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HEAD TO HEAD

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RESEARCH AND DEVELOPMENT

Reducing the carbon impact of sprayed concrete

RESEARCH INTO LOW-CARBON SPRAYED CONCRETE

Michael Sataya of **Arup**, **Chris Goodier**, **Sergio Cavalaro** and **Zhi Hu** of **Loughborough University**, **Chris Peaston** of **Peaston Concrete Consultancy**, **John Reddy** of **Ecocem** and **Stuart Manning** of **Shotcrete Services** report on the early stages of a research and development project aiming to significantly reduce the carbon impact of sprayed concrete, while maintaining contemporary performance requirements.

In underground construction applications including tunnelling, the requirements for rapid setting and early-age strength development, coupled with a practicable small aggregate size, lead to cement-rich sprayed concrete mixes mainly using CEM I. It is common for sprayed concretes to have cement contents in excess of 400kg/m^3 which, along with greater admixture usage and dosage rates, lead to a high carbon footprint compared with typical cast-in-situ concretes.

SUPPLEMENTARY

The use of supplementary cementitious materials (SCMs), such as fly ash or GGBS, with the potential to reduce the carbon impact, has hitherto been limited in sprayed concrete, compared with cast-in-situ applications. This is because they typically react more slowly than CEM I and hence lack the strength development necessary for sprayed concrete tunnel linings in particular. There is also the problem of a lack of compatibility of GGBS with aluminium sulfate and sodium aluminate liquid accelerators that are typically used in sprayed concrete construction. Consequently, the sustainability benefits derived from the use of high-volume CEM I replacement with SCMs, as employed in cast concretes, have not yet been realised in sprayed concrete tunnel linings.

However, the development of powdered accelerators based on calcium aluminate (CA) and calcium sulfoaluminate (CSA) has the potential to facilitate greater SCM use in sprayed concrete. Indeed, GGBS has been sprayed in tunnel applications in Japan using CSA accelerators. This has been relatively limited, however, due to the increase in the setting time and reduction in the rate of early-age strength development brought about by the addition of GGBS.

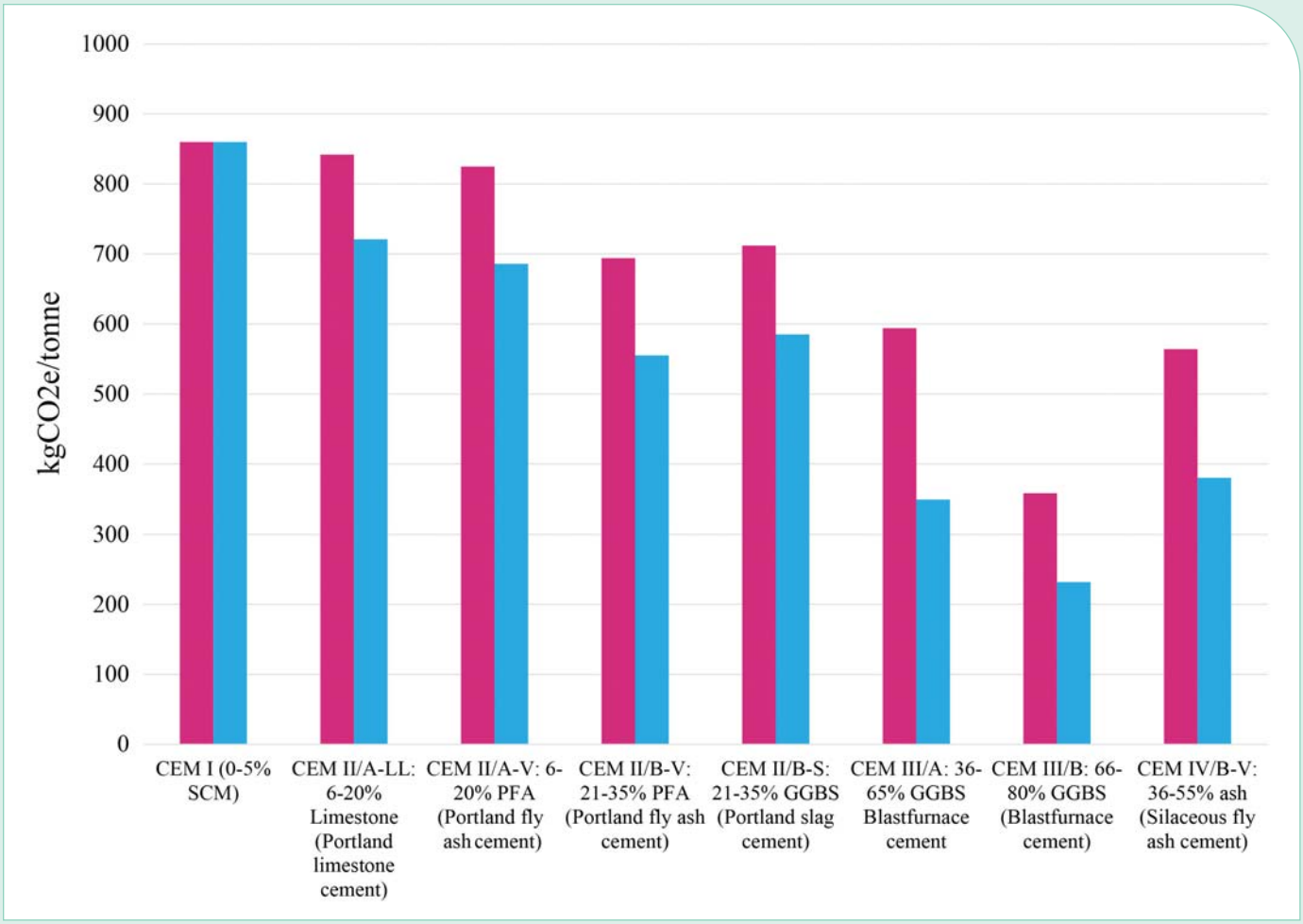
In the UK, the set-up of most sprayed concrete subcontractors, including their spraying and dosing machines and handling procedures, are designed for liquid admixtures. There is generally insufficient knowledge on powdered accelerators, a lack of industry experience and inadequately developed dosing and spraying machines. This is compounded by industry-standard prescriptive specifications for large infrastructure projects in the UK, which typically stipulate *liquid* alkali-free accelerators, thereby excluding powdered accelerators. This hampers the development and adoption of alternative technologies such as CSA-based powdered accelerators with the potential to provide equivalent performance.

Relevant cement and concrete Standards including EN 197[1], EN 206[2] and BS 8500[3] permit the use of SCMs and these are commonly used in cast structural concrete applications. Cement type CEM III/B or CIIIB, for example, can contain up to 80% GGBS. Many ready-mixed concrete producers also offer mixes containing SCMs as part of their 'eco-friendly' range, for example, CEMEX's Vertua, Hanson's EcoPlus and Aggregate Industries' ECOPact.

Figure 1 compares the estimated embodied carbon per tonne of cements/cement blends containing different replacement levels of SCMs. The pink and blue bars respectively show the embodied carbon for the cement at the minimum and maximum replacement levels. Incorporating up to 80% GGBS in the cements has the potential to reduce the embodied carbon of the cement by approximately 70%, from circa 860kgCO_2e/tonne to approximately 240kgCO_2e/tonne. The ability to incorporate GGBS at high replacement levels might therefore significantly reduce the carbon footprint of sprayed concrete.

SPRAYED CONCRETE

The authors have worked closely together this year on a variety of research and development projects related to low-carbon sprayed concrete. Michael Sataya has just completed an MSc in Advanced Concrete Technology at the University of Leeds, with this research forming part of his dissertation. This masters course is accredited by the Institute of Concrete Technology and Chris Goodier is the external examiner. Zhi Hu is also half way through a PhD at Loughborough University investigating the impact of powdered accelerators on the consistence and strength development of sprayed concrete,



ABOVE:
Figure 1 – comparison of embodied carbon for different supplementary cementitious material replacement levels.

supervised by Chris Goodier and Sergio Cavalaro. The team has also recently secured funding from the HS2 innovation team for a 'proof of concept' project with respect to the feasibility of low-carbon sprayed concrete, which we will report back on in future issues of *Concrete*.

LABORATORY TRIALS

Between February and August 2021, a consortium of Arup, Ecocem, Loughborough University, Peaston Concrete Consultancy and Shotcrete Services conducted a series of laboratory trials at Loughborough University and the University of Leeds. The main aim of the laboratory trials was to complement work previously undertaken by Ecocem and Shotcrete Services to evaluate the impact of high-slag-content cements with powdered accelerators on the mechanical performance and durability of the resultant sprayed concrete.

Samples from spraying trials conducted by Ecocem and Shotcrete Services between 2017 and 2019 showed that the mix had the potential to conform to the specifications for sprayed concrete in tunnel linings for large UK infrastructure projects and, in particular, the current HS2 project.

Within the scope of the HS2 innovation-team-funded project, further trials are planned for later this year, which will provide a comprehensive suite of samples for testing by Loughborough and Arup.

The laboratory trials at Loughborough University involved measuring cement paste setting time using Vicat apparatus to BS EN 196-3[4], with GGBS replacement from 0 to 80%, liquid accelerators and CSA-based powdered accelerators. The work at the University of Leeds involved material characterisation, including X-ray fluorescence (XRF) spectrometry, to determine the chemical composition of the CEM I, GGBS and powdered accelerators. This aided the understanding of the chemical reactions and micro-structural changes that take place during the early stages of hydration when different accelerators are added to the blended cements.

The setting time results indicated that in the CEM I pastes, the conventional liquid alkali-free accelerator based on an aluminium sulfate solution provided much quicker setting times than the CSA-based powdered accelerators. As the GGBS content was increased, the setting times in the pastes increased, even with an associated increase in liquid accelerator, indicating a low reactivity with the GGBS. However, in the cement pastes with the CSA-based powdered accelerators, the setting times *decreased* as the GGBS content was increased. At GGBS contents of 70 and 80%, the setting times in the cement pastes with the CSA powdered accelerator were comparable with the CEM I pastes with liquid alkali-free accelerator.

As the liquid accelerator used in these laboratory trials is regularly used in sprayed concrete tunnelling applications, this result also indicates that the CSA powder accelerators may have the potential to provide the requisite setting times for a sprayed concrete for underground construction at GGBS contents of 80%. Nonetheless, it is also worth noting that, as the powdered accelerators have a higher pH, this may pose additional health and safety risks for operators

LEFT:
Figure 2 – sprayed concrete panels from Ecocem and Shotcrete trials.

on-site if not properly managed and therefore materials handling procedures adopted for the use of CSA powdered accelerators need to provide appropriate risk mitigation.

PREVIOUS SPRAYING TRIALS

The Ecocem and Shotcrete spraying trials on similar mixes conducted prior to this laboratory work used a machine prototype capable of incorporating the CSA-based powdered accelerators with concretes containing up to 70% GGBS. Figure 2 shows a panel from these spraying trials, with the testing being conducted against a specification for the Thames Tideway project.

The results of the early-age strength development using a needle penetrometer between six and 60 minutes after spraying and the nail pull-out tests between six and 24 hours indicate that at 70% replacement with GGBS, the early-age strength is above the J2 curve from BS EN 14487[5].

The results of the 28-day compressive strength on core samples taken from the panels, flexural strength, bond strength and water penetration measurements all met the requirements of the Thames Tideway specification.

Durability testing to establish the resistance to carbonation, chloride ingress, sulfate attack, freeze–thaw and fire damage also met the specification.

CONCLUDING REMARKS

From the laboratory and spraying trials detailed above, the following conclusions can be drawn:

- CSA-based powdered accelerators may facilitate the incorporation of 70% GGBS in sprayed concrete, while successfully meeting the early-age strength requirements of the J2 curve from BS EN 14487. This would enable a reduction in the embodied carbon of the cement of potentially more than 60%.
- Sprayed concrete containing 70% GGBS has the potential to meet the long-term strength and durability requirements of typical industry-standard infrastructure specifications, such as the Thames Tideway specification.

RECOMMENDATIONS

The results from the laboratory trials indicate that the CSA powdered accelerators may provide the required setting time in sprayed concretes containing 80% GGBS. Additional sprayed concrete trials are to be conducted to establish the feasibility of increasing the GGBS content from 70 to 80% and its impact upon mechanical and durability properties. These trials will evaluate the short to medium-term strength gain from three to 28 days, which could become the critical factor in the maximum usable GGBS content.

The Ecocem and Shotcrete trials were conducted using a prototype spraying machine. Therefore, new accelerator dosing and spraying equipment will also need to be developed to provide a route to market for the use of the CSA powders. As noted earlier, most of the accelerators currently used are liquid alkali-free accelerators. Therefore, most sprayed concrete contractors in the UK and Europe are currently unlikely to have the equipment and processes in place to spray concrete successfully using powdered accelerators.

Materials handling procedures developed as part of the trials will also evaluate the health and safety concerns associated with the highly alkaline CSA powders and provide appropriate risk mitigation measures. The trials will also evaluate the amount of waste from rebound as well as the amount of dust generated and the related effects on productivity. C

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