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RESPONSE OF HIGH-PERFORMANCE FIBRE REINFORCED CONCRETE REINFORCED BY TEXTILE REINFORCEMENT TO IMPACT LOADING

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Abstract. Generally, cement composites like high-performance concrete (HPC) are very brittle. The resistance to the impact loading of the HPFRC and the HPFRC reinforced by the textile reinforcement are compared in this article. The samples (0.56 × 0.1 × 0.1 m) were experimentally tested in three-point bending, by using horizontal impact machine. The better resistance of the textile reinforced HPFRC is obvious from the collected data (impact force, acceleration of hammer and acceleration of the tested sample).

Keywords: high-performance fibre reinforced concrete (HPFRC); textile reinforcement; impact; drop height; pendulum impact machine.

1. Introduction

Many structure elements, such as bridge piers, columns or beams around traffic structures or many similar places where impact to the structure occurs, can be exposed to a dynamic impact loading. The cement composites, like high-performance concrete, are very suitable for production of structure concrete elements in difficult conditions (high mechanical loading or aggressive environment). Generally, high-performance concretes have high strength, but they are very brittle. There are lot of ways of testing of the HPC in the impact loading. One of them is to use an impact loading machine. Basically, there are two types of impact machines, drop-off machines and pendulum machines. The pendulum machine was used for testing concrete elements strengthened by the textile reinforced shells in impact in [1]. In this case, the impactor, which weight was 90 kg, fell from height of 60 mm to the experimental specimen. The drop-off machines, which are more widespread, were used in many works, e.g., in [2, 3]. The ultra-high performance fibre reinforced concrete was tested in three-point bending of impact loading in [4]. This work demonstrates that the advantageous properties of high-performance cement composites also subsist under high strain rates during impact loading. Many papers interest in cement composites in impact loading, because it is necessary to increase the ductility of the cement composite. There are two ways how to increase the ductility of the cement composite. The first way is to disperse fibres in cement mixture. The fibres can be made of polyethylene, polyvinyl alcohol or steel fibres, like in [5]. According to the results, the most suitable fibres, for the use in cement composites, are the steel fibres. The fracture energy of the fibre reinforced concretes with different dosage of steel fibres was studied in [6]. The second way of improving the ductility of HPC is the use of the textile reinforcement, like in [7]. The alkali-resistant glass textile reinforcement and polyethylene textile reinforcement were compared in this work. Based on experimental data, the samples with AR glass reinforcement were much suitable in resistance in impact loading. The samples reinforced with glass textile reinforcement absorbed less energy (20–40 % of potential energy), than samples reinforced by PE textile reinforcement (45–60 % of potential energy) and therefore damage of specimens reinforced by PE textile reinforcement was more significant.

2. Experimental program

The experimental program creates main part of this work. The high-performance fibre reinforced concrete (HPFRC) samples were tested in the horizontal impact machine, which was developed and build at Faculty of Civil Engineering at the CTU in Prague. More information about impact machine and its development are in [8]. Principle of this horizontal impact machine is based on pendulum principle. This experimental setup allows horizontal placement of a specimen. Its setup has several advantages, such as elimination of double hit, easy access to the experimental sample and free space for the sensor mounting.

2.1. Production of experimental samples

A total of six prisms, with dimensions 100×100×560 mm, were made for experimental program. All six samples were made from the same high-performance fibre reinforced concrete (HPFRC), three of them were reinforced by one-layer textile reinforcement (TRHPFRC). The HPFRC was developed for textile reinforced concrete samples production [9]. The composition of the HPFRC has typical cement composites features (higher amount of cement and low water/cement ratio). Exact composition of HPFRC is written in Table 1. The weight ratio relating to the cement is in the second column. The

Component	Weight ratio [–]	Weight of component [kg/m^3]
Cement CEM 42.5 R	1	680
Microsilica	0.19	129
Silica sand 0.1/0.6 mm	0.48	326
Silica sand 0.3/0.8 mm	0.50	340
Silica sand 0.6/1.2 mm	0.38	258
Silica powder	0.48	326
Superplasticizer	0.01	9
Water	0.35	252
Steel fibres 0.14/13 mm	0.13	91

Table 1. Composition of the high-performance fibre reinforced concrete.

amount of components in one cubic meter is written in the third column. The HPFRC contains steel fibres in addition of 1.25 % of volume for higher ductility and higher tensile strength. The steel fibres are 13 mm long and 0.14 mm in diameter. Tensile strength of the steel fibres is 3000 MPa and modulus of elasticity 210 GPa. The aspect ratio l/d of the steel fibres is 93.

The textile reinforcement R 585 A 101 that was used for three experimental samples is product of the Adfors Saint-Gobain Company (Fig. 1). This textile reinforcement is made from glass fibres and has an alkali-resistant surface. The basic weight of textile reinforcement is 585 g/m^2. The tensile strength of the textile reinforcement is 8.5 kN/50 mm in warp direction and 6.5 kN/50 mm in weft direction.

The HPFRC mixture were stirred in a vertical mixing machine with capacity of 10 litres. A production of the HPFRC is technologically very demanding, so it is always necessary to strictly follow a prescribed procedure for mixing all the components, especially the time of mixing. Total mixing time was 15 minutes. In the first step, all the dry components (silica sand, silica powder, cement and microsilica) were mixed. The mixing took 5 minutes in the first step. In the second step, water with superplasticizer and steel fibres were added. The fresh cement mixture was placed into a steel mould and it was compacted by using lower vibration. During the casting of the TRHPFRC samples, a textile reinforcement was placed on the bottom of the steel mould and after that, the mould was filled by a fresh mixture. The textile reinforcement and fresh cement matrix was brought together during the vibration of the mould. The textile reinforcement was perfectly jointed in the concrete in two millimetres under the surface, when the cement matrix hardened. The samples were removed from the moulds after 24 hours and subsequently placed into a wet environment. The samples were in wet environment for the next 27 days and after that, they were tested in the age of precisely 28 days. Six cubes (100 × 100 × 100 mm) were made for the determination of the compressive strength and six prisms

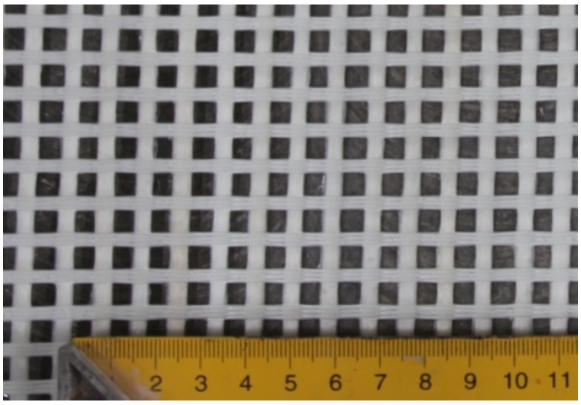

Figure 1. Textile reinforcement R 585 A 101.

(40 × 40 × 160 mm) were made for the determination of the flexural strength in a three-point bending. The compressive strength was 139 MPa (standard deviation was 3.44 MPa) and the flexural strength, in the three-point bending, was 35.5 MPa (standard deviation was 0.67 MPa). The bulk density of HPFRC was 2300 kg/m^3. The testing was conducted in accordance with CSN EN 123 90-3 [10].

3. Testing procedure

The HPFRC and TRHPFRC samples were tested in horizontal impact machine, which is based on the pendulum principle (Fig. 2). The samples were fixed in machine by steel jokes (Fig. 3). The three-point bending was conducted by hitting the specimen with an impactor. The length of the span was 500 mm. The samples with the textile reinforcement were oriented with the textile reinforcement on the back side (not on the front side, where the impact force hit). In this case, the textile reinforcement was on surface where the tension stress was expected. The steel impactor, which weight was 37 kg, created a dynamic impact loading. The impactor was dropped off from height of 400 mm above experimental sample. Initial velocity of the impactor was 2.8 m/s before impact. All of the six samples were tested using the same way. Three samples (without textile reinforcement) were broken and three samples with textile reinforcement were not broken. Data from two accelerometers on the impactor and data from an accelerometer on the back side of the sample were recorded during the test. The tests were conducted with sampling frequency of 500 kHz. The signals contained significant noise of very high frequencies. The Fast Fourier Transformation was used for a filtration and smoothing of the signals. In this approach, frequencies over 2 kHz were considered as a noise and were filtered out. The same approach for filtering and smoothing of raw data was used in [11]. In Fig. 4, there is a comparison of the raw and the filtered data of the acceleration of the impactor. The filtered acceleration data are much lower and smoother than raw data because of the high frequency noises were filtered out.

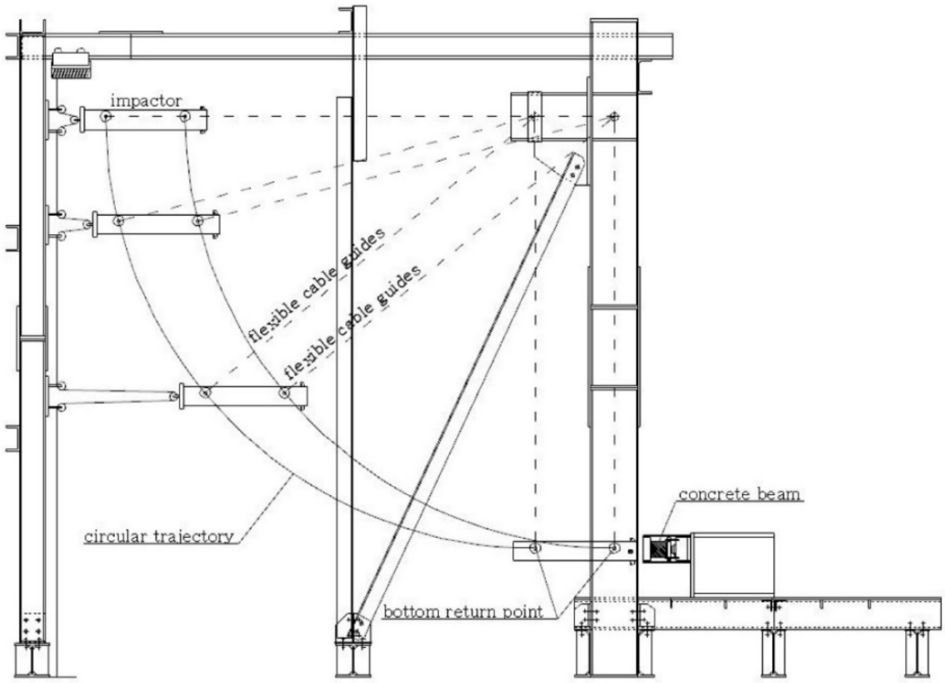

Figure 2. The horizontal impact machine [8].

Figure 3. The HPFRC sample fixed in the horizontal impact machine.

4. Method of data analysis

The input energy is a potential energy of the impactor, without energy loss during the free fall of the impactor. Part of the input energy is absorbed by the test specimen and remaining energy is dissipated by friction or transferred to the supports of the tested sample after the impact event [12]. The potential energy, which depends on mass of the impactor and the drop height, can be calculated by the next equation:

$$U_{\mathrm{i}} = mgh = U_{\mathrm{k}} + U_{\mathrm{f}} + U_{\mathrm{d}},$$

where m is mass of the impactor, g is the acceleration of gravity and h is the dropping height of the impactor. U_{d} represents the amount of the energy loss during free fall. This energy part (U_{d}) is irrelevant of the total potential energy and therefore it was not considered furthermore. U_{k} represents the energy absorbed by the sample and U_{f} represents the energy transmitted through the specimen to the supports or energy elastically transformed back to the impactor for its rebound. The absorbed energy U_{k} can be calculated from the equation

$$U_{\mathrm{k}} = \int P(t)v(t)dt \approx \sum P(t)\Delta dt,$$

where $P(t)$ represents an impact force and $v(t)$ represents a velocity history of the impact event, Δdt represents the deflection increment history of the tested sample. We can say that the absorbed energy can be obtained from the area under the load-deflection curve [13]. The impact force history was obtained from a history of acceleration of the impactor. The Newton's second law of motion was used:

$$P(t) = ma(t),$$

where m is the mass of the impactor (37 kg) and $a(t)$ is the history of acceleration of the impactor. There were two accelerometers on the impactor. For the analysis, their average was used. The history of the deflection of each sample was obtained from the history of acceleration from the accelerometer at the mid-span of the back side of the sample by using a double integration by the following equation of motion:

$$\frac{d^2u}{dt^2} = a_{\mathrm{b}}(t),$$

where u represents deflection of the sample and $a_{\mathrm{b}}(t)$ is the history of the acceleration measured by the accelerometer at the mid-span at the back side of the sample. The ratio of the absorbed energy to the input potential energy is determined by

$$\beta = U_{\mathrm{k}}/U_{\mathrm{i}}.$$

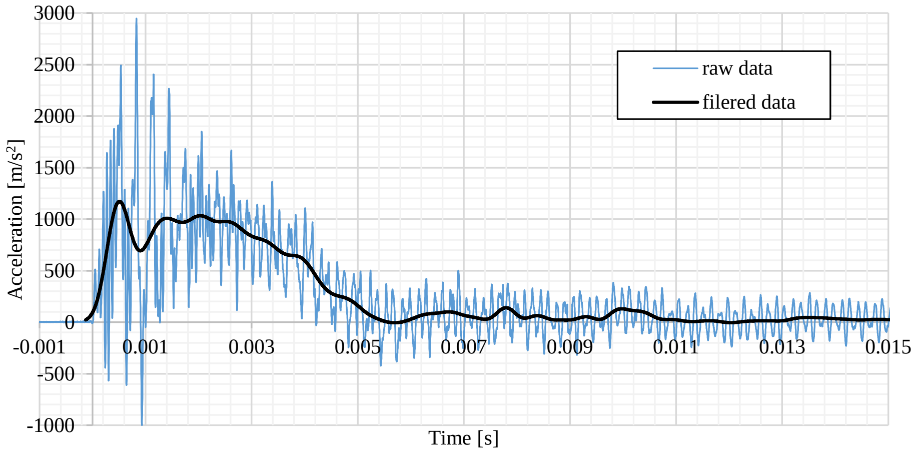

Figure 4. The comparison of the raw and the filtered data of the acceleration of the impactor.

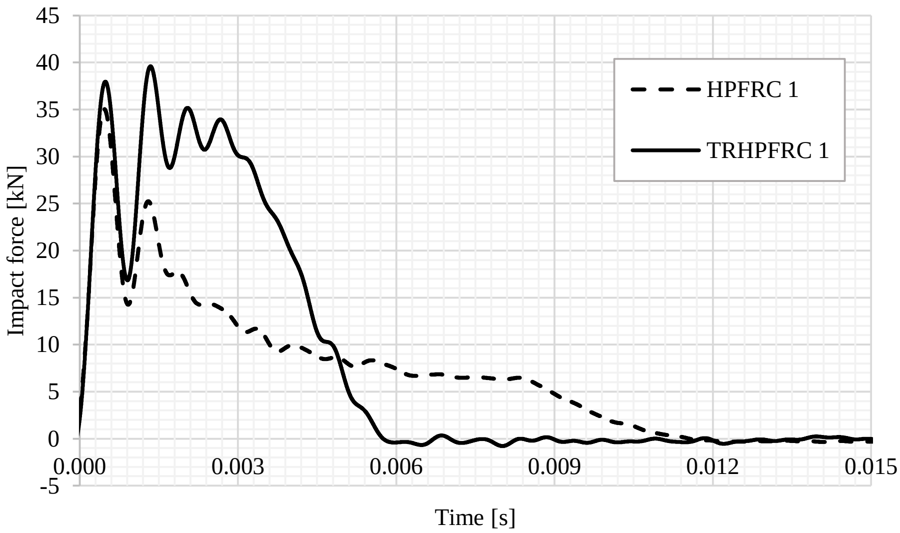

Figure 5. History of the impact force in time, applied on the sample with the textile reinforcement (TRHPFRC) and on the sample without the textile reinforcement (HPFRC).

The ratio β gives a value how much of the energy was absorbed by the sample during the impact. If β equals exactly one, all energy is absorbed by the plastic deformation of the sample. However, in the opposite case when β equals zero, all energy is transferred by the sample to the supports. The higher β ratio could mean more significant damage to the sample. The maximum value from the impact force history was used for the determination of the maximum flexural stress:

$$\sigma_\mathrm{m} = \frac{3}{2}\frac{P_\mathrm{max}L}{bh^2},$$

where P_max represents maximum value of the impact force, L represents span of the supports (0.5 m), b and h are width and thickness of the sample (both dimensions are 0.1 m). The maximal flexural stress in the three-point bending is a maximal value of tensile stress on the sample during the test, not the flexural strength that means the maximal value of tensile stress in the instance of the sample breakdown.

5. Results and discussion

Six samples, which were made of high-performance fibre reinforced concrete, were tested in the impact loading. Three of them were reinforced by the textile reinforcement (TRHPFRC 1, TRHPFRC 2 and TRHPFRC 3) and three were made only from the HPFRC (HPFRC 1, HPFRC 2 and HPFRC 3). All six samples were tested by the same way. Three samples (without textile reinforcement) were broken during the impact testing and three samples reinforced by textile reinforcement were not broken. The history of the impact force in time is in chart in next figure (Fig. 5). There are only two curves in the chart, one for HPFRC and one for TRHPFRC, for better lucidity of the chart. We can see that the time of the event, when the force impacts, is very short, 12 ms for the HPFRC and 6 ms for the TRHPFRC. A maximum values of the impact forces are close to each other. We can see this fact also in Table 2. There is a difference between the curves after the first

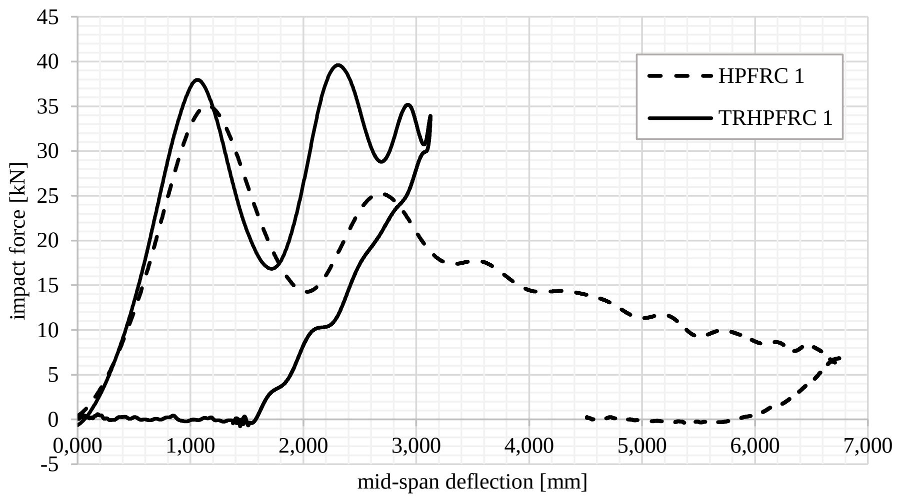

FIGURE 6. Process of the impact force, in dependence on the mid-span deflection, on the sample with the textile reinforcement (TRHPFRC) and on the sample without the textile reinforcement (HPFRC).

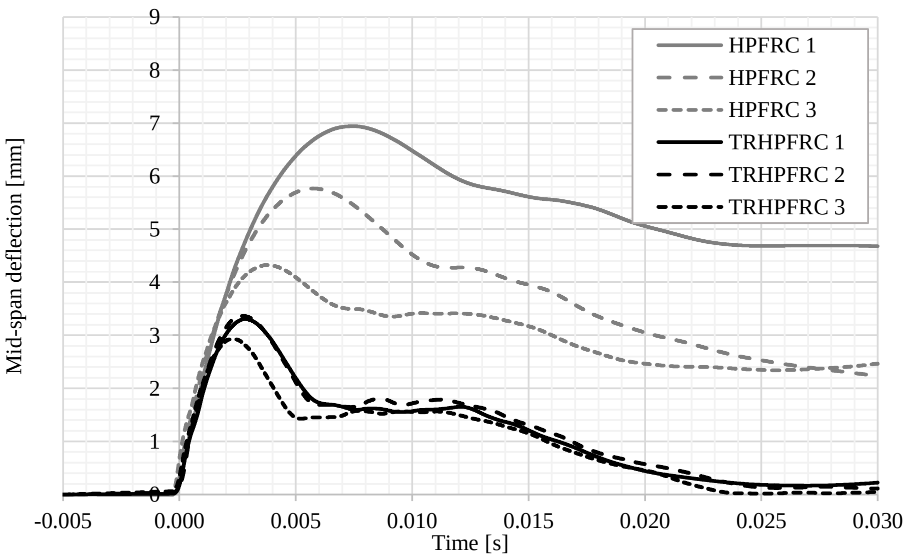

FIGURE 7. The mid-span deflection in time each sample.

peak. The HPFRC curve decreases after first peak and the TRHPFRC curve is still approximately on the same value of the impact force, but it takes only half time of the duration of the HPFRC impact force. It is caused by the plastic deformation. As it was written earlier, all the HPFRC samples were broken. There were cracks and large failures (Fig. 9). Only an elastic deformation was on TRHPFRC samples, no plastic deformation and no wide cracks (Fig. 10). Two curves are also in the chart in Fig. 6. This chart shows that the impact force depends on mid-span deflection of the samples. We can observe the same facts on the curves like in the previous chart. The absorbed energy for each sample was calculated from this curves. In Table 2, there is a summary of the calculated and absorbed energy of all samples by using the equations above. There are values of drop height of the impactor in the second column of the table. The drop height of the impactor was the same for all tested samples, therefore, the impact energy for all the samples was the same value ($U_\mathrm{i} = 145.2\,\mathrm{J}$). The third column of the table contains absorbed energy for each tested sample and there is a β ratio of the absorbed energy to the input impact energy in the fourth column of the table. The β ratio explains how big part of the impact energy was absorbed by the sample during the impact. The rest of the impact energy was not absorbed by the sample and it was transferred to the supports of the samples. There are values in the range from 0.526 to 0.723 for the HPFRC samples and values in the range from 0.343 to 0.436 for the TRHPFRC samples. We can say that the TRHPFRC samples can transfer more energy to supports without creation large cracks, because the TRHPFRC samples absorbed in average only 38.87 % of the impact energy and rest of the energy

Sample	Drop height (h) [m]	Impact energy (U_i) [J]	Absorbed energy (U_k) [J]	Ratio (β) [–]
HPFRC 1	0.4	145.2	105.1	0.723
HPFRC 2	0.4	145.2	97.6	0.672
HPFRC 3	0.4	145.2	76.4	0.526
TRHPFRC 1	0.4	145.2	56.2	0.387
TRHPFRC 2	0.4	145.2	63.3	0.436
TRHPFRC 3	0.4	145.2	49.8	0.343

Table 2. Summary of calculated impact and absorbed energy of samples.

Sample	Drop height (h) [m]	Max. impact force ($P_{\max}$) [kN]	Max. flexural stress [MPa]	Max. deflection [mm]
HPFRC 1	0.4	35.1	26.3	6.94
HPFRC 2	0.4	42.7	32.4	5.76
HPFRC 3	0.4	36.5	27.4	4.32
TRHPFRC 1	0.4	39.6	29.7	3.31
TRHPFRC 2	0.4	43.2	32.4	3.36
TRHPFRC 3	0.4	43.5	32.6	2.93

Table 3. Summary of impact response of samples.

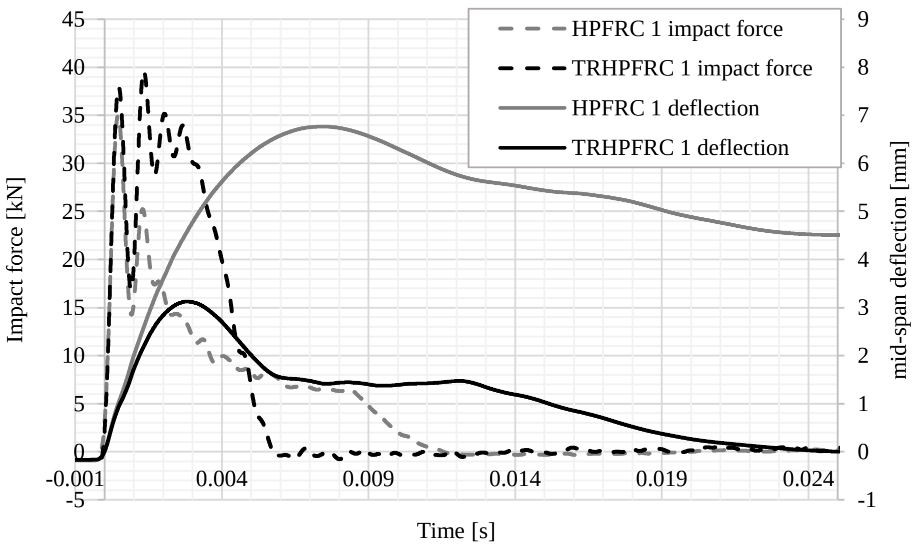

Figure 8. Time history of the impact force and mid-span deflection.

was transferred to the supports. The HPFRC samples absorbed in average 64.03 % of impact energy, which is almost two times higher value, than in the case of TRHPFRC samples. The rest of the data of the impact response of samples are written in Table 3. This table contains values of the maximal impact forces during the impact event in the third column. The maximal value of the flexural stress in the bending during test is given in the fourth column of the table. This value was calculated from the maximal impact force by using the equation above. The values of the maximal impact force and maximal flexural stress are very similar. The values of the impact force are in the range from 35.1 kN to 43.5 kN and values of the maximal flexural stress are in the range from 26.3 MPa to 32.6 MPa. It is obvious that the samples reinforced by the textile reinforcement achieve higher resistance in bending, because the failure have not occurred in the case of the HPFRC samples during the similar flexural stress values. In the fifth column of the table, the maximal value of the mid-span deflection of each sample is written. The maximal deflections of the HPFRC samples are in the range from 4.32 mm to 6.94 mm. This big disperse in values is caused by the plastic deformation failure and formation of a large cracks on the HPFRC samples. There was only elastic deformation in the case of the TRHPFRC samples, therefore, the maximal mid-span deflection is in the range from 2.93 mm to 3.36 mm. Figure 7 contains evaluation of the mid-span deflection in time. In this chart, we can observe maximal deflection and a

Figure 9. The mid-span of the HPFRC sample after the impact.

Figure 10. The mid-span of the TRHPFRC sample after the impact.

decrease of the deflection after the impact. In the case of all HPFRC samples, there was a residual deflection after the failure of the samples. In the case of the TRHPFRC samples, the deflection decreased back to a zero value of the deflection without any residual failure of the samples. The comparison of the evaluation of the impact force and the mid-span deflection in time is in chart in Fig. 8. In this chart, we can observe a lag between the impact force peak and the deflection peak. In the case of TRHPFRC, the lag between peaks is 1–2 ms, but in the case of HPFRC sample, it is more than 5 ms. Decreasing of the mid-span deflection, back to the zero value, takes 20 ms after end of the impact load.

6. Conclusions

The response of the high-performance fibre reinforced concrete to the impact loading was tested in this work. Totally six samples were tested in the horizontal impact machine, which is based on the pendulum principle. Three of them were made only from the HPFRC and the next three samples were reinforced by the glass fibres textile reinforcement (TRHPFRC). The steel impactor (mass 37 kg) was dropped from the height of 0.4 m above the specimen. Signals from the accelerometers on the impactor and in the mid-span on the back side of the sample were recorded during the tests. For evaluation, the results were calculated from the durations of the impact force signals in dependence on time and mid-span deflection of the sample. Three samples of the HPFRC were broken and three samples of the TRHPFRC were not broken during the experimental testing. According to performed experimental testing, we can make conclusions:

(1.) The maximal values of mid-span deflection were in the range from 4.32 mm to 6.94 mm, in the case of the HPFRC samples. This samples were broken during impact. There were large cracks and residual plastic deformation. There was only elastic deformation on the TRHPFRC samples and maximal mid-span deflection was in the range from 2.93 mm to 3.36 mm. After the impact, the TRHPFRC samples were in good state, without any large cracks and any plastic deformation.

(2.) The absorbed energy was calculated for each of the tested samples. The HPFRC samples absorbed in the range from 52.6 % to 72.3 % of the impact energy (145.2 J) and the TRHPFRC samples absorbed in the range from 34.3 % to 43.6 % of the impact energy. The rest of the energy was transferred by the specimen to the supports. It can be concluded, considering this fact, that the TRHPFRC samples have more capacity for carrying energy from the impact point through the specimen to the supports.

(3.) The maximum values of the impact force were in the range from 35.1 kN to 42.7 kN for the HPFRC samples and from 39.6 kN to 43.5 kN for the TRHPFRC samples. The calculated values of the maximal flexural stress were in the range from 26.3 MPa to 32.4 MPa for the HPFRC samples and from 29.7 MPa to 32.6 MPa for the TRHPFRC samples. Maximal values of the impact force and the flexural stress are a little bit higher for the TRHPFRC samples, but there was bigger difference in the impact force - deflection diagram. This fact correlates with the amount of absorbed energy, which is mentions above. The TRHPFRC samples can resist this value of impact force and flexural stress without any failure, which the HPFRC samples cannot.

From points of conclusion, we can say that the samples of the HPFRC, reinforced by the glass fibre textile reinforcement, have greater resistance to impact loading.

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