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Impact and dynamic resistance of SFRCC modified by varied superplasticizers

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The paper presents results of examinations of steel fiber reinforced cement composites (SFRCC) modified by superplasticizers based on different chemical substances. The described SFRCC were made on the basis of fine aggregate cement matrix modified by steel fibers of an aspect ratio l/d = 50. Fine aggregate matrix composed of waste aggregate (obtained during hydroclassification) was modified by an addition from 0% to 2.8% (by volume) of hooked steel fibers and 1% of superplasticizer. After establishing basic parameters of fresh mix and hardened fiber reinforced composites, the main tests were a drop-weight test of the SFRCC plates and dynamic harmonic loading of beams. Results achieved this way allowed to specify the influence of the specific superplasticizer on the behaviour of SFRCC subjected to a dynamic force.

Keywords: *aggregate, cement, composite, fiber, waste*

1. Introduction

Development of modern civil engineering includes an urgent need to develop higher performance engineering materials characterized by high strength, toughness, energy absorption, durability, etc [1]. One of such still developing high performance engineering materials is steel fiber reinforced cement composite (SFRCC). This paper presents an experimental investigation carried out on three series of SFRCC. Steel fiber-reinforced cement composite is more difficult to mix and place than plain concrete. Adding any type of steel fiber to cement composite reduces fluidity of the mixture because of the needle-like shape and high specific surface of the fibers. The geometry and water requirements of SFRCC are an obstacle to its workability [2–4]. These factors lead to a reduction in consistency and the necessity to use superplasticizer. It is much more difficult to quantitatively investigate dynamic properties of material than to qualitatively study static or quasi-static properties [5–6]. Static and quasi-static properties of SFRCC are already well-known and described [7–10], but there is still lack of research programs concerning dynamic properties of such composites.

2. Materials and test method

Materials consisted of ordinary Portland cement with 28-day compressive strength of 32.5 MPa (CEM I 32.5), waste fine aggregate of maximum size 2 mm, tap water for mixing and curing and three superplasticizing admixtures. There were used: one superplasticizer based on polycarboxylate, one superplasticizer based on polyether and one special multifunctional superplasticizer. All three superplasticizers, used in the research programme are commercially available products offered by large and well known admixture producers and can be classified by ASTM C-494 and ASTM C-1017 as high range water reducers.

Superplsticizers based on polycarboxylate were introduced into civil engineering in 1993 [11–12]. The performed dispersion mechanism of these superplasticizers is related to a steric hindrance effect produced by the presence of neutral side long graft chains of the polymer molecules. The graft chains on the surface of cement are hindered by themselves from flocculating into large and irregular agglomerates of cement particles. Superplsticizers based on polyether were introduced into civil engineering in 1997 [11–12]. The performed dispersion mechanism of these superplasticizers is similar to the mechanism of polycarboxylate superplasticizers. A polyether based superplasticizers are characterized by much longer side chains of ethylene oxide (130 moles) than polycarboxylate based superplasticizers (25 moles of ethylene oxide). This change creates a lower adsorption speed and reduces the typical retarding effect related to the early adsorption in comparison to polycarboxylate based superplasticizers. Special multifunctional superplasticizers were introduced into civil engineering in the beginning of the 21st century [11–12]. The action of used special multifunctional superplasticizer is twofold − traditional water reduction effect on the one side and the formation of pore closing crystals, on the other side. These active processes of the admixture are permanent and not reversible and achieved due to small addition of highly reactive and very fine silica fume. Raw silica fume is widely and successfully used all over the world as an additive to special concretes [5, 11, 13–15]. In recent years due to numerous technological and health concerns about proper shipping and unloading and process of batching of raw silica fume and restrict storage requirements, more and more admixture and additive producers switch to production either of silica fume paste or superplasticizer containing silica fume [16].

The superplasticizers are codified as PC3, PE and CRSP. The PC3 is a superplasticizer based on polycarboxylate, the PE superplasticizer is based on polyether, and the CRSP superplasticizer contains silica fume. The density of PC3, PE and CRSP superplasticizers was equal to 1.1 g/cm^3, 1.1 g/cm^3 and 1.45 g/cm^3 respectively. These superplasticizers (and their influence on properties of the fresh mix) were described in previous work [17]. The superplasticizing admixture was batched in quantity equal to 1% (by mass of cement). The water to cement ratio (w/c) was 0.50.

The waste fine aggregate used in the examinations was of glacial origin and was obtained as a by-product from the process of hydro-classification of natural all-in-aggregate. The main mineral component of the aggregate is quartz and crystalline rock, dominated by granite. As far as smoothness of the grain surface is concerned fine aggregate is composed of angular and partially subrounded grains. Main properties of used aggregate are presented in Table 1. This aggregate was described in detail in previous works [18–19].

Table 1. Physical features of waste fine aggregate

Feature	Symbol	Size
Loose bulk density	$\rho_n^{\ l}$	1631 kg/m^3
Compacted bulk density	$\rho_n^{\ z}$	1805 kg/m^3
Fineness modulus by Kuczyński	U_K	3.279
Fineness modulus by Hummel	U_H	66.4
Fineness modulus by Abrams	U_A	2.206
Cavity of loose aggregate	j_l	38%
Cavity of compacted aggregate	j_z	32%
Porosity	P	3.39%

Hooked steel fibers of a length equal to 50 mm and circular cross-section, with an aspect ratio l/d = 50 and breaking strength of 1100 MPa were used in this research study. The shape of applied steel fibers is presented in Figure 1. The mix was modified by the addition of steel fibers used of volume fractions varying between 0 and 2.8%. Mixing, vibrating and curing of SFRCC was applied according to the procedures described in [11, 14].

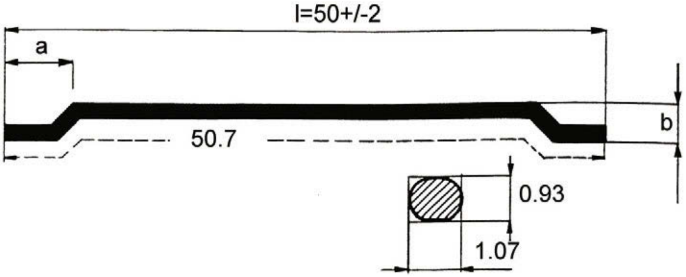

Fig. 1. Shape of applied steel fibers (a = 5 mm ± 2mm, b = 3 mm ± 1 mm)

The specimens were in a form of big beams, small beams and plates. Before testing, small beams (100 × 100 × 400 mm) were cut into three cube specimens. These specimens were used to determine the compression strength f_{cube} and density ρ. For the impact test, a drop-weight apparatus was used. A steel ball of 2381 *g* was falling onto the centre of a freely supported plate (250 × 250 × 50 mm) from a fixed height of 500 mm. Energy passed to the plate during one weight drop was equal to 11.7 *J*. Number of dropping the weight until the appearance of the first crack n_{crack} and until ultimate destroying the plate n_{max} was counted. Big beams (100 × 200 × 2000 mm) were exposed to an exciting harmonic force changeable in time. These beams were examined in the open air test facility consisted of two large concrete support blocks, and an electronically controlled inertial inductor comprising two counter-rotating cast steel discs was used to expose the beams to a time-varying harmonic force excitation. Six different attachment positions for the spinning elements enabled forces to be set with values equal to 100%, 85%, 70%, 55%, 40% and 25% of the maximum force. In this way six different levels of dynamic loading from Q_1 to Q_6 were easily achieved (for Q_1

from 44 N to 1097 N, for Q_2 from 70 N to 1755 N, for Q_3 from 96 N to 2414 N, for Q_4 from 123 to 3070, for Q_5 from 149 to 3730 N and for Q_6 from 175 to 4388 N). The applied inertial inductor is shown in Figure 2. Both the inertial inductor and whole test facility are described in detail in previous publications [6, 17].

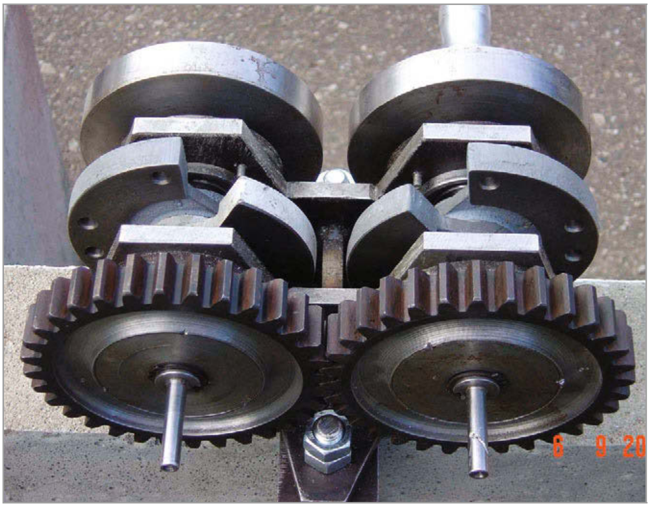

Fig. 2. Inertial inductor

All examined beams were dynamically loaded until failure or until execution all six levels of loading. Beam failure is taken as the condition when the first crack propagates through the beam cross-section. The moment was accompanied with an instant increase of vibration acceleration. Beams were loaded in cycles which lasted 225 seconds. At a given cycle of loading, the spinning disks of the inertial inductor were accelerated within 10 seconds to reach rounds generating exciting force of a frequency equal to 8 Hz. Then, within 5 seconds the first measurement of acceleration of vibration was made. Further on, within 5 seconds the rounds of spinning disks were increased by 2 Hz, and within the next 5 seconds new measurement of acceleration of vibration was carried out. This procedure was repeated until the rounds of spinning disks reached 50 Hz. The scheme of a single cycle of dynamic loading is shown in the Figure 3. In total, 15 mixtures were made, including 5 mixtures modified by superplasticizing admixture PC3, 5 mixtures modified by the PE, and 5 mixtures modified by the CRSP. These three groups of mixtures had the same contents (fine aggregate = 1780 kg/m^3, cement = 400 kg/m^3, water = 200 kg/m^3, superplasticizer = 4 kg/m^3). The only difference between them was the volume of the applied steel fiber.

The examination results were statistically processed, and values bearing the gross error were assessed on the basis of Grabbs criterion [20]. The objectivity of the experiments was assured by the choice of the sequence of the realization of specific experiments from a table of random numbers. All calculations connected with specifying a correlation coefficient and graphic interpretation of the model was carried using a statistical computer program [21–22]. Polynomial fit was used to achieve contour plots. Fitted functions were characterized by a correlation coefficient equal to at least 0.9.

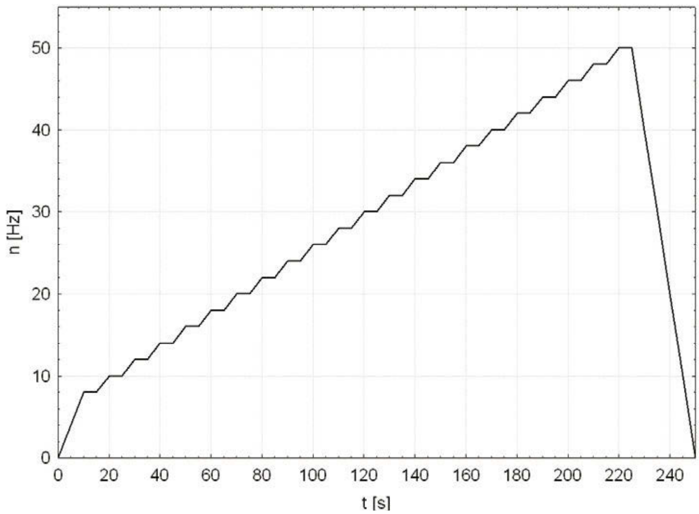

Fig. 3. Single cycle of dynamic loading

3. Test results

Workability is shown on a line plot in Figure 4 independently for each applied admixture in relation to the volume of batched steel fibers.

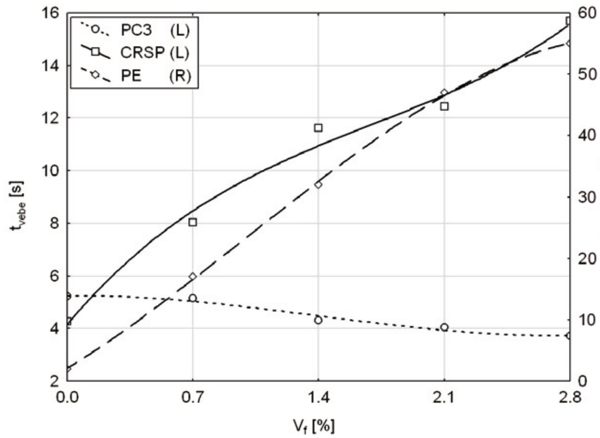

Fig. 4. Workability of fresh SFRCC

Mixtures modified by the PC3 and CRSP admixtures were examined according to Vebe procedure. Mixtures modified by the PE admixture were too liquid to warrant the use of the Vebe; instead the consistency was determined using the slump procedure. All three admixtures are shown to influence workability in different ways. The PC3 admixture enables to maintain constant workability at a level of t_{Vebe} = 4.5 ± 0.8 seconds for all examined mixtures. In the case of the CRSP admixture, consistency becomes stiffer together with the increased addition of steel fibers. Unreinforced composite modified by CRSP was characterized by t_{Vebe} = 4.3 s, and the mixture with maximum addition of steel fibers was characterized by t_{Vebe} = 15.7 s. Admixture PE led to relatively high fluidity. As the quantity of batched fibers increases, the consistency becomes more and more liquid. Unreinforced composite is characterized by h_{slump} = 2 mm and the composite with the maximum addition of steel fibers is characterized by h_{slump} = 55 mm. This phenomenon is caused by high air content in fresh SFRCC. Effect of high airing of some fresh SFRCC will be discussed in a separate study.

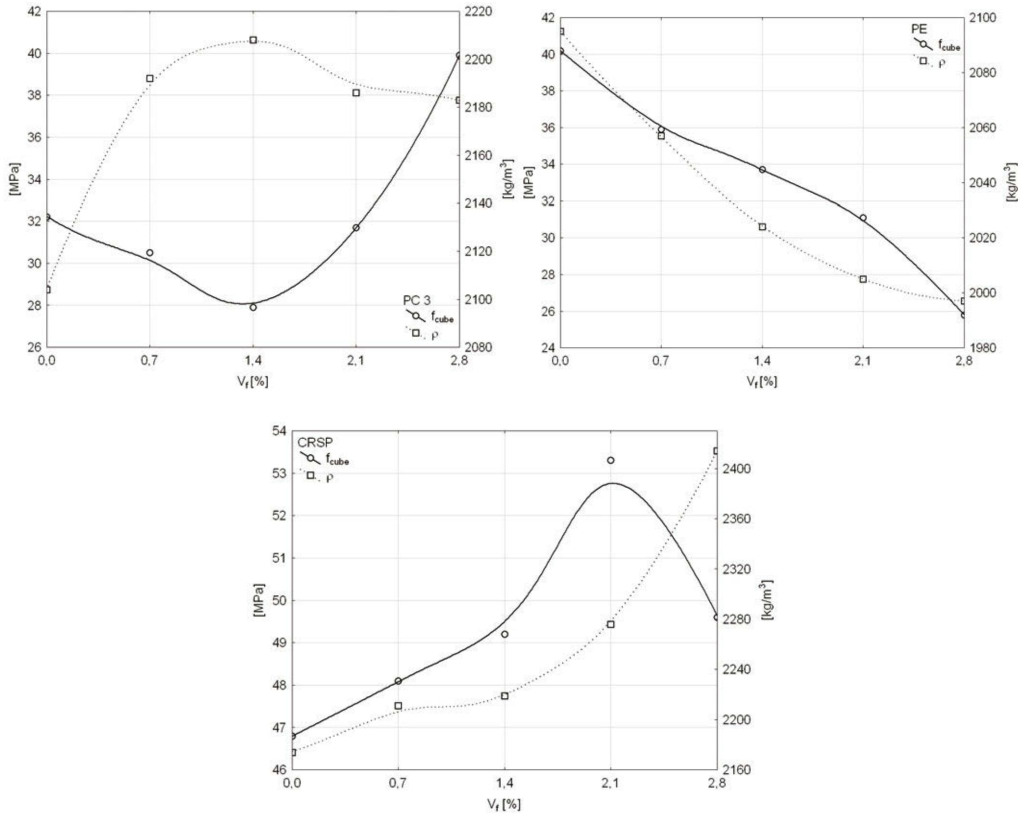

Fig. 5. Compressive strength and density of SFRCC modified by different superplasticizers

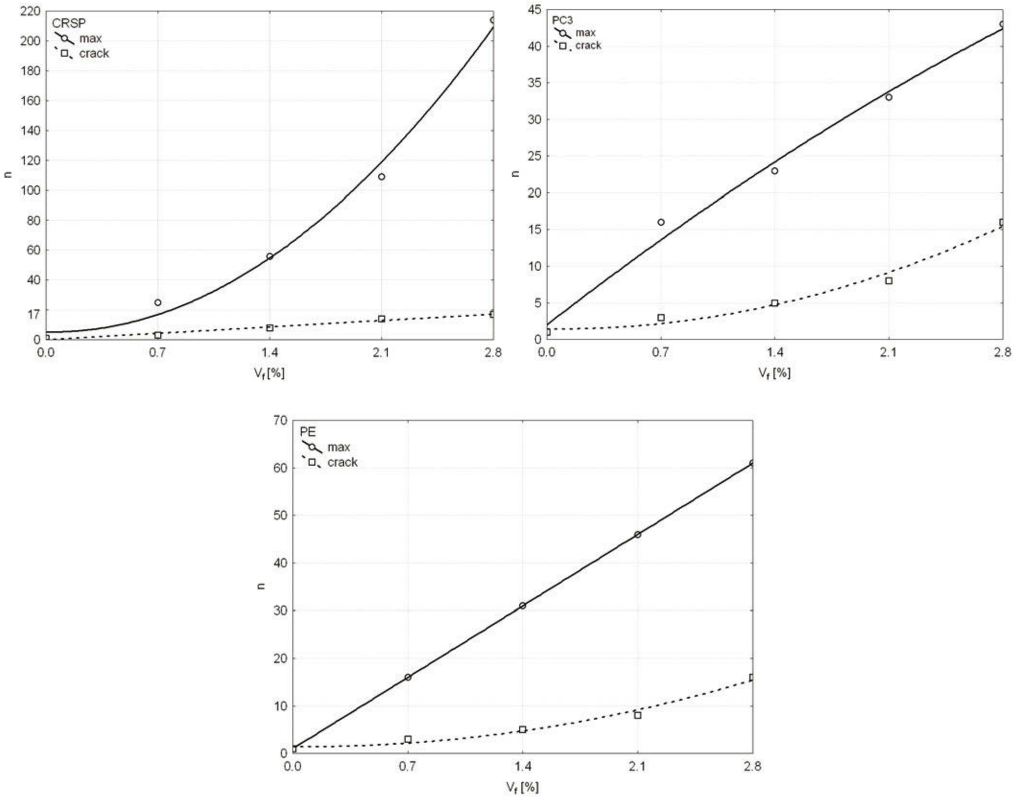

Fig. 6. Number of dropping the weight until the appearance of the first crack n_{crack} and until ultimate destroying the plate n_{max} was counted

Compressive strength and density of the hardened SFRCC are shown on Figure 5 independently for each of the applied admixtures in relation to the volume of batched steel fibers. Compressive strength of cement composites with the admixture PC3 decreased from f_{cube} = 32.20 MPa for unreinforced composite to a value of f_{cube} = 27.90 MPa at a V_f = 1.4%. Thereafter the strength increased again with further increase in the volume of fibers until it reaches f_{cube} = 39.90 MPa at the maximum addition of fibers. Unreinforced composite is characterized by a density ρ = 2104 kg/m^3. The density increased with an increase in the addition of fibers until it reaches ρ = 2208 kg/m^3 at V_f = 1.4%. Further dosing of fibers slightly decreased the density of composite which is characterized by ρ = 2183 kg/m^3 at a maximum addition of fibers. In case of composite modified by admixture PE, together with the increase of fiber content there is a decrease of both strength from f_{cube} = 40.20 MPa to f_{cube} = 25.80 MPa, and the density from ρ = 2095 kg/m^3 to ρ = 1997 kg/m^3. The addition of the admixture CRSP increased the density of composite from ρ = 2174 kg/m^3 for unreinforced one to ρ = 2414 kg/m^3 for composite modified by a maximum quantity of fibers. Compressive strength increased from f_{cube} = 46.80 MPa for unreinforced composite to f_{cube} = 53.30 MPa for composite of fibre contents V_f = 2.1%. The number of dynamic loading until the appearance of the first crack n_{crack} is equal to 16 for all three superplasticizers. The number of dynamic loading until ultimate destroying the plate n_{max} is equal 43, 61 and 214 for PC3, PE and CRSP admixture respectively (Figure 6).

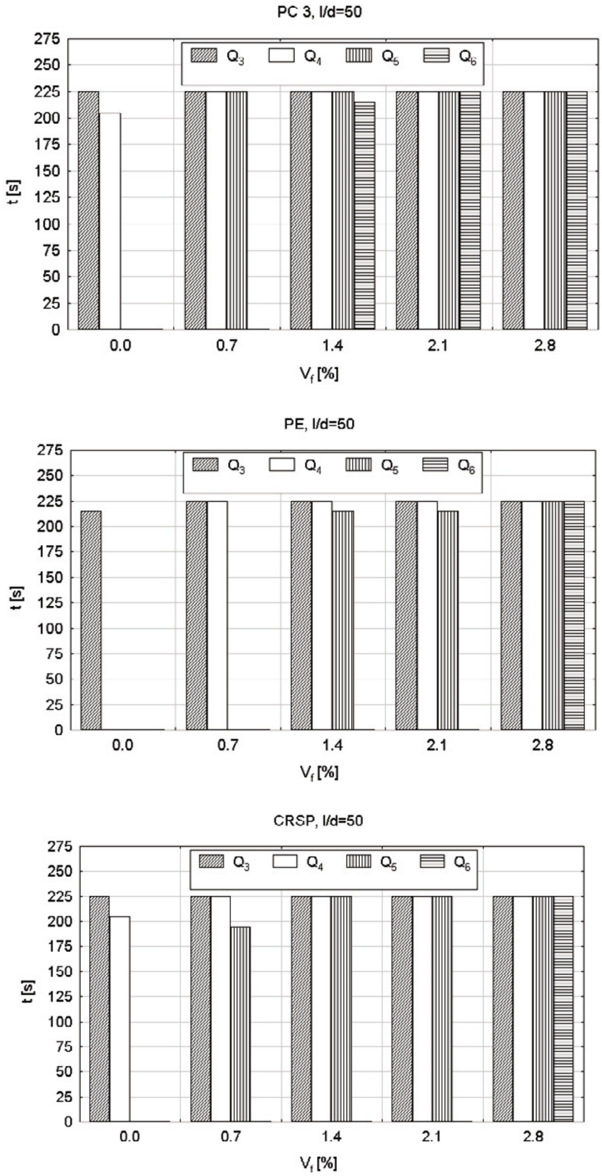

Fig. 7. Duration of cycles of loading of beams modified by different superplasticizers

The duration of a dynamic loading of a beam until its failure was taken as to estimate load-carrying ability. Because of the specificity of the examination connected with six separate cycles of loading from Q_1 to Q_6, time of loading was shown in a form of a column plot for each type of beams separately. None of the beams failed during the first two cycles of loading (from Q_1 to Q_2). Therefore, Figure 7, shows only the duration of loadings for cycles from Q_3 to Q_6. The maximum duration of a cycle of loading (Figure 3) was 225 seconds. Beams modified by the PC3 admixture were characterized by the highest resistance to dynamic loading. The addition of fibers ranging from 2.1% to 2.8% allowed the load-carrying ability of beams through 255 seconds during the cycles of loading Q_3, Q_4, Q_5, and Q_6. In case of beams modified by the PE and CRSP admixtures, only the maximum addition of fibers, of 2.8% enabled to maintain the load-carrying ability of beams subjected to the cycles of loading Q_3, Q_4, Q_5 and Q_6. Beams modified by the PE admixture were characterized by the overall smallest load-carrying ability under cycles of dynamic loadings.

4. Discussion and conclusions

The PC3, PE, and CRSP admixtures, represent three groups of most frequently used superplasticizers. Modifying the same cement composite mixtures by each of the mentioned superplasticizers allowed to achieve fiber-reinforced composites of entirely different features of density, strength and dynamic parameters. The main advantage to SFRCC beams mechanical properties resulting from the admixture of particular superplsticizer is the increase in number of impact loading until its failure and the increase in duration of a dynamic loading until its failure. The number of impact loading until the appearance of the first crack n_{crack} is the same for all free superplasticizers. The total number of a dynamic loading of all SFRCC plates modified by the CRSP admixture is the highest one. It is nearly four and five times higher then the number of a dynamic loading of plates modified by the PE and PC3 admixtures, respectively. The total duration of a dynamic loading of all SFRCC beams modified by the PC3 admixture is the highest one. It is nearly 13% and 24% higher then the duration of a dynamic loading of all beams modified by the CRSP and PE admixtures, respectively. The choice of superplasticizer is shown to have marked influence on strength and impact resistance of SFRCC.

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Uderzeniowa i dynamiczna odporność fibrokompozytów cementowych modyfikowanych różnymi superplastyfikatorami

W referacie przedstawiono wyniki badań nad fibrokompozytami cementowymi wykonanymi na bazie drobnych kruszyw odpadowych. Do wykonania fibrokompozytów wykorzystano

włókna stalowe produkcji krajowej. Włókna dozowano w ilości od 0 do 2,8% (objętościowo). Badania obejmowały swym zakresem dwa etapy. Etap pierwszy stanowiły badania cech świeżej mieszanki (konsystencja) oraz badania stwardniałych fibrokompozytów wykonane w sposób statyczny (gęstość, wytrzymałość na ściskanie). Drugi etap stanowiły badania cech dynamicznych omawianych fibrokompozytów obejmujące swym zakresem badania uderzeniowe oraz badania przy obciążeniu harmonicznym. Badania przy obciążeniu harmonicznym prowadzono na polowym stanowisku laboratoryjnym przy wykorzystaniu próbek wielkowymiarowych o długości 2000 mm i przekroju 200 mm × 100 mm.