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Effect of different fiber type on sprayed concrete support capacity.

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ABSTRACT: Nowadays there are several types of fiber for the reinforcement of the sprayed concrete used in tunnel support; most popular among them are steel fibers and macro synthetic fibers. However, in most cases the assessment of fiber reinforced sprayed concrete ductility is focused on the fulfillment of energy absorption capacity requirements without considering the effect of the reinforcement type on the Load-Displacement behavior. The following study aims to find out if the support capacity provided by each fiber type is the same for similar levels of energy absorption capacity or how it can be affected through the analysis of the load bearing capacity. After the analysis of energy absorption tests according to EFNARC of more than 50 specimens separately reinforced with steel and macro synthetic fibers, it was observed the specimens reinforced with steel fiber absorbed more energy since the beginning of deformation than those reinforced with macro synthetic fibers. In other words, the required work to start deforming the steel fiber reinforced sprayed concrete is greater than the required with the other fiber type. Likewise, the ultimate strength or maximum load bearing capacity provided by steel fibers was higher than the other fiber type. Therefore, the support capacity of the sprayed concrete and the related safety factor provided by each fiber type is different.

KEYWORDS: Underground mining, sprayed concrete, shotcrete, fiber reinforced sprayed concrete

1 INTRODUCTION

Fiber reinforced sprayed concrete (FRSC) is a material widely used for tunnel support, not only because it contributes to advance speed but also because it has demonstrated to be an efficient and safe solution in different rock qualities.

As known, the concrete can have an extraordinary behavior in compression; in return, it has small flexural tensile strain capacity or ductility (Nash *et al.*, 1972). Once placed, the sprayed concrete is subjected to deformations caused by surrounding rock mass pressure in such a way that, when its flexural capacity is exceeded, which is very limited, it fails and cracks.

For this reason, sprayed concrete must be capable of developing the necessary support capacity to be able facing deformations promptly after it cracks. Here is where fibers play a fundamental role as they increase post-crack strength of the sprayed concrete; therefore, it is very important to analyze their behavior besides meet the technical requirements stablished by the designer.

One of the most used methods to evaluate the FRSC ductility is the plate test according to the section 10.4 of the European Specification for Sprayed Concrete published by EFNARC (1996), then adopted by CEN according to EN 14488-5 (2006), which determines the energy absorption capacity or toughness. The test simulates the stress distribution within the FRSC around a rock bolt and fits to support design method Q-system (NGI, 2013).

This test, often known as EFNARC test or square panel test (because of the shape of its specimens), simulates the stress distribution within the FRSC around a rock bolt and allows the formation of an irregular crack pattern similarly to which occurs inside the tunnel. It represents in a better way the indeterminate behavior of the FRSC structure unlike the energy absorption test according to ASTM C 1550 (round panel test) which represents a determined crack pattern.

During the test (see Figure 1), a load is applied at the center of a square specimen of FRSC supported on a steel square frame at a rate of 1.5 mm per minute. The specimen dimensions are 600 mm by 600 mm by 100 mm. The energy absorption capacity (expressed in Joules) represents the necessary work of the applied force to deform the specimen up to displacement of 25 mm.

Figure 1. Energy absorption test according to EFNARC on a fiber reinforced sprayed concrete specimen.

Likewise, this test is frequently used to compare different type of fibers; however, considering the importance they have on the FRSC post-crack behavior, it comes certain questions up, which requires further analysis like, for example: Is enough to compare just the 25 mm-energy absorption value obtained by each fiber type to determine the safer alternative? Will the reinforcement effect be the same independently of material which fibers are made of? In what way can behavior of each fiber type impact on the support safety factor? The study is intended for clearing these questions up.

2 THE STUDY

For years, steel fibers have characterized by being a reliable alternative for sprayed concrete reinforcement; however, in recent years the offer with fibers made of other materials has widened, as it is the case of macro synthetic fibers.

Considering this situation, the study analyzed energy absorption tests according to EFNARC of 55 FRSC specimens separately reinforced with steel and macro synthetic fibers at the most frequent dosages used in several underground mines of Peru.

The evolution of accumulated energy and the post-crack behavior in Load-Displacement curve were compared in order to analyze the FRSC behavior independently of the values of energy absorption capacity obtained at the end of the tests (when displacement equals 25 mm).

The study considered tests of 28 specimens reinforced with steel fibers with dosage of 20 kg/m³ and 27 specimens reinforced with macro synthetic fibers of different producers with dosages of 4 and 5 kg/m³.

The dosages were considered due to fiber suppliers declares to obtain an average energy absorption capacity of 700 Joules in the plate test according to EFNARC, taking into account the inherent variables related to production process and sampling conditions of the sprayed concrete.

The employed steel fibers were “65/35” type, hooked-end and glued. The declared Young modulus equals 20 GPa (same producer). Their length was 35 mm and their diameter, 0.55 mm.

On the other side, the employed macro synthetic fibers were from three different producers (two of them were tested with 4 kg/m³ and one, with 5 kg/m³). Their lengths varied from 48 mm to 60 mm. The Young modulus declared by one of the suppliers was 10 GPa (tested with 4 kg/m³).

The specimens were sampled inside the tunnel at different mines under operation conditions (see Figure 2), with the available concrete mix, equipment and materials. All of the concretes were produced using the wet mix process and cement type I according to ASTM C 150. The mix designs aimed to obtain in situ compressive strengths of at least 30 MPa in 28 days.

Figure 2. Sampling of the fiber reinforced sprayed concrete specimens inside a mining tunnel.

The registered water/cement ratios varied from 0.40 to 0.44, and the amounts of cement varied among 400 and 440 kg/m³ for both steel and macro synthetic fibers, according to the specific mix design adopted at each mine. The variations related to batching, mixing, conveying and spraying processes were present in both cases in the same extent.

2.1 *Relative Accumulated Energy*

It is defined as the fraction of energy absorption capacity as the FRSC plate (specimen) deforms and it is expressed by the Equation 1:

$$RAE_i = \frac{E_i}{E_{25}}.100, \quad (1)$$

where RAE_i is the Relative Accumulated Energy corresponding to a given displacement in the test in %, E_i is the accumulated energy up to the following displacements: 5, 10, 15, 20 and 25 mm in Joule (i = 5, 10, 15, 20, 25, respectively) and E_{25} is the accumulated energy up to 25 mm displacement in Joules.

For example, RAE_i corresponding to 25 mm displacement (RAE_{25}) equals 100%, which is the case for all of the specimens analyzed. Likewise, if RAE_{15} equals 70%, it means the accumulated energy up to 15 mm displacement is the 70% of the energy absorption capacity (see Figure 3).

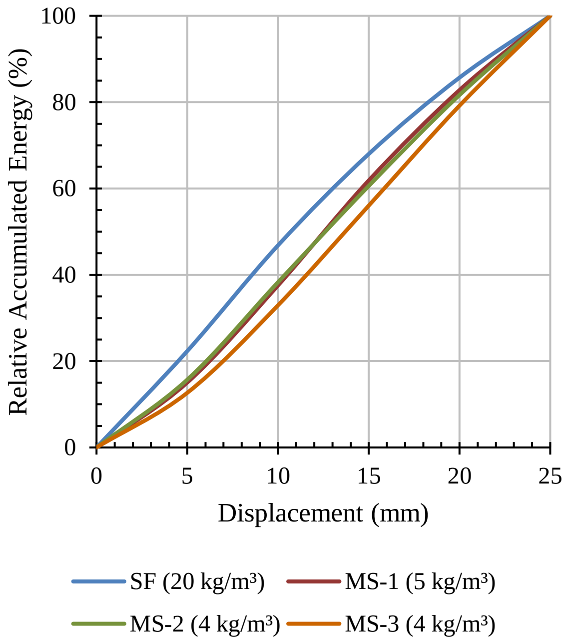

Figure 3. Relative accumulated energy (RAE_i) obtained by sprayed concrete specimens separately reinforced with steel fibers (SF) and macro synthetic fibers (MS) with different producers and dosages on EFNARC tests.

According to the tests, the average relative accumulated energy up to 5 mm displacement (RAE_5) of specimens reinforced with steel fibers was 22% and in the case of specimens reinforced with macro synthetic fibers was among 13% and 16% (depending on the producer and dosage).

In the same way, the average relative accumulated energy up to 10 mm displacement (RAE_{10}) was 47% for steel fibers and among 33% and 38% for macro synthetic fibers.

The energy is closely related to work, which is defined by the Equation 2:

$$W = F.d, \quad (2)$$

where W is the work in Joule, F is the applied force in kN and d is the distance in mm.

If distance is the same in both cases (at certain displacement of the test), the only way the work increases is by increase in the force (or load in the test), then a higher load is required to deform the specimen.

This aspect is very important if what we are looking for is the FRSC support is able to absorb more energy since the beginning of deformation, otherwise FRSC would have to deform considerably to increase the absorbed energy, which could be a counter-productive situation for workers safety.

2.2 *First Crack Load*

It is commonly visualized as the first peak in the Load-Displacement curve and it occurs at small levels of deformation (displacement in the test).

Usually, the corresponding load is associated with the flexural tensile strength of concrete, which depends on its quality; hence, the load values obtained by the specimens with each fiber type should be within the same range as all of the samples were obtained under operation conditions, favorable and unfavorable, for each fiber type in the same extent. However, the load values showed different ranges for each fiber type.

After the analysis, the results showed the first crack load obtained by specimens reinforced with steel fibers was among 30 kN and 50 kN; whilst specimens reinforced with macro synthetic fibers obtained values among 20 kN and 40 kN (see Figure 4). In order to compare the most likely values, the confidence ellipse (with 95% likelihood) for specimens with each fiber type was calculated.

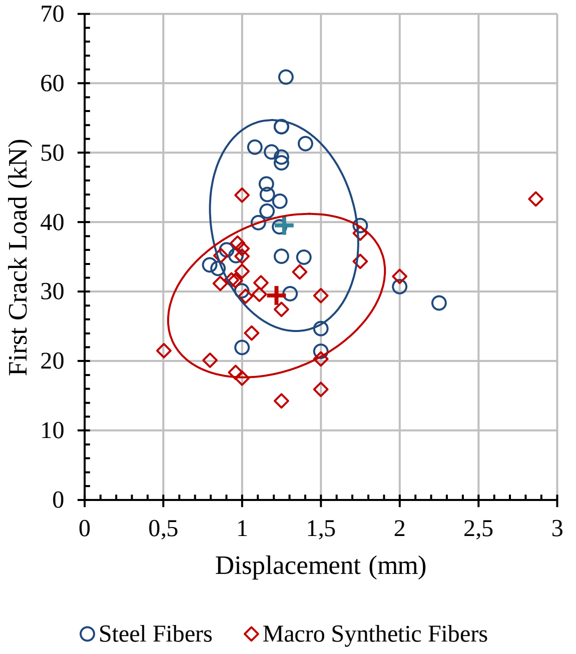

Figure 4. First crack load of FRSC specimens and confidence ellipses (95% likelihood) by fiber type obtained from EFNARC tests.

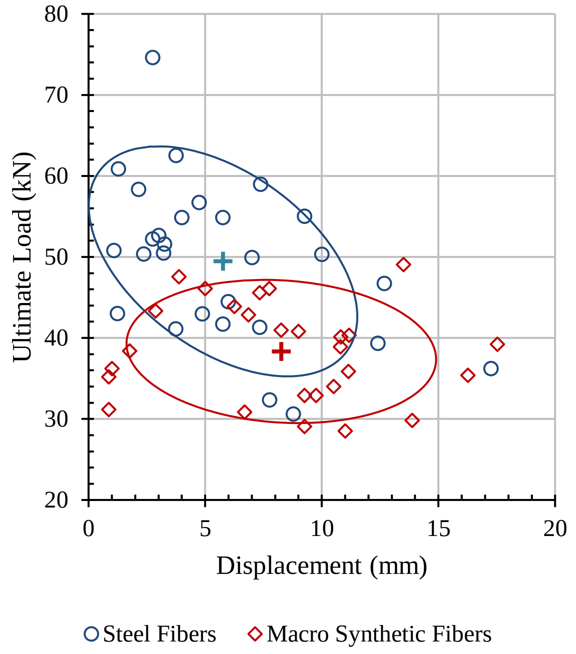

Figure 5. Ultimate load of FRSC specimens and confidence ellipses (95% likelihood) by fiber type obtained from EFNARC tests.

When comparing centers of each confidence ellipse, the average first crack load of specimens reinforced with steel fibers (39.5 kN) was 34% higher than the corresponding to specimens reinforced with macro synthetic fibers (29.4 kN).

These results confirm the proposed hypothesis for the relative accumulated energy regarding to the steel fiber reinforced sprayed concrete requires higher force to start deforming it. The absorbed (or accumulated) energy from the start of deformation is higher as well in consequence.

The difference in average first crack loads may be result of stress distribution produced by the interaction between fibers and the concrete matrix since the test starts. This fact constitutes an evidence the stress distribution has influence on the first crack strength, which was higher in the case of steel fiber reinforced sprayed concrete; hence, its support capacity or strength is higher since the deformation begins.

2.3 *Ultimate Load*

It represents the maximum load bearing capacity or ultimate strength of the FRSC. The ultimate load registered by the specimens reinforced with steel fibers varied from 40 kN to 60 kN, whilst the specimens reinforced with macro synthetic fibers varied from 30 kN to 50 kN (see Figure 5).

When comparing the centers of their respective confidence ellipses, the average ultimate load of the specimens reinforced with steel fibers was 29% higher than that obtained by the specimens reinforced with macro synthetic fibers. Thus, the maximum load bearing capacity using steel fibers was approximately 29% higher than the obtained with macro synthetic fibers independently of the energy absorption capacity obtained at the end of the test.

In order to understand how the ultimate load may impact on the FRSC support capacity, it is important to consider the Load-Deformation characteristics of rock-support interaction (Hoek *et al.*, 1980). Consequently, a safety factor determined by the Equation 3 could be applied:

$$\gamma = \frac{f_M}{\sigma_R}, \qquad (3)$$

where γ is the safety factor for the FRSC support capacity, f_M is the ultimate strength of the FRSC in MPa (determined by the ultimate load) and σ_R is the rock mass pressure in MPa.

For example, assuming a hypothetical case where the ultimate strength provided by the FRSC equals the magnitude of the pressure applied by the rock mass, the safety factor would be one. The FRSC support capacity is consistent when safety factor is greater than one. Accordingly, the higher ultimate load the higher safety factor.

In the hypothetical case where the load (or pressure) applied by the rock mass equals the ultimate load (or ultimate strength) provided by sprayed concrete reinforced with steel fibers, in which case the safety factor equals one, the steel fibers should not be replaced by macro synthetic fibers as safety factor would be smaller than one.

According to the confidence ellipses of each fiber type, the ultimate load provided by steel fibers (49.5 kN) was 29% higher than the provided by macro synthetic fibers (38.3 kN). Thus, the dosage of macro synthetic fibers would have to be greater than the considered in the study in order to equal the support capacity provided by steel fibers.

In the case where the load (or pressure) applied by the rock mass is the same as the previous example and steel fibers are replaced by macro synthetic fibers, the applied load will continuously deform the FRSC support. The accumulated energy will continue increasing but not by increasing of the load (or strength) but because of the displacement increases. This condition may unleash into a creep behavior (continuous deformation until FRSC support collapses).

Conversely, in the case where the load (or pressure) applied by the rock mass equals the ultimate load (or ultimate strength) provided by sprayed concrete reinforced with macro synthetic fibers (safety factor equals one). Macro synthetic fibers can be replaced by steel fibers, in which case, the FRSC support capacity would be increased and the safety factor would be greater than one. Otherwise, the dosage of steel fibers may be reduced to obtain the same support capacity and same safety factor obtained by macro synthetic fibers.

On the other hand, according to the tests, the displacement of the average ultimate load was 5.8 mm in the case of steel FRSC and 8.3 mm in the case of macro synthetic FRSC. If ultimate load is not exceeded, the equilibrium or rock mass stabilization would be achieved by steel FRSC with 30% smaller deformation than the obtained by macro synthetic FRSC, which contributes to workers safety.

Finally, no evidence was found about once ultimate load is obtained, the load increases as the displacement increases, in both fiber type. In consequence, the ultimate load determines to a large degree the support capacity of fiber reinforced sprayed concrete, which –as it was observed– should not be considered the same for each fiber type indiscriminately.

3 CONCLUSIONS

The relative accumulated energy provided by steel FRSC was higher than the provided by macro synthetic FRSC since the beginning of deformation. The required load applied by the rock mass to start deforming the FRSC had to be greater in the case of steel fiber reinforcement. Therefore, steel FRSC provided higher load bearing capacity since the deformation starts.

The ultimate load provided by steel FRSC was approximately 29% higher than the provided by macro synthetic FRSC. Thus, the steel FRSC provided higher ultimate strength and higher maximum load bearing capacity.

Taking into account the dosages applied in the study, the load applied by the rock mass to exceed the ultimate load provided by macro synthetic FRSC would be covered by steel FRSC due to steel fibers provided higher safety factor. Consequently, the dosage of macro synthetic fibers would have to be higher than 5 kg/m³ to equal the ultimate load provided by 20 kg/m³ of steel fibers.

Steel FRSC obtained higher ultimate load with smaller displacement in comparison with macro synthetic FRSC. Obtaining the rock mass stabilization with the less deformation possible is key factor to reduce risks and watching over workers integrity.

The FRSC ductility developed with each fiber type was different. The support capacity obtained by each one of them was not the same. In the case of macro synthetic FRSC, the ultimate load (and ultimate strength) was smaller and it was obtained with bigger displacement (deformation) in comparison with steel FRSC.

There was no evidence the load (or strength) increases after ultimate load is reached for both fiber type (see Figure 6).

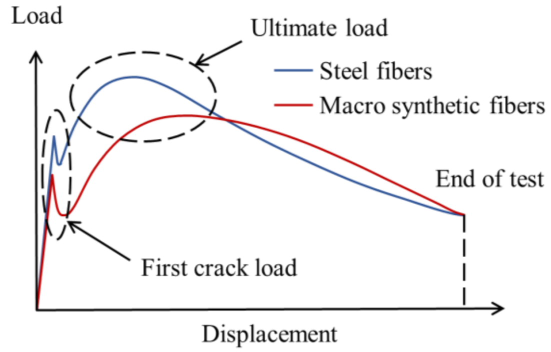

Figure 6. Typical Load-Displacement curves plotted according to values obtained from analyzed tests.

It was not possible to prove the load increases as long as the displacement increases for both fiber type. The accumulated energy beyond the ultimate load is increased by the increase of displacement and not by the increase of load (because the load decreases).

Therefore, independently of the energy absorption capacity, the FRSC support capacity is defined to a large degree by the ultimate load, which is different for each fiber type.

It is advisable complementing the EFNARC test with bending tests according to EN 14651 and the three point bending test on square panel with notch (EFNARC, 2011) in order to evaluate the effect of each fiber type on flexural tensile strength. The residual flexural tensile strength values obtained from these tests are applicable in characterization of fiber reinforced concrete and design codes (Fib, 2010).

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