JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
ISSN 1392-3730 / eISSN 1822-3605
2015 Volume 21(1): 1–10
doi:10.3846/13923730.2014.929024

STRESS FAILURE OF CEMENT CONCRETES UNDER COMPRESSION – SYNTHESIS OF KNOWLEDGE, CONCLUSIONS

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Received 16 Jan 2014; accepted 22 May 2014

Abstract. This paper presents a synthetic review of the existing knowledge on the stress failure of cement concretes under compression, based on the available literature and the authors' own research. It is pointed out that there is no knowledge on the stress failure of new-generation concretes, which needs to be acquired through proper research. The usefulness of the knowledge on the stress failure of concrete under compression for building practice is highlighted.

Keywords: ordinary concrete, special concrete, stress failure, initiating stress, critical stress, acoustic techniques, fatigue strength.

Introduction

The problem of the stress failure of concrete subjected to compression covers the initiation, evolution, accumulation and propagation of microcracks in the concrete structure under an external load. The course of stress failure depends on the presence of various internal stresses and defects initiated when the concrete was not under the load (Beres 1971b; Flaga 1993, 1995; Hsu *et al.* 1963; Khatib, Mangat 1999; Newman, K., Newman, J. 1971). It is thought that the stresses and the defects stem from a whole range of technological factors involved in the broadly understood process of concrete making and that they have a decisive influence on the course of the stress failure of the concrete, manifesting itself in cracking initiating stress σ_i and critical stress σ_{cr} in laboratory tests (Beres 1971b; Flaga 1993, 1995; Hoła, Ranachowski 1992; Hoła 2002; Hsu *et al.* 1963; Khatib, Mangat 1999; Newman, K., Newman, J. 1971).

Many researchers regard cracking initiating stress σ_i and critical stress σ_{cr} as the two key strength characteristics of concrete under compression, indicating its predisposition to signalled or unsignalled cracking (Beres 1971a; Flaga, Furtak 1982; Furtak 1997; Hoła 2000b, 2002; Hsu 1981). The interest in exploiting these stresses in the assessment of the destructive processes taking place in concrete under compression is far from waning (Furtak 2002; Gorzelańczyk 2007; Goszczyńska 2014; Hoła 1994, 2000b; Moczko 1996; Ranachowski *et al.* 2010, 2012; Stroeven, Moczko 1996) and covers the ever new concretes, including special concretes (Błaszczyński *et al.* 2008; Gorzelańczyk 2007; Hoła 1998, 2000a, b; Przybylska-Fałek 2013).

The aim of this paper was to provide a synthetic review of the existing knowledge on the stress failure of cement concretes under compression. The review is based not only on literature reports, but also on the results of extensive studies carried out by the present authors (Gorzelańczyk 2007; Hoła 2000b). It is indicated that there is a lack of knowledge on the stress failure of new generation concretes and that it should be made up for through research. The usefulness of the knowledge on the stress failure of concrete under compression in building practice is highlighted.

1. Stress failure of ordinary concrete

The stress failure of ordinary concrete under compression has been the subject of numerous studies and has been fully explored. It has been demonstrated that the failure of this concrete under a momentary compressive load is a three-stage process (Beres 1971b; Flaga, Furtak 1981, 1982; Hoła 2000a, b; Moczko 1991; Ngab *et al.* 1981; Perry, Gillott 1977; Stroeven, Moczko 1996). The stages are: the stable initiation of microcracks, the stable evolution and propagation of the microcracks and the unstable propagation of the microcracks (Beres 1971b; Flaga, Furtak 1982; Hoła 1992a, 2000b; Hsu *et al.* 1963; Moczko *et al.* 1995; Ranachowski 1990, 1991; Stroeven, Moczko 1996). The above stages demarcate the levels of cracking initiating stress σ_i and critical stress σ_{cr}.

Tests show that in ordinary concretes under compression the cracking initiating stress and the critical stress may reach different levels. This may be due to different technological factors and the concrete making conditions as well as to nonmechanical service factors, such as the ones shown in Figure 1.

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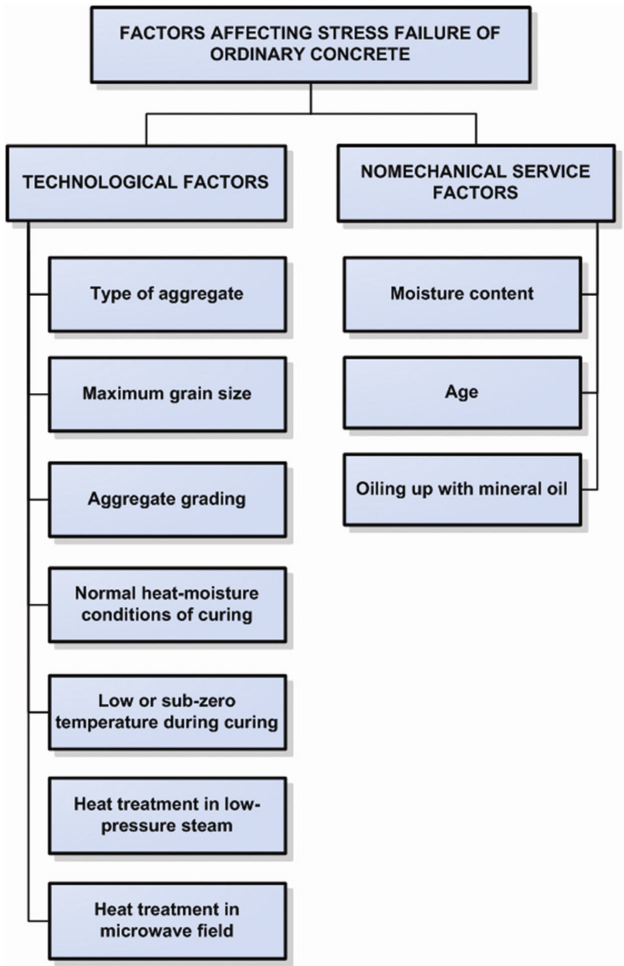

Fig. 1. Major technological and nomechanical service factors affecting stress failure of ordinary concrete under compression

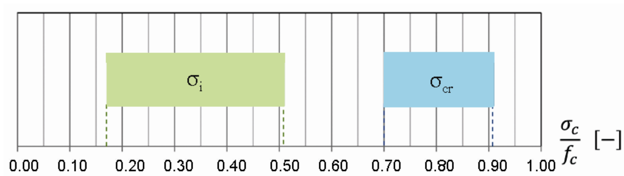

Fig. 2. Ranges of levels of cracking initiating stress σi and critical stress σcr in ordinary concretes subjected to various technological and nonmechanical service factors

The relative levels of cracking initiating stress σ_i and critical stress σ_{cr} depending on various technological and service factors acting on ordinary concrete under compression are presented in Table 1 (Błaszczyński 2011; Błaszczyński *et al.* 2008, 2009; Broniewski *et al.* 1994; Flaga, Furtak 1981, 1982; Furtak 1997; Gorzelańczyk 2011; Hoła 1992a, b, 1994, 1996a, b, 2000b, 2002; Hoła, Ranachowski 1992; Hsu *et al.* 1963; Moczko 1991; Moczko *et al.* 1995; Newman, K., Newman, J. 1971). It appears that the relative levels of cracking initiating stress σ_i and critical stress σ_{cr} range widely. And so stress σ_i is in a range of 0.17–0.60 σ_c/f_c and stress σ_{cr} is in a range of 0.66–0.91 σ_c/f_c, as illustrated in Figure 2.

2. Stress failure of special concretes

This section presents the results of investigations into the stress failure of special concretes selected from the ones most commonly used in construction. The concretes were investigated using the acoustic techniques of acoustic emission and ultrasonic emission since these techniques have been found to be particularly useful for studying the stress failure of concrete under compression (Furtak 2002; Gorzelańczyk 2011; Goszczyńska 2014; Hoła 1994, 2000a, b; Moczko 1991; Moczko *et al.* 1995; Ranachowski 1991, 1997; Ranachowski *et al.* 2012; Stroeven, Moczko 1996). The AE descriptors usually recorded are: the AE counts sum, the rate of AE events and the RMS signal. The levels of cracking initiating stress σ_i and critical stress σ_{cr} are determined on the basis of the above descriptors in accordance with the criteria specified in Gorzelańczyk (2007), Hoła (1994, 2000b), Przybylska-Fałek (2013). In the case of the ultrasonic technique, the velocity of longitudinal ultrasonic waves (V_L) versus the increment in compressive stress is the recorded descriptor (Flaga, Furtak 1982; Furtak 2002; Gorzelańczyk 2011; Hoła 1992a, 1996a, 2000a, b; Moczko 1991). The criteria for determining the levels of stresses σ_i and σ_{cr} by means of this technique are given in Gorzelańczyk (2007), Hoła (2000b), Moczko (1991). Exemplary schematics of the test rigs and views of specimens being investigated using the acoustic techniques can be found in Gorzelańczyk (2007) and Hoła (2000b).

2.1. Polymer impregnated concrete

Polymer impregnated concrete (PIC) is obtained by impregnating hardened concrete with a monomer or a propolymer, which then undergoes polymerization inside the concrete. This composite is characterized by very high compressive and tensile strength and consequently by markedly increased tightness, manifesting itself in an about fifteen-fold decrease in water absorption in comparison with unimpregnated concrete (Czarnecki 2009; Czarnecki, Łukowski 2002; Neville 2000).

Literature reports (Broniewski *et al.* 1994; Hoła 2000b, 2002) indicate that the level of cracking initiating stress σ_i in polymer impregnated concrete cannot be explicitly determined, whereas in the reference unimpregnated concrete this level amounts to 0.50 σ_c/f_c. This is due to the fact that the failure of the concrete structure strengthened with polymer inclusion takes place not in three, but rather in two stages. In the first stage of this process, covering a stress range of 0–0.90 σ_c/f_c, a cascading effect is observed using the AE technique. This effect markedly intensifies beginning with the stress level of 0.55 σ_c/f_c, indicating the occurrence of several stress levels in the interval of 0.55–0.90 σ_c/f_c, which could be regarded as initiating. At these levels the momentary stable propagation of microcracks and the momentary rapid propagation of the microcracks take place. The upper limit of this interval corresponds to critical stress σ_{cr}. The level of this stress, amounting to 0.90 σ_c/f_c, is higher than in the reference unimpreganted concrete, where it amounts to 0.80 σ_c/f_c. The above findings are illustrated in

Table 1. Relative levels of cracking initiating stress σ_i and critical stress σ_{cr} for various technological and nonmechanical service factors acting on ordinary concrete under compression

Technological and service conditions		Researchers	Relative levels of stress σ_i and σ_{cr}	
			σ_i/f_c	σ_{cr}/f_c
Normal heat-moisture conditions of curing		(Flaga, Furtak 1981, 1982; Hoła 2000b)	0.46–0.51	0.80–0.88
Air-dry heat-moisture conditions of curing		(Flaga, Furtak 1981, 1982; Hoła 2000b)	0.40–0.46	0.70–0.81
Full saturation with water		(Hoła 2000b)	0.20–0.30	0.90
Drying to fully dry condition, at 105 °C		(Hoła 2000b)	0.30	0.80–0.82
Low or sub-zero temperatures during curing		(Flaga 1993)	0.17–0.23	0.71–0.75
Heat treatment in low-pressure steam at <80 °C		(Hoła 1992b, 1996a)	0.36–0.41	0.81–0.90
Heat treatment in low-pressure steam at ≥80 °C		(Hoła 1992b, 1996a)	0.34–0.35	0.76–0.91
Heat treatment in microwave field		(Hoła 2000b, 2002)	0.37	0.83
Hot forming at 45 °C		(Hoła 2000b, 2002)	0.41	0.81
Type of aggregate	rounded	(Beres 1971b; Flaga, Furtak 1981; Furtak 1997; Hoła 1992a, 2000b)	0.41–0.50	0.70–0.83
	limestone		0.51	0.88
	basalt		0.45	0.80
Aggregate grading	20% ≤ sand content ≤ 37.5%	(Hoła 1992a, 2000b)	0.40–0.45	0.70–0.81
	37.5% ≤ sand content ≤ 47.5%	(Hoła 1992a, 2000b)	0.40–0.50	0.81–0.82
	47.5% < sand content ≤ 60%	(Hoła 1992a, 2000b)	0.50	0.82–0.83
	60% < sand content ≤ 85%	(Hoła 1992a, 2000b)	0.34–0.50	0.83–0.85
	85% < sand content ≤ 100%	(Hoła 1992a, 2000b)	0.24–0.34	0.85–0.90
Condition of aggregate surface		(Perry, Gillott 1977)	0.40–0.50	0.83–0.86
Age of concrete	below 28 days	(Moczko 1991; Moczko *et al.* 1995)	0.20–0.30	0.76–0.80
	above 28 days	(Moczko 1991; Moczko *et al.* 1995)	0.30–0.45	0.76–0.80
Oiling up with mineral oil		(Błaszczyński 2011; Hoła 1996b)	0.30–0.40	0.75–0.80

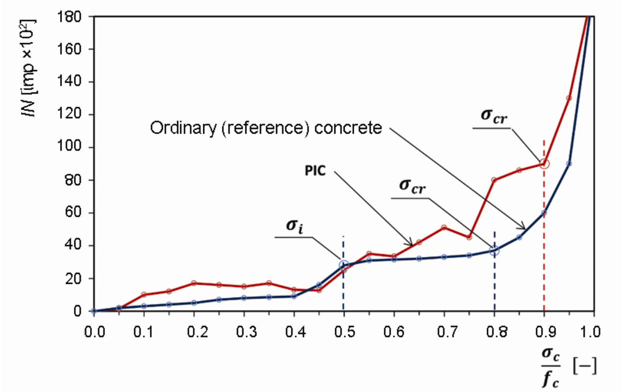

Fig. 3. Rate of AE counts sum increment in PIC and in reference unimpregnated concrete, under compression, versus increment in relative stress value (Hoła 2000b)

Figure 3 which shows the diagram of the rate of AE counts sum increment in the reference concrete and in the polymer impregnated concrete, subjected to compression, versus increment in the relative stress value (Hoła 2000b).

The test results indicate that the strengthening of concrete with polymer inclusion has a beneficial effect on the failure processes. As shown in Czarnecki (2009) and Czarnecki and Łukowski (2002), the mechanisms of this strengthening consists in:

- a reduction in stress concentration in places where defects and structural discontinuities occur, owing to the filling of the discontinuities with the polymer;
- an increase in the load-bearing capacity of the hardened cement paste as a result of the consolidation of its crystalline skeleton;
- the formation of polymer bridges in the larger pores of the hardened cement paste, having a inhibiting effect on the propagation of cracks;
- an increase in the adhesion of the hardened cement paste to aggregate grains as a result of the filling of voids and pores in the intermediate layer and in the cement paste with the polymer and the strengthening of the hardened cement itself.

2.2. Fibre-reinforced concrete

Fibre-reinforced concrete contains usually steel fibres, less often glass, aramid or polypropylene fibres (Błaszczyński *et al.* 2008, 2009; Neville 2000; Stroeven, Moczko 1996). Because of its advantageous mechanical properties and high durability fibre-reinforced concrete is widely used in transport infrastructure and industrial building construction (Błaszczyński *et al.* 2008, 2009; Neville 2000).

The studies carried out in Błaszczyński *et al.* (2008, 2009), Przybylska-Fałek (2013) showed that the failure of concretes containing steel fibre reinforcement does not take place in three stages as in the case of ordinary concrete. There is some similarity between the failure of fibre-reinforced concrete and that of polymer impregnated concrete, but no such a marked cascading effect is observed (Broniewski *et al.* 1994; Hoła 2000b).

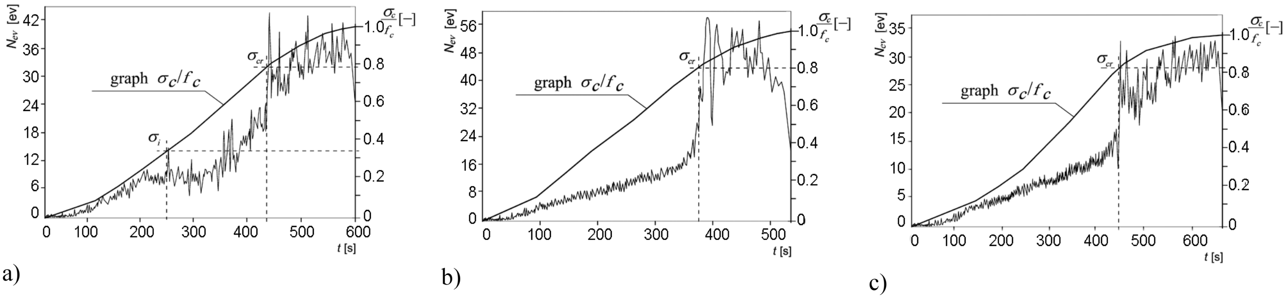

Fig. 4. Rate of AE events (N_{ev}) versus failure time for fibre-reinforced concrete: a) not containing steel fibres (SF); b) containing 1% of steel fibres (F1), c) containing 3% of steel fibres (F3) (Błaszczyński *et al.* 2008; Przybylska-Fałek 2013)

Figure 4 shows the recorded rate of AE events (N_{ev}) versus compression time for two fibre-reinforced concretes with a steel fibre content of respectively 1% (F1) and 3% (F3) relative to the mass of the concrete and for a reference concrete (SF) without such fibres. The diagrams include a graph of the increment in relative compressive stress value σ_c/f_c versus failure time.

An examination of the recorded rate of AE events in Figures 4b and 4c reveals that the presence of fibre reinforcement in concrete has an inhibiting effect on the propagation of cracks and contributes to a reduction in stress concentration in places where defects and structural discontinuities occur. The level of critical stress σ_{cr} in the fibre-reinforced concretes was found to be substantial, amounting to 0.80 σ_c/f_c for the concrete containing 1% of steel fibres and to 0.81 σ_c/f_c for the concrete containing 3% of steel fibres. It was higher than that in the reference concrete without fibre reinforcement, amounting to 0.78 σ_c/f_c. The experimental results presented by Przybylska-Fałek (2013) seem to indicate that in fibre-reinforced concretes the level of cracking initiating stress σ_i is equal to the level of critical stress.

2.3. Self-compacting concrete

The novelty of this special concrete consists in the self-compaction of the concrete mixture whereby its mechanical compaction during placing has been completely eliminated (Kaszyńska 2012; Neville 2000; Okamura *et al.* 2005; Okamura, Ouchi 1991, 2003). The self-compactability of concrete mixture is obtained through the use of appropriate additions and admixtures, combined with the proper selection of the other components (Gorzelańczyk, Hoła 2011; Holschemacher 2004; Kaszyńska 2012; Li, Hwang 2003; Łaźniewska-Piekarczyk 2012; Nagamoto, Ozawa 1999). Generally, in comparison with ordinary concrete, self-compacting concrete contains more dusty fractions and less coarse aggregate, as well as new-generation superplasticizers endowing the mixture with the required liquidity (Gorzelańczyk, Hoła 2011; Holschemacher 2004; Nagamoto, Ozawa 1999; Okamura, Ouchi 1991, 2003).

It appears from Gorzelańczyk (2007, 2011) that the stress failure of self-compacting concretes under compression takes place in three stages. The values of cracking initiating stress σ_i in such concretes, determined by the acoustic emission technique and the ultrasonic technique, are in an interval of 0.24–0.38 σ_c/f_c, while the values of critical stress σ_{cr} are in an interval of 0.84–0.93 σ_c/f_c, as shown in Figure 5.

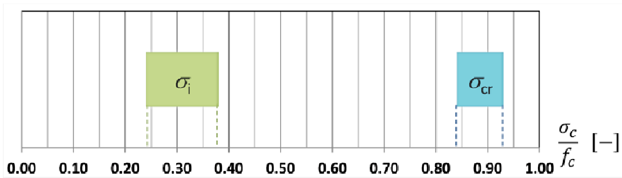

Fig. 5. Intervals of cracking initiating stress σ_i and critical stress σ_{cr} levels in self-compacting concretes

Studies (Gorzelańczyk 2007, 2011) also showed that similarly as in ordinary concretes, moisture content has a significant influence on the level of cracking initiating stress σ_i in self-compacting concretes. Taking concretes curing in a climatic chamber, in which the level of stress σ_i is in an interval of 0.30–0.38 σ_c/f_c, as the reference, as the moisture content in the concrete increases, the mean level of stress σ_i decreases and at full saturation with water it is in an interval of 0.24–0.26 σ_c/f_c. A similar dependence is observed when moisture content is reduced from the maximum moisture sorption to the dry condition. Concretes in this moisture condition are characterized by a level of stress σ_i in an interval of 0.28–0.30 σ_c/f_c. As regards the level of stress σ_{cr}, the studies (Gorzelańczyk 2007, 2011) showed that in the tested concretes the moisture content had little influence on this level.

The above findings are illustrated in Figures 6 and 7. Figure 6 shows the rate of AE events (N_{ev}) together with a graph of the increment in the relative value of compressive stress σ_c/f_c as a function of failure time for a selected self-compacting concrete damp to different degrees. For the same concrete Figure 7 shows the change in the velocity of longitudinal ultrasonic waves as a function of the increment in the relative value of stress σ_c/f_c.

2.4. High-performance concrete

High-performance concrete after 28 days of curing is characterized by a compression strength of at least 60 MPa and high durability combined with high tightness (Neville 2000). The best way of obtaining such concrete is through shaping a tight structure of the cement paste by

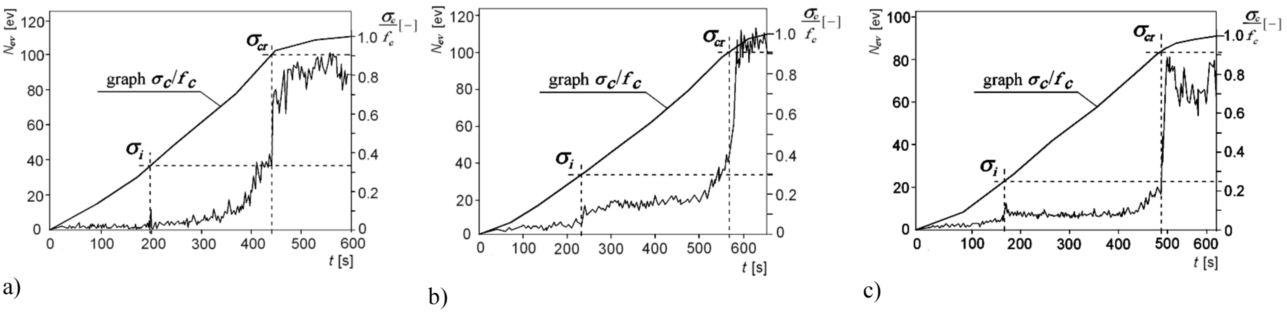

Fig. 6. Rate of AE events (N_{ev}) versus failure time in self-compacting concrete: a) concrete stored in climatic chamber; b) dry concrete; c) concrete fully saturated with water

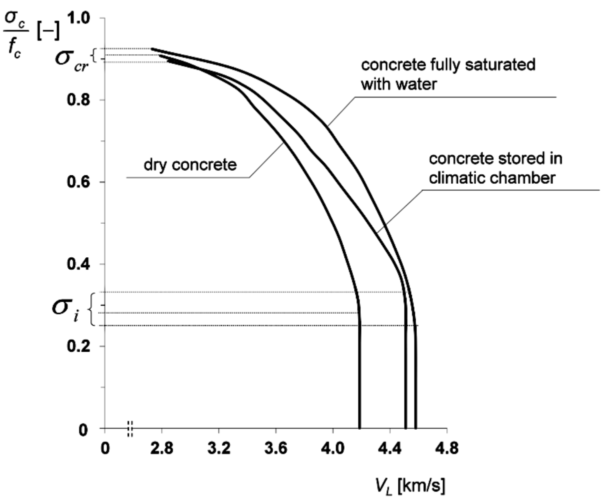

Fig. 7. Change in velocity of longitudinal ultrasonic waves in self-compacting concretes under compression versus increment in relative value of stress

reducing the water/cement ratio with additions strongly plasticizing the concrete mixture and by sealing micropores by introducing a micrograin phase into the grain size distribution. Such microfillers as silica fumes, fly ash, ground granulated slag, metakaolin and other mineral components are used (Hoła 1998, 2000b; Neville 2000; Ngab *et al.* 1981). High-performance concrete is characterized by a highly strong dense cement matrix well bound with the surface of the aggregate particles. Owing to the high homogeneity of its structure and the lack of weak spots (air voids produced by gravitational water or bleeding) and shrinkage cracks the behaviour of high-performance concrete is radically different from that of ordinary concrete.

The available literature data seem to indicate that the stress failure of high-performance concretes takes place in three stages (Hoła 1998, 2000a, b). However, it was found that in the failure of such concretes it is rather difficult to distinguish the stage of the stable initiation of microcracks from the stage of the unstable propagation of microcracks since the acoustic activity of HPCs under compression is very low in the stress interval covering the two stages. This is undoubtedly due to the much smaller amount of microcracks arising and developing in the course of the failure stages in comparison with ordinary concrete. On the other hand, the final stage is very clearly visible in the failure of high-performance concretes, manifesting itself in the rapidly growing values of the AE descriptors being recorded, as shown in Figure 8 (Hoła 2000b).

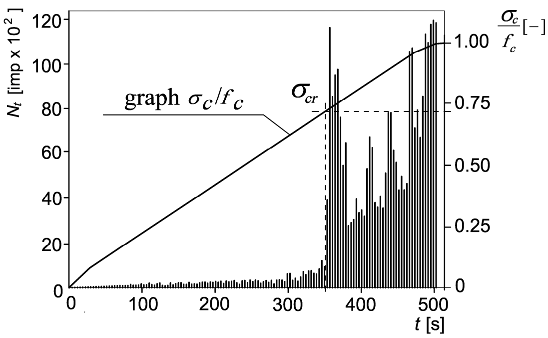

Fig. 8. Typical pattern of rate of AE events versus failure time for high-performance concrete (Hoła 2000b)

On the basis of literature data (Hoła 1998, 2000a, b) it can be assumed as proven that in high-performance concretes cracking initiating stress σ_i is within an interval of 0.39–0.56 σ_c/f_c while critical stress σ_{cr} is within an interval of 0.72–0.86 σ_c/f_c, as shown in Figures 9 and 10.

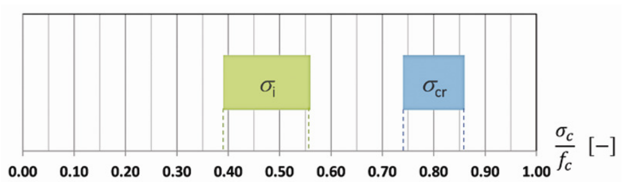

Fig. 9. Initiating stress σ_i and critical stress σ_{cr} intervals in high-performance concretes under compression

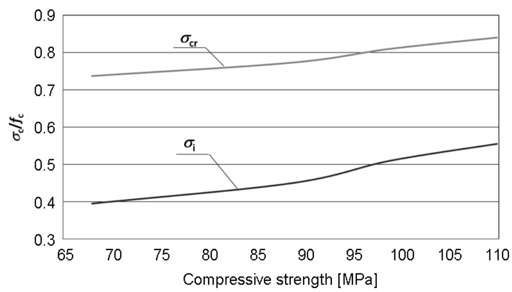

Fig. 10. Levels of cracking initiating stress σ_i and critical stress σ_{cr} in high-performance concretes under compression versus compressive strength

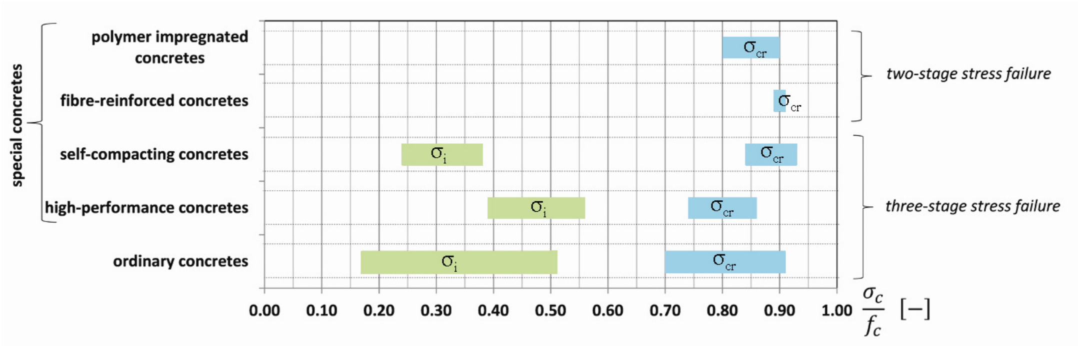

Fig. 11. Cracking initiating stress σ_i and critical stress σ_{cr} intervals in ordinary concretes, high-performance concretes and special concretes

2.5. Recapitulation

In order to recapitulate the experimental results on the stress failure of ordinary cement concretes and selected special concretes the intervals of cracking initiating stress σ_i and critical stress σ_{cr} have been collected together in Figure 11. It appears that from among the considered special concretes polymer impregnated concrete and fibre-reinforced concrete are characterized by two-stage stress failure whereas in the case of high-performance concretes and self-compacting concretes stress failure takes place in three stages, similarly as for ordinary concretes.

3. New-generation concrete

The most important group of composite materials with a cement matrix today are reactive powder concretes (RPC) belonging to ultra high-performance concretes (UPHC) (Cheyrezy *et al.* 1995; Czarnecki 2009; Kurdowski *et al.* 2009; Richard, Cheyrezy 1995; Zdeb, Śliwiński 2009). The production of such materials became possible owing to the advances in the cement binder technology, the availability of highly effective superplasticizing admixtures and the extensive identification of the mechanisms of the action of mineral additions on the microstructure and properties of cementitious materials. The compressive strength of an RPC may be much above 150 MPa. According to the available data, Ductal – a concrete produced from reactive powders on an industrial scale – is characterized by a compressive strength of about 250 MPa (Czarnecki 2009; Zdeb, Śliwiński 2009). Reactive powder concretes are the result of many years of research aimed at reducing to minimum the drawbacks of ordinary concrete. They owe their excellent strength properties mainly to:

- the minimized, mainly by reducing the water-binder ratio and simultaneously using highly effective superplasticizers and optionally pressing the mixture in the initial period of cement hydration, porosity of the composite;
- the advantageous modification of the material matrix binder microstructure through proper hydrothermal treatment;
- the increased packing density of the mixture of dry particulate components through the proper selection of their grading;
- the increased homogeneity of the material through the use of only very fine (below 600 µm in diameter) aggregate;
- the reduced brittleness of the obtained mature material through the addition of fibre reinforcement with suitable properties, shapes and dimensions.

Figure 12 shows a curve illustrating the evolution of concrete with regard to quality improvement as reflected in the compressive strength of concrete, based on the data found in the literature (Czarnecki 2009) and presented in this paper.

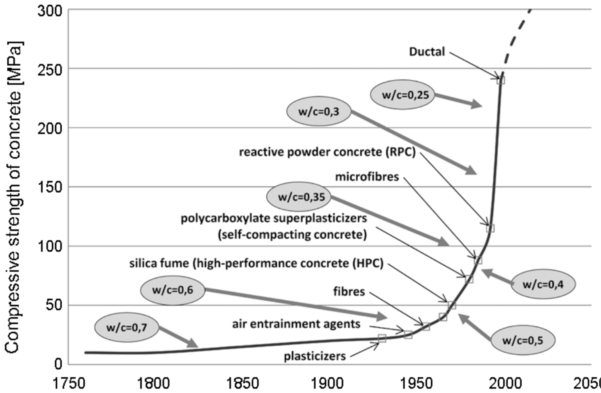

Fig. 12. Curve of concrete evolution (Czarnecki 2009)

The question arises: how does stress failure proceed in reactive powder concrete? So far no reports on this subject have appeared. Undoubtedly, the results of such studies would be very interesting for not only theory, but also practice since such concretes will be increasingly commonly used in the near future.

4. Example showing how knowledge of stress failure of concrete can be used in practice

As already mentioned, stress failure manifests itself in cracking initiating stress σ_i and critical stress σ_{cr}. It has been demonstrated that the levels of the above stresses in concrete have a bearing on the durability and service safety of structures made of the concrete, under mainly sustained cyclic loading (Beres 1971a; Flaga, Furtak 1982; Furtak 1997; Hoła 2000b, 2002; Hsu 1981).

It has been found (Flaga, Furtak 1982; Furtak 1997) that the level of cracking stress σ_i is equal to the permanent fatigue strength of concrete. It appears from the above studies that stress $\sigma_c^{\max} < \sigma_i$ does not cause fatigue failure. It is assumed, however, that this is true at number of load cycles $N \leq 10^7$ and at cycle asymmetry coefficient $\rho^f > 0$. It should be noted that if stress $\sigma_i < \sigma_c^{\max} < \sigma_{cr}$, concrete under compression fails after finite number of cycles N determined by asymmetry coefficient ρ^f and the load cycle duration. This kind of failure is referred to as high-cycle fatigue and takes place in two stages. Whereas when stress $\sigma_c^{\max} > \sigma_{cr}$, the so-called low-cycle failure of concrete occurs (Flaga, Furtak 1982; Furtak 1997).

Considering the above information and the concretes analyzed in this paper, it should be observed that the visible reduction in the level of stress σ_{cr} in concretes fully saturated with water results in a considerable reduction in their fatigue strength. This observation is of critical importance for the durability and safety of structures subject to sustained cyclic loading or overloads, which may become damp in the course of their service life. On the other hand, a very high level of stress σ_{cr} in damp concretes can be regarded as advantageous for their high strength under compression produced by sustained static loading.

For better illustration of the above information, using relation (1) given in Furtak (1997) fatigue strength f_c^f as a function of number of cycles N, assuming cycle asymmetry coefficient $\rho^f = 0$ and load change frequency $f = 1$ Hz, was calculated for selected concretes:

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

where: C – a coefficient expressing a ratio of dynamic strength to static strength under a single loading; ρ^f – a coefficient of cycle asymmetry; $\sigma_c^{\min}$ – a minimum cycle stress; $\sigma_c^{\max}$ – a maximum stress cycle; C_f – a coefficient representing the effect of load change frequency on fatigue strength; A, B – coefficients representing concrete structure condition, through their dependence on the values of stress σ_i and σ_{cr}, amounting to respectively:

$$A = 0.008 - 0.118\log\left(\sigma_i / f_c\right), \quad B = 0.118\left(\sigma_{cr}/\sigma_i - 1\right).$$

The results of the calculations are shown in Figure 13.

The following values of cracking initiating stress σ_i and critical stress σ_{cr} were used in the calculations:

- ordinary concrete curing in air-dry condition: σ_i = 0.42 and σ_{cr} = 0.75 (Hoła 2000b);
- ordinary concrete fully saturated with water: σ_i = 0.20 and σ_{cr} = 0.90 (Hoła 2000b);
- high-performance concrete: σ_i = 0.51 and σ_{cr} = 0.81 (Hoła 2000b);
- self-compacting concrete in air-dry condition: σ_i = 0.38 and σ_{cr} = 0.93 (Gorzelańczyk 2007);
- self-compacting concrete fully saturated with water: σ_i = 0.25 and σ_{cr} = 0.94 (Gorzelańczyk 2007);
- steel fibre reinforced concrete: σ_i = σ_{cr} = 0.81 (Przybylska-Fałek 2013).

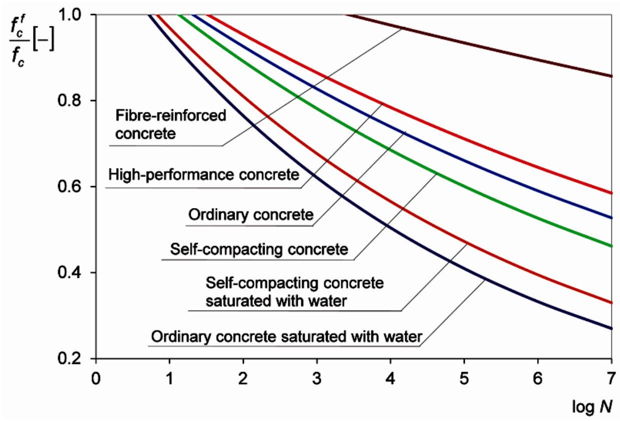

Fig. 13. Fatigue strength versus load cycles, calculated for ordinary concrete, high-performance concrete, self-compacting concrete and fibre-reinforced concrete assuming ρ^f = 0 and f = 1 Hz

The calculated fatigue strength values presented in Figure 13 differ greatly between the analyzed concretes, which is of consequence for building practice. This means that, for example, structural members made of fibre-reinforced concrete, subjected to sustained cyclic loading may fail after a much larger number of cycles than ordinary concrete, high-performance concrete and self-compacting concrete. The calculations also show a marked decrease in the fatigue strength of ordinary concrete and self-compacting concrete, which were fully saturated with water. This is of consequence for building practice since concrete can become damp as a result of, for example, damage to the waterproof insulation of the bridge deck slab.

Conclusions

1. The stress failure of ordinary concretes under compression takes place in three stages: a stage of the stable initiation of microcracks, a stage of the stable evolution and propagation of the microcracks and a stage of the unstable propagation of microcracks. The length of the particular stages of failure in such concretes depends on the various technological and nonmechanical service factors acting on the concrete. For this reason the relative levels of cracking initiating stress σ_i and critical stress σ_{cr} delimiting the above stages range relatively widely.
2. The stress failure of special concretes under compression takes place in two or three stages for respectively polymer impregnated concretes and steel fibre-reinforced concretes. It has been shown that both the polymer and the fibre reinforcement inhibit the propagation of microcracks until the propagation becomes rapid.
3. From among the concretes considered here, the high-performance concrete is characterized by the

highest value of cracking initiating stress σ_i. Whereas the self-compacting concrete and the steel fibre-reinforced concrete are characterized by the lowest critical stress values.

4. Currently there is no information on the stress failure of new-generation concrete, i.e. reactive powder concrete. Such knowledge would be very useful considering that this type of concrete is likely to be increasingly often used in construction.
5. Finally, it should be noted that many researchers consider cracking initiating stress and critical stress to be the two key strength characteristics of concrete under compression, indicating its predisposition to signalled or unsignalled cracking. Also dependence between the fatigue strength of concrete and the above stresses is observed. Therefore in building practice it is essential to know the values of the stresses since on this basis one can properly evaluate the static-strength performance of a particular concrete in specific structural elements.

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