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EXPERIMENTALLY DETERMINED EFFECTS OF TECHNOLOGICAL AND SERVICE FACTORS ON STRESS-INDUCED DESTRUCTION OF CONCRETE UNDER COMPRESSION

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In the paper, the effects of different technological and service factors on the levels of fracture-initiating stress σ_i and critical stress σ_{cr} in concrete under compression have been compiled. Experimentally determined ranges of the stresses are given. Technological and service factors contributing to a high or low level of the stresses have been grouped together. It is shown how some technological and service factors affect the fatigue strength of concrete. This is done for a few selected concretes on the basis of known levels of the fracture-initiating stress σ_i and critical stress σ_{cr}.

1. Introduction

The influence of technological and service factors on the stress-induced destruction of concrete has been the subject of research for some time. This is connected with a desire to improve the operational safety and durability of structures made of this material. In this context, knowledge of the level of fracture-initiating stress denoted as σ_i and the level of critical stress denoted as σ_{cr} becomes useful. The levels are understood to be certain conventional thresholds delimiting three qualitatively different (from the structural damage point of view) stages in the destruction of concrete [1-5].

The level of stress σ_i is associated with such an effort of concrete at which the initiation of technological microdefects is no longer stable. The level of critical stress is assumed to correspond to such an effort of concrete at which unstable propagation of microcracks starts in the structure of concrete under compression [1–5, 6]. It should be noted that indirect methods, such as the strain measurement method and the acoustic emission (AE) method, are successfully applied to determine these conventional levels of stress [6, 9].

The levels of stress σ_i and σ_{cr} are regarded as the two principal strength characteristics of concrete under compression informing us about its tendency to signalled or not signalled cracking [5, 8, 10]. Attempts have been made to relate the design compression strength of concrete in reinforced and prestressed bridge structures to the above stress levels [5, 11]. Also proposals to calculate the fatigue strength and long-term strength of concrete on the basis of the levels of stress σ_i and σ_{cr} have been offered [5, 12].

Research has shown that stresses σ_i and σ_{cr} reach different levels even in concretes with similar compression strength. This is so because the levels are correlated with the state of the structure prior to loading (including the presence of internal stresses and the associated structural microdefects) and with the increment of the microdefects as a result of loading [4, 5, 11, 13]. They are thus correlated with such technological factors as the concrete mix composition and the conditions existing during concrete formation. The levels of the considered stresses have also been found to be linked to nonmechanical service factors, including the conditions in which concrete works [10, 14]. Therefore the mentioned above tendency of concretes to signalled or not signalled cracking is not equal, even if their compression strengths are similar.

Also the dependence of the fatigue strength of concrete not only on the number and parameters of the load cycles but on technological and service factors as well – significant for the safety and durability of structural elements subjected to repeatedly variable loads – is perceived [5, 12]. Since the influence of these factors on the fatigue strength cannot be measured directly, attempts are made to handle this indirectly through the levels of stress σ_i and σ_{cr} directly dependent on technological and service factors [5, 12].

The above considerations give sufficient grounds for the investigation of the relationship between the levels of stress σ_i and σ_{cr} in concretes under compression, and the main technological factors and nonmechanical service factors having an influence on the formation of this material. Experimental results shedding light on how the levels of the considered stresses are determined by particular factors can be found in [8, 10, 12, 13, 15–25]. But the results have not been compiled and systematized, which makes it difficult to utilize them in the controlled shaping of the structure of concrete (to obtain the prescribed characteristics suitable for given service conditions), and in prediction of the behaviour of this material in such conditions.

In other words, what is needed is a compilation of the levels of fracture initiating stress σ_i and critical stress σ_{cr} and their ranges depending on the various technological and service factors affecting concrete. Also the factors whose effects on concrete are similar as regards the levels of the considered stresses should be grouped together. The explanation of the influence of technological and service factors on the fatigue strength of concrete provided in the literature seems to be inadequate. The relevant experimental results found in [12] apply only to a narrow group of factors which occur in practice. The present paper to a large extent fills the above mentioned gaps in the literature on the subject.

2. Factors and associated ranges of fracture-initiating stress and critical stress values

The relative levels of fracture-initiating stress σ_i and critical stress σ_{cr} depending on the various investigated technological factors and nonmechanical service factors acting on concrete under compression have been compiled in Table 1. The compilation is based on experimental results obtained by different authors, including the present one (the data sources are given in the table).

An analysis of the results compiled in Table 1 shows that the relative levels of stresses σ_i and σ_{cr} range widely for the various technological and nonmechanical service factors affecting concrete under compression. On the whole, the level of stress σ_i is within the range of 0.17 – 0.60 σ_c/f_c and that of stress σ_{cr} within the range of 0.66 – 0.91 σ_c/f_c. Many researchers report that concretes in which the σ_i/f_c ratio is high are characterized by, e.g., linear elasticity up to quite a high relative value of compressive stress, limited plastic deformability, higher fatigue strength, better corrosion resistance, cracking under a greater load but more

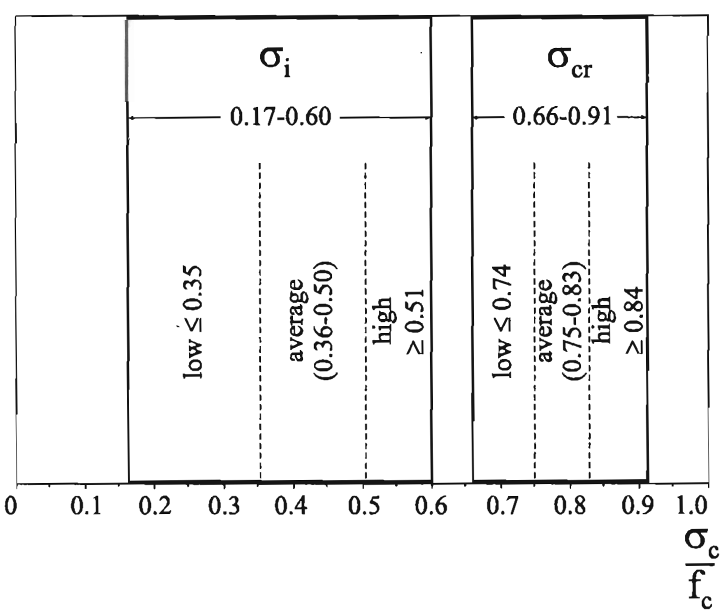

FIG. 1. Ranges of relative levels of fracture-initiating stress σ_i and critical stress σ_{cr} in concretes under compression.

Table 1. Compilation of relative levels of fracture-initiating stress σ_i and critical stress σ_{cr} for different investigated technological and service factors affecting concrete under compression.

No.	Investigated technological or service factor		Relative levels of stresses σ_i and σ_{cr}	
			σ_i/f_c [-]	σ_{cr}/f_c [-]
1	2		3	4
1.	Normal thermal-moisture conditions of curing [**8, 10, 26**]		0.46 - 0.51	0.80 - 0.88
2.	Air-dry thermal-moisture conditions of curing [**8, 10, 26**]		0.40 - 0.46	0.70 - 0.81
3.	Wetting to full saturation with water [**26**]		0.20	0.90
4.	Drying to dry condition at temperature of 105°C [**26**]		0.30	0.80 - 0.82
5.	Subzero temperature during curing [**5, 24**]		0.17 - 0.23	0.71 - 0.75
6.	Heat treatment in low-pressure steam at temperature < 80°C [**16, 17**]		0.36 - 0.41	0.81 - 0.90
7.	Heat treatment in low-pressure steam at temperature ≥ 80°C [**16, 17**]		0.34 - 0.35	0.76 - 0.91
8.	Heat treatment in microwave field [**18**]		0.37	0.83
9.	Heating concrete mix components up to temperature of 45°C [**27**]		0.41	0.81
10.	Kind of coarse aggregate [**10, 28**]	rounded	0.41 - 0.50	0.70 - 0.83
		limestone	0.51	0.88
		basaltic	0.45	0.80
11.	Sand content in rounded aggregate in relation to total aggregate [**19**]	20 % ≤ sand ≤ 47%	0.40 - 0.45	0.70 - 0.81
		47 % < sand ≤ 60%	0,50	0,82 - 0,83
		60 % < sand ≤ 100 %	0.34 - 0.24	0.86 - 0.90
12.	Aggregate surface condition [**15**]		0.40 - 0.50	0.83 - 0.86
13.	Aggregate's adhesion to mortar [**1**]	weak	0.10 - 0.20	0.74
		strong	0.43	0.76
14.	Plasticizer additive [**21**]		0.45	0.66 - 0.77
15.	Plasticizer and silica fumes additive [**21**]		0.50 - 0.60	0.81 - 0.84
16.	Steel fibre reinforcement [**22**]		0.45	0.89
17.	Impregnation of concrete with polymer [**23**]		-	0.90
18.	Impregnation of concrete with mineral oil [**29**]		0.30 - 0.40	0.75 - 0.80
19.	Age of concrete [**24, 25**]	up to 28 days	0.20 - 0.30	0.76 - 0.80
		over 28 days	0.30 - 0.45	0.76 - 0.80

abruptly and with longer and wider cracks spaced (on the average) more apart [5, 11, 12, 28, 30–34]. Whereas concretes in which the σ_{cr}/f_c ratio is high are characterized by, e.g., higher resistance to cracking induced by sustained static loading, and less signalled subsequent failure [5, 6, 33, 35].

Taking the above into consideration, a division of the wide ranges of the levels of stress σ_i and σ_{cr} into three parts is proposed. Levels of stress σ_i and σ_{cr} in the extreme parts of the ranges will be referred to respectively as low and high, and the ones situated in their middle part – as average. This is illustrated in Fig. 1 where the conventional boundary levels dividing low values from average values and average values from high values, are marked with a broken line.

Taking into account the research results compiled in Table 1 and the proposals shown in Fig. 1, the most important technological and service conditions affecting the levels of stress σ_{i} and σ_{cr} have been grouped as shown in the figures below.

3. Relationship between fatigue strength of concrete and technological and service factors

Since the effect of technological and service factors on the fatigue strength of concrete cannot be measured directly, it was determined indirectly. For this purpose, results of the author's own research on the levels of stress σ_{i} and σ_{c} in concretes under compression and relation (3.1) for the calculation of the fatigue strength proposed in [12] were used. It should be noted that relation (3.1) was verified experimentally [12].

$$f_c^f / f_c = C N^{-A} \left(1 + B \rho^f \log N\right) C_f, \tag{3.1}$$

where:

- f_c^f – fatigue strength of concrete under compression,
- f_c – compression strength of concrete,
- C – ratio of dynamic-to-static strength under single-time loading,
- N – number of loading cycles,
- ρ^f – cycle asymmetry coefficient,
- $\sigma_c^{\min}$ – minimum cycle stress,
- $\sigma_c^{\max}$ – maximum cycle stress,
- C_f – a coefficient taking into account the influence of load change frequency on fatigue strength,
- A, B – coefficients which take into account the influence of concrete structure condition by being related to levels of stress σ_{i} and σ_{cr}.

Cycle asymmetry coefficient ρ^f is described by the following relation:

$$\rho^f = \sigma_c^{\min} / \sigma_c^{\max}, \tag{3.2}$$

and coefficient C_f can be expressed by

$$C_f = 1 + 0,07(1 - \rho^f) \log f, \tag{3.3}$$

where f is the load change frequency (in Hz) and coefficients A and B can be calculated from relations (3.4) and (3.5)

$$A = 0,008 - 0,118 \log\left(\sigma_{\mathrm{i}} / f_{\mathrm{c}}\right), \tag{3.4}$$

$$B = 0,118(\sigma_{\mathrm{cr}} / \sigma_{\mathrm{i}} - 1). \tag{3.5}$$

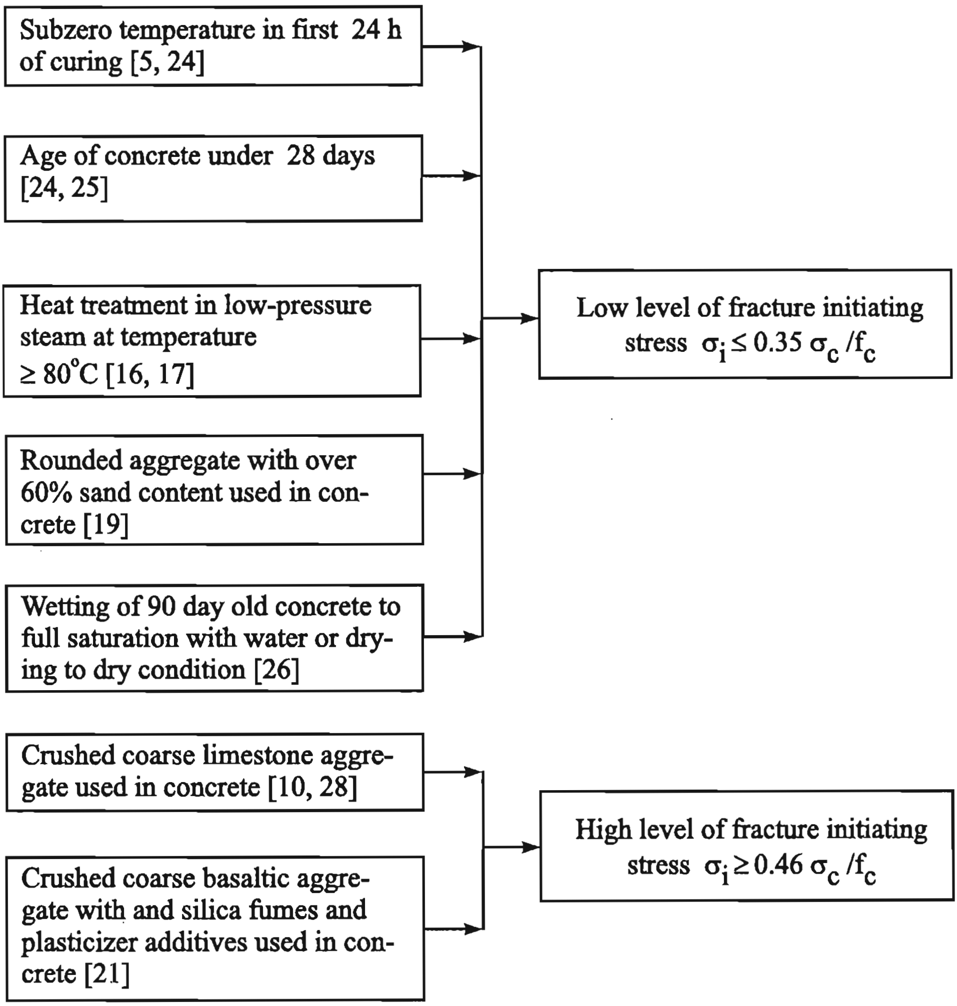

FIG. 2. Most important technological and service factors affecting levels of fracture-initiating stress in concretes under compression.

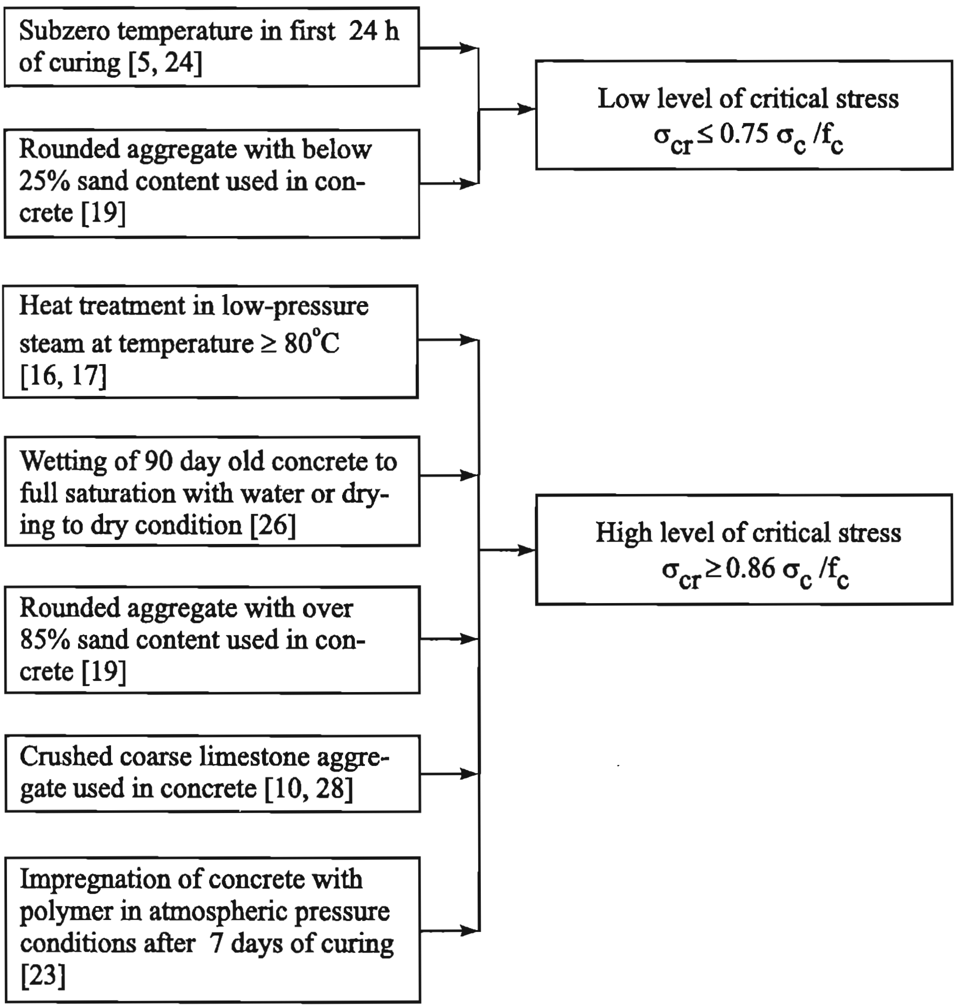

FIG. 3. Technological and service conditions affecting levels of critical stress in concretes under compression.

Figures 4-6 show the fatigue strength of different concretes under compression, calculated from relation (3.1) as a function of number of loading cycles N, cycle asymmetry coefficient ρ^f and load change frequency f for some of the technological and service factors listed in Table 1. The designations of the concretes are given in Table 2 where one can also find references to the source papers which contain all the details about the composition, curing conditions, etc., of the concretes.

Table 2. Basic data on concretes for which fatigue strength was calculated in the paper.

Concrete designation	Technological or service factor affecting concrete	Age of concrete [days]	Compression strength f_c[MPa]	Relative level of stress	
				σ_i	σ_{cr}
1	2	3	4	5	6
D_w1	wetting until full saturation with water [26]	90	37.10	0.20	0.90
DN3	heat treatment in low-pressure steam 95°C [16, 17]	90	36.00	0.32	0.87
D_k	normal curing in climatic chamber at temperature of +18°C and relative air humidity of 95 % [26]	90	42.40	0.45	0.81
E	rounded aggregate containing 47.5 % of sand [19]	90	42.10	0.50	0.82
H*	rounded aggregate containing 100 % of sand [19]	90	38.40	0.24	0.90
0	crushed coarse basalt aggregate [21]	90	68.00	0.40	0.74
3	crushed coarse basalt aggregate, silica fumes and plasticizer additive [21]	90	110.30	0.56	0.84

Figure 4 shows the fatigue strength of water-saturated concrete D_w1 and that of concrete DN3 heat-treated in low-pressure steam at a temperature of 95°C, in comparison with normally cured reference concrete D_k. The comparison shows that concrete D_k has the highest fatigue strength and also the highest level of stress $\sigma_i - 0.45\ \sigma_c/f_c$. Concrete D_w1 has the lowest fatigue strength and the lowest level of stress $\sigma_i - 0.20\ \sigma_c/f_c$. This confirms that there is a close relationship between fatigue strength and the level of fracture-initiating stress. In practice such a situation may occur, for example, when a bridge's deck plate grows saturated with moisture as a result of damage to its waterproofing insulation.

Figure 5 shows that the fatigue strength of concrete depends largely on the amount of sand contained in the rounded aggregate, regardless of the cycle asym-

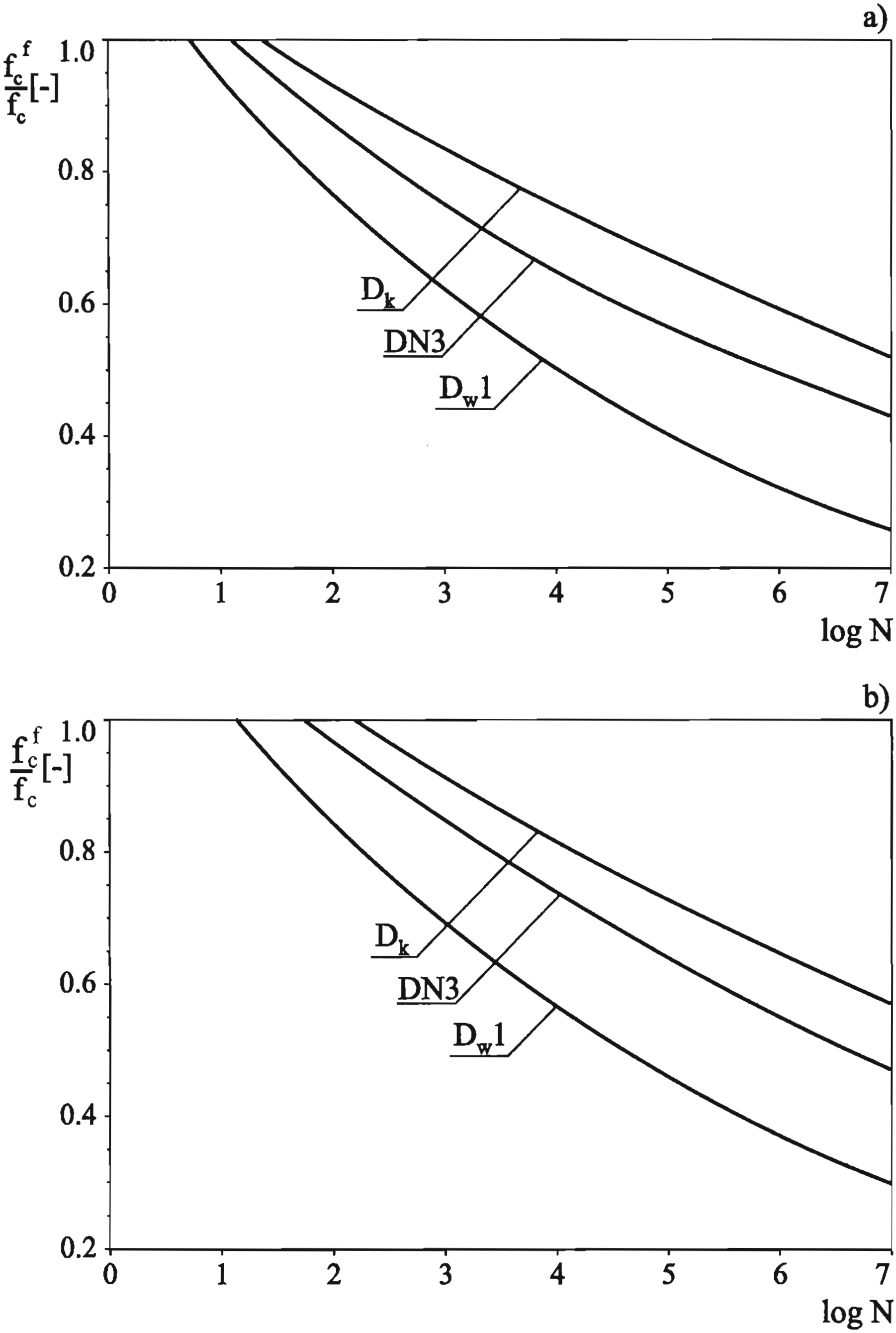

FIG. 4. Calculated fatigue strength of concretes D_k, DN3 and D_w1 as function of loading cycles: a) $\rho^f = 0$; $f = 1$ Hz, b) $\rho^f = 0$; $f = 15$ Hz.

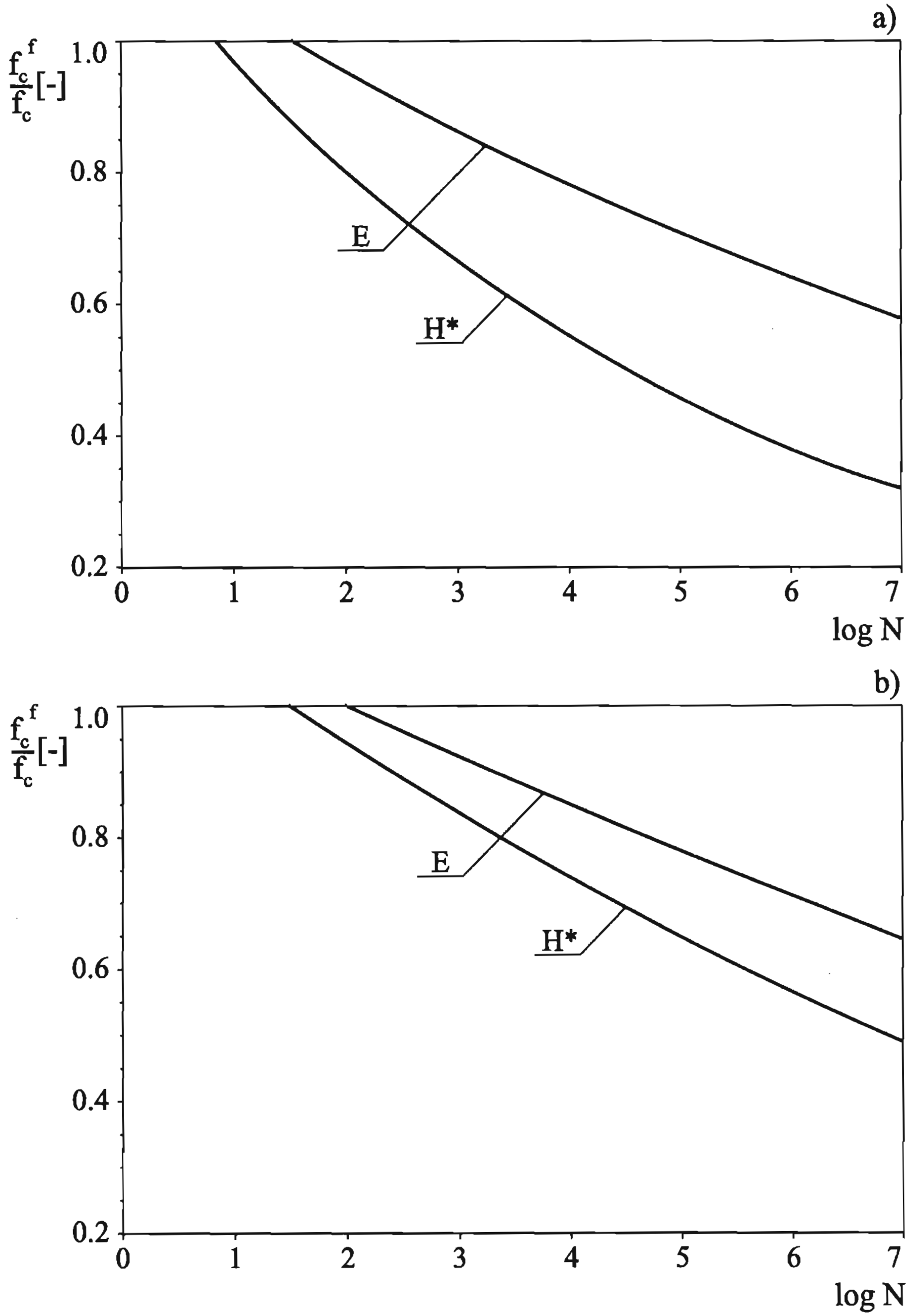

FIG. 5. Calculated fatigue strength of concretes E and H* as function of loading cycles: a) $\rho^f = 0$; $f = 1$ Hz, b) $\rho^f = 0.25$; $f = 1$ Hz

metry coefficient value. From among concretes E and H* the former concrete, in which sand constitutes 47.5 % of the total aggregate, has higher fatigue strength and its level of stress σ_i is 0.50 σ_c/f_c. Concrete H*, in which fine aggregate (sand) makes up 100 % of the total aggregate, has lower fatigue strength and a very low level of stress σ_i – 0.24 σ_c/f_c.

It can be concluded from Fig. 6 that the fatigue strength of concrete 3, containing plasticizer and silica fumes, is considerably higher than that of concrete 0 which does not contain these additives. It should be noted that the fracture-initiating stress levels in the concretes are respectively 0.56 σ_c/f_c and 0.40 σ_c/f_c.

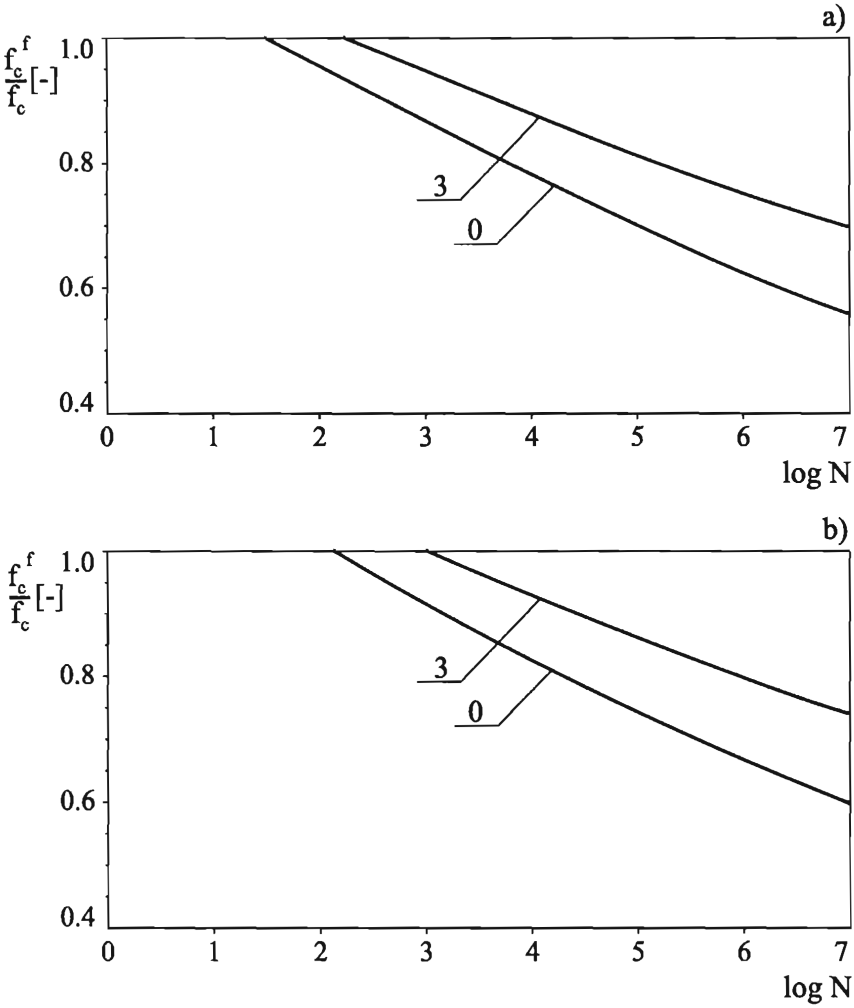

FIG. 6. Calculated fatigue strength of concretes 0 and 3 as function of loading cycles: a) $\rho^f = 0.25$; $f = 1$ Hz, b) $\rho^f = 0.25$; $f = 15$ Hz

It should be stressed that the observations based on an analysis of the results shown in Figs 4-6 apply to concretes with specific material composition and subjected to a specific testing program. The details can be found in source papers [16, 17, 19, 21, 26] (also referred to in Table 2) by the author.

4. Conclusions

1. An analysis of the experimental results compiled in this paper for concrete under compression shows that, depending on various technological factors being at work during the formation of this material and nonmechanical factors acting on it during its service, the levels of fracture-initiating stress σ_i and critical stress σ_{cr} range very widely. The level of stress σ_i is within a range of $0.17 - 0.60$ σ_c/f_c and that of stress σ_{cr} within a range of $0.66 - 0.91$ σ_c/f_c. For example, according to the classification adopted in the paper, the low level of stress σ_i is within a range of $0.17 - 0.35$ σ_c/f_c. It is characteristic chiefly of concretes which: were cured at a subzero temperature, completely saturated with water or so dried that they are totally devoid of water, are not older than 28 days, whose sand share exceeds 60 % of their total rounded aggregate, were fast cured in low-pressure steam at a temperature of 80°C or higher. A high level of stress σ_i – higher than 0.45 σ_c/f_c – is characteristic of a narrow group of concretes, which comprises mainly concretes: (3.1) with a limestone aggregate admixture and curing in normal thermal-moisture conditions, and (3.2) with plasticizer and silica fumes additives. In turn, a low level of stress σ_{cr} – below 0.75 σ_c/f_c is characteristic mainly of concretes which were cured at subzero temperatures or contained no more than 47 % of sand in the total rounded aggregate. A high level of stress σ_{cr} – above 0.85 σ_c/f_c – is characteristic of, e.g., concretes: with a sand admixture – 100 % of the total aggregate, with a limestone aggregate admixture, cured in low-pressure steam at a temperature above 80°C, with plasticizer and silica fumes additives, totally saturated with water, impregnated with polymer, and containing steel fibre reinforcement.

2. The research results presented in this paper may serve as guidelines for designing concretes with a desired, depending on their intended function, high or low level of fracture initiating stress σ_i or critical stress σ_{cr}.

3. Having in mind the safety and durability of concrete structures, particularly under repeatedly variable loading, it seems that it would be useful to include the levels of fracture-initiating stress and critical stress in the profile of concrete under compression. This would make it possible, for example,

to take into account the effect of technological and service factors that occur in practice on the fatigue strength of concrete under compression.

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