

# Effect of Pozzolan-Based Rheology Control Agent as a Replacement for Silica Fume

## on Wet-Mix Shotcrete Performance

By Ezgi Yurdakul and Klaus-Alexander Rieder

**T**he purpose of this article is to present the performance evaluation of wet-mix shotcrete containing a pozzolan-based rheology control (RC) agent as a replacement for silica fume (SF). The RC agent used in this study is a liquid-based product that contains nanoscaled colloidal silica particles with high pozzolan reactivity. In this experimental program, five different mixtures were evaluated. One mixture was prepared as a reference mixture incorporating 5% SF by mass of cement. Four mixtures were prepared with RC agent at dosage rates of 0.67%, 0.80%, 1.30%, and 1.60% by mass of cement. Slump, rebound, early- and later-age strength, and the depth of water penetration were tested.

Test results showed that the SF mixture and mixtures containing RC agent provided similar slump and they were all very efficient in reducing rebound to the range of 5 to 6%. The addition of the RC agent increased the early-age strength compared to the SF mixture and provided similar strength at 7 and 28 days. The water penetration depth of the mixtures containing the RC agent was slightly lower than that of the SF mixture, as desired. The RC agent was more dosage-efficient, as it required much lower addition rate to provide equivalent performance to SF. Overall, it was found that for the investigated mixtures, the RC agent was a suitable alternative to SF in wet-mix shotcrete applications.

### Introduction

SF is commonly added to shotcrete mixtures to improve strength and durability while reducing rebound. However, there are a number of limitations associated with its use. The first limitation is due to the variability of the purity of  $\text{SiO}_2$ , which results in a significant variation in the performance of SF in shotcrete. In addition, SF is a by-product of silicon and ferrosilicon production. Therefore, it contains impurities

that may cause unwanted side effects, such as delays in setting time. Furthermore, the handling of SF may be challenging due to its powder form. As a result of these limitations, there is a need to replace SF with another substance that can provide similar performance while avoiding the challenges associated with the use of SF.

The pozzolan-based RC agent is an alternative to SF, as it provides better (or at least equivalent) performance characteristics while avoiding the limitations mentioned previously. The RC agent used in this study is a liquid-based, fully stable product that contains uniformly distributed nanoscaled colloidal silica particles with a long shelf life. The specific surface of colloidal silica is higher than that of conventional SF and it consists of more than 99%  $\text{SiO}_2$ . Therefore, it has a very high purity and pozzolan reactivity compared to SF.<sup>1,2</sup> When added to a wet-mix shotcrete, the RC agent significantly increases the cohesiveness while reducing bleeding and segregation.<sup>3</sup> Therefore, while also improving the sprayability and pumpability characteristics, it reduces rebound and increases maximum thickness of buildup. In addition, many researchers<sup>4-8</sup> stated that colloidal silica fills the space between particles of calcium silica hydrate (CSH) gel; hence, it acts as a filler to improve the microstructure. It also reacts with calcium hydroxide, thus increasing the amount of CSH gel, which in turn increases the densification of the matrix and improves durability. Furthermore, at sufficiently high addition rates, colloidal silica can accelerate the early-age hydration process of the shotcrete mixture, which reduces the time of setting and increases early-age strength compared to shotcrete mixtures containing SF.<sup>9</sup>

This article presents a comparative study to evaluate the performance of RC agents as alternatives to SF in wet-mix shotcrete applications.

The influence of different grades and dosage rates of RC agents on the fresh and hardened properties of shotcrete was evaluated.

## Experimental Program

An extensive experimental test program was conducted at the Hagerbach Testing Gallery (VSH), which is an underground facility in Flums, Switzerland. A total of five mixtures were batched as shown in the following:

- Mixture 1—A reference mixture incorporating SF with the addition rate of 5% by mass of cement;
- Mixture 2—A mixture containing RC agent Grade 1 with the dosage rate of 0.67% by mass of cement;
- Mixture 3—A mixture containing RC agent Grade 1 with the dosage rate of 1.30% by mass of cement;
- Mixture 4—A mixture containing RC agent Grade 2 with the dosage rate of 0.80% by mass of cement; and
- Mixture 5—A mixture containing RC agent Grade 2 with the dosage rate of 1.60% by mass of cement.

RC agent Grade 1 had a smaller average particle size compared to RC agent Grade 2. Table 1 shows the mixture design used in this experimental program for the reference mixture selected to represent a generic mixture containing SF that is commonly used for shotcrete applications

in Europe. It should be noted that as a result of replacing powder-based SF with liquid-based RC agents, the total cementitious materials content was 796 lb/yd<sup>3</sup> (472.5 kg/m<sup>3</sup>) for the SF mixture and 758 lb/yd<sup>3</sup> (450 kg/m<sup>3</sup>) for the mixtures incorporating the RC agents. The water-cementitious material ratio (*w/cm*) was kept constant at 0.435 for all mixtures.

Table 2 shows the test matrix used in this study. The presented results represent the average of two test results conducted on separate batches of the same mixture carried out on subsequent days.

## Results and Discussion

### Sprayability and Pumpability

Sprayability and pumpability are two key properties that reflect the distinctive process of shotcrete application and distinguish it from traditional cast-in-place concrete. Hence, it is important to understand the differences between these two parameters. Sprayability is the efficiency of a mixture at sticking to the applied surface (adhesion) and to itself (cohesion).<sup>14</sup> Pumpability is the stability and mobility of a mixture under pressure.<sup>15</sup> One of these two parameters is often compromised due to requiring conflicting properties. For pumpability, it is desired to have a mixture with low viscosity and high flowability (usually associated with high slump). However, for sprayability, a stiff and

Table 1: Mixture Design of SF Mixture

Mixture design	Quantity
Fine aggregate 0 to 0.04 in. (0 to 1 mm), lb/yd <sup>3</sup> (kg/m <sup>3</sup> )	238 (141)
Fine aggregate 0.04 to 0.16 in. (1 to 4 mm), lb/yd <sup>3</sup> (kg/m <sup>3</sup> )	1748 (1037)
Intermediate aggregate 0.16 to 0.32 in. (4 to 8 mm), lb/yd <sup>3</sup> (kg/m <sup>3</sup> )	855 (507)
Cement (CEM I 42,5 N), lb/yd <sup>3</sup> (kg/m <sup>3</sup> )	758 (450)
SF*, lb/yd <sup>3</sup> (kg/m <sup>3</sup> )	38 (22.5)
High-range water-reducing admixture, % of total cementitious materials content	1.2
Hydration control, % of total cementitious materials content	0.3
Alkali-free accelerator, % of total cementitious materials content	6
<i>w/cm</i>	0.435

\*SF was fully replaced with RC agents.

Table 2: Test Matrix

Tested property	Method	Age
Slump flow	EN 12350-5 <sup>10</sup>	N/A
Early-age strength	EN 14488-2 <sup>11</sup>	10 min, 30 min, 1 h, 3 h
Later-age strength	EN 12390-3 <sup>12</sup>	7 d, 28 d
Water penetration resistance	EN 12390-8 <sup>13</sup>	28 d

sticky mixture with low slump and high cohesiveness is desired to minimize rebound and increase buildup thickness.<sup>15</sup>

Currently, there are no standardized test methods that can measure sprayability and pumpability. Therefore, it is a common practice to assess consistency, viscosity, rebound, and buildup thickness to evaluate the sprayability and pumpability of a particular mixture. In this study, slump flow was tested to evaluate the flowability as an indicator of pumpability, and rebound was tested to evaluate the sprayability characteristics of the tested mixtures.

Figure 1 shows the effect of two RC agents and SF mixtures on slump flow, which was targeted as  $20 \pm 1.25$  in. ( $500 \pm 30$  mm). All the tested mixtures were within the acceptable variation limits of the target slump, and they performed similar to each other regardless of their mixture constituents. For a given grade of RC agent, increasing the dosage rate slightly reduced slump due to the increased particle packing, which decreased the volume between

them as well as the free water. However, because the selected dosage rates for the two RC agents were within the manufacturer's recommended limits, the impact on the water demand was negligible.

It should be noted that slump flow only indicates consistency (ease of flow) and does not evaluate cohesiveness (tendency to bleed and segregate). It is especially important for shotcrete mixtures to have high cohesiveness, as they are less prone to segregation under pressure. Having a mixture with high cohesiveness and stickiness is also desired to maximize thickness buildup and minimize rebound. Due to the smaller particle size associated with higher specific surface area of the RC agents, they work as nucleation sites for the precipitation of CSH gel, and have stronger Van der Waals and electrostatic ionic forces between particles.<sup>8</sup> Considering that the main source of cohesion in cement paste is the CSH gel,<sup>16</sup> it is expected for RC agents to increase cohesion due to a) its impact on accelerating and forming additional CSH gels; and b) its reactant surface particles exhibiting stronger tendency for adsorption of ions and increasing the surface adhesion between adjacent particles and to other materials.

## Rebound

The mixture was sprayed with a pump rate of  $7.85 \text{ yd}^3/\text{h}$  ( $6 \text{ m}^3/\text{h}$ ) with a pump pressure ranging between 800 and 870 psi (55 and 60 bar) on a vertical concrete wall of  $6.6 \times 6.6 \text{ ft}$  ( $2 \times 2 \text{ m}$ ) with a thickness of about 4 in. (100 mm). TYTRO<sup>®</sup> SA alkali-free set accelerator was added at 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 were measured with a balance.

Rebound loss is affected by many factors, such as the position of the application, distance and angle of the nozzle from the sprayed location, skill and expertise of the nozzleman, air pressure, impact velocity, thickness of layer, amount of reinforcement, and mixture design (for example, cementitious materials content, water and air content, size and gradation of aggregates, and the presence and dosage rate of admixtures). According to the ACI 506 guideline,<sup>17</sup> 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% rebound. According to Fig. 2, mixtures containing SF and RC agent were efficient in reducing rebound to as low as 5 to 6%. Based on the aforementioned information, it is a significant improvement to obtain a rebound loss at such low percentages for vertical walls. The

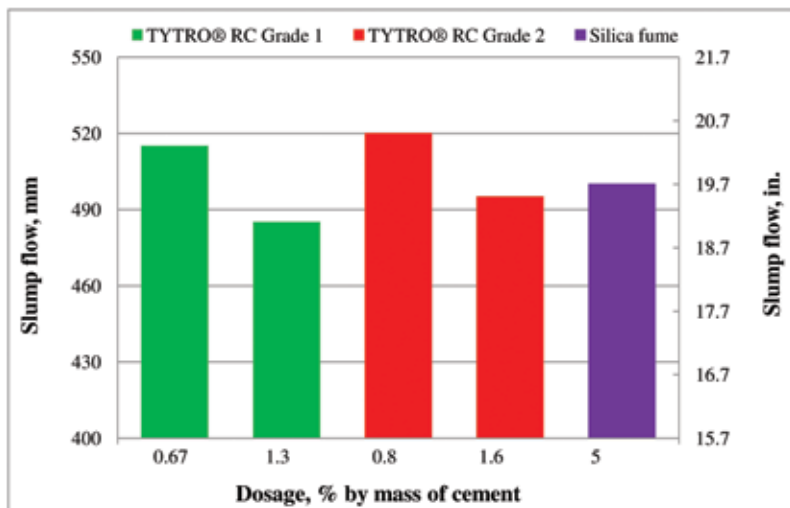


Fig. 1: Effect of two RC agents and SF on slump flow

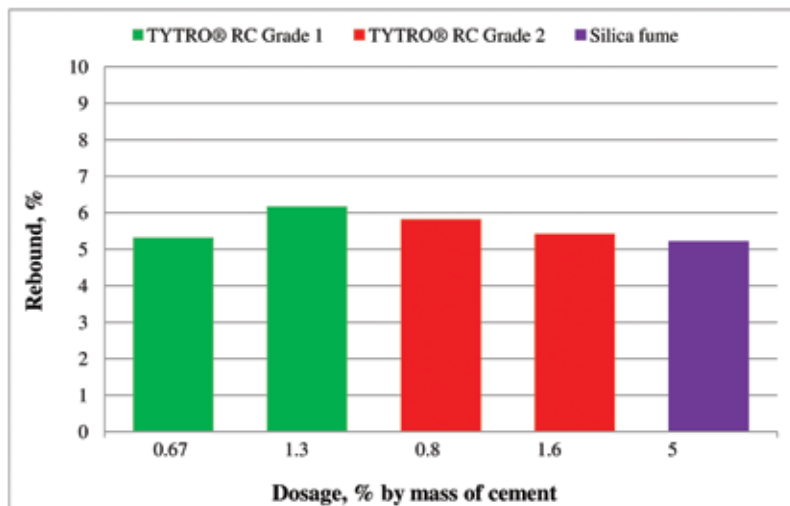


Fig. 2: Effect of RC agent and SF on rebound

improvement on rebound loss is related to the mixture design of the reference mixture. The reference mixture containing 5% SF was already optimized, and thus had the optimum combined aggregate gradation along with the cementitious materials content and  $w/cm$ . Because the rebound loss of the baseline mixture was already considered to be very low, the impact of the RC agents in achieving similar low rebound loss at much lower dosage rates was a significant improvement. However, case studies have shown that when the performance of the RC agents on rebound is compared with those of mixtures containing portland cement only, or mixtures containing SF with rebound losses higher than the one obtained in this study, the decrease in rebound with mixtures containing RC agents is more dramatic.

### Early Strength Development

The first few hours are critical in mining/tunneling operations for re-entry; therefore, it is desirable for shotcrete mixtures to have a high strength-development rate. Figure 3 shows the comparison of the early-age strength between the SF mixture and mixtures containing the RC agents. From the initial testing conducted at

10 minutes after spraying until 3 hours after spraying, mixtures containing the RC agents outperformed the mixture containing SF. This is likely due to the specific surface area difference between these two materials because the rate of pozzolanic reaction is proportional to the amount of surface area available for reaction.<sup>1</sup> In addition, colloidal silica in the RC agents also reacts with the calcium hydroxide released by the cement hydration, forming additional CSH gel, and also accelerates the primary CSH gel formation, which is responsible for strength development. Distinct from the RC agents, SF only reacts to form CSH gels and does not contribute to the acceleration of CSH formation at typically used dosage rates.

### Later-Age Strength

Strength at 28 days is commonly specified in project specifications that are often used for quality control of the structure. Figure 4 shows the effect of SF mixture and mixtures containing RC agent on 7- and 28-day cube strength. The two tested RC agents provided similar strength to SF at 7 and 28 days. Generally, admixtures accelerating the strength development rate at early ages may cause an ultimate strength reduction.

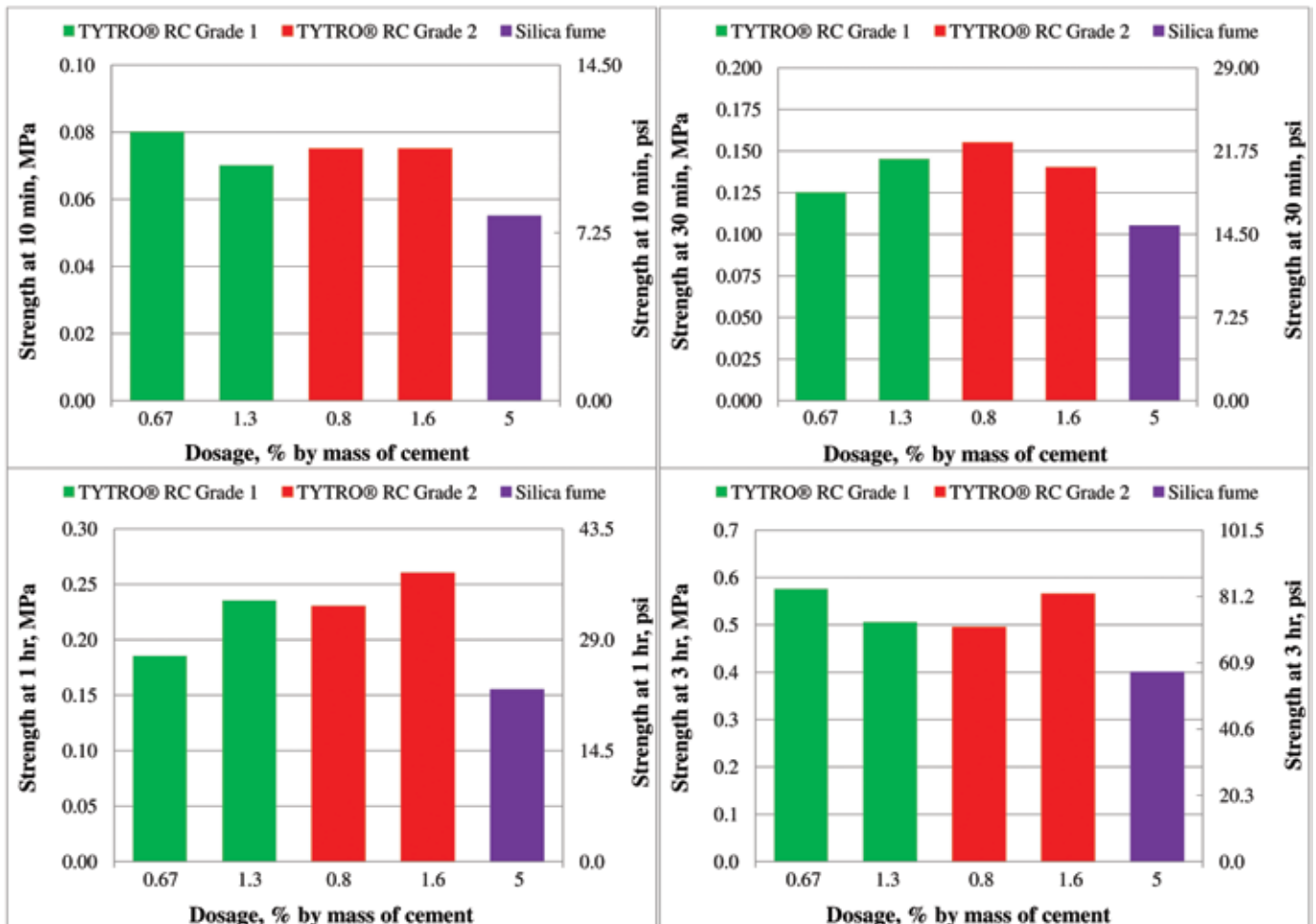


Fig. 3: Effect of RC agents and SF on early strength development

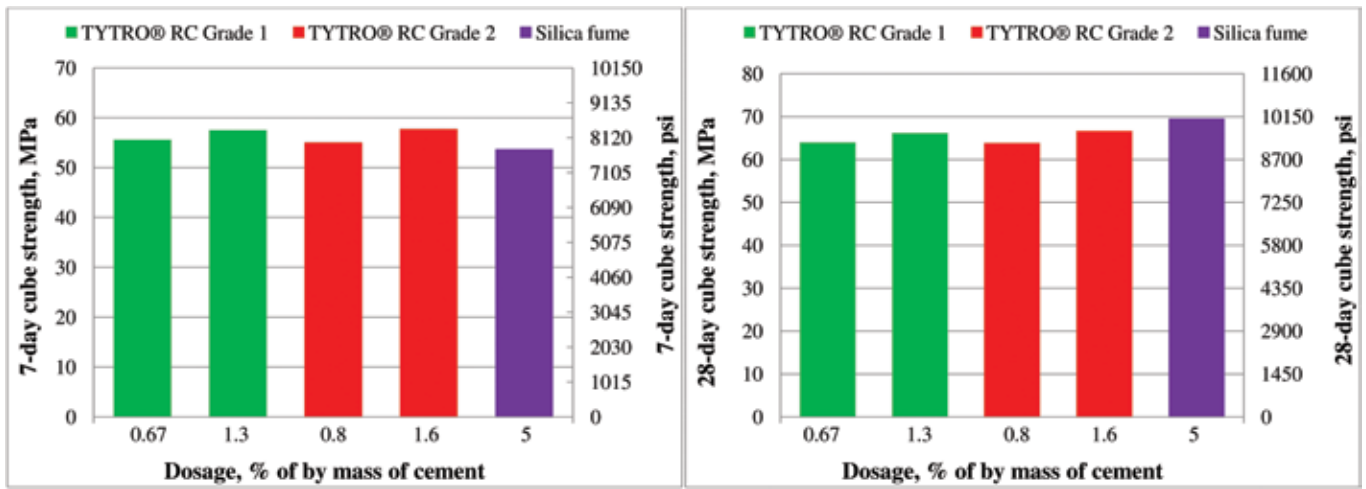


Fig. 4: Effect of RC agents and SF on the strength at 7 and 28 days

However, these results show that due to their pozzolanic nature, the RC agents reacted faster than the SF at early ages, and still achieved comparable 28-day strength. In addition, the impact of the selected dosages and grades of the RC agents on 28-day strength was marginal.

### Durability

Durability plays a key role in determining the life span of structures, and it is often assessed by evaluating the permeability, which governs the rate of flow of a fluid (or gas) into a porous solid. If concrete or shotcrete mixtures have high permeability, deleterious substances can migrate into the structure, especially if they are exposed to chemical attack or freezing-and-thawing cycles. To evaluate the effect of the two RC agents and SF on the permeability, water penetration tests were carried out at 28 days.

Figure 5 shows that the water penetration depths of the mixtures containing the two RC agents were slightly lower than those of the SF mixture, as desired. This is most likely due to the

following two potential reasons. The paste content of the mixtures containing the RC agents was lower than that of the SF mixture (as a result of replacing the powder-based SF with the liquid-based RC agents). In general, aggregates are likely to be denser than the cement paste and have a lower permeability than the cement paste, so mixtures with lower paste content tend to have lower permeability. On the other hand, the colloidal silica contained in the RC agents decreases the permeability by increasing the density of the interfacial transition zone (the weakest phase in concrete) as a result of the combination of its filler effect and high pozzolanic reactivity. SF also has pozzolanic properties, but because the reactivity and the surface area of the RC agents are higher than those of SF, the degree of their contribution to the permeability/durability will be influenced accordingly.

### Conclusions

The following conclusions were drawn based on the test results obtained from the investigated shotcrete mixtures:

- The SF mixture and mixtures containing the RC agents provided similar slump and were all very efficient in reducing the rebound loss to a range of 5 to 6%;
- The addition of the RC agents increased the early-age strength compared to the SF mixture, and provided similar compressive strength at 7 and 28 days;
- The water penetration depth of the mixtures containing the RC agents was slightly lower than that of the SF mixture, as desired;
- The impact of the selected dosages and grades of the RC agent on the performance was minor for the investigated non-fiber-reinforced shotcrete mixtures;
- The RC agents were more dosage-efficient than SF, as they required a much lower dosage rate to provide equivalent performance; and

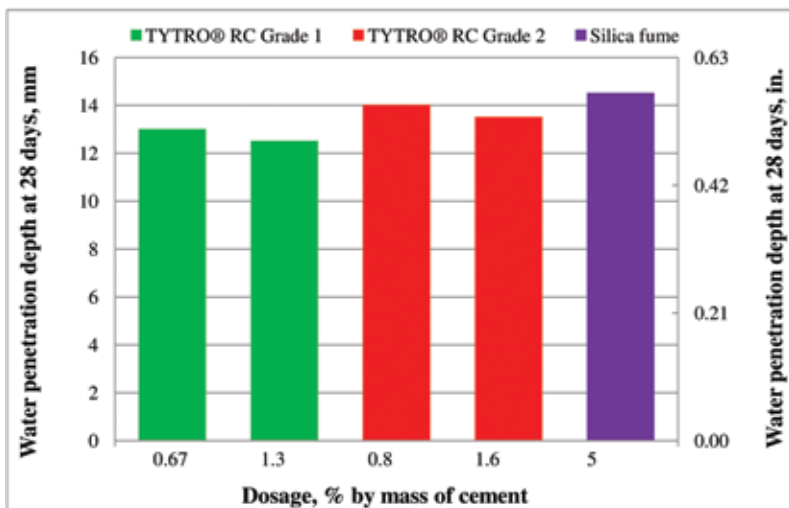


Fig. 5: Effect of the RC agents and SF on the water penetration depth at 28 days



- Overall, the RC agents tested were found to be efficient components to enhance the properties of wet-mix shotcrete.

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**Ezgi Yurdakul** is a Concrete Scientist in the R&D Division at W. R. Grace, Cambridge, MA. She received her PhD from Iowa State University, Ames, IA. She is currently Secretary of ACI Subcommittee 211-A, Proportioning-Editorial, and a member of ACI Committees 211, Proportioning Concrete Mixtures; 212, Chemical Admixtures; 506, Shotcreting; 544, Fiber-Reinforced Concrete; and ACI Subcommittees 506-A, Shotcreting-Evaluation; 506-B, Shotcreting-Fiber-Reinforced; 506-C, Shotcreting-Guide; and 506-E, Shotcreting-Specifications. Her research interests include shotcrete, performance-based specifications for concrete, mixture design optimization, and chemical admixtures.



**Klaus-Alexander Rieder** is a Global Concrete Technology Manager at W. R. Grace, Luegde, Germany. He received his ScD in physics from the Technical University of Vienna, Vienna, Austria, in 1995. He is a member of ACI Committees 209, Creep and Shrinkage in Concrete; 215, Fatigue of Concrete; 360, Design of Slabs on Ground; 506, Shotcreting; 544, Fiber-Reinforced Concrete; ACI Subcommittees 544-C, FRC-Testing; 544-D, FRC-Structural Uses; 544-E, FRC-Mechanical Properties; 544-F, FRC-Durability; and Joint ACI-ASCE Committee 446, Fracture Mechanics of Concrete. His research interests include all durability- and cracking-related aspects of concrete and the development of high-performance fibers for concrete applications.