Enhancing the performance and sustainability credentials of sprayed concrete lining

***John Reddy** of **Ecocem**, **Stuart Manning** of **Shotcrete Services** and **Kazuto Tabara** of **Denka** report on research and development to help improve early strength gain and other benefits for sprayed concrete lining.*

While vastly advantageous in engineering performance and flexibility, sprayed concrete lining (SCL) is known to be a poor performer in terms of sustainability. As a result of the associated rapid setting and high early-age strength requirements of SCL, cement-rich concrete based on high-quality CEM I has been specified and used traditionally.

Up until now the sustainability benefits of cement replacements, such as fly ash and GGBS, have not been available to the tunnelling industry using SCL due to the slower rate of set and strength gain over the first few hours. The main reason for this is that the traditional alkali-free accelerating admixtures used in SCL are not sufficiently effective in accelerating the cement replacements to meet the requirements of strength class J1, J2 and J3 according to BS EN 14487[1].

Less than two years ago, the innovation team at Ecocem Materials (a major supplier of GGBS) commenced R&D collaboration with sprayed concrete design and construction firm Shotcrete Services and Denka (a Japanese special cement additives manufacturer) with the objective of introducing GGBS into SCL and overcoming the significant technical challenges to enhance the performance and sustainability credentials of SCL.

It was soon discovered that not only are the traditional alkali-free liquid SCL accelerating admixtures not sufficiently reactive with GGBS, they also have an extremely low pH in the range 2–3. This causes a reaction with GGBS to create hydrogen sulfide (H_2S) gas, which is detrimental from a health and safety perspective and clearly rules out their use.

Significant technological breakthrough of this collaboration has resulted in industrial scale trials that produced SCL based on CIII/A+SR[2] and CIII/B+SR which can produce the specified early strengths required for SCL tunnelling around the world. This breakthrough offers significant enhancements to the technical performance and sustainability credentials of sprayed concrete lining.

The trials

The objective of the works was to examine and test the performance of a new powder set accelerator 'Natmic' with GGBS concrete. The product has been developed by Denka for use with Ecocem's GGBS in SCL mixes and is an alternative to the industry-wide liquid accelerating admixtures.

Trials were conducted at the head office of Shotcrete Services in Cranbrook, Kent. Its premises contain an on-site batching facility for the production of the ready-mixed concrete, allowing different types of mix combinations to be produced.

Most SCL tunnel mixes require critical cement mortar testing to ensure the most reactive CEM I available (52.5R) is chosen to ensure that the high early strength and set can be obtained. These trials used a CEM I 52.5N that is normally used for ordinary ready-mixed production and is normally not deemed suitable SCL tunnel works.

The weather was fair for the two days of trials with ambient air temperature around 28°C. The mix used was strength class C40/50 with a slump category of S4 and a standard superplasticiser was used to obtain a water:cement ratio of 0.40. The total cement content was 450kg/m^3.

All mixes were produced without silica fume; this is often required in SCL mixes to assist in the high early strength gain required. A set retarder was used in all mixes to allow an 'open' time of six hours; this is again common in SCL mixes.

Sprayed test panel boxes 1200 × 1200 × 300mm deep were positioned at 80°. The first trial was performed using a control mix based on CEM I only; this was sprayed with a traditional alkali-free liquid accelerator. Subsequent trials used the same base mix quantities but included the replacement of CEM I with 50 and 70% GGBS, with the addition of 8 and 10% Natmic powder accelerator in place of the traditional alkali-free liquid admixture.

The equipment used for these trials consisted of the Denka powder dosing machine and a Meyco Suprema SCL pump. These two machines have been connected to provide a fully synchronised dosing system. Both units were electrically powered and the compressed air supply was supplied by a 500cfm/120psi compressor. Spraying was completed using a tracked spraying manipulator. The concrete was supplied from the pump via 75mm-diameter hoses. Compressed air was added at 6.0m from the nozzle; at the back of the nozzle a mixture of compressed air and the powder admixture was introduced. This was then forced with the concrete and air through a plastic nozzle, which reduced to 50mm at the tip.

The SCL was tested using the following methods:

- Visual assessment of spray pattern, dust and rebound.

- Initial set and early strength assessment was completed using a needle penetrometer[3] from three to 60 minutes. This test was completed as soon as the SCL had enough strength to allow the needle to be pushed against the surface without sinking all the way into the surface. An average of ten results was obtained for each time period.
- The nail penetration test was used to further investigate the early-age strength development once the SCL was too hard to be tested by the penetrometer. This test method used studs of various lengths depending on the strength of the SCL, which were fired into the surface. These were then 'pulled' using a calibrated pull tester. The strength of the concrete was calculated, using a specific formula that took into account the length of the stud used, the cartridge power rating and the resulting pull force. The nail test again used ten results for each time period that was tested, with the average reported. The time periods for this test were six, 10, 12 and 24 hours.

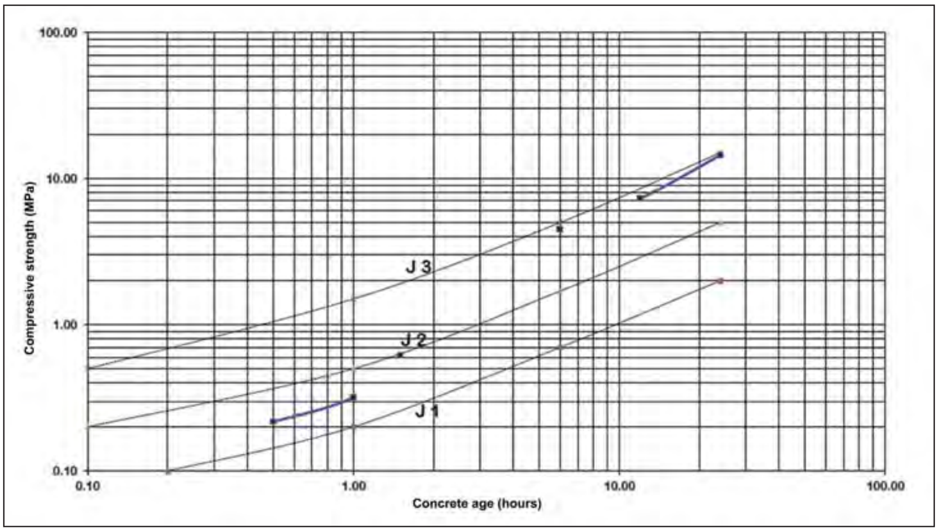

Figure 1: J curve for CEM I control with 10% liquid accelerator.

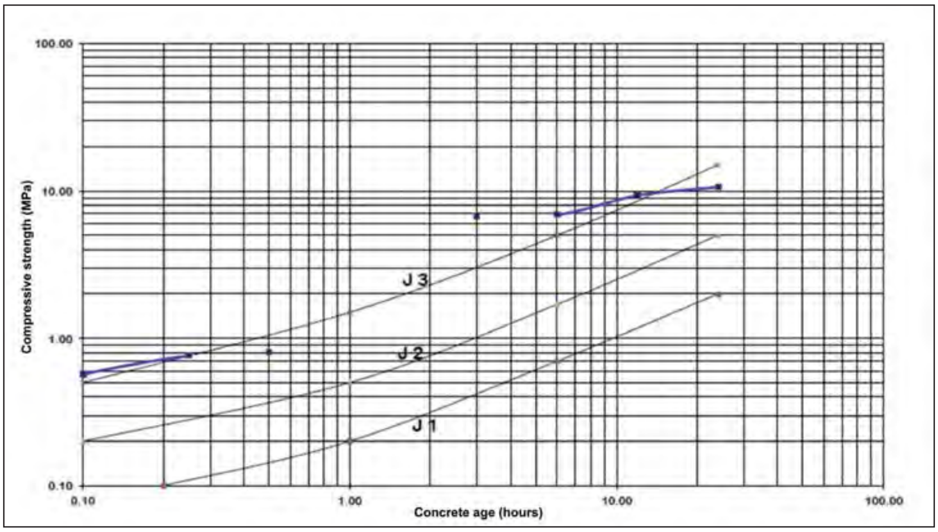

Figure 2: J curve for 50% GGBS with 10% Natmic.

Discussion of results

Trial 1 – Control

The first trial used a standard CEM I concrete and a traditional alkali-free liquid accelerator. Two panels were sprayed. The first was dosed at 8% accelerator. The mix was stiff enough to stay in the panel but the concrete showed no signs of hardening over the first half hour. A second panel was then sprayed at 10% accelerator and initial set was quicker. However, the penetration needle could not obtain a result until 30 minutes. When examining the strength gain results at one hour, it was below the J2 curve and only just on the J3 curve at 12 hours (as shown in Figure 1). Rebound was very low as the concrete was absorbing all the impact of the following material. The results indicate the need for an alteration to the mix design to achieve J3 performance for the control concrete. This could be an increase in cement content, a higher dosage of accelerator and/or the addition of silica fume.

Trial 2 – 50% GGBS

Two panels were sprayed using 50% GGBS and the Natmic powder accelerator. The first panel was dosed at 8% Natmic and stiffened very quickly. There was a set time of 60 seconds from the time of impact to a stiff material. The spray pattern was very good. Rebound was still low but the surface of the concrete was significantly harder. It was not possible to push a finger into the concrete 60 seconds after spraying and there were some harder patches evident. The penetration needle was obtaining results at six minutes and was off the scale after 90 minutes. Performance was on or above the J3 strength curve from the point of spraying.

The second panel was sprayed with a dose rate of 10% Natmic. The initial set was very fast: the penetrometer could obtain a result at three minutes and it was off the penetrometer scale at 30 minutes. Results showed that this concrete was on or above the J3 strength curve from the point of spraying (as shown in Figure 2 above).

The results for this trial do not reflect this higher early strength as the penetrometer could not record this higher strength. Rebound was higher but this was due to the concrete continually hitting a harder substrate as the set time was so fast.

Trial 3 – 70% GGBS

On the second day, the GGBS content was increased to 70%. Again, two panels were sprayed, the first at 8% Natmic and the second at 10% Natmic dosage. For the first panel the concrete showed signs of fast initial set, with low rebound and still a good spray pattern. The concrete was hard

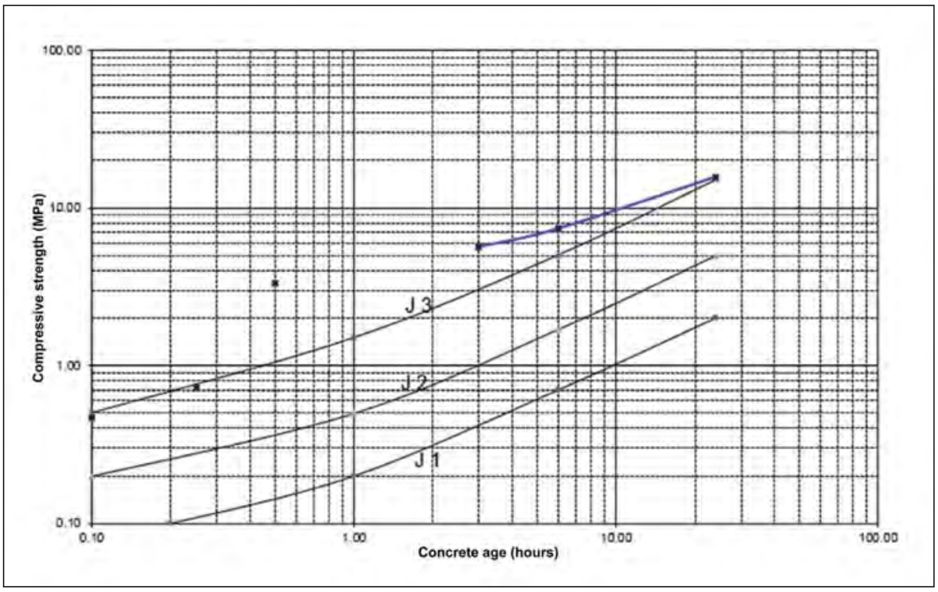

Figure 3: J curve for 70% GGBS with 10% Natmic.

Figure 4: Spraying the test panels.

enough to start needle penetrometer tests at six minutes and was off the scale at 15 minutes. Performance was on or above the J3 strength curve from the point of spraying. The dosage of Natmic was increased to 10% for the second panel. The initial set time was again very fast and the concrete was sufficiently hard to complete a penetration needle test at six minutes. Initial stiffening was also very quick and the concrete could not be moved with a finger after two minutes. Rebound was again slightly higher due to the rapid stiffening not absorbing the preceding concrete. Again, results showed that this mix was on or above the J3 strength curve from the point of spraying (as shown in Figure 3).

The benefits of accelerated GGBS concrete in SCL can be seen in terms of both technical performance and sustainability. Benefits of the former include:

- Quicker times to achieve J1, J2 and J3 offers cost reduction in fast-track construction and quicker handover times.
- Setting time extension of high replacement of cement with GGBS is desirable for pumping long distances and reduces the requirements of retarding admixtures, offering cost reduction.
- Silica fume liquids or powders that are often used to further enhance the early-age properties of rapid setting and strength development were not used in the trials and offers considerable cost reduction, handling, storage and health and safety benefits.
- Flexibility of CEM I quality used.

The sustainability benefits include:

- Incorporating GGBS in SCL as CIII/B will reduce the embodied CO_2 of the concrete by 60–70%[4].
- Improved durability in harsh environments, namely acid, sulfate and chloride environments, and enhanced resistance to fire and alkali–silica reaction. This will extend the service life of concrete and the structures cast and have a positive effect on their life-cycle analysis.
- Points can be gained in BREEAM and LEED.
- Using by-products such as GGBS in SCL plays a significant role in the circular economy.

Opportunity

With many large-scale civil and infrastructure works scheduled in the UK and further afield over the next ten years, engineers on projects such as Crossrail, Hinkley Point, Thames Tideway, HS2, Grand Paris and many rail, road and coastal improvement schemes can now specify sprayed concrete lining with GGBS to offer enhanced technical performance and sustainability credentials. Quicker handover times are possible as it was demonstrated that J3 classification was achieved in quicker time than the CEM I control without the associated added cost of additional materials to boost performance. A demonstration day is planned for March/April of this year with independent testing to verify the exciting results obtained during these trials. ■

Figure 5: Completed test panel.

References:

1. BRITISH STANDARDS INSTITUTION, BS EN 14487-1. *Sprayed concrete. Part 1 – Definitions, specifications and conformity*. BSI, London, 2006.
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3. BRITISH STANDARDS INSTITUTION, BS EN 14488-2. *Testing sprayed Concrete. Part 2 – Compressive strength of young sprayed concrete*. BSI, London, 2006.
4. MINERAL PRODUCTS ASSOCIATION. *Embodied CO_2e of UK cement, additions and cementitious material*. MPA Cement Fact Sheet 18, Revision No.2, 15 July 2015.