Fiber-reinforced shotcrete lining for stabilizing rock blocks around underground cavities

(Article begins on next page)

Transportation Geotechnics 49 (2024) 101407

Contents lists available at ScienceDirect

Transportation Geotechnics

journal homepage: www.elsevier.com/locate/trgeo

Fiber-reinforced shotcrete lining for stabilizing rock blocks around underground cavities

Pierpaolo Oreste [a,*], Claudio Oggeri [a], Giovanni Spagnoli [b]

[a] Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca Degli Abruzzi 24, 10129 Torino, Italy
[b] Sweco, Zeche Katharina 6, 45307 Essen, Germany

ARTICLE INFO

Keywords:
Fiber-reinforced shotcrete
Rock block stability
In situ loading test
Curing time
Induced damage
Factor of safety

ABSTRACT

Fiber-reinforced shotcrete is a high-performance material that presents some special characteristics, which can provide some suitable applications in the excavation of underground cavities. The presence of fibers induces an increase in the tensile strength, flexural strength and shear strength in the concrete, as well as allowing a ductile rather than brittle type of behavior. It can be used to create a lining of the underground cavity that allows the stabilization of rock blocks that show a tendency to slip or fall (from the side walls or from the crown area, respectively). In this work, some full-scale tests on the fiber-reinforced shotcrete lining are presented. From these tests, it was possible to measure the behavior of this material when it is loaded locally: it is the same type of action produced by the rock block when it is held back from falling or slipping. The results obtained have allowed to characterize this type of material from a mechanical point of view. A subsequent detailed analysis of the stability of rock blocks surrounding an underground cavity permitted to determine the static stabilizing contribution offered by the fiber-reinforced shotcrete lining, leading to the definition of the minimum thickness required, in relation to the type of block that is present (shape and size). It was possible to predict how a lining thickness of about 3.5 cm is able to stabilize (just 15 min after its spraying) rock blocks with an exposed surface area of up to 10 m^2 and a distance of the internal vertex from the border of the cavity of up to 3 *m*.

Introduction

Ordinary shotcrete (or sprayed concrete, here abbreviated as SC) has low tensile strength, toughness, crack resistance, making it unsuitable for the harsh climate and engineering construction needs (e.g. [17,41]. Steel fibers are (among other techniques such as steel mesh) typically used to reinforce SC tunnel linings. Tests with other materials, such as polypropylene (PP) [5], polyvinyl alcohol (PVA)[29], and plastic waste (PW) fibers [41], have been conducted too.

Fiber reinforced shotcrete is a composite material that exhibits compressive resistence immediately after the installation thanks to the rate of strength development, and fibers employed as structural reinforcement are intended to enhance tensile strength or energy absorption in the concrete matrix after it has cracked [11]. The fibers are bent in some way to make them more resistant to being pulled out of the concrete when a crack occurs [35]. The fundamental function of fibers in shotcrete is to provide ductility to a brittle material. Layer construction details are important for proper quality assessment [25].

Understanding the underlying differences in mechanical qualities of steel and synthetic fiber, for example, may aid in identifying the best fiber to utilize in a certain application [11].

Steel fibers and synthetic ones in SC have been found to perform well in rockburst situations because it has a high capacity for absorbing energy during deformation [12] and steel fibers should be considered as part of the support system [38].

Typical dosage for steel fibers ranges from 20 to 60 kg/m^3 [35], whereas for synthetic fibers range between 5 to 9 kg/m^3 [22] due to the difference in density. As a matter of fact, load vs. deflection tests with steel and synthetic-reinforced SC in unrestrained and restrained conditions showed that synthetic fibers reached the same values with factor 10 lower dosage than for steel fibers [21].

However, there are conflicting researches regarding whether the addition of steel fibers affects the compressive strength of sprayed concrete [35]. Yan et al. [40] state that fibers have no effect on the peak strength of shotcrete; nevertheless, the fiber content presents an effect on the post peak strength (residual strength). Vandewalle [36] claims that they have little benefit on UCS, however the same author states that steel fibers change shotcrete from a brittle material into a highly ductile one, giving a steel fiber reinforced shotcrete lining a higher bearing

* Corresponding author.
E-mail address: pierpaolo.oreste@polito.it (P. Oreste).

https://doi.org/10.1016/j.trgeo.2024.101407
Received 8 July 2024; Received in revised form 9 October 2024; Accepted 14 October 2024
Available online 16 October 2024
2214-3912/

Nomenclature

A_{slab}	area of the detached slab
A_{load}	loaded surface by the flat jacks action or contact surface of a rock block
B	width of the block on the exposed surface on the wall
d	distance of the internal vertex of the rock block from the edge of the tunnel
F_s	safety factor of the rock block
H	height of the block on the exposed surface on the wall
s	thickness of the fiber-reinforced shotcrete lining
s_{min}	minimum thickness of the lining needed to stabilize the rock block on the border of an underground cavity
T	stabilization force perpendicular to the tunnel wall
t	curing time, from the moment of the spraying of the shotcrete
W	block weight
γ	specific weight of the rock
ε	calculation parameter useful for obtaining s_{min}
φ	friction angle on the discontinuities that constitute the sliding surfaces of a rock block
η	calculation parameter useful for obtaining s_{min}
ξ	internal angle of a rock block, measured in a section perpendicular to the line of intersection of the sliding surfaces
τ_{lim}	ultimate shear stress at failure of the fiber-reinforced shotcrete slab

capacity by the effect of a better load redistribution [37]. Besides, Brite Euram [5] claims that steel fibers increase compressive strength by 10 to 35 %. Wood et al. [39] showed that the addition of steel fibers to silica fume shotcrete increases its compressive and flexural strength by up to 20 %. PP fibers have also been proven to improve the SC strength, but they significantly increase water demand, resulting in minimal overall benefit (Brite Euram [5]. Furthermore, steel fiber reinforced concrete outperforms plain concrete under cyclic loads [38].

The orientation of the fibers also plays an important role. Fukui et al. [10] observed higher elastic modulus and tensile strength values from the set of cores oriented perpendicular to the spraying direction with respect to those extracted along the spraying direction. Khan et al. [14] found also that shotcrete strength perpendicular to the spraying direction is greater than that parallel to it. Yan et al. [40] investigated the fundamental characteristics of fiber reinforced shotcrete. The authors came to the conclusion that tensile strength is anisotropic, i.e. a greater strength perpendicular to the applied stress direction. However, Celestino et al. [6] found only 1 % anisotropy in strength, and they argued that for this reason it can be considered negligible.

Nevertheless, steel fibers absorb and redistribute the tensile stress inside the matrix more quickly when concrete solidifies. Steel fibers can retain cracks as they form and prevent them from spreading further. This can result in the structural multi-cracking and load redistribution. The ability to control the width of fractures in a structural application is a key distinction between steel and synthetic fibers. Synthetic fibers are ideal for temporary ground support applications when significant deformations and crack widths are necessary, such as in mining [11].

According to some experimental findings, reinforcement (such as fibers) lowers creep [8]. This is most likely owing to its restricting impact. When compared to plain concrete, 20 kg/m^3 of steel fibers (0.21 % of steel by volume) and 0.39 % of bar reinforcement lowers the magnitude of creep by the same amount [8]. Because of their scattered nature, the fibers have a greater impact than the bar reinforcement. Several authors have investigated by testing the presence of fibers on behaviour of shotcrete, e.g. [16,18,3], however due to the complexity of the topic, this is not considered further in this research.

Basically, SC reinforced with steel fibers behaves virtually elastically and fully plastically [24]; it is more effective than traditional mesh at controlling shrinkage cracking [35]and corrosion of the fibers is not widely regarded as a significant issue [23]. For sure durability in correlated with compressive strength, porosity, gas permeability, and chloride migration, and both laboratory and onsite tests have been widely carried out to ameliorate mix design [1,20].

Uncracked SC layers protect unexposed steel fibers impeding therefore corrosion [13].However, steel fibers in combination with waterglass and alkali-free accelerators were assessed in the Nordkapp subsea road tunnel [19] and corrosion was observed in the carbonation area of the shotcrete (i.e. carbon dioxide from the environment reacts with the calcium hydroxide in cement over time). The reaction generates calcium carbonate, which lowers the pH of the concrete.

Shotcrete is particularly useful in the construction of tunnel linings, because it allows for the creation of an effective and functional support structure in the short term, shortly after its construction. This lining is often planned together with steel sets and/or radial bolting, in order to increase the capacity to react to deformations of the rock mass, applying significant pressure on the perimeter of the cavity[32,33,30,9,34]. The fiber-reinforced SC allows the lining to be provided with significant tensile strength and also, therefore, flexural strength (bending moments develop as a result of the ground/support interaction).

In underground cavities excavated in rock masses, the shotcrete lining has also the important task of preventing the movement of blocks, potentially unstable due to falling from the crown of the tunnel or slipping from the sidewalls. Such rock blocks tend to form at the border of the cavity due to the presence of natural discontinuities. If such discontinuities isolate a block and it shows a tendency to slip or fall inside the cavity, the shotcrete lining can be very useful, reacting to the micro movements of the block with a stabilizing pressure acting in a direction approximately perpendicular to the cavity wall. The stabilizing pressure is equivalent to the pressure applied by the block to the shotcrete lining: it acts on a limited surface, equal to the surface of the block face overlooking the cavity border.

Fiber-reinforced shotcrete is very good at stabilizing rock blocks that tend to fall or slide from the cavity border; in fact, it well withstands a pressure applied perpendicular to it. The shear strength that develops on the edge of the contact area between the exposed face of the block and the lining is high thanks to the presence of the fibers. However, it should be considered that shear resistance is highly dependent on bond to the rock surface, which is often less than the shear strength of the shotcrete: wide testing experiences have been carried out by Bernard [2] and Kikkawa et al. [15].

When underground cavities are excavated in rock masses with natural discontinuities, it is therefore appropriate to define in detail the thickness of the fiber-reinforced shotcrete lining, in order to allow the stabilization of the blocks that can potentially slip or fall; this thickness must be such as to allow the absorption of localized pressures that the block may apply to the lining in the zone of contact with the exposed face.

Shotcrete alone commonly achieves high stiffness and a brittle behaviour: it could be a problem for tunnel walls where displacements of blocks and convergence can still occur for hours after excavation. Thanks to fibers added to the concrete mix, shotcrete become suitable to allow a better ground control: a ductile behaviour with a significant post peak strength becomes evident, so toughness is a property that can be taken into account. The fibrous elements can sustain cracks opening during the tunnel convergence, thus conferring an ability to stabilize wider ranges of ground conditions.

Fibers remain dispersed in a random mode and this is not a concern, as cracks can develop along different alignments, while for other specific geometries and induced oriented stresses a regular layout of fibers could be considered. During the construction of a tunnel in fractured rock masses, it is often necessary to ensure the safety of the zone, close to the

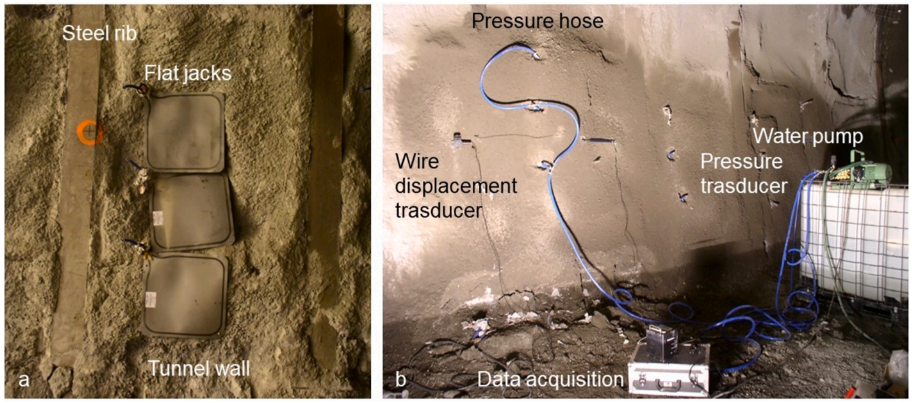

Fig. 1. (a): Positioning of flat jacks on a prepared tunnel surface, consisting of a preliminary shotcrete lining. (b): Overall view of testing zone, after spraying the shotcrete covering the loading jacks shown in (a), with connections for water pressurizing circuit and sensors for pressure and displacement measurements (modified after [26]).

excavation face, just cleared by the advancement operations. It is often necessary to prevent potential blocks present around the edge of the cavity from slipping or falling, involving personnel and excavation and transport equipment for the excavated rock. The shotcrete lining is very well suited to ensuring the safety of this area, as it can be realized from a certain distance, without requiring the presence of personnel in dangerous zones (areas not yet stabilized).

Shotcrete is characterized by a quick evolution of its strength properties, due to the need to self-support its weight immediately after the application and to promptly work together with additional first phase support systems (bolts, steel arches, wire mesh), and rate of strength development is highly relevant. In this paper a specific site testing on thin shotcrete layers has been described and following analysis has focused on early-age behaviour.

After the description of some full-scale experiments carried out in a tunnel on the fiber-reinforced shotcrete lining, the stability of rock blocks surrounding underground cavities was analyzed. Subsequently, through a specific analytical study, the minimum thickness of the lining in order to be able to guarantee the stabilization of the rock blocks and the safe presence of personnel inside an underground cavity was evaluated. Recently, authors have implemented site testing on 70–100 mm thick lining sectors with fiber reinforced shotcrete stressed by means of air bags [4].

Mechanical tests on fiber-reinforced shotcrete

The fiber-reinforced concrete lining has been studied in detail with in-situ and laboratory tests [7]. The in-situ tests involved a 70 m^2 cross-section tunnel excavated in the Briançonnais (Houillier), Unité La Praz formation, whose constituents are mainly shale and sandstone in the Alpine region of France. The laboratory tests were carried out in the Applied Geomechanical Laboratory of the Department of Environmental, Land and Infrastructure Engineering (DIATI) of the Politecnico di Torino (Italy). The in-situ test consisted of a full-scale load test on a fiber-reinforced shotcrete lining, in which the pressure applied by the rock blocks is simulated by the presence of flat jacks each measuring 50 cm x 50 cm, operating with pressurized water. The loading area of this equipment may be adjusted to fit the studied case, and it is inexpensive, portable, and easy to handle. For shotcrete with a compressive strength of up to 8 MPa and linings with thicknesses up to 100 mm, failure can be induced by the loading test. The benefit and innovation of this equipment is the ability to monitor the behavior of the fiber-reinforced shotcrete even when significant displacements develop, and some induced damages can be revealed.

In the current case, a lateral drift of a main tunnel was arranged to host the site testing. The full-scale load tests were carried out by positioning inflatable water flat jacks commonly used in the detachment of blocks in ornamental stone quarrying, fixing along the vertical wall surface before spraying (Fig. 1a). The wall surface was the previously existing, so care has only being paid the avoid excess of roughness at rear. Then spraying over these steel jacks has been carried out, and timeline for pressurizing has been set up. In the meanwhile the equipment for basic measurements has been arranged: the electric pump with valves to pressurize the water, the pressure transducers, the pressure hoses, the potentiometric displacement transducers with sensitivity 0.1 mm (two equipped by wire and two equipped by rod) and the data acquisition system model MCDR (Fig. 1b).

The mix design use for the concrete was in the class type S3, Projeté SDG 385 + 20, Formule 350, cement CEM I 525 PM, with uniaxial compressive strength at 28 days of maturation of 30 MPa. The content of steel fibers (Dramix® type) is equal to 25 kg/m^3. The used mix design (for one m^3 of concrete) is the following:

- fine aggregates: 1145 kg,
- coarse aggregates: 590 kg
- cement: 385 kg,
- silica: 20 kg,
- Glenium® additive: 0.60 %,
- Water: 205 kg.

The thickness of the tested lining varies from 5 to 10 cm.

Three tests were performed, each of which involved the formation of a loading zone with 3 flat jacks, for a net loading surface of 50 cm (width) x 150 cm (height) (Fig. 1) (admissible maximum inflating pressure of about 12 MPa):

Test no. 1: after 2 h from the shotcrete installation; the pressure reached by the flat jacks at the shotcrete failure was 0.114 MPa, with a measured maximum displacement of 25–30 mm at the detachment of the shotcrete slab; the length of the edge of the detached slab is 450 cm, the measured thickness 36 mm.

Test no. 2: after 17 h from the shotcrete installation; the pressure reached by the flat jacks at the shotcrete failure was 0.160 MPa, with a measured maximum displacement of 40 mm at the detachment of the shotcrete slab; the length of the edge of the detached slab is about 490 cm, the measured thickness 40 mm.

Test no. 3: after 24 h from the shotcrete installation; the pressure reached by the flat jacks at the shotcrete failure was approximately 0.300 MPa, with a measured maximum displacement of 70 mm at the detachment of the shotcrete slab; the length of the edge of the detached slab is about 540 cm, the measured thickness about 36 mm.

The transportable electric pump for water used has an analog–digital pressure gauge and two supply lines (hoses) capable of withstanding a

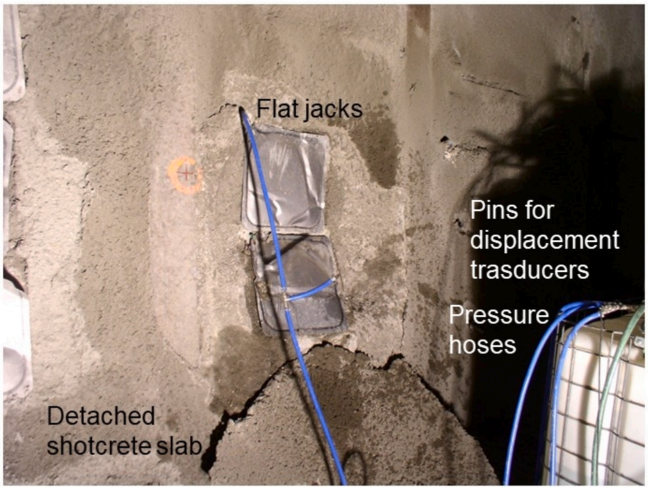

Fig. 2. Detachment of the concrete slab at the end of the second test, involving area more extended than the jack surface (modified after [26]).

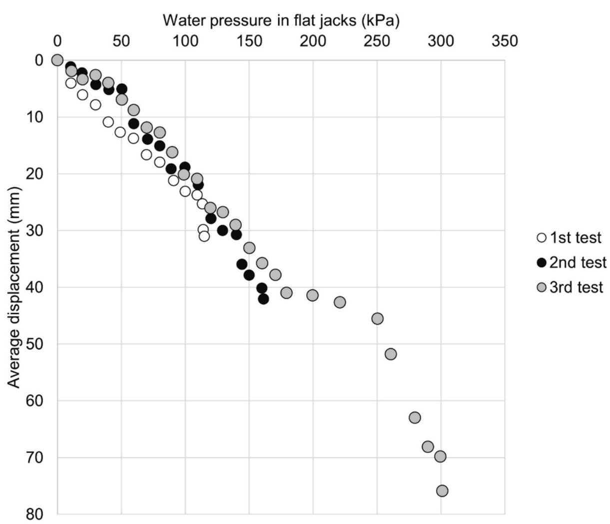

Fig. 3. Evolution of average value of slab detachment from initial undisturbed position following the applied pressure of water in the inflatable flat jacks. Steps can be observed for test n.2 and test n.3, where fibers network contribute to crack extension development. Limit values of displacement are referred to the physical separation of the slab from the tunnel wall. 1st test refers to 2 h of curing, 2nd test refers to 17 h of curing, 3rd test refers to 24 h of curing.

limit pressure of 10 MPa.

In all three cases, a ductile and non-brittle failure was noted during the tests, due to the presence of steel fibers inside the shotcrete. The displacements measured at the detachment of the shotcrete slab are considerable and increase with the increase of the breaking pressure. The image of the conditions of the test zone at the end of test no. 2 is shown in Fig. 2.

Raw data from the three tests have been summarized in the following Fig. 3, where the pressure applied to inflate the flat jacks with water has been considered together with the average value of detachment of the slab, obtained considering the results measured on the two wire transducers and reporting the displacement component normal to the wall. It can be observed that stiffness of the system increases with curing duration and that steps in displacement evolution are corresponding to the toughness and additional work provided by fibers.

The evolution of the detached slab is passing through the involvement of modest adhesion with previous existing support because fibers do not cross the interface old – new stratum and the area covered by the flat jack is relevant. Those elements and also the final contour of the detached slab (with few cracks inside) are demonstrating that the relevant role for strength has been played by shear resistance along the contour thickness of the shotcrete. One could argue that adhesion at the interface between the preexisting surface and the new shotcreted coating is working in a dominant mode: however, this is not always true, as cases occurred with sudden detachment of the only layer of shotcrete from the crown. It may happen that due to the presence of dust particles on the surface or excess of moisture a not perfect contact of the shotcrete can occur. In our testing, adhesion is not driving the evolution of cracking because there is a progression of involved strength: at the very beginning adhesion is present, then it is quite completely lost when the flat jacks expand and the structural shield reacts mainly along its periphery. It is possible to see in Fig. 1a and Fig. 2a "red cross" on the steel rib, that after the detachment results a little covered by the presence of some coatings of shotcrete remaining at the contact. The detached shield is a sort of slab where shear across the thickness of the contour is governing its behaviour: in fact, fibers are crossing this thickness, while no fiber can cross the interface at the rear with the preexisting surface of the wall.

Based on the acquired data during the test, a surface of the slab detached from the action of the flat jacks is measured, progressively larger with the increase of the curing time and the shotcrete strength: 2.15 times the loaded area at 2 h from the shotcrete spraying time, 2.55 times at 17 h, 3.10 times at 24 h.

In fact, the interaction between the loading area, the shotcrete lining and the contact area between the cavity wall and the shotcrete, in the vicinity of the loading area, represents a complex phenomenon, which is influenced by the following parameters:

- strength and elastic modulus of the shotcrete; both vary over time during the curing time[27–28,31],
- size and geometry of the loading area, i.e. the surface where the pressure is applied to the shotcrete lining;
- value of the applied load;
- adhesion of the shotcrete lining to the tunnel wall: adhesion means the tensile strength on the contact surface between the tunnel wall and the shotcrete.

By analyzing the results of the three performed in situ tests, it is possible to determine the ultimate shear stress at failure of the fiber-reinforced shotcrete slab:

1. at 2 h of curing: $\tau_{lim} = 0.528$ MPa
2. at 17 h of curing: $\tau_{lim}=0.612$ MPa
3. at 24 h of curing: $\tau_{lim}=1.157$ MPa

Since the normal stress acting perpendicularly to the failure plane that develops along the edge of the detached slab is negligible, these limit values of the shear stress correspond to the cohesion of the material.

An in-situ pull-out test performed according to the Kaindl-Meyco technique allowed to obtain an estimate of the uniaxial compressive strength of the fiber-reinforced shotcrete equal to 6.5 MPa after 30 h of curing and 11.2 MPa after 7 days. Compressive tests on the same shotcrete used in the tunnel tests, in cubic specimens after 14 days of curing, provided a uniaxial compressive strength varying from 12.1 to 14.2 MPa.

The developed in situ tests represent a first phase of the in-depth study of the behavior of fiber-reinforced shotcrete at the real scale of the problem, i.e. at the scale of the underground cavity. These tests are very complex to carry out and represent novel experiments available on this type of material at the real scale of the problem. The available data are not numerous but they allow, however, to develop some useful considerations for design purposes in order to have a preliminary estimate of the necessary thickness of the fiber-reinforced shotcrete lining.

Stabilization of rock blocks at the cavity boundary for low shotcrete curing times

During the construction of the tunnels, immediately after the advancement of the excavation face, a shotcrete lining is sprayed around the tunnel, in order to secure the newly excavated area. In that same area, workers and machines are expected to be able to operate and it is therefore necessary to guarantee the stability of the rock and prevent the blocks from falling or slipping into the cavity.

Of particular interest, therefore, are the results of the in-situ tests carried out for short curing times, shortly after the shotcrete lining has been placed. It is during this time that the fiber-reinforced shotcrete lining can be able, on its own, to guarantee the stability of the rock blocks and eliminate or strongly contain the risk of the blocks falling or slipping.

In the period between 2 h and 17 h (shotcrete curing time), two in-situ tests were carried out on the fiber-reinforced shotcrete lining, which allow the area of the detached slab (A_{slab}) and the limit shear stress (τ_{lim}) of the fiber-reinforced shotcrete to be estimated; assuming a linear relationship as a function of time t:

$$\frac{A_{slab}}{A_{load}} = 0.0267 \bullet t(h) + 2.10 \tag{1}$$

$$\tau_{lim}(MPa) = 0.0056 \bullet t(h) + 0.5168 \tag{2}$$

where: A_{slab}: surface of the shotcrete slab that tends to peel off when the fiber-reinforced shotcrete lining is loaded;

A_{load}: loaded surface by the flat jacks action or contact surface of the rock block;

τ_{lim}: limit shear stress within the fiber-reinforced shotcrete, and in particular on the outer edge of the detached slab;

t: curing time expressed in hours, from the moment of production of the shotcrete.

Equations (1) and (2) were derived from the results of the carried out in situ tests, and in particular from the tests with 2 h and 17 h of curing of the shotcrete.

Equations (1) and (2) represent two fundamental relationships capable of giving a preliminary indication of two fundamental parameters of the subsequent analytical development. Unfortunately, the available data are not enough to be able to hypothesize more complex trends than the linear one. However, considering very small time interval after the shotcrete realization, the error that could be made by adopting the linear trend is considered negligible.

Thanks to Eqs. (1) and (2) it is possible to analyze the static contribution to the stabilization of the blocks offered by the shotcrete lining and presented separately below, for the blocks that tend to slide from the sidewalls and for those that tend to fall from the tunnel crown.

More specifically, adopting the hypothesis of a circular shape of the slab at the moment in which the fiber-reinforced shotcrete reaches failure, due to the presence of a load acting on its extrados, the lining is able to offer a stabilization force T perpendicular to the tunnel wall equal to:

$$T = 2 \bullet \sqrt{\pi \bullet A_{slab}} \bullet s \bullet \tau_{lim} \tag{3}$$

where: s: thickness of the fiber-reinforced shotcrete lining.

Substituting A_{slab} Eq. (1) and τ_{lim} Eq. (2) in Eq. (3), we obtain:

$$T(MN) \cong 2 \bullet \sqrt{\pi \bullet A_{load}(m^2) \bullet [0.0267 \bullet t(h) + 2.10]} \bullet s(m) \bullet [0.0056 \bullet t(h) + 0.5168] \tag{4}$$

Blocks that tend to fall from the tunnel crown

The rock blocks that are identified in the crown are made up of at least 3 different natural discontinuities and the sub-horizontal face that represents the cavity profile. In order to stabilize a block of this type, the fiber-reinforced shotcrete lining must be able to counteract its own weight. The weight of such a block (W), in the simplest case of a triangular-based pyramid (Fig. 4), is a function of the surface area that faces the edge of the cavity (A_{load}) and the distance of the internal vertex (d):

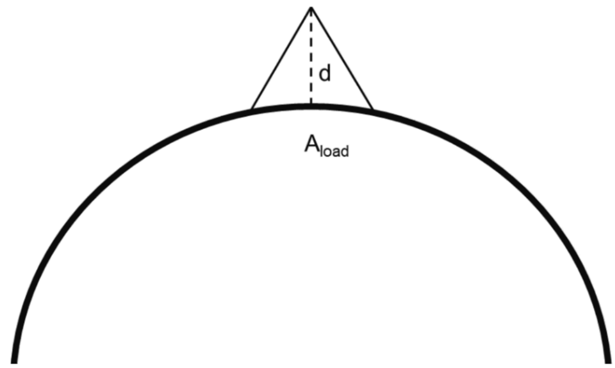

Fig. 4. Basic scheme of a rock block prone to fall from the crown of an underground cavity in a 2D vertical section perpendicular to the cavity axis.

$$W = \gamma \bullet A_{load} \bullet d/3 \tag{5}$$

where: γ: specific weight of the rock;

A_{load}: surface of the rock block that faces the edge of the cavity;

d: distance of the internal vertex of the rock block from the edge of the tunnel.

Considering a safety factor (F_s) that cautiously leads to an increase in the stabilizing force T offered by the fiber-reinforced shotcrete lining, we have:

$$T = F_s \bullet W \tag{6}$$

Substituting the value obtained in Eq. (4) for T and the value from Eq. (5) for W, we have:

$$s_{min}(m) = F_s \bullet \eta \tag{7}$$

where: $\eta = \frac{\gamma(MN/m^3) \bullet d(m)}{6} \bullet \frac{\sqrt{A_{load}(m^2)}}{\sqrt{\pi \bullet [0.0267 \bullet t(h) + 2.10]} \bullet [0.0056 \bullet t(h) + 0.5168]}$

From equation (7) it is possible to identify the minimum thickness of the lining to ensure the stability of a rock block having a surface A_{load} that faces the edge of the cavity in the crown and the internal vertex at a distance d from the edge of the cavity.

Blocks that tend to slide off the tunnel wall

A rock block that forms on the wall of an underground cavity tends to slide on one or more natural discontinuities. Considering the cohesion of the natural discontinuities that represent the sliding surfaces of the block to be negligible or non-existent, the only forces that resist the movement of the block are the friction ones.

In the case of a rock block identified by only three natural discontinuities and the subvertical surface of the tunnel wall, the following further simplifying hypotheses can be made, which however lead to a cautious overestimation of the stabilization force necessary for the block:

- the two sliding surfaces (the two lower surfaces of the block) have a symmetrical orientation with respect to the vertical plane perpendicular to the cavity wall (the lateral surface of the underground cavity): this means that the direction of the intersection line of the two sliding surfaces (in the plan view) is perpendicular to the cavity wall;

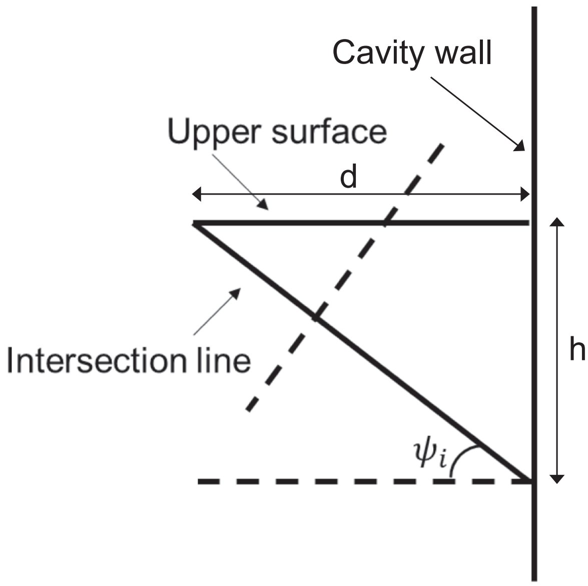

Fig. 5. Schematic representation of a rock block that tends to slide on the wall of an underground cavity (vertical section perpendicular to the cavity side wall). The dotted line represents a section perpendicular to the intersection line between the two sliding surfaces (the two lower surfaces of the block). Key: ψ_i: inclination angle of the intersection line between the two sliding surfaces; d: distance (in the horizontal direction) of the internal vertex of the rock block from the cavity side wall; h: height of the rock block measured in the vertical direction.

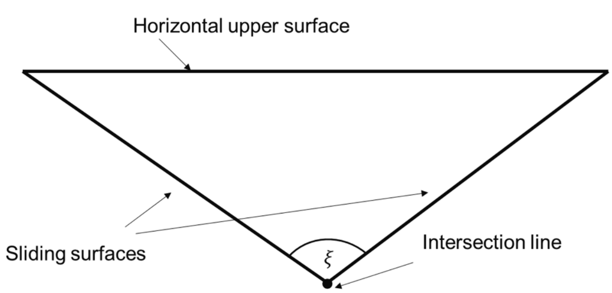

Fig. 6. Representation of the rock block in a section perpendicular to the intersection line (the dotted line in Fig. 5). Key: ξ: block internal angle between the two sliding surfaces, evaluated in a section perpendicular to the intersection line; this angle has a significant importance in the definition of the geometry of the block in order to obtain the safety factor with respect to the potential slipping on the two lower surfaces (discontinuities) of the rock block.

- the third natural discontinuity which is the last surface of the block is represented by a horizontal surface, which isolates the rock block from above.

Based on these hypotheses, the geometry assumed by the block is shown in Figs. 5-6 and the surface of the block in correspondence with the vertical wall assumes a triangular shape, with the base in the upper zone and the vertex in the lower zone. This surface represents the loading area (A_{load}) of the fiber-reinforced shotcrete lining.

For a block of this type, the safety factor (F_s) is given by the following expression:

$$F_s = \frac{(W \bullet cos\psi_i + T \bullet sin\psi_i) \bullet tan\varphi}{(W \bullet sin\psi_i - T \bullet cos\psi_i) \bullet \sin\frac{\xi}{2}} \tag{8}$$

where: ψ_i: inclination angle of the intersection line of the two sliding surfaces;

φ: friction angle on the discontinuities that constitute the sliding surfaces;

ξ: internal angle of the block, measured in a section perpendicular to the line of intersection of the sliding surfaces (Fig. 6);

W: block weight;

T: horizontal stabilizing force produced by the fiber-reinforced shotcrete lining.

From Eq. (8), the value of the stabilizing force T required to achieve the desired safety factor F_s against block slippage can be obtained:

$$T = \frac{W \bullet \left(F_s \bullet sin\psi_i \bullet \sin\frac{\xi}{2} - cos\psi_i \bullet tan\varphi\right)}{sin\psi_i \bullet tan\varphi + F_s \bullet cos\psi_i \bullet \sin\frac{\xi}{2}} \tag{9}$$

By setting Eq. (9) equal to Eq. (4), the minimum thickness of the lining needed to stabilize the rock block on the side wall of an underground cavity can be obtained:

$$s_{min}(m) = \eta \bullet \varepsilon \tag{10}$$

where: $\eta = \frac{\gamma(MN/m^3) \bullet d(m)}{6} \bullet \frac{\sqrt{A_{load}(m^2)}}{\sqrt{\pi \bullet [0.0267 \bullet t(h) + 2.10]} \bullet [0.0056 \bullet t(h) + 0.5168]}$

$$\varepsilon = \frac{\left(F_s \bullet sin\psi_i \bullet \sin\frac{\xi}{2} - cos\psi_i \bullet tan\varphi\right)}{sin\psi_i \bullet tan\varphi + F_s \bullet cos\psi_i \bullet \sin\frac{\xi}{2}}$$

Since there are uncertainties related to the experimentation on the fiber-reinforced shotcrete lining, it is advisable to adopt high safety factors (i.e. higher than 2) as is commonly done in similar cases.

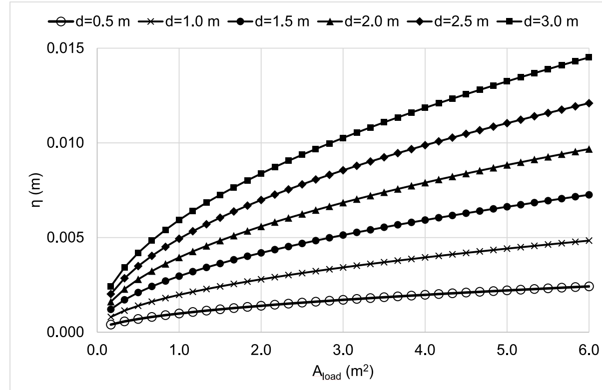

Fig. 7. Trend of the parameter η (Eq. (7) as the area A_{load} (area of the block exposed surface on the cavity wall) varies, for different distances d of the internal vertex of the block and for a shotcrete curing time of 15 min.

Designing the thickness of the fiber-reinforced shotcrete lining to ensure the stabilization of the rock blocks surrounding an underground cavity

Thanks to Eqs. (7) and (10) it is possible to proceed to the definition of the thickness of the fiber-reinforced shotcrete lining in order to stabilize the rock blocks that tend to fall from the crown area or slide from the side walls of an underground cavity. The required thickness of the lining also depends on time t: it is the curing time, following the shotcrete sprayed, for which it is necessary to guarantee the stability of the rock blocks through the development of an adequate stabilizing force by the lining.

In fact, different activities alternate near the excavation face and it is therefore necessary that after a certain period from the spraying of the lining, the area can be occupied by workers and by machines and other equipment. It is precisely this period that must be evaluated in order to identify the strength of the fiber-reinforced shotcrete, which allows for the development of an adequate stabilizing force of the rock blocks.

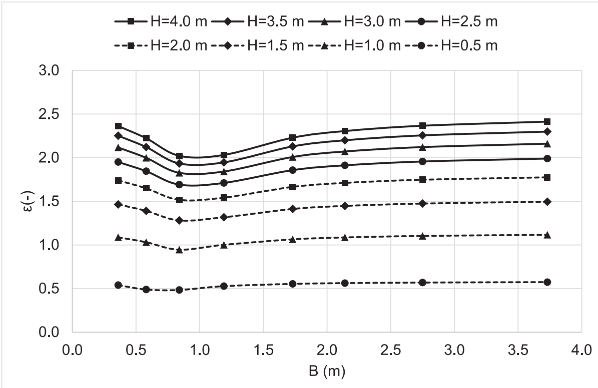

Fig. 8. Trend of the parameter ε (Eq. (10) as the width B of the exposed surface of the block varies, for different heights H, for a distance d of the internal vertex of the block from the wall of 0.5 m.

As regards the rock blocks that can be in the crown, equation (7) allows to obtain the diagram shown in Fig. 7, assuming the specific weight of the rock γ to be conservatively equal to 28 kN/m^3. The figure shows the parameter η as the area A_{load} of the exposed surface of the block varies, for a shotcrete curing time of 15 min, considering different values of d in the range 0.5–3.0 m.

In particular, for a curing time of 15 min (0.25 h), it is possible to obtain the following equation describing the value of η as A_{load} and d vary (Fig. 7):

$$\eta \cong [0.0010 + 0.0020 \bullet (d - 0.5)] \bullet \sqrt{A_{load}} \quad (11)$$

As regards the lateral blocks that tend to slide on the walls of underground cavities, by varying the geometry of the block (B: width of the surface of the block exposed on the wall; H: its height; d: the distance of the internal vertex from the wall) it is possible firstly to determine ψ_i and ξ (Eq. 8–10) and subsequently the value of ε (Eq. (10).

By adopting a safety factor (F_s) equal to 2, the parameter ε can be determined considering a precautionary value of the friction angle φ of the sliding surfaces of the block equal to 28°: this value is to be considered a lower limit of the typical variability intervals of the friction angle of natural discontinuities in rock masses. In Figs. 8-13, ε is reported for values of d from 0.5 to 3 m, as the width B of the block surface exposed on the wall and its height H vary. The negative values of ε show conditions for which it is not necessary to provide for the stabilization of the blocks using the shotcrete lining.

From the obtained results, it is possible to identify the maximum value of ε (ε_{max}), useful for designing the fiber-reinforced shotcrete lining, as H (height of the block on the exposed surface on the wall) and d (distance of the internal vertex of the block from the cavity wall) vary:

$$\epsilon_{max} \cong (-0.1071 \bullet d + 0.5451) \bullet H - 0.416 \bullet ln(d) + 0.2243 \quad (12)$$

It is therefore possible to define the minimum thickness of the fiber-reinforced shotcrete lining by considering all the possible rock blocks that may be present around the cavity (both in the crown and on the

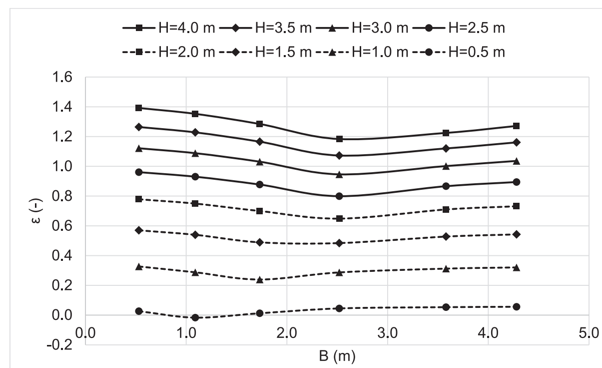

Fig. 10. Trend of the parameter ε (Eq. (10) as the width B of the exposed surface of the block varies, for different heights H, for a distance d of the internal vertex of the block from the wall of 1.5 m.

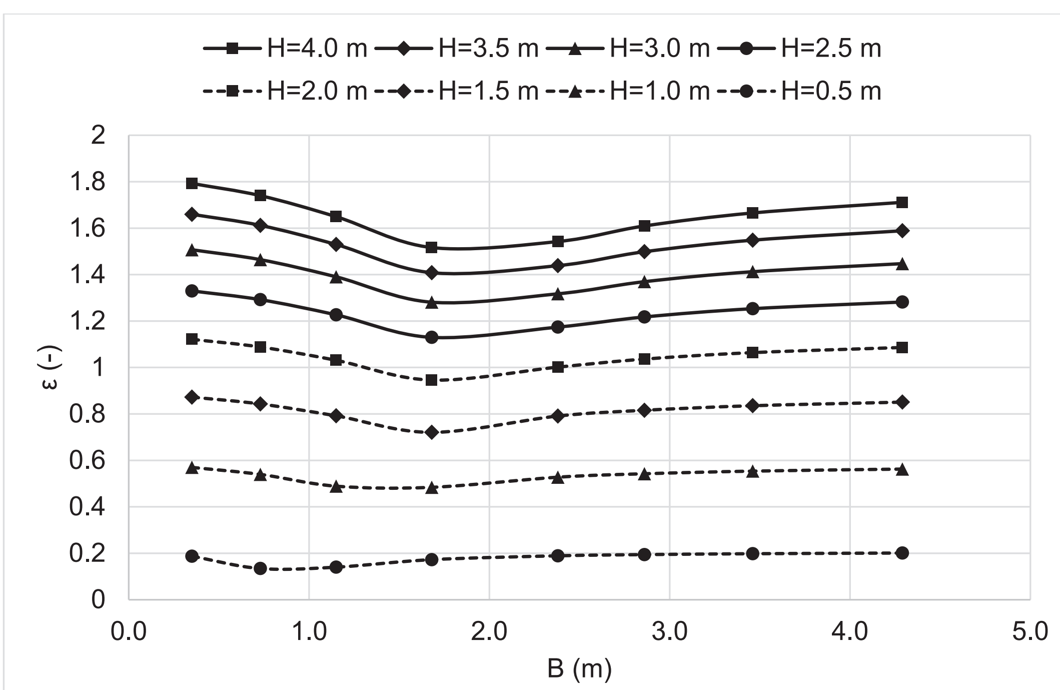

Fig. 9. Trend of the parameter ε (Eq. (10) as the width B of the exposed surface of the block varies, for different heights H, for a distance d of the internal vertex of the block from the wall of 1.0 m.

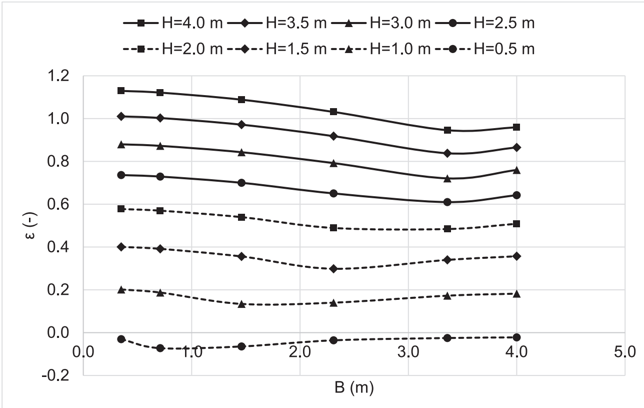

Fig. 11. Trend of the parameter ε (Eq. (10) as the width B of the exposed surface of the block varies, for different heights H, for a distance d of the internal vertex of the block from the wall of 2.0 m.

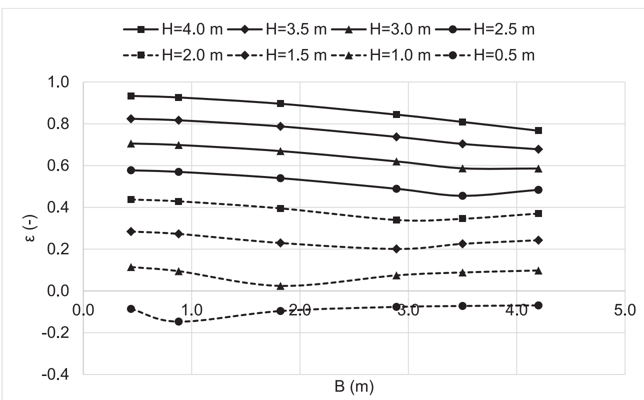

Fig. 12. Trend of the parameter ε (Eq. (10) as the width B of the exposed surface of the block varies, for different heights H, for a distance d of the internal vertex of the block from the wall of 2.5 m.

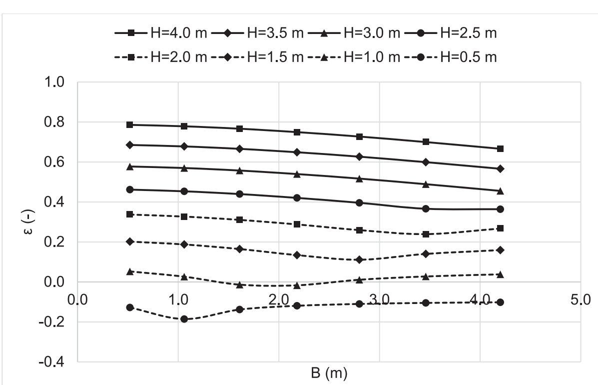

Fig. 13. Trend of the parameter ε (Eq. (10) as the width B of the exposed surface of the block varies, for different heights H, for a distance d of the internal vertex of the block from the wall of 3.0 m.

wall) (Eq. (7), 10, 11, 12):

$$s_{min} \cong max(F_s; \varepsilon_{max}) \bullet [0.0010 + 0.0020 \bullet (d - 0.5)] \bullet \sqrt{A_{load}} \quad (13)$$

Figs. 8-13 show the values of the parameter ε as the width B of the block varies, for different values of H (height of the block); while the previous Fig. 7 shows the trend of the parameter η as the exposed surface area of the block (A_{load}) varies, for different values of the depth of the internal vertex d.

The shown figures allow to obtain the minimum thickness of the shotcrete lining necessary for the stabilization of the blocks around the underground cavities.

These two parameters ε and η, therefore, are fundamental to obtain a first estimate of the thickness of the fiber-reinforced shotcrete necessary to stabilize the blocks around the underground cavities. The shown graphs are very useful tools for quickly sizing the fiber-reinforced shotcrete lining.

The obtained preliminary estimate must, however, be subsequently verified through the detailed characterization of the shotcrete on site using common tools capable of evaluating the strength through punching.

For a rock block with an exposed surface area at the cavity border equal to 10 m^2 and a distance d of the internal vertex of the block from the border equal to 3 m, the minimum thickness required for the fiber-reinforced shotcrete lining is approximately 3.5 cm. For smaller exposed surface areas and d distances, the minimum required lining thickness is reduced.

Conclusions

The behaviour of fresh fiber reinforced shotcrete during simulated convergence has been tested: as reported in the technical literature, the presence of fibers (steel and plastic) in shotcrete induces a significant improvement in the properties of the shotcrete, in particular with regard to tensile strength and flexural strength, as well as shear strength. The advantage caused by the presence of fibers allows the shotcrete lining to react well to the concentrated thrusts produced by potential blocks of rock that tend to slide from the side walls of an underground cavity or fall from the crown area. Furthermore, fibers have the effect of increasing the ductility of the shotcrete and, therefore, allow the lining to still be effective in containing the blocks, even in the presence of significant deformations. On site testing for this study had the role to prove the feasibility of applying a controlled pressure to a shotcrete lining simulating a sort of 'convergence while curing' the shotcrete: this is what happens in practice in the great majority of cases while face is advancing. In a similar mode, if a uniform convergence does not occur, flat jack can simulate the punctual load of a removable block from the wall. Limitations are at this stage related to a single type of shotcrete, a single thickness and to a limited range of curing timeline. Damage while curing is nevertheless a feature that could be beneficially investigated also in lab.

In this research, some real scale tests on the fiber-reinforced shotcrete were presented. From the obtained results, it was possible to characterize its behavior with a certain precision. The tests simulated the presence of concentrated loads on the extrados of the lining, in order to verify the behavior of the fiber-reinforced shotcrete when a rock block shows a tendency to slip or fall inside the cavity. Based on the obtained information from the in-situ experimentations, the stabilizing effect on the rock blocks produced by the shotcrete lining was evaluated. More specifically, the rock blocks, of different sizes and geometry, present in the crown area and on the side walls of the cavity were studied. The analysis developed considering rock blocks with an exposed surface area on the wall of up to 10 m^2 and a distance of the internal vertex of the block from the edge of the cavity of up to 3 m. It was possible to detect how a minimum thickness of approximately 3.5 cm of the fiber-reinforced shotcrete lining is sufficient to ensure the stability of the blocks just 15 min after its spraying, if the bond to the rock is capable to induce a shear failure in the shotcrete. The fiber-reinforced shotcrete lining has therefore proven to be an exceptional material, capable of ensuring the safety of the underground cavity, allowing the stabilization of rock blocks even before it is possible to proceed with the construction of support structures through steel sets and/or radial bolts.

CRediT authorship contribution statement

Pierpaolo Oreste: Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Claudio Oggeri:** Writing – review & editing, Validation, Investigation, Data curation. **Giovanni Spagnoli:** Writing – review & editing, Writing – original draft, Resources, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] Armengaud J, Cyr M, Casaux-Ginestet G, Husson B. Durability of dry-mix shotcrete using supplementary cementitious materials. Constr Build Mater 2018;Volume 190: p. 1-12, doi 10.1016/j.conbuildmat.2018.09.107.

[2] Bernard ES. Early-age load resistance of fibre reinforced shotcrete linings. Tunn Undergr Space Technol 2008;23:451–60.

[3] Bernard ES. Influence of fiber geometry and type on creep rupture of cracked fiber-reinforced shotcrete mixtures. ACI Mater J 2021;118(2):3–12.

[4] Bernard ES, Oliveira DAF, Forrest BH. In situ flexural failure of unbonded fibre reinforced shotcrete linings in response to point loading. Tunn Undergr Space Technol 2022;119. https://doi.org/10.1016/j.tust.2021.104235.

[5] Brite Euram (1998). New materials, Design and Construction Techniques for Underground Structures in Soft Rock and Clay Media. BRE-CT92–0231 Final Technical Report, Mott MacDonald Ltd.

[6] Celestino TB, Bortolucci AA, Re G, Ferreira A. Diametral compression tests for determination of shotcrete anisotropic elastic constants. In: In: Shotcrete for Underground Support VIII. ASCE; 2001. p. 27–35.

[7] Costamagna E, Oggeri C, Vinai R. Damage and contour quality in rock excavations for quarrying and tunnelling: Assessment for properties and solutions for stability. In: in IOP Conference Series, EUROCK 2021 Conference on Rock Mechanics and Rock Engineering from Theory to Practice; 2021. https://doi.org/10.1088/1755-1315/833/1/012137.

[8] Ding Y. Technologische Eigenschaften von jungem Stahlfaserbeton und Stahlfaserspritzbeton. University of Innsbruck; 1998. PhD Thesis.

[9] Do N-A, Dias D, Oreste P, Djeran-Maigre I. Behaviour of segmental tunnel linings under seismic loads studied with the hyperstatic reaction method. Soil Dyn Earthq Eng 2015;79:108–17.

[10] Fukui K, Okubo S, Yang Q, Ochi T. Mechanical properties of steel fiber reinforced shotcrete in uniaxial tension. Journal-Mining and Materials Processing Institute of Japan 1996;112:69–74. https://doi.org/10.2473/shigentosozai.112.69.

[11] Gagnon A, Geers W. Fiber-reinforced shotcrete—applications and testing overview. American Shotcrete Association; 2019.

[12] Grimstad, E. (1999). Experiences from excavation under high rock stress in the 24,5 km long Laerdal Tunnel. International Conference on Rock Engineering Techniques for Site Characterisation, 135–46. Bangalore, India.

[13] Kaufmann, J.P. (2014). Durability performance of fiber reinforced shotcrete in aggressive environment. Proceedings of the World Tunnel Congress 2014, Foz di Uguacu, Brazil May 2014.

[14] Khan MU, Tahir MU, Emad MZ, Raza MA, Saki SA. Investigating Strength Anisotropy of Plain and Steel Fiber Reinforced Shotcrete. Mining, Metallurgy & Exploration 2023;40:291–303. https://doi.org/10.1007/s42461-022-00715-9.

[15] Kikkawa N, Ito S, Hori A, Sakai K, Hiraoka N. Punching fracture mechanism and strength formula of early-age shotcrete. Tunn Undergr Space Technol 2020;110 (2021):103765.

[16] Larive C, Rogat D, Chamoley D, Regnard A, Pannetier T, Thuaud C. Influence of fibres on the creep behaviour of reinforced sprayed concrete. In: Proceedings of ITA World Tunnel Congress WTC 2016, April 22-28, San Francisco, United States; 2016.

[17] Liu G, Guo X, Cheng W, Chen L, Cui X. Investigating the migration law of aggregates during concrete flowing in pipe. Constr Build Mater 2020;251:119065. https://doi.org/10.1016/j.conbuildmat.2020.119065.

[18] Llano-Torre A, Arango SE, Garcia-Taengua E, Marti-Varas JR, Serna P. Influence of Fibre Reinforcement on the Long-Term Behaviour of Cracked Concrete. Creep Behaviour in Cracked Sections of Fibre Reinforced Concrete. In: Proceedings of the International RILEM Workshop FRC-CREEP 2016 (Ed. Serna et al); 2017. p. 195–209.

[19] Manquehual CJ, Jakobsen PD, Holter KG, De Weerdt K, Danner T, Bruland A. Comparison of the condition of steel fiber-reinforced shotcrete with water-glass and alkali-free activators after more than 20 years of service in a subsea road tunnel. Constr Build Mater 2022;328:127090. https://doi.org/10.1016/j.conbuildmat.2022.127090.

[20] Marcos-Meson V, Michel A, Solgaard A, Fischer G, Edvardsen C, Skovhus TL. Corrosion resistance of steel fibre reinforced concrete - A literature review. Cem Concr Res 2018;103. January, pp. 1–20.

[21] Morgan, D.R., McAskill, N., Richardson, B.W. and Zellers, R.C. (1989). A comparative evaluation of plain, polypropylene fiber, steel fiber, and wire mesh reinforced shotcretes. International Symposium on Recent Developments in Concrete Fiber Composites, 1989, Washington, DC, USA, 78-87.

[22] Nitschke, A. and Winterberg, R. (2016). Performance of Macro Synthetic Fiber Reinforced Tunnel Linings. Proceedings of the World Tunnel Congress 2016, San Francisco, USA, April 2016.

[23] Nordstrom, E. (2001). Durability of steel fibre reinforced shotcrete with regard to corrosion. In Shotcrete: Engineering Developments, Bernard (ed), Swets & Zeitlinger, Lisse, 213–17.

[24] Norris P, Powell D. Towards quantification of the engineering properties of steel fibre reinforced sprayed concrete. 3rd International Symposium on Sprayed Concrete. 1999.

[25] Oggeri C, Ova G. Quality in tunnelling. In Tunnelling and Underground Space TechnologyVolume 2004;19(3):239–72. https://doi.org/10.1016/j.tust.2004.01.002.

[26] Oggeri, C., Ronco, C. and Venditti, G. (2009). Standard and in situ tests. In Construction methodologies and structural performance of tunnel linings, G. Plizzari Editor, Starrylink Publisher, Brescia. ISBN 978-88-96225-31-8.

[27] Oggeri C, Oreste P, Spagnoli G. The influence of the two-component grout on the behaviour of a segmental lining in tunnelling. Tunn Undergr Space Technol 2021;109:103750.

[28] Oggeri C, Oreste P, Spagnoli G. Creep behaviour of two-component grout and interaction with segmental lining in tunnelling. Tunn Undergr Space Technol 2022;119:104216.

[29] Ohno M, Li VC. A feasibility study of strain hardening fiber reinforced fly ash-based geopolymer composites. Constr Build Mater 2014;57:163–8.

[30] Oreste P. Face stabilisation of shallow tunnels using fibreglass dowels. Proc Inst Civ Eng Geotech Eng 2009;162(2):95–109.

[31] Oreste P, Sebastiani D, Spagnoli G, de Lillis A. Analysis of the behavior of the two-component grout around a tunnel segmental lining on the basis of experimental results and analytical approaches. Transp Geotech 2021;29:100570.

[32] Pelizza S, Oreste P, Peila D, Oggeri C. Stability analysis of a large cavern in Italy for quarrying exploitation of a pink marble. Tunn Undergr Space Technol 2000;15(4):421–35.

[33] Ranjbarnia M, Fahimifar A, Oreste P. A simplified model to study the behavior of pre-tensioned fully grouted bolts around tunnels and to analyze the more important influencing parameters. J Min Sci 2014;50(3):533–48.

[34] Spagnoli G, Oreste P, Bianco LL. New equations for estimating radial loads on deep shaft linings in weak rocks. Int J Geomech 2016;16(6):06016006.

[35] Thomas, A. (2009). Sprayed Concrete Lined Tunnels. Oxon, Taylor & Francis.

[36] Vandewalle, M. Dramix: Tunnelling the World. Bekaert S.A; 1996.

[37] Vandewalle M. The use of steel fibre reinforced shotcrete for the support of mine openings. The Journal of The South African Institute of Mining and Metallurgy 1998;98(3):113–20.

[38] Vandewalle M, Rock T, Earnshaw G, Eddie C. Concrete reinforcement with steel fibres. Tunnels and Tunnelling International, April, 39–41; 1998.

[39] Wood, D.F., Banthia, N. and Trottier, J-F. (1993). A comparative study of different steel fibres in shotcrete. In Shotcrete for underground support VI, Niagara Falls, 57-66. New York: Am. Soc. Civ. Engrs.

[40] Yan X, Liu L-m, Zhang J-p, Li Y-h, Wang H. Experimental study on basic mechanical properties of steel fiber-reinforced siliceous wet shotcrete. Adv Mater Sci Eng 2018:1637261. https://doi. org/ 10. 1155/ 2018/ 16372 61.

[41] Zhao J, Meng X, Chen L, Liu G, Zhang Z, Xu Q. Correlation between the mechanical properties and the fiber breaking morphology of fiber reinforced shotcrete (FRS). Compos Struct 2021;277:114641. https://doi.org/10.1016/j.compstruct.2021.114641.