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PROPERTIES OF CONCRETE MANIFESTED IN THE STRESS-VOLUMETRIC STRAIN DIAGRAM

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The unknown load history of structures in service does not allow determining the long-term compressive strength, critical for their reliability, from short-term tests of drilled concrete cylinders by the use of relationships derived on specimens without previous overloading. The extent of damage of the material must be taken into account when the residual strength should be estimated correctly. The existing knowledge of the microcracks in concrete, their origin and growth during loading, as well as their impact on the degradation of the long-term strength is dealt in the article. In this context, the possibility of the application of nonlinear acoustic methods is briefly pointed out. The main attention is paid to the stress-volumetric strain diagram. Based on experimental measurements, its ability to indicate the mechanical properties of concrete is studied.

Keywords: concrete, residual strength, combined microcracks, stress-volumetric strain diagram, environmental factors

1. Introduction

At the assessment of the state of the structure it is necessary to specify its load-carrying capacity (Králik, 2004; Kralik, 2013; Melcer and Lajčáková, 2003). The cores drilled from concrete could be available, serving for the compressive short-term tests. Ignoring the load history one could try to calculate the *sustained compressive strength* from these cylindrical strengths. However the relationships, e.g. Eq. 5.1-54 in Model Code 2010, were derived providing a monotonically increasing load – without previous overloading. The concrete acting in the structure in conditions of static indeterminacy could reach, during its existence, deformations in the region even behind the peak of the stress-strain diagram, as depicted in Figure. 1. Then we do not know at the compressive test, whether the peak load is actual, of the concrete intact at the start of the test – point *A*, or one from the area near the descending branch – point *B*, with substantial microcracks presence already before the beginning of the loading. It is dangerous, that these stages are hardly to be differentiated visually (Tesar, 2012 a; Tesar and Melcer, 2008). The *residual long-term strength*, defined as the force action that a damaged material can still carry without failing, should be determined therefore with regard to possible microcracks proliferation. The behaviour of concrete at sustained load is aptly demonstrated by the well-known graph from Rüsch (1960) – Figure 2. The stress level-strain diagram has deformation limits either by the failure line (above the sustained strength), or by the limit creep

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deformations. The presented courses were obtained providing that no previous load exceeded the investigated one. But if the material is situated already in the post peak area, another dependence must be sought.

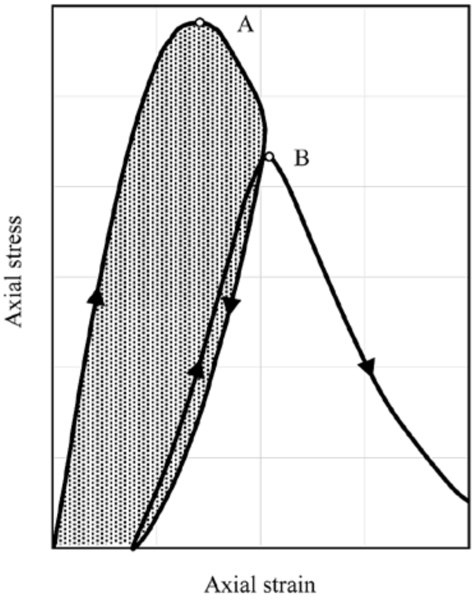

Figure 1. Short-term strength at testing of intact (A) and previously overloaded specimen (B)

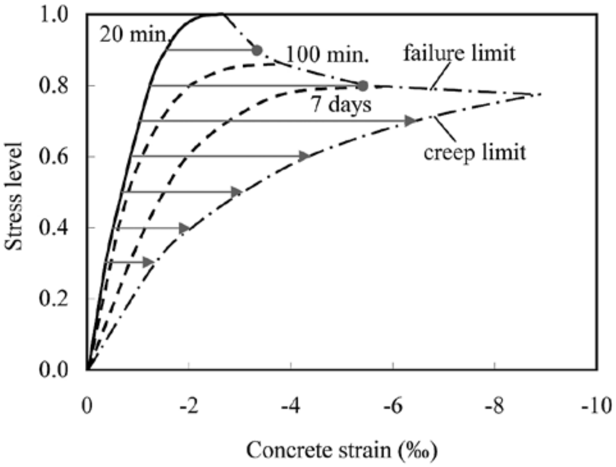

Figure 2. Existence perspectives of long-term loaded concrete material due to stress level (Rüsch, 1960)

The direct experimental determination of residual long-term strength is time-consuming and inapplicable in the practice (Klusáček and Bažant, 2010; Klusáček and Nečas, 2007), therefore other ways were looked for (Tesar, 2005; Tesar, 2012 b). A question is presented in (Jerga, 2004; Jerga, 2011), if the state of damage is reflected in the rate of long-term deformation stabilization of concrete expressed by the halftime of deformation (Fecko, 1975; Hanečka, 1975). This may be a proper tool helping at the decision making about the health of concrete. Hsu (1981 and 1984) suggests the use of *critical stress* (in the articles called as *discontinuity stress*) to establish the failure criterion of concrete rather than ultimate strength. He introduced the element of period of repetitive loads T into the f-N curve (Wöhler curve) and created the three dimensional space f-N-T. The intersection line of surfaces corresponding to high-cycle fatigue and low-cycle fatigue is considered as a definition of the discontinuity stress, which is a measurable quantity. From further works it should be mentioned an attempt to express the state of damage due to microcracks propagation by a value of the degree of reversibility (Ringot, 1988), so as the description of deformation processes by cracking Poisson's ratio (Zhao et al., 2005). The monotonically increasing stress-strain diagram, even in the strain rate controlled testing procedure, could provide with information about possible overloading in the past only in a limited extent. In contrast the unloading curve, as well as the *dissipated energy* (Hájek, 1994) reveals much about the damage development in material.

The straight way of concrete damage determination is the microscopic observation of microcracks. A prerequisite is the correlation between the parameters of microcracks development and the mechanical properties of concrete. To advantage could be used the observation of *Kaiser effect* and *felicity effect* at the measurement of *acoustic emission*, closely linked with the state of damage. The traditional ultrasonic methods expressing the quality of the material by sound velocity, attenuation and transmission or reflection coefficients could detect reliably the gross defects; however the sensitivity to evenly distributed microcracks is insufficient. In contrast with them extraordinary good results in the damage diagnostic are obtained by the use of *nonlinear acoustic non-destructive testing methods* (Armitage et al., 2008; Hoła and Schabowicz, 2010; Jhang, 2009). Their essential feature is the frequency difference of the input and output signal caused by high--intensity amplitudes of ultrasound compared with linear acoustic methods. One of the basic is the *higher harmonic generation* – alongside the transmitted ones. Another way is the observation of the modulation of ultrasonic wave by additional low frequency vibration, called as mixed frequency response, or *actively modulated acoustic* – if the low frequency waving is wittingly forced into the material. It is based on the periodically opened and closed cracks in concrete by the action of the low-frequency vibration. At the damaged concrete sideband frequencies will be revealed (Warnemuende and Wu, 2004; Zumpano and Meo, 2008). The nonlinear behaviour of the material affects the resonance curves significantly. The damaged material corresponds to the softening spring, so the resonance will move towards lower frequencies at the increase of the excitation level. The method is termed as *nonlinear ultrasound spectroscopy* (NRUS) (Jhang, 2009) or *single mode nonlinear resonant acoustic spectroscopy* (SIMONRAS) (Van Den Abeele et al., 2001; Van Den Abeele and De Visscher, 2000).

It turns out that a rich source of information on the state of concrete is the stress – volumetric strain diagram obtained from the compressive tests. Properties of such dependences for intact and damaged concrete are analyzed in the following, together with trends of further experimental research for reliable assessment of concrete strength in structures in service.

2. Microcracks in the progress of damage

The microcrack, significantly characterizing the damage state of concrete, is defined in the literature (Chini and Villavicencio, 2006; Jensen and Chatterji, 1996; Kjellsen and Jennings, 1996) as a crack with the upper *width* of 10 μm (0.01 mm). The interval of microcracks is wide-ranging and it is unclear (Jensen and Chatterji, 1996), whether microcracks relevant to the dynamic conditions of fracture propagation are of the same size range as those relevant for the semi-static conditions. Three other parameters are important – their *length*, *density* per unit area (per unit volume) and especially their *interconnectivity*. Caused by environmental actions, the microcracks are present in concrete already before onset of mechanical loading.

2.1 Microcracks formation – external environmental and internal special factors

Formation and evolution of microcracks in concrete is connected with changes in phase composition, presence of crystalline new-species and compounds of flexible constitution which are generated as a result of various chemical reactions. One would state that concrete of high quality with appropriate composition and dense pore structure creates presumptions for a high resistance against microcracks formation. The most essential from this point of view are:
– external effects and unusual circumstances, and
– internal factors resulting from specific aspects and related situations in concrete.

Thus, both the interactions of individual constituents in concrete and interactions with surrounding environment – in term of microcracks formation – represent facts of a high importance.

The external effects on concrete are ensured especially from the gaseous and liquid aggressiveness. Gaseous action is represented by carbonation, i.e. diffusion of carbon dioxide CO_2 into concrete structure (Parrott, 1994; Krajči and Janotka, 2000). The interaction of $Ca(OH)_2$ – as a main product of hydration – with gaseous CO_2 leads to formation of carbonation products (calcite, vaterite, aragonite). Crystals of different size and shape cause internal stresses that create assumptions for gradual microcracks formation. The reason lies in gradual permeating of large crystals, especially aragonite through cement paste of relevant matrix. The relation between CO_2 penetration into concrete and microcracking is characterized by Castel et al. (1999). Microcracks with the width of 1 – 2 μm in the paste near the aggregate boundary at the phase interface with paste were found (Wellman et al., 2008). Otherwise is in progress carbonation in a surface layer. Shrinkage by drying and subsequent carbonation shrinkage leads to so-called shrinking microcracks. Accelerated carbonation tests with increased CO_2 content can emphasize cracks formation (Krajči and Janotka, 2005).

The constituents of cement matrix react also with liquid aggressive environment. These prevailingly exchange reactions which are constantly in progress result in accumulation of voluminous crystalline salts. Very dangerous is mainly sulfate deterioration of concrete (Holden et al., 1983). Effect of sulfates is connected with substantial voluminous growth. Reaction products accumulate in pores of cement matrix that induce changes in concrete structure accompanied with microcracks initiation. These products, mainly ettringite and gypsum are responsible for concrete expansion and microcracking (Basista and Weglewski, 2008). The ettringite crystallization pressure is the driving force for microcracking of surrounding hardened cement paste. Thus, the relevant pressure may cause nucleation and propagation of microcracks. Lee et al. (2005) introduce evidence for spatial association of ettringite with microcracks in the paste. The proceeding chemical reactions contribute to such an increase of internal stresses in concrete that cracks on concrete surface are observed. It is necessary to note that the sulfate attack and cracks propagation are closely related to the passivation of relevant reinforcing steel (Krajči, 2006; Janotka and Krajči, 2008).

The unfavorable effect of chlorides on concrete resulting in deterioration is well-known as well (Janotka et al., 1992; Guzmán et al., 2011). This effect has either internal (chlorides in concrete as accelerating admixtures) or external (diffusion of chlorides from surrounding environment) nature. Concrete deterioration caused by penetration of chlorides occurs quickly when chloride ions react with calcium. The expansion of hydrated calcium oxy-chloride increases the permeability and gives conditions for microcracks initiation. Penetration of chlorides into concrete is influenced by many factors (Midgley and Illston, 1984). Chlorides from seawater enter into concrete and form some expansive compounds including Friedel´s salt that cause microcracks and consequently the concrete strength is gradually decreased (Islam et al., 2009).

The formation of harmful voluminous reaction products leads to the generation of microcracks in the initial state and appearance of cracks on concrete surface connected with exhibition of various concrete damages in the final state. To restrain these facts, the using of blended cements containing Portland cement and pozzolana as supplementary cementitious material (metakaolin, silica fume, clayey diatomite etc.) is convenient and effective approach. Thus – as a result of relevant pozzolanic reaction in the system – the amount of $Ca(OH)_2$ is reduced and consequently the generation of expansive reaction products is remitted. The modification of cement composition can be operative manner for attainment of mentioned scope as well (Papadakis and Tsimas, 2002; Krajči et al., 2010).

The unusual circumstances from external environment in which concrete occurs are presented mainly by the freeze-thaw attack and the influence of high temperatures (firing). Concrete that is not resistant to freezing and thawing cycles manifests two principal types of damage: internal microcracking and surface scaling (Janotka and Krajči, 2000). Generally, freezing-thawing damage involves the expansion of cement paste generated by the 9 % increase in volume as water is converted to ice inside a concrete element. Cement paste may be frost resistant if the amount of freezable water is not large and if the air void system is proper (Reynolds, 2006). Bubble spacing factor is 0.2 mm or less (Mehta et al., 1992). Likewise, Huai-Shuai and Ting-Hua (2013) present that the direction and distribution of microcosmic cracks formed in the process of freezing and thawing are stochastic. These cracks become broad as freeze-thaw cycles are repeated.

In the case of high temperatures action, the formation of microcracks is connected with various thermal coefficient of expansion in cement matrix and aggregate. The concrete resistance can be increased by cement and aggregate with suitable chemical and mineralogical composition. Creation of microcracks and their effect manifest on the flexural strength and modulus of elasticity more markedly than on the compressive strength (Bellová, 2010 a; Bellová, 2010 b). Concrete pore structure and amount of free and bound water are main factors affecting "antifiring" properties (Janotka and Jávor, 1997; Janotka and Mojumdar, 2005). It was found that temperature of about 200 °C is sufficient for shrinkage and inertial expansion of concrete (Janotka and Krajči, 1994). Rehydration back on $Ca(OH)_2$ is connected with voluminous growth and microcracks formation in matrix and consequently cracks formation on concrete surface. Setyowati et al. (2012) describe typical microcracks as a result of the effect of extremely high temperature (800 °C) on concrete. Microstructure is changed and mechanic and physics characteristics of concrete are strongly decreased. Fire-affected structures are characterized by microcracks too (Davis and Tremel, 2008).

As regards some internal factors in concrete and their relations to microcracks formation, the alkali-aggregate reaction (AAR) has a special position. AAR is a slow chemical process in which alkalis usually predominantly from the cement, react with certain reactive types of silica (e.g. opal, quartzite etc.) in the aggregate, when moisture is present (Guedon and Leroux, 1994; Lim et al., 2000; Shafaatian et al., 2013). This reaction produces special gel that can absorb water and expand to cause microcracking in concrete (NRC Information, 2011). Microcracks exist predominantly between interface of cement paste and coarse aggregate. Excessive expansion of the gel can lead to significant cracking which can change the mechanical properties of concrete.

Initiation of steel reinforcement corrosion and their progress represent a special factor leading to microcracks formation (Krajči, 2003; Guzmán et al., 2011). Progress of steel corrosion is accompanied with the rust formation, i.e. oxides and hydroxides of Fe with variable constitution (Pfeifer et al., 1986). Products of steel corrosion have multiple volumes in comparison with original steel. As a result, internal tensile stresses will develop in the cement matrix at the steel/paste interface. Under the tensile stress developed during corrosion existing fine cracks and microcracks in the surrounding concrete will enlarge (Andrade et al., 1993). When microcracks are formed, complicated anodic and cathodic reactions in a given system again proceed. Simultaneously, the changes in composition lead to gradual cement matrix deterioration. Cracks in the concrete cover layer as a result of these processes are characteristic in the final effect. An analytical model was suggested by Wang and Liu (2004) to predict the corrosion pressure caused by the uniform expansive action of corrosion products before and after appearance of microcracks. The effects of the crucial parameters associated with the mechanical behavior of rust and concrete on the time of appearance of first microcracks was also investigated in some detail (Kiani and Shodja, 2011). A great deal of research oriented to microcracks is connected with the investigation of mass transport processes (absorption, permeation, diffusion) (Koronthalyová and Matiašovský, 2007).

2.2 Microcracks formation – mechanical loading

The mechanical loading starting to act on the concrete element will cause new microcracks, which will be formed predominantly from already existing weak points and flaws in the material (Bilčík and Hudoba, 2002; Hroncová et al., 2009; Hroncová and Piták, 2006). The transition zone – the interfacial zone between cement paste and aggregates is regarded as one of the weakest (Hsu and Slate, 1963; Hsu et al., 1963). At compression the transfer of forces is concentrated in contacts of greater aggregates with a thin layer of mortar (Hájek, 1994), causing the actions in transversal direction. The initiated cracks are then oriented nearly parallel with the direction of compression. The microcracks are classified in (Carrasquillo et al., 1981) as *bond cracks* (between coarse aggregate and mortar), *mortar cracks* (Fig. 3) and *cracks through the aggregate*. For the damage assessment of concrete it is of extraordinary importance if the cracks are simple – isolated (single crack of any type not connected to any other crack), or combined – connected (containing two or more cracks connected to each other – e.g. combined bond and mortar cracks). Simple cracks are characteristic for lower load levels – cracking occurs first at the interfaces between coarse aggregate and mortar (bond cracks), followed by cracks through the mortar at higher loads. Unless the load is increased, the simple bond cracks are stable. Two types of combined cracks are recognized. The stable Type I, consisting of a bond crack and a mortar crack and Type II of at least two bond cracks and two mortar cracks. This one is generally unstable and may lead to failure under constant load.

It is the question, in what proportion are cracks due to environmental actions and due to loading, respectively if their scatter will allow a reliable assessment of the load history. The total length of simple and combined cracks in the dependence on the compressive stress level according to results in (Carrasquillo et al., 1981) is plotted in Figure 4 and Figure 5. The labels L and G denote limestone and gravel, letters N, M and H correspond to normal, medium and high strength concrete. It could be seen that simple microcracks are present already before the application of load and their increments due to load action are comparable with values originating from environmental actions even at stress levels far greater than 0.9. The great variation would impede the reliable deduction about the state of the material based on the total length of cracks. Entire absence of combined cracks is at zero stress level. More distinctive increase of combined cracks starts at the stress level exceeding 0.8, but their total length is considerably lower comparing with simple cracks. By more detailed analysis we would find, that Type II combined cracks were present only above the stress level of 0.8. Similar results are at the investigation of the number of microcracks. Important from the point of view of the influence of long-term deformation on microcracking of concrete are results presented in (Ngab et al., 1981) and (Sriravindrarajah and Swamy, 1989), where the approximately linear relation was found between the amount of microcracking and strain, regardless caused by loading or by shrinkage. Microcracks caused by sustained load (60 days) are analysed in (Smadi and Slate, 1989), describing the linear creep, nonlinear creep and unstable creep. The polar diagrams of aggregate matrix bond microcracks density at different load levels possess a high predictive value (Dhir and Sangha, 1974), so as the description of four stages in the crack proliferation under increasing stress (Kotsovos, 1979).

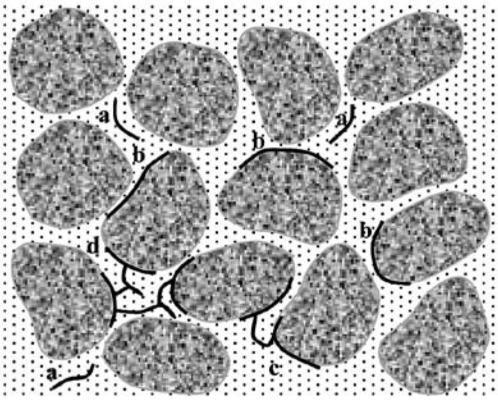

Figure 3. Classification of microcracks according to (Carrasquillo et al., 1981): a – simple (mortar) crack, b – simple (bond) crack, c – combined crack (Type I), d – combined crack (Type II)

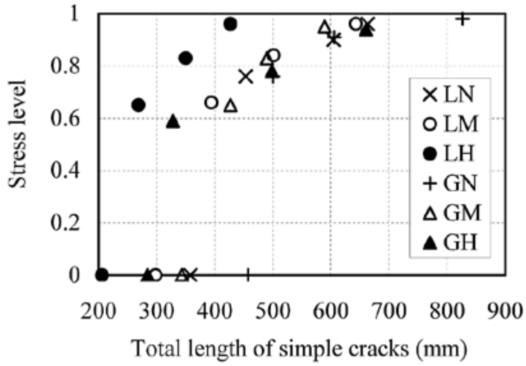

Figure 4. Dependence of the total length of simple microcracks on the stress level at uniaxial compression of concrete cylinders – plotted from results presented in (Carrasquillo et al., 1981)

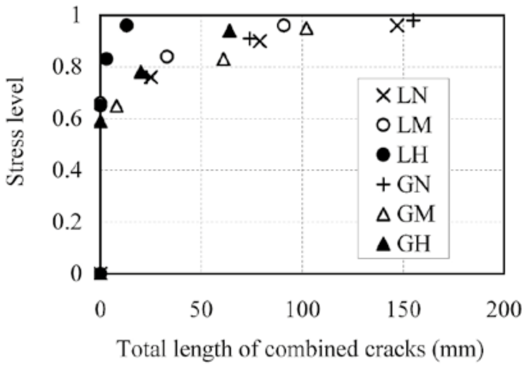

Figure 5. Dependence of the total length of combined microcracks on the stress level at uniaxial compression of concrete cylinders – plotted from results presented in (Carrasquillo et al., 1981)

3. Stress-volumetric strain diagram

As early as the twentieth years of the last century it was found (Richart et al., 1929) that from the deformation in a perpendicular direction to the action of stress derived *volumetric strain* plays a dominant role in the explanation of processes in the material at extreme loads. An uniaxial compressive stress acting on an infinitesimal element causes deformations $\varepsilon_{c,x}$ in the longitudinal direction, so as $\varepsilon_{c,y}$ and $\varepsilon_{c,z}$ in lateral directions. The negative ratio of lateral and longitudinal strain (ν) is called as *coefficient of lateral strain* or *secant Poisson's ratio*. The *volumetric strain* ε_{vol} is defined as a ratio of volume change after loading to the original volume of the unloaded element. Neglecting the multiples of two and three strains we receive the final expression of *volumetric strain*

$$\varepsilon_{vol} \cong \varepsilon_{c,x} + \varepsilon_{c,y} + \varepsilon_{c,z} = \varepsilon_{c,x}.(1-2\nu). \tag{1}$$

The relationship is dominantly controlled by the parameter ν. As found, the coefficient of lateral strain of concrete depends significantly on the *stress level.* While its value is between 0.1 and 0.3 at initial deformations, its magnitude is growing with the increase of compression. On the basis of experiments Prof. Hájek (1994) recommends the expression

$$\nu = \nu_{c,0} + \beta_\nu . \gamma_\varepsilon^3, \tag{2}$$

where $\nu_{c,0}$ is the coefficient of lateral strain in the initial part of the stress-strain diagram, γ_ε the level of longitudinal strain and β_ν the coefficient equal to about 0.35.

An example of the course of the volumetric strain and the secant Poisson's ratio in the dependence on the longitudinal compressive stress is presented in Figure 6. The volume is decreasing approximately linearly up to the stress level of about 0.6 (point A) and then nonlinearly (up to point B). At further growth of strain the volume starts to increase as a mark of a significant damage increment. The original volume before loading (point C) corresponds to coefficient of lateral strain equal to 0.5. The point, where volume starts to increase at compression (zero value of the inverse tangent slope of stress-volumetric strain diagram), is called as *critical stress*. This behaviour was attributed already in an early research (Richart, 1929) to "internal discontinuity, presumably a splitting of the material". If the material is without previous overloading, the progress of microcracks is represented very aptly by the turn in the course of volumetric strain, offering relevant information needed for the structural diagnostic. Sharp increase of combined cracks is reported at stress levels corresponding at about to the critical stress in (Shah and Chandra, 1968), but large variation (50÷95 % of the ultimate) is reported „for the values quoted for the critical stress and conjecturally related phenomena". Similar, the close correlation between the *onset of unstable fracture propagation*, minimum of the volume of the material and the *long-term strength* of concrete (below which concrete does not collapse under sustained load) is stated in (Kotsovos, 1979). While at normal strength concrete it is generally accepted, that the critical stress corresponds to the sustained strength, a slight difference was observed at high strength concretes. Concrete cylinders Ø100 mm x 200 mm made from washed sand, crushed coarse aggregate with maximum size of 14 mm and with/without silica fume (U in the second letter) were investigated in (Iravani and MacGregor, 1994) under high long-term compressive stresses. The mixes were designed for a nominal 56 days compressive strength in four groups between 65 and 120 MPa. Except for short-term tests, a sustained concentric load between 70% and 95% of the average of the ultimate strengths was applied on cylinders. If not failed, the specimens were replaced after 90 days of loading. Corresponding to short-term strengths the stress levels are plotted in Figure 7, distinguishing if the specimen failed or not failed under sustained load. Though the boundary interval between these both groups could not be regarded as definite with regard to the duration of load, there is a visible significant difference with levels of critical stress. Especially at strengths in the region of 120 MPa there could be observed at compression the decrease of volumetric strain almost up to the peak value of the stress-strain diagram.

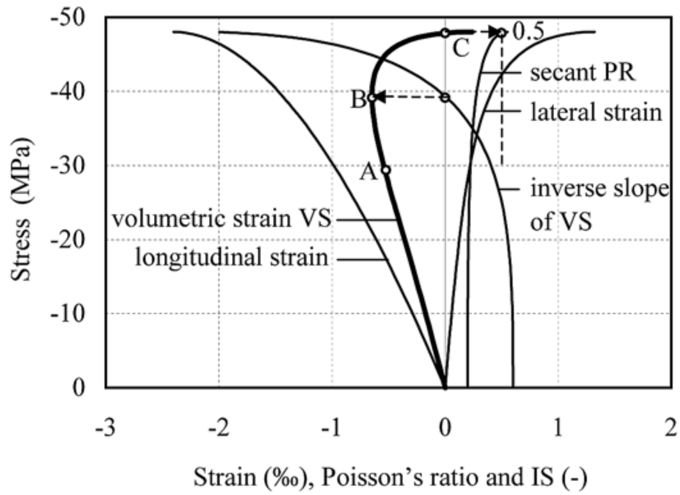

Figure 6. Dependence of secant Poisson's ratio (PR), volumetric strain (VS) and inverse slope of VS on longitudinal stress

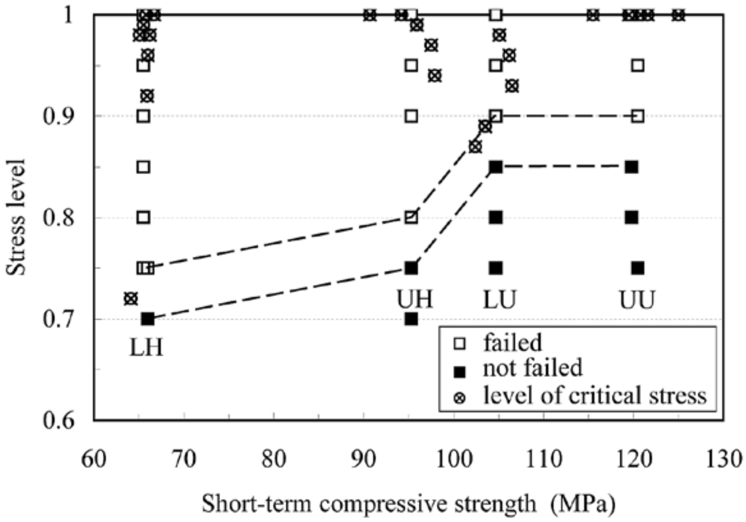

Figure 7. Relation between the critical stress and failure at long-term loading of high-strength concrete cylinders according to results in (Iravani and MacGregor, 1994)

The variance of volumetric strain parameters can be seen in Table 1, where there are compressive test results of cylinders Ø 50 x 100 mm made from concrete with mix proportions (cement : sand : water) 1 : 2.75 : 0.6 (Mix A) and 1 : 2.75 : 0.45 (Mix B), derived from measurements presented in (Lok, 1997). The standard loading rate (0.25 $MPa.s^{-1}$) was applied at the specimen BC1, while at other five samples the loading rate was 0.1 $mm.min^{-1}$ and they were also sealed by room temperature vulcanized rubber, which could slightly affect their stiffness. Significantly greater scatter could be observed at volumetric strain corresponding to the critical stress $\varepsilon_{v,crit}$ as at the compressive strength f_c. Similarly the level of the critical stress $\gamma_{\sigma,crit}$ has a smaller variance comparing with the volumetric strain level of the peak stress value $\gamma_{\varepsilon v,fc}$ (related to the volumetric strain of critical stress). Very illustrative is the dependence between axial stress level and the *inverse tangent slope of stress-volumetric strain diagram* ($d\varepsilon_v$ / $d\sigma$). The courses derived from measurements in (Lok, 1997) are plotted in Figure 8. The critical stress level is determined by the intersection with the vertical axis. It is possible to observe significant variance of the shape of curves even at specimens made from identical mixtures.

Table 1. Parameters of volumetric strain derived from measurements presented in (Lok, 1997)

Sample	A7	A10	AC3	B6	B8	BC1
f_c (MPa)	37	33	35.2	57	57	56
$\varepsilon_{v,crit}$ (‰)	-0.9673	-0.6026	-1.2360	-0.9122	-0.5498	-1.0861
$\gamma_{\sigma,crit}$ (-)	0.9510	0.8780	0.9635	0.9048	0.7685	0.9524
$\gamma_{\varepsilon v,fc}$ (-)	0.5865	0.4436	0.8945	0.5582	-1.0283	0.7143

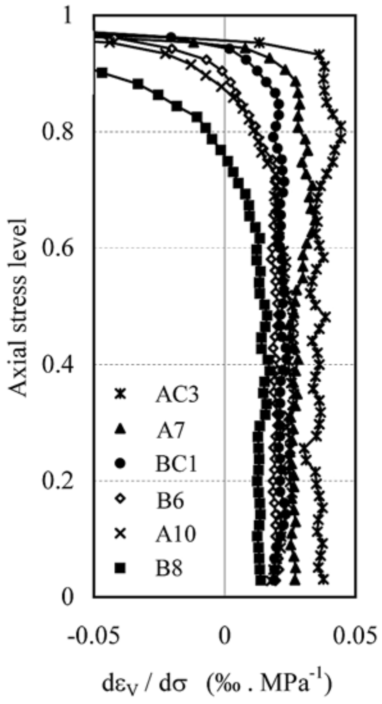

Figure 8. Dependence between axial stress level and the inverse tangent slope of stress-volumetric strain diagram derived from measurements presented in (Lok, 1997)

The effect of the gravel content on the volumetric strain is demonstrated in Figure 9. Based on measurements presented in (Shah and Chandra, 1968), inverse tangent slope of stress-volumetric strain diagram was derived for mixtures 1 : 2 : G : 0.54 (cement : sand : gravel : water – by weight). As it could be seen in Figure 9, the axial stress level of critical stress is decreasing with the increase of the gravel amount (G). As stated in (Shah and Chandra, 1968) the explanation of this fact is the observed "absence of microcracking at the interfaces of finer sized aggregates and the predominance of interfacial cracks around the larger sized aggregates".

Very important from the point of view of explanation of particles interaction are the compression tests of concrete prisms made from concrete with different surface conditions of aggregate presented in the same study (Shah and Chandra, 1968). The silicone rubber material was applied on the surface of aggregate to eliminate the bond between the paste and aggregates. Except for specimens with "coated" aggregate, further composition used "cleaned" aggregate with a jet of water and subsequently with acetone to improve the bond and at the third set of specimens the "untreated" aggregate was used. The courses of $d\varepsilon_v/d\sigma$ derived from the stress-volumetric strain diagram in (Shah and Chandra, 1968) (Fig. 10) confirm the significant influence of interfacial bond. The level of critical stress shows considerable decrease for specimens with coated aggregate, comparing with untreated and cleaned ones. Characteristic for the "cleaned" set is also relatively long part of the curve with constant negative slope beyond the critical stress level.

The presented results suggest that there is a significant correlation between properties of concrete material and parameters of stress-volumetric strain diagram. The question is now, into which extent the stress-volumetric strain diagram is able to reflect the degree of damage. In Figure 11 the inverse tangent slope of stress-volumetric strain diagram is plotted, derived from courses of volumetric strain of cyclically loaded (with a triangular pattern) sealed concrete prisms in the stress level region between 0.1 and 0.9 presented in (Shah and Chandra, 1970). The average number of cycles before failure was 17 and each additional cycle caused volume dilation. With the increase of cycles the critical stress level decreased and it is interesting, that the shape of the slope course in the damaged state shows similar relatively long part with negative magnitude beyond the critical stress level as at cleaned set of specimens in Figure 10.

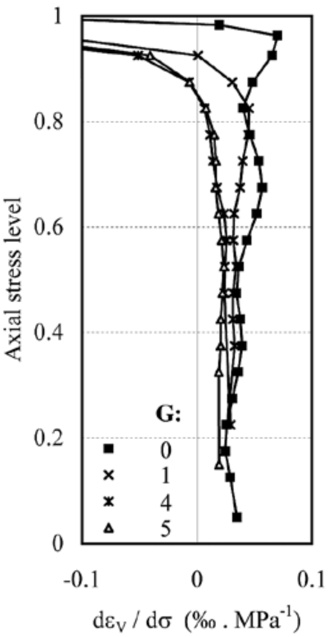

Figure 9. The influence of gravel content in the mixture on volumetric strain parameters – derived from measurements presented in (Shah and Chandra, 1968)

Results of volumetric strain of axially loaded concrete cylindrical specimens in strain-rate controlled testing procedure are available in (Poinard et al., 2010). The dependence of axial stress level and inverse tangent slope of stress-volumetric strain diagram of first five load cycles is plotted in Figure 12. Already in the first cycle there is a visible tendency to approach the critical stress (zero value of $d\varepsilon_v/d\sigma$), which was fully achieved at the second cycle. It is noteworthy, that after relief the third cycle exhibited a higher axial stress level at zero value of $d\varepsilon_v/d\sigma$, what is even repeated at the fourth cycle (which reached the peak value of stress). Subsequently the fifth cycle has a course characteristic for damaged material – a low stress level at zero value of $d\varepsilon_v/d\sigma$ and the following long part with nearly constant negative magnitude. This observation is of high importance for the diagnosis of structures – the stress level at minimum volume is dependent on the damage state of material. If the load history is unknown, as it generally is at testing of drilled cores from concrete structures in service, we cannot be sure whether we have identified actually the critical stress.

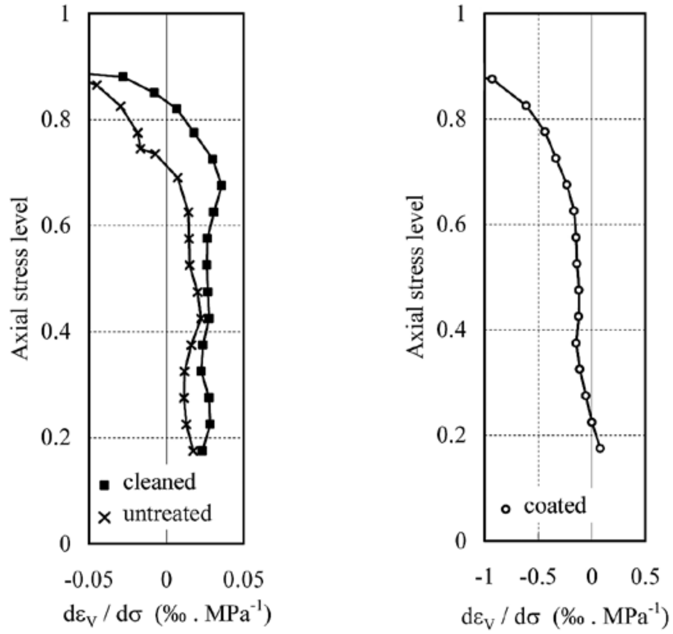

Figure 10. The influence of aggregate-paste bond strength on volumetric strain parameters – derived from measurements presented in (Shah and Chandra, 1968)

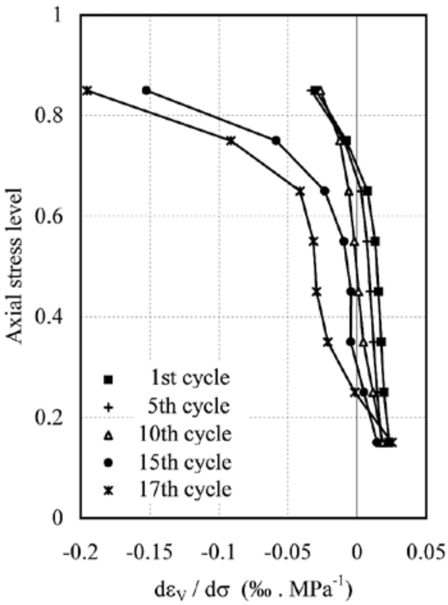

Figure 11. Dependence between axial stress level and the inverse tangent slope of stress-volumetric strain diagram derived from courses of volumetric strain of cyclically loaded concrete prisms measurements presented in (Shah and Chandra, 1970)

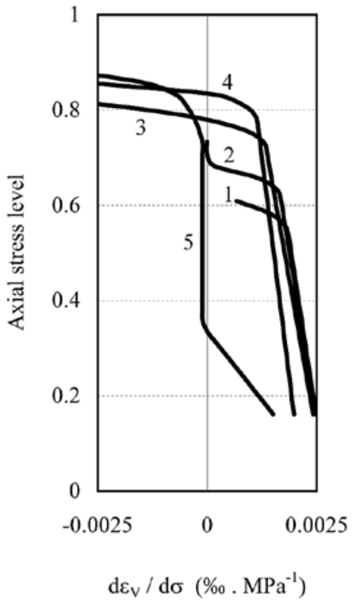

Figure 12. Dependence between axial stress level and the inverse tangent slope of stress-volumetric strain diagram derived from first five cycles of volumetric strain of concrete cylinders presented in (Poinard et al., 2010)

The presented results suggest the need for a broader investigation, which will allow resolving the question of how the properties of concrete are manifested in the stress-volumetric strain diagram.

4. Conclusions

Considerable amount of microcracks due to environmental actions is usually present in concrete before the onset of loading.

The amount of microcracks alone or the sum of the lengths of microcracks does not express unambiguously the degree of damage of concrete. Decisive is the assessment of the stage of the development of unstable combined cracks of Type II.

Stress-volumetric strain diagram is a rich source of information about the mechanical properties of concrete. It is also an important stone in the mosaic depicting the degree of damage.

Longer – nearly constant negative magnitude of inverse tangent slope of stress-volumetric strain diagram beyond the stress level corresponding to minimum volumetric strain is characteristic for an advanced stage of concrete damage. For a practical decision-making process the magnitude of stress level corresponding to minimum volumetric strain seems to be a relevant parameter, which should be investigated.

Stress-volumetric strain diagram is dependent on the load history and corresponding state of concrete damage – various compressive stress levels at the minimum volumetric strain could be obtained according to the way in which the load was reached.

The relationship between the stress level of minimum volumetric strain (critical stress) and the long-term strength of material with previous overloading (even beyond the peak load) should be investigated, using additional information from nonlinear acoustic testing methods, acoustic emission and microscopic observation of microcracks proliferation.

The determination of the residual long-term strength in a real time and at reasonable financial costs should be then the practical application.

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