TYTRO®

Technical Bulletin 1

TYTRO®

SHOTCRETE SYSTEM

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1. TYTRO® Shotcrete System

GCP Applied Technologies introduces its state-of-the-art TYTRO® shotcrete system to help customers reduce shotcrete operating costs, minimize excavation downtime, achieve desired technical properties, and meet safety standards. GCP provides service and technical support to help customers integrate our advanced TYTRO® technologies into their shotcrete batching and ground support operations for increased safety, efficiency, and productivity.

TYTRO® shotcrete system, an advanced full shotcrete system for ground support, has been formulated to achieve faster and increased early strength, enhanced bond to rock substrate, increased pumpability and sprayability characteristics, larger thickness build-up, and minimum rebound and dust.

TYTRO® shotcrete system is composed of the following additives:

- **High-range water-reducing admixture (HRWR)**

  TYTRO® WR polycarboxylate ether-based high-range water-reducing admixtures for shotcrete provides superior flow and workability, and maximize strength performance by allowing lower water-to-cementitious materials ratio (w/cm).

- **Hydration control admixture**

  TYTRO® HC cement hydration control admixture allows optimal logistical operations by extending the working life of shotcrete up to 72 hours.

- **Air—entraining admixture**

  TYTRO® AE is an air-entraining admixture for use in shotcrete mixes to increase resistance of structures that are exposed to freezing and thawing cycles.

- **Set accelerators**

  TYTRO® SA series are the latest generation of alkali-free accelerators that provide high early strength at low dosage rates without compromising long-term strength development.
  Main advantages provided by TYTRO® SA are:

  - Highly active formulation for lowest dosages
  - Accelerated hydration, reduced time of setting that speeds up the hardening process to allow for earlier finishing
  - Increased adhesion and rapid early age strength development
  - Increased layer thickness for overhead work
  - Reduced rebound and dust
  - Non-alkaline formulation for healthier work environment

It is well known that set accelerators are influenced by cement chemistry. TYTRO® SA series is adjusted according to cement sensitivity and project specifications.

A large scale of field experiments was conducted to compare the performance of TYTRO® SA and another alkali-free accelerator available in the market. Figure 1 shows that TYTRO® SA is very effective in providing early strength development.

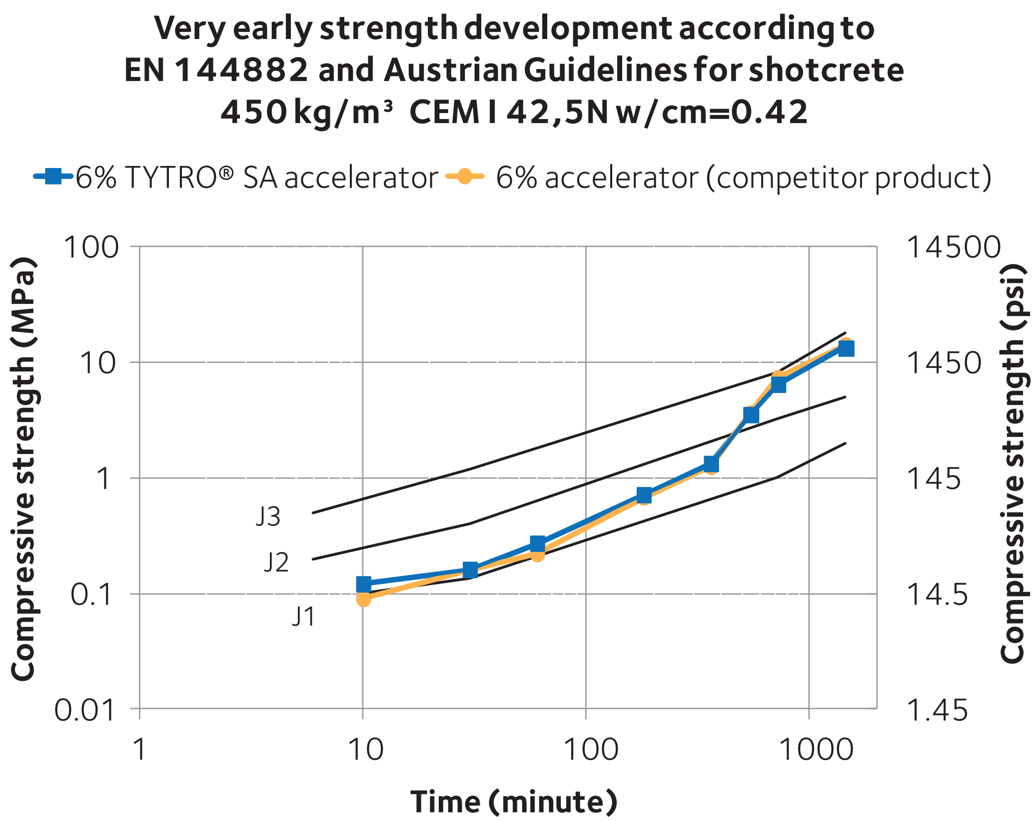


Figure 1. The performance comparison of TYTRO® SA accelerator and a competitor product.

- **Rheology control admixture**

  TYTRO® RC is a rheology control admixture that is added to shotcrete to improve cohesion and sprayability of the mix and increase high early strength while minimizing the rebound and dust. Detailed information about TYTRO® RC will be provided in the following sections.

- **Rheology modifying admixture**

  TYTRO® RM is a rheology modifying admixture that is based on a high molecular weight polymer and designed to improve cohesion and pumpability of shotcrete.

- **Macro-synthetic fibers**

  STRUX® BT50 is a macro-synthetic fiber that is added to shotcrete to provide toughness, impact, and fatigue properties. In addition to its superior crack control and resistance, STRUX® BT50 also eliminates corrosion issues or safety concerns associated with the use of steel fibers.

1.1 Synergetic Benefits of Using the TYTRO® Admixture Series

The TYTRO® system is designed to be used as a whole package as TYTRO® admixtures are specifically formulated to provide synergetic benefits on overall shotcrete performance when used together, and are highly compatible with each other.

The combination of TYTRO® WR and TYTRO® HC products provides enhanced rheology and extended slump life to meet the project needs and requirements. Testing was conducted to evaluate the combined effect of TYTRO® WR superplasticizer and TYTRO® HC hydration control admixtures on slump retention life of a mix containing 5% silica fume with the total cementitious materials content of 450 kg/m^3 at a w/cm of 0.40. As shown in Figures 2 and 3, when TYTRO® WR and TYTRO® HC were combined at the selected dosages, slump and slump flow of the tested mix were retained up to 8 hours without further addition of water, superplasticizer, or retarder.

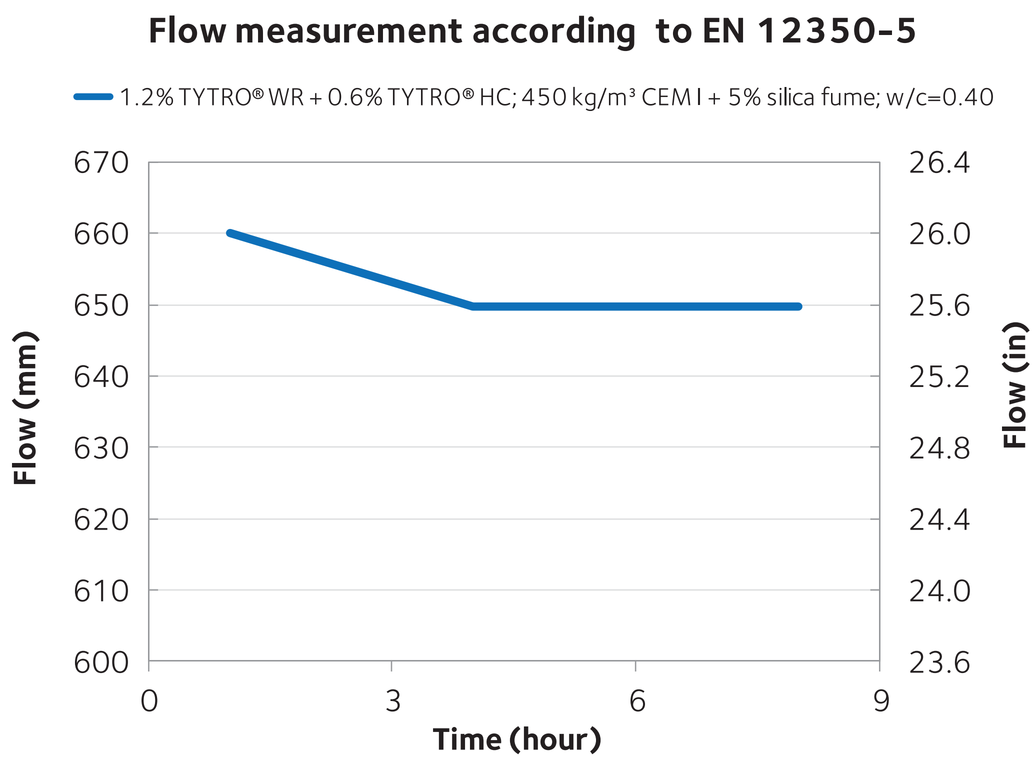


Figure 2. The synergetic benefit of TYTRO® WR and TYTRO® HC combination on flow.

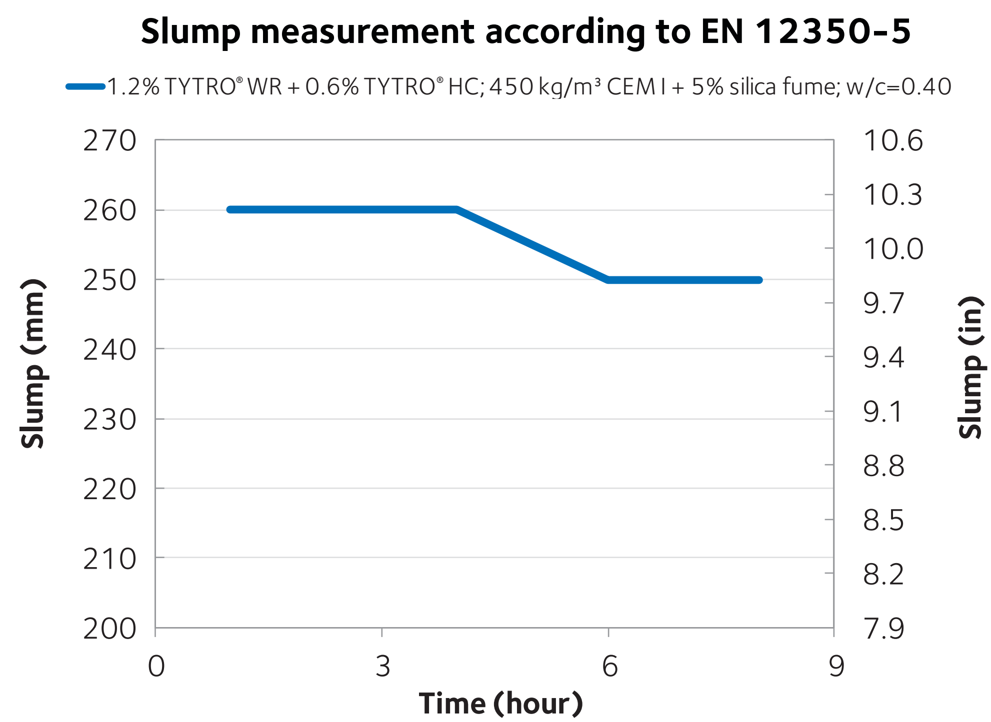


Figure 3. The synergetic benefit of TYTRO® WR and TYTRO® HC combination on slump retention.

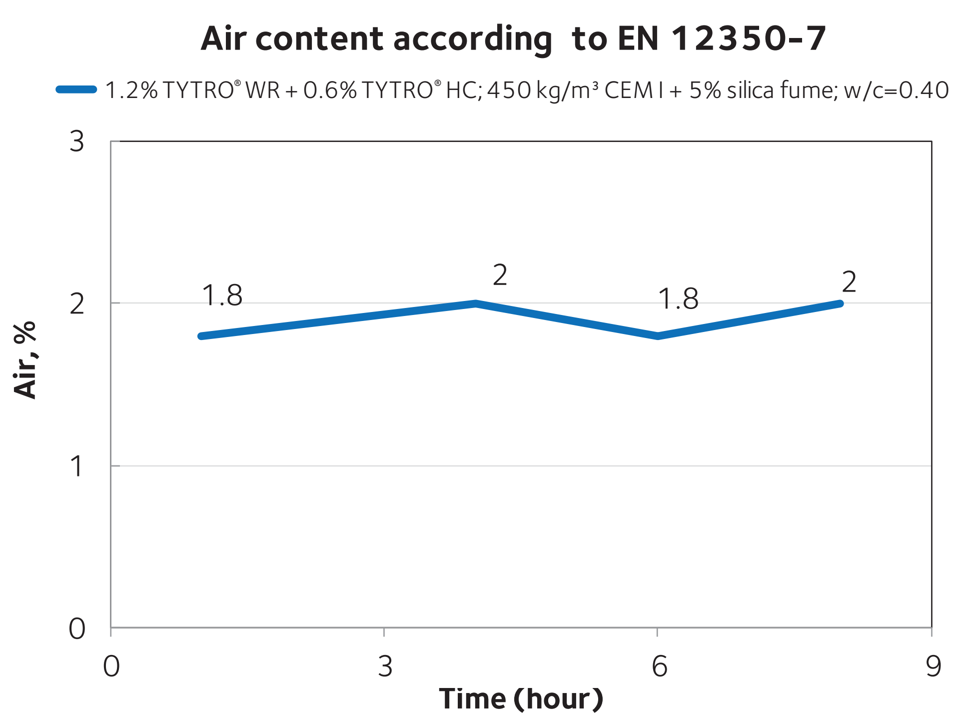


Figure 4. . The synergetic benefit of TYTRO® WR and TYTRO® HC combination on air content.

2. Application of TYTRO® RC

2.1 BACKGROUND

In order to improve the durability of shotcrete, silica fume is commonly added as a supplementary cementitious material. Due to its small particle size and pozzolanic reactivity, silica fume increases the compactness of concrete, reduces permeability, and increases the ultimate strength. In addition, the use of silica fume also facilitates pumping of concrete, thereby allowing higher yields. However, there are a number of problems and limitations associated with the use of silica fume. First limitation is due to the variability of the purity of SiO2 which results in a significant variation in the performance of silica fume in shotcrete. Silica fume is a waste product of silicon and ferro-silicon production. Therefore, it contains impurities such as carbon of various sources that are responsible for the dark color of the silica fume (SiO2 is white). These impurities are generally organic compounds that may cause unwanted side effects such as delays in concrete setting, and increased water and admixture demand. Another limitation, especially for shotcrete, is delaying the reaction to generate CSH gels which results in a poor initial mechanical strength development.

The main challenge when using silica fume is related to the handling of this material. Silica fume that is stored in special silos can be added into the concrete during mixing with automated dispensing systems. In this case, the silo must be equipped with a complete set of vibrators because silica fume tends to cake in the silo, thereby making it difficult to discharge. The silo in question must also be kept watertight as moisture in silica fume is hygroscopic and tends to form agglomerates. As an alternative solution, silica fume may be manually added on the aggregates belt; however, it requires extraordinary craftsmanship and also exposes potential risks and safety concerns. Other possibility to supply silica fume is in slurry form. These suspensions are normally stable for short period of time and then require some extra agitation in order to avoid any problems with settlement and sedimentation of active particles. These issues with settlement can lead to a very short shelf life. Due to these limitations, there is a need to replace silica fume with another substance that can provide similar performance while avoiding the challenges associated with the use of silica fume.

TYTRO® RC is an alternative to silica fume that is based on a synthetic silica suspension which has a higher fineness and purity than silica fume, and is highly reactive. TYTRO® RC offers mostly superior benefits and effects than silica fume while eliminating its problems and limitations. TYTRO® RC is a liquid product free of chemical hazards that can be handled the same way as a traditional liquid admixture is handled. Therefore, problems associated with handling silica fume are completely avoided. In addition, TYTRO® RC is more cost-effective than silica fume due to its high specific surface area requiring a smaller amount of replacement to provide the desired performance than silica fume.

2.2 SYNERGETIC BENEFITS OF USING THE TYTRO® ADMIXTURE SERIES

Physical Properties of Silica Fume vs TYTRO® RC

Silica fume (and derivatives based on the reactivity of the oxide, amorphous silica) is a pozzolanic material that, unlike cement, it does not react with water but reacts with Ca(OH)2 (portlandite) released during cement hydration. Since silica fume reacts with this by-product of cement hydration, compared to a mix containing only portland cement, water demand is increased as a result of surface wetting due to its small particle size. Thus, the reactivity of the silica fume is directly related to its particle size which ranges between 200 to 1000 nm.

TYTRO® RC is suspension of fine amorphous nanometric silica particles in a liquid phase. It fulfills the requirements for concrete admixtures according to EN 934-2.T4 (water retaining) and EN 934-2.T13 (viscosity modifier). TYTRO® RC is non-porous, spherical, non-aggregated, and dispersed in water free from chlorides and low alkali. There are several grades of TYTRO® RC available which are selected based on the surface area of silica fume, mix design (i.e. type and dosage of fiber), project specifications (i.e. durability or later age strength), specific needs (i.e. very early strength), and customer issues (i.e. low quality / variability of raw materials). The properties for TYTRO® RC series are summarized in Table 1.

Table 1. The properties of TYTRO® RC

Key properties	TYTRO® RC series (several grades available)
Diameter (nm)	7 to 22
Surface area (m^2/g)	120 to 380
Total solids (%)	30 to 50
Specific gravity (g/cm^3)	1.2 to 1.4
Dosage rate (% owc)	0.5 to 2.0

Quality of Silica Fume vs TYTRO® RC

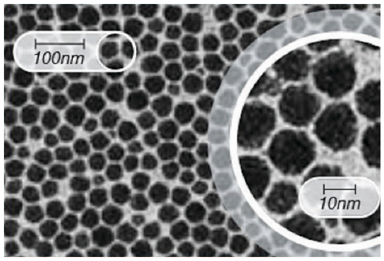
Since silica fume is a by-product, its particle size and distribution has a high variability as opposed to TYTRO® RC which goes through specific industrial processes to be deliberately composed of uniform particle size distribution. In addition, the purity of TYTRO® RC is over 99% in SiO2 whereas silica fume consists of impurities which results in reduced quality. This is because TYTRO® RC is subjected to intense quality control, and high quality of raw materials is used for its manufacturing. In addition, particle size of TYTRO® RC is approximately ten times smaller than the size of a silica fume particle, thereby resulting in significantly higher specific surface area. As a result, TYTRO® RC requires much smaller dosage rate than silica fume to meet the target shotcrete properties.

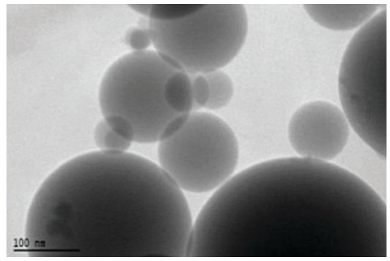
Table 2 and Figure 5 summarize the comparison of properties between silica fume and TYTRO® RC.

Table 2. The comparison of properties between silica fume and TYTRO® RC

Silica fume	TYTRO® RC series
Powdered product	Liquid product
Variable particle size and distribution	Uniform particle size & distribution
Particle size: 200 and 1000nm	Particle size 7 to 22nm (various grades available)
Specific surface: 15 to 30 m^2/g	Specific surface: 120to 380 m^2/g

TYTRO® RC	VS	SILICA FUME





TYTRO® RC	SILICA FUME
Nanometric	Micrometric
Engineered Material	Industrial Waste
Pure and Amorphous	Containing Impurities
Liquid	Powder
Robust	Variable Quality
Easy to use	Difficult to Handle

Figure 5. The comparison of properties between silica fume and TYTRO® RC

Comparison of Storage and Handling

One of the most distinguishing features of TYTRO® RC in respect to conventional silica fume is that it is a liquid product which makes it easier and cheaper to manage than powder products with high fineness and hygroscopicity. The facilities required for storing and dispensing TYTRO® RC are less expensive than silica fume powder, and require less maintenance and attention. Thus, problems caused when the silica cakes in the silo or when forming lumps due to moisture absorbed, and the variations in product quality are eliminated. Due to its liquid form, TYTRO® RC is more effectively dispersed in shotcrete than silica fume, thereby reducing the required mixing time and minimizing the formation of lumps in shotcrete.

2.3 Synergetic Benefits of Using the Tytro® Admixture Series

The principles behind the working mechanism of TYTRO® RC are explained below:

1. Rheology Control

Due the chemical composition and mainly larger surface induced, shotcrete containing TYTRO® RC will have improved mix cohesion leading to a superior bond to rock substrate, as well as improved cohesion to adhere to itself. In addition, TYTRO® RC also reduces the risk of bleeding and segregation. Therefore, shotcrete containing TYTRO® RC provides major spraying productivity gains by allowing greater thickness of shotcrete layers, and minimizing rebound and dust in spray applications, particularly when shooting overhead.

2. Early Strength Enhancement

Portland cement reacts with water to form calcium silicate hydrate (CSH) gel. In addition to CSH gel, calcium hydroxide Ca(OH)2 is also released as part of this hydration process. However, since silica fume is a pozzolanic material, it does not contribute to the hydration which occurs in the first stage of reaction. It reacts with calcium hydroxide to form additional CSH gels in the second stage where pozzolanic reaction occurs.

1st Stage	*Cement hydration*	$C_3S + H_2O \longrightarrow CSH\ (gel) + Ca(OH)_2$
2nd Stage	*Pozzolanic reaction*	$SiO_2 + Ca(OH)_2 \longrightarrow CSH\ (gel)$

However, unlike silica fume, TYTRO® RC contributes in both first and second stages which results in its superior performance as compared to silica fume. TYTRO® RC reacts during the first stage by accelerating the C3S hydration process. This accelerated hydration effect is accentuated with smaller particle sizes given the higher surface area. During the second stage, it reacts with Ca(OH)2 similar to silica fume. Therefore, TYTRO® RC can be approached as an early strength enhancer because it not only improves hardened properties by providing additional CSH gels, but also accelerates the hydration process.

3. Filler Effect

Nanoparticles fill the voids between cement grains, thereby leading to higher compactness. When used at recommended dosages, TYTRO® RC significantly reduces permeability, and improves interface areas where significant amount of Ca(OH)2 is accumulated which these accumulations are known to constitute zones of low compactness. As a result, TYTRO® RC overcomes this phenomenon.

Below shows the technical benefits of using TYTRO® RC in shotcrete that are equivalent as those achieved with the use of silica fume:

- Pumping enhancer in mixes with low or variable fine contents
- Rebound reduction
- Permeability reduction
- Durability improvement
- Strength enhancement at later ages

However, TYTRO® RC offers additional advantages to those achieved with the use of silica fume as a result of its superior formulation, quality, handling, and storage:

- Higher cohesion effect
- Larger and faster thickness build-up
- Shorter setting time
- Higher initial strength development
- Reduced dust generation

For each property, the benefits obtained from using TYTRO® RC as compared to silica fume is summarized and presented in Table 3.

Table 3. The benefits os using TYTRO® RC as compared to silica fume

Properties *TYTRO® RC vs. Silica fume*	**Benefits** *TYTRO® RC vs. Silica fume*
More dose efficient	Lower use cost
Enhanced cohesion effect	Minimum rebound/material waste
Larger thickness build-up	Productivity gains
Higher reactivity in early age	Faster early strength
Comparable reactivity	Comparable later strength
Comparable filler effect	Comparable permeability behavior
Higher quality consistency	High stability & homogeneity
Minimum dust generation	More environment & user friendly
Liquid vs powder	Easier handling/ dispersing

3. Performance of Shotcrete Mixes Incorporating TYTRO® RC vs. Silica Fume

In order to validate previous comments and confirm the effect of TYTRO® RC in shotcrete mixes, a large scale field testing was conducted in (VSH) Hagerbach Gallery Testing (Flums, Switzerland). VSH is running an underground facility for research and development activities for underground construction for more than 40 years. The tests have been sprayed in a test section called "Sedrun".

Table 4 shows the mix design used in this experimental program for the control mix that was selected to represent a generic mixture commonly used for shotcrete applications.

Table 4. The selected mix design of control mix

Mix design	Name	Source	Quantity
Sand, kg/m^3	0/1 mm	Hagerbach	141
Sand, kg/m^3	1/4 mm	Hagerbach	1037
Gravel, kg/m^3	4/8 mm	Hagerbach	507
Cement, kg/m^3	CEM I 42,5N	Holcim	450
Silica fume , kg/m^3			225
Superplasticizer, % owc	TYTRO® WR	GCP	1.3
Hydration control, % owc	TYTRO® HC	GCP	0.2
Alkali -free accelerator, % owc	TYTRO® SA	GCP	6
Water-to-cementitious materials ratio (w/cm)			0.42

In order to assess the effects of TYTRO® RC on fresh and hardened properties, silica fume at the selected dosage of 5% was fully replaced with TYTRO® RC at 0.67% of the total cementitious materials content (owc). All of the tested mixes contained 6% of TYTRO® SA alkali-free set accelerator of the total cementitious materials content that was added directly at the nozzle.

To validate the impact of the full TYTRO® shotcrete system containing TYTRO® RC and macro-synthetic fibers, fiber-reinforced shotcrete systems were tested with the following changes in the control mix design shown in Table 4:

- **Mix 1:** 5% silica fume + 40 kg/m³ steel fiber
- **Mix 2:** 5% silica fume + 6 kg/m³ competitor macro-synthetic fibers
- **Mix 3:** 0.67% TYTRO® RC + 6 kg/m³ STRUX® BT50 macro-synthetic fibers
- **Mix 4*:** 0.8% TYTRO® RC + 6 kg/m³ STRUX® BT50 macro-synthetic fibers

*****_In the following section, the majority of the test results and graphs will present the performance comparison between 5% silica fume and 0.67% TYTRO® RC. However, since the early strength development is affected by the TYTRO® RC dosage rate, a few figures will also present data from 0.8% TYTRO® RC on early strength development to demonstrate how the early strength is improved when TYTRO® RC dosage is increased from 0.67% to 0.8%._

The aim of this experiment was to compare the following properties:

- **Fresh state properties**

  Slump, slump flow, air content at discharging into the pump before adding accelerator in accordance with EN 12350

- **Sprayability properties**
  - Rebound and thickness build-up
- **Very early strength development**
  - Penetrometer up to 6 hours according to EN 14488-2
  - Hilti stud up to 24 hours according to EN 14488-2
- **Hardened properties**
  - Strength development: Cores tested at 1, 7 and 28 days according to EN 12504-1 and EN 12390-3
  - Permeability resistance under water penetration test according to EN 12390-8

The list of the standards and guidelines used in this study is provided in Chapter 5.

3.1 Workability

The effect of STRUX® BT50 macro-synthetic fibers on workability as compared to steel fibers and competitor macro-synthetic fibers was investigated. Furthermore, the combined effect of STRUX® BT50 macro-synthetic fibers and TYTRO® RC at the dosage rate of 0.67% was investigated. Slump and slump flow were tested as an indicator of workability, as shown in Figure 6.

Figure 6. Testing slump and slump flow as an indicator of workability.

Figure 7 shows that the slump of all the tested mixes were within the target slump value of 200±20 mm, however there were slight variations depending on the mix constituents. The comparison between the steel fibers and macro-synthetic fibers show that incorporating macro-synthetic fibers increased slump and slump flow compared to steel fibers. In addition, when 5% silica fume was replaced with TYTRO® RC at the dosage rate of 0.67% with the combination of 6 kg/m^3 STRUX® BT50 macro-synthetic fibers, both slump and slump flow was further improved.

The obtained results validate that mix containing TYTRO® RC provided higher cohesion effects leading to adhesive behavior which helps the spraying operation for both rebound reduction and larger layer thickness build-up. Slump assessed after one hour of batching and prior to discharge into the pump was almost equivalent; around target 200 + 20mm, however flow measured in jolt table was very different with higher flow for TYTRO® shotcrete mixes. High surface area induced by TYTRO® RC and slightly higher HRWR dosage rate in TYTRO® shotcrete system is leading such effect.

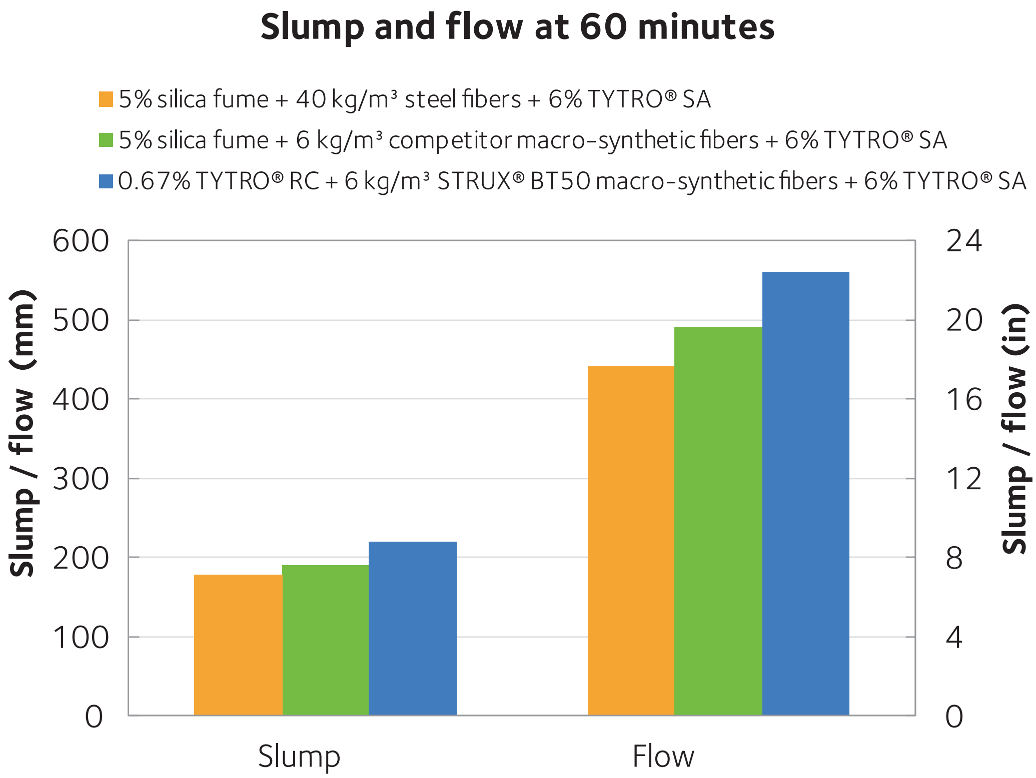


Figure 7. The effect of TYTRO® RC and STRUX® BT50 macro-synthetic fibers on slump and slump flow at 60 minutes.

3.2 Air Control Management

Air content was tested to ensure that the TYTRO® shotcrete system does not have an adverse impact. As presented in Figure 8, similar air content values were obtained from the tested mixes regardless of their mix constituents. Therefore, it is verified that incorporating TYTRO® RC and STRUX® BT50 macro-synthetic fibers have neutral effect on air content.

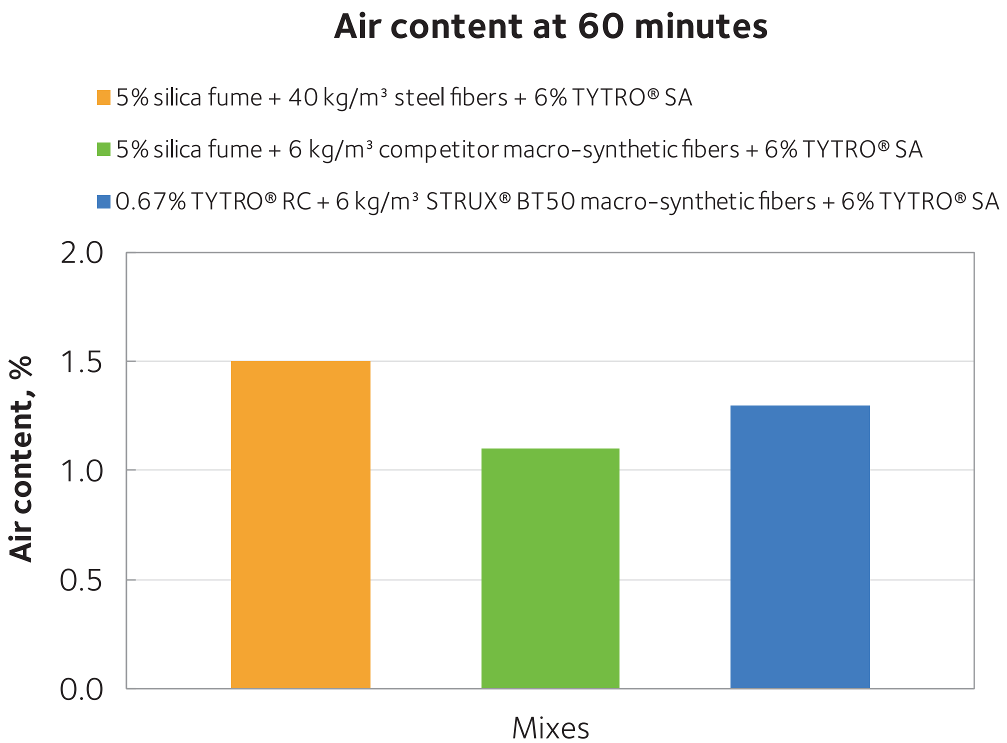


Figure 8. The effect of TYTRO® RC and STRUX® BT50 macro-synthetic fibers on air content.

3.3 Sprayability

Stickiness is a measure of the ability of fresh shotcrete to adhere to a solid surface, whereas cohesion is the ability of the material to adhere to itself. Highly sticky and cohesive shotcrete is desirable as it will exhibit a lower tendency to fall thus provides a mix with a better coating of the rebar surface and less voids than shotcrete displaying poorer cohesive characteristics. Stickiness and cohesion can be assessed using simple techniques such as overhead spraying to determine the maximum thickness build-up before collapse occurs, and by spraying onto vertical walls followed by floating using a wooden float to subjectively determine how cohesive a mixture is. Cohesiveness can also be assessed by observing whether shotcrete that detaches from overhead, failed internally or whether it suffered an adhesion failure at the surface of the rock. Also, the stickiness and cohesion of shotcrete have a direct influence on safety under freshly sprayed ground as well as the ultimate cost of the construction operations due to their impact on rebound.

Rebound

The mix was sprayed with a pump rate of 6 m^3/hour on a vertical concrete wall of 2 m by 2 m with a thickness of about 10 cm. TYTRO® SA accelerator was added with an amount of 6% of the total cementitious materials content directly at the nozzle. After finishing the spraying process, the amount of concrete on the concrete slab and the rebound have been measured with a balance. For each mix, 800 kg to 1000 kg of sprayed concrete have been applied.

The rebound loss is affected by many factors such as the position of the application, angle of the nozzle, skill and expertise of the nozzleman, air pressure, impact velocity, thickness of layer, amount of reinforcement, and mix design (e.g. cementitious materials content, water content, size and gradation of aggregates, the presence and dosage of admixtures etc.). According to ACI 506 guideline, for vertical walls, the approximate range of rebound loss is 10% to 30%. In many field applications, it is common to obtain higher than 15% of rebound. According to Figure 9, both silica fume and silica mixes were efficient in reducing rebound to as low as 5% to 6%. Based on the information provided above, it is a significant improvement to obtain a rebound loss at such low percentages for vertical walls. Having such a high reduction in rebound loss is due to the mix design selected in this study. The improvement on rebound loss depends on the mix design of the reference mix. The reference mix containing 5% silica fume was already optimized, thus had the optimum combined aggregate gradation along with cementitious materials content and w/cm. Therefore, since the rebound loss of the baseline mix is already considered to be very low, the impact of TYTRO® RC in achieving similar rebound loss is a significant improvement. However, our case studies have shown that when the performance of TYTRO® RC on rebound is compared with a mix containing portland cement only, or a mix containing silica fume with rebound loss higher than the one obtained in this study, the improvement on rebound loss with TYTRO® RC is more dramatic.

In addition, due to its lower cost, TYTRO® RC requires lower dosage rate to provide equivalent rebound characteristics as silica fume which leads TYTRO® RC to be more cost-effective and also more sustainable than traditional silica fume.

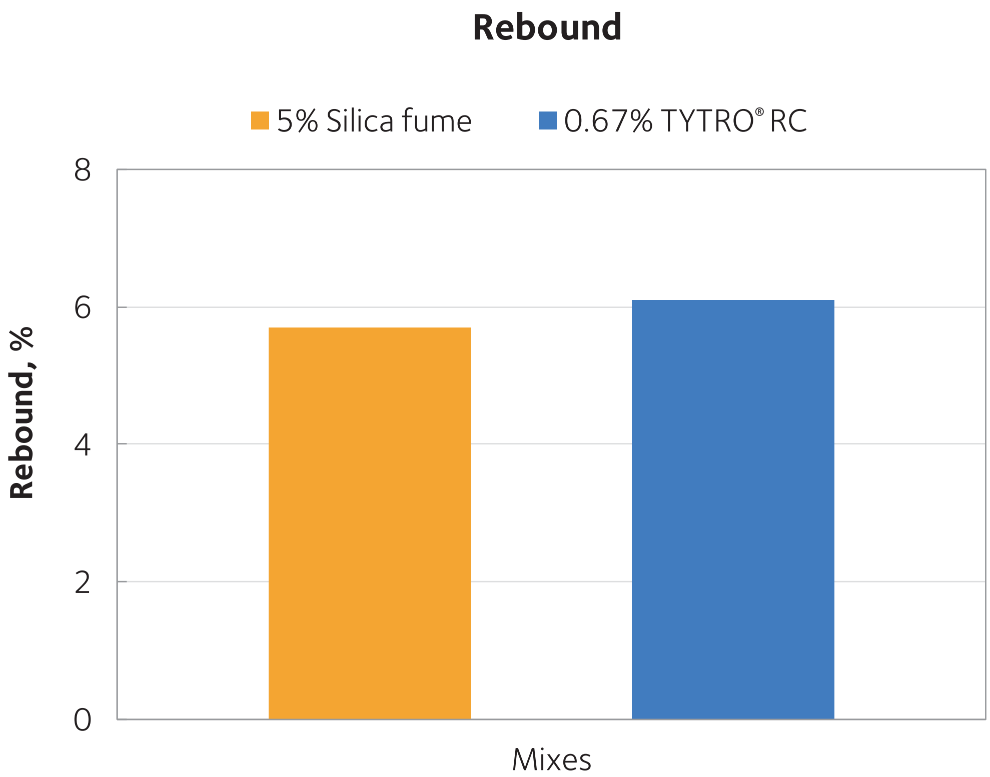


Figure 9. The effect of TYTRO® RC on rebound.

Build-up

One of the major advantages of TYTRO® RC is its larger thickness build-up. As mentioned before, mixes containing TYTRO® RC leads higher cohesion providing higher adhesion to the rock substrate, and adhesion to itself under spraying operations. TYTRO® shotcrete system provides major spraying productivity gains by allowing faster and greater thickness of shotcrete layers, particularly when shooting overhead. Additionally, it can minimize rebound and dust in spray applications. Please contact your GCP Applied Technologies salesperson in your area of operation to obtain an access of videos presenting TYTRO® RC thickness build-up characteristics that were assessed at Hagerbach.

3.4 Time of Setting and Early Strength Development

In shotcrete, for ground support in tunneling and mining, it is necessary to know the rate of early-strength development. As mentioned previously, shotcrete systems containing TYTRO® RC leads to shorter setting times and faster strength development. In order to validate the performance of TYTRO® shotcrete system, extensive full scale testing was carried out at Hagerbach Gallery based on the selected control mix design shown in Table 4.

During the first 6 hours, which is critical for re-entry mining/tunneling operations, penetrometer measurement was carried out in accordance with EN 14488-2. As mentioned in the previous section, the early strength development is affected by the TYTRO® RC dosage rate. Therefore, Figures 10-12 will show data from 0.8% TYTRO® RC in addition to the other three mixes. Figure 10 shows that competitor macro-synthetic fibers performed similar to steel fibers in mixes containing 5% silica fume because fibers are not designed to have a strength acceleration property.

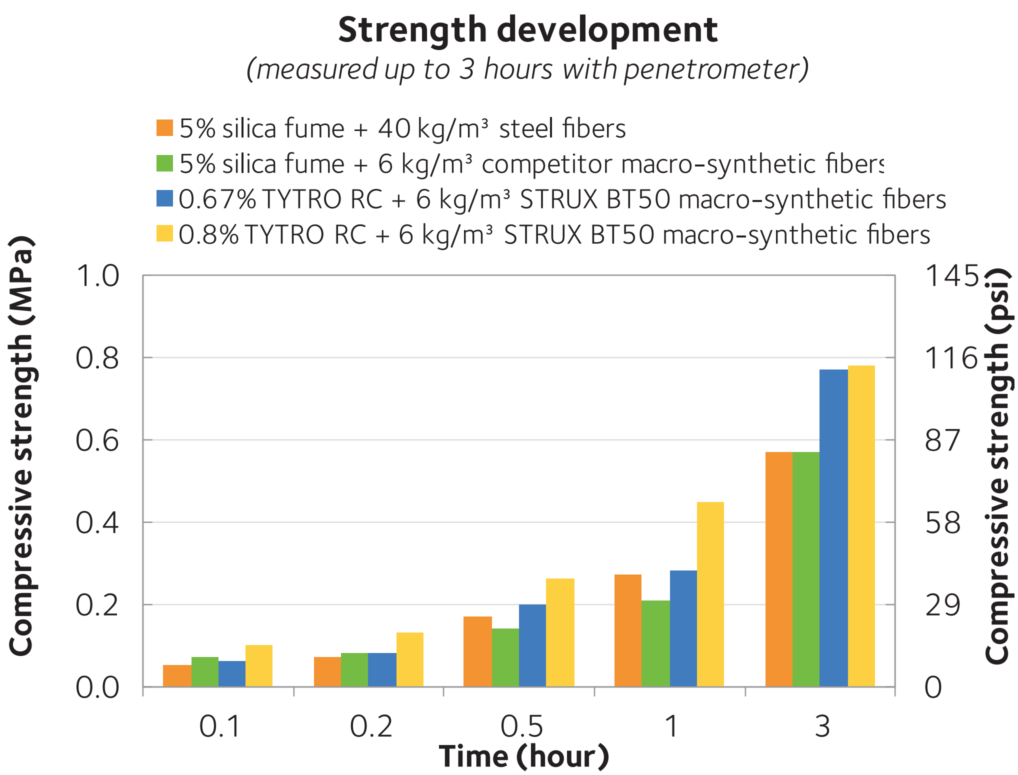


Figure 10. The effect of TYTRO® shotcrete system on very early age strength development up to 3 hours.

However, replacing 5% silica fume with TYTRO® RC resulted in increasing very early age strength development due to its impact on hydration acceleration in stage 1 and its contribution to the production of additional CSH gels in stage 2 (please refer to the previous section for further information). Especially up to 1 hour, the improvement in strength development is more dramatic in shotcrete mix containing 0.8% TYTRO® RC compared to the mix with 0.67% because increasing TYTRO® RC dosage increases early strength as a result of higher amount of TYTRO® RC becoming available to participate for the pozzolanic reaction.

Strength development between 6 to 12 hours was conducted according to EN 14488-2 (Hilti stud). Figure 11 shows that the mix containing TYTRO® shotcrete system with the combination of 0.8% of TYTRO® RC and 6 kg/m^3 of STRUX® BT50 macro-synthetic fibers outperformed in strength development compared to silica fume mixes. The mix containing 0.67% of TYTRO® RC also provided higher strength compared to silica fume mixes up to 9 hours, and then provided equivalent strength at 12 hours as silica fume mixes.

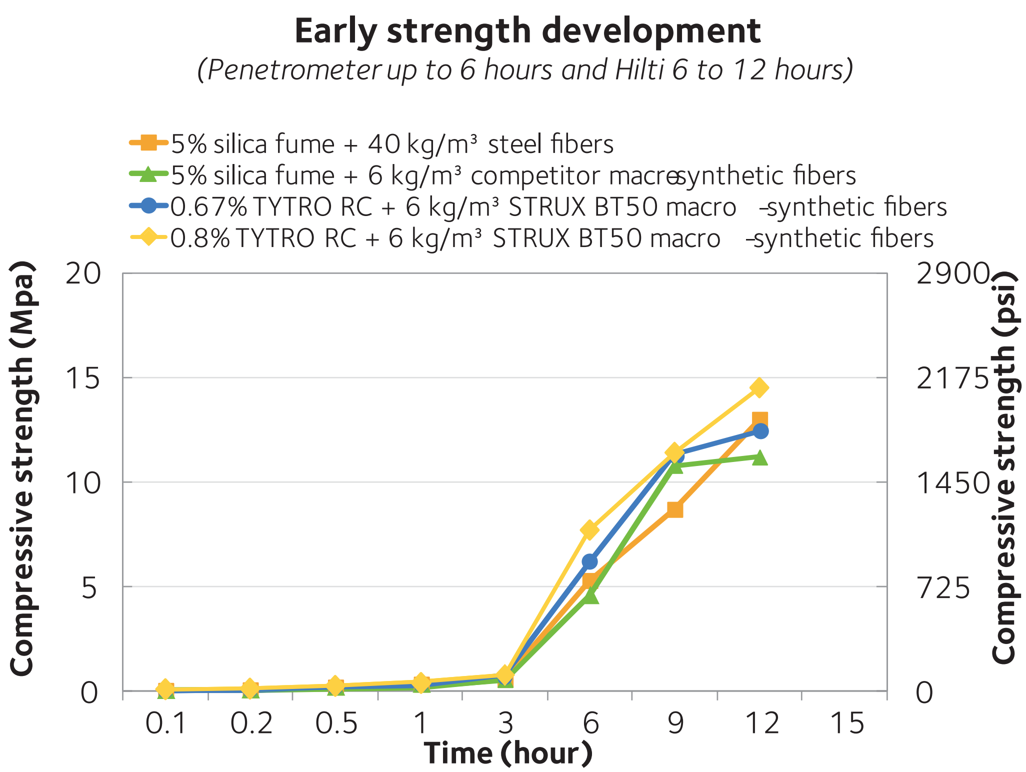


Figure 11. The effect of TYTRO® shotcrete system on early age strength development between 6 to 12 hours.

In order to compare these systems, results were plotted in J curves according to EN 14488-2 (Figure 12). The obtained trends show that the mix containing TYTRO® RC (especially the mix with the TYTRO® RC dosage rate of 0.8%) leads to a much faster and higher strength development rate than silica fume mixes. Therefore, the obtained test results have validated that TYTRO® shotcrete system incorporating TYTRO® RC significantly reduces the time of setting which enables earlier finishing, and also higher strength development than silica fume.

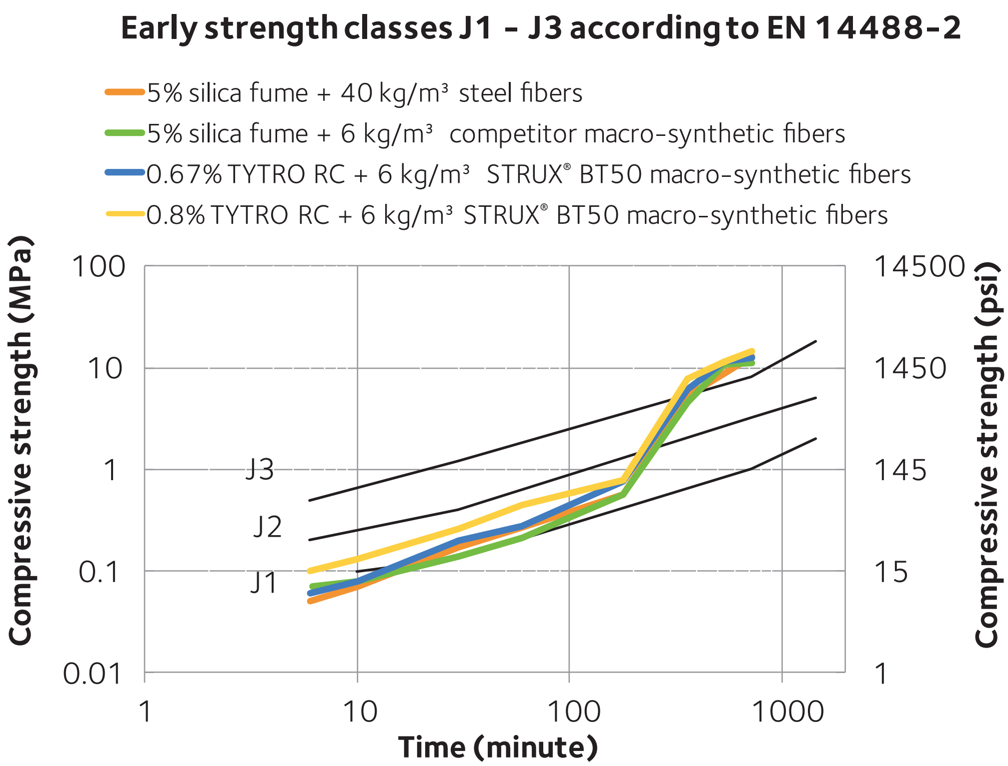


Figure 12. The performance assessment of TYTRO® shotcrete system based on J curves.

3.5 Hardened Properties

Later-Age Strength

Strength at 28 days is commonly specified in project specification that is often used for quality control of the structure. Testing was carried out on drilled cores to assess the effect of TYTRO® shotcrete system on 28 day compressive strength in accordance with EN 12504-1 and EN 12390-3. The selected mix design of control mix is shown in Table 4.

Figure 13 shows that incorporating TYTRO® RC significantly accelerated the strength development at 11 and 24 hours, and provided equivalent strength as silica fume at 7 and 28 days. Overall, test results confirm that TYTRO® RC reacts faster than silica fume at early ages, and achieves comparable strength to silica fume at 28 days, as desired. Therefore, the use of TYTRO® RC provides the benefit of increasing productivity and efficiency in shotcrete operations.

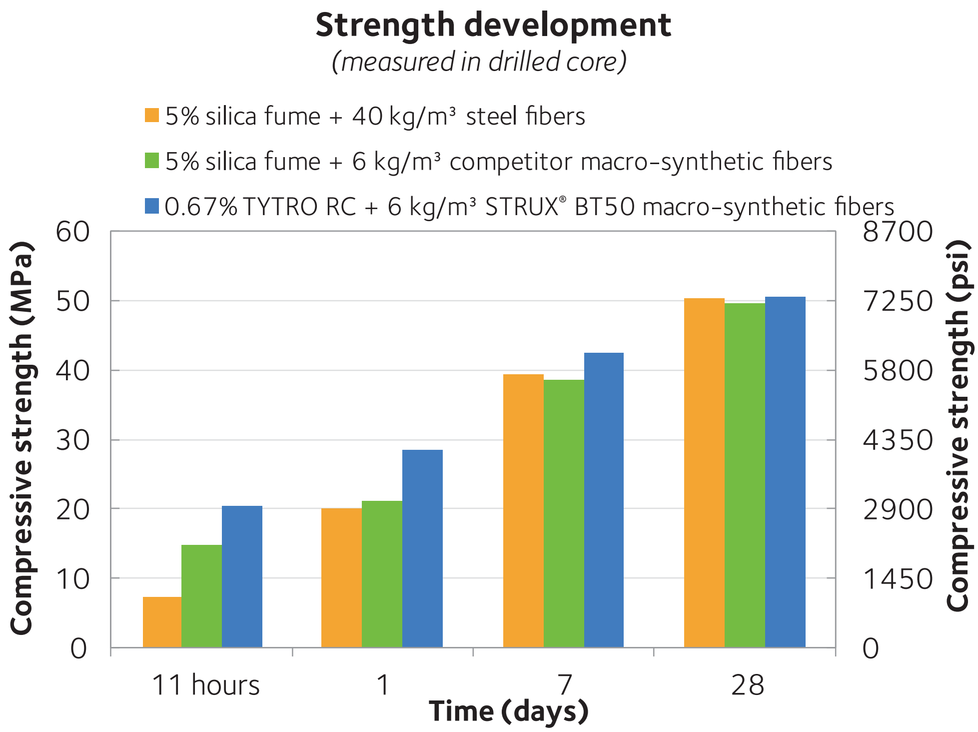


Figure 13. The effect of TYTRO® shotcrete system on strength development up to 28 days.

Permeability

Permeability is an important durability indicating property that determines the longevity of structures. In order to measure permeability resistance of the selected mixes, water penetration test according to EN 12390-8 was carried out at 28 days. The test consists of applying a water pressure over three days, and then splitting the specimens which is followed by measuring the penetration depth of water.

Figure 14 shows the impact of TYTRO® shotcrete system on permeability and its comparison in water tightness with the selected control mixes containing silica fume. Results show that TYTRO® RC performed similar to the silica fume mixes. Both silica fume and TYTRO® RC are efficient in filling the voids and reducing permeability due to their filler and pozzolanic effect. In addition, fibers did not affect the permeability characteristics which are mainly driven by the paste quality.

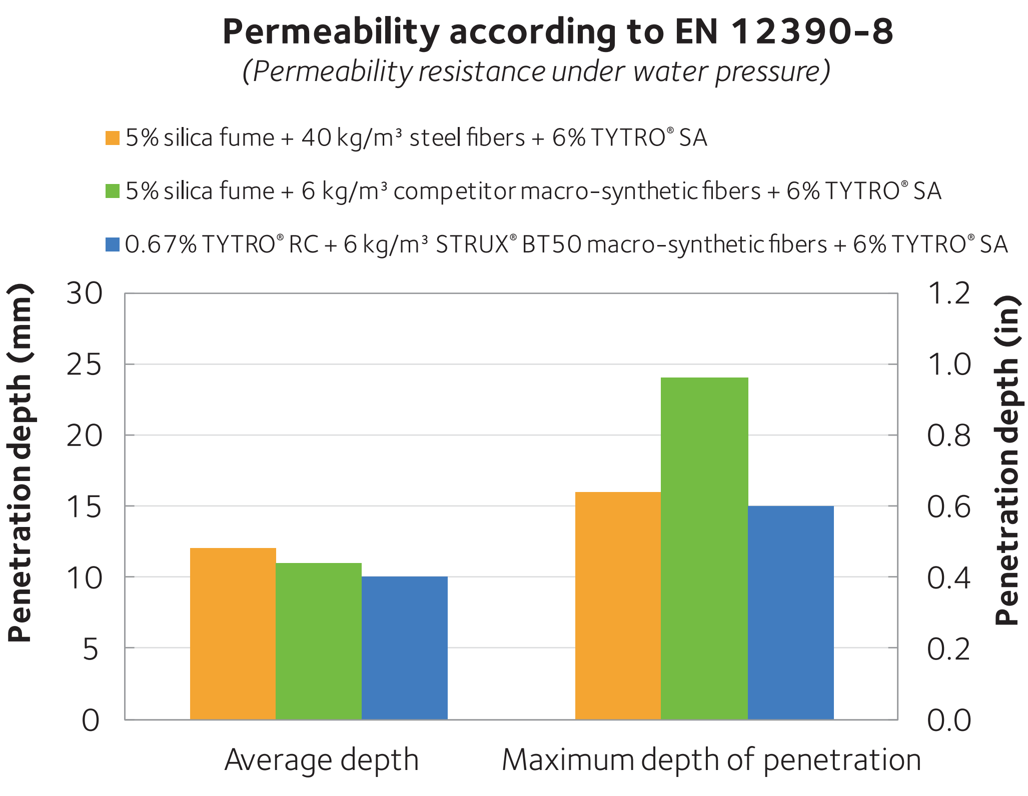


Figure 14. The effect of TYTRO® shotcrete system on permeability at 28 days.

4. SUMMARY

A large scale of experiment has been conducted to analyze and present the benefit of using TYTRO® shotcrete system. Fresh and hardened properties including workability, air content, sprayability, rebound, strength, and permeable voids have been tested on the following mixes with different designs: 5% silica fume + 40 kg/m³ steel fibers; 5% silica fume + 6 kg/m³ competitor macro-synthetic fibers; and 0.67% TYTRO® RC + 6 kg/m³ STRUX® BT50 macro-synthetic fibers. A mix containing 0.8% TYTRO® RC + 6 kg/m³ STRUX® BT50 macro-synthetic fibers was also included in the early strength development testing only to demonstrate the impact of TYTRO® RC dosage on the strength development rate. According to the laboratory analysis, TYTRO® RC conforms to the ASTM C494 standard for Type S specific performance admixtures.

As shown in Table 5, compared to a traditional shotcrete mix containing 5% silica fume, TYTRO® shotcrete system improves cohesiveness, reduces time of setting, provides faster and higher early age strength development (especially up to 12 hours), increases layer thickness build-up, and reduces rebound while providing equivalent hardened shotcrete performance (e.g. later age strength, permeable voids and absorption, and energy absorption).

In addition to providing these additional benefits with no compromised performance, TYTRO® shotcrete system is also more cost-effective than traditional shotcrete mixes containing silica fume due to the lower dosage requirement of TYTRO® RC than silica fume. Each additives used in the full TYTRO® shotcrete system is selected based on their individual performance as well as their synergetic benefits when used together. Therefore, the full TYTRO® shotcrete package should be used to ensure achieving the desired performance.

The obtained results presented in this technical bulletin can be further improved upon mix optimization which is offered by our technical team. Please contact your GCP Applied Technologies salesperson in your area of operation for further information.

Comparison of traditional shotcrete mix with 5% silica fume vs. TYTRO® system	
RHEOLOGY	
Workability and slump retention	⇔
SPRAYABILITY	
Rebound	⇔
Build -up	⇧
AIR	
Air content	⇔
SETTING AND EARLY AGE STRENGTH	
Strength up to 6 hours	⇧
Strength up to 12 hours	⇧
Strength up to 24 hours	⇧
HARDENED PROPERTIES	
Strength at 28 days	⇔
Permeability	⇔
Permeable voids and absorption	⇔
Energy absorption	⇔

Table 5. Performance comparison of silica fume vs. TYTRO® shotcrete system

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