Determination of ballistic resistance of cementitious composites

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Abstract. The paper describes the possibility of using the DOP test, standardly used to evaluate the ballistic resistance of ceramics, to determine the ballistic resistance of cement composites. DOP - Depth of penetration test - is based on measurement of residual penetration of projectile in witness system after the sample perforation; this parameter is used to determine differential efficiency factor (DEF), characterizing the ballistic resistance of the particular material. To verify the method for non-ceramic materials, four variants of cementitious composites with compressive strengths in the range of 30–150 MPa have been tested. The obtained results confirm the method's suitability for determining the ballistic resistance of cement composites in terms of ease of implementation, sensitivity, and accuracy of the obtained results for both composites of common strengths and high-performance variants. The paper also discusses some aspects of the relationship between the mechanical parameters of cement composites under static loading and their ballistic resistance.

1. Introduction
Concrete has been widely used as a structural material due to its excellent and well-described static mechanical properties and their relatively low price. Nevertheless, there is the probability that the structure will be loaded in a way that has not been designed for. Beside accidental causes (car accident) or natural disasters (earthquake) the impact of a high-velocity moving object can be critical for such a structure. In other words, the protective capacity of concrete-like materials against ballistic loading has to be taken into account. The need to evaluate such properties increases nowadays in resonance with a higher risk of the terrorist attack. Due to this fact, the properties of concrete materials at high-strain rates and dynamic conditions need to be defined to determine the response of such a material on this type of loading and to estimate its protective capacity. The method for the determination of cementitious composites ballistic resistance from the material point of view is therefore needed.

The ultra-high performance fibre reinforced concrete (UHPFRC) has the greatest potential for the high ballistic resistance of cementitious composites family. The UHPFRC has superior mechanical properties and energy absorption capacity compared to ordinary construction concrete (such as C25/30, C45/55) and can resist intense dynamic loading induced by the impact of high velocity moving object. The ballistic impact resistance of concrete materials is mainly dependent on their compressive strength as well as the type, size, and hardness of coarse aggregate used. It is known that projectile penetration
depth is dependent on the compressive strength of concrete materials, but when the compressive strength of the concrete material reaches a certain value (> 100–150 MPa), the penetration depth of the projectile remains more or less the same and the effect of increased compressive strength is diminished. [1]. Steel fibers used in UHPFRC improve the toughness, fracture energy and limit the initiation and propagation of cracking. However, high steel fibers volume may reduce the workability of concrete, so the optimal limit of the fiber volume ratio of 2.0% is suggested [2].

The standard and commonly used mechanical examination of cement-based materials is realized under static conditions (e.g., compressive strength and tensile strength testing). However, the behavior of cement-based materials differs under high-velocity impact loadings compared to static load [3, 4]. Therefore, a specific ballistic test is required to evaluate the response of protective materials. One of the well-known ballistic methods for characterization and evaluation of materials is the Depth of penetration test (DOP), which was initially designed for testing ceramic materials intended for add-on armour [5–7]. In the presented study, the same principle was used to verify the suitability of the DOP method to determine the ballistic resistance of the cement-based composites with various mechanical parameters. There is no available information about the method of ballistic resistance of cementitious composites. Currently, the evaluation of concrete materials’ resistance is based on a simple assessment of "perforation / no perforation" at the particular projectile velocity. This method is connected with several difficulties, e.g., problematic transferability of results, inaccuracy due to projectile velocity dispersion. The proposed DOP method and the resulting DEF factor can bring the accurate output, characterizing the ballistic resistance of the cementitious materials, enabling to compare them effectively and accurately.

2. Theory

In Depth of penetration test method, the cementitious sample is backed by a semi-infinite witness material. The impacting projectile must penetrate through the sample into the backing material. By comparing the penetration of a projectile into the backing material with and without the tested sample, the cementitious sample ballistic performance may be determined.

The main goal of Depth of penetration test method is to determine the residual penetration $P_{res}$ of the projectile in the backing witness material after perforation of testing material with defined thickness $H_s$ and bulk density $\rho_s$. The witness material consists of thick homogenous reference material with a defined density $\rho_{Al}$ (e.g., aluminum alloy). From the bulk density of the tested cementitious sample, its thickness and knowledge of the reference penetration of the projectile $P_r$ (penetration of the projectile in reference witness material without the cementitious sample), the differential efficiency factor (DEF) can be calculated based on the equation (1):

$$\text{DEF} = \frac{\rho_{Al}(P_{Al} - P_{res})}{\rho_s H_s}$$  \hspace{1cm} (1)

The test setup is shown in the following Figure 1.
The projectile must penetrate backing witness material. Hence, the thickness of cementitious sample must be chosen so as to achieve the complete perforation of tested sample. Measuring the penetration depth in witness material (residual penetration) can be done by X-ray or cutting a witness material. Although, cutting a thick metal witness material is laborious, especially when the hard projectile AP core remains inside.

The main output of the presented test method is the dimensionless differential efficiency factor (DEF). The higher the DEF number, the higher the ballistic resistance of the tested cementitious material. If the DEF = 1, the tested material has the same ballistic resistance as the backing witness system used. By comparing the ballistic efficiencies, one may rank the ballistic performance of cementitious materials for a given projectile.

3. Experiment

Depth of penetration test provides a method for evaluating ballistic resistance of cementitious materials for specific projectiles. The test ammunition was 7.62 mm × 54R B32 API (Armor Piercing Incendiary) projectile. This projectile consists of a high hardness steel core with weight of 5.35 g, brass jacket and incendiary composition. Overall weight of the projectile is 10.4 g. The diameter and length of steel core are 6.05 mm and 23.71 mm, respectively. The standard impact projectile velocity for cementitious samples testing was set at 854 ± 20 m/s.

The test configuration was the same for each cementitious sample. The barrel-sample distance was set at 15 m from the muzzle. The sample was fixed perpendicularly to the projectile trajectory. The tested cementitious sample was backed with witness material – an aluminum cylinder. Projectile velocity was measured by LS-04 Intelligent Light Gates placed 2.5 m from tested sample.

In this study, four different cementitious samples were examined. The ballistic resistance of two ordinary concrete samples (C25/30, C45/55) and two ultra-high strength concrete samples (UHPC KŠ Prefa, UHPFRC TBG Metrostav) was compared. The Basic mechanical properties of tested samples are given in table 1. It is evident that studied cementitious samples had very different values of compressive strength. Properties of materials were evaluated according to the relevant standards valid in the Czech Republic. Compressive strength and density were determined according to standard ČSN EN 12390-3 [8] and ČSN EN 12390-7 [9], respectively and the particle size of aggregates were determined according to standard ČSN EN 12620 [10]. Before mechanical properties and ballistic resistance testing, the samples were cured for up to 28 days in water.

For DOP test, all cementitious materials were prepared into cylindrical steel mold with an inner diameter of 150 mm (20 times the projectile diameter) and 40 mm (5 times the projectile diameter) of height ($H_s$). From each cementitious material, 10 cylindrical-shaped samples were prepared. In total, 40 samples were subjected to ballistic testing. A single bullet was fired at the centre of each cementitious sample and the residual penetration into the backing witness material was measured.
Table 1. Material properties of tested cementitious samples.

|                          | Compressive strength [MPa] | Density [kg/m³] | $D_{\text{max}}$ [mm] |
|--------------------------|----------------------------|----------------|------------------------|
| Concrete C25/30          | 35                         | 2.260          | 16                     |
| Concrete C45/55          | 56                         | 2.290          | 16                     |
| UHPFRC TBG Metrostav     | 154.5                      | 2.360          | 1.5                    |
| UHPC KŠ Prefa            | 111                        | 2.350          | 2                      |

The backing witness system material shouldn’t undergo brittle fracture after the projectile impact. Also, the backing witness material must not be subjected to strain hardening. The dimensions of backing witness material are chosen appropriately, so the deformation zone doesn’t reach the edge of the material. As the backing witness material was used cylinder made from aluminium alloy AW-2030-T4 ($\rho = 2.809$ kg/m³) as described in original DOP test method for ceramic materials. The diameter and thickness of aluminium witness material were 90 mm (12 times of projectile diameter) and 80 mm (11 times of projectile diameter), respectively.

For each projectile and witness material, it is necessary to determine the dependence of projectile penetration into witness material on the impact projectile velocities. This calibration curve is used to calculate the residual velocity of the projectile (projectile velocity after perforation of the cementitious sample). So firstly, the testing was conducted against monolithic witness material only (without cementitious sample). Then, the ballistic tests of cementitious samples backed with aluminium witness material were executed. The penetration into aluminium alloy witness material was measured after testing for both the monolithic witness material and the concrete-faced targets. X-ray technique was employed for the measurement of actual residual penetration on aluminium alloy witness material.
4. Results and Discussion
Firstly, the dependence of the projectile penetration \( (P_r) \) into aluminium witness material on projectile impact velocity \( (v) \) was determined. Obtained regression curve can be seen in Figure 2 and shows a linear dependency; therefore there was no deformation strengthening in the aluminium alloy during the projectile penetration. This confirmed selected aluminium alloy AW-2030-T4 is a suitable witness material. Aluminium alloy is the most commonly used witness system. Franzen R.R. et al. measured the depth of penetration into RHA (Rolled Homogeneous Armor) after perforation of the materials (AlN, SiC, B4C) by the projectile [11]. The aluminium alloy as a witness system is cheaper and easier for change of dimensions.

From the regression equation it is possible to calculate the residual velocity of the projectile after perforating the tested cementitious material. For the regression equation it is desirable to obtain the dependency of projectile’s penetration depth over wide range of impact velocities.

![Graph](image)

**Figure 2.** Calibration curve for projectile 7.62mm x 54R B32 API and witness material AW 2030-T4.

Table 2 summarized the values of measured parameters, which were obtained from 10 ballistic experiments for each cementitious material. Two ordinary concrete samples (C25/30 and C45/55) which contained large aggregates \( (D_{\text{max}} = 16 \text{ mm}) \) had a similar value of obtained DEF parameter \( (0.528 \text{ and } 0.545) \) with a relatively high standard deviation for DEF parameters. Deviation in DEF could be a result of the inhomogeneity of tested concrete samples. It is known that the penetration process of rigid projectile is different when it is penetrating through cementitious matrix and coarse aggregates. In most cases, aggregates have much higher strength than cementitious matrix, therefore their resistance to projectile impact is higher [12].

Unlike heterogeneous concrete materials (C25/30 and C45/55), the UHPC materials (UHPC KŠ Prefa, UHPFRC TBG Metrostav) were much more homogenous due to a smaller maximum particle size \( (D_{\text{max}} = 2 \text{ mm}) \). Therefore, the DEF values for UHPC materials hadn’t scattered. Furthermore, the UHPC samples reported a higher values of DEF parameter because the ballistic resistance of concrete-based materials is to some extend dependent to the compressive strength of concrete materials. It should be noted that the compressive strength of tested materials is not the only main parameter affecting the ballistic resistance of concrete-based materials. For example, the presence of high-strength aggregate could significantly increase the ballistic resistance of concrete-based materials [12].
Table 2. Summary of DOP test results for cementitious samples.

|                  |  \(v\) [m/s] |  \(H_s\) [mm] |  \(P_{res}\) [mm] |  \(P_r\) [mm] | DEF   | \(\sigma\) |
|------------------|--------------|--------------|-----------------|-------------|-------|-----------|
| Concrete C25/30  | 849.2        | 39.7         | 32.4            | 49.5        | 0.528 | 0.140     |
| Concrete C45/55  | 850.5        | 41.8         | 31.0            | 49.6        | 0.545 | 0.147     |
| UHPFRC TBG Metrostav | 848.6    | 42.4         | 20.7            | 49.4        | 0.786 | 0.035     |
| UHPC KŠ Prefa    | 819.4        | 42.6         | 23.2            | 46.9        | 0.664 | 0.042     |

Figure 3 shows a dependency of calculated DEF parameters on the compressive strength of tested cementitious materials. As shown in Figure 3, the DEF is dependent on compressive strength, although the compressive strength is not the only main factor affecting the ballistic resistance, as mentioned in the previous paragraph - a big influence on ballistic resistance has also the type and size of aggregate used in cementitious matrix (high strength aggregate will increase the ballistic resistance).

Results from testing concrete materials by DOP test method could be used for calculation of the ballistic limit thickness \(H_{bl}\) of the concrete materials by following equation (2):

\[
H_{bl}(DEF) = \frac{P_{res} \rho_{Al}}{DEF \rho_s} + H_s
\]  

Ballistic limit thickness obtained from equation (2) represents the minimum thickness of the protective concrete panel, at which complete penetration doesn’t occur. The dependence of ballistic limit thickness on DEF is shown in the following Figure 4.

The measured results in this article are compared with a study by Savio S.G. et al, who investigated ballistic limit thickness. Ceramics material (boron carbide) were studied on residual DOP and DEF was studied using aluminium alloy 6063-T6 as the reference witness material. Comparing the results, the DEF values have a similar character for ceramics and cementitious composites [13].
Figure 4. Dependence of $H_{bl}$ value on DEF of cementitious composites.

Based on the results, it is possible to say that the presented ballistic test methodology could be applicable for a large spectrum of concrete-based materials with different material properties (e.g., compressive strength). Presented methodology was verified for $7.62 \times 54R$ B32 API projectile. Moreover, it could be used for other similar-types projectiles, i.e., for projectile with rigid and non-deformable core, which is not significantly deformed during penetration of the cementitious composite. In presented test method, the core of armour piercing projectile could be considered non-deformable compared to cementitious materials (the erosion of the projectile core is not considered). For large calibre types projectiles, the following scaling for sample and witness material dimensions can be applied: the sample diameter is 20 times the projectile diameter and the sample thickness must not be less than 5 times the projectile diameter. The diameter of the witness material can be calculated as 12 times of projectile diameter and the thickness of the witness material is 11 times the projectile diameter. The dimensions of the specimens for large projectiles are calculated the same as a dimension of tested specimens in this article.

The following tables summarize the recommended dimensions for cementitious samples and witness material for different projectile calibres.

Table 3. Samples dimensions for the various AP projectiles.

| Projectile          | D [mm] | h [mm] |
|---------------------|--------|--------|
| 14.5 mm AP          | 300    | 80     |
| 12.7 mm AP          | 250    | 70     |
| 7.62 mm AP          | 150    | 40     |
| 5.56 – 7.62 mm Ball | 115    | 30     |

Table 4. Witness system dimensions for the various AP projectiles.

| Projectile          | $D_w$ [mm] | $h_w$ [mm] |
|---------------------|------------|------------|
| 14.5 mm AP          | 180        | 200        |
| 12.7 mm AP/MP       | 150        | 160        |
| 7.62 mm AP          | 90         | 80         |
| 5.56 – 7.62 mm Ball | 90         | 80         |
5. Conclusion
In this paper, the methodology for evaluating the ballistic resistance of cementitious samples was verified. The main output of this test method is a differential efficiency factor (DEF), which can be used for comparison of ballistic resistance of different cement-based materials. Applicability of presented ballistic test method for cementitious samples was validated for a 7.62 mm × 54R B32 API projectile. The advantage of this methodology is that the sample dimensions and witness material dimensions can be scaled for different projectile calibers. Suitable projectiles for scaling must have rigid and non-deformable core (e.g., armor piercing projectile).

- The methodology was verified on cementitious materials with a wide range of compressive strength (30–155 MPa). Based on the obtained results, it could be said that the ballistic resistance of cementitious materials is dependent on compressive strength. It is probable that compressive strength is not the only main factor affecting the ballistic resistance. This must be verified by additional experiments.
- Cementitious samples containing larger aggregates reported higher deviation in DEF parameter. It is known that the penetration process of a rigid projectile is different when it is penetrating through cementitious matrix and coarse aggregates, thus in inhomogeneous sample higher deviation of DEF could be observed.
- Results from Depth of penetration test could be used for ballistic limit thickness determination and prediction of cementitious protective panel thickness.
- By assessing the obtained DEF values, it is possible to conclude the good sensitivity of the method - the obtained values of the DEF parameter vary substantially for individual materials and allow a sensitive comparison of them.

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