process for the tested concrete series, the lengths of which depend on the temperature at which the curing took place. According

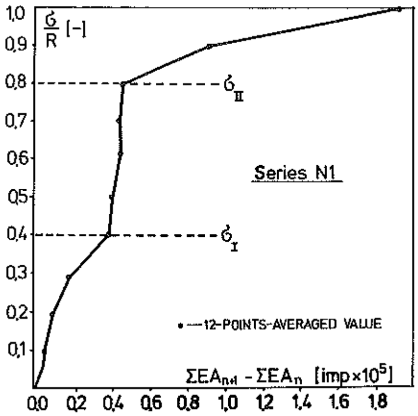

FIG. 5. **Intensity of total acoustic emission counts in N1 series for quasi-axially, compressed concrete as a function of stress**

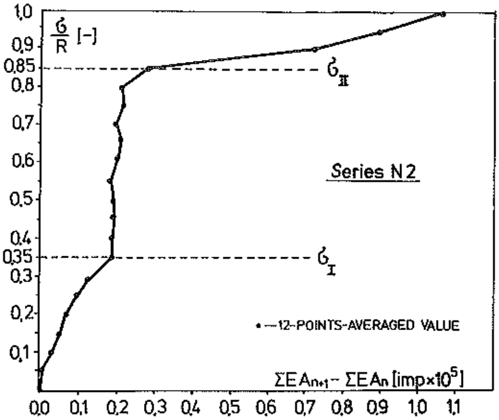

FIG. 6. **Intensity of total acoustic emission counts in N2 series for quasi-axially compressed concrete, as a function of stress.**

to [10], the first stage is the one of stable initiation of cracks. During the stage, microdefects appear at isolated points, in the forms of microcracks and pores. At this stage of fracture the existing microcrack do not propagate. Nevertheless, they tend to get multiplied, which – as was inferred from the tests (Figs.5, 6, 7 and 8) – is indicated by a constant increment of the total acoustic emission counts. As the load increases, the damage of concrete reaches the stage of stable propagation of crack during which the existing microcracks and those that have appeared at the first stage develop, new stable microcracks come into being – especially due to the loss of both the grip between the aggregate grains and the slurry and the grip between

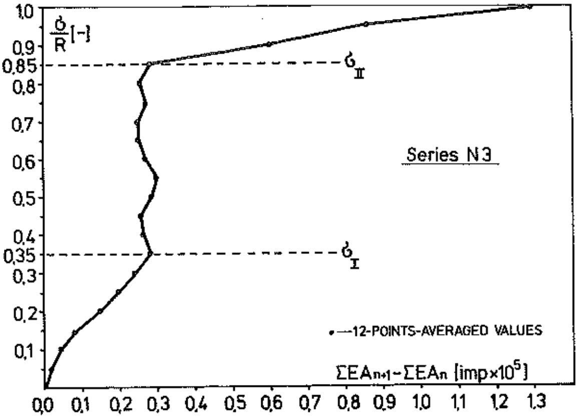

FIG. 7. Intensity of total acoustic emission counts in N3 series for quasi-axially compressed concrete, as a function of stress.

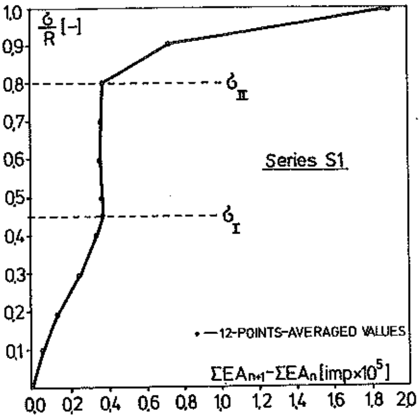

FIG. 8. Intensity of total acoustic emission counts in S1 series for quasi-axially compressed concrete, as a function of stress.

the very slurry grains [10]. This state is indicated by a stabilisation of total acoustic emission counts growth intensity (Figs.5, 6, 7 and 8). With further stress growth, the process of concrete damage reaches the stage of catastrophic destruction. During this stage wide distinct cracks are formed and spread out in an unstable manner until the entire material is destroyed. This phenomenon, observed during the tests, is manifested by a rapid increase of total acoustic emission counts growth intensity (Figs.5, 6, 7 and 8).

The boundaries between the particular stages of destruction are determined by critical streses σ_I and σ_{II} which, as mentioned before, are identified with fatigue strength of concrete and its long-term strength, respectively [14, 8, 10, 13, 16].

In the particular series of the tested concrete, the values of these stresses were determined by the acoustic emission method according to the criteria given in [6] and, additionally, by using the method of strain measurements according to the criteria given in [14, 3, 4]. The initial basis for determining the critical stress values by the strain measurement method is provided by longitudinal ε_x and transversal ε_y strains measured in the concrete, as functions of the stress increment.

Following the criteria given in [14, 3, 4], the critical stresses $\sigma_{\rm I}$ are identical with the stress level at which the following events occur:

1) minimum values of transversal expansion coefficients

$$\nu = \varepsilon_y/\varepsilon_x \qquad \text{(Fig. 9)},$$

2) maximum values of dilatation

$$\Delta V/V = \Delta\varepsilon_x - 2\Delta\varepsilon_y \qquad \text{(Fig. 9)}.$$

On the other hand, critical stresses $\sigma_{\rm II}$ are identical with the stresses when:

1) the value of the differential coefficient of transversal expansion $\Delta\nu = \Delta\varepsilon_y/\Delta\varepsilon_x$ assumes a value of 0.5 (Fig.9),

2) dilatation $\Delta V/V$ resumes the value of zero (Fig.9),

3) the maximum of the total value of dilatation $\Delta V = \varepsilon_x - 2\varepsilon_y$ is displayed (Fig.9).

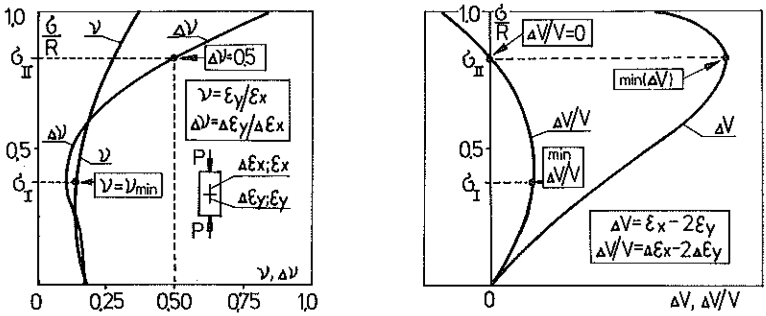

FIG. 9. Criteria for critical stresses in concrete explained by means of the strain measurement method [4].

The values of critical stresses determined in the tested concrete series with the help of the two measurement methods are compiled in Table 2. They have also been adduced in Figs. 5, 6, 7 and 8. Moreover, Fig.10

includes a graphical representation of the research results listed in Table 2.

Table 2. Critical stress average values σ_I and σ_{II} as determined in the tested concrete series.

Concrete series \ Test Method		Accoustic emission		Strain measurements	
		σ_I	σ_{II}	σ_I	σ_{II}
Series	N1	0.40	0.80	0.40	0.82
Series	N2	0.35	0.85	0.37	0.85
Series	N3	0.35	0.85	0.34	0.86
Series	S1	0.45	0.80	0.46	0.81

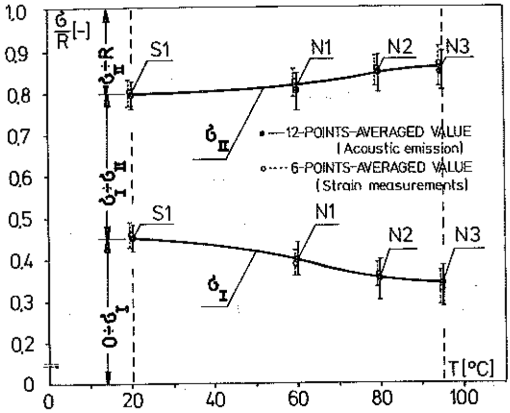

FIG. 10. Variation of critical stress values σ_I and σ_{II}, in relation to the temperature of heat treatment of concrete.

When analysing the results in Table 2, it can be seen that the values of critical stresses σ_I are markedly lower in comparison with these stress values in concrete cured normally. This reduction refers mostly to N2 and N3 series, for which isothermal heating temperature was the highest. This fact proves that, in the case of concretes subjected to low-pressure steam heat treatment, there is a limitation on the stress range 0 - σ_I. Consequently, the process of failure of these two kinds of concrete reaches its second stage – that of, among other things, stable propagation of the microcracks formed during the technological processing – at a smaller strain of the material than that of the material cured normally. This also means that concrete manufactured at plants for prefabricated elements on the basis of accelerated curing in low-pressure steam displays a lower value of fatigue strength in comparison with normally cured concrete. This fact should be taken into account when designing structures of high safety requirements.

Critical stresses σ_{II} exhibit an opposite tendency. Nevertheless, it should be noted that, from the viewpoint of structure safety, high values of critical stresses σ_{II} in concrete do not necessarily increase its strength properties [12]. Hence, when assessing the structures made of concrete subjected to heat treatment, the lack of marked symptoms preceding their failure should always be taken into account.

4. CONCLUSIONS

We have found distinct differences in the total acoustic emission counts recorded during fracture of heat-treated concrete in comparison to the emission recorded in normally cured concrete.

It has been pointed out that the concrete fracture process depends on heat treatment, what is proved by the values of critical stresses σ_I and σ_{II} separating the particular stages of fracture. Compared with the normally cured concrete, heat-treated concrete displays a marked reduction of critical stresses σ_I, this tendency increasing together with growth of the heating temperature in concrete. This is tantamount to a decrease of this concrete fatigue strength. This fact should be taken into consideration either in planning the cycles of heat treatment of concrete or in calculating a prefabricated structure, the safety of which will be decided by its strength. In case of critical stresses σ_{II} in heat-treated concrete, the values of these stresses slightly grow up.

REFERENCES

1. G.CHRABCZYŃSKI, *Heat treatment of concrete in industrial production of prefabricated elements,* [in Polish], Warsaw Techn. Univ. Sci. Reports (Civil Enging),**68**, 1980.
2. K.FLAGA, *Energy principles of strength increase in concrete solidifying under heat treatment conditions,* [in Polish], Cracow Techn. Univ. Sci. Reports (Civil Enging), 40, 1971.
3. K.FLAGA and K.FURTAK, *Effect of aggregate quality on critical stress levels in compressed concrete,* [in Polish], Arch. Inż. Ląd., **26**, 4, pp.653-666, 1982.
4. K.FURTAK, *Load carrying capacity of reinforced concrete cross-sections subject to variable bending; application to bridge structures,* [in Polish], Cracow Techn. Univ. Sci., Reports (Civil Enging.), 64, Hab. Dissertation, 1985.

5. К.Е.Горянов, Е.С.Векслер, Деструкция в твердеющем бетоне раннего возраста при нагреве и способы умещния ее интенсивности, Труды РИЛЕМ ИЛПС, 56-61, Москва 1968.

6. J.Hoła and A.Moczko, *Failure analysis of certain concrete structures by means of the ultrasonic and acoustical emission methods,* [in Polish], Wrocław Techn. Univ., Ph. D.-Dissertation, 1984.

7. J.Hoła, *Selected problems of fracture mechanics of concrete subject to ageing treatment,* [in Polish], Cement – Wapno – Gips, 10-11, pp. 230-252, 1990.

8. T.C.Hsu, F.O.Slate, G.M.Sturman and G.Winter, *Microcracking of plain concrete and the shape of the stress-strain curve,* ACI J., **60**, 2, pp. 209-224, 1963.

9. A.Kuśnierz and K.Flaga, *Heat treatment of concrete in microwave field,* [in Polish], XXXIII Sci. Conf. of the P.A.S. Civil Enging. Committee, Krynica 4, pp. 85-90, 1987.

10. K.Newman and I.B.Newman,*Failure theories and design criteria for plain concrete. Structure, solid mechanics and engineering design,* Proc. Southampton, 1969; Civ. Eng Mat. Conf., pp. 963-995, London 1971.

11. С.Реинсдорф, Пропаривание бетона при атмосферном давлении, Труды, РИЛЕМ, 130-139, Москва 1968.

12. J.Ruppert, M.Libura and W.Zarębska, *Limit states of cracking of reinforced concrete beams made of carbonate concrete,* [in Polish], Inż. i Bud., 9-10, pp.326-327, 1980.

13. H.Rüsch, *Physikalische Fragen der Betonprüfung,* Zement-Kalk-Gips, 12, 1, pp. 1-9, 1959.

14. S.P.Shah and S.Chandra, *Critical stress volume change and microcracking of concrete,* ACI J., **65**, 9, pp. 770-781, 1968.

15. B.Stawiski, *Effect of heat treatment and aggregate size on the quality parameters of concrete in prefabricated elements tested by ultrasonic methods,* [in Polish], Wrocław Techn. Univ., Ph.D.-Dissertation, 1975.

16. V.A.Yerlici, *Behaviour of plain concrete under axial tension,* ACI J., **62**, 8, pp.987-991, 1965.

INSTITUTE FOR BUILDING ENGINEERING
WROCŁAW UNIVERSITY OF TECHNOLOGY, WROCŁAW.

Received January 24, 1991.