Case Study

The Use of Slag Cement, Alkali-Free Accelerator, and Macro-Synthetic Fibers

in Wet-Mix Shotcrete for Tunnel Applications

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This paper presents the results of a case study conducted in a wet-mix shotcrete application of a major tunnel construction located in Sydney, Australia. The total concrete production volume of this project is estimated to be 1,300,000 yd^3 (1,000,000 m^3), of which 330,000 yd^3 (250,000 m^3) will be shotcrete. The performance specifications were developed to comply with RMS B82, "Shotcrete Works," that is set by the Roads and Maritime Services. According to these specifications, slump was targeted to be a minimum of 6.25 in. (160 mm). The compressive strength at 28 days for both cored and cylinder samples was required to be a minimum of 6000 psi (40 MPa) and a maximum of 10,000 psi (70 MPa). In addition, a compressive strength of 145 psi (1 MPa) was desired to be reached within 3 to 4 hours after spraying. The material selection was based on the cost and listed performance criteria. Macro-synthetic fibers were preferred, as they provide the desired post-crack energy absorption while eliminating the corrosion potential associated with steel fibers. In addition, the performance of slag cement was evaluated as a replacement material due to the shortage of fly ash in this region.

Materials

Aggregates

The combined particle size distribution of all coarse and fine aggregates used in this case study was within the gradation limits shown in Table 1.

Cementitious Materials

Ordinary portland cement (OPC) and various supplementary cementitious materials were used in accordance with RMS 3211[2] to compare the performance of slag cement as a replacement of fly ash.

Chemical Admixtures

The following admixtures were used:

- TYTRO® WR 172, a polycarboxylate-based high-range water reducer to maintain the target workability;

Table 1: Combined Coarse and Fine Aggregate Particle Size Distribution
(after Table B82.1 in RMS B82[1])

Sieve size	Mass of sample passing, % Specification	Mass of sample passing, % Case study
0.5 in. (13.2 mm)	100	100
3/8 in. (9.5 mm)	90 to 100	95
0.25 in. (6.7 mm)	—	76
No. 4 (4.75 mm)	70 to 85	69
No. 8 (2.36 mm)	50 to 70	56
No. 16 (1.18 mm)	35 to 55	42
No. 30 (600 μm)	20 to 40	31
No. 50 (300 μm)	8 to 20	19
No. 100 (150 μm)	2 to 10	9

- TYTRO® HC 270, a hydration control agent to provide the desired slump retention;
- TYTRO® RC 430 as a pozzolanic-based rheology control agent to reduce rebound and enhance the early-age strength development rate to reduce the re-entry time (this admixture was used in all the mixtures as a silica fume replacement to reduce the cementitious materials content);
- TYTRO® RM 471, a rheology-modifying agent to reduce rebound and increase pumpability; and
- TYTRO® SA 530, an alkali-free shotcrete accelerator.

Fibers

STRUX® BT 50 was the macro-synthetic fiber used to increase crack resistance, ductility, and toughness required for this tunnel application. The performance comparison was made using an alternative 2.1 in. (54 mm) modified olefin macro-synthetic fiber.

Mixture Design

Mixture design was prepared in accordance with the B2 exposure classification limits set by RMS B82,[1] as shown in Table 2.

A total of four mixtures were tested with various mixture proportions and mixture constituents to evaluate the impact of different supplementary cementitious materials, macro-synthetic fibers, and alkali-free accelerator dosage rate on wet-mix shotcrete performance (Table 3).

Results and Discussion

Effect of Slag Cement on Shotcrete Performance

The use of supplementary cementitious materials (SCMs) in shotcrete mixtures as a partial replacement of portland cement has several benefits, including the improved durability as a function of reduced permeability of the hydrated cementitious paste, enhanced workability due to their particle size and morphology, and increased

Table 2: Minimum Cement Content and Maximum Water-Cement Ratio
(after Table B82.4 in RMS B82[1])

Exposure classification	Minimum cement content, lb/yd³ (kg/m³)	Maximum water-cement ratio (by mass)
A	539 (320)	0.45
B1	539 (320)	0.45
B2	624 (370)	0.40
C	708 (420)	0.40
U	In accordance with Annexure B82/A Clause A1	

Table 3: Mixture Proportions

Mixtures	Mix 1	Mix 2	Mix 3	Mix 4
Ordinary portland cement, lb/yd³ (kg/m³)	570 (338)	455 (270)	759 (450)	759 (450)
Fly ash, lb/yd³ (kg/m³)	189 (112)	—	—	—
Slag cement, lb/yd³ (kg/m³)	—	303 (180)	—	—
Total binder content, lb/yd³ (kg/m³)	759 (450)	759 (450)	759 (450)	759 (450)
Water, lb/yd³ (kg/m³)	303 (180)	303 (180)	303 (180)	303 (180)
water-cementitious materials ratio	0.40	0.40	0.40	0.40
Coarse aggregate 1, lb/yd³ (kg/m³)	876 (520)	876 (520)	876 (520)	876 (520)
Coarse aggregate 2, lb/yd³ (kg/m³)	624 (370)	624 (370)	624 (370)	624 (370)
Sand, lb/yd³ (kg/m³)	1214 (720)	1214 (720)	1214 (720)	1214 (720)
Sand-to-total aggregate ratio	0.677	0.677	0.677	0.677
TYTRO® WR 172, oz/yd³ (L/m³)	80 (3.1)	85 (3.3)	88 (3.4)	88 (3.4)
TYTRO® HC 270, oz/yd³ (L/m³)	41 (1.6)	41 (1.6)	41 (1.6)	41 (1.6)
TYTRO® RC 430, oz/yd³ (L/m³)	103 (4)	103 (4)	103 (4)	103 (4)
TYTRO® RM 471, oz/yd³ (L/m³)	103 (4)	103 (4)	103 (4)	103 (4)
TYTRO® SA 530, % of total binder content	4, 7, 10	7, 10	7, 10	7
STRUX® BT 50, lb/yd³ (kg/m³)	12 (7)	12 (7)	12 (7)	—
Alternative 2.1 in. (54 mm) modified olefin macro-synthetic fiber, lb/yd³ (kg/m³)	—	—	—	8 (5)

Fig. 1: Setup for beam end test

Fig. 2: Beams prepared to test early-age strength development

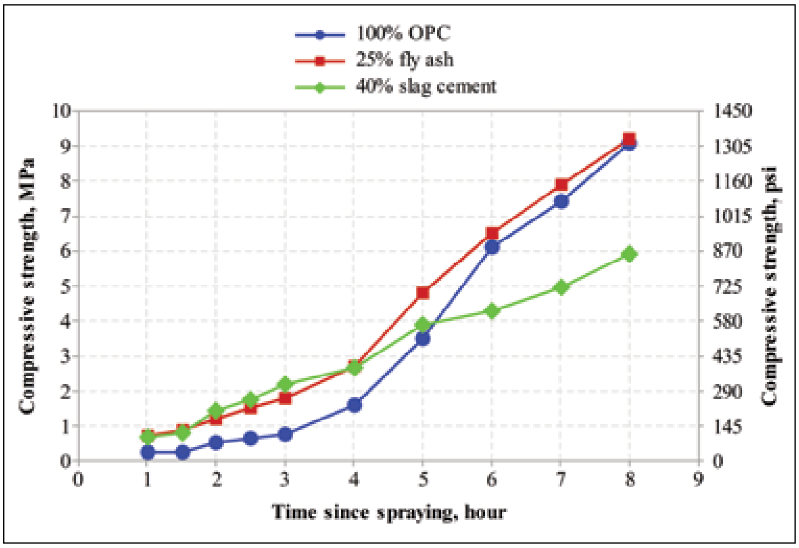

Fig. 3: Impact of cementitious materials on early-age strength development

ultimate strength as a result of their pozzolanic activity.[3] However, the percent of these contributions may vary depending on the SCM type and replacement level.

Slag cement is widely used in conventional concrete due to its advantages on long-term strength and durability. As a waste material of the iron refining industry, the contribution of slag cement as an economical and sustainable material to be used in shotcrete is well known.[4] However, as a result of its lower hydration rate, which decreases the early-age strength development, the application of shotcrete mixtures containing slag cement in tunnel projects is limited.[5] To offset this detrimental impact on early-age performance that differs from other shotcrete applications containing SCMs, mixtures tested in this case study included a pozzolanic-based rheology control agent (TYTRO RC 430), which contributes and accelerates the C-S-H gel formation leading to increased early-age strength development.

The early-age strength development is measured with beam end testing (Fig. 1). The beam end test involves the crushing of sprayed beams, which are 3 x 3 x 16 in. (75 x 75 x 400 mm) in size, by the use of a small hydraulic pump that applies direct compression until failure occurs (Fig. 2). Although the device is similar in design to other compressive testing machines, its small size makes it portable, which provides an advantage in field conditions.[6]

Figure 3 shows the comparison of early-age strength development of three different binder systems containing a plain mixture with 100% OPC (Mix 3), a binary system with 25% fly ash (Mix 1), and a binary system with 40% slag cement (Mix 2), which were tested with the beam end test. All the mixtures met or exceeded the specification requirement to reach 145 psi (1 MPa) within 3 to 4 hours. However, it should be noted that mixtures containing fly ash and slag cement had slightly higher strength than the OPC mixture up to 4 hours followed by a slower strength development for slag cement mixture between 5 and 8 hours. Considering the very early-age strength development is mainly influenced by the accelerator, these results are expected because all three mixtures have the same type and dosage rate of accelerator (TYTRO SA 530 at 10% of total cementitious weight). On the other hand, equivalent strength for fly ash and OPC mixtures, even after 5 hours, is most likely due to the synergetic impact of the SCM and pozzolanic-based rheology control agent (TYTRO RC 430 at 0.89% of total cementitious weight), which balances the early-age strength reduction associated with fly ash with strength improvement of TYTRO® RC 430.

Figure 4 shows the impact of three different binder systems on the compressive strength of cored samples at 1, 7, and 28 days. Similar to the trends shown in Fig. 3, at a very early age, such as 1 day, the mixture with 40% slag cement had lower strength than the OPC mixture and binary system with 25% fly ash. However, due to the improved pozzolanic reactivity at later ages, slag cement outperformed the other two mixtures starting from day 7.

Figure 5 shows the impact of three different binder systems on compressive strength of cast samples at 7 and 28 days. Results correlate well with the cored samples, as similar trends were observed where slag cement exhibited the highest strength. Overall, it can be concluded that, with the aid of pozzolanic-based rheology control agent, both early-age and ultimate strength on beams, cored, and cast samples met the specification as they reached 145 psi (1 MPa) in 3 hours while exhibiting strengths higher than 6000 psi (40 MPa) and lower than 10,000 psi (70 MPa) at 28 days.

Figure 6 shows the impact of OPC mixture, fly ash, and slag cement on workability. Fly ash showed the highest slump and required the lowest dosage of water reducer, which is most likely due to its particle shape and size distribution, whereas slag cement and OPC mixture had similar workability slump and water reducer dosage. This effect with slag cement is likely due to its influence on paste characteristics and absorption. Overall, all three mixtures met the requirement of having a minimum of 6.25 in. (160 mm) slump.

The Effect of Alkali-Free Accelerators on Early- and Later-Age Strength

There is a misconception in the industry that increasing the accelerator dosage reduces the later-age shotcrete strength. While this may seem to be the case for some applications, it should be clarified that such strength reduction is observed most likely when the shotcrete mixture has an inadequate rheology, resulting in poor compaction, which becomes more pronounced at higher accelerator dosage rates due to reduced set times. Therefore, for a shotcrete mixture with desired rheology allowing sufficient consolidation, accelerator amount used within the manufacturer's recommended dosage rate (for example, 4 to 10% of the total cementitious materials content) does not necessarily decrease the later-age strength.

Figure 7 shows the impact of increased dosage rate of TYTRO SA 530 accelerator on early-age strength of a binary binder system containing 25% fly ash (Mix 1). A significant strength improvement was observed, especially when the dosage was

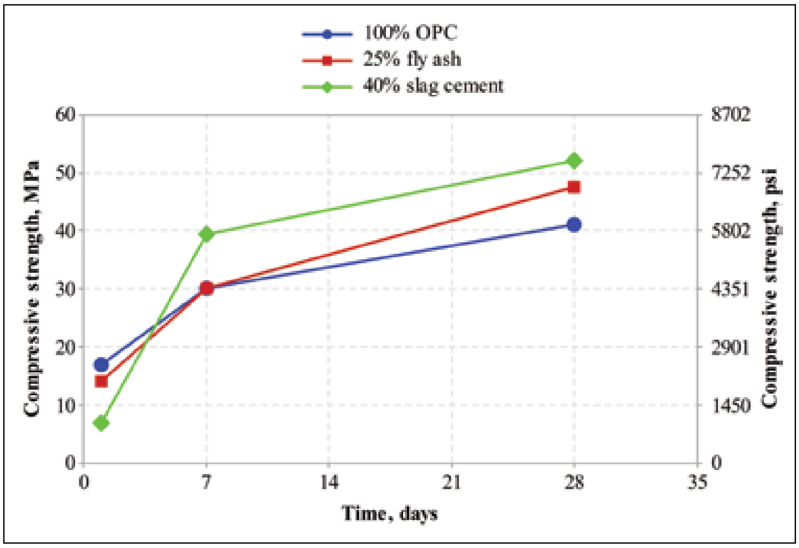

Fig. 4: Impact of cementitious materials on strength development of cored samples

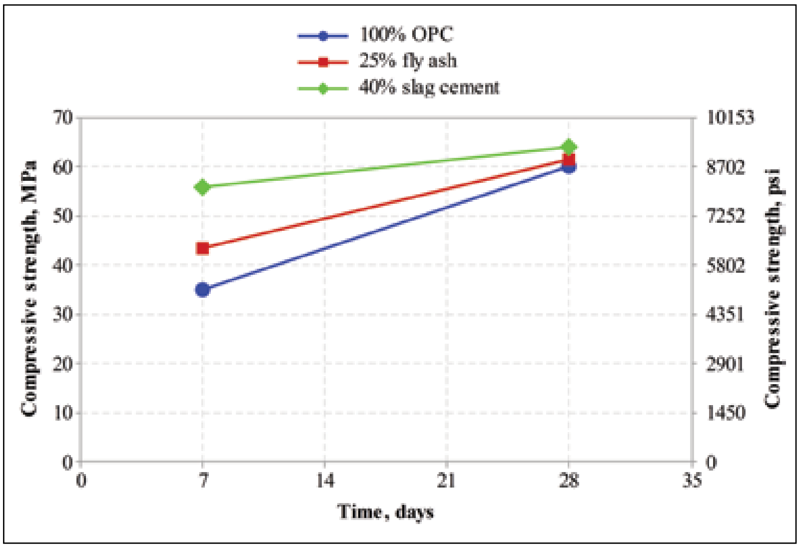

Fig. 5: Impact of cementitious materials on strength development of cast samples

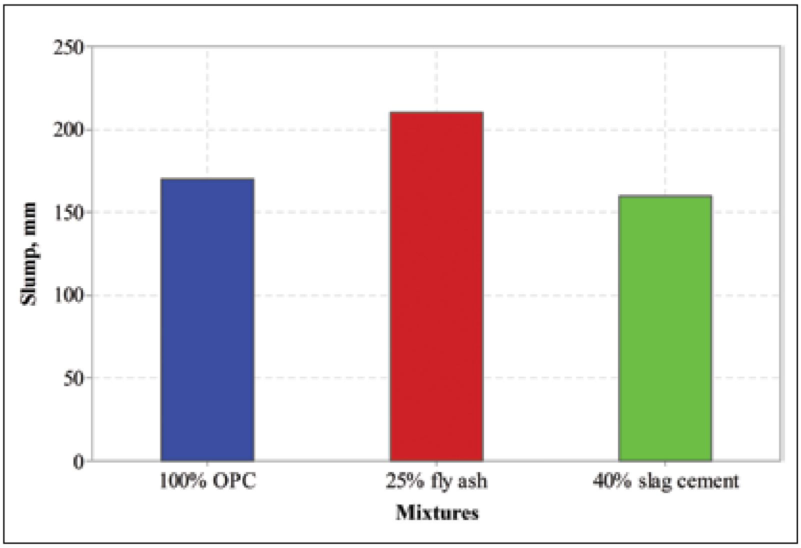

Fig. 6: Impact of cementitious materials on slump (Note: 1 mm = 0.0394 in.)

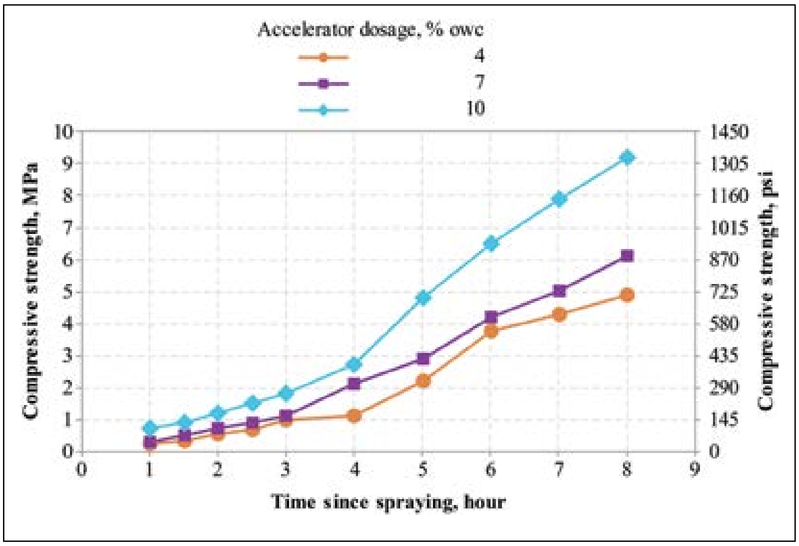

Fig. 7: Impact of TYTRO SA 530 accelerator dosage rate on early-age strength

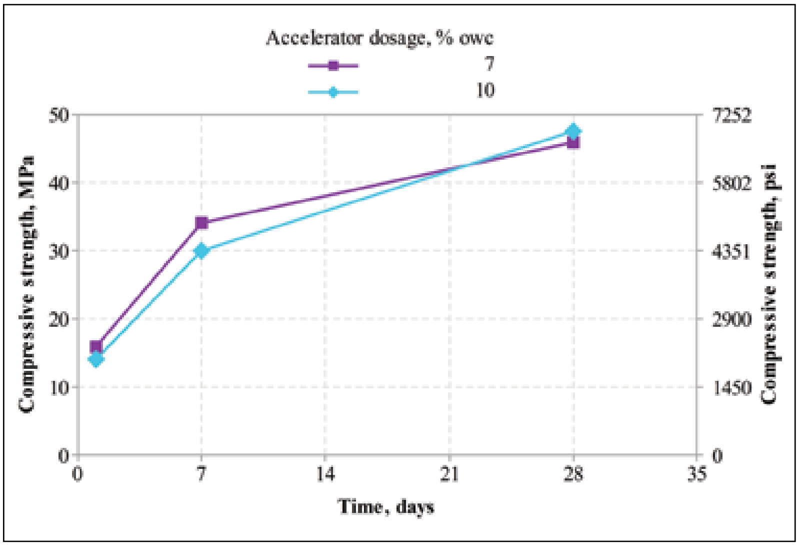

Fig. 8: Impact of TYTRO SA 530 accelerator dosage rate on ultimate strength

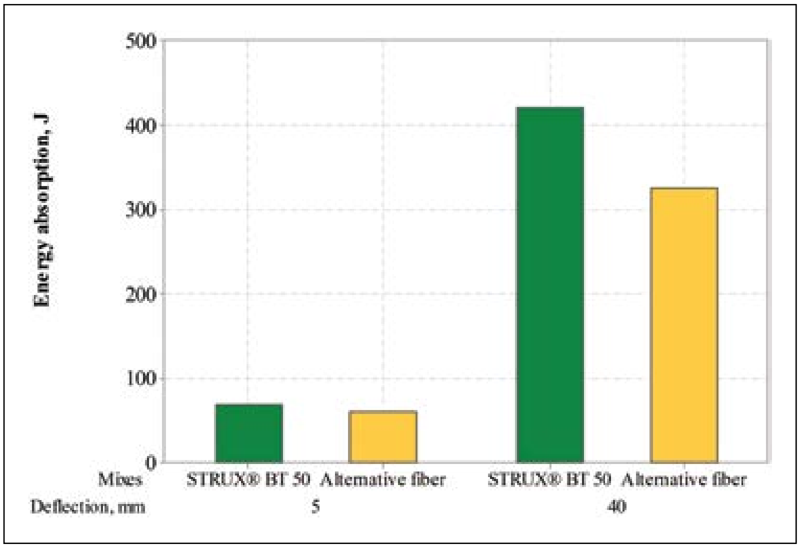

Fig. 9: Effect of STRUX BT 50 and alternative fiber on energy absorption (Note: 1 mm = 0.0394 in.)

increased from 7 to 10%. However, no strength reduction was observed on the mixture containing 10% accelerator at later ages, as shown in Fig. 8.

The Effect of Macro-Synthetic Fibers on Shotcrete Performance

Macro-synthetic fibers are commonly used in underground applications as they improve the following properties[7]:

- Post-crack energy absorption;
- Durability after cracking;
- Strain-softening behavior under deformation;
- Cost competitiveness compared to steel fibers and welded wire reinforcement; and
- Elimination of corrosion potential.

Figure 9 shows the comparison of average energy absorption measured according to ASTM C1550-12a[8] obtained from five panels for mixtures containing STRUX BT 50 and alternative 2.1 in. (54 mm) modified olefin macro-synthetic fibers. According to the round panel test, both fibers performed similar to each other at 0.2 in. (54 mm) deflection. At 1.6 in. (40 mm) panel deflection, STRUX BT 50 met the target energy absorption of 400 Joules, whereas the alternative fiber was around 325 Joules. However, when the results are evaluated considering the energy absorption and weight of fiber content at 1.6 in. (40 mm) deflection, both mixtures perform very similarly because STRUX BT 50 had 60 J/kg while the alternative fiber had 65 J/kg.

Figure 10 shows the comparison of STRUX BT 50 and the alternative fiber regarding workability. Both mixtures had comparable workability, as they had the same water reducer dosage to achieve similar slump despite the higher fiber dosage of the mixture incorporating STRUX BT 50. They both met the requirement of having a minimum of 6.25 in. (160 mm) slump. However, the aligned packaging of the STRUX BT 50 fibers (Fig. 11) helped to further reduce balling and prevented individual fibers from curling and becoming tangled prior to use, thereby enhancing placement.

Conclusions

Based on the obtained test results, the following conclusions are drawn:

- Slag cement can be used as a replacement for fly ash or ordinary portland cement as the impact of slag cement on early-age strength is offset with the presence of a pozzolanic-based rheology control agent;
- For a shotcrete mixture with desired rheology allowing sufficient consolidation, an accelerator amount used within the manufacturer's recommended dosage rate does not necessarily decrease the 28-day strength, as demonstrated in these tests;

- STRUX BT 50 is found to be a more cost-efficient option as compared to the tested alternative 2.1 in. (54 mm) modified olefin macro-synthetic-based fiber, meeting the desired energy absorption requirements; and
- With use of the full TYTRO system, all the specification requirements for this major tunnel project were met.

References

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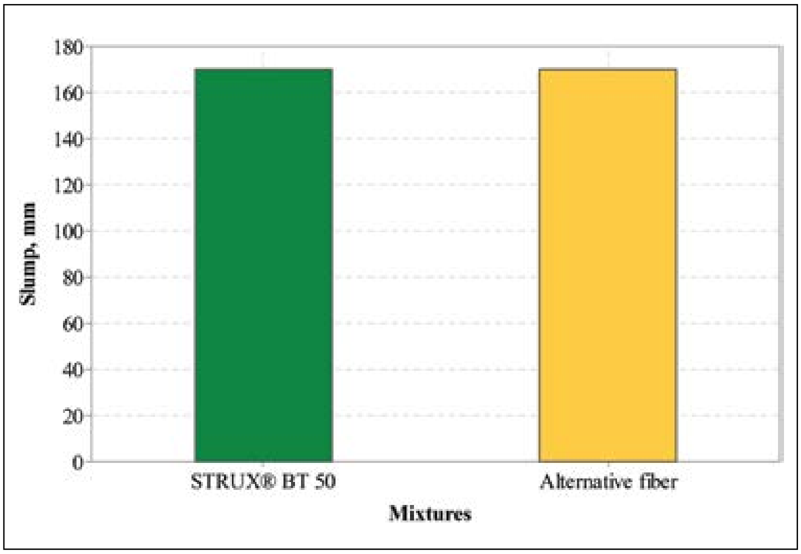

Fig. 10: Impact of macro-synthetic fibers on slump (Note: 1 mm = 0.0394 in.)

Fig. 11: Aligned packaging of STRUX BT 50 fibers

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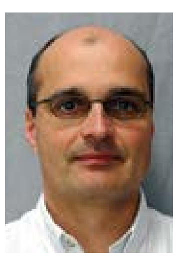

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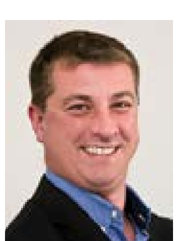

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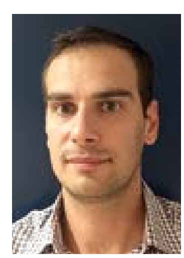

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