Centrifugal sprayed concrete for lining horizontal pipes, culverts, and vertical shafts

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ABSTRACT: Conventional dry-mix shotcrete (where water is added at the nozzle) or wet-mix shotcrete (where air is added at the nozzle to pneumatically convey the material to the receiving surface) has long been used for lining horizontal pipes, culverts, and vertical shafts. This paper, however, describes a different technology for spraying concrete onto such surfaces: the use of wet-mix centrifugal sprayed concrete (CSC). Instead of adding water at the nozzle (as in dry-mix shotcrete), or air at the nozzle (as in wet-mix shotcrete), the concrete mix is pumped to a spinning head, which spins at between about 4000 to 5000 rpm. The concrete is then centrifugally sprayed onto the receiving surface at high impacting velocity. This paper describes the use of this CSC technology for lining horizontal pipes, culverts and other circular structures and vertical raise-bore shafts. A case history example is described for a vertical raise-bore shaft at New Gold Inc's New Afton copper-gold mine near Kamloops in British Columbia, Canada, using a macro-synthetic Fibre Reinforced Concrete. This is believed to be the first use of this technology in North America, if not the world. Productivity with the CSC was much greater than that previously achieved in using a conventional robotically supplied dry-mix, steel fibre reinforced shotcrete system to line similar vertical shafts at the mine.

1 INTRODUCTION

Since 1991 Shotcrete Technologies Inc. has provided remotely-controlled equipment and know-how for wet-mix shotcrete lining of many horizontal pipes, culverts, and vertical shafts in tunnels and mines. Some of these horizontal structures were over 1000 m long and some of the shafts were over 100 m deep. Pipe and culvert diameters ranged from as little as 450 mm to as much as 2.5 m. Shafts were typically in the 2.5 to 3.5 m diameter range. Plain and synthetic or steel Fibre Reinforced Shotcrete mixes have been used in many such applications, depending on the engineer's requirements. A remotely-control wet-mix shotcrete lining rig is shown being being winched through a pipe in Figure 1. Visual monitoring is provided by a television camera attached to the robotic rig. Figure 2 shows a similar wet-mix shotcrete robotic rig being used to line a raise-bore shaft at a mine.

While the preceding systems have generally worked well and provided high quality lining systems, they are not without their challenges. There are many moving parts in the robotic rig that need to be maintained and the shotcrete nozzle needs to be regularly cleaned in order to maintain an optimal spraying pattern. Recognizing this, Shotcrete Technologies Inc. embarked on development of an innovative new system for spraying concrete; the development of the centrifugal sprayed concrete (CSC) spinner head system. A list is provided in Table 1 of some of the projects where robotically applied CSC has been used for lining horizontal pipes, culverts and other structures. Most of this paper, however, concentrates on the CSC lining of a 3.5 m diameter 290 m deep raise-bore shaft at New Gold Inc's New Afton copper-gold mine near Kamloops, British Columbia, Canada in June 2009, using a macro-synthetic fibre reinforced wet-mix CSC. This is believed to be the first use of this technology in North America, if not the world.

Figure 1. Robotic lining of pipe with conventional wet-mix shotcrete.

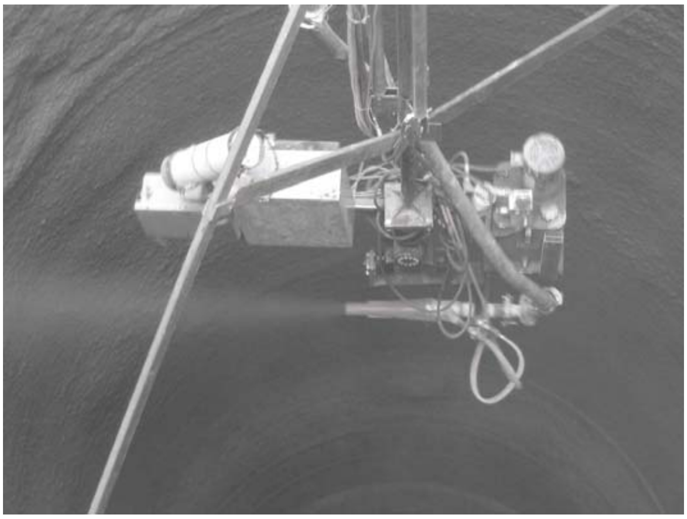

Figure 2. Robotic lining of raise bore shaft with conventional wet-mix shotcrete.

2 CENTRIFUGAL SPRAYED CONCRETE SYSTEM

The spinning head used on the gold mine project is shown in Figure 3. The small hose is the 25 mm diameter line connected to the coupling which feeds compressed air into the spinner head to rotate it at 4000 to 5000 rpm. The greater the volume of air provided, the faster the head spins. The concrete is pumped into the spinner head, which has a conical dispersion feature.

As the head spins the pumped concrete is centrifugally sprayed at high impacting velocity onto the receiving surface (pipe, culvert or shaft). The ejected material dispersion and velocity is such that unlike conventional wet-mix shotcrete, where a dense shotcrete stream ejecting from the nozzle is clearly visible, the ejected material is barely visible. One simply sees material building up on the receiving surface. The rate at which the material builds up on the receiving surface depends on the diameter of the pipe, culvert or shaft and the rate at which the spinning head is pulled through the pipe, culvert, or shaft.

Start-up of spraying of an ASTM C1550 round panel in an above ground test chamber at the gold mine project is shown in Figure 4. Figure 5 shows the filled test panel prior to cutting back and trowelling to provide a flat surface. There is some rebound of sprayed concrete and fibre on the floor at the base of the test chamber. Systematic studies to quantify the amount and constitution of the rebound materials have not yet been conducted, but are planned prior to lining the next raise-bore shaft at the gold mine project. However, reports from the mining engineers at the project on completion of lining the approximately 290 m deep, 3.5 m diameter raise-bore shaft lined in June 2009 indicated that very little rebound material was found at the base of the shaft.

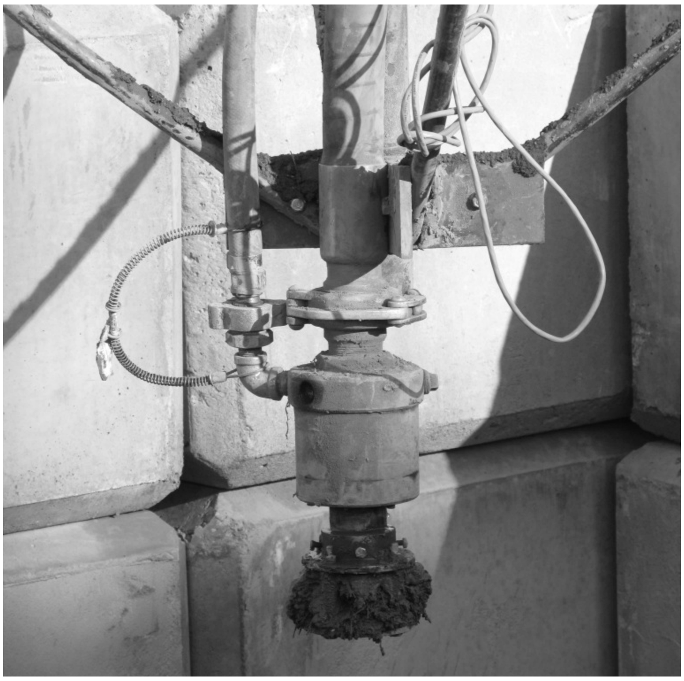

Figure 3. Spinner head assembly connected to pump hose and compressed air line.

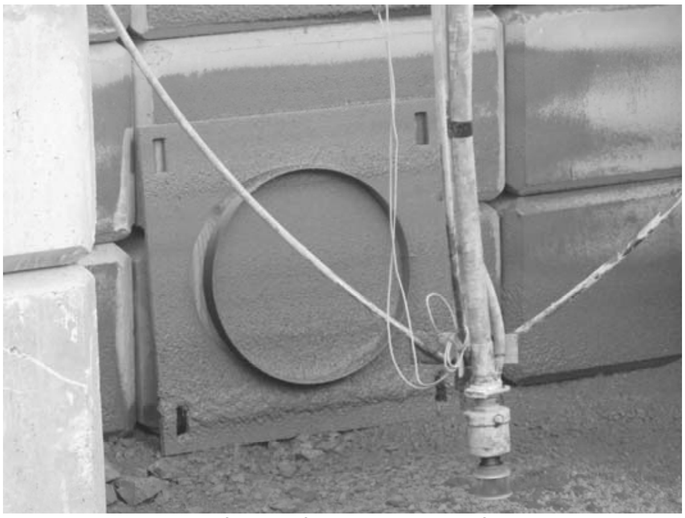

Figure 4. Start-up of centrifugal spraying of an ASTM C1550 round test panel in an above ground test chamber.

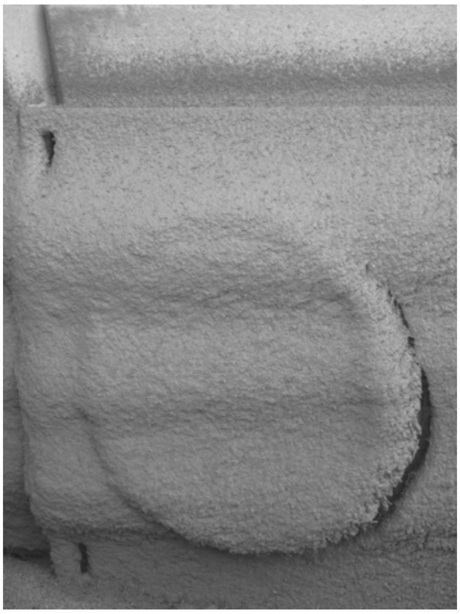

Figure 5. Sprayed ASTM C1550 Round panel prior to cutting back to flat surface.

At the New Afton mine the specified sprayed concrete lining thickness was a minimum of 50 mm. In spraying the ASTM C1550 test panel in the above-ground test chamber the concrete was centrifugally sprayed to a thickness of 100 mm on the panel and test chamber walls, before cutting back the round test panel to the required 75 mm thickness. Even at 100 mm sprayed concrete thickness, adherence to the test chamber walls was excellent and there was no sagging or sloughing of the sprayed concrete. This is for concrete which was discharged into the pump from the ready-mix concrete truck at about 170 mm slump. Note that no accelerator was used in this sprayed concrete. Special sprayed concrete mixture designs are required to enable this type of performance. Concrete mixture proportioning is discussed in the next section.

3 SPRAYED CONCRETE MIXTURE DESIGNS

Since 2005 Shotcrete Technologies Inc. has been using a proprietary natural pozzolan-modified concrete, which also contains a superplasticizer, 'Kelcrete' rheology modifier and a low dosage of micro-synthetic fibre reinforcement for robotically lining horizontal pipes, culverts and other circular structures. Such centrifugal sprayed concrete has typically had a 5 mm maximum size aggregate, as lining thicknesses have mainly been in the 20 to 40 mm range. This mixture formulation has worked well in these horizontal lining applications, with almost no rebound and good adhesion and productivity. Review of cast concrete cylinder test results from concrete supplied to centrifugal sprayed concrete projects shows that this mixture design typically produces compressive strengths of around 40 MPa at 28 days.

For the gold mine project it was decided to evaluate the potential for use of a macro-synthetic fibre reinforced concrete for lining raise-bore shafts, using the centrifugal sprayed concrete process. Proof-of-concept trials were conducted in Vancouver, British Columbia in December 2008. Two different sprayed concrete mixes were evaluated: a natural pozzolan mix provided by Shotcrete Technologies Inc.; and a silica fume modified mix designed by AMEC. Both mixtures contained 6 kg/m^3 of Barchip Shogun macro-synthetic fibre reinforcement. The gold mine project requirements were as follows:

- Slump: 150 ± 20 mm (at end of hose),
- Maximum aggregate size: 5 mm (aggregate to meet ACI 506 grading No. 1 requirement),
- Maximum water/binder ratio: 0.45,
- Minimum compressive strength: 30 MPa at 7 days, 40 MPa at 28 days,
- ASTM C642 at 28 days: maximum absorption: 8%, maximum volume of permeable voids: 17%
- ASTM C1550 round panel test: target 320 J at 28 days and 40 mm central deflection.

The trials in Vancouver demonstrated that it was possible to spray both the natural pozzolan mix and the silica fume mix containing 6 kg/m^3 of macro-synthetic fibres, using the centrifugal sprayed concrete system. Mixture proportions for the silica fume mix are provided in Table 2.

Mixture proportions for the natural pozzolan mix are not provided in this paper, since for logistics and costs reasons, it was subsequently decided not to import the natural pozzolan from the USA to the New Afton project in British Columbia.

The silica fume mix produced compressive strengths (on cores extracted from sprayed test panels) of 73 MPa at 8 days and a toughness at 7 days on a sprayed round ASTM C1550 test panel of 389 J. Clearly, the sprayed concrete was of very high quality. It was, however, observed that the silica fume mix was very sticky and consequently did not spray out as efficiently as the natural pozzolan mix (lower rate of productivity). In order to address this concern, a decision was made to trial a different, less sticky supplementary cementing material. The selected product was Whitemud Resources calcined metakaolin from Saskatchewan, Canada.

Hand cast laboratory trials were conducted at the AMEC Vancouver laboratory and subsequently centrifugal sprayed concrete trials were undertaken at the gold mine project site using a metakaolin mix. While some sprayed concrete incorporating both metakaolin and a reduced amount of silica fume was also used in the trials and in some shaft lining work, most of the shaft lining was completed using the metakaolin mix detailed in Table 3.

Note that in this mix design the synthetic macro-fibre addition rate was reduced to 5 kg/m^3. This was done as a precautionary measure, to reduce the potential for blockages during pumping down a 290 m deep shaft. This mix design generally shot well, provided the slump at the end of the hose was in the specified slump range of 150 ± 20 mm. A hydration controlling admixture was added to keep the pumped concrete live for an extended period of time, given that it had to be pumped through at least 300 m of hose. Figure 6 shows the hose laid out at the raise-bore shaft site. The hydration control admixture dosage rate was varied depending on the ambient and sprayed concrete temperatures and the depth at which the spinner head was spraying in the raise-bore shaft. Concrete was kept live for up to as much as 8 hours. Note that the summer temperatures at the gold mine often exceeded 30°C. The black hoses baked in the sun and it was found necessary to supply the concrete at a slump of 180 to 200 mm at the point of discharge into the pump in order to meet the specified slump range of 150 ± 20 mm at the end of the hose.

Table 1. List of pipes and culverts lined with centrifugal sprayed concrete.

Date	Project	Location	Type	Dimensions	Thick.	Remarks, All Structural Repair
2005	Union Pacific Railroad	Hotchkiss, Colorado	CMP	2500 lf x 42"ID	¾"	Lined 400 lf/day for 7 days
2005	Mesa County, Colorado	Grand Junction, CO	CMP	110 lf x 36" ID	1"	Lined in one day
2005	Elbert County, Colorado	Simla, Colorado	CMP	85 lf x 96" ID	1"	2 Culverts at this dimension
2005	City of Glenwood Springs	Glenwood Springs, Colorado	CMP		½"	Several culverts, multiple diameters
2005	Town of Castle Rock	Castle Rock, Colorado	CMP	450 lf x 60" ID	1"	Storm sewer
2007	Kiewit Western	Rocky Mtn National Park	CMP	96 lf x 24" ID	¾"	45 degree grade in national park
2007	El Paso County	El Paso, Texas	CMP	60 lf x 60" ID	1"	2 Culverts at this dimension
2007				80 lf x 36" ID	1"	3 Culverts at this dimension
2008	City of Idaho Springs	Idaho Springs, Colorado	Brick	Manhole		3 Manholes
2009	El Paso County	El Paso, Texas	CMP	60 lf 36" ID	1"	6 Oval culverts, structural repair
2008	Jeffco Road & Bridge	Colorado	CMP	38 lf x 18" ID	1"	3 Culverts on golf course
		Colorado	CMP	42 lf x 18" ID	1"	Difficult access
		Colorado	CMP	28 lf x 24" ID	1"	
2008	Mt. Snow Resort	Vermont	CMP	450 lf x 48" ID	¾"	Reline culvert under parking lot
				120 lf x 72" ID	2"	Dam outlet
2008	Kansas DOT	Topeka, Kansas	CMP	50 lf x30"x50"	¾"	Under I-70 Various Oval
				55 lf x 23"x36"	¾"	Oval highway culvert
				196 lf x42"x32"	¾"	Oval highway culvert
				175 lf x 44" ID	¾"	Circular, stepped inclines
2009	BNSF Railroad (Ae-com)	LaJunta, Colorado	Tile	550 LF x 5.5 ft	1 ½"	Storm sewer – diesel inflow
2006	MMWS Sewer District	Milwaukee, Wisconsin	Con-crete	9000 lf, 60" ID	¾"	Sewer tunnel & various manholes
2009	Sequoia National Park		CMP	Various	1"	9 Various lengths and diameters
2005-09	CO Dept of Transportation	Colorado	CMP	Various		Many culvert repairs under I-70

CMP = Corrugated Metal Pipe Culvert

Table 2. Silica fume trial mix design.

Material	Mass (kg)	Density (kg/m^3)	Volume (m^3)
Cement Type GU	428	3150	0.1359
Silica Fume	44	2200	0.0200
Fine Aggregate (SSD)	1647	2670	0.6169
Water	199	1000	0.1990
Barchip Shogun Fibre	6	900	0.0067
Superplasticizer	0.66	1000	0.0007
Air Content (as shot)	(2.0%)	-	0.0200
Totals	2324	-	0.9992

Table 3. Metakaolin sprayed concrete mix design.

Material	Mass (kg)	Density (kg/m^3)	Volume (m^3)
Cement Type GU	420	3150	0.1333
Metakaolin (Whitemud Resources)	85	2570	0.0331
Fine Aggregate (SSD)	1630	2670	0.6116
Water	200	1000	0.2000
Barchip Shogun Fibre	5.0	900	0.0056
HRWR Admixture (BASF Glenium 7101)*, L	2.5	1000	0.0025
Hydration Control Admix-ture (Delvocrete), L	8.0	1000	0.0080
Air Content (as shot), %	2.0	-	0.0202
Totals	2343	Yield = 1.0118	

* High range water reducing admixtures adjusted as necessary to provided required slump.

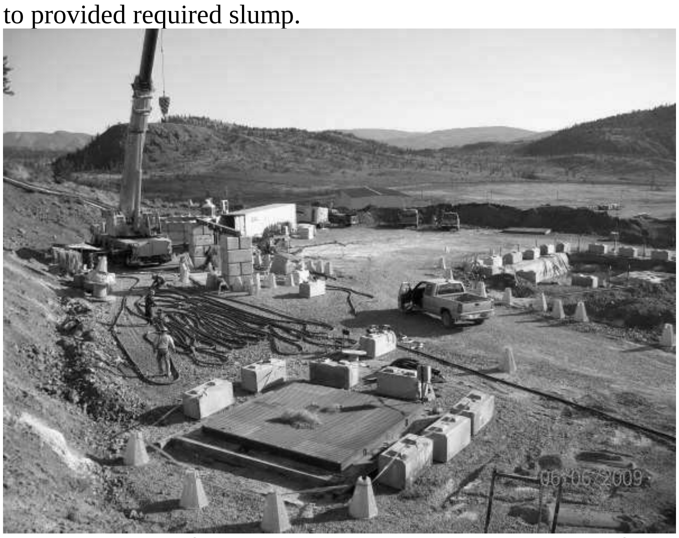

Figure 6. 300m of concrete hose laid out at raise bore shaft.

4 HORIZONTAL PIPE AND CULVERT LINING

As mentioned previously, Shotcrete Technologies has been using remote control, robotic centrifugal sprayed concrete for lining pipes, culverts and other horizontal structures since 2005. Table 1 provides a list of some of these projects. As can be seen, pipe diameters ranged from 457 mm (18 in) to 2438 mm (96 in). Lengths of the pipes ranged from 8.5 m (28 ft) to 762 m (2500 ft). One concrete sewer tunnel lined was 2744 m (9000 ft) long.

A robotically applied CSC lining is shown being applied to a corrugated metal pipe culvert in Figure 7. The robot is winched through the culvert, with the rate of travel of the winch controlling the lining thickness. Obviously the robot travels more rapidly in smaller diameter pipes, to apply a given thickness of CSC lining. A television camera is mounted on the robot to provide real time monitoring of the spray application. In areas with voids or cavities in the original structure the rate of winching can be slowed down to provide local void filling and a smooth CSC finish profile.

Figure 7. Robotically applied centrifugal sprayed concrete lining horizontal metal culvert.

5 CSC LINING OF RAISE BORE SHAFT AT NEW AFTON GOLD MINE, BRITISH COLUMBIA

An elliptical guidance device referred as the ‘egg’ is shown in Figure 8 about to be lowered into the shaft at the gold mine project. This elliptical ‘egg’ was constructed from tubular steel and is designed to keep the spinner head centred in the shaft at all times during concrete spraying. Interestingly, the ‘egg’ was not needed to keep the spinner head stable. During spinning the spinner head does not move around during centrifugal spraying; it remains stable in one position even if it is simply dangling freely from the suspended hose without connection to the egg. The egg has slightly smaller lateral dimensions than the raise-bore shaft, so that it can be raised and lowered (even after lining spraying) without friction.

Figure 8. Top of raise bore shaft prior to centrifugal sprayed concrete lining.

The shroud at the top of the egg protects TV cameras mounted on the central tubular pipe from damage due to any falling objects during spraying. Figure 9 shows a close-up view of the cameras mounted on the egg while Figure 10 shows the general rigging set-up for the CSC lining of the raise-bore shaft. A 20 ton crane was used for lowering and raising the spinner head, egg, concrete pump lines, compressed air line and TV cable. The crane had a 22 mm diameter hoist cable to which the pump line was attached. Every 15 m (50 ft) of pump hose was connected with a custom-built coupling. Figure 13 shows this coupling. The U-bracket welded to the coupling was used in the rigging to connect the pump hose to the crane hoist cable.

Figure 9. View of TV cameras mounted at top of “egg”.

Figure 10. General rigging set-up for CSC lining of raise bore shaft.

Figure 11. Coupling used for connecting lengths of pump hose and connecting pump hose to crane hoist cable.

A cable reel is shown in Figure 12 suspended from straps mounted on the steel beam spanning between the concrete lock-blocks shown in Figure 10, over which the concrete and air hoses pass as the egg is lowered down the shaft.

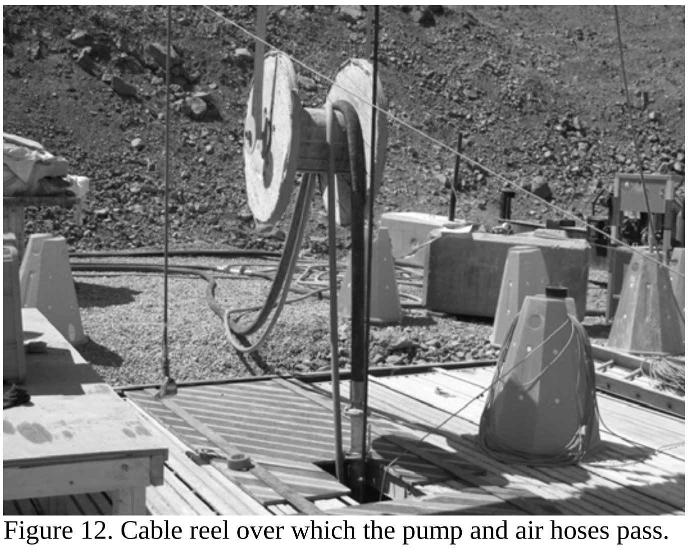

Figure 12. Cable reel over which the pump and air hoses pass.

Two miners are shown in Figure 13 connecting the concrete pump line to the crane hoist cable. This was done using a 1.2 m long steel rope lanyard, connected with toggle bolts to the coupling shown in Figure 11, and with two wire rope clips connecting the lanyard to the cable hoist. In this way the weight of the concrete pump hose (full of concrete) was connected to the crane hoist rope every 15 m (50 ft). This had to be done for every 15 m (50 ft) of hose as the ‘egg’ was lowered down the shaft. The air line and TV cable were strapped to the pump hose with duct tape. This enabled quick and easy disconnection of the air line and TV cable as the “egg” was raised.

Figure 13. Miners cinching bolts coupling wire rope lanyard to pump hose and crane hoist rope.

As the egg was raised up the shaft during CSC lining operations, the bolts and lanyard had to be disconnected every 15 m (50 ft) so that the hose could be winched back over the cable reel. Proper rigging was key to the successful completion of this project and ergonomics and efficiency increased as the work progressed. The miners wore full safety harnesses at all times while working on the platform and inside a 1 m stand-off distance from the edge of the shaft over the raise-bore shaft.

The logistics of lining the shaft varied somewhat, but the general concept was to pump the required length of 50 mm ID pump line for the day’s production full with concrete before attaching the egg and spinner head. The pump and spinner head was then started. When it was verified that the spinner head was operating correctly, the assemblage was then lowered down the shaft. The egg was lowered down fairly rapidly, spraying about 6 mm of CSC onto the rock face in the shaft as it went down. Once the spinner head reached the lowest point for the day's production, the egg was withdrawn slowly, so that the required full minimum 20 mm of thickness required for the shaft lining was produced. Ventilation in the shaft during CSC operations was kept neutral, or down-drafting, to enhance TV camera viewing and air quality for workers.

A materials balance count was used to control lining thickness (i.e. a known volume of concrete discharged from the ready mix concrete trucks, applied over a known depth of shaft with an allowance for some materials loss through rebound). A special spring loaded flow control device was installed on the pump hose 3 m above the spinner head to prevent free-fall of concrete onto the spinner head. A total of 198 m^3 of sprayed concrete was used to line the shaft. Towards the end of the project between 35 to 40 m^3 of CSC were applied to the shaft lining per working day. The work took 6 working days of actual shooting to line the shaft. Total time to complete the project was 10 days. This included time for orientation, rigging optimization and maintenance. The AMEC Kamloops laboratory carried out quality control testing on CSC. Cores extracted from test panels sprayed in a special above-ground test chamber produced 7 day compressive strengths averaging about 38 MPa and 35 day compressive strengths averaging about 70 MPa for the metakaolin modified mix detailed in Table 3; clearly a very high quality concrete.

Round panel test results to ASTM C1550 produced results of 270 J which was close to the target toughness value of 320 J. Lower results were found in other companion test panels sprayed at the same time and on other days. Some of these lower test results were, however, attributed to the test panels being finished, cured and handled in a less than optimal manner. In a couple of cases the panels did not break with the classic Y yield line failure pattern (broke in two) and this resulted in lower toughness results. Increased fibre contents will likely be needed on future projects to meet the target toughness value of 320 J.

6 CONCLUSIONS

This paper demonstrates that centrifugal sprayed concrete (CSC) provides a viable alternative to conventional wet or dry-mix shotcrete for lining circular or slightly oval horizontal pipes and culverts and circular vertical shafts. It is further demonstrated that CSC technology can be used with macro-synthetic fibre reinforcement to provide enhanced toughness to the sprayed concrete lining.

It has been demonstrated in this paper that CSC technology, with appropriate rigging, can be used to line 3.5 m diameter by 290 m deep raise-bore shafts with high rates of productivity. CSC linings in such shafts can be completed in considerably less time than is achievable with robotically applied dry-mix, steel fibre reinforced shotcrete (10 days versus about 6 weeks). This is very attractive to the owner with regard to overall costs. Additionally, this paper demonstrates that with appropriate mixture designs and using conventional ready-mixed concrete batching, mixing and delivery, the CSC system is capable of producing high compressive strength and adequate toughness for most applications.

This paper presents a case history example of a North American first application of CSC with macro-synthetic fibre reinforcement for lining large diameter (3.5 m) and deep (290 m) raise-bore shaft. It is expected that as similar shafts are lined with CSC, further enhancements in rigging and spraying methodologies will evolve, with further improvements in CSC quality and productivity and the economics of such linings.

7 ACKNOWLEDGEMENTS

The raise-bore shaft lining with centrifugal sprayed concrete at the New Gold Inc. gold mine near Kamloops, British Columbia, Canada was conducted as a joint effort between Shotcrete Technologies Inc. and New Gold Inc. Proof of concept spraying in Vancouver, British Columbia of macro-synthetic fibre reinforced CSC was provided by Bel Pacific Limited. AMEC Earth & Environmental, a division of AMEC Americas Limited, British Columbia provided CSC mixture designs and quality control testing during preconstruction trials and during shaft lining operations. Finally, the permission of New Gold Inc. to allow publication of this case history example of the raise-bore shaft lining with CSC is gratefully acknowledged.