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DAMAGE IN CONCRETE AND ITS DETECTION BY USE OF STRESS-VOLUMETRIC STRAIN DIAGRAM

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Abstract

The reliable determination of the damage degree of concrete in the structure is difficult and not seldom short-term compressive strengths are considered as real strengths of concrete. Because the load history of the construction is generally unknown, we do not know, whether there have been reached values in the vicinity of the peak of the stress-strain diagram. The strength at the sustained or repeated loading would be then significantly lower, as obtained from tests performed on intact samples. The diagnostic of concrete damage is impeded by environmental effects, resulting in the anisotropy of the development of microcracks. The possibility is pointed out to use the characteristics of the stress-volumetric strain diagram for the assessment of the condition of the material, with the perspective of the application for the determination of the residual long-term strength of concrete.

Keywords:

Concrete;
Damage;
Detection methods;
Strain diagram;
Stress analysis.

1. Introduction

The disobedience of the first people in the Garden of Eden [1] meant the beginning of the damage in the world. While its presence is considered generally as regularity by the mankind, its absence, on the contrary, is a sign of a miracle – the clothes and shoes did not wear out during the forty years-long exodus in the wilderness [2]. Damage and failure is an everyday reality of each of us – not excluding our physical health. No less attention should be given to the health of the constructions – its omission can be just as dangerous.

Concrete is a material very susceptible to damage. It is already encoded in its structure, created by variety of crystals – mutually irregularly overgrown. The breach could be caused by direct chemical attack and subsequent decomposition, but very often new compounds are created in course of the chemical reactions having greater volume compared with the original ones. The result is a volume increase, causing the tension connected with formation and proliferation of microcracks (cracks with the width < 0.01 mm – [22, 33]), what is the origin of failure of concrete. Restricted shrinkage and drying deformations lead to same consequences [16, 17]. Concurrently the action of mechanical load adds the strain [34, 35, 42, 43, 44].

Various damaging effects produce different levels and types of microcracks, with divers shape and number [57, 58]. It was found also [47] an approximately linear relation between the amount of microcracking and strain, regardless caused by short-term or sustained loading, or by shrinkage. It follows, that the question of damage should be treated in a broader interdisciplinary context, looking for a common denominator [61, 62]. The great task for an engineer is to assess the level of damage – directly related to the long-term residual strength [45, 59, 60]. It is the established practice to express the quality of concrete by the short-term strength. The problem is, that the load history is unknown. If the concrete is acting in conditions of static indeterminacy, the deformations could reach the region even behind the peak of the stress-strain diagram. Then at the compressive test of the core drilled from the structure we do not know, whether the peak load is authentic (point A in Fig. 1), or one from the area near the descending branch (points B or C). Accordingly, the magnitude of sustained strength will vary significantly. The best way to explore the state of concrete is the contemporary application of miscellaneous testing procedures, both destructive and nondestructive [15, 29, 30]. The aim of this contribution is to look for the manifestation of damage in the stress-volumetric strain diagram of concrete, with a perspective to help in determining the residual long-term strength in the future.

It is important both for diagnosis of structures in service, as well as for the evaluation of laboratory examination of the effects of aggressive substances on concrete.

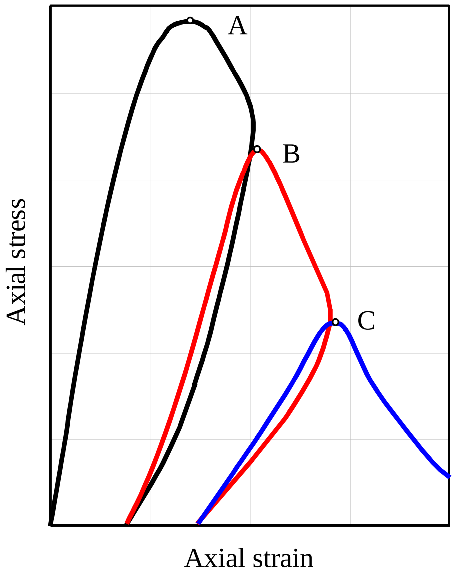

Fig. 1: Uncertainty at the sustained strength determination of concrete with unknown load history.

2. Anisotropoc character of damage due to various environmental causes

The formation and proliferation of microcracks due to environmental actions could originate either from restricted volume decrease (analogy with implosion), or from effects causing the volume increase (analogy with explosion). The restriction could be caused e.g. by the resistance of coarse mineral aggregate with higher modulus of elasticity against the shrinkage of mortar, but also at cooling after the previous warming due to hydration – the thermal expansion coefficients of aggregate are as a rule lower than those of cement paste [9]. The process of damage will depend on the magnitude of the deformation and on the rate of its increase – simultaneous action of creep will mitigate the effects. To assess the danger of the process acting in/on concrete, it is advantageous to introduce parameters characterizing its time course. The term halftime [12] was introduced at the investigation of long-term deflections of RC slabs, expressing the time, in which half of the long-term increment of deformation will be reached. For the approximation of experimental results, which showed the stabilization, he used the three-parametric hyperbolic equation

$$y = a + b\frac{t}{c+t}, \tag{1}$$

where *t* is the time and parameters *a*, *b* and *c* correspond to initial value, long-term increment and halftime, respectively. The theoretical expressions of shrinkage (models BP [6], BP-XK [5] or B3 [4]) set the limit value (LV) multiplied by the function of the time development (FTD), where the difference is made mainly between autogenous and drying shrinkage. The role of aggregate is generally accounted by Pickett's model [51]

$$\varepsilon_C = \varepsilon_P (1 - V_A)^n, \tag{2}$$

where ε_C is the shrinkage of concrete, ε_P the shrinkage of the paste, V_A the volume fraction of the aggregates and *n* the correlation parameter called as a shrinkage restraining factor. While the type of aggregate is reflected in LV in modern standards [46], the FTD remains unaffected. According to the analysis in [28], the degree of reinforcement is significantly modifying the halftime

(HT) of shrinkage [13] – its magnitude drops sharply with the increase of the product of the modular ratio with the reinforcement ratio [25, 26, 27]. Considerable stresses are achieved despite the moderating effects of creep [28]. So the anisotropy of reinforcement arrangement is immediately reflected in the anisotropy of microcracks proliferation. An overview of HT magnitudes of creep and shrinkage in different standards could be found in [24].

Because of severe environmental effects, concrete structure can deteriorate and are known to be not maintenance-free [48]. One of the critical deteriorations is just formation of microcracks in cement matrix of concrete. Subsequently, the occurrence of the cracks on concrete surface may be observed. From the physical point of view cracks could result from an accumulation process of microcracks, which create the fracture process zone as rationalized in fracture mechanics. Then, microcracks coalesce macroscopically to nucleate a tensile crack.

The microcrack formation is markedly emphasized by the process of carbonation [39, 41]. LV and HT of shrinkage increments due to carbonatation of concrete prisms (100×100×400) mm at accelerated carbonation tests at enhanced concentration of CO_2 in hermetic chambers are presented in [23]. The rate of the increase of the shrinkage increments was inversely proportional to the cement content in the concrete mixture. Magnitudes of HT in the interval between 83 and 395 days and a slower increase of the shrinkage increments with respect to the density increments were observed.

Products of carbonation process in concrete (calcite, vaterite and aragonite as carbonates) in the form of crystals of different size and shape cause internal stresses that create assumptions for gradual microcracks formation. Shrinkage by drying and subsequent carbonation shrinkage lead to so-called shrinking microcracks. Accelerated carbonation tests with increased carbon dioxide content enable to analyse yet mentioned facts [20, 40]. Experiments confirmed that the pores were partially filled by carbonation products and increase in strength was found. Moreover, it appears that shrinkage of cement gel during carbonation is accompanied by the part of the newly-formed calcium carbonate being accumulated in the pores. As mentioned, the forming internal stresses have contributed to the microcracks formation. Generally, the formation of microcracks developing from inner part of concrete element towards its surface is always responsible for weakening of the structure. This processes connected with next proliferation of microcracks are irreversible and have the tend to continue (according to limited surrounding conditions).

The interconnectivity of various processes is well recognized at the action of sulphate. Sulphate ions ingressing into concrete form gypsum and ettringite, which are the main sources of expansion and following cracking. The increase in volume between the formed gypsum and origin $Ca(OH)_2$ is approximately 2.2 times and between ettringite and hydration products of tricalciumaluminate C_3A 2.6 times higher in hydrated cement systems when exposed to the sulphate solution. Thus, the formation of such corrosion reaction products is then a source of internal expansive stresses forming microcracks in structure. In the final effect the proceeding expansion led to the strong damage of concrete connected with the possible loss of integrity.

However, the sulphate attack doesn't work separately, but in the interaction with other aggressive agents and also mechanical actions causing damage. A chemo-transport-mechanical model is presented in [18], taking into account the fact, that the ingress of an aggressive solution is a function of cracks opening (coupling effect), facilitating the ion diffusion and accelerating the degradation process. In a simplified model the volumetric strain is expressed as a function of the volume of the reaction products that deposit within the cement paste and initial capillary porosity. Other approach to the solution of diffusion-reaction process reflecting the change in diffusivity due to cracking is presented in [63]. The behaviour of concrete under the complex chemo-mechanical conditions – simultaneous influence and interaction of sustained compressive stress and Na_2SO_4 solution attack is dealt in [50]. Considerable effect on residual static modulus of elasticity, compressive strength and character of rheological deformations was experimentally stated. The questions on sulphate resistance and especially the rate of strain increase due to sulphate attack are presented in [21, 38]. Sulphate deterioration is often manifested from the viewpoint of individual components present in matrix, mainly by the increase in the bound SO_3 content. However, it is possible to prevent sulphate deterioration using blended Portland cements with pozzolanas instead "pure" Portland cements without partial substitutions by pozzolanas.

The increased sulphate resistance of the pozzolana cement is markedly higher than that of the Portland cement due to pozzolanic reaction of relevant pozzolana with CaO resulting in reductions of the formed $Ca(OH)_2$ opposite to hydrated Portland cement. The high sulphate resistance of the mortar made with pozzolana cement containing natural zeolite as 35 wt.%

substitution of Portland cement was proved [21]. The 720-day results showed that specimens subjected to 5 % Na_2SO_4 attack exhibit expansion value of 9.33 ‰ in the case of mortar made from Portland cement, but only 0.66 ‰ in mortar specimens with zeolite blended Portland cement.

Microcracks formation and volumetric changes in concrete structure are caused also by alkali-aggregate reaction (ASR). ASR is slow chemical process in which alkalis usually predominantly from the cement, react with certain reactive types of silica (opal, quartzite etc.) in the aggregate, when moisture is present. This reaction leads to special gel formation that subsequently may absorb water and expand to cause microcracking in concrete. Damage to concrete structures due to ASR and consequent expansion is being observed nowadays in many countries. ASR is often connected with sulphate deterioration [49]. It was indicated the occurrence of large amounts of ettringite in concrete – the evidence of the ASR – in sulphate environment. The portlandite solution in the pore water frees hydroxyl ions that can generate or intensify the ASR. The coexistence of secondary ettringite and ASR gel indicates that ASR reached the advanced phase.

The process of alkali-aggregate reaction (ASR) in real structure is discussed in [11]. The expansion of concrete is affected by various external parameters, particularly temperature, relative humidity and the stress state. It was found [10, 14], that at applied compressive stresses (inhibition pressure) between 3 and 10 MPa the expansion is suppressed in the direction of the load and the lateral expansion is affected too. Concrete cylinders were subjected to creep tests (5, 10 and 15 MPa) [11] – always one non-reactive and two reactive samples in series to allow to distinguish strains due to creep from those of the expansion induced by ASR. The microscopic material damage was simulated using a non-local damage method. As expected, the orientation of the microcracks corresponded to the direction of the applied load. This is extremely important for the diagnostic. At the test of the sample taken from the structure, the anisotropy of the damage must be taken into account. In this sense also the restriction of deformation due to reinforcement action need to be considered.

The influence of restraint and load direction on volumetric expansion anisotropy and non-uniform cracking distribution of concrete subjected to ASR is analysed in [3]. No preferential orientation in the crack distribution is to be found at simulated unrestrained free expansion. Redirection of cracks in the radial direction could be seen for the same specimen with passive restraining (5-mm steel ring – without axial loading) and at specimen without restraint subjected to axial stress of 20 MPa there are clear vertical crack propagation, without cracks orthogonal to the applied compressive load. However as stated in conclusions, cracking develops subsequently, if the confining stresses are released, what complicate the evaluation of ASR affected structures.

Steel reinforcement corrosion in concrete is accompanied with changes in the steel surrounding. The formed corrosion products occupy a more volume than the parent steel reinforcement. Subsequently, expansive pressure is exerted at the steel-rust-concrete interfaces. As the volume of corrosion products reaches to a critical value, it results in appearance of microcracks within the surrounding concrete. The reduction of steel cross area and expansion of the rust result in weakening the bond strength between steel and concrete and further growth of microcracks [31].

After appearance of the microcracks the concrete behaviour becomes nonlinear anisotropic with post-cracking softening, and the associated problem is analytically intractable [32]. With the next progress of steel corrosion, the expansion volume of rust products, which is about 2-6 times the volume of the rusted steel, produces increasing mechanical forces to the surrounding concrete and eventually results in the damage to the structures in the form of (longitudinal) cracking, spalling and delamination of concrete cover.

It was found also [32, 56], that the volume of microcracks plays an important role in the process of concrete deterioration due to rebar corrosion [37]. The ratio of the volume of the rust penetrated into the microcracks (corrosion products allowed to be deposited in the vacant spaces) to the total volume of the microcracks effects the evolution of further microcracks and determines the time to cover cracking. A nonlinear mathematical model is proposed for the stress field determination, in which the nonlinearity of the processes is taken into consideration. Other environmental actions could be mentioned [29, 30], many of them causing significant anisotropy in cracks proliferation (e.g. fire [7, 8] and freezing-thawing cycles).

3. Warning of damage by shape of the stress-volumetric strain diagram

Already in 1929 Richart, Brandtzaeg and Brown [53] found, that the deformation in lateral direction reacts very sensitive to the damage state in concrete. In their experiments they evaluated the volumetric strain ε_{vol}, defined as the ratio of change in volume (V_σ – V_0) to the original one (V_0). This could be expressed approximately as

$$\varepsilon_{vol} = \frac{V_\sigma - V_0}{V_0} \cong \varepsilon_{c,x} + \varepsilon_{c,y} + \varepsilon_{c,z}, \tag{3}$$

where $\varepsilon_{c,x}$ is the strain in the longitudinal direction (direction of the axial stress) and $\varepsilon_{c,y}$ respectively $\varepsilon_{c,z}$ the strain in lateral directions [29]. When plotting the relation between axial stress level (at uniaxial compressive stress) and the volumetric strain (Fig. 2), we can observe a linear, later a nonlinear volume decrease up to a critical stress ($\sigma_{cr,2}$). As a consequence of a damage increment, the volume starts to increase at higher stress levels. There was observed a relation between the critical stress and the long-term strength [36, 54] at normal strength concrete. However at high strength concretes the critical stresses were greater than the strength at sustained loading [19].

Unambiguous results could be achieved for intact specimens at monotonically increasing loading. But when the load increase is interrupted on given stages with following unloading (e.g. for the dissipated energy determination), we obtain several stress-strain diagrams, which vary with regard to the previous loading. It is similar at load / overload repetitions on real structures. Ascending branches of axial stress level – volumetric strain diagram of axially loaded concrete cylindrical specimens in strain-rate controlled testing procedure according to [52] are plotted in Fig. 2. During the first cycle (green) the load was interrupted before reaching the critical stress. After the unloading the ascending branch of the second cycle (brown) – almost identical with the first branch in the common interval, slightly exceeded the critical stress level $\gamma_{\delta,cr,2}$. The third branch (blue) starts with the residual volumetric strain and if considered separately, exhibits its own minimum of volumetric strain at fictitious (with regard to previous load history) critical stress level $\gamma_{\delta,cr,3}$. Even more significant is this reflected at the fourth branch – further increase of the fictitious critical stress is visible. The stress level is approaching the peak value, indicating the progress of damage process in concrete. At the last branch the minimum volumetric strain is achieved at considerable lower stress level ($\gamma_{\delta,cr,5}$).

Presented example demonstrates the limitation of use of critical stress for damage detection on cores drilled from structure with an unknown load history. For practical purposes a tool for rough estimate of the state of the material is needed. Interesting features shows the inverse tangent slope of stress-volumetric strain diagram ($d\varepsilon_v / d\sigma$). The dependence between axial stress level and $d\varepsilon_v / d\sigma$ derived from first five branches of volumetric strain of concrete cylinders presented in [52] is plotted in Fig. 3. The critical stress level is determined by the intersection with the vertical axis. There is visible a substantial difference between the course corresponding to the fifth branch – with a high degree of damage, comparing with the first four. The zero value of $d\varepsilon_v / d\sigma$ is reached at low stress level, which follows a long part with nearly constant negative magnitude. It is the question, if this shape could be regarded as a characteristic of advanced degree of damage. There is plotted (Fig. 4) the dependence between axial stress level and the inverse tangent slope of stress-volumetric strain diagram derived from 1st and 17th cycle (last before failure) of volumetric strain of concrete prisms presented in [55]. Similar features as in Fig. 3 can be observed at the 17^{th} cycle – the high degree of damage is manifested by very low level of critical stress followed by longer part with nearly constant negative magnitude. It is interesting that the described shape of stress-volumetric strain diagram shows also intact concretes with eliminated bond between the paste and aggregate (concrete with coated aggregate in [54]).

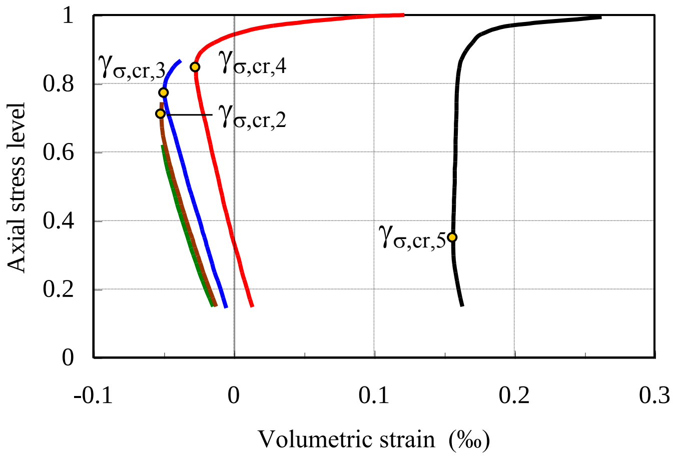

Fig. 2: Ascending branches of axial stress level – volumetric strain diagram according to [52].

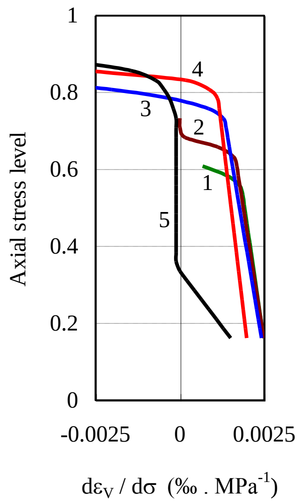

Fig. 3: Dependence between axial stress level and the inverse tangent slope of stress-volumetric strain diagram derived from first five branches of volumetric strain of concrete cylinders presented in [52].

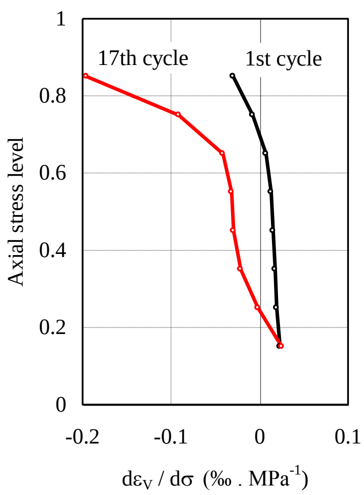

Fig. 4: Dependence between axial stress level and the inverse tangent slope of stress-volumetric strain diagram derived from 1st and 17th cycle of volumetric strain of concrete prisms presented in [55].

4. Conclusions

The microcracks development expressing the state of concrete damage is a result of interaction of various environmental and mechanical load effects. The rate of deformation increase has a significant impact on the harmfulness of processes. Great attention should be paid to the anisotropy of microcracks proliferation when analysing the orientation of drilled cores in the structure. The best way to explore the state of concrete is the contemporary application of miscellaneous destructive and nondestructive testing procedures. Extensive information about the condition of the material provides the axial stress-volumetric strain diagram. The inverse tangent slope of stress-volumetric strain diagram could be used as a tool for rough estimate. Its plot in the dependence on axial stress level is characterized by longer part with nearly constant negative magnitude following the low critical stress. It seems, that this feature is a practical characteristic of the damage of concrete – however more experimental research would be needed to confirm and specify this opinion.

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