New Hemp-Based Fiber Enhances Wet-Mix Shotcrete Performance

By Dudley R. (Rusty) Morgan, Lihe (John) Zhang, and Mike Pildysh

An innovative processed natural hemp-based fiber has been developed for use in concrete and shotcrete (wet- and dry-mix shotcrete processes) in lieu of conventional synthetic fibers, which are derived from hydro-carbon (oil and/or gas) feedstock. A driving force behind this development has been the desire to produce a truly sustainable green fiber with dramatic reductions in CO_2 emissions into the atmosphere during fiber production, compared to the synthetic (mainly polypropylene) fibers currently being used in the concrete and shotcrete industries. Synthetic microfibers have mainly been used in concrete and shotcrete to help mitigate early-age plastic shrinkage cracking. In the absence of adequate protection and initial curing, plastic shrinkage cracking has been an issue in the shotcrete industry. Figure 1 shows an example of shotcrete used for slope stabilization at a project in California that developed severe plastic shrinkage cracking in unfavorable environmental conditions (high ambient temperatures and winds and a low relative humidity).

Initial laboratory and field trials in Calgary, AB, Canada, indicated that natural hemp-based fiber was very effective in mitigating plastic shrinkage cracking. Consequently, the fiber manufacturer decided to commission a comprehensive study to evaluate the performance of the natural hemp-based fiber in cast-in-place concrete and wet- and dry-mix shotcretes, compared to plain concrete control mixtures without any fibers and mixtures with a synthetic (polypropylene) microfiber. These studies, conducted in Vancouver, BC, Canada, demonstrated that when used at equivalent fiber-volume addition rates, not only was the natural hemp-based fiber more effective in mitigating plastic shrinkage cracking than synthetic microfiber but it also provided many additional benefits in the plastic and hardened concretes. This was particularly true for the wet-mix shotcrete process, where some marked benefits to the shotcrete application and finishing processes were found.

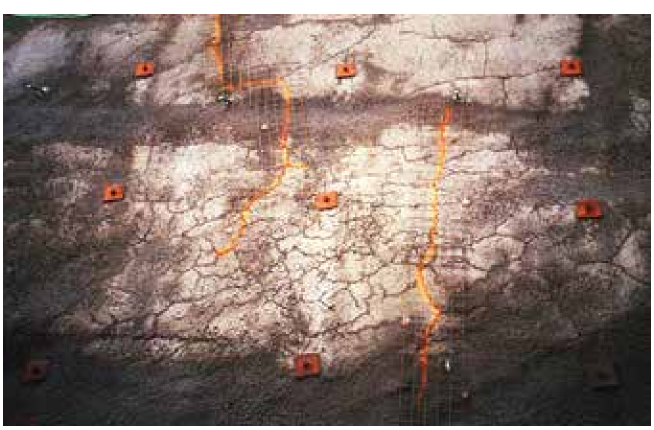


Fig. 1: Plastic shrinkage cracking in shotcrete slope stabilization

This article provides a summary of the findings from the wet-mix shotcrete laboratory study. It also provides observations from a subsequent full-scale field application of wet-mix shotcrete with the natural hemp-based fiber, with ready mixed concrete batching, mixing, and supply and conventional pumping, shooting, and finishing of structural shotcrete walls at a project in California.

Introduction

Natural fibers have been used in building products such as brick, mortar, and plaster since ancient times for the known benefits they provide to such products. One of the strongest and most durable of natural fibers has been hemp-based fiber, the same product widely used in marine ropes. Up until now, such fiber has, however, not found any significant use in portland cement-based products. This has been in part because of concerns about the durability of such fiber in a highly alkaline portland cement environment.

The manufacturers of the natural hemp-based fiber used in this report have, however, developed a process for production and surface treatment of the fiber, which makes it suitable for use in an alkaline portland cement environment. The hemp-based fiber has a higher modulus of elasticity (E-value) and tensile strength than high-quality polypropylene synthetic fibers. Also, unlike synthetic fibers, which are hydrophobic (repel water), the treated hemp-based fiber is hydrophyllic (absorbs water). This is a highly beneficial attribute for portland cement-based products such as concrete, as it promotes development of both mechanical and chemical bond of the paste to the fiber. It also reduces bleeding in concrete, thus reducing the formation of continuous bleed channels, which increase permeability and reduce durability. In addition, the fibers act as an internal curing aid, releasing water into the cement paste matrix as the concrete dries. It is believed that this, in conjunction with the higher modulus of elasticity and higher tensile strength of the hemp-based fiber, is what helps mitigate plastic shrinkage cracking in concrete and shotcrete.

In addition to the previously mentioned beneficial attributes, the incorporation of the natural hemp-based fiber in wet-mix shotcrete was found to impart several other benefits to the application and performance of shotcrete, as detailed in the Laboratory and Field studies described in the article, which follows.

LABORATORY STUDY

Shotcrete Mixture Designs

In the wet-mix shotcrete laboratory study, a comparative evaluation was conducted on the performance of shotcrete made with the natural hemp-based fiber (mixture designation WNF) compared to a plain control shotcrete without any fiber (mixture designation WP) and a shotcrete with a microsynthetic (polypropylene) fiber (mixture designation WSF). The fiber addition rates for the different mixtures are shown in Table 1. While the natural and synthetic fibers have the same fiber volume addition rate, the quantities added in kg/m^3 (lb/yd^3) differ because the natural fiber has a relative bulk density (specific gravity) of 1.48, while the synthetic fiber has a relative bulk density (specific gravity) of 0.92.

Table 2 shows the concrete mixture proportions for each of the three shotcreted mixtures. The cement, fly ash, coarse and fine aggregate contents, and water added in all three mixtures was the same. The only differences in the mixtures were the type of fiber added and small variations in the amount of water-reducing admixture and air-entraining admixture added to provide the required slump and air content. The shotcretes were designed to meet CSA A23.1/23.2-2014 Class C1 exposure requirements—that is, structurally reinforced concrete exposed to chlorides with or without freezing-and-thawing conditions. Such concrete (or in this case, shotcrete) is required to have a maximum water-cementitious materials ratio (*w/cm*) of 0.40, a minimum compressive strength of 5100 psi (35 MPa) at 28 days, and be suitably air entrained. The base shotcrete mixture design in Table 2 has a fly ash content of 20% by mass of cementitious material and is typical of structural wet-mix shotcrete used in Western Canada and other parts of North America. The slightly higher water-reducing admixture dosage rate in the WNF mixture is attributed to water uptake by the natural fiber and hence the need to increase the admixture dosage to provide the required slump.

Shotcrete Batching, Mixing, and Application

The shotcrete mixtures for this laboratory study were pre-batched with aggregates in an oven-dry condition and supplied in 0.5 yd^3 (0.38 m^3) bulk bin bags. The dry bagged materials were discharged into a pan mixer with counter-rotating paddles, where the mix water and liquid air-entraining and water-reducing admixtures were added. Figure 2 shows dry-bagged material being discharged into

Table 1: Wet-mix shotcrete mixtures

Mixture type	Shotcrete designation	Fiber content		
		kg/m^3	lb/yd^3	% volume
Plain	WP	0	0	0
Natural fiber	WNF	2	3.4	0.15
Microsynthetic fiber	WSF	1.35	2.3	0.15

Table 2: Wet-mix shotcrete mixture proportions

Material	Mixture WP: Plain shotcrete		Mixture WSF: Microsynthetic fiber shotcrete		Mixture WNF: Natural fiber shotcrete	
	kg/m^3	lb/yd^3	kg/m^3	lb/yd^3	kg/m^3	lb/yd^3
Cement type GU (ASTM Type I)	360	607	360	607	360	607
Fly ash	90	152	90	152	90	152
Coarse aggregate (10-5 mm, SSD)	430	725	430	725	430	725
Fine aggregate (SSD)	1290	2174	1290	2174	1290	2174
Water, L	180	303	180	303	180	303
Water-reducing admixture, L*	1.15	2	1.05	2	1.3	2
NForce fiber	—	—	—	—	2	3.4
Microsynthetic fiber	—	—	1.35	2.3	—	—
Total	2351.15	3963	2352.4	3965	2353.3	3967

*Water-reducing admixture added during mixing at dosage required to achieve the maximum allowable *w/cm* and required slump

Fig. 2: Prepackaged dry shotcrete materials discharging into pan mixer

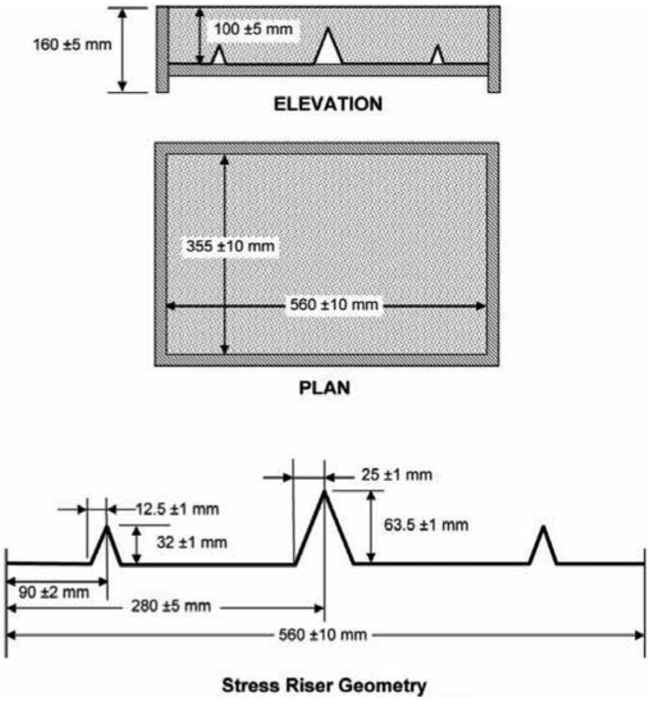


Fig. 3: Configuration of plastic shrinkage cracking test mold (Note: 1 mm = 0.0394 in.)

Fig. 4: Shooting into mold for plastic shrinkage cracking testing

the 1.0 yd^3 (0.76 m^3) pan mixer. Such mixers are commonly used in the precast concrete industry but are also very useful for laboratory studies. Weighed-out quantities of the loose natural and synthetic fibers were added to mixtures WNF and WSF and mixed for a minimum of 5 minutes. The quantities of water-reducing and air-entraining admixtures added were adjusted as necessary to produce the required slump and air content.

The mixed shotcrete was discharged into a Putzmeister shotcrete pump, which conveyed the shotcrete in a 2 in. (50 mm) internal diameter rubber hose to the nozzle, where air was introduced from a 185 ft^3/min (5.24 m^3/min) air compressor to pneumatically project the shotcrete at high impacting velocity onto the receiving surface. The fibers appeared well dispersed in both fiber mixtures and the mixtures shot well with no problems of fiber balling or pump blockages being encountered. Shotcrete application was done by an ACI Certified Shotcrete Nozzleman.

The nozzleman shot standard vertical test panels with sloped sides, from which cores were extracted for testing for:

a. Compressive strength at 7 and 28 days to ASTM C39;
b. Boiled absorption (BA) and volume of permeable voids (VPV) at 28 days to ASTM C642; and
c. Rapid chloride penetrability (RCP) at 91 days to ASTM C1202.

In addition, two molds were shot horizontally for each of the fiber mixtures for production of test specimens for ASTM C1579, "Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert)." Figure 3 shows the configuration of the test mold. Figure 4 shows shooting into the mold.

Plastic Shotcrete Properties

The temperature, slump, and air content of the plastic shotcrete was tested at the point of discharge into the shotcrete pump. In addition, the as-shot air content was determined by shooting the shotcrete into a standard ASTM C231 air pressure meter bowl. Test results for all three mixtures are provided in Table 3. The slump for all three mixtures was in the design range of 2 to 3 in. (50 to 75 mm). The slightly higher-than-design air content in the as-batched WNF mixture is attributed to the effect of the higher water-reducing admixture dosage in this mixture.

In addition to the standard tests, the plastic shotcretes were assessed for characteristics such as shootability (adhesion and cohesion and resistance to sagging and sloughing) when applied to a vertical surface. Figure 5 shows shooting a beehive (extended thickness mounded in center of shotcreted area) of the plain concrete mixture (WP) on a vertical plywood panel.

While all three mixtures shot well and could be built up to a 6 in. (150 mm) thickness on a vertical plywood form in a single pass, some marked differences were found in the shooting characteristics of the mixtures. The plain WP mixture displayed the lowest adhesion and cohesion performance. Shortly after being built up to the full 6 in. (150 mm) thickness, it started to sag, and then sloughed

Table 3: Plastic shotcrete properties

Mixture	Fiber content			Slump		Air content, %		Temperature	
	kg/m³	lb/yd³	% volume	mm	in.	As-batched	As-shot	°C	°F
WP	0	0	0	50	2.0	5.5	4	13	55
WNF	2	3.4	0.15	70	3.0	9	4.3	18	64
WSF	1.35	2.3	0.15	60	2.5	8	4.8	20	68

Note: Specified slump is 3 ± 1 in. (70 ± 20 mm); specified as-shot air content is 3.0 to 6.0%.

Fig. 5: Shooting a beehive of plain concrete mixture (WP) 6 in. (150 mm) thick on a vertical plywood panel

Fig. 7: Measuring thickness of natural fiber mixture (WNF) beehive

Fig. 6: Synthetic fiber mixture (WSF) sloughed off plywood panel after being disturbed by cutting

Fig. 8: Cutting and trimming natural fiber mixture (WNF) with no sagging or sloughing

off the plywood panel under its own weight. The synthetic fiber mixture (WSF) displayed better performance in that it did not sag or slough off the plywood form immediately after shooting. However, when it was disturbed and when an attempt was made to cut it with a trowel, it sloughed off the plywood form, as shown in Fig. 6.

By contrast, the natural fiber mixture (WNF) displayed great adhesion and cohesion and did not sag or slough when built up to the full 6 in. (150 mm) thickness, as shown in Fig. 7. The WNF mixture could be cut, trimmed, and finished without any sagging or sloughing, as shown in Fig. 8. In fact, considerable effort had to be expended by a finisher to dislodge the beehive from the plywood form using a flat spade. It is believed this markedly enhanced adhesion and cohesion is attributable not only to the reinforcing effect of the natural fiber but also due to the hydrophyllic fiber absorbing some of the excess water of workability from the shotcrete and reducing bleeding tendencies in the applied mixture.

Plastic Shrinkage Cracking Test

As previously mentioned, evaluation of the plastic shrinkage cracking characteristics of the plain concrete mixture (WP), compared to the synthetic fiber mixture (WSF) and natural fiber mixture (WNF), was conducted using the ASTM C1579 test procedure. In this test, two molds were shot, finished, and tested for each mixture. After finishing in a prescribed manner, the test specimens were placed in individual environmental chambers (essentially heated wind tunnels), which provided an environment of: temperature 97 ± 5°F (36 ± 3°C); wind velocity of 15.4 ft/s (4.7 m/s); and relative humidity 30 ± 10%, as required by the test method. In addition, a water sample in a beaker was placed in each environmental chamber to monitor the evaporation rate. ASTM C1579 specifies a minimum evaporation rate of 0.2 lb/ft^2-h (1.0 kg/m^2-h) and this requirement was met in all environmental chambers. A setting time test was conducted to ASTM C403, "Standard Test Method for Time of Setting by Penetration Resistance." Once the shotcrete samples reached final set, the samples, still in their molds, were removed from the environmental chambers and placed in still air in a temperature- and humidity-controlled room in the laboratory for curing at 73 ± 4°F (23 ± 2°C) and 50% relative humidity for 24 hours, as prescribed by the test method. Average crack widths in the specimens were then measured with a crack comparator.

The test method requires the plain concrete control sample (WP) to develop a minimum crack width of 0.02 in. (0.5 mm). The average crack widths in the fiber-reinforced samples (WSF and WNF) were compared against the WP mixture specimen crack widths. A factor called the crack reduction ratio (CRR), expressed as a percentage (%), is then calculated.

CRR = [1 – average crack width of fiber-reinforced shotcrete mixture/average crack width of plain control shotcrete mixture] × 100%.

In this study, the plain concrete control mixture (WP) developed an average crack width of 0.025 in. (0.63 mm), which satisfies the ASTM C1579 requirement. The synthetic fiber mixture (WSF) developed an average crack width of 0.004 in. (0.10 mm) and the natural fiber mixture (WNF) developed an average crack width of 0.002 in. (0.05 mm). The calculated CRR was 84% for the synthetic fiber mixture WSF and 92% for the mixture WNF. In other words, the synthetic fibers and natural fibers were effective in reducing plastic shrinkage crack widths by 84% and 92%, respectively. In short, both fiber types were effective in mitigating plastic shrinkage cracking, but when used at equal fiber volume addition rates (0.15%), the natural fiber was more effective than the synthetic fiber.

Finishability

While in some shotcrete applications, such as ground support in tunnels and mines and rock-slope stabilization, the final surface is left in the rough, natural, as-shot surface condition (such as can be seen in Fig. 7), there are many applications where the applied shotcrete is cut and trimmed to line and grade and then finished to a specified surface tolerance and finish texture. This is common in structural shotcrete walls and other elements, canal linings, bobsleigh and luge tracks, resurfacing of concrete dams and spillways, swimming pools and other liquid-retaining structures, and architectural applications. Finishing is labor-intensive and can require three to five or even more finishers to keep up with one nozzleman, depending on the nature of the project. (For example, finishing of a bobsleigh/luge track may require as many as eight finishers for one nozzleman). Thus, anything that can be done to enhance the finishability of shotcrete can have significant impact on productivity and hence costs of a shotcrete operation.

Fig. 9: Finishing tools used, from left to right: steel trowel, magnesium trowel, wood float, hard rubber float, textured rubber float, and sponge float

In this study, the wet-mix shotcrete mixtures were shot into 14 x 22 x 4 in. (355 x 550 x 100 mm) plywood boxes and finished using different hand-held finishing tools to evaluate the finishability of the different mixtures. The finishing tools used (in sequence from smoothest to most textured surface finish) are shown in Fig. 9 and were: steel trowel, magnesium trowel, wood float, hard rubber float, textured rubber float, and sponge float.

The plain shotcrete mixture (WP) was relatively easy to finish with all the selected finishing tools, showing the expected sequence of smoothest to more textured surface finishes for the different tools, as described earlier. The mixture with synthetic fibers (WSF) proved to be the most difficult to finish, particularly with the tools producing more textured surface finishes, as they tended to pull fibers to the surface, leaving a rougher surface with many protruding fibers. Even the steel- and magnesium-troweled surfaces displayed some protruding synthetic fibers. This is attributed to the hydrophobic characteristics of the synthetic fiber. Some architects and engineers find this to be an annoyance and ask the contractor to burn off protruding synthetic fibers using a torch. Figure 10 shows an example of the WSF mixture finished with a magnesium trowel. Protruding synthetic fibers were present in the finished surface.

By contrast, the mixture with natural fiber displayed superior finishing characteristics to both the plain shotcrete mixture and the synthetic fiber mixture. The treated natural fiber provided the applied shotcrete with greater cohesion

Fig. 10: Synthetic fiber mixture WSF finished with a magnesium trowel

Fig. 11: Natural fiber mixture (WNF) finished with a magnesium trowel

and appeared to act as a finishing aid. This resulted in relatively smoother-textured surface finishes for all the finishing tools used, particularly when compared against the mixture with synthetic fiber. Virtually no fibers were present in the finished surface of the WNF mixture finished with steel and magnesium trowels. Figure 11 shows an example of the WNF mixture finished with a magnesium trowel. Very few fibers were drawn to the surface, or were evident in the panels finished with wood, rubber, or sponge floats. The greater ease of finishing for mixtures incorporating the natural fiber has very positive implications for shotcrete productivity.

Hardened Shotcrete Tests

Tests were conducted on cores extracted from hardened shotcrete test panels for determination of:

a. Compressive strength to ASTM C39;
b. Boiled absorption (BA) and volume of permeable voids (VPV) to ASTM C642; and
c. Rapid chloride penetration to ASTM C1202.

Test results for the hardened shotcrete properties are provided in Table 4.

With respect to compressive strength, all three mixtures readily meet the CSA A23.1 minimum design strength of 5100 psi (35 MPa) at 28 days for concrete with a Class C1 exposure. Clearly, natural fiber addition does not have any detrimental effect on compressive strength. The mixture with natural fibers displayed the highest compressive strength at both 7 and 28 days of all three mixtures tested.

With respect to tests for BA and VPV, all three mixtures had values well below the typical maximum of 8% for BA and 17% for VPV for quality shotcrete with nonporous aggregate with normal cement factors as recommended in ACI 506R-16, "Guide to Shotcrete." Natural fiber addition does not have any detrimental effect on permeability. The mixture with natural fiber displayed the lowest BA and VPV values of all three mixtures tested.

With respect to the tests for rapid chloride penetration (RCP), CSA A23.1 requires a maximum allowable value of 1500 Coulombs at 91 days for a concrete with Class C1 exposure. With test results for all three mixtures in the 898 to 1037 range, ASTM C1202 and CSA A23.1 would rate such shotcretes as having "Low" chloride penetrability. The addition of natural fiber to the mixture is not detrimental to the chloride penetrability of the shotcrete.

FIELD EVALUATION

Mixture Designs and Shotcrete Batching, Mixing, and Supply

The second phase in the evaluation of the use of the natural hemp-based fiber in wet-mix shotcrete was to assess its

Table 4: Hardened shotcrete properties

	Fiber content			Compressive strength				Boiled absorption	Volume of permeable voids	RCP results at 91 days
Mixtures	kg/m³	lb/yd³	% volume	7 days, MPa	7 days, psi	28 days, MPa	28 days, psi	%	%	Coulombs
WP	0	0	0	35	5075	47.9	6950	5.3	11.9	966
WNF	2	3.4	0.15	43.7	6340	57.6	8355	5.1	11.5	1037
WSF	1.35	2.3	0.15	36.6	5310	51.7	7500	5.4	12	898
Design/specified value:				**30**	**4350**	**40**	**5800**	**max. 8.0%**	**max. 17%**	**1500**

performance in a full-scale field trial, with ready mixed concrete batching, mixing, and supply, in a structural shotcrete application. The evaluation was carried out at the Jos. J. Albanese yard in Santa Clara, CA. Two different wet-mix shotcrete mixture designs commonly used by them in the Bay Area were modified by the addition of the natural hemp-based fiber, and used to construct two structural shotcrete walls for aggregate storage bins. The actual shotcrete mixture designs used are proprietary and so are not reproduced in this paper. Both mixtures had the same portland cement content and contained 15% fly ash by mass of cement. The main difference between the two mixtures was Mixture A had a 3/8 in. (10 mm) pea gravel coarse aggregate and the second mixture, Mixture B, had a 0.5 in. (13 mm) crushed granite coarse aggregate.

Fig. 12: Natural fiber-reinforced shotcrete (Mixture B) being discharged from concrete truck chute into pump hopper; note highly cohesive nature of mixture

Fig. 13: Reed C50 pump used to pump wet-mix process shotcrete

Fig. 14: Formwork and reinforcing bar for L-shaped wall

The natural hemp-based fiber was supplied in 1 lb (0.45 kg) shreddable bags and added to the concrete truck during batching and mixing. The fibers were incorporated into the mixtures at addition rates of 1.5 lb/yd^3 (0.89 kg/m^3) for Mixture A and 3.0 lb/yd^3 (1.8 kg/m^3) for Mixture B. Figure 12 shows Mixture B being discharged from the concrete truck chute into the pump hopper. An 8.0 yd^3 (6.1 m^3) load of Mixture A was supplied at a slump of 3.5 in. (90 mm). A 7.0 yd^3 (5.4 m^3) load of Mixture B was supplied at a slump of 3.0 in. (75 mm). The shotcrete temperature for both mixtures was 76°F (24°C) and the ambient temperature was around 72°F (22°C) at the time of shooting.

Both Mixtures A and B were highly cohesive and pumped and shot well, without any signs of fiber clumps or remnants of the water-shreddable bags being evident during shotcrete discharge, pumping, and shooting or in the as-shot structural walls. The shotcretes were pumped to the nozzle where compressed air was added to pneumatically project the shotcrete at high impacting velocity onto the receiving surface, using the Reed C50 pump shown in Fig. 13.

Structural Shotcrete Walls Construction

Two structural shotcrete walls, one L-shaped and the other straight, were formed and shot. The L-shaped wall was approximately 16 ft (4.9 m) long and 6 ft (1.8 m) high. The straight wall was approximately 20 ft (6.1 m) long and 4 to 5 ft (1.2 to 1.5 m) high. Both walls were 18 in. (450 mm) thick and were reinforced with a double mat of No. 6 (No. 20M) reinforcing bar. Figure 14 shows the L-shaped wall. The walls were constructed as extensions to aggregate storage bins in the Jos. J. Albanese yard and provided a good opportunity to evaluate how the natural fiber-reinforced shotcrete behaved during shotcrete application, finishing, and subsequent field performance.

Both shotcrete mixtures were observed to be very cohesive and the ACI Certified Nozzleman doing the shooting could bench shoot (stack) the structural shotcrete to the full height in both walls without any sagging, sloughing, or fallout. The shotcrete was applied to just cover the outer layer of reinforcing bar. A blow-pipe operator worked alongside the nozzleman, blowing out any accumulations of rebound and overspray from the areas about to receive shotcrete. A finish coat of the shotcrete was then applied from the top down, to build the walls out to their full thickness. Figure 15 shows bench-gun shooting the L-shaped structural wall.

Shooting wires had been installed to control line and grade and the nozzleman shot the final layer to just cover the

Fig. 15: Bench-gun shooting L-shaped wall

Fig. 17: View of finished straight wall

Fig. 16: Trimming shotcrete to shooting wires with cutting screed (rod)

Fig. 18: Stripped face of L-shaped wall is defect-free

shooting wires. Because of the very cohesive characteristics of the natural fiber-reinforced shotcrete, the finisher using the cutting screed (rod) could follow immediately behind the nozzleman (only a few feet away), cutting and trimming the shotcrete to the shooting wires to control line and grade. Figure 16 shows the finisher trimming the shotcrete to the shooting wires in the straight wall.

A finisher with a darby (long wood float) followed right behind the cutting screed operator, closing and smoothing the shotcrete surface. Final finishing with wood hand floats was carried out to provide a stucco-like surface finish appearance. No fibers were found protruding in the finished shotcrete surface. Figure 17 provides a view of the finished face of the straight wall. The nozzleman and finishers were impressed with the enhanced productivity provided by being able to bench shoot the walls to their full height in one pass and, after shooting of the layer, follow immediately behind the nozzleman with finishing operations, without any problems of shotcrete sagging, sloughing, or fallout. The finishers also commented on how easy it was to finish the walls; the natural fiber appeared to act as a finishing aid for the shotcrete.

Shotcrete Examination and Testing

A few days after shooting, the plywood forms were stripped from the back side of the aggregate bin walls and the stripped faces of the aggregate bin walls were examined. The walls were observed to be essentially defect-free, with no significant voids from incomplete consolidation, sags, tears, or shadows behind the reinforcing bar. Figure 18 shows the stripped face of the L-shaped wall. Also, examination of the structural shotcrete walls after several weeks of service showed no evidence of plastic or restrained drying shrinkage cracking.

In addition to shooting the structural walls, the nozzleman shot a 2 ft x 2 ft x 4 in. (610 x 610 x 100 mm) test panel with Mixture A. The test panel was cured on site until shipment to a testing laboratory in Vancouver for testing. Cores were extracted for testing for compressive strength to ASTM C39, and values of BA and VPV to ASTM C642 at an age of 28 days. The average 28-day compressive strength was 4440 psi (30.7 MPa), which satisfied the specified minimum compressive strength of 4000 psi (27.6 MPa) at 28 days for this project. The average values for BA and VPV were 7.6 and 16.9%, respectively, which satisfied the maximum allowable values of 8% BA and 17% VPV.

These values are higher than measured in the laboratory study (refer to Table 4), but this is because the Field Evaluation mixture had a higher *w/cm* of 0.45, compared to a *w/cm* of 0.40 in the laboratory study mixtures shown in Table 2.

SUMMARY

The comparative laboratory study and field evaluation detailed in this paper has demonstrated that treated natural hemp-based fiber has several beneficial attributes that enhance the performance of wet-mix shotcrete with no detrimental effects. These beneficial attributes include the following:

1. The treated natural hemp-based fiber is hydrophyllic (absorbs water) and as such is compatible with portland cement-based systems. In particular:
   a. The fiber is readily dispersible in wet-mix shotcrete, providing uniform distribution of the fiber during mixing, pumping, and shooting, without fiber balling or segregation.
   b. Water absorbed by the fiber during batching and mixing acts as an internal curing aid because water is available to the cement paste during hydration. This is beneficial in helping to mitigate early-age plastic and drying shrinkage-induced cracking.
2. The natural fiber shotcrete displayed a superior CRR in the ASTM C1579 plastic shrinkage cracking test, compared to the microsynthetic fiber-reinforced shotcrete.
3. The natural fiber addition produced a very cohesive wet-mix shotcrete, suitable for pumping and shooting without segregation or pump blockages.
4. The natural fiber shotcrete displayed remarkable adhesion characteristics when applied to a vertical plywood form, compared to the plain control shotcrete and shotcrete with microsynthetic fiber. Unlike those two shotcretes, considerable effort was required to dislodge a beehive of natural fiber shotcrete from the plywood form. This has very positive implications for shotcrete applications to vertical and overhead surfaces, where adherence of fresh shotcrete to the substrate surface is an important consideration (for example, in shotcrete repair and restoration works and in tunneling, mining, and rock slope stabilization projects).
5. Because of the very adhesive and cohesive rheology of the natural fiber mixture, it was possible to bench shoot (stack) 18 in. (450 mm) thick structural shotcrete walls to heights up to 6 ft (1.8 m) in a single pass without sagging, sloughing, or fallout. This provides opportunities for accelerating the shotcrete construction schedule.
6. The natural fiber shotcrete displayed superior finishing characteristics to the microsynthetic fiber-reinforced shotcretes because fibers were not drawn to or exposed on the surface by finishing operations. The finishers commented that the natural fiber appeared to act almost like a finishing aid.
7. Because of the stable nature of the just-shot natural fiber shotcrete (resistance to sagging, sloughing, and fallout), finishers could follow closely behind the shotcrete nozzleman. This provides opportunities for accelerating the shotcrete construction process.
8. Tests conducted on cores extracted from the hardened shotcrete demonstrated that the natural fiber had no detrimental effects on properties of the hardened shotcrete, such as compressive strength, BA, and VPV (an indicator of permeability), or rapid chloride penetrability (an indicator of resistance to chloride ion intrusion). In fact, the natural fiber shotcrete displayed slightly higher values of compressive strength and lower values of BA and VPV compared to the plain control shotcrete or shotcrete with microsynthetic fibers.
9. Finally, because the natural fiber is produced from custom-farmed hemp plants, it is a sustainable green product, with much reduced CO_2 emissions compared to microsynthetic fibers that are derived from hydrocarbon (oil and gas) feedstock.

Based on the studies detailed in this paper, it is recommended that the treated natural hemp-based fiber be added to wet-mix shotcrete at fiber addition rates as follows:

a. In favorable ambient environmental conditions with low evaporation rates (cooler temperatures, high relative humidity, and low wind speeds) and thus a low potential for early-age plastic and drying-shrinkage-induced cracking, use a fiber addition rate of approximately 1.5 lb/yd^3 (0.89 kg/m^3).
b. In less-favorable ambient environmental conditions with higher evaporation rates (warm temperatures, lower relative humidity, and higher wind speeds), with a higher potential for early-age plastic and drying shrinkage cracking, use a fiber addition rate of approximately 3.0 lb/yd^3 (1.78 kg/m^3).
c. In severe ambient environmental conditions (high temperatures and wind speeds and very low humidity) with a consequent high potential for early-age plastic shrinkage and drying-shrinkage-induced cracking, use a fiber addition rate of approximately 3.4 lb/yd^3 (2.0 kg/m^3), or even higher if necessary.

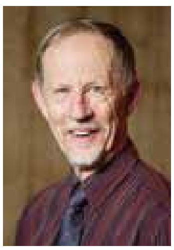
For each of environmental conditions (a), (b), and (c), good shotcrete protection and curing practices, as detailed in ACI 506R-16, "Guide to Shotcrete," should still be implemented.

Acknowledgments

The laboratory study and field evaluation of wet-mix shotcrete presented in this paper were sponsored by Canadian Greenfield Technologies Corporation of Calgary, AB, Canada. The processed natural hemp-based fiber used is manufactured by them and sold under the trade name NForce-Fiber. The shotcrete used in the laboratory study was batched and dry-bagged by Basalite Concrete Products Vancouver ULC and the wet-mix shotcrete production and testing was carried out at their Surrey, BC, Canada, plant. Shotcrete equipment and application was provided by Structural Shotcrete Ltd., Surrey, BC, Canada. The ACI Certified Shotcrete Nozzleman used to apply the shotcrete in the laboratory study was S. Ellis of Structural Shotcrete Ltd. The field and laboratory testing was conducted by LZhang Consulting & Testing Ltd., Vancouver, BC, Canada.

The field evaluation of the NForce-Fiber in wet-mix shotcrete was carried out in the Jos. J. Albanese plant in Santa Clara, CA. Wet-mix shotcrete mixture designs and supply were by Central Concrete Supply Company, a division of U.S. Concrete Company. Shotcrete equipment and structural shotcrete walls construction were provided by Jos. J. Albanese. Laboratory testing was carried out by LZhang Consulting & Testing, Vancouver, BC, Canada. Overall project initiation and management was provided by D. R. Morgan of Victoria, BC, Canada.

The support of the following individuals for this laboratory study and field evaluation project is gratefully acknowledged: M. Pildysh, Canadian Greenfield Technologies Corporation, Calgary, AB, Canada; D. Ceolin, Basalite Concrete Products Vancouver ULC, Surrey, BC, Canada; L. Rutt and S. Ellis, Structural Shotcrete Ltd., Surrey, BC, Canada; L. Zhang, LZhang Consulting & Testing Ltd., Vancouver, BC, Canada; C. Zynda, Jos. J. Albanese, Santa Clara, CA; and P. Frawley, Central Concrete Supply Company, San Jose, CA.



***Dudley R. (Rusty) Morgan**, PhD, PEng, FACI, is a Civil Engineer with over 50 years of experience in the concrete and shotcrete industries. He was a member and Secretary of ACI Committee 506, Shotcreting, for over 25 years. He is a past member of ACI Committees 365, Service Life Prediction, and 544, Fiber-Reinforced Concrete. Morgan is a founding member and Past President of ASA. He is an ACI C660-approved Shotcrete Nozzleman Examiner and presenter for the ASA Shotcrete Nozzleman Education course. Morgan is a past member of the Canadian Standards Association Concrete Steering Committee and was Canadian Representative on the International Tunneling Association Committee: Shotcrete Use. He has worked on over a thousand concrete and shotcrete projects around the world during his consulting career and has edited five books and published over 150 papers on various aspects of concrete and shotcrete technology. In 2001, Morgan was elected as a Fellow of the Canadian Academy of Engineering.*

***Lihe (John) Zhang**, PhD, PEng, is an Engineer and Owner of LZhang Consulting & Testing Ltd. He received his PhD in civil engineering from the University of British Columbia, where he conducted research on fiber-reinforced concrete. He has over 15 years of experience in concrete and shotcrete technology and the evaluation and rehabilitation of infrastructure. Zhang is a member of the American Concrete Institute. He is Chair of ACI Subcommittee 506-F, Shotcreting-Underground, and a member of ACI Committees 130, Sustainability of Concrete; 506, Shotcreting; and 544, Fiber-Reinforced Concrete. He is an ACI C660-approved Shotcrete Nozzleman Examiner and presenter for the ASA Shotcrete Nozzleman Education course. Zhang is a member of ASTM Committee C09, Concrete and Concrete Aggregates, is an ASA Officer and Board Member, and chairs the ASA Technical Committee.*

***Mike Pildysh**, MEng, PEng, is President of Canadian Greenfield Technologies Corporation. He is a civil engineer with over 35 years of experience in the building materials industry. He was, for a time, Head Civil Engineer for Monenco Engineering, which was then the second largest engineering company in Canada. He subsequently founded and operated a group of companies, including the very successful Cementec Industries Inc., which supplies specialty construction materials to the civil engineering and oil industries. Pildysh is a licensed professional engineer in Alberta, British Columbia, and Ontario. He has authored 12 patents and has over 20 publications. He is a former member of the United States Research Technology Board. Pildysh is a member of ASA, the American Concrete Institute, the American Chemical Society, and the Chemical Institute of Canada.*