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Assessment of the failure process of self-compacting concrete modified with SiO₂ nanoparticles by acoustic emission method

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Abstract

One of the new directions in self-compacting concrete (SCC) research is the modification of its composition with the addition of nanoparticles, which due to their unique properties are believed to improve the mechanical properties of cementitious composites. An important issue concerning the mechanical behavior of concrete under compression load is the failure process. At the moment, however, there is no knowledge of the effect of nanoparticles on the failure process of compressed SCC. The aim of the work is to investigate the failure process of compressed self-compacting concrete based on coarse and fine granite aggregate made both without and with SiO₂ nanoparticles in the amount of 2.0% and 4.0% of the cement weight. The research includes the determination of the levels of the initial cracking stresses σ_i and the critical stresses σ_{cr} that delimit individual stages of the studied process. Investigations were carried out using the acoustic emission (AE) method, and during the tests the recorded descriptors were the sum of counts (N_c) and the average effective value of the acoustic emission signal (RMS). The paper shows that the addition of SiO₂ nanoparticles has a positive effect on the failure process of compressed SCC. Moreover, the practical aspect of the obtained results for engineering purposes is provided.

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Keywords: *acoustic emission; failure process; initiate cracking and critical stresses; nanoparticles; self-compacting concrete.*

1. Introduction

Self-compacting concrete (SCC) is widely used in the construction industry. Its uniqueness is confirmed by a number of advantages, including: the ability to compact itself under its self-weight, the possibility to execute structures with a high degree of reinforcement and with complex shapes, good adhesion to old concrete, and also the ability to obtain elements with smooth surfaces that lack of cracks [1]. This concrete has been used in building practice for about 35 years. However, there are continuous works carried out to improve this material. They involve the improvement of its composition with the use of additives with finer and smaller grains, including nanoparticles [2].

Nanoparticles are a very fine material with grains not exceeding 100 nm [3]. The obtaining of such small grains has become possible due to the development of building material engineering and the achievements of nanotechnology. The improvement of the composition of concrete with the use of components with an increasingly smaller grain size (Fig. 1) is seen to be positively influencing the structure of this structural material [4].

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Fig. 1. The reduction in the grain size of components used to make concrete over time [4].

The following compounds are considered as a potential additive for the production of concrete: SiO_2 , Al_2O_3 , CuO , TiO_2 , ZnO , Fe_2O_3 and Cr_2O_3 [5]. Nanoparticles that form nuclei around which products of the cement hydration process grow, as a result of high chemical reactivity, effectively reduce not desired calcium hydroxide and create additional amounts of the C-S-H phase in the concrete structure, while at the same time acting as a nano-filler of the concrete microstructure [6]. Thus, they increase the corrosion resistance of concrete [9] and improve its physical properties by reducing, among other things, porosity [7] and permeability [8]. At the same time, nanoparticles have a positive effect on the mechanical parameters of concrete, such as its compressive and bending strength [11], and they also increase its hardness, which is evaluated at the micro scale level [10]. Despite the advantages of modifying cement composites with nanoparticles, investigations concerning the failure process of concrete with the addition of nanoparticles are very selective [12-14]. It is worth emphasizing that knowledge of this process, mainly due to the influence of compressive loading, is an important and significant issue regarding the durability and safety of using building structures made of concrete [15].

The problem of the failure process of compressed concrete includes the formation, development, accumulation and propagation of micro-damage of a concrete structure under load. It has been proved that this process consists of three stages that are distinguished by the levels of stresses that initiate cracking σ_i and critical stresses σ_{cr} [16]. These levels are understood as certain contractual stress levels in loaded concrete, which delimit the qualitative changes that take place in the structure of concrete as a result of increasing loads. They are measures of the condition of constructions made of concrete, which allow changes that occur in it to be tracked. These levels are also considered as important strength characteristics of concrete, which describe its predisposition to signalled or not signalled cracking under the influence of the acting load [15]. It has been shown on the basis of research that the course of the failure process of compressed concrete is affected by a number of technological factors, including, among others, an additive that was used to make the concrete [15]. The effect of the addition of nanoparticles on the formation of levels of stresses that initiate cracking and critical stresses in SCC is interesting and necessary to investigate. This is especially due to the fact that these levels are correlated with the appropriate fatigue strength and long-term durability of concrete [17]. The knowledge acquired during scientific research would fill the existing gaps in literature concerning this subject.

The acoustic emission (AE) method is a method that enables continuous monitoring of the failure process of loaded concrete [15,18]. This method uses the phenomenon of creation and propagation of elastic waves in a material, which arise due to the release of the elastic energy that has accumulated in it. In the process of concrete failure, the source of the AE are the emerging and spreading micro-cracks, which occur as a result of the compressive load. When reaching a surface, the micro-cracks are received by acoustic emission transducers that convert them into electrical voltage. Finally, the signals, after being registered and digitally processed in the measuring apparatus, obtain the form of AE descriptors, such as, among others, the rate of AE counts, the sum of AE counts (N_c), and the average effective value of the AE signal (RMS).

The following components were used to make mixes of self-compacting concrete for testing: Portland cement CEM I 52.5 R, which meets the requirements of EN 197-1 [19] and has a composition shown in Table 1; superplasticizer (SP) Glenium Sky 600 that is applied in an amount of 4.0% of the cement weight; tap water; and also granite aggregates with fractions of 10-5, 5-2, 2-1, 1.2-0.5, and 0.6-0.1 mm, as well as a fraction that has a grain size <0.1 mm and that acts as a small filler. Fine aggregate with a fraction of up to 2 mm accounted for 48% of the total aggregate. The W/C ratio of the designed concrete mixes was equal to 0.42.

Component	Content in the composition (%)
Cao	65.00
SiO ₂	22.00
Al ₂ O ₃	5.40
Fe ₂ O ₃	3.30
MgO	3.20
Cl ⁻	< 0.08
Loss of roasting	3.0

Scanning electron micrograph showing a dense field of ZnO nanorods. The rods are vertically oriented and appear to have a rough surface. A scale bar at the bottom right indicates 500 nm. Technical parameters at the bottom include: det mag g WD HV x bias curr dwell, 3.0 kV 20.0k 1.2 mm 0.0 kV 2000 V 4.5 nA 100 us.

From the above-mentioned components, three mixes of self-compacting concrete were designed and made. One mix was prepared without the addition of nanoparticles and used as the reference one. The composition of all the designed mixes, calculated per 1 m³, is shown in Table 2.

Mix	Cement (kg)	Aggregate (kg)	Water (kg)	Nanoparticles (kg)	SP (kg)
S1	460.0	1640.0	193.2	-	18.4
S2 (2.0% SiO ₂)	450.8	1640.0	193.2	9.2	18.4
S3 (4.0% SiO ₂)	441.6	1640.0	193.2	18.4	18.4

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After one year, from the previously prepared cubes, 6 specimens with dimensions of 50 x 50 x 100 mm were made for the tests using the acoustic emission method.

Tests using the acoustic emission method were carried out with the use of the Vallen-Systeme GmbH AMS3 apparatus set, two VS 150-M sensors with a 100-450 kHz transmission band, and a hydraulic press. During compression of the specimens, the recorded acoustic emission descriptor as a function of time was the effective value of the RMS signal. The compression of the specimens was conducted with the elimination of friction at the interface of their surfaces with the pressure plates of the testing machine. For this purpose, the surfaces of the specimens were grinded until they were mutually parallel with an accuracy of 0.05 mm. They were then covered with a thin layer of technical grease. Figure 3 shows the view of the test stand for measuring the acoustic emission.

Fig. 3. The stand for testing the failure process using the acoustic emission method.

3. Research results and their analysis

Figures 4, 5 and 6 show the results of the course of the effective sound signal (RMS) of the acoustic emission. They were recorded as a function of time of the compressed tested concretes for the S1, S2 and S3 series. The diagrams also show an increase in the relative value of compressive stresses σ_c/f_c as a function of time of the compressed specimens, as well as the average levels of stresses that initiate cracking σ_{im} and critical stresses σ_{crm} .

Fig. 4. The course of the effective value of the (RMS) acoustic emission signal with a diagram of the increase in the relative value of the compressive stresses σ_c/f_c as a function of time of the failure of the self-compacting concrete of series S1.

Fig. 5. The course of the effective value of the (RMS) acoustic emission signal with a diagram of the increase in the relative value of the compressive stresses σ_c/f_c as a function of time of the failure of the self-compacting concrete of series S2.

Fig. 6. The course of the effective value of the (RMS) acoustic emission signal with a diagram of the increase in the relative value of the compressive stresses σ_c/f_c as a function of time of the failure of the self-compacting concrete of series S3.

The presented test results confirm the three-stage process of the failure of all the tested concretes. On the course of the effective value of the acoustic emission signal (RMS), two thresholds between different stages are distinguished. The first, and less obvious, corresponds to the level of stresses that initiate cracking σ_i , and the second one, which is very distinct, corresponds to the level of critical stresses σ_{cr} . The obtained levels of these stresses are different depending on the tested series, and are summarized in Table 3.

Table 3. Results of average levels of stresses that initiate cracking σ_{im} and critical stresses σ_{crm} of the tested concrete.

Concrete series	σ_{im}/f_c (-)	σ_{crm}/f_c (-)
S1	0.52	0.78
S2 (2.0% SiO ₂)	0.58	0.83
S3 (4.0% SiO ₂)	0.60	0.86

In the case of the concrete with the addition of 2.0% of SiO₂ nanoparticles (S2), the obtained average levels of stresses that initiate cracking σ_i and critical stresses σ_{cr} are higher when compared to the reference series S1, which was without the addition of nanoparticles. It should be noted, however, that it is difficult to precisely determine the level of stresses that initiate cracking σ_i in the case of series S2. However, it can be assumed that it is higher when compared to the concrete series S1 after obtaining the result for the concrete with the addition of 4.0% of SiO₂ nanoparticles (S3). It is worth noting that the addition of 4.0% of SiO₂ nanoparticles results in a significant increase in the average levels of stresses that initiate cracking σ_i and critical stresses σ_{cr} in concrete in relation to series S1 and S2. It is a simultaneous effect of improving the compressive strength and porosity of concrete due to the addition of nano-sized particles, which was confirmed on the basis of the same concrete tests in study [20]. When considering the relationship between stresses that initiate cracking σ_i and fatigue strength, the obtained results indicate that concrete made with the addition of SiO₂ nanoparticles will be characterized by higher fatigue strength than the reference concrete.

4. Summary

The paper presents the results of tests of self-compacting concrete with the addition of SiO₂ nanoparticles using the acoustic emission method. The three-stage process of destruction of this concrete was confirmed. It was found that the addition of SiO₂ nanoparticles causes an increase in the level of stresses that initiate cracking σ_i and critical stresses σ_{cr} , which may be related to the improvement of other physical and mechanical properties of the tested concrete. Considering the fact that the level of stresses that initiate cracking σ_i is seen to be equal to the fatigue strength of concrete, it can be concluded that the durability and safety of structures subjected to repeatedly variable loads, such as girders, bridge plates or gantry beams made of concrete with the addition of SiO₂ nanoparticles, will be higher when compared to structures made of concrete without this additive.

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