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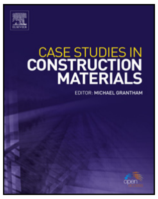

Case study

Utilization of crumb rubber and FBC-based ternary binder in shotcrete lining

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ABSTRACT

This paper describes the early-age properties of shotcrete modified by i) up to 12.5% by volume crumb rubber as a replacement for aggregates and ii) substitution of ordinary Portland cement (OPC) by a fluidized bed combustion-based ternary binder (FBC-TB) up to 80% of mass. For the tests conducted, an increase in the crumb rubber volumetric fraction of the mixture always led to a decrease in uniaxial compressive strength. Replacing OPC with FBC-TB up to 20% enhanced the development of the early-age compressive strengths; however, a larger substitution resulted in the reduction in the concrete's final compressive strength. In a full-size experimental mock-up test, the highest-performing mixture—in terms of acceptable mechanical properties and a reasonable amount of reused by-products—was subjected to full deployment in a concrete batching plant. Two batches (6 m^3 in total) of concrete with crumb rubber and FBC-TB replacement were sprayed onto a full-scale model of a tunnel for the mock-up test. Evaluation of shotcrete performance included an analysis of the development of compressive strength and a comparison of results with criteria from the relevant code of practice, the New Austrian Tunnelling Method. Based on laboratory experiments, optimization, and in-situ measurements, the mock-up tests proved shotcrete containing crumb rubber and FBC-TC is applicable for full-scale use.

1. Introduction

Modifying concrete with various additives and admixtures is a standard method for improving its properties while utilizing industrial by-products [1,2]. With increased environmental awareness about the potential hazardous effects of such by-products, their recycling and reuse have become attractive alternatives to disposal [3]. Furthermore, the concept of reusing by-products builds upon international directives regarding waste reduction and the utilization of by-products, including the Czech Republic's 2015–2024 Waste Management Plan [4]. The Czech government, which approved this plan, additionally supports CO_2 reduction in newly designed structures.

The applicability of using crumb rubber from tires in concrete has been investigated in several prior research studies due to the significant environmental impact imposed by tire waste around the world [5–9]. Mendis et al. and other authors have

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implied that even if a small percentage of aggregate in concrete is replaced with crumb rubber, considerable natural resources can be saved [7,10]. Prior researcher has demonstrated that use of crumb rubber in monolithic concrete results in a reduction of a compressive strength [11,12], elastic modulus [13,14] and tensile strength [11], with the reduction of strength and elastic modulus attributed to the relatively low strength and elastic modulus of crumb rubber. As the percentage of the crumb rubber increases, the properties of concrete become increasingly controlled by the properties of the rubber [15]. This decrease in performance when using crumb rubber might also arise from the weak interface between smooth rubber particles and aggregate and a lack of adhesion between smooth rubber particles and cement paste [8].

On the other hand, the addition of crumb rubber increases ductility and energy absorption capacities in concrete [16–18]. Using crumb rubber in shotcrete applications may therefore be advantageous by increasing the fracture process zone, subsequently resulting in reduced macrocrack localization, which may be beneficial in conditions where resistance to cracking due to imposed deformation is a priority [19].

While the use of crumb rubber in cast concrete has been the subject of prior studies, its applicability for use in sprayed concrete has—to the best of our knowledge—not yet been investigated, perhaps because shotcrete mixture design is unique in several ways. Any shotcrete mixture design must achieve high early-age compressive strength within a few minutes after deposit on a lining. Furthermore, these mixtures must achieve reasonable compressive strength at 28 days and exhibit good adhesion despite small fallouts during spraying. The temperature of a sprayed concrete mixture also plays an important role, because it guarantees a reaction with the alkali-free accelerator (AFA), necessary for achieving desirable early-age strengths. In our experience, temperatures should remain at around 22°C (minimally 20°C) during spraying; lowering temperatures to 16-18°C limits the AFA reaction leading to low early-age strengths and more fallouts.

Calcium sulfoaluminate (CSA) cement and a fluidized bed combustion-based ternary binder (FBC-TB) produce ettringite and C-S-H/C-A-S-H phases as their main hydration products [20–22]. The appearance of primary ettringite may be beneficial due to its hydraulic properties: extremely high early-age strengths, reduced plastic shrinkage, lower drying shrinkage, and excellent sulfate resistance [20]. When produced traditionally, standard CSA cement follows the ye'elimite + belite reaction, resulting in ferroaluminate clinker and utilizing waste materials and industrial by-products such as blast furnace slag, fly ash, and kiln dust [23]. CSA cements have been successfully used as shrinkage-compensating binders for mitigating long-term shrinkage, cracking, and warping [24–26].

A recent study analysed FBC-TB produced by grinding fluidized bed combustion fly ash, conventional fly ash, and the Ca$(OH)_2$ activator [21,22]. The chemical composition of FBC-TB in the study was approximately SiO_2 39%, Al_2O_3 29%, CaO 16%, and SO_3 4%. No expansion occurred within four years of monitoring underwater/wet/air exposure conditions, supporting confidence in long-term volume stability [22].

Alkali-free accelerators (AFA) used in shotcrete are traditionally based on aluminium sulphate $Al_2(SO_3)_3 \cdot (\approx 12\text{-}15)H_2O$. The aluminium sulphate reacts with lime and water while producing ettringite, which is responsible for early-age strengths [27]. Early-age reactions from FBC-TB mimic ettringite formation during alkali-free acceleration, and thus illustrate a synergetic effect between AFA and FBC-TB.

1.1. Research significance

This study is novel in its analysis of the effect of crumb rubber and FBC-TB on the resulting mechanical properties of sprayed concrete tested, using the most suitable mixture, in a full-scale mock-up experiment simulating a real shotcrete application to a tunnel wall. In order to characterize the effect of crumb rubber and FBC-TB on various mixtures, a series of tests evaluated changes in early-age compressive strengths and enabled a comparison to code of practice criterion, the New Austrian Tunnelling Method.

1.2. Objectives

1.2.1. Goals of this investigation included

- Evaluating the effect of crumb rubber and FBC-TB on the early-age compressive strength of shotcrete,
- Comparing the early-age development of compressive strength of modified shotcrete to standardized J-curves,
- Estimating the optimal amount of crumb rubber and FBC-TB for real-world shotcrete applications.

2. Materials and methods

2.1. Crumb rubber and FBC-TB

The experimental part of this study focused on the utilization of crumb rubber obtained from old tires and FBC-TB. Various crumb rubber grain fractions (0-0.8 mm, 1–3 mm, 1–4 mm and 3–6 mm) were used (Fig. 1). A series of uniaxial compression tests on 150 mm cubes were performed in order to evaluate the early-age strengths of the young concrete mixtures according to so-called J-curves. J-curves show an increase in strength of young sprayed concrete, defined in the New Austrian Tunnelling Method according to 3 possible scenarios: J1, J2, and J3 [28,29].

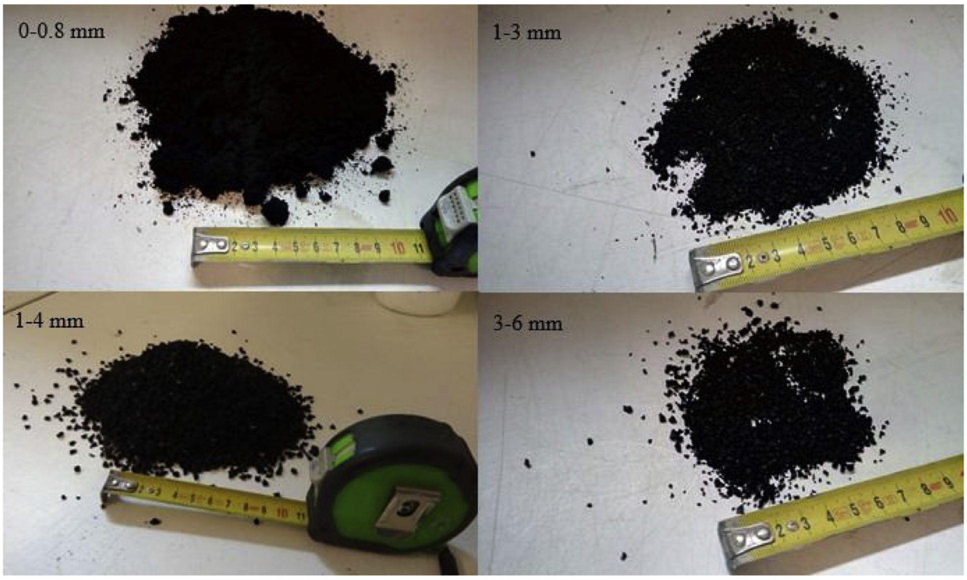

Fig. 1. Crumb rubber in various size fractions: 3–6 mm, 1–4 mm, 1–3 mm, 0–0.8 mm.

Sprayed concrete, according to the J1-curve, is suitable for applying a mixture in thin layers onto a dry substrate, without special static strength requirements in the first hours after spraying. J2 sprayed concrete is suitable in conditions where rapid application is required in thicker layers because of an inflow of groundwater or because of additional construction requirements such as anchoring, hammering, or needling. J2 sprayed concrete can be applied overhead and under difficult drilling and blasting circumstances. The J2 curve is frequently applicable in underground conditions; therefore, this study incorporated its threshold values. J3 sprayed concrete, which exhibits rapid setting and more dust and rebound in its application, is solely employed in exceptional cases; e.g., in severely damaged rock or where there is a strong inflow of groundwater.

2.2. Concrete mix design

The structural shotcrete components from which sprayed tunnel linings are constructed are primarily made of concrete grades ranging from C25/30 to C35/45 [30]. The laboratory specimens for this study had similar target strengths and were composed of materials commonly used in practice. Mixtures included volume fractions for crumb rubber (0% to 12.5% of total volume) and weight fractions for FBC-TB (0% to 80% of the mass of the cement). In addition to FBC-TB and crumb rubber, the experimental mixtures contained common ingredients: OPC, water, aggregates in three different grain fractions, a high-range water reducer (HRWR, i.e. superplasticizer), and an alkali-free accelerator (AFA, BASF MasterRoc SA 193) (Table 1). All laboratory mixtures were prepared with 2% AFA; here, the AFA percentage was derived from the weight of the binder.

Batch C1 had a variable amount of aggregates and crumb rubber, with crumb rubber incorporated into the mixture in volumes ranging from 0% to 12.5% of the volume of the mixture as a substitute for aggregates. Batch B2 was designed with a variable amount of cement and FBC-TB, where FBC-TB replaced cement in dosages ranging from 0% to 80% of the weight of the cement.

Batch C1 in Table 1 shows a mixture designed for a case in which crumb rubber replaces aggregate in regular steps after 2.5%, and Batch C2 shows a mixture where FBC-TB replaced cement in regular steps after 20%.

For instance, for mixture C1-i, the amount of crumb rubber was increased from 0 kg to 125 kg in regular steps after 25 kg, decreasing the amount of the aggregate from 450 kg to 126 kg in regular steps after 64.8 kg, respectively. Similarly, five various volume fractions of 0-0.8 mm crumb rubber were established within Batch C1-i. Consistently, mixture C2 was manufactured by increasing the amount of FBC-TB from 0 kg to 360 kg in regular steps after 90 kg, decreasing the amount of cement from 450 kg to 90 kg in regular steps after 90 kg. Four various mass fractions of the FBC-TB were examined.

3. Results and discussion

3.1. Laboratory tests

Cube compressive tests were carried out on an electrohydraulic loading machine with a constant stress-rate of 0.6 MPa/s [31]. Cubes with side lengths of 150 mm were used.

All cubes were accurately weighed and measured, and the obtained force was divided by the cross-sectional area of the test specimen. The resulting strengths were compared to two criteria. The first criterion was the J2-curve, a standard

Table 1
Mix designs for laboratory batches in kg/m^3 for mixtures with crumb rubber (C1), with various crumb rubber grain fractions (i-iv), and FBC-TB (C2).

	C1				C2
	i	ii	iii	iv	
CEM I 42.5R	450				450→90
FBC-TB	–				0→360 (0→80% mass)
Water	200				200
Aggregate 0-2 mm	450→126	450	450	450	450
Aggregate 0-4 mm	740	740→416	740→416	740→578	740
Aggregate 4-8 mm	418	418	418	418→256	418
Crumb rubber 0-0.8 mm	0→125 (0→12.5% vol.)	–	–	–	–
Crumb rubber 1-3 mm	–	0→125 (0→12.5% vol.)	–	–	–
Crumb rubber 1-4 mm	–	–	0→129 (0→12.5% vol.)	–	–
Crumb rubber 3-6 mm	–	–	–	0→134 (0→12.5% vol.)	–
HRWR	3.6				3.6
AFA (2% binder mass)	9				9

requirement for underground works in the New Austrian Tunnelling Method. The limit value of compressive strength for the specimens aged 24 h, derived from the J2-curve, was 5 MPa. The industrial partner for this study established the second criterion: a maximum decrease in compressive strength of no more than 30%. This is the maximal acceptable decrease relative to the reference mixture for a mixture to be used in underground works.

Crumb rubber (bulk density 1000 kg/m^3) replaced aggregate (bulk density 2600 kg/m^3) (Table 1). As the percentage of crumb rubber increased, the bulk density of concrete became increasingly controlled by the bulk density of the rubber. This resulted in a reduction of the bulk density of the resulting mixtures (Table 2).

3.1.1. Substitution with crumb rubber

The results showed that greater volumes of crumb rubber in concrete had notably negative effects on the resultant strength of specimens. The resulting cubic strengths decreased throughout all the tested rubber grain fractions along with the increments in their volume contents in concrete (Fig. 2). A drop in the compressive strength—30% relative to the reference value (13.3 MPa)—was gained when crumb rubber content was circa 5% by volume of the concrete. However, the requirement for minimum compressive strength established by the J2 curve after 24 h (5 MPa) was met for all crumb rubber grain fractions and volume contents tested in this study.

The results of compressive strength testing showed that it was slightly better to supply the concrete with coarser grain fractions of crumb rubber, i.e. 1–4 mm and 3–6 mm, where the strengths were approximately 15% higher than within the same volume content of crumb rubber with a 0-0.8 mm grain fraction. This is due to the fineness of the crumb rubber 0-0.8 mm grain fraction. Mixtures that contained smaller grains of crumb rubber, i.e. fraction 0-0.8 mm, exhibited reduced workability, which resulted in a decrease in compressive strength.

The compressive strength of crumb rubber concrete (CRC) is lower when compared to concrete without crumb rubber because the grains of crumb rubber practically act as voids in hardened concrete. This is because the modulus of elasticity of crumb rubber is approximately 0.1 GPa, two orders of magnitudes lower than that of concrete. The increased crumb rubber volumetric fraction in hardened concrete results in a decrease in compressive strength and in higher deformability. It can be concluded that replacing aggregate with crumb rubber decreased the uniaxial compressive strength and also the modulus of elasticity of concrete in our study, which has also been observed by other authors [5,8]. This can be logically justified by the well-established fact that the modulus of elasticity of concrete depends on the modulus of elasticity of the aggregates and on their volumetric proportions in the matrix [19,32].

Table 2
Bulk densities in kg/m^3 of the resulting mixtures with crumb rubber of various grain fractions in concretes having various volume contents.

		Crumb rubber volumetric content					
Batch	Grain fraction	0%	2.5%	5%	7.5%	10%	12.5%
C1-i	0-0.8 mm	2177	2034	2009	2006	1932	1889
C1-ii	1-3 mm		2078	2063	2052	1978	1960
C1-iii	1-4 mm		2137	2090	2090	1992	1960
C1-iv	3-6 mm		2154	2094	2009	1971	1947

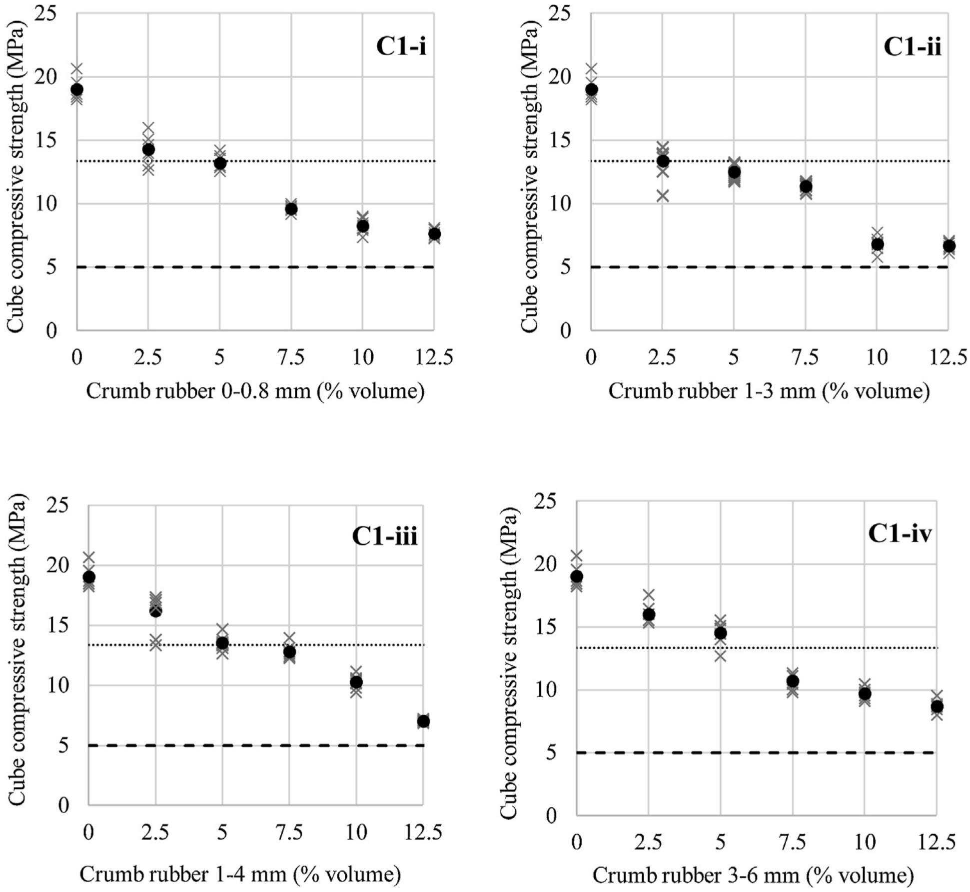

Fig. 2. Cube compressive strengths for crumb rubber concrete incorporating various crumb rubber volumetric fractions at 24 h. The black dots represent the average of the measured values. The dotted line is the 30% limit of the decrease relative to the reference specimens given by the industrial partner, and the dashed line is the limit established by the J2 curve for a specific age of 24 h.

3.1.2. Micromechanical simulation

The validation of laboratory tests with the addition of crumb rubber followed a heterogeneous continuum of two phases: the concrete matrix and random rubber inclusions. The onset of damage triggered by exceeding the equivalent strain $\tilde{\varepsilon}$ takes the form of Rankine's condition for tensile-dominated loadings

$$\tilde{\varepsilon} = \frac{\sigma_1}{E}, \sigma_1 > 0$$

where σ_1 is the first principal stress and E is the elastic modulus of undamaged material. For compression-dominated loading, the Griffith condition yields

$$\sim \varepsilon = \frac{1}{\mathrm{E}} \cdot \frac{-(\sigma_1 - \sigma_3)^2}{8(\sigma_1 + \sigma_3)}$$

where σ_3 is the third principal stress [33,34]. Since the micromechanical model uses tensile softening during loading, higher equivalent deformation from both conditions enters a linear softening law in the form

$$\omega = \left(1 - \frac{\varepsilon_0}{\sim \varepsilon}\right)\left(1 - \frac{\mathrm{h}\mathrm{E}\varepsilon_0^2}{2\mathrm{G}_\mathrm{f}}\right)^{-1}$$

where ω is isotropic damage, h is the characteristic size of the element, G_f is fracture energy and ε_0 is the onset of cracking in uniaxial tension. The stress-strain law in a material point is modified accordingly as

$$\sigma = (1 - \omega)E\tilde{\varepsilon}$$

The material models presented here were implemented using OOFEM, an open-source, finite element software which provided a framework for isotropic damage material models, numerical solvers, and post-processing [35]. For fabrication of unit cells, a simple Python generator provided the random spatial assignment of crumb rubber. Computation in this manner takes several minutes, depending on required accuracy and displacement steps.

Two materials represented heterogeneous concrete with a crumb rubber addition:

- Mortar matrix with $E = 25$ GPa, Poisson's ratio 0.24, tensile strength 2.6 MPa, fracture energy (80 J/m^2),
- Crumb rubber inclusion with $E = 0.1$ GPa, Poisson's ratio 0.49, no damage.

The unit cell in Fig. 3 was 100 × 100 pixels, representing 100 × 100 mm under plane stress conditions. Rubber placement was random; load was controlled by a kinematic vertical movement of the top nodes. The reference sample shows diagonal crack bands (Fig. 3), while the sample with 12.5% crumb rubber by volume deviated to a distorted crack band (Fig. 4).

Further micromechanical simulations validate nicely with the experimental data in Fig. 5 for crumb rubber volumes ranging from 0% to 12.5%.

Micromechanical simulations provided a complete stress-strain diagram. The addition of 12.5% of crumb rubber by volume showed about two-fold higher ductility during the compression test (Fig. 6). Consistently, other authors also reported that rubber aggregate incorporation improves the strain capacity of concrete before macrocrack localization [19].

3.1.3. Substitution with FBC-TB

Cement production contributes to approximately 5–8% of the world's CO_2 production and therefore significant efforts are being made to reduce the amount of cement used in the construction industry, including underground works. In this study, FBC-TB replaced cement by up to 80% of mass. Since the ternary binder generates a large amount of ettringite during early hydration, the idea was to use this reaction for early-strength gain in shotcrete, in a manner similar to the reactions of alkali-free accelerators.

Substitution of ordinary portland cement (OPC) with FBC-TB at about 20% of its weight led to a slight increase in compressive strength measured 24 h after spraying. However, the addition of more FBC-TB led to a decrease in the compressive one-day strength of the resulting mixture (Fig. 7).

3.1.4. Effect of FBC-TB in concrete with crumb rubber

Mixture C1-iii (5% vol. 1–4 mm crumb rubber) was used to verify the effect of FBC-TB. This mixture was chosen because it had been demonstrated previously that the maximum possible decrease in compressive strength in 24 h—specified as a 30% drop relative to the reference specimen—was obtained at 5% of the volumetric fraction of crumb rubber in the concrete (Fig. 5). Selection of FBC-TB, 20% of OPC replacement, was due to its possible enhanced early-age development and increased one-day compressive strength, found to be slightly higher than in the reference counterparts (Fig. 7).

Ten penetrometer readings—performed until compressive strength reached 0.5 MPa—were used to determine the compressive strength of young concrete, see Fig. 8. Compressive strengths above 0.5 MPa were measured on 150 mm cubes with standard uniaxial compression tests, and the values presented in Fig. 8 represent the average of three readings. Both mixtures were prepared, according to the weight of the binder, with 2% AFA.

The mutual strength developments in Fig. 8 show a synergetic effect between FBC-TB and AFA in early-age strengths, likely because of the formation of ettringite. The ettringite benefits from an early-age reaction of FBC-TB, which contains lime and sulfates, and improves early-age strengths.

J2 curve requirements were not satisfied due to the low amount of AFA used in the laboratory tests. A higher amount of AFA (6%–8%) than is normally used in the construction process [28] would likely increase the initial values of shotcrete strength and result in higher values in order to satisfy the aforementioned J2 curve.

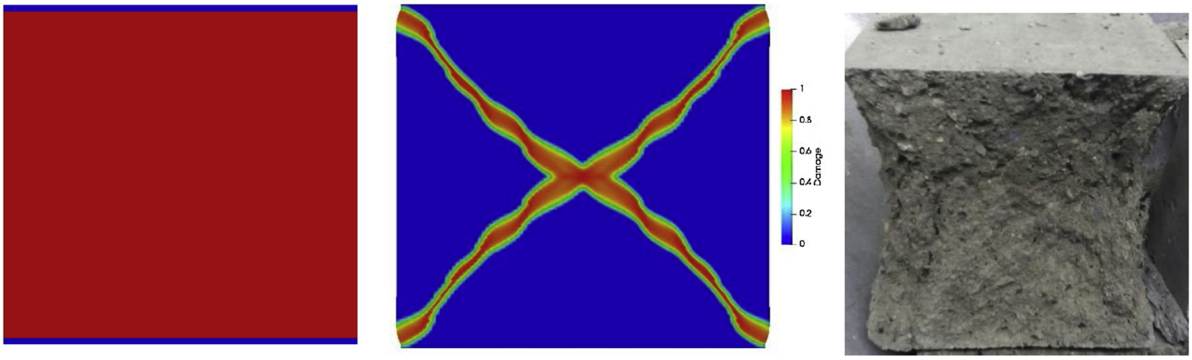

Fig. 3. Failure mode from the numerical simulation and its comparison with the experiment for a reference specimen with a diagonal crack pattern.

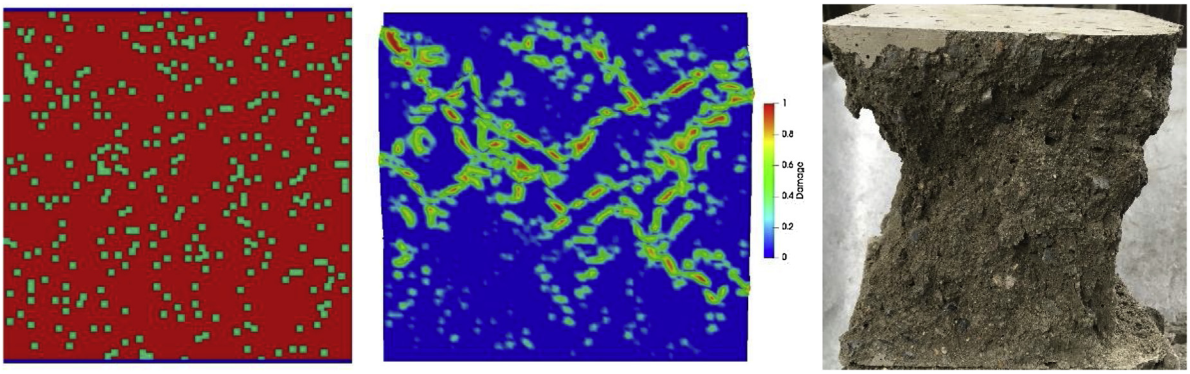

Fig. 4. Failure mode from the numerical simulation and its comparison with the experiment for a specimen with 12.5% crumb rubber by volume showing a distorted crack band.

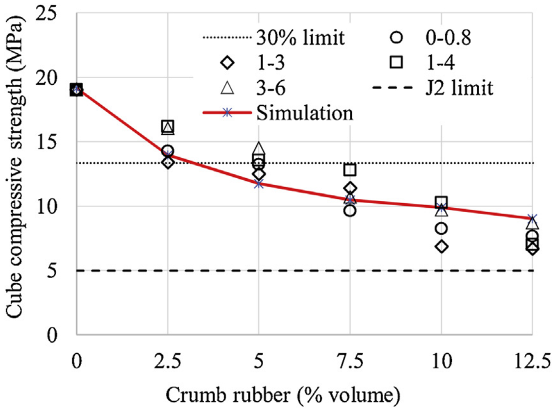

Fig. 5. Validation of a micromechanical simulation of compressive strength for concrete with the addition of crumb rubber at 24 h.

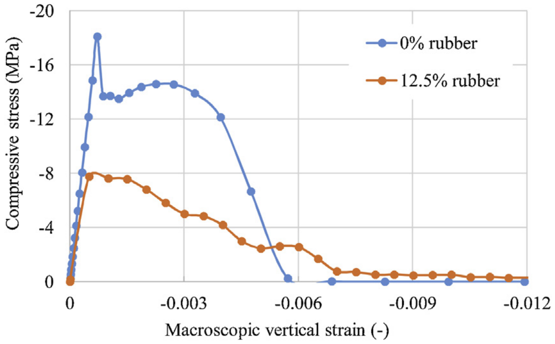

Fig. 6. Stress-strain diagram under uniaxial compression for reference concrete and concrete with 12.5% of crumb rubber by volume.

3.2. Mock-up experiment

For the mock-up experiment, a bretex frame (BTX, i.e. truss tunnel frame) was constructed using 150 × 150 mm steel reinforcing mesh and 8 mm diameter rebar (Fig. 9a). The outer surface was covered with a geotextile membrane and attached to the BTX frame (Fig. 9b). Welding each BTX frame into a reinforced concrete block on the ground underneath anchored the frame.

Two batches of fresh concrete mixture, a total volume of six cubic meters, were sprayed onto the inner surface of the frame (Fig. 9c). The first batch contained both crumb rubber and FBC-TB; the second batch contained FBC-TB only (Table 3). The design of both batches was intended to utilize by-products as part of the experiment, both in terms of their resultant contributions to compressive strengths as well as to reasonably reuse.

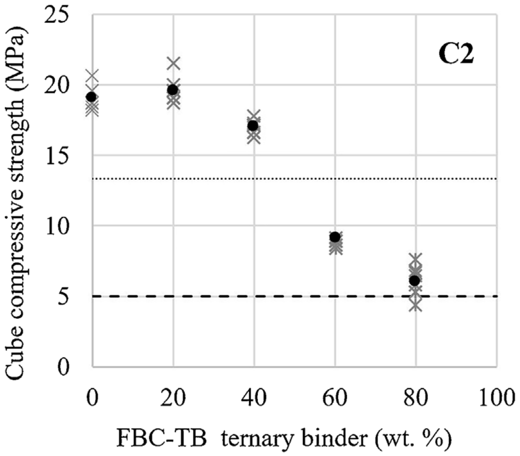

Fig. 7. Cube compressive strength for concrete incorporating FBC-TB at 24 h. The black dots represent the average of the measured values. The dotted line is the 30% limit of the decrease relative to the reference specimens provided by the industrial partner, and the dashed line is the limit given by the J2 curve at a specific age.

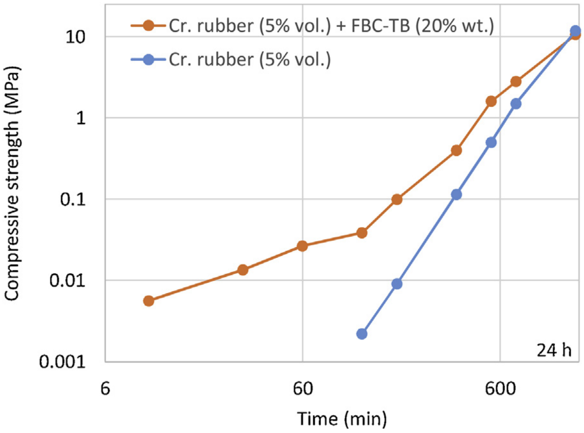

Fig. 8. Strength development of a mixture with 1–4 mm crumb rubber and FBC-TB within the first 24 h.

The batch with crumb rubber additive, 5% of vol., was sprayed on the lower part of the BTX frame because it was considered likely to have an acceptably small effect on the strength of sprayed concrete.

The replacement of OPC with FBC-TB ranged from 45% to 50% of OPC mass. The higher volumes of FBC-TB were intended to enhance early-age development of strength, despite the fact that the 24 h-strength might end up lower relative to the reference mixture.

In the first batch (C3), FBC-TB replaced 50% of OPC, and crumb rubber replaced 5% of coarse aggregate by volume. In the second batch (C4), FBC-TB replaced 45% of OPC. The shotcrete was applied in two parts, with two different amounts of AFA added at the nozzle of the spraying machine (Table 3).

Mixing water was heated slightly due to low local temperatures during the day spraying took place (11 °C to 14 °C). The temperature of the resultant heated water mixture was 21 °C, assuring sufficient reaction of AFA with the mixture. The consistency of the mixture was determined using the Abrams cone and was 200 mm for mixture C3, and 210 mm for C4.

The first batch (C3) with the addition of crumb rubber and FBC-TB was sprayed on the lower part of the BTX frame, and 6.5% AFA—determined from the weight of the binder—was added at the nozzle. The second batch (C4), with the addition of FBC-TB, was sprayed on the upper sides of the BTX frame, including the ceiling of the frame. The first half of the second batch (C4-i) was sprayed with 7.5% of the AFA that had been added at the nozzle, and the second half of the second batch (C4-ii) was sprayed with 8.5% of the AFA that had been added at the nozzle.

Wooden boxes (500 × 500 × 150 mm) served for taking measurements, with cores of sprayed concrete used to determine compressive strength (Fig. 9d). The compressive strength of young sprayed concrete was tested according to ČSN EN 14488-2 with the help of a shotcrete penetrometer, with a penetration needle according to method A, where the penetrometer provides readings of the forces required to penetrate sprayed concrete during the first few hours, up to 1.2 MPa of its

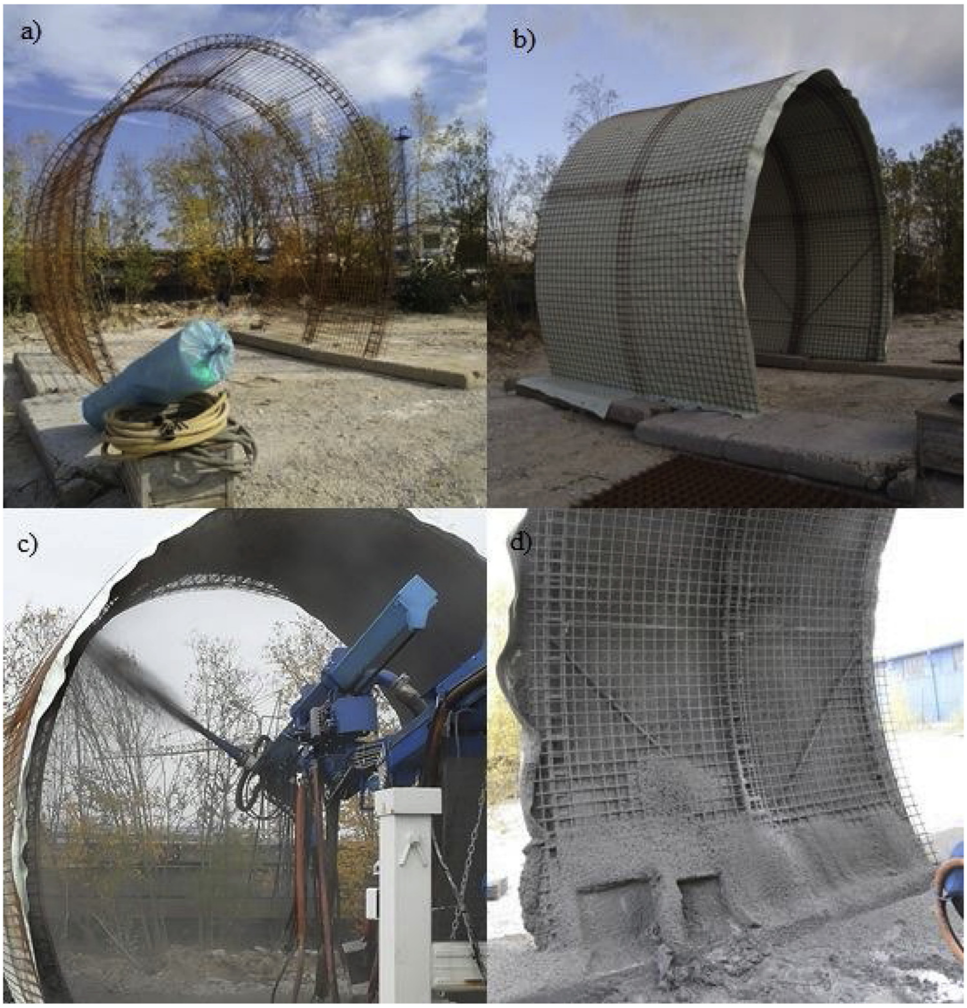

Fig. 9. Mock-up experiment: a) Bretex frame during construction, b) application of a geotextile membrane, c) spraying concrete, d) sprayed concrete on the inner side of the frame. The two rectangular footprints at the bottom of the frame are from the boxes from which the compressive strengths were derived.

compressive strength. For strengths above 1.2 MPa, stud driving into the concrete was performed according to method B [36]. The final compressive strength at 28 days was determined from cores 100 mm in diameter and 100 mm in height.

The penetration needle was inserted into the shotcrete at specific time intervals, and the values shown in Table 4 present the average of ten readings. The results for 6, 12 and 24 h were determined by stud driving into the concrete, and the values shown in Table 4 also present the average of ten readings.

Table 3
Batches of concrete in kg/m^3 for the mock-up experiment.

	C3	C4	
		i	ii
CEM I 42.5R	225	250	250
FBC-TB	225	200	200
Water	200	180	180
Aggregate 0-2 mm	250	250	250
Aggregate 0-4 mm	720	760	760
Crumb rubber 1-4 mm	50	–	–
Aggregate 4-8 mm	480	480	480
HRWR	4	4	4
AFA (% of a binder)	29 (6.5%)	34 (7.5%)	38 (8.5%)
Batch volume	2 m^3	4 m^3 (2 m^3 + 2 m^3)	

Table 4
Development of average compressive strengths in MPa from the mock-up experiment. The values in parentheses show the standard deviation for each tested specimen.

	6 min	15 min	30 min	1 hr	2 hr	3 hr	6 hr	12 hr	24 hr
C3	0.29 (0.03)	0.32 (0.05)	0.43 (0.04)	0.60 (0.05)	0.77 (0.04)	0.94 (0.03)	1.95 (0.09)	3.61 (0.50)	6.69 (0.46)
C4-i	0.28 (0.02)	0.34 (0.05)	0.52 (0.06)	0.78 (0.03)	0.90 (0.04)	1.19 (0.06)	2.45 (0.15)	3.90 (0.36)	9.67 (0.86)
C4-ii	0.53 (0.07)	0.73 (0.05)	0.78 (0.03)	0.94 (0.05)	1.17 (0.03)	1.26 (0.04)	2.50 (0.15)	4.20 (0.40)	10.0 (0.90)

The compressive strengths determined using the penetration needle and stud driving (Table 4) for mixtures C3, C4-i and C4-ii satisfied J2 curve requirements and therefore can be used in spraying applications (Fig. 10).

The mock-up experiment showed that the newly designed mixture of sprayed concrete with the addition of crumb rubber and FBC-TB had reasonable adhesion and acceptable fallout, estimated to be less than 10%. In view of the fact that the experiment was carried out directly under operation, there appears to be a sufficient guarantee that—even in a normal execution regime with strict adherence to technological discipline—the required compressive strengths can be achieved. The test satisfied the requirements for the properties of sprayed concrete and demonstrated the suitability of using the proposed mixtures for temporary priming linings of the required quality.

Compressive strengths at the age of 28 days were derived from i) cores 100 mm in diameter and 100 mm in height taken from the boxes that were placed on the bottom of the BTX frame during spraying, ii) 150 mm cubic specimens taken directly from the mixer. The cubic specimens were directly cast into moulds without vibration and without AFA being applied. By comparing the values in Table 5, the effect of spraying and AFA can be easily recognized. It is a well-known phenomenon that using a high amount of AFA results in a reduction in 28-day compressive strength [28], which was also the case in this study. Unfortunately, no cores were taken from Mixture C4-ii, where a higher amount of AFA than in C4-i was applied.

The mixture was originally designed for class C25/30, where the mean value of cubic strength is 38 MPa [37]. It can be seen that the cores with an aspect ratio of 1:1, which can be treated as cubic specimens, showed lower values of strength due to the usage of by-products. The lower value of compressive strength in Batch C3 compared to Batch C4-i is due to the utilization of crumb rubber. However, in none of the cases was the strength decrement greater than 30% of the mean value of class C25/30 (38 MPa), which was the threshold given by the industrial partner for possible utilization in real-world practice.

4. Conclusions

This research project focused on the early-age properties of shotcrete with the utilization of crumb rubber and fluidized bed combustion-based ternary binder (FBC-TB). The conclusions obtained in the context of this study are:

1 The addition of crumb rubber reduces compressive strength and the modulus of elasticity of concretes across all tested grain fractions;
2 Addition of crumb rubber increases the deformability of the resulting mixture. Lower stiffness was observed for higher crumb rubber contents compared to reference counterparts not containing the tire waste product. Increased

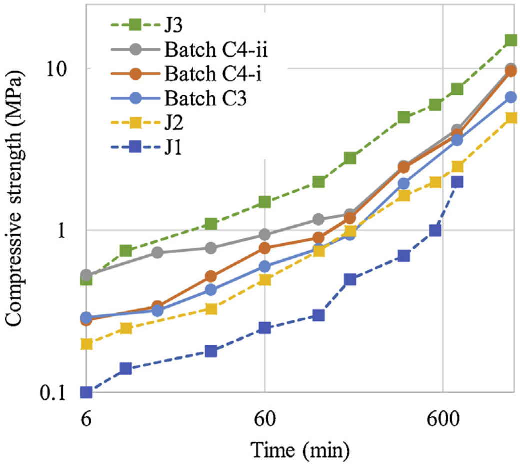

Fig. 10. Development of compressive strengths from the mock-up experiment, 6 min to 24 h (full lines with circular dots) and standard development according to J-curves (dashed lines with square dots).

Table 5
Average compressive strengths in MPa and bulk densities in kg/m^3 at the age of 28 days. The values in parentheses give the standard deviation for each specimen tested.

		Batch C3	Batch C4-i
Core drilling from boxes of shotcrete	MPa kg/m^3	31.9 (1.35) 2180 (10)	36.7 (0.83) 2245 (15)
Cubes taken directly from the mixer (not sprayed, not vibrated, no AFA)	MPa kg/m^3	33.6 (0.23) 2083 (3.0)	50.9 (1.64) 2107 (0.8)

deformability can be advantageous in primary linings where higher deformations are expected. Using crumb rubber could possibly result in lower stressing when compared to the reference counterparts;

3 Using FBC-TB resulted in enhanced early-age development of compressive strength in the mock-up experiment and was much cheaper because less cement was used.

4 The addition of FBC-TB accelerated the strength development rate at early ages and achieved sufficient strengths, i.e. those greater than J2. Reducing the amount of cement during construction also supports current ecological trends, where significant emphasis is placed on CO_2 reduction in newly designed structures.

5 Based on laboratory experiments and optimization, the mock-up tests proved the full-scale applicability of crumb rubber and FBC-TB. The substitution of 45%–50% of OPC by mass with FBC-TB and 5% by vol. aggregates with crumb rubber represents a reasonable amount of reuse of industrial by-products for shotcrete applications.

Thus, these results will contribute to the development of rubberized concrete with a fluidized bed combustion-based ternary binder for shotcrete applications. It is important to mention that high technological discipline must be maintained when using such mixtures, particularly the minimum temperature of the shotcrete mixture. In addition, the results presented here are primarily valid for the mixtures specified: a water-to-binder ratio ranging from 0.4 to 0.44, AFA ranging from 6.5% to 8.5%, and binder content of 450 kg/m^3.

Conflict of interest

We have no conflict of interest to declare.

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