Microfibrillated cellulose as additive for wet-mix shotcrete

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ABSTRACT: Shotcrete is a widely used rock reinforcement method that significantly impacts the carbon footprint of underground construction and mining. The sustainability of shotcrete can be improved by, e.g., replacing a portion of cement in the mix with low-carbon materials or minimizing shotcrete rebound by increasing the plastic yield stress of fresh shotcrete. A microfibrillated cellulose (MFC) has recently drawn interest from the shotcrete industry due to its potential for improving the sustainability and cost-efficiency of shotcrete. The MFC is low-carbon footprint material that has rheology-modifying effects on aqueous systems, such as shear thinning behavior and high zero-shear viscosity. In this study, a preliminary investigation of the benefits of MFC in shotcrete application was done through a series of laboratory tests. Results indicate that the MFC improves the immediate stiffness of accelerated shotcrete, and other essential performance factors are not significantly affected.

Keywords: Microfibrillated cellulose, shotcrete, additives, carbon footprint, rebound.

1 INTRODUCTION

1.1 Sustainability of shotcrete

Concrete production releases roughly 5% of the global atmospheric CO_2 emissions (Hasanbeigi et al., 2012) of which a large part is derived from the production of cement. Considering the underground rock construction and mining, shotcrete has a high impact on the carbon footprint of tunneling as being cement intensive rock reinforcement method (Yurdakul et al. 2016). Not only that shotcrete consumes high volumes of cement, typically 5-15% of the batched wet-mix shotcrete is wasted during the spraying process as rebound (Lindlar et al. 2020), making rebound a significant factor regarding the sustainability and cost-efficiency of shotcrete.

One of the typical approaches for reducing the carbon footprint of shotcrete is by replacing a portion of cementitious materials with low-carbon materials such as fly ash, silica fume or metakaolin (Yurdakul et al. 2016). However, the sustainability and cost-efficiency of shotcrete are also controlled by factors related to the shooting process. According to scientific literature (Gang et al. 2019; Lindlar et al. 2020; Yurdakul et al. 2016), increasing the plastic viscosity and yield stress (also described as “cohesion” in literature) of fresh shotcrete have been reported to reduce rebound during spraying, which means that the fresh state performance of shotcrete can have a major impact on the cost-efficiency and carbon footprint of shotcrete. In addition to rebound, maximum build-up thickness (maximum thickness of fresh shotcrete layer that remains stable) has been reported to improve with increased plastic yield-stress of shotcrete (Yun et al. 2015). From cost-efficiency point of view, it is essential to minimize the amount of sprayed shotcrete layers due to long waiting time and mobilization of equipment between the spraying of individual layers (Beapure 1994).

1.2 Microfibrillated cellulose (MFC)

Microfibrillated cellulose (MFC) has recently drawn interest from the rock engineering society due to its ability to efficiently modify the rheological behavior of fresh concrete. The MFC is an environmentally friendly additive as it is typically made from renewable sources, such as wood pulp, or industrial side streams, such as sugar beet pulp. In plant cell walls, cellulose microfibrils (See Figure 1a) form a major structural element of the tissue bringing the needed mechanical support for the plant. With a combination of chemical and mechanical processing, cellulose microfibrils can be isolated from the biomass and 4-200 nanometer sized cellulose fibrils can be recovered (See Figure 1a). Once the cellulose fibrils are mixed in water, the large surface area of fibrils promotes hydrogen bonding with water molecules, giving the MFC hydrogel a high zero-shear viscosity. The MFC has also been reported to have a shear thinning behavior (also called non-Newtonian behavior), which means fluid’s decrease of viscosity under shear strain (See example in Figure 1b).

High zero-shear viscosity and shear thinning behavior are together beneficial properties for materials used in applications such as shotcrete. Shotcrete base mix is required to have sufficiently high mobility (low viscosity) at the mixing, pumping, and spraying stages of the process (Beapure 1994), while at the final stage, when fresh shotcrete has been shot on the rock surface, the rapid development of stiffness is essential for working safety and maximum build-up thickness. Rapid development of stiffness of fresh shotcrete is usually carried out with the use of accelerating admixtures. However, shotcrete accelerators are often based on chemicals with working safety and environmental issues and are relative expensive (Myrdal 2007).

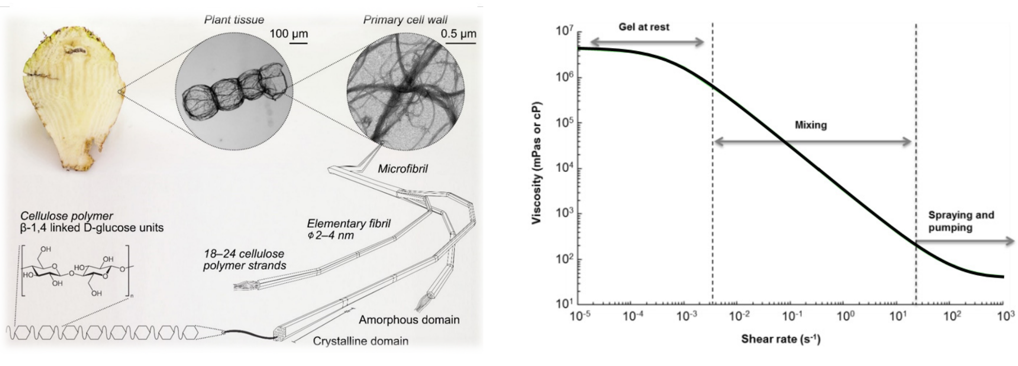

Figure 1. Elementary fibrils (a) and shear thinning behavior of MFC hydrogel (b).
Modified after Teirfolk et al. 2012).

2 MATERIALS AND METHODS

2.1 Shotcrete base mix recipes

The appropriate way of studying the benefits of MFC in shotcrete applications in laboratory conditions was to conduct a dose-response study with a series of standard concrete tests. The reference base mix recipe (Table 1) used for the study represented a typical shotcrete mix design used in industry. Experimental mixes were conducted based on the reference mix, with the systematic dosing of MFC.

Table 1. Reference base mix design used in laboratory experiments.

Constituent materials	Material type	Manufacturer	Quantity [kg/m^3]
Cement	CEM I 52.5N	Schwenk	461,2
Coarse aggregate	3/6 mm CR	Rudus	439,6
Fine aggregate	0/4 mm Sand	Rudus	1177,6
Superplasticizer	TamCem 106	Normet	6,4
Hydration control	TamCem VE	Normet	1,4
Accelerator	AF90	Normet	30,0
Micro-silica	940U	Elkem	34,3
Water (Tap water)	Espoo, Finland	Local	216,8
Water to cement ratio = 0,47			

The MFC product was provided by Betulium ltd, and it was made according to process described in Laukkanen et al. (2020). Dosing of the MFC hydrogel into experimental shotcrete base mixes was done in three steps, starting from 0,5 % by weight of cement up to 1,5 %. Microfibril concentration in the used MFC hydrogel was 4,0 %.

2.2 Laboratory methods and workflow

Laboratory testing of MFC hydrogel was carried out with a testing sequence consisting of standard concrete tests according to Eurocode presented in Table 2. Laboratory workflow consisted of two parts, where the first part covered the testing of fresh state properties (mobility, stability, bleeding, air content, temperature development, and very-early strength development) of shotcrete and the second part the hardened state properties (final compressive strength and bond strength to rocks). Measuring very-early strength development and bond strength to rocks had a special setup for simulating the shotcrete in laboratory conditions. See Lauraeus (2022) for a detailed description of the testing workflow, methods, and error considerations.

Table 2. Test methods and their timing in the laboratory workflow for different parameters measured.

Tested parameter	Test method	Sample type	Timing of test in the workflow	Result type
Flow value development	EN 12350-5	Fresh concrete sample	After initial mixing, repeated for 3 hrs in 30 min intervals	Quantitative
Bleeding and segregation	EN 12350-5	Fresh concrete sample	After initial mixing, repeated for 3 hrs in 30 min intervals	Qualitative
Air content	EN-12350-7	Fresh concrete sample	After initial mixing, no repetition	Quantitative
Temperature development	Thermocouple sensor	Fresh concrete sample	After initial mixing, monitoring up to 12 hrs	Quantitative

Very-early strength development	EN-14488-2	Fresh concrete sample, accelerated*	Cast after acceleration, repeated in 10-15 min intervals	Quantitative
Final compressive strength	EN-12390-3	Cast cube specimen	Cast after initial mixing, tested after 28 d	Quantitative
Bond strength to rocks	EN-14488-4	(Part 1) Specimen cast on rock plate* (Part 2) Cored specimen	(Part 1) Cast after initial mixing (Part 2) Cored and tested after 28 d	Quantitative

*) shotcrete simulated in laboratory conditions

3 RESULTS AND DISCUSSION

3.1 Affection of MFC on fresh state properties of shotcrete base mix

Results from flow table tests presented in Fig. 2a indicate increasing stiffness of the shotcrete base mix as the dose-response of MFC from 0,5 to 1,5% BWOC (by weight of cement), showing the effect of MFC's high-zero shear viscosity. Moreover, it was visually observed that re-agitation of the static batch with the inclusion of MFC momentarily decreased the viscosity of the mix, which aligns with the reported shear thinning behavior of MFC. In practical use, the shear thinning behavior could potentially provide sufficient mobility for the mix during mixing, pumping, and spraying, despite the high stiffness of the mix in the static state.

Furthermore, no segregation or bleeding was visually observed during flow table tests, reflecting similar or better stability for the experimented mixes than the reference base mix. As can be seen from Fig. 2b, an increase in MFC dosage was observed to increase the air content of the mix, showing an air-entertaining effect of MFC on the shotcrete base mix.

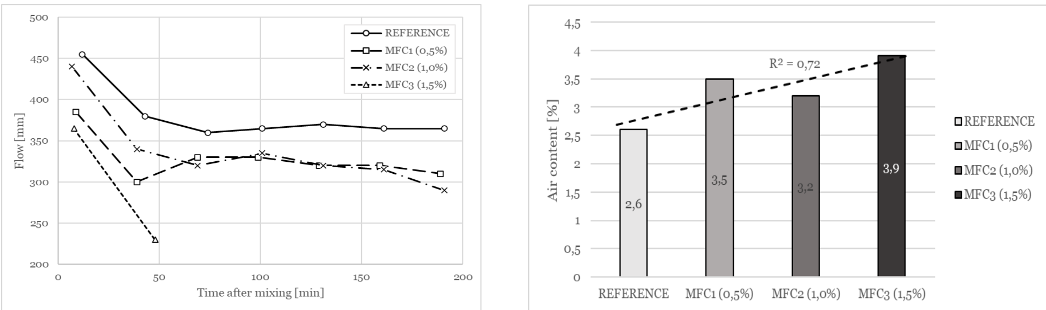

Figure 2. Flow value development (a) and air content test results (b) conducted for fresh base mix samples.

Temperature monitoring data measured from the reference batch and from the batch with the inclusion of MFC (Figure 3) shows the initiation of hydration reactions at 8-10 hours after the initial mixing of the batches. As the exponential part of the curves has almost identical timing, it can be concluded from this data that the MFC does not negatively affect the performance of the setting retarding admixture used in this study.

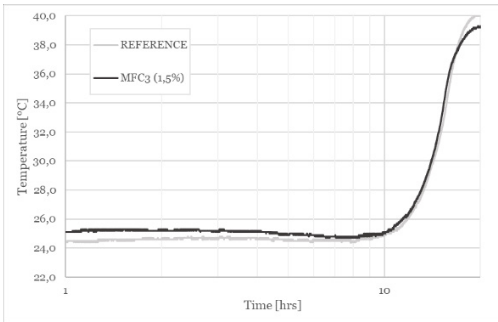

Figure 3. Temperature development data of the reference mix and the mix with 1,5% BWOC dosage of MFC measured using a thermo-couple temperature monitoring device.

Very-early strength development of accelerated mixes is presented in Fig. 4a indicates increasing immediate stiffness with an increased dosage of MFC. A relative difference of 380% in very-early compressive strength between the reference mix and mix with 1,5% BWOC of MFC (at 50 min after acceleration) was measured, which can be considered as a significant difference. Based on the background literature and the needle penetration test results (see the measuring device in Figure 4b), it can be concluded that the MFC has the potential for decreasing shotcrete rebound and increasing maximum build-up thickness due to the improved plastic yield stress. An increase in very-early compressive strength (or plastic yield stress) along with the dosage of MFC occurs most likely as a sum of primary reactions of accelerating admixture and MFC's high zero-shear viscosity. Moreover, the effects of the MFC in shotcrete should be studied with an actual spraying robot or laboratory-scale spraying equipment in the future.

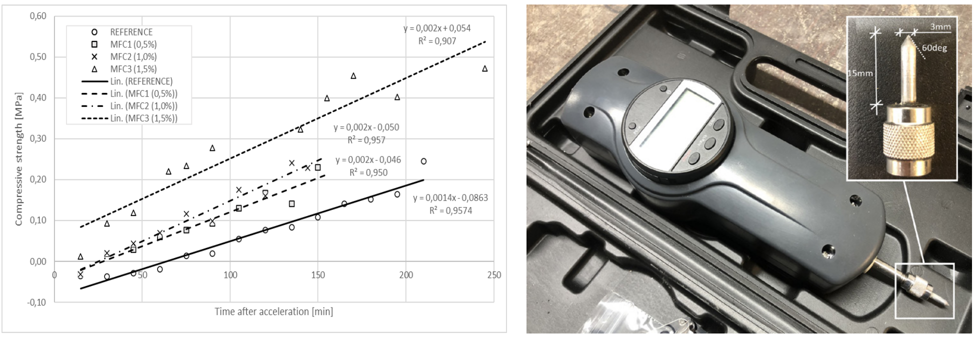

Figure 4. Estimated very-early compressive strength development of accelerated shotcrete base mix samples based on needle penetration resistance data (a). Negative values occur due to empirical formula used for calculating the very-early compressive strength values from penetration resistance readings. Force gauge device with penetration needle according to EN-14488-2 standard (b).

3.2 *Affection of MFC on hardened state properties of shotcrete*

Final compressive strength (28-day) test results shown in Fig. 5a indicate a low correlation between final compressive strength and increasing dosage of the MFC. The samples with inclusion of MFC demonstrated a maximum deviation of 12% relative to the reference mix. However, these deviations are presumably caused by the increased air content of the base mix (see Fig. 2b). Similar results can be seen from bond strength test results presented in Fig. 5b, where bond strength to diorite rock plates show no correlation with increased dosage of MFC. A maximum value of 70% deviation from the reference sample was measured. Nevertheless, the utilization of the highest dosage of MFC (1,5% BWOC) resulted in a 17% negative deviation. According to the scientific literature (Bernard 2018), a relationship exists between the final compressive strength and bond strength of shotcrete, which may help explain the negative deviations observed in bond strength relative to the reference sample. Moreover, due to the limited number of samples analyzed, the available data does not provide solid evidence regarding the effect of MFC on the key performance parameters of shotcrete base mix.

However, based on the results available we can cautiously conclude that the affections are not significant.

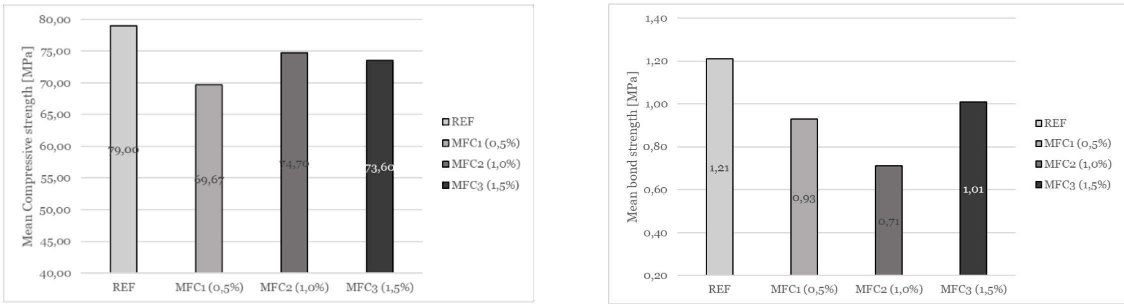

Figure 5. Mean final compressive strength (a) and bond strength test results (b). The results are calculated from test results from three cube specimens and five cored cylindrical specimens for each experimented mix.

4 CONCLUDING REMARKS

The results of the study indicate that the viscosity of the fresh shotcrete base mix increases as the dosage of MFC is increased. However, the observed shear-thinning behavior of MFC in the shotcrete base mix could potentially provide the necessary mobility for practical applications, such as sufficient pumpability. The study also shows that MFC promotes immediate stiffness of accelerated shotcrete and potentially reduces shotcrete rebound, through which the carbon footprint and cost-efficiency of shotcrete could be improved. The use of MFC does not affect the performance of setting retarding admixtures. The study found no significant impact of MFC on the key performance parameters of hardened shotcrete, such as final compressive strength and bond-strength to rocks. However, negative deviations in these parameters were observed relative to the reference mix, presumably caused by the increased air content of the base mix. Future studies should consider the effects of MFC on shotcrete using actual spraying robots or laboratory-scale spraying equipment.

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