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CO_2-reduced fiber sprayed concrete for permanent tunnel linings (Part 2): A rheological investigation

Abstract

As part of an ongoing research project "SpOC" (sprayed optimized concrete), CO2-reduced fiber sprayed concrete (FSpC) is being developed as a permanent and thin inner tunnel lining. Concerning shotcrete mixtures to be used as such permanent lining, adding micro- and macrofiber and chemical admixtures to reduce crack risk and to improve the mechanical properties and durability seems to be a smart approach. However, adding such components will change the rheological behavior and can lead to pumping problems. Therefore, this paper presents the rheological investigation of different fiber-reinforced sprayed concrete mixes. We will demonstrate the fiber's influence on the fresh properties and how to optimize them.

Introduction

Shotcrete has gained increased prominence in recent years, particularly due to its potential to be used as a permanent lining in tunneling applications [1,2]. The heightened interest in utilizing shotcrete as a permanent lining is due to its efficacy in addressing complex cross-sectional regions. Moreover, the application of shotcrete as a permanent lining confers several notable advantages, including cost reduction, enhanced sustainability, and increased productivity.

In the context of decarbonization, shotcrete offers significant benefits through material savings compared to traditional multi-layer linings, which are typically associated with high concrete consumption and corresponding CO2 equivalent emissions or global warming potential (GWP). Conventional thick-walled in-situ concrete linings can be replaced by thinner, waterproof, and durable fiber-reinforced shotcrete linings, thereby mitigating environmental impact and promoting sustainability in construction practices.

Reducing the Portland cement content as a key factor to reduce the GWP of concrete and at the same time adding fibers to control crack width and increase the tensile strength of concrete is a difficult task, because in both scenarios the workability of concrete and, consequently, its pumpability will be compromised. Thus, incorporating additional air by using an air-entraining admixture (AEA) could be an effective and straightforward method to enhance the pumpability [3] and to make it possible to produce Portland cement reduced and thus CO2-reduced fiber sprayed concrete.

The pumping process applies high pressure to the concrete in a way that the concrete starts to flow in pipes. The delivery of fresh concrete in a pump line can be based on the Kaplan model as a first approximation [4,5]. Accordingly, in the practically relevant range of low concrete delivery speeds, a concrete plug forms inside a pipe, which moves as a whole due to the pump pressure applied, while a thin sliding layer (consisting of binder paste and fine particles) acts as a "lubricating film" on the wall, which is sheared. Therefore, the paste (consisting of cement, water, mineral admixtures, chemical admixtures, and fine aggregates smaller than 125µm) plays a crucial role. It’s because due to the pressure transmission along the pipe and the fact that the coarse aggregate can’t be easily deformed; thus, the paste will be the agent to make the concrete move [6]. During the pumping process, part of the paste will migrate to the wall forming a lubricant layer while the coarse aggregate and the remaining paste will be concentrated in the core, forming a plug. Thus, as long as the pressure is applied, the concrete plug will move forward.

Adding extra air to improve the pumpability seems to be a smart solution. It’s because the air content increases the paste content while lowering its viscosity [7] and, adding air extra air will increase the paste content artificially. Additionally, it’s assumed that the final air will be reduced to 3% after spraying due to the compactness provoked by the spraying process [8]. However, a review of the literature reveals that the air content after spraying can vary in a range of 2% to 5% [9–12]. Therefore, it is crucial to understand the effects of pumping on the air content throughout the spraying process.

Materials and methods

Within the ‘SpOC’ research project (see acknowledgment), a series of tests to explore fiber shotcrete was executed, from which the aspect of air entrainment into shotcrete is presented in the outlined paper. The concrete mix design can be found in Table 1**Fehler! Verweisquelle konnte nicht gefunden werden.**. The cement was CEM II/A-S 42.5 R, regionally available aggregate 0/8mm with the grading curve shown in Figure 1**Fehler! Verweisquelle konnte nicht gefunden werden.**, and chemical admixtures according to Table 3 were used. The used steel fiber´s properties can be found in Table 2.

For the concretes with air, it’s important to highlight that initially the base mixture (without fiber) was produced with and without AEA. This methodology was adopted aiming to fix the “starting air” and, after that, the fibers were introduced into the concrete increasing the air content by the mixing process. Thus, the concrete fresh state properties were checked before and after the fiber addition.

It’s important to highlight that mixture Reference_0%, Reference_7%-10%, Reference_15-20%, and SF0.34_0% were one of the mixtures used in a Real-scale Experimental Test carried out at Trostberg, more details can be found in Soares et al. (2024) [13].

Tab. 1 Mix design

Mix ID.	Cement	Aggregate 0-8mm	w/c	AEA(1) (kg/m³)	SP(2)	Ret. (3)	Macrofiber Fiber type	Macrofiber Content (Vol.% | kg/m³)
Reference_0%	440 kg/m³	1728 kg/m³	0.45	0,0	0.65%	1.80%	No fiber	0,00%
Reference_7%-10%				1,0				0,00%
Reference_15%-20%				5,0				0,00%
SF0.34_0%				0,0			steel macrofiber	0,34% | 2,67
SF0.55_0%				0,0				0,55% | 4,32
SF1.00_0%				0,0				1,00% |7,85
SF1.50_0%				0,0				1,50% | 11,76
SF0.34_7%-10%				1,0				0,34% | 2,67
SF0.55_7%-10%								0,55% | 4,32
SF1.00_7%-10%								1,00% |7,85
SF1.50_7%-10%								1,50% | 11,76
SF0.34_15%-20%				5,0				0,34% | 2,67
SF0.55_15%-20%								0,55% | 4,32
SF1.00_15%-20%								1,00% |7,85
SF1.50_15%-20%								1,50% | 11,76

(1) – Air entrainer admixture
(2) – Superplasticizer
(3) - Retarder

Tab. 2 Fiber's properties

Fiber	L (µm)	ϕ (µm)	λ	f_x (MPa)	E (MPa)	γ (kg/m³)
Steel macrofiber	35	600	58	1250	210000	7850

ID.: Fiber's identification
L: Fiber's length
ϕ: Fiber's diameter
f_x: Ultimate tensile strength
λ: fiber's aspect ratio L/f
E: Fiber's Young modulus
γ: Fiber's true density

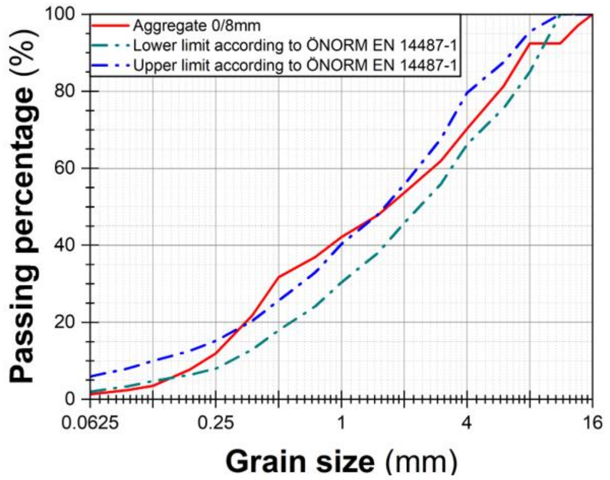

Fig. 1 Aggregate grading curve

Fresh properties

Regarding the fresh properties, the concrete was characterized by the following tests: i) spread flow and spread on the flow table according to ÖNORM EN 12350-5 [14], ii) air content according to ÖNORM B 4710-3 [15], iii) V-Funnel test in accordance to ÖNORM EN 12350-9 [16].

Tab. 3 Chemical admixture densities

Admixture	Density (g/cm³)
Accelerator	1,08
Retarder	1,10
Air entrainer	1,02
Superplasticizer	1,05

The rheological behavior characterization was performed by a Sliding pipe rheometer test ("sliper" Schleibinger).

Results

The fresh state and the rheological results can be found summarized in Table 4. It highlights the air increase due to the fiber addition, also clearly visible in Figure 2.

Tab. 4 Fresh state and rheological results

Mix ID.	Air content (%)	Spread flow **Before strokes** (mm)	Flow table spread **After strokes** (mm)	V-Funnel flow time (s)	Sliper yield stress	Sliper viscosity
Reference_0%	1,8	401,7 ± 0,4	609,2 ± 0,2	4,6	0,4	2,8
Reference_7%-10%	10,1	440,0 ± 1,3	612,2 ± 2,5	4,1	1,3	1,8
Reference_15%-20%	17,0	393,8 ± 1,6	591,9 ± 2,0	3,3	1,6	1,2
SF0.34_0%	2,1	370,0 ± 0,4	601,3 ± 0,1	5,3	1,4	2,7
SF0.55_0%	1,9	300,0 ± 14,1	530,0 ± 14,1	10,1	1,1	2,9
SF1.00_0%	2,4	210,0 ± 7,1	410,5 ± 7,8	(1)	1,2	3,5
SF1.50_0%	2,2	195,3 ± 7,4	270,0 ± 14,1	(1)	1,3	3,6
SF0.34_7%-10%	14,0	430,5 ± 0,7	622,5 ± 3,5	4,1	2,2	1,5
SF0.55_7%-10%	17,0	426,5 ± 33,2	605,5 ± 12,0	4,5	2,0	1,4
SF1.00_7%-10%	13,0	356,0 ± 8,5	556,5 ± 2,1	8,2	1,8	1,7
SF1.50_7%-10%	10,0	262,5 ± 3,5	464,0 ± 15,6	(1)	0,3	3,0
SF0.34_15%-20%	22,0	372,5 ± 3,5	574,0 ± 1,4	2,6	2,8	0,5
SF0.55_15%-20%	26,0	391,0 ± 5,7	575,0 ± 7,1	2,5	0,4	1,2
SF1.00_15%-20%	30,0	352,5 ± 3,5	552,5 ± 3,5	2,8	1,5	1,0
SF1.50_15%-20%	35,0	360,0 ± 14,1	550,0 ± 0,0	2,7	1,7	2,3

Remarks:
(1) – The concrete doesn't flow through the device (Blockage).

For standard mixtures (without artificial air addition) the air content introduction due to the fiber addition is not significantly high; however, when AEA is used, the higher the original air content, the stronger the increase in air content by fiber addition. See the plane inclination behavior plotted in Figure 2.

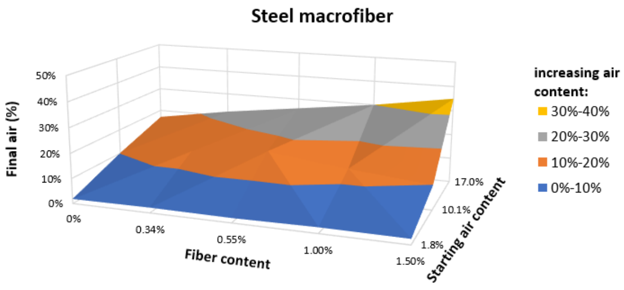

Fig. 2 Fiber addition influences on the final air content

Regarding the spread-flow and flow-table spread, it is shown in Table 1 that adding fiber leads to o a consistency reduction in general. However, artificial air addition helps to lower such reduction significantly, as shown in Figure 3. In shotcrete tests, the mixes Reference_0%, Reference_7%-10%, Reference_15-20%, and SF0.34_0% were sprayed and their air content before and after spraying was tested, showing that independent of the fresh concrete´s air content, after spraying the air tends to reduce to the range of 3%-5% due to the compactness provoked by the spraying process [13].

Concerning the V-funnel results, it's shown in Table 1 and Figure 3 that adding fibers leads to a lower V-tunnel flow time, meaning higher flow resistance but, as much as air is added, the flow resistance reduces. Figure 4 shows that for the concretes without AEA, as much as the fiber is added, the flow resistance increases and, for the mixture with 1,0% of fiber, it wasn't possible to flow the concrete through the device, provoking blockage.

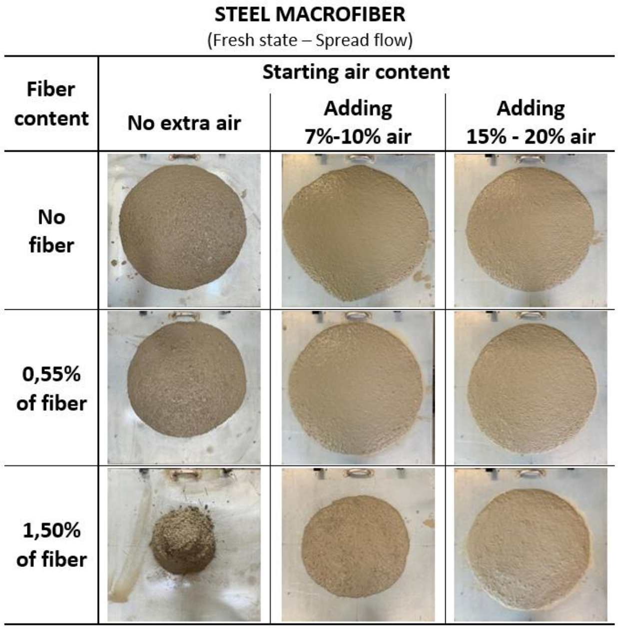

Fig. 3 Air content influences on fiber's reinforced concrete spread flow

However, when extra air was added, it was possible to incorporate more fibers into the concrete, as shown by the results of mixes with 7%-10% of starting air. In this case, the mixture with 1,00% of fiber was able to flow through the device but, the concrete with 1,50% provoked blockage. Thus, more artificial air was added, reaching the range of 15%-20% of starting air. In this case, even the mixture with 1,50% of fiber was able to flow. Therefore, it seems clear that adding extra air results in a benefit regarding the concrete's workability. Additionally, it was noticed that the mixtures SF1.00_0%, SF1.50_0%, and SF1.50_7%-10% got stuck during the V-Funnel test; however, the mixture SF0.55_0% didn't, even though it took 10.1sec. to flow through the device. The main assumption is that the V-funnel test is correlated to the viscosity and, after a certain viscosity limit, the mixture is not able to flow through the device.

Regarding the sliper viscosity, the conclusion is clear that adding air implies a viscosity decrease. When the fibers were added, initially, the viscosity tended to decrease for all mixtures with a low fiber content of 0,34% fiber (Figure 5) but when more fibers were added, the behavior will depend on the initial air content. For example, for the mixture without AEA, after 0,34% the viscosity started to increase but, for the mixtures with AEA presenting 7%-10% of air, the viscosity also decreased and the increasing slope between the concretes with 0,55% and 1,00% is smaller than the slope between 1,00% and 1,50%. However, applying this analysis to the concretes in which the starting air were between 15% and 20%, the mixture with 0,55% fibers seems to be an outlier, which is corrected by the more plausible red dot line in this region.

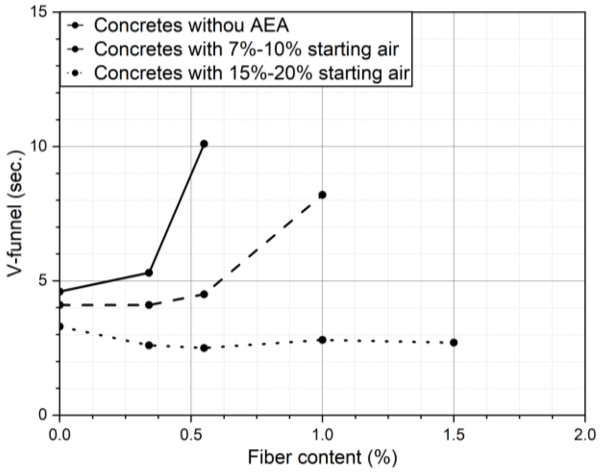

Fig. 4 Correlation between the fiber content and V-funnel-time of different air content ranges

Thus, it's possible to conclude that AEA usage will bring beneficial behavior regarding the viscosity reduction and, consequently, improving pumpability.

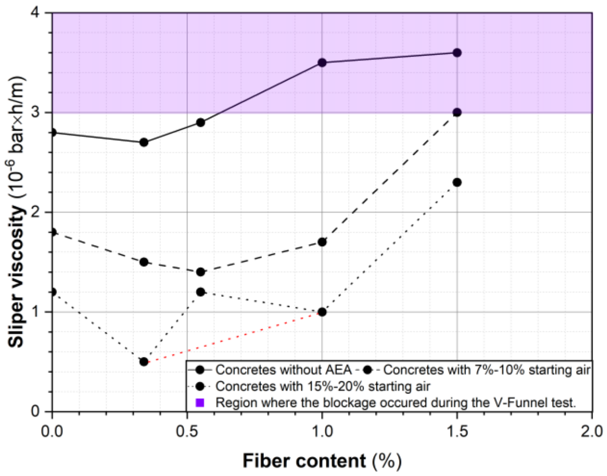

Fig. 5 Correlation between the fiber content and the sliper viscosity in mixtures with different air content.

Conclusions

From the analysis of the results obtained the following conclusions can be drawn:

The first main conclusion is that adding fiber without AEA will lead to consistency changes. This means that in regard to the spread flow and flow-table spread, adding fibers will provoke a reduction in these parameters and, in relation to the V-funnel test, the fiber addition will imply more time for the concrete to flow through the V-funnel apparatus. Moreover, after a certain dosage limit, the fiber-reinforced concrete will be so stiff that the concrete will get stuck inside the V-funnel apparatus, provoking blockage.

Adding artificial air shows a clear benefit regarding the workability of the fresh concrete because it helps to reduce the fiber's negative impact on consistency even at high dosages. Regarding the V-funnel time as a measure of the viscosity, adding extra air reduces the viscosity and flowability resistance as the time will reduce as much air the mixture possesses. Regarding sliper viscosity AEA usage overall also causes viscosity reduction.

Finally, the results clearly show that the AEA reduces the viscosity of fiber-reinforced shotcrete mixes and, consequently, will enable the pumpability of mixes up to a relatively high steel fiber content of 120 kg/m^3.

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