Article

Effect of Corundum and Basalt Aggregates on the Ballistic Resistance of UHP-SFRC

Michal Mára , Přemysl Kheml , Kristýna Carrera, Jindřich Fornůsek and Radoslav Sovják *

Faculty of Civil Engineering, Czech Technical University in Prague, 166 29 Prague, Czech Republic; michal.mara@fsv.cvut.cz (M.M.); premysl.kheml@fsv.cvut.cz (P.K.); kristyna.carrera@fsv.cvut.cz (K.C.); jindrich.fornusek@fsv.cvut.cz (J.F.)

* Correspondence: sovjak@fsv.cvut.cz; Tel.: +420-224-354-941

Abstract: Ultra-high-performance steel-fibre-reinforced concrete (UHP-SFRC) is a technologically advanced composite with a high ability to absorb and dissipate mechanical energy. This work investigates the possibility of increasing ballistic resistance by adding different percentages of corundum and basalt aggregate into this type of concrete. The most common type of ammunition, a 7.62 mm × 39 mm calibre with a full-metal jacket and a mild-steel core (FMJ-MS), was used to test all samples. The size of the damage and the mode of failure were determined using a 3D scanner operating on the principle of photogrammetry. The experimental campaign showed that the addition of basalt and, especially, corundum aggregate has a positive effect on ballistic resistance. In particular, the increase in compressive strength and the slight decrease in depth of penetration (DOP) was observed in the case of the usage of the corundum aggregate.

Citation: Mára, M.; Kheml, P.; Carrera, K.; Fornůsek, J.; Sovják, R. Effect of Corundum and Basalt Aggregates on the Ballistic Resistance of UHP-SFRC. *Crystals* **2021**, *11*, 1529. <https://doi.org/10.3390/cryst11121529>

Academic Editors: Yang Yu, Weiqiang Wang, Rafael Shehu and Beatrice Pomaro

Received: 20 October 2021

Accepted: 2 December 2021

Published: 8 December 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: penetration resistance; projectile impact; high-speed loading; ballistic resistance; UHP-SFRC; corundum; basalt

1. Introduction

The European and global geopolitical situation has changed in recent years, and as a result, many questions have been raised about the security of the population but also of the members of the security forces of individual states. One of these issues is the production and development of protective structures that can increase the safety of the population or the intervening units. This work focuses on the analysis of the structure of composite protective structures that are capable of withstanding extreme loads. The most common representatives of these extreme loads today include direct armed attacks employing firearms, the effects of explosives, and attacks carried out with the aid of vehicles. In recent times, there has been an increase in the number of security breaches, and it is necessary to respond to these threats. Structured composites with the right parameters can respond to these challenges more than satisfactorily. However, great care must be taken concerning the properties of the individual components of the composite, including their interaction together with the parameters of the applied loads.

The data obtained in this research can be used to fine-tune the properties of composite materials and to increase the ballistic resistance of existing structures and new buildings that serve as critical infrastructure or buildings necessary for national defence. It is important to note that many structures and buildings can be subjected to extreme loads and must be provided with sufficient resilience to withstand these actions. This often-overlooked capability of structures is the last line of defence against extreme loads: especially when all other protective measures fail, and these loads are projected into the structure. Attackers can use many types of attack, and such events cannot always be predicted in time. Although the risk of extreme loads can occur almost anywhere, the use of the right information and expert risk assessment can provide effective mitigation measures for such incidents [1].

Ultra-high-performance steel-fibre-reinforced concrete (UHP-SFRC) appears to be one of the highly promising materials that can be used in these cases [2–6]. This composite material has high compressive strength and, because of dispersed fibres, has significantly increased tensile strength [7–10]. To increase the tensile strength of the resulting mixtures, steel, glass, or polymer fibres are introduced into the mixture [11–13]. Previous studies have shown that the optimal fibre content for thin-walled structures with ballistic resistance is ranging from 1.5% to 2.0% by volume [14,15]. The most important preference for this material is its cost, which is also very high compared to other commonly used alternatives, which is significantly lower.

The resistance of concrete to projectile impact depends on many aspects. Improving impact resistance in terms of penetration depth and crater diameter can be achieved, for example, by reducing the water-to-cement ratio (w/c) and increasing the compressive strength of the concrete. However, an important factor influencing compressive strength and impact resistance is also the size, strength, and hardness of the added coarse aggregate [1–3].

The presence of dispersed steel fibres results in a reduction in the diameter of the crater. For these reasons, the use of UHP-SFRC is an ideal solution when constructing structures that could potentially be subjected to impact loads. Traditional fibre-reinforced concrete (FRC) with a normal strength matrix is known to have a large energy absorption capacity when impacted by a projectile. However, studies show that UHP-SFRC has a much higher energy absorption capacity under quasi-static and dynamic loadings.

2. Materials and Methods

2.1. Ultra-High-Strength Micro Concrete with Dispersed Reinforcement

UHP-SFRC is a technologically advanced material that offers many possibilities both architecturally and in terms of structural design. UHP-SFRC is characterised by a low water-to-binder ratio, a high proportion of microsilica (i.e., silica fume), and aggregates with grains no larger than 4 mm. Fibres added to the composite help negate the brittleness of the resulting composite. Typical strengths are 150–200 MPa in compression and 7–15 MPa in uniaxial tension. Moreover, these materials exhibit strain hardening under tension and high energy absorption capacity. These properties make this material suitable for ballistic protection [16].

2.2. Cement

One of the critical components of UHPC is cement, which has a major influence on the strength of the entire composite. The grade and quality of the cement are very important. CEM I (Portland cement with 95% clinker) and strength grades 52.5 or 42.5 are most frequently used. Cements with a small amount of alite (tricalcium aluminate) tend to reduce the development of hydration heat, which is already sufficiently high because of the large amount of cement in the mixture [11].

2.3. Aggregates

The bearing matrix of UHP-SFRC is made of fine-grained aggregate, which is subject to high demands in its strength and high quality. The composition of the aggregate is chosen so that it is assembled to fulfil the optimum grain size curve to create a dense matrix with a minimum number of pores.

The resistance and response of concrete to projectile impact depends on many aspects. Improvements in impact resistance in terms of penetration depth and crater diameter can be achieved, for example, by disperse fibre reinforcement, reducing the water-to-cement (w/c) ratio and increasing the compressive strength of the resulting mixture. However, the size, strength, and hardness of the coarse aggregate added are also important factors affecting compressive strength and impact resistance [17].

2.4. Corundum

To achieve the highest compressive strength possible, the presence of coarse aggregate in the UHP-SFRC (ultra-high-performance steel-fibre-reinforced concrete) was reduced or even eliminated to achieve the necessary homogeneity and compactness of the resulting mixture. Therefore, the contribution to the ballistic resistance of the coarse aggregate was almost neglected. However, later in the projectile penetration experiments conducted by Zhang et al. [2], H. Langberg and G. Markeset [18], or H. Wu et al. [19], it was found that the depth of penetration of the projectile continues unabated when the compressive strength of the concrete reaches a certain limit. The optimal compressive strength for UHP-SFRC, from which protective structures were designed, is in the range of 90 to 150 MPa, taking into account complex considerations of the effectiveness of protection and the cost of its production [20].

With increasing grain size of the added filler, the probability of a direct particle hit of the coarse aggregate increases. Therefore, it is possible to considerably strengthen the impact resistance of the UHP-SFRC against the projectile impact if the coarse aggregate is used with high hardness and strength.

One of the ideal materials for the coarse aggregate function in the UHP-SFRC is artificial white corundum (Figure 1), mainly due to its very high hardness, which reaches a value of 9 on a ten-grade Mohs scale. Corundum is the collective name for minerals that are essentially Al_2O_3 , but as a result of their colouration, they come in different varieties. The detailed composition of the composite mixtures containing 10–30% corundum aggregate is shown in Table 1. The corundum aggregate used was only the 3 to 5 mm fraction, and the water-to-cement ratio (w/c) was determined to be 0.30 and 0.31 (Table 1).

Figure 1. Artificial white corundum fraction 3–5 mm.

2.5. Basalt

Basalt aggregate (Figure 2) is very often used in concrete design, mainly due to its contribution in terms of mix stabilisation, where it reduces the segregation of individual components and improves the stability of the workability of the concrete mix. A less exploited advantage of basalt aggregate is its durability and hardness, with a Mohs hardness of up to 7. The basalt aggregate used in this study does not achieve such hardness as the corundum aggregate, with 2 degrees on the Mohs scale hardness, but from an economic point of view, basalt is significantly cheaper and therefore more industrially available. The value of the water-to-cement ratio (w/c) ranges from 0.30 to 0.35. The detailed composition of composite mixtures containing 10–30% basalt aggregate is shown in Table 1.

Figure 2. Basalt fraction 4–8 mm (left) and basalt fraction 0–2 mm (right).

Table 1. Mix design with corundum and basalt aggregates.

Component	Portion					
	REF	10%	15%	20%	25%	30%
Cement	1	1	1	1	1	1
Additives	0.39	0.39	0.39	0.39	0.39	0.39
Plasticiser	0.025	0.02	0.02	0.02	0.02	0.02
Steel fibres	0.17	0.17	0.17	0.17	0.17	0.17
Corundum aggregates	–	0.17	0.26	0.34	0.43	0.53
Water	0.30	0.30	0.30	0.30	0.31	0.31
Silica sand 0.1–1.2 mm	1.76	1.59	1.50	1.42	1.34	1.23
Basalt aggregates	–	0.17	0.26	0.34	0.43	0.53
Water	0.30	0.33	0.34	0.34	0.35	0.35
Silica sand 0.1–1.2 mm	1.76	1.59	1.51	1.42	1.33	1.24

2.6. Steel Fibres

The steel fibres used in this research were 13 mm long and 0.15 mm in diameter (Figure 3). These are high-strength steel fibres treated with a surface brass with a yield strength of more than 3000 MPa. The number of fibres added was 1.5% of the total volume of the composite for all samples.

Figure 3. Steel fibres with a length of 13 mm and a diameter of 0.15 mm.

2.7. Test Samples

To investigate the behaviour of UHP-SFRC with coarse aggregate added in terms of projectile impact resistance, a total of eight UHP-SFRC mixtures were designed in an experimental program for sample production. Each of them was made in three variations. The thickness of all the slabs was set at 50 mm. Their size was $400 \times 300 \text{ mm}^2$. All mixes contained the same cement type CEM I 52.5 R and identical types of admixtures such as silica fume with a mean grain size of $6 \text{ }\mu\text{m}$. The micro-sand used consisted of multiple fractions with a mean grain size ranging from 0.36 to $0.93 \text{ }\mu\text{m}$, i.e., the grain size range was from 0.1 mm and the largest grain size did not exceed 1.25 mm . In all cases, the mechanical parameters were measured on beams with dimensions of $40 \text{ mm} \times 40 \text{ mm} \times 160 \text{ mm}$. The spacing of the supports in the three-point bending test was 100 mm . The compression test was carried out on the remaining halves after the bending test, i.e., on specimens with dimensions $40 \times 40 \times 40 \text{ mm}^3$. The average values of the flexural and compressive strength of UHP-SFRC with corundum and basalt aggregate are given in Table 2.

Table 2. Flexural and compressive strength of mixtures.

Mixture	Flexural Strength [MPa]	Compressive Strength [MPa]
Reference	25.6	158.0
Corundum 10%	30.2	164.6
Corundum 15%	30.9	164.2
Corundum 20%	28.2	173.3
Corundum 25%	31.3	163.5
Corundum 30%	26.4	170.4
Basalt 10%	19.8	110.7
Basalt 15%	23.5	125.1
Basalt 20%	27.3	125.0
Basalt 25%	31.1	127.5
Basalt 30%	27.7	131.4

2.8. Methodology for Ballistic Resistance Testing

All samples were hit with a single shot. A single shot was chosen for clarity and to eliminate craters from interacting with each other over multiple shots. Test specimens were first anchored to a special steel structure (Figure 4) that provided a 3% deviation from the straight horizontal line. At the same time, this structure ensured the stability of the specimen throughout the test to prevent displacement or rotation due to the impact of the projectile on the specimen. Each specimen was inserted into the special structure, and each of the four corners was anchored with rectifying screws located 50 mm from each edge. This also achieved uniform anchoring and therefore uniform distribution of stresses. All test specimens were placed 20 m from the firing line for security reasons. A schematic of the ballistic test is shown in Figure 5.

For all samples, ammunition with a full-metal casing, steel core with a yield strength of 550 MPa , and lead penetrator was used. The projectile weight of the ogival shape projectile considering the core and jacket was 8.04 g . The projectile length was 26.6 mm and the projectile diameter was 7.92 mm (Figure 6). A shooting chronograph operating with a pair of optical gates was used to measure the muzzle velocity of each projectile, which was placed approximately 1 m from the firing line [21,22]. The average measured velocities ranged between 680 and 720 m/s (Table 3). The impact velocity of the projectiles was, as determined by Kneubuehl [23], 22 m/s lower than their impact velocity.

Figure 4. Special anchoring structure for seating test samples.

Figure 5. Ballistic test schematics; (1) Shooter, (2) Chronograph, (3) Test specimen, (4) Specimen mounting structure.

Figure 6. Symmetrical half of the FMJ-MSD projectile, calibre 7.62 × 39 mm.

Table 3. Technical parameters and characteristics of the ammunition used.

Calibre Type	Weight Projectile [g]	Energy [J]	Velocity [m/s]	Type of Projectile
7.62 × 39	8.0 ± 0.1	2000	710 ± 10	FMJ-MSC *

* Abbreviations used: FMJ-MSC—full metal jacket-mild steel core.

2.9. Measurement of the Amount of Puncture Damage

During ballistic tests, the test samples were damaged by the projectile, which created a cone-shaped crater. Then, all these craters were scanned from both sides using a 3D scanner operating on the principle of multi-frame photogrammetry. This principle is based on taking multiple photographs with every two images overlapping. Due to this overlap, it is possible to determine and calculate spatial coordinates and subsequently create a 3D model [24]. The use of this method is completely equivalent to laser scanners and in some ways even more suitable, as proposed by Steve Werner et al. [25]. In his study, his team specifically looked at a comparison between the David 3D photogrammetry-based device and the LEICA T-scan laser scanner. In this research, the SLS-2 David 3D scanner was used, which works on the principle of the aforementioned multi-frame photogrammetry. It is a setup (Figure 7) of a data projector, a high-resolution camera, and David software, which subsequently processes and evaluates the captured data (Figure 8).

Figure 7. Three-dimensional (3D) scanning assembly.

In Figure 9, more scanned images can be seen once displayed globally in the DAVID laser scanner. After scanning a single sample from all necessary angles, we proceeded to create a 3D model. In the first stage of this task, it is necessary to take individual scans; the wrong points or unwanted pores must be removed, which have been created by reflected rays. This purpose serves the editing postprocessor of the program, where individual models can be rotated and at the same time mark their parts. The next step after the scanned data corrections was the so-called matching. In the software, the individual images are matched to each other by following the same significant points on all the images. If two given images overlap, these points are found and then matched together with as little variation as possible. Based on complex mathematical algorithms involving, among other things, i.e., wavelengths, this program can assign the corresponding depth to the points, that is, creating a three-dimensional matrix corresponding to their coordinates and thus creating the relief of the crater, or three-dimensional model (Figure 10) [24]. Then, the crater area, crater volume, and DOP were measured in the software.

Figure 8. Three-dimensional (3D) model of the scanned data.

Figure 9. Multiple scans.

Figure 10. Spatial visualisation of the formed crater.

3. Results

3.1. UHP-SFRC Samples with Corundum Aggregate

The penetration depths, diameters, and crater area sizes with individual quantities including their standard deviations can be seen in the following graphs (Figures 11–15). The observed values show the relatively similar depth of penetration (DOP) values regardless of the increasing percentage replacement of corundum aggregate. Taking into account the standard measurement deviations, it can be said that the DOP depth does not show a significant dependence on the amount of corundum aggregate added. The maximum difference in DOP values was 3.7 mm, which corresponds to approximately 7.4% of the total thickness of the tested samples. The higher the compressive strengths, the less evident the penetration depth dependence. On the contrary, the downward trend of crater diameter values can be seen as a function of the increasing amounts of corundum aggregate used. The highest diameter of the front crater reached 81.0 mm when a 10% replacement was used. On the other hand, the lowest value was achieved with 30% corundum, which was 66.7 mm, with a percentual difference showing less than 18%.

Figure 11. Depth of penetration by percentage substitution.

Figure 12. Diameter of the entrance crater according to the individual percentage substitutions.

Figure 13. Size of the entrance crater area according to individual percentage substitutions.

Figure 14. Rear side crater area by percentage substitution.

Figure 15. Rear side crater area versus flexural strength.

3.2. UHP-SFRC Samples with Basalt Aggregate

The penetration depths, diameters, and crater area sizes for samples incorporating basalt aggregate with individual quantities, including their standard deviations, can be seen in the following graphs (Figures 16–20). Compared to the previous results, the depth of penetration (DOP) varies with the amount of basalt aggregate. In the graph (Figure 16),

it can be seen that in the interval between 10% and 25% basalt replacement, there is a linear increase in penetration depth. This increase corresponds to an increasing dissipation of energy on the front side of the sample as a function of the increasing amount of basalt aggregate. Furthermore, these data correlate well with the increasing trend in the size of the area and diameter of the entrance crater. The measured DOP values for mixtures with 20%, 25%, and 30% basalt are similar to those for UHP-SFRC samples and samples with corundum replacement, which were around 40% of the total thickness. On the other hand, in the case of 10% and 15% replacement, the penetration depths of 10.9 mm and 14.5 mm correspond to less than 22% and 29% of the total thickness, respectively. A slight decrease in penetration depth can be seen for the 30% mixture of basalt, which is due to the only partial penetration of the tested samples.

Figure 16. Depth of penetration by percentage substitution.

Figure 17. Diameter of the entrance crater according to the individual percentage substitutions.

Figure 18. Size of the entrance crater area according to individual percentage substitutions.

Figure 19. Size of the rear crater area according to individual percentage substitutions.

Figure 20. Dependence of the rear crater area on the flexural strength according to individual percentage substitutions.

4. Discussion

4.1. UHP-SFRC Samples with Corundum Aggregate

The penetration depths, diameters, and crater area sizes are presented in Figures 11–15. The observed values show relatively similar depth-of-penetration (DOP) values regardless of the increase in percentage replacement of the corundum aggregate. When the standard deviations of the measurements are taken into account, it can be said that the DOP does not show a significant dependence on the amount of corundum aggregate added. The

maximum difference in the DOP values was 3.7 mm, which corresponds to approximately 7.4% of the total thickness of the samples tested. This fact is confirmed to some extent by other studies [17,26]. In general, there is a relationship between decreasing DOP and increasing compressive strength (f_c), but this is mostly in the interval up to 100 MPa [17]. The higher the compressive strength, the smaller the effect on the DOP. In contrast, a decreasing trend of crater diameter values can be seen as a function of the increasing amounts of corundum aggregate used. The highest diameter of the front crater reached 81.0 mm when 10% replacement was used. On the other hand, the lowest value achieved with 30% corundum, which was 66.7 mm, showed a difference of less than 18%. This trend shows a linear decrease.

Another correlation can be seen between the size of the crater and the compressive strength. There can be seen a decreasing trend, with the area of the front crater decreasing as a function of the increasing amount of corundum. The highest values of the surface area of the crater were reached at 10% corundum aggregate, precisely 6604 mm². When the corundum addition was increased to 15%, 20%, and 25%, the average crater size values were 6355 mm², 6260 mm², and 6191 mm², respectively. The decrease between 10% and 25% was 413 mm², corresponding to approximately 6.3% of the surface area of the samples with 10% replacement. However, the highest decrease was achieved for samples with 30% corundum, with a surface area of 5224 mm². These data show that between samples with 25% and 30% corundum, the surface area of the anterior crater was reduced by more than 15%. This significant reduction in surface size will occur in the case of 30% corundum replacement, which will be further tested in follow-up research.

Figure 14 shows the dependence of the surface area of the rear crater on the amount of corundum aggregate. Increasing the percentage of corundum is correlated with increasing the surface area of the rear crater. This trend can be explained by the same failure mode and an increase in absorption energy on the rear side as in the reference UHP-SFRC samples without corundum aggregate. In other words, it can be said that the more energy is absorbed from the projectile, the greater the damage to the sample on the rear side and the greater the area of the crater that is formed. Assuming that the size of the breach on the rear side is largely defined by the tensile parameters, it is necessary to consider a graph of the dependence of the rear side crater area on the flexural tensile strength (Figure 15). However, it can be concluded from this graph that a direct correlation between the two quantities is not entirely clear. Due to these data, it is necessary to consider not only the size of the crater on the rear side and the tensile strength but also the amount of energy damage or the amount of consumed energy in breaking the input side of the test specimen.

The measured values show that the use of corundum aggregate as a partial replacement for silica sands has a positive contribution to increasing the compressive strength of the composite. The use of corundum aggregate also results in an increase in the overall hardness of the material, with a greater localisation of damage at the front of the specimen and a reduction in the size of the entrance crater [27–29].

4.2. UHP-SFRC Samples with Basalt Aggregate

The compressive and flexural strengths obtained from the test samples show that compared to the corundum aggregate samples, all mixtures with basalt were lower in parameters, especially in the case of compressive strengths. A comparison of the individual quantities including their standard deviations can be seen in Figures 16–20. Compared to previous results, the depth of penetration (DOP) varies with the amount of basalt aggregate. In Figure 16, it can be seen that in the interval between 10% and 25% basalt replacement, there is a linear increase in penetration depth. This increase corresponds to an increasing dissipation of energy on the front side of the sample as a function of the increasing amount of basalt aggregate. Furthermore, these data correlate well with the increasing trend in the size of the area and the diameter of the entrance crater. On the contrary, the data obtained are not consistent with research that defines a relationship between decreased penetration depth (DOP) and increased compressive strength (f_c) [17,26]. The measured DOP values

for the mixtures with 20%, 25%, and 30% basalt are similar to those for the mixtures with 20%, 25% and 30% corundum.

However, in the case of 10% and 15% replacements, penetration depths of 10.9 and 14.5 mm, corresponding to less than 22% and 29% of the total thickness, respectively, were obtained. A slight decrease in penetration depth can be seen for the 30% basalt mixture, which is due to the only partial penetration of the tested samples. Values of diameters and sizes of the entrance crater areas (Figures 17 and 18) are correlated well throughout the interval from 10% to 30% basalt aggregate. In the case of 30% replacement, both variables show lower values, again compared to the other mixtures, which is due to the only partial penetration of the samples.

In the case of the size of the rear crater area (Figure 19), there is a linear relationship between the amount of basalt and the value of the crater area, and this trend is valid in the interval from 10% to 25% basalt aggregate. Since the samples with 30% replacement were not perforated, their rear crater size was not measured or has a value of zero. In the next chart (Figure 20), an increasing trend of the dependence of the rear crater area on the bending strength can be seen. An increase in concrete strength can be observed between mixes with 10% and 25% basalt in flexural strength from 19.8 to 31.1 MPa, which is an increase of 57%. An increase in the average surface crater at the rear side is from 6516 to 18,928 mm². These data correspond to the results of other studies, where the increase in tensile strength on the rear side of the body has a positive effect on the absorption and dissipation by the energy exerted of the projectile. Due to the correct bridging interaction between the fibres and the matrix, only small cracks are formed when the projectile penetrates the matrix. Fibres played a crucial role in spreading stresses over a larger area of the material body. As a result, it is possible to absorb a greater amount of energy, thus increasing the ballistic resistance of the composite.

5. Conclusions

The use of basalt aggregate has been found to have a positive effect, especially on the ballistic resistance of the composite. In the case of basalt, from 30% replacement of silica sands by basalt, the depth of penetration was reduced to a value similar to that of the corundum aggregate. In addition, also, none of the tested samples was perforated through. In contrast, in the case of the lower percentages of basalt replacement (10% and 15%), the material properties were worse than those of the UHP-SFRC reference mix.

In the case of basalt, an increasing trend was observed in the size of the rear crater area as a function of increasing replacement volume, except for 30%, where, due to only partial penetration on the back of the samples, no rear crater was formed. The crater size measurements showed the highest values of all samples tested, with the UHP-SFRC achieving the highest values 2.8 times and almost 1.4 times the area for samples with corundum aggregate. Assuming a dependence of the crater area on the magnitude of the dissipated energy of the projectile, it can be said that the ballistic resistance of the composite increases with the increasing area of the craters.

The results of the measured damage degrees indicate that the replacement of part of the silica sands with basalt aggregate may have a positive effect, particularly on ballistic resistance. In the case of 30% replacement with corundum aggregate, no perforation occurred with the radial cracks that formed on the backside of the samples tested. Furthermore, the 10% basalt mixture and the other mixtures achieved mechanical parameters similar to those of the UHP-SFRC samples. Compared to corundum aggregates, in particular, significantly lower strengths were measured in the case of basalt compressions. The data also show that the most significantly positive contribution in the case of basalt is only noticeable from 20% replacement. It was also found that with an increasing percentage of basalt, the depth of penetration increases as well as the size of the area of the rear crater. This can be considered as a positive failure mode, but it places greater demands on the mix design. Some types of basalt aggregate may contain surface defects due to their mode of extraction, which,

especially in the case of larger fractions, can have a significant effect on the cohesion with the matrix in the ITZ zone.

Author Contributions: Conceptualisation, M.M. and P.K.; methodology, P.K.; software, M.M.; validation, M.M., J.F. and K.C.; formal analysis, M.M.; investigation, M.M.; resources, J.F.; data curation, M.M.; writing—original draft preparation, M.M.; writing—review and editing, P.K.; visualization, M.M.; supervision, R.S.; project administration, R.S.; funding acquisition, R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Technology Agency of the Czech Republic, grant number FW03010141 and by the CTU in Prague, grant number SGS21/055/OHK1/1T/11.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors acknowledge the assistance from students and technical staff at the Experimental Centre of the Czech Technical University in Prague who participated in the project.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Krauthammer, T. *Modern Protective Structures*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2008.
- Zhang, M.H.; Shim, V.P.W.; Lu, G.; Chew, C.W. Resistance of high-strength concrete to projectile impact. *Int. J. Impact Eng.* **2005**, *31*, 825–841. [\[CrossRef\]](#)
- Sovják, R.; Shanbhag, D.; Konrád, P.; Zatloukal, J. Response of thin UHPFRC targets with various fibre volume fractions to deformable projectile impact. *Procedia Eng.* **2017**, *193*, 3–10. [\[CrossRef\]](#)
- Nicolaides, D.; Kanellopoulos, A.; Petrou, M.; Savva, P.; Mina, A. Development of a new Ultra High Performance Fibre Reinforced Cementitious Composite (UHPFRCC) for impact and blast protection of structures. *Constr. Build. Mater.* **2015**, *95*, 667–674. [\[CrossRef\]](#)
- Nicolaides, D.; Kanellopoulos, A.; Savva, P.; Petrou, M. Experimental field investigation of impact and blast load resistance of Ultra High Performance Fibre Reinforced Cementitious Composites (UHPFRCCs). *Constr. Build. Mater.* **2015**, *95*, 566–574. [\[CrossRef\]](#)
- Vavřínek, T.; Zatloukal, J.; Fornusek, J.; Konvalinka, P. Numerical analysis of projectile impact on cementitious composite. In *AIP Conference Proceedings*; American Institute of Physics AIP: College Park, MD, USA, 2013; pp. 1012–1015.
- Yoo, D.-Y.; Lee, J.-H.; Yoon, Y.-S. Effect of fiber content on mechanical and fracture properties of ultra high performance fiber reinforced cementitious composites. *Compos. Struct.* **2013**, *106*, 742–753. [\[CrossRef\]](#)
- Abbas, S.; Soliman, A.M.; Nehdi, M.L. Exploring mechanical and durability properties of ultra-high-performance concrete incorporating various steel fiber lengths and dosages. *Constr. Build. Mater.* **2015**, *75*, 429–441. [\[CrossRef\]](#)
- Smith, J.; Cusatis, G.; Pelessone, D.; Landis, E.; O'Daniel, J.; Baylot, J. Discrete modelling of ultra-high-performance concrete with application to projectile penetration. *Int. J. Impact Eng.* **2014**, *65*, 13–32. [\[CrossRef\]](#)
- Lovichova, R.; Fornusek, J.; Mara, M.; Kocova, M.; Rihova, Z. The fibre orientation influence in cementitious composite against extreme load resistance. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2018.
- Aitcin, P.-C. *High Performance Concrete*; CRC Press: Boca Raton, FL, USA, 2011.
- Banthia, N.; Majdzadeh, F.; Wu, J.; Bindiganavile, V. Fiber synergy in Hybrid Fiber Reinforced Concrete (HyFRC) in flexure and direct shear. *Cem. Concr. Compos.* **2014**, *48*, 91–97. [\[CrossRef\]](#)
- Pająk, M.; Janiszewski, J.; Kruszka, L. Laboratory investigation on the influence of high compressive strain rates on the hybrid fibre reinforced self-compacting concrete. *Constr. Build. Mater.* **2019**, *227*, 1166–1187. [\[CrossRef\]](#)
- Máca, P.; Sovjak, R.; Konvalika, P. Mix design of UHPFRC and its response to projectile impact. *Int. J. Impact Eng.* **2014**, *63*, 158–163. [\[CrossRef\]](#)
- Kravanja, S.; Sovják, R. Ultra-high-performance fibre-reinforced concrete under high-velocity projectile impact. Part II. applicability of prediction models. *Acta Polytech.* **2018**, *58*, 355–364. [\[CrossRef\]](#)
- Rydval, M. Technologie a vlastnosti UHPC. Master's Thesis, CTU Fsv, Czech Technical University, Praha, Czechia, 2012.
- Wang, S.; Nam Le, H.T.; Poh, L.H.; Feng, H.; Zhang, M.H. Resistance of high-performance fiber-reinforced cement composites against highvelocity projectile impact. *Int. J. Impact Eng.* **2016**, *95*, 89–104. [\[CrossRef\]](#)
- Langberg, H.; Markeset, G. High performance concrete-penetration resistance and material development. In *Proceedings of the Ninth International Symposium on Interaction of the Effects of Munitions with Structures*, Berlin, Germany, 3–7 May 1999; pp. 933–941.
- Wu, H.; Fang, Q.; Chen, X.W.; Gong, Z.M.; Liu, J.Z. Projectile penetration of ultra-high performance cement based composites at 510–1320 m/s. *Constr. Build. Mater.* **2015**, *74*, 188–200. [\[CrossRef\]](#)

20. Wu, H.; Fang, Q.; Gong, J.; Liu, J.Z.; Zhang, J.H.; Gong, Z.M. Projectile impact resistance of corundum aggregated UHP-SFRC. *Int. J. Impact Eng.* **2015**, *84*, 38–53. [[CrossRef](#)]
21. Kravanja, S.; Sovják, R. Ultra-high-performance fibre-reinforced concrete under high-velocity projectile impact. Part I. experiments. *Acta Polytech.* **2018**, *58*, 232–239. [[CrossRef](#)]
22. Kravanja, S.; Sovjak, R.; Konrad, P.; Zatloukal, J. Penetration resistance of semi-infinite UHPFRC targets with various fiber volume fractions against projectile. *Impact. Procedia Eng.* **2017**, *193*, 112–119. [[CrossRef](#)]
23. Kneubuehl, B.P.; Coupland, R.A.; Rothschild, M.A. *Wound Ballistics: BASICS and Applications*; Springer: Berlin/Heidelberg, Germany; New York, NY, USA, 2011.
24. Werner, S.; Thienel, K.; Kustermann, A. Study of fractured surfaces of concrete caused by projectile impact. *Int. J. Impact Eng.* **2013**, *52*, 23–27. [[CrossRef](#)]
25. Werner, S.; Neumann, I.; Thienel, K.C.; Heunecke, O. A fractal—Based approach for the determination of concrete surfaces using laser scanning techniques: A comparison of two different measuring systems. *Mater. Struct.* **2013**, *46*, 245–254. [[CrossRef](#)]
26. Peng, Y.; Wu, H.; Fang, Q.; Liu, J.Z.; Gong, Z.M. Residual velocities of projectiles after normally perforating the thin ultra-high performance steel fiber reinforced concrete slabs. *Int. J. Impact Eng.* **2016**, *97*, 1–9. [[CrossRef](#)]
27. Wu, H.; Fang, Q.; Zhang, Y.D.; Gong, Z.M. Semi-theoretical analyses of the concrete plate perforated by a rigid projectile. *Acta Mech. Sin.* **2012**, *28*, 1630–1643. [[CrossRef](#)]
28. Chen, X.W.; Li, X.L.; Huang, F.L.; Wu, H.J.; Chen, Y.Z. Normal perforation of reinforced concrete target by rigid projectile. *Int. J. Impact. Eng.* **2008**, *35*, 1119–1129. [[CrossRef](#)]
29. Luk, V.K.; Forrestal, M.J. Penetration into semi-finite reinforced concrete targets with spherical and ogival nose projectiles. *Int. J. Impact. Eng.* **1987**, *6*, 291–301. [[CrossRef](#)]