



## 2018 Winter Olympics Sliding Track Mockup Test

By *Kyong-Ku Yun, Yong-Gon Kim, and Dudley R. (Rusty) Morgan*

On June 4, 2014, a mockup of the 2018 Winter Olympics sliding track was constructed by Daesang E&C Co. Ltd., constructors of the track, with the help of Kyong-Ku Yun, Professor of Civil Engineering at Kangwong National University, Chuncheon, Gangwon-do, South Korea, and with consultation by D. R. (Rusty) Morgan, PEng, FACI. Morgan had previously communicated with Yun about shotcrete construction of the track; on the day of the mockup construction, provided advice to Yun and, through him, to the Daesang construction team regarding optimal means and methods for the mockup construction. This article provides observations and evaluation on construction of the mockup, together with insight on opportunities for improvement.

The mockup was constructed in accordance with the project design drawings and specifications. The cooling pipes and reinforcing steel were installed as specified, except for one small area in the invert, where some of the reinforcing steel intruded into the “covercrete” zone of the mockup. The contractor acknowledged this item will be corrected during construction of the actual track. It was also noted that the stay-in-place form installed at the back of the structure had V-ribs that were only 0.3 in. (8 mm) high. As a result, the stay-in-place form will be chaired only 0.3 in. (8 mm) off the back row of vertical reinforcing steel. This is less than the 0.4 in. (10 mm) diameter of the vertical bars. While not a major concern for the “coved” areas of the track, where the shotcrete can be further consolidated by

### TRACK MOCKUP CHALLENGES Mockup Procedures

Figure 1 shows a general view of the track mockup prior to shotcrete placement with the reinforcing steel and cooling pipes installed in the track. Also note the open edge forms used at the top of the lower wall section (low wall) and the plastic screed pipes used to control final finish line and grade. Figure 2 shows an end view of the cooling pipes and reinforcing steel in the higher wall section of the track (high wall). Also note the stay-in-place form installed at the back of the wall.



Fig. 1: General view of track mockup prior to shotcrete construction



Fig. 2: End view of reinforcing steel, cooling pipes, and Stay-Form in high wall

use of immersion vibrators after shotcrete application, it is a concern for the high wall and shotcreted portion of the low wall, where it becomes difficult for the shotcrete material to wrap behind the back row of bars and fully encase them during shooting. A stay-in-place form, similar to the AMICO product, with a taller 0.8 in. (20 mm) high V-rib (as used in the Canadian Whistler 2010 Winter Olympics track) should be used in future shotcreted tracks. This should make it easier to consolidate the shotcrete around the back row of bars and at the contact area with the stay-in-place form.

Another issue was noted: while the plastic screed pipe used to control line and grade in the high wall and the adjacent side of the invert was suitable for its intended purpose, the screed pipe extending from the low wall to the invert was too flexible. The result is that the screed guide had some bumps in it as installed and did not properly control line and grade. The product used for the screed pipe in the high wall was too stiff to bend to the radius of the low wall without kinking. It is recommended that another screed pipe product with a stiffness between the current mockup high wall and low wall screed pipes be identified and used in the actual track construction.

### Shotcrete Mixture Design and Performance

Details of the shotcrete mixture design used for the mockup construction are provided in Table 1. The blended cement contained 93% portland cement and 7% condensed silica fume by mass. The mixture was air entrained to provide the shotcrete with resistance to freezing and thawing. The measured plastic air content at the point of discharge into the shotcrete pump was over 10% and the slump was 5.5 in. (140 mm). After shooting, the as-shot air content reduced to 4% and the as-shot slump reduced to 1.2 in. (30 mm). This demonstrates the beneficial “slump-killing” effect of using high air entrainment to improve pumpability in the concrete mixture. The residual air content of 4% is expected to provide the shotcrete with good freezing-and-thawing resistance. The aggregate gradation meets ACI 506 Gradation No. 2 (coarse aggregate gradation) for shotcrete.

The shotcrete mixture shot quite well, with no significant sloughing or fall-out on vertical surfaces. In Morgan’s opinion, it was, however, a bit “sticky.” The ability of the mixture to wrap around the reinforcing steel and cooling pipes and provide full consolidation could be enhanced by making the mixture a bit less sticky. It is suggested that smaller-scale trials be conducted on vertical test panels to assess the shooting characteristics of a mixture with the silica fume

content reduced to 5% by mass of cement and a second mixture with 15% fly ash by mass of cement and no silica fume. Such mixtures would be less sticky than the mixture used in the mockup and would be expected to provide better encasement of the reinforcing bar and cooling pipes and be a bit friendlier for finishing operations—that is, be less stiff and thus less susceptible to “tearing” during troweling and finishing operations.

### Shotcrete Supply

Shotcrete was batched and mixed using the mobile mixer unit shown in Fig. 3. The shotcrete was discharged from the mixing auger on the mobile mixer into an Allentown P20 shotcrete pump, as shown in Fig. 3. This was an excellent system for shotcrete batching, mixing, and supply for



Fig. 3: Bench gun shooting shotcrete in high wall

the track construction. Mobile batching units enable the production of shotcrete that is always “fresh” and facilitates fine tuning of the workability (slump) of the shotcrete to optimize it for shooting the different parts of the track. Control of workability of the shotcrete during construction of the mockup was generally good, indicating that the mobile batcher unit and pump were operated by an experienced and competent crew.

### Shotcrete Installation

The shotcrete was placed in a sequence generally consistent with that the process recommended for the construction of bobsleigh/luge tracks. More specifically, the mockup track was constructed in this sequence:

1. Shotcrete placed in the coved area of the low wall;

Table 1: Mockup Construction Mixture Design

Design strength	Max. size of coarse aggregate	Targeted slump	Air content as shotcrete	W/B	S/a	Unit content (kg/m)					
						water	Pre-blended cement	Sand	Gravel	WR	AE
MPa	mm	mm	%		%						
35	10	80 ± 20	10	0.40	75	184	460	1099	380	2.300	0.181

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2. Shotcrete applied to the coved area of the high wall (Fig. 4);
3. Shotcrete placed in the track invert;
4. Shotcrete placed in the high wall using a “bench” shooting method;
5. Shotcrete placed in the formed low-wall head beam;
6. Shotcrete placed in the high-wall head beams;
7. After a suitable delay period to allow the shotcrete in the low-wall head beam to set sufficiently, the inside form boards were removed in preparation for application of the final lift of shotcrete;
8. The inner form board in the high wall was removed in preparation for the application of the final lift of covercrete shotcrete;
9. The finish “flash” coat of shotcrete, approximately 1.2 in. (30 mm) thick, was applied to the high wall;
10. After completion of troweling, the plastic screed pipes were released by cutting the steel wires securing them to the reinforcing steel and removed;
11. After a suitable delay period, the final shotcrete surface was given a light hand-applied broom finish;



Fig. 4: Shotcrete applied to the coved area of the high wall



Fig. 5: Finishing radius cove of low wall with a custom-built tool

12. The form board was removed from the low-wall header beam and the shotcrete trimmed in the same way as the high wall in preparation for application of the final lift of covercrete shotcrete;
13. After cutting with the cutting screed to the screed pipes, the shotcrete was finished with hand floats and special tools. Figure 5 shows finishing of the radius edge of the low wall using a tool custom built for this purpose;
14. After setting, the shotcrete was covered with a plastic sheet; and
15. Finally, it is recommended that, prior to applying shotcrete to the back side of the stay-in-place form, the back side should be high-pressure water-blasted (minimum 5000 psi [35 MPa]) to remove any loose or porous shotcrete “dribble” and open the screen.

Figure 6 shows the completed mockup after application of the broom texture finish. Figure 7 shows members of the mockup engineering design, inspection, and construction team.



Fig. 6: Completed mockup after application of broom finish texture



Fig. 7: Members of the engineering design, inspection, and construction team

## EVALUATION OF MOCKUP TEST

### Hardened Shotcrete Evaluation

On June 6, 2014, after the shotcrete had been able to harden and gain sufficient strength, seven cores and a 1.6 x 1.6 ft (500 x 500 mm) slab were extracted from the shotcrete mockup at locations selected by the design engineer, Uwe Deyle, President of Planungsburo Deyle GmbH, and Giacomo Dariz, Chair of the Track Committee for the FIBT.

Four of the cores were taken from the corners of the slab in the high wall to assist in extraction of this slab. A fifth core was taken from the slab cove, a sixth from the slab invert, and a seventh core from high up in the high wall. Figure 8 shows diamond-tipped core drill extracting the first core.

### Condition of Extracted Cores

Figures 9 and 10 show the sides of the slab removed from the high wall.

Figure 11 shows Core No. 1. There is excellent consolidation of the shotcrete and encapsulation of the front layer of reinforcing steel and around the cooling pipe. The shotcrete is, however, porous and not well consolidated around the back layer of reinforcing steel (left side of the photo) adjacent to the stay-in-place

form. This shotcrete was considered unacceptable. The likely reasons for the shotcrete around the back layer of reinforcing steel and adjacent to the stay-in-place form being porous have been discussed previously in this article in the section discussing shotcrete application.

Figure 12 shows a side view of Core No. 2. This core broke in two during core extraction at a porous zone behind



Fig. 8: Diamond drilling extraction of first core



Fig. 10: View of top of slab removed from high wall. Note voids behind cooling pipe and back reinforcing bar



Fig. 11: Side view of Core No. 1. Note voids around back layer of reinforcing bar near stay-in-place form. Assigned ACI Core Grading No. 4



Fig. 9: View of right side of slab removed from high wall. Note typically good encapsulation of reinforcing bar and cooling pipes



Fig. 12: View of middle of Core No. 2. Note porosity behind cooling pipe. Assigned ACI Core Grade No. 3

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the cooling pipe. Some porosity was also noted adjacent the stay-in-place form. Shotcrete in this core would be considered marginally acceptable.

Figure 13 shows a side view of Core No. 3. While shotcrete consolidation is generally good around the reinforcing steel and cooling pipes, there are some voids in front of the cooling pipes. This was considered marginally acceptable shotcrete.



Fig. 13: Side view of Core No. 3. Note voids in front of cooling pipes. Assigned ACI Core Grade No. 3



Fig. 14: Side view of Core No. 4. Note porous shadow behind cooling pipe. Assigned ACI Core Grade No. 3



Fig. 15: Side view of Core No. 5. Core broke in two at porous zone behind cooling pipe. Assigned Core Grade No. 4

Figure 14 shows a side view of Core No. 4. The shotcrete in front of and around the cooling pipe is well consolidated. There is, however, a porous "shadow" behind the cooling pipe and, overall, this core would be considered marginally acceptable.

Figure 15 shows a side view of Core No. 5 extracted from high up in the high wall. The core broke in two at a porous zone behind the cooling pipe. This porous zone was also visible in the core hole. This core was considered unacceptable.

Figure 16 shows a side view of Core No. 6 extracted from the mockup invert. While the core fractured during extraction, the shotcrete was observed to be well consolidated and essentially void-free. This core was considered acceptable.

Finally, Fig. 17 shows a side view of Core No. 7 extracted from the shotcrete cove on the high wall. This shotcrete was observed to be generally well consolidated and was considered acceptable.

In summary, the shotcrete in Core No. 6 from the invert and Core No. 7 from the high wall cove is high quality. The shotcrete in Core No. 5 from high in the high wall is of unacceptable quality. Three of the four cores (Cores



Fig. 16: Side view of Core No. 6 from invert. Shotcrete well consolidated and assigned ACI Core Grade No. 1



Fig. 17: Side view of core No. 7 from high wall cove. Shotcrete typically well consolidated and assigned ACI Core Grade No. 2

No. 2, 3, and 4) from the slab cut out in the high wall are of marginally acceptable quality and the fourth core in this area (Core No. 1) is of unacceptable quality.

The voids observed in some of the extracted cores, as detailed earlier, are not as apparent in the sides of the saw-cut holes or in the extracted panel, as shown in Fig. 9 and 10. This is in part because raveling and washout caused by the coring operation and cracking sometimes caused by core extraction tends to exaggerate the extent of any defects in the shotcrete.

## Remedial Considerations

Defects at the back of the shotcrete section, such as the voids observed behind the cooling pipes at some locations and voids around the back row of reinforcing steel bars, can be remediated by the following process before applying the back-lift of shotcrete to the stay-in-place form. Remove the stay-in-place form at areas of concern, then use hydro-milling (high-pressure water blasting, typically 29,000 to 40,000 psi [200 to 275 MPa]) to remove all porous shotcrete and open the voids to allow full encapsulation of the back layer of reinforcing steel and back of the cooling pipes when shooting in the back layer of shotcrete. The substrate shotcrete should be in a saturated surface-dry (SSD) condition at the time the back layer of shotcrete is applied. Note that in the final track construction, there will be some areas, such as at the baffle ends of the cooling pipes, where the steel congestion is so great that some back voids are likely to occur during the initial shooting. Such areas should be carefully evaluated for the need for remedial work, as described herein, and be part of the design/construction process.

## Opportunities For Improvement

A summary of the “opportunities for improvement” include:

1. Care should be taken to ensure that reinforcing steel does not intrude into the “covercrete” zone;
2. Use stay-in-place form with deeper 0.8 in. (20 mm) V ribs, rather than the 0.3 in. (8 mm) deep V ribs used in the mockup, to better support the stay-in-place form off the back vertical reinforcing steel bars;

3. Use a more rigid screed pipe in the low wall;
4. Run trials with less “sticky” shotcrete mixture designs on vertical test panels. Trials with a mixture containing 5% silica fume and a second mixture with 15% fly ash are recommended;
5. Extend the shotcrete application in the coves in the low and high walls further down into the track invert;
6. The nozzleman should increase the air volume or hold the nozzle closer to the work to increase the shotcrete material impact velocity;
7. The nozzleman should systematically first shoot below and then above the horizontal cooling pipes with a sweeping motion to optimize shotcrete consolidation;
8. More systematic insertion of the immersion vibrator is required to improve concrete consolidation in the coved areas, invert and low- and high-wall header beams;
9. Consideration should be given to judicious use of stay-in-place form at the open bottom of the header beam to improve the vibration and consolidation of the shotcrete with reduced fallout;
10. The low-wall finish coat should be applied and trimmed prior to shooting the invert finish coat;
11. The finishers should use longer cutting screeds and trowels to improve productivity and the final finish grade and tolerance;
12. A wider stiff-bristle broom should be used for application of the broom finish to improve productivity and the final finish appearance; and
13. The shotcrete should be fogged/misted as soon as finishing operations have been completed and it has reached initial set. As soon as it has reached final set, it should be covered with presaturated curing fabric and then kept wet for at least 7 days using soaker hoses or a suitable equivalent.

## SUMMARY

In summary, except for the long void behind the cooling pipe at the top of the saw-cut hole and porous zones in cores No. 1 and No. 5, the shotcrete in the mockup is considered



Fig. 18: Sliding track under construction



Fig. 19: Overview of completed sliding track

close to being of suitable quality. It is believed that, with implementation of the “opportunities for improvement” referred to in this report, and with the increasing skills that will be developed by the nozzleman and crew as the final track construction proceeds, the owner should receive a quality track that conforms to the intent of the project specifications.

As a result of the mockup and evaluation, the entire sliding track for bobsleigh, luge, and skeleton was successfully constructed by the end of 2015 (refer to Fig. 18 and 19).



**Kyong-Ku Yun** is a Professor at Kangwon National University, Chuncheon-si, Gangwon-do, South Korea. He received his PhD from Michigan State University, East Lansing, MI, in 1995. His research interests include shotcrete and concrete materials. Recently, he has been heavily involved in shotcrete

research and has consulted on the shotcrete material and overall procedures for this rehabilitation project.



**Yong-Gon Kim** is CEO of Daesang E&C, a leading Korean company for shotcrete research and application. He received his PhD from Kangwon National University, Chuncheon, Gangwon-do, South Korea, in 2010, with an emphasis on latex-modified concrete and steel fiber-reinforced concrete. His research interests include shotcrete application.



**Dudley R. (Rusty) Morgan, PhD, P.Eng, FACI**, is a civil engineer with over 50 years of experience in the concrete and shotcrete industries. He is a Fellow of the American Concrete Institute and was a member and Secretary of ACI Committee 506, Shotcreting, for over 25 years. He was a 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 Committee C660-approved Shotcrete Nozzleman Examiner and presenter for the ASA Shotcrete Nozzleman Education course. He is a past member of the Canadian Standards Association Concrete Steering Committee and was Canadian Representative on the International Tunneling Association Committee: Shotcrete Use. Morgan has worked on over 1000 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, he was elected as a Fellow of the Canadian Academy of Engineering.

## PROJECT PARTNERS

*Project Name*  
Pyeongchang 2018 Winter Olympic Sliding Track  
Mockup Test

*Project Location*  
Pyeongchang, Korea

*Shotcrete Contractor*  
Daesang E&C

*General Contractor*  
Daelim Co.

*Engineer*  
Yooshin Engineering Co.

*Material Supplier*  
Daesang E&C

*Project Owner*  
Gangwon-do Provincial Government, Korea