Shotcrete in tunnelling and mining

Authors: Prof. Dr. habil. Heinz Konietzky (TU Bergakademie Freiberg, Geotechnical Institute)

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TU Bergakademie Freiberg, Institut für Geotechnik, Gustav-Zeuner-Straße 1, 09599 Freiberg • sekr_fm@ifgt.tu-freiberg.de

1 Introduction

Shotcrete is often used in tunneling and mining to seal freshly uncovered surfaces and for the support of cavities (Fig. 1 and Fig**. 2**). In tunneling, shotcrete is used at various stages throughout the process (construction and post-construction), whereas it is locally used for mining.

Shotcrete is a special concrete conveyed in a closed tube or hose to the application site. The application takes place pneumatically or hydraulically through a spray nozzle. The concrete is compacted by the impact energy and can be sprayed onto a surface with any shape, including vertical walls and roofs. The shotcrete recipe depends on many factors and is determined by the desired outcome.

Shotcrete can be reinforced by steel rods, steel meshes and/or fibres (steel or synthetic). It should be noted that the proportions in the base mixture can be different to those of the compacted shotcrete on the wall due to the loss of material during the spaying process. The thickness of shotcrete layers typically varies from 2 to 30 cm. This depends on whether and to what extent a reinforcement is necessary. For one spraying layer the thickness varies from 2 – 5 cm. Greater thicknesses are achieved by spraying several layers one on the other.

Shotcrete can have several functions (AFTES, 2000):

- It can act as a ***protective skin*** to ensure cohesion develops between rock blocks / fragments and to avoid further weakening due to weathering etc.
- It can act as a ***structural layer*** to support the ground, where additional support elements like anchors act as main load bearing and stabilizing factors
- It can act as a ***structural ring***, which can resist normal and shear forces as well as bending moments (in this case often reinforced concrete is used)

In Germany, the requirements of shotcrete are regulated in the standard DIN 1045. The standards for the mixtures are regulated in DIN 18314 and DIN 18551. In Europe there is also a corresponding guideline called EFNARC. The International Tunnel Association (ITA) provides recommendations for sprayed concrete (AFTES, 2000).

Fig. 1: Partial support with shotcrete in a mine

Fig. 2: Shotcrete application at a tunnel portal

2 Ingredients of shotcrete

Shotcrete is a three-component system consisting of:
- water
- cement
- aggregates

In some cases, it can be extended to a five-component system with the addition of following components:
- additives
- admixtures

There is a complex interdependency between these components. By changing the concrete recipe, the properties of the shotcrete can be adjusted for requirements such as:
- high early hardness
- user-friendliness
- increased strength
- etc.

2.1 Cement

The most important requirements of cement used for shotcrete are:
- fast solidification
- high early strength

Cement is a hydraulic binder, meaning that it hardens on air and in water. The cement proportion in shotcrete generally ranges between 325 and 450 kg/m³. Another basic requirement of shotcrete is the cement content should be sufficient to achieve a minimum compressive strength of 10 MPa after two days and 35 MPa after 28 days. For situations where aggressive mountain water presents sulphate resistant concrete is necessary.

2.2 Aggregates

Aggregates form the matrix of the shotcrete and act as filling material. Early days, rounded aggregates, directly sourced from the environment, were mainly used in shotcrete. However, nowadays, the required aggregates are often produced from the excavated rock materials and these irregular-shaped aggregates may have internal micro-cracks, which can lower the strength of individual grains to some extent. Nevertheless, these crushed rock aggregates can improve the interlocking properties of the shotcrete, which eventually results in better ultimate strength and stability. In addition, the use of crushed excavated rock as aggregates helps for the management strategies of solid wastes

2.3 Additives

Fly ash, silica fumes, powder and fibres are the main types of additives used in shotcrete. Care should be taken on the material reference when using additives in shotcrete.

2.4 Fly ash

Fly ash improves the sulphate resistance, strength, sticking effect and structural density of shotcrete. According to EU standards fly ash can be partially taken into account as a binder.

2.4.1 Silica fume

Silica fumes are approximately one hundred times finer than the cement grains. For this reason, the cavities between the cement particles can be filled by them. This results in higher compressive strength and resistance to sulphate, frost, de-icing salt and water.

2.4.2 Fibres

Fibres used in shotcrete are made of steel or synthetic material. Conventional reinforcement could be replaced by fibres. The load bearing capacity, tensile strength and the mechanical working capacity of shotcrete are enhanced by adding fibres. The main drawbacks of using fibres are the possibility of clumping and the requirement of special equipment.

2.5 Admixtures

The amount of admixtures in the shotcrete recipe is usually very low. Main types of admixtures are: setting accelerator, concrete plasticizer, dust-trapping agent or retarder. Only setting accelerator as the most important admixture is considered here.

2.5.1 Setting accelerator

In tunnelling, quick setting of the concrete is essential. By using a setting accelerator, it is possible to achieve a start of setting after 3 minutes and a compressive strength of more than 3 MPa after 4 hours (“flash set”). Fig. 3 shows the variation of compressive strength (UCS) against the percentage of setting accelerator in the mix for different periods of time. Within the first few days, the concrete shows a higher strength when a setting accelerator is used. However, the use of setting accelerators results in lower final strength.

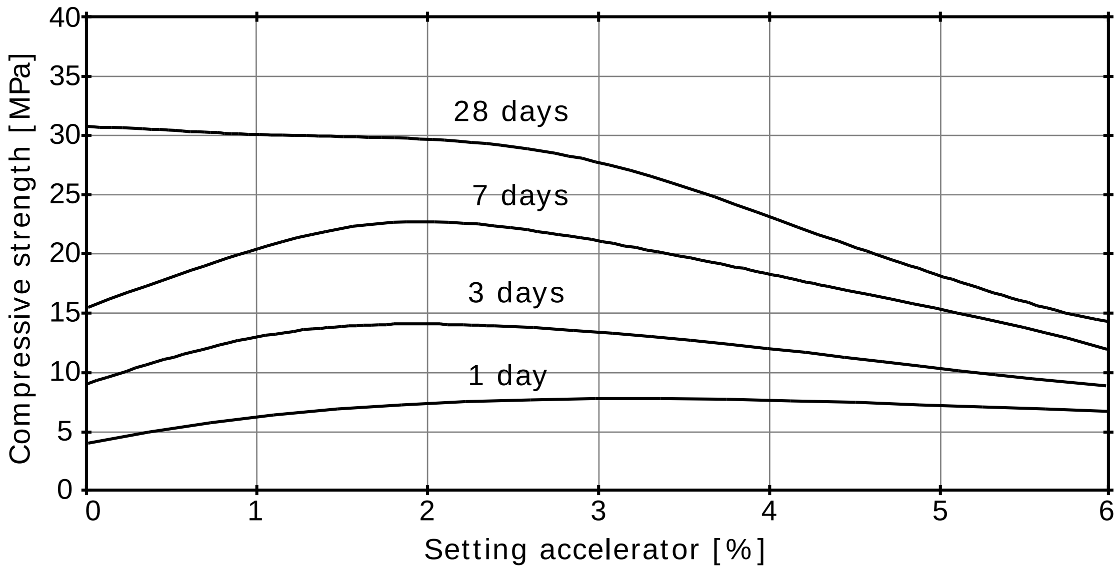

Fig. 3: Influence of the setting accelerator on the compressive strength of dry-mix concrete (Modified after (Girmscheid, 2000))

3 Equipment

Shotcrete can be applied in two different ways:

I. as dry-sprayed concrete (dry mix)
  - pneumatic transport (thin-flow process)
    - conventional (bone-dry aggregates)
    - conventional plus accelerating agent
    - modified (aggregates of natural moisture plus accelerating agent)

II. as wet-sprayed concrete (wet mix)
  - pneumatic transport (thin-flow process or plug conveying)
  - hydraulic transport (dense-flow process)

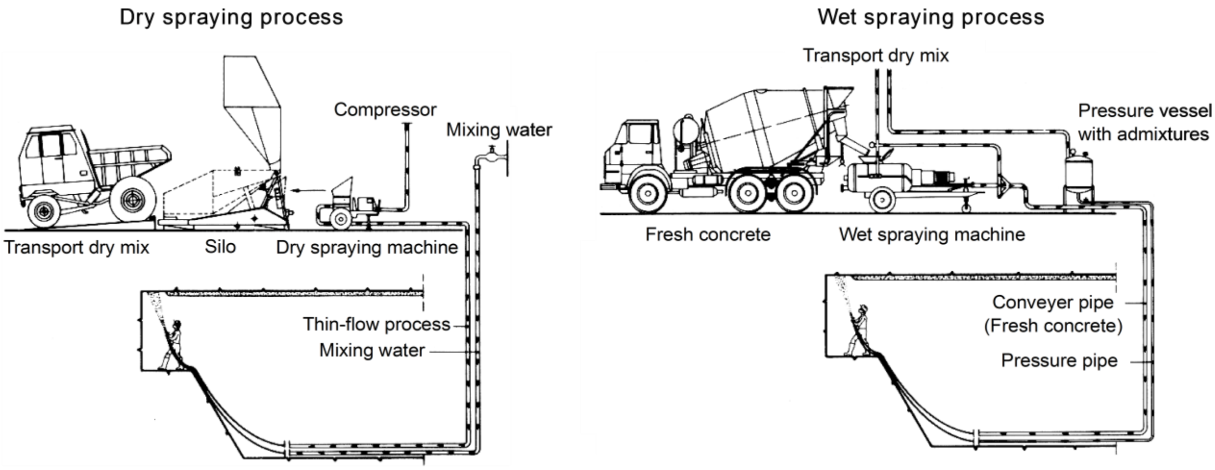

Fig. 4: Schematic illustration of the equipment used for the shotcrete application (Modified after (Girm-scheid, 2000))

Fig**.** 4 (left) shows the equipment for the dry spraying process. The dry mix shotcrete with dry cement, oven dried additives and powdery setting accelerator will be transported to a silo. Then they are further transported to the spray nozzle through the dry spraying machine using compressed air (Fig. 5+6). The water is hydro-dynamically mixed with the dry mass at this stage. The application takes place with a velocity of approximately 20 m/s. It is also possible to add setting accelerator directly to the water. Fig. 4 (right) shows the equipment which is needed for the wet spraying process. The fresh cement with all additional ingredients except setting accelerator is added directly to the wet spraying machine. The wet mix will be transported to the spray nozzle using compressed air in the thin flow process (Fig.). The dense-flow process is conducted with standard cement piston pumps. The material is hydraulically transported in a compact form to the spray nozzle. For any wet spraying shotcrete process additional compressed air acts as process accelerator. Setting accelerator can be added at the spray nozzle.

Fig. 5: Application of dry sprayed concrete (I) (Source:AF Toscana AG)

Fig. 6: Application of dry sprayed concrete (II) (Source:AF Toscana AG)

Fig. 7: Application of wet sprayed concrete in a mine

4 General properties

The Young's modulus of shotcrete is slightly lower than that of cast concrete. However, stiffness and hardness of shotcrete after 28 days are similar to those of cast concrete. Assuming a sufficient amount of moisture is available, the shotcrete strength reaches the desired final value after 28 days. Typical values of different material properties of shotcrete are shown in Tab. 1.
Tab**. 2** shows how the compressive strength increases with time.

Based on
Tab**. 2**, young shotcrete (1 min to 24 h) can be subdivided into three classes based on the compressive strength development (Fig.). Shotcrete type J_1 is used for thin layers with no static requirements. Shotcrete type J_2 is used for faster applications. It is also used in the cases of low water pressure and faster excavation resistance requirements. For the applications in weak or squeezing rocks and under high water pressures shotcrete with strength characteristics of type J_3 should be used to provide immediate support.

Tab. 1: Material parameters of shotcrete

Shotcrete	
Young's modulus, E_c	10 000 – 50 000 MPa
Compressive strength, f_c	30 – 70 MPa
Tensile strength, f_t	3 - 7 MPa (~f_c/10)

Tab. 2: Increase of shotcrete strength with time

Age	Strength (MPa)
6 min	0.1 – 0.5
1 h	0.2 – 10
24 h	2 – 20
7 d	30 – 35
28 d	30 – 70

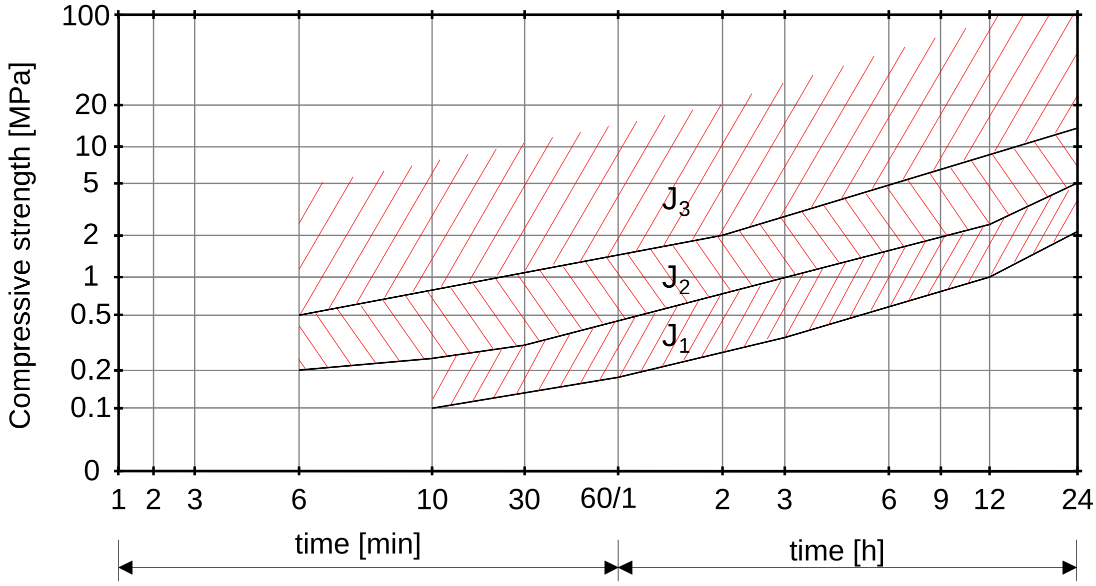

Fig. 8: Classification of shotcrete types based on the early strength level (Modified after (Girmscheid, 2000))

5 Adhesion between shotcrete and rock

The reinforcing effect of shotcrete is strongly depending on the adhesion between shotcrete and rock. Therefore, several aspects have to be considered, which have major influence on the adhesive strength:

- Mineral composition of the rock
- Roughness of the rock surface
- Scaling/cleaning of the rock surface
- Shotcreting technique and type
- Degradation of adhesion due to environmental, aging or dynamic effects

Typical adhesive strength (equivalent to tensile strength) values are shown in Fig. 9.

Especially degradation due to ice pressure and frost shattering are important. Ice pressure can reach several MPa due to the volumetric expansion of up to 9%. An additional effect of frost shattering is the migration of water in the frozen fringe between unfrozen and frozen rock.

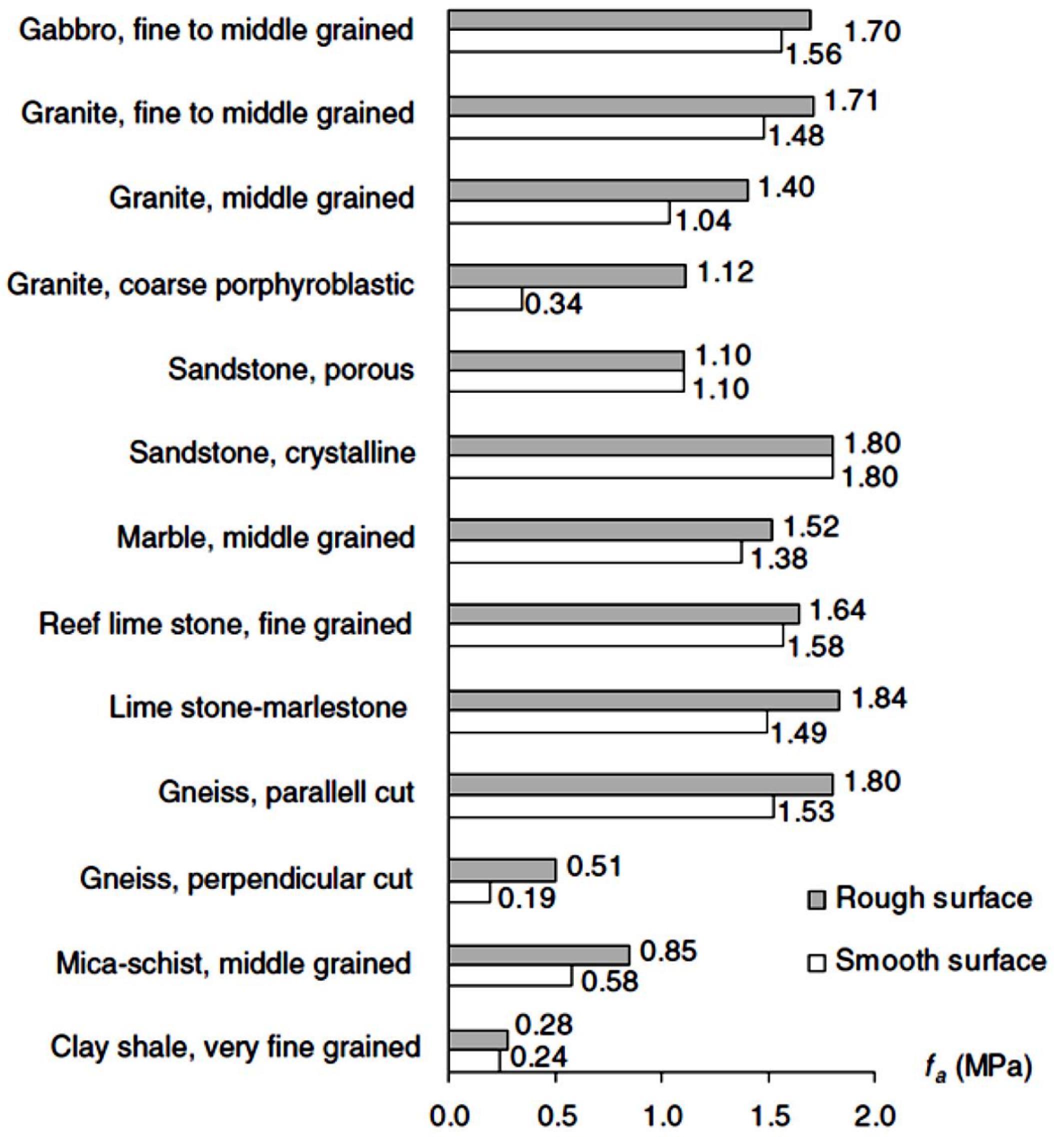

Fig. 9: Adhesive strength between shotcrete and rock on the early strength level (after Andren et al., 2020)

6 Reinforcement

For short near-surface tunnels or local support in mining shotcrete lining can be used as final support measure. In that case, final support is established by one work step. If the load-bearing capacity of shotcrete alone is not sufficient, additional reinforcement is necessary. There are different types of reinforcements to be used in combination with shotcrete:

- steel meshes
- steel fibres (fibre reinforced shotcrete)
- synthetic fibres (fibre reinforced shotcrete)
- anchors
- special elements

The characteristics and behaviours of these different types of reinforcements are explained below in detail.

6.1 Steel meshes

Steel meshes are often used as a regular reinforcement in combination with shotcrete lining or to stabilize locally damaged sections. These meshes can be applied typically in one or two layers (Fig. 10). Steel meshes are often used in combination with anchors or bolts to attach the meshes to the walls. In Germany and Europe, there is a standard to follow when using steel meshes in combination with concrete (DIN-488-4, DIN1045-1 and EN 1992). The meshes consist of ribbed steel bars having a diameter of between 6 – 10 mm. Depending on the requirements these bars have different ductility. A typical standard size of one mesh is 6 m x 2.30 m. There are two types of meshes:

- Q-meshes (quadratic layout and same bar diameter in both directions)
- R-meshes (rectangular layout and different bar diameter in both directions)

Q-mesh bars could serve as load bearing and load distribution bars (Fig. left). Longitudinal bars of R-meshes serve as load bearing bars and transverse bars (thinner) as load distribution bars (Fig. 11 right). Tab. **3** and

Tab. 4 show parameters of typical steel meshes. In the bar designation code, the initial capital letter indicates the type of mesh (i.e. Q or R) and the number that follows represents for the cross sectional area per meter (mm²/m) in the load bearing direction.

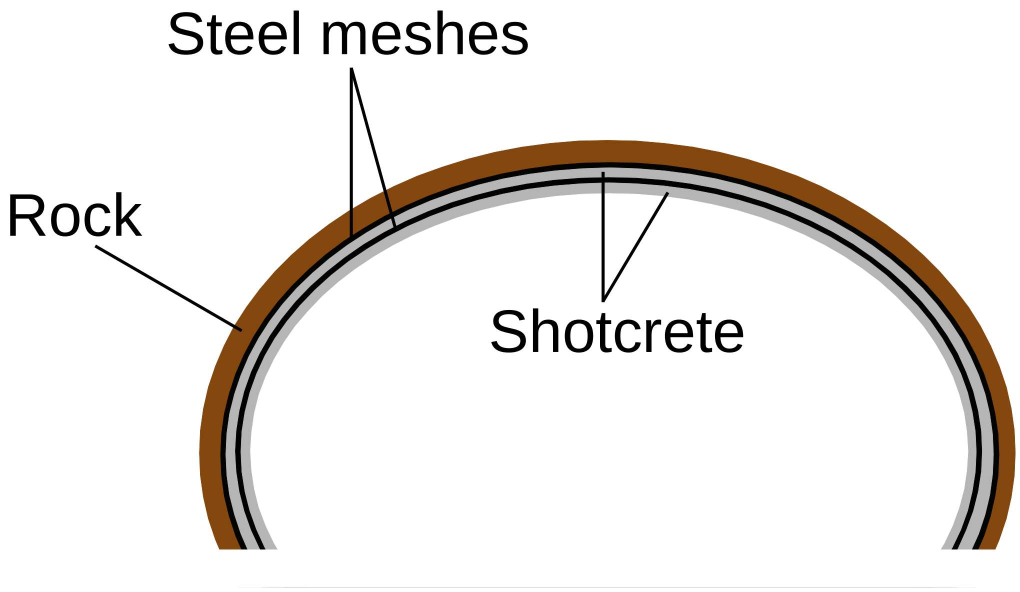

Fig. 10: Shotcrete application with two layers of steel meshes

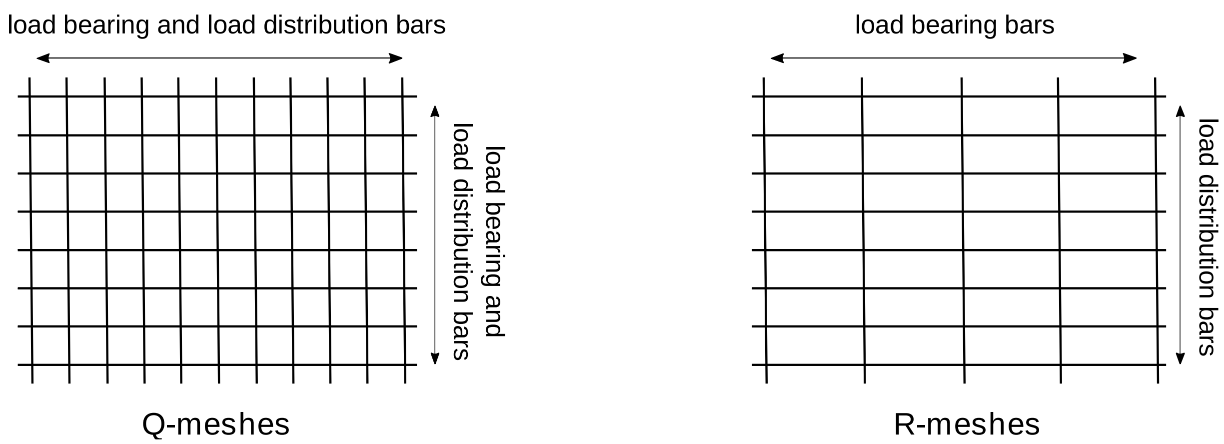

Fig. 11: Sketch of Q- and R-meshes with steel bars as reinforcement for shotcrete

Tab. 3: Customary designations and properties of Q-meshes (Modiefied after (Kämpfe, 2010))

Designation	Q188	Q257	Q335	Q424	Q524	Q636
Diameter of bars (transverse direction) [mm]	6	7	8	9	10	9
Diameter of bars (longitudinal direction) [mm]	6	7	8	9	10	10
Cross sectional area per meter [mm²/m] (transverse direction)	188	257	335	424	524	636
Cross sectional area per meter [mm²/m] (longitudinal direction)	188	257	335	424	524	636

Weight [kg/m²]	3,02	4,12	4,38	6,12	7,31	9,36

Tab. 4: Customary designations and properties of R-meshes (Modiefied after (Kämpfe, 2010))

Designation	**R188**	**R257**	**R335**	**R424**	**R524**	**-**
Diameter of bars (transverse direction) [mm]	6	7	8	9	10	-
Diameter of bars (longitudinal direction) [mm]	6	6	6	8	8	-
Cross sectional area per meter [mm²/m] (transverse direction)	188	257	335	424	524	-
Cross sectional area per meter [mm²/m] (longitudinal direction)	113	113	113	201	201	-
Weight [kg/m²]	2,43	2,99	3,64	4,87	5,49	-

6.2 Synthetic fibre reinforced shotcrete

Synthetic fibres can improve several properties of shotcrete. There are two types of synthetic fibres:

- synthetic macro fibres
- synthetic micro fibres

Synthetic macro fibres (Fig. 12 left) have lower Young’s modulus than steel fibres. They are very effective in preventing cracks in the shotcrete and reducing the crack width. The shotcrete becomes more ductile and shows better corrosion protection when these fibres are used.

Fig. 12: Synthetic macro-fibers (left) and micro-fibers (right): company material from Sika.

The Young's modulus of synthetic micro-fibres (12 right) is even lower than those of synthetic macro-fibres. This type of fibres can reduce the shotcrete shrinkage in the early stage of the hydration process. Tab. **5** shows the necessary amount in shotcrete, the length and the diameter of both types.

Tab. 5: Data for synthetic fibers

	Macro-fibres	**Micro-fibres**
Amount	3 – 10 kg/m³	0.6 – 2 kg/m³
Length	40 – 60 mm	5 – 15 mm
Diameter	0.4 – 1mm	0.015 – 0.2 mm

The application of synthetic micro-fibres is beneficial when there is a potential for heat exposure, e.g. fire, (Stelzner, 2015). If the temperature increases up to 160 °C, the polypropylene fibres melt inside the concrete forming new cavities, which help to release additional pressures. Therefore, explosive spalling of concrete can be reduced.
In the silica fume technology a combination of silica fumes and concrete additives is used, similar to synthetic polymers and superplasticizers. This approach can be used for both, wet- and dry-mixes. The benefits of silica fume are described in chapter 2.4.1.
By using synthetic polymers in shotcrete, the following characteristics of the concrete can be expected:

- better processing
- higher density
- higher adhesive tensile strength
- increased chemical resistance
- improved thermal behaviour
- improved quality of thin lining
- higher early/final strength

This type of reinforcement is often used for the renovation of tunnels. After 28 days this type of reinforced shotcrete shows a UCS in the range of 44 – 61 MPa. Fig. 13 shows the variation of tensile strength against the deformation for shotcrete with different amount of fibres. Concrete without fibres shows a marked softening after the peak strength (brittle behaviour). Increasing the amount of fibres leads to a more ductile behaviour and even partial hardening in the post-failure region. Synthetic and steel fibres are important elements to improve the ductility and strength of shotcrete.

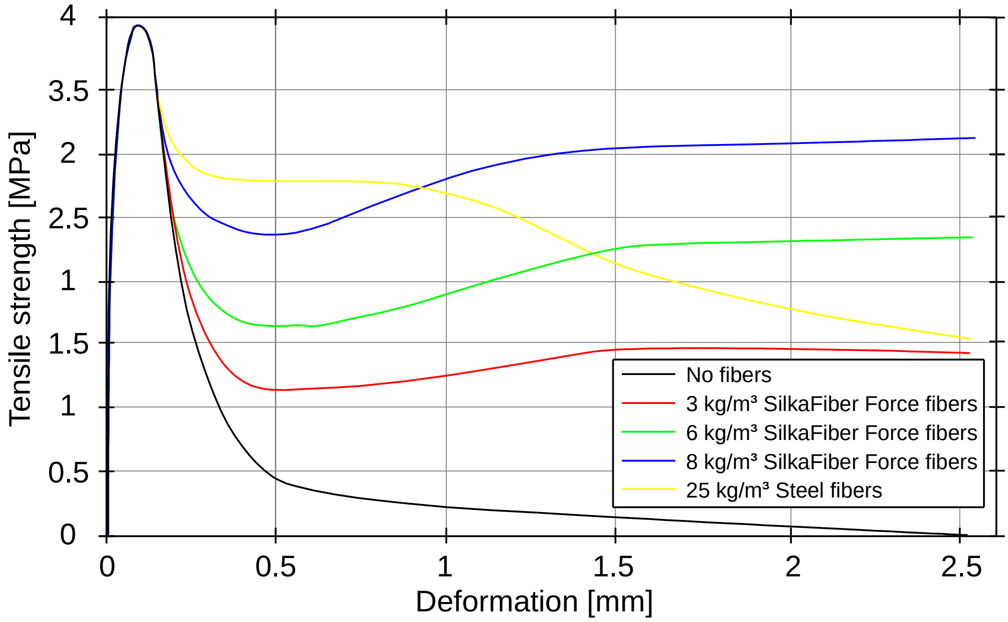

Fig. 13: Tensile strength versus deformation: plate loading tests on shotcrete with different amount of fibers (Modified after (Sika Österreich GmbH, 2015))

6.3 Steel fibre reinforced shotcrete

Steel fibres are often used as reinforcement of shotcrete. To select the appropriate shape of the steel fibres (Fig. 14), their tensile strength and length-to-diameter ratio have to be considered in line with the design requirements. The following improvements of the shotcrete can be expected by application of steel fibres:

- increased ductility
- higher compressive and tensile strength
- reduced crack formations

The amount of steel fibres in the final concrete mix should be in the range of 30 – 90 kg/m^3. Because of the loss by rebound during the application of shotcrete, 35 – 120 kg/m^3 of fibres should be included in the base mixture.
Steel fibres with a high length-to-diameter ratio are essential for efficient reinforcement. However, the processing is difficult with such steel fibres. In current practice, bundles of 30 - 50 fibres are added to the shotcrete mix. The wrapping of these bundles is water- soluble, which leads to a dispersion of the fibres in the mixture at the beginning of the mixing process. Steel fibre reinforced shotcrete has economic benefits if the required project specific static values are equivalent to the use of shotcrete lining with one- or multi-layered reinforcements (steel meshes). It can also be applied as a subsequent reinforcement. Fig. 15 displays the variations of compressive strength against the deformation for shotcrete with different contents of steel fibre reinforcements (plate loading test).

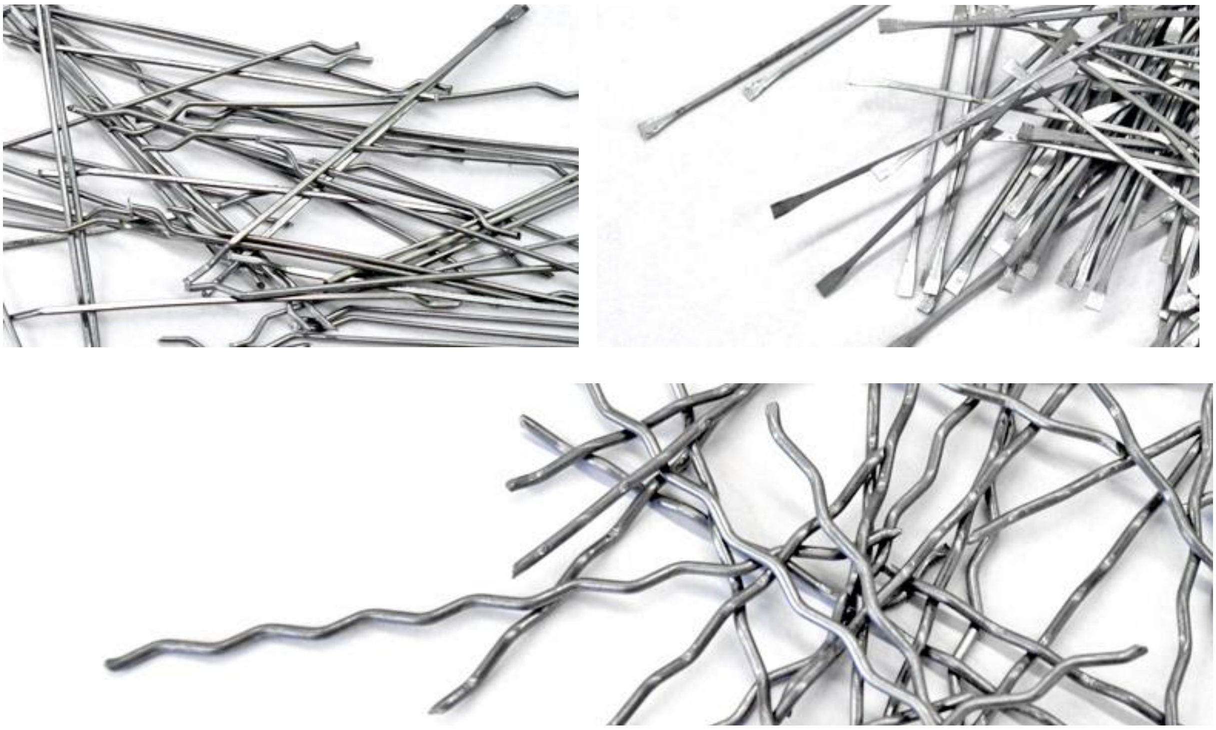

Fig. 14: Different steel fibre products (hooked end fibre (left), flat end fibre (right), undulated fibre (bottom): company material from AcelorMittal

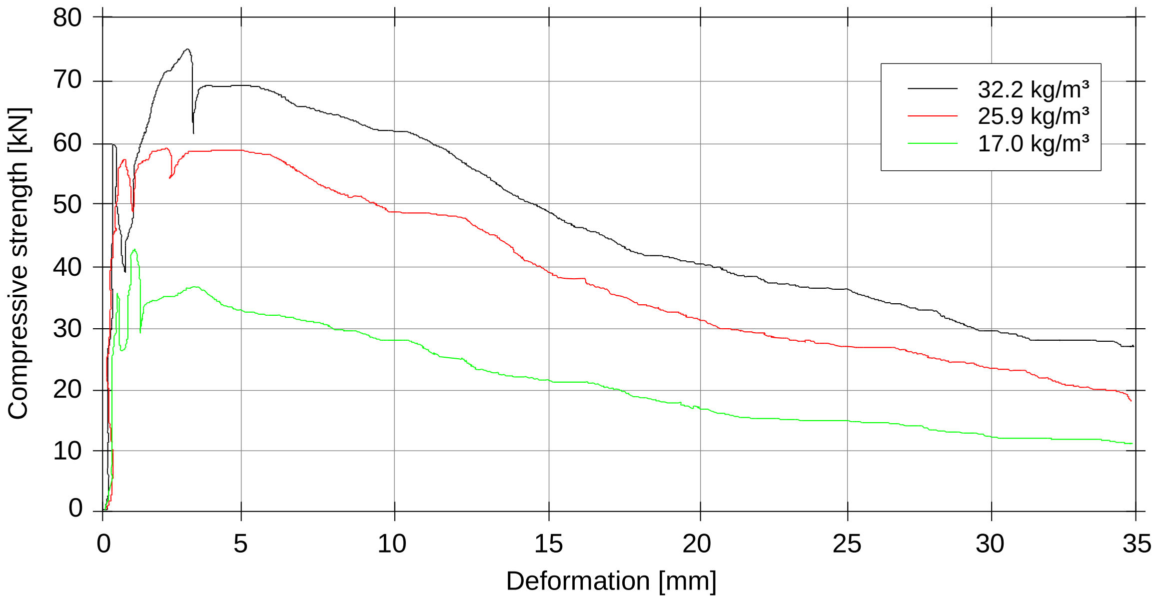

Fig. 15: Compressive strength versus deformation: plate loading tests on shotcrete with different amount of steel fibers (Modified after (J. Höfler, 2004))

Tab. **6** shows experimental results for Young's modulus and Poisson's ratio obtained from uniaxial compressive tests on three steel fibre (30 kg/m³) reinforced shotcretesamples at different curing times. The UCS increases with time, but elastic properties (Young's modulus and Poisson's ratio) do not show a systematic variation.

Tab. **7** shows experimental results obtained from triaxial compression tests on three steel fibre reinforced shotcrete samples. The shear strength parameter cohesion increases with time. Friction and dilatation angles do not show significant changes.

Tab. 6: Uniaxial compressive test on steel fiber reinforced shotcrete samples (Saw et al. 2009)

Sample No.	Curing (days)	Compr. Strength (MPa)	Elastic properties	
			Young's modulus (MPa)	Poisson's ratio
			E	v
1	1	16.2	-	-
2	1	18.1	14000	0.42
3	1	18.3	11000	0.19
1	3	23.4	-	-
2	3	18.3	12000	0.28
3	3	22.9	8000	0.16
1	7	28.5	-	-
2	7	23.2	16000	0.22
3	7	25.7	14000	0.17
1	28	32.8	14000	0.21
2	28	27.2	17000	0.29
3	28	31.5	10000	0.15

Tab. 7: Triaxial test results of steel fiber reinforced shotcrete samples (Saw et al. 2009)

Sample No.	Curing (days)	Shear strength				Average dilation angle [°]
		Peak		Residual		
		Cohesion [MPa]	Friction angle [°]	Cohesion [MPa]	Friction angle [°]	
1	1	4	38	-	-	-
2	1	4	45	2	45	8
3	1	5	36	5	32	13
1	3	5	40	3	42	-
2	3	4	40	3	41	10
3	3	6	38	-	-	12
1	7	8	35	5	35	-
2	7	5	40	4	41	10
3	7	6	40	5	38	10
1	28	8	38	7	18	12
2	28	11	18	-	-	12
3	28	8	38	-	-	10

6.4 Anchors

Anchors can be used in combination with shotcrete to increase strength and stability. In that case, a composite system of three elements: shotcrete, anchors and rock mass is created. This composite system can be further qualified by the use of steel meshes in combination with anchors (Fig. 16). The load-bearing capacity can be adjusted by appropriate choice of shotcrete thickness as well as type, amount, length and positioning of anchors.

In case of squeezing rock, buckling and spalling of shotcrete might occur. To reduce the damage of shotcrete, small slots (gaps) inside the shotcrete are created and the remaining shotcrete parts are fixed with anchors. If pre-stressed anchors are used, the pre-stress level can be adjusted according to in-situ measurements. With time, the slots inside the shotcrete tend to close due to the stress redistributions inside the rock mass and subsequent displacements. When the rock mass – shotcrete – anchor system has reached an equilibrium state and the deformation rates are close to zero, the deformed slots are finally closed with shotcrete.

Fig. 16: Shotcrete shell with anchor and steel mesh reinforcement

6.5 Special elements

In squeezing rocks, plastically deformable steel elements can be inserted into special fabricated gaps in the shotcrete lining. These elements are called **l**ining **s**tress **c**ontrollers (LSC). Fig. 17 shows a schematic diagram of such a LSC. In response to the normal stress, the LSC will undergo buckling before the shotcrete is damaged. An example of using these elements is the Semmering pilot tunnel project. Fig. 18 (left) displays the actual load-deformation curve along with the corresponding theoretical curve of a LSC (Semmering pilot tunnel project). Fig. 18 (right) shows the deformation of the LSCs against time. A FEM model (**f**inite **e**lement **m**ethod) was used for the calculation of axial forces and shear stresses of the shotcrete (Fig. 19 and 20). After nine days, the stresses in the shotcrete have nearly disappeared due to the deformation of LSCs and triggered stress redistributions inside the rock mass. Finally, the gaps can be filled with shotcrete.

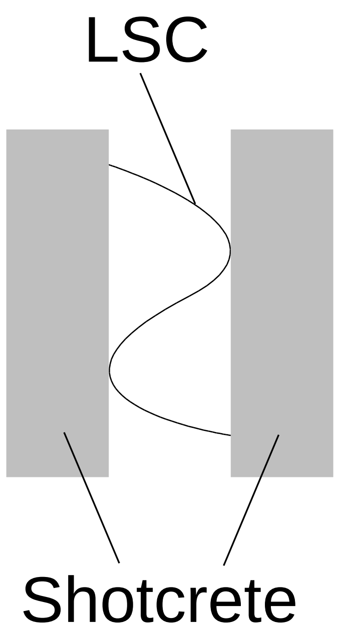

Fig. 17: Shematic illustration of a LSC in a gap in the shotcrete lining

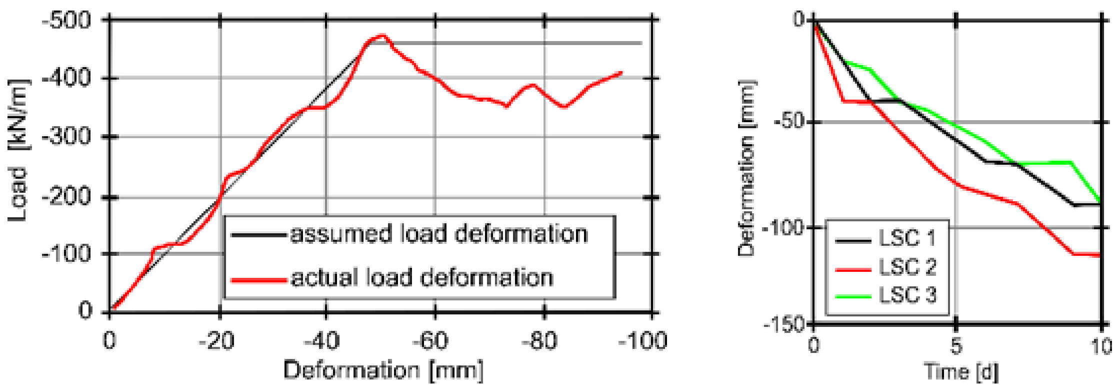

Fig. 18: Left: Experimentally obtained relation between applied deformation of LSC and resulting load (Semmering pilot tunne); **Right:** Deformation of LSCs (in-situ measurement in Semmering pilot tunnel); (Modified after (Lackner et al. 2002))

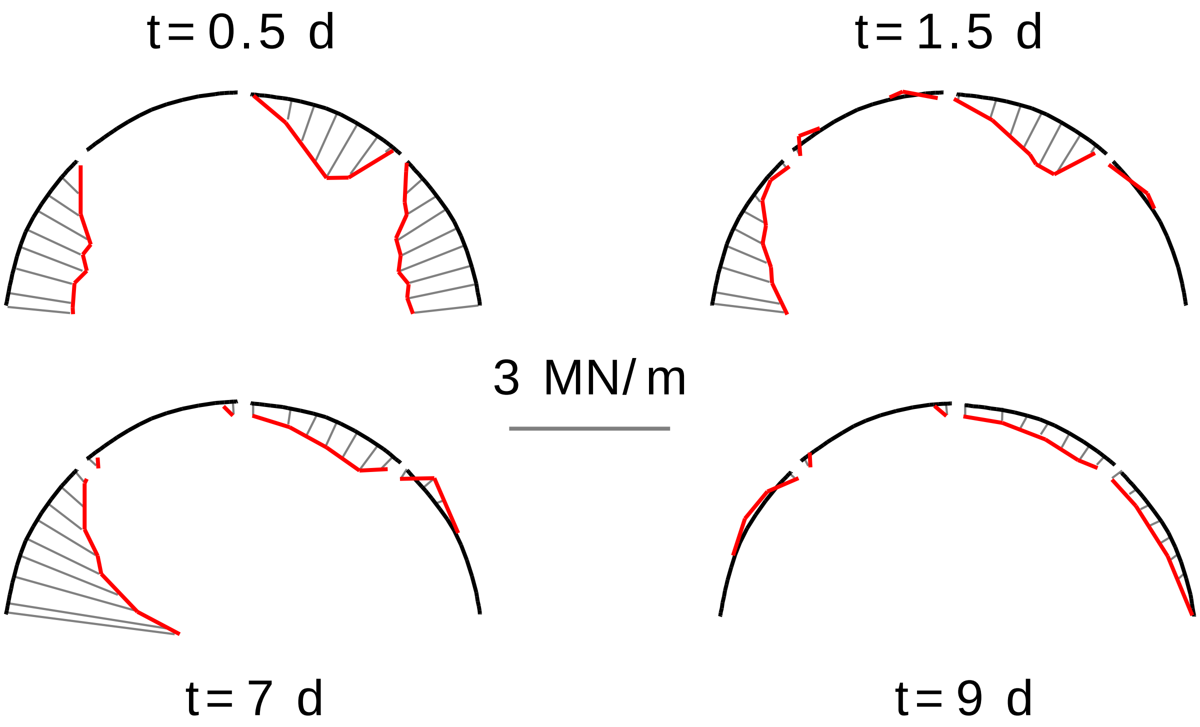

Fig. 19: Distribution of axial forces at different time intervals (Semmering pilot tunnel) (Modified after Lackner et al. 2002)

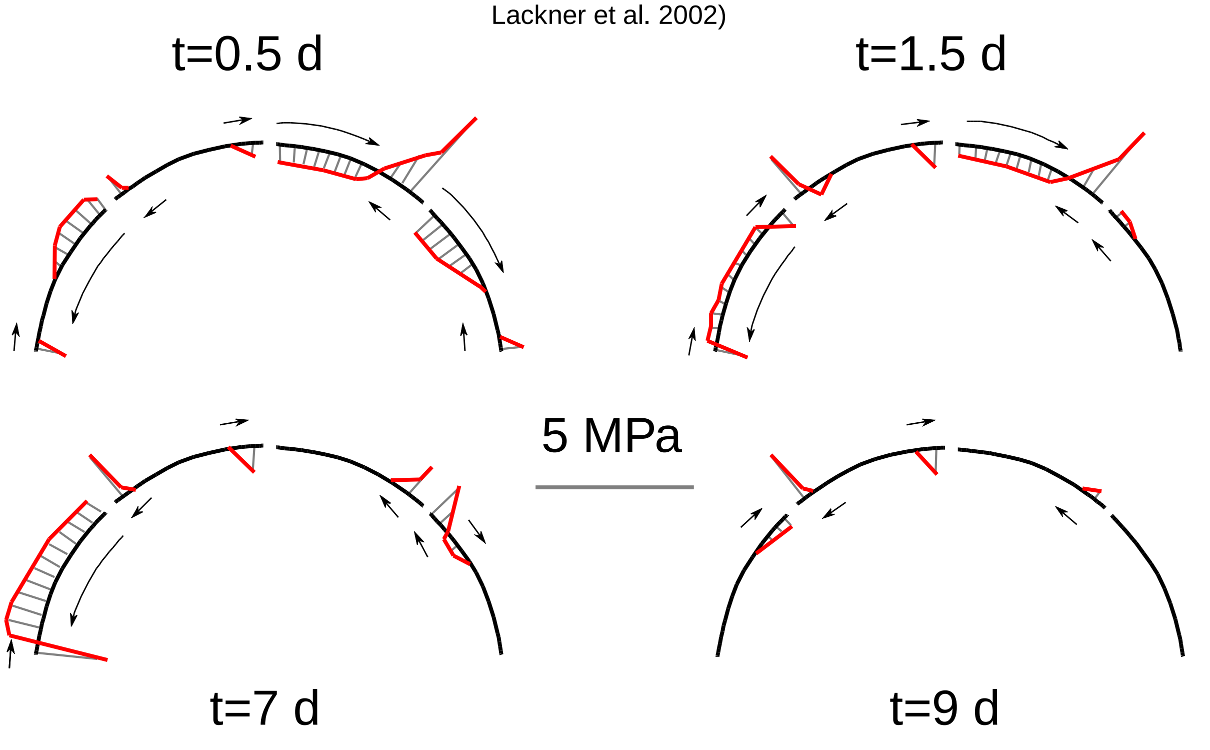

Fig. 20: Distribution of the shear stresses along the shotcrete rock interface at different time intervals (Semmering pilot tunnel) (Modified after Lackner et al. 2002)

7 Behaviour under different temperatures

The ambient temperature has significant influences on the behaviour and properties of shotcrete. If the ambient temperature is 0°C or less and the concrete is frozen the strength can be reduced by 20 – 50 %. The strength can further be reduced by another 5 – 10% by subsequent freezing events. The longer the freezing continues more the damage occurs. Between 28 and 90 days the concrete still hardens and this hardening process is supported if the temperature is above 0°C.

Early strength of shotcrete can be increased by 5 – 10 % if the temperature is between 50°C and 60°C. However, the final strength will be approximately 25% less in this case. According to the European guidelines for shotcrete (EFNARC, 1997) the temperature of the mixture should not be below 5 °C and not above 35 °C.

8 Shrinkage behaviour and post-treatment

The sprayed concrete experiences a faster drying under ventilation. This leads to higher shrinkage resulting in new crack development. These cracks affect the durability and density of the concrete. This effect is more pronounced in thin-layered shotcrete. A possible solution is to keep the shotcrete wet during the first seven days after spraying. If the prevailing humidity is over 70%, no post-treatment is necessary. Some issues arise when spraying shotcrete on already existing concrete surfaces: adhesion problems and the problem of transferring stresses between old and new shotcrete layers due to their different creep behaviours.

The strength development of shotcrete can be monitored using different methods at different stages. Fig. 21 shows the typical compressive strength development of shotcrete. The graph depicts three phases of compressive strength development. Tab. **8** shows corresponding measuring methods.

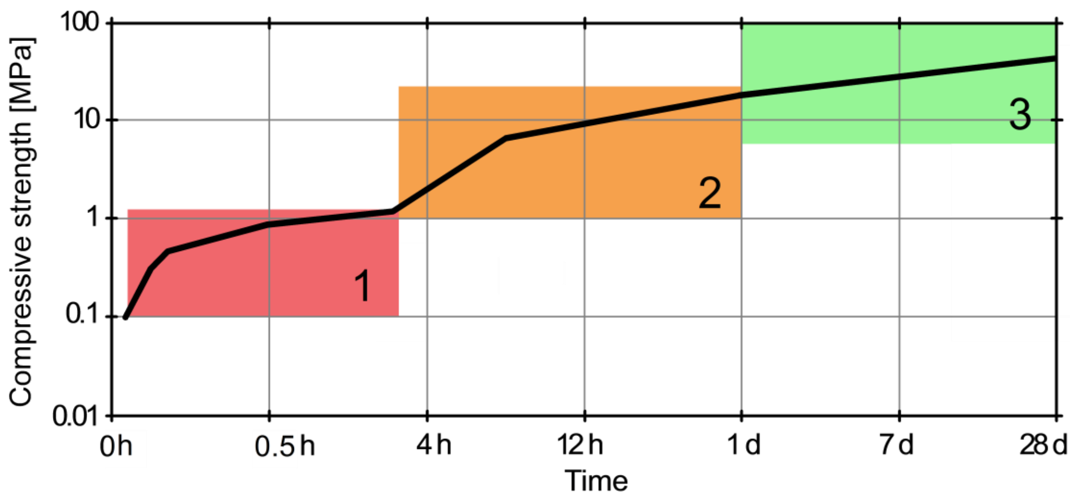

Fig. 21: Compressive strength versus time (Modified after (Sika Schweiz AG, 2012))

Tab. 8: Methods to check the shotcrete lining in tunnelling (Sika Schweiz AG, 2012)

Phase (see Fig. 19)	Method	Equipment	Compr. strength [MPa]	Time
Early strength (1)	Intrusion with needle	Penetrometer	up to 1.5	0 – 3 h
Early strength (2)	Threaded bolt	Bolt-firing tool	1 - 20	3 – 24 h
Final strength (3)	Core drilling	Pressure strength test	5 - 100	1 – 28 d

9 Numerical simulation of shotcrete

Besides the classical bedded-beam models, nowadays, most of the other numerical methods are used for the dimensioning of shotcrete. Within numerical models the shotcrete can be represented by either 2-dimensional beam-elements and 3-dimensional shell elements, or volume elements in case of thicker shotcrete. Fig. 22 shows a 3-dimensional tunnel model with several excavation steps including the installation of shotcrete.

Dimensioning of shotcrete is based mainly on the determination of shotcrete loading in terms of moments and axial forces. Fig. 23 shows a simplified 2-dimensional example of a horseshoe-shaped tunnel with thin shotcrete lining using beam elements directly attached to the grid. Alternative to the direct attachment an interface can be installed between lining and rock mass to take into account the interaction in more detail.

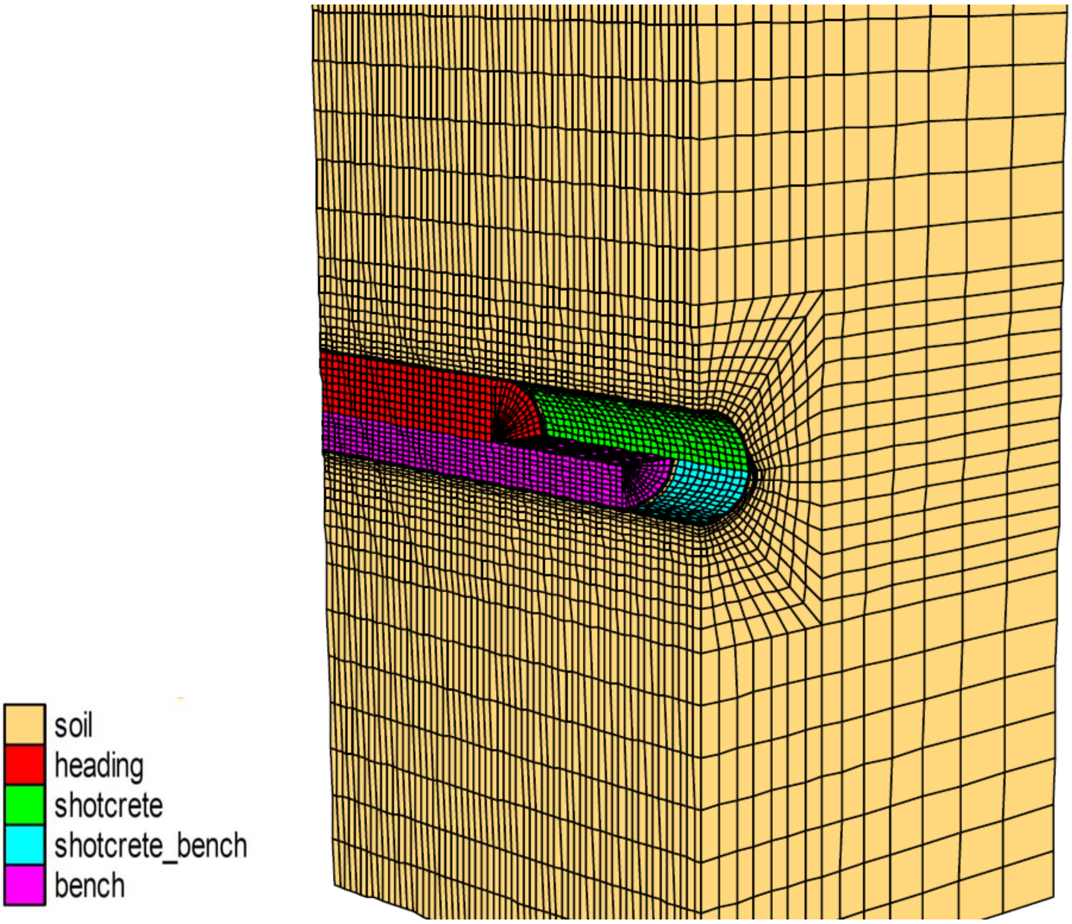

Fig. 22: 3-dimensional numerical tunnel model (shotcrete is represented by shell elements)

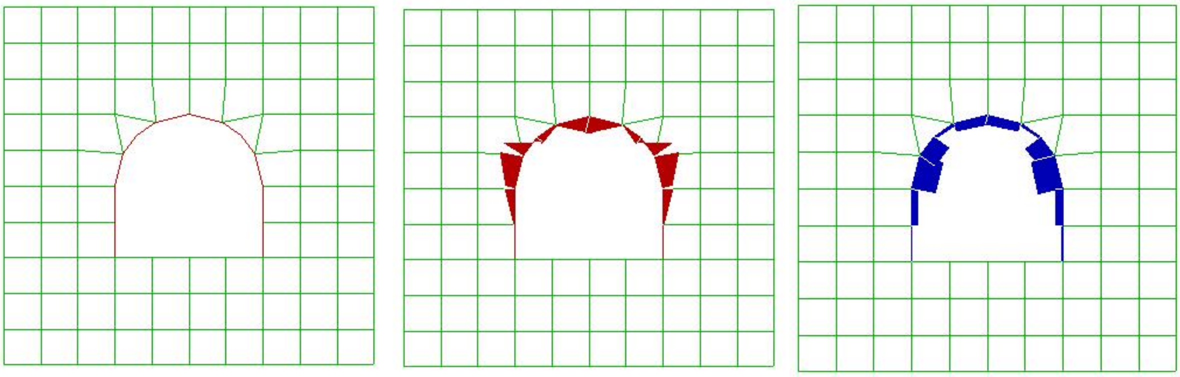

Fig. 23: Simplified example of shotcrete lining (from left to right: numerical mesh (green) with beam elements (red) representing the shotcrete; moments (red) inside shotcrete; axial forces (blue) inside shotcrete)

Konietzky et al. (2001) describe a numerical approach to simulate the hydration process of concrete including the time-dependent development of strength and stiffness. Fig. 24 illustrates the time-dependent hydration process, which leads to increasing stiffness and strength. Such a modelling approach allows to simulate (predict) the time-dependent behaviour of the interaction between rock mass and shotcrete.

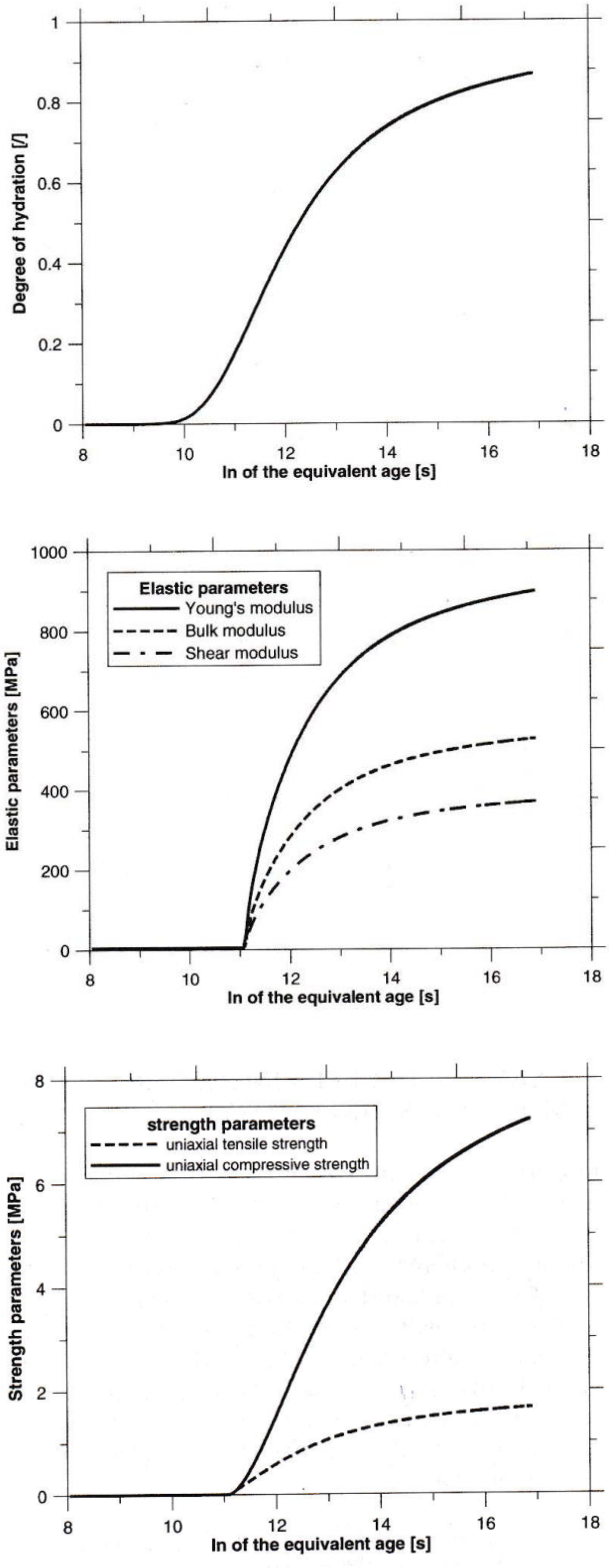

Fig. 24: Evolution of stiffness and strength of concrete versus time (Konietzky et al., 2001)

10 Monitoring

The behaviour of the shotcrete in combination with other support measures and in interaction with the rock mass is typically monitored via different methods:

- Measurement of displacements inside the opening (convergence measurements), for instance via laser or optical devices
- Measurement of stresses via pressure cells (inside the shotcrete or at the interface between shotcrete and rock mass)
- Measurement of deformation via extensometers covering the shotcrete and the rock mass behind

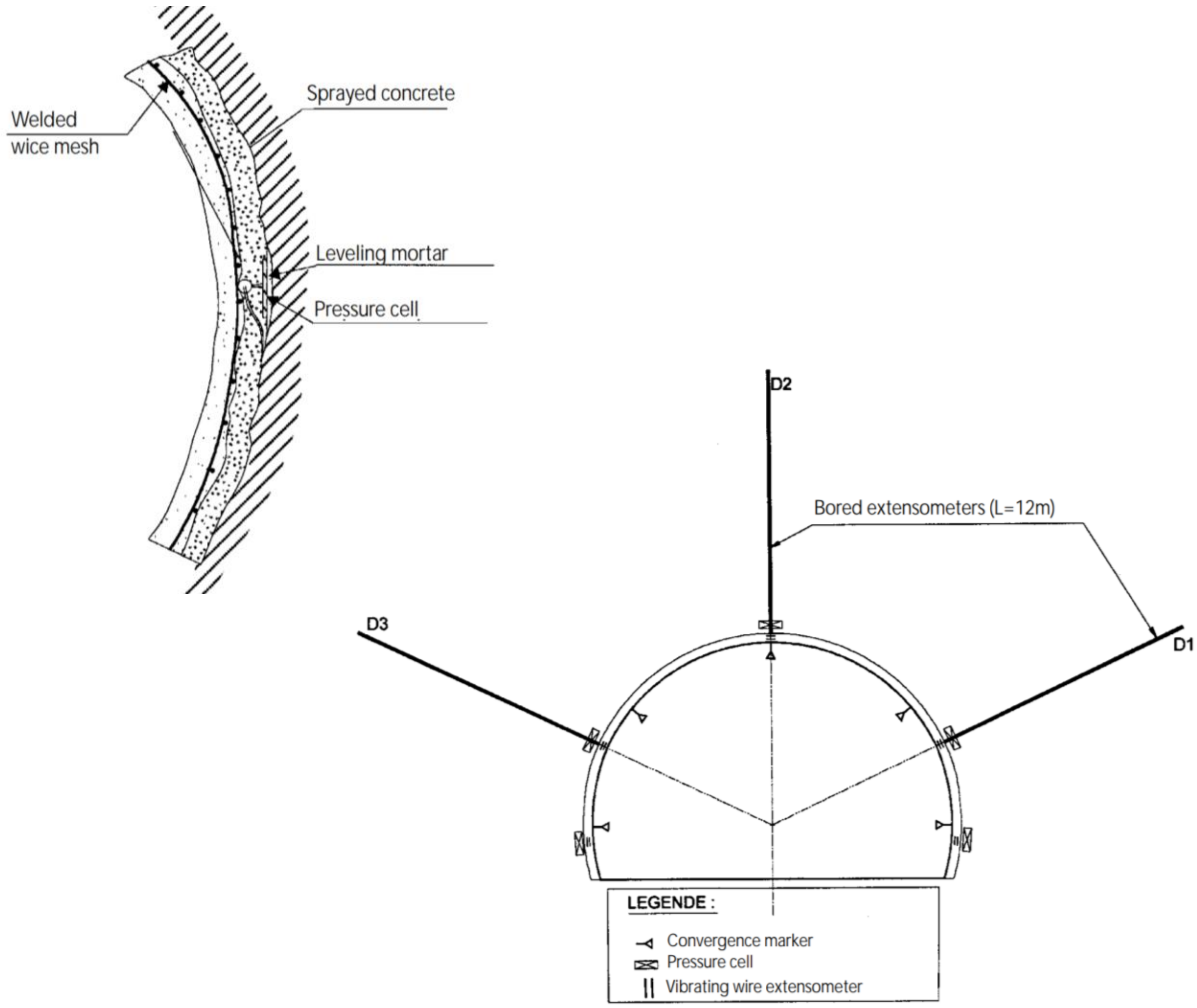

Fig. 25: Typical set-up for monitoring sprayed concrete in tunnels (AFTES, 2000)

11 References

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