Institution of Structural Engineers

# Research Award Report

# Low Carbon Sprayed Concrete

IStructE/2021-10

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# Contents

# 1 Introduction

## 1.1 Context

Sprayed concrete is a widely used construction technique for new infrastructure and repairs to existing structures. Millions of cubic meters of concrete are sprayed every year, with underground construction constituting a major use of sprayed concrete. It can offer several advantages over more conventionally cast concrete such as easier access to the work area and substrate, where the use of formwork is not possible, where thin or variable thickness is required or where it offers a cheaper and faster construction method. In tunnelling applications, sprayed concrete can offer several economic and technical advantages over conventionally placed concrete such as quicker progression and protection against tunnel collapse. In the UK, several tunnelling projects including Thames Tideway have employed sprayed concrete for the tunnel lining; sections of tunnels on High Speed 2 (HS2) rail project will also include a sprayed concrete lining.

In order to bind to the substrate, prevent section convergence and collapse as well as allow quick progression of the tunneling operations, the sprayed concrete has to have a very short setting time and early age strength development. These requirements for rapid setting, early age strength development, good pumpability and good bond to the substrate, coupled with a small aggregate size necessary for the practicalities of spraying, leads to the use of cement rich mixes mainly using CEM I. The maximum aggregate size in sprayed concrete is typically is typically limited to between 6 and 8 mm (Trussell and Jacobsen, 2020). It is common for sprayed concretes to have cement contents in excess of 400 kg/m$^3$. Sprayed concretes, therefore, tend to have a larger carbon footprint compared with conventionally cast concretes.

Small amounts of silica fume are often also incorporated into the sprayed concrete to reduce the amount of waste from rebound, as well as improving the concretes fresh and hardened properties. The (cement) replacement level is typically in the range of 6-10 % as permitted by EN 197-1. European standards such as NF EN 206/CN also stipulate a maximum silica fume replacement level of 10%. Recent developments in European practice also include the incorporation of some limestone filler in CEM II/A-L cements at replacement levels of between 6 and 20 % (Galobardes et al., 2015).

Pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS) are by-products of burning coal in coal fired power stations and the manufacturing of steel respectively and as such, have a much lower embodied $CO_2$ than CEM I. They are typically used in cast in situ concrete applications as supplementary cementitious materials (SCMs) and can help reduce carbon footprint of concrete. Relevant cement and concrete standards including EN 197, EN 206 and BS 8500 permit the use of SCMs and these are commonly used in cast structural concrete applications. For example, cement type CEM III/B or CIIIB can contain up to 80% GGBS. Many ready-mix concrete producers offer concretes containing SCMs as part of their 'eco-friendly' range of concretes.

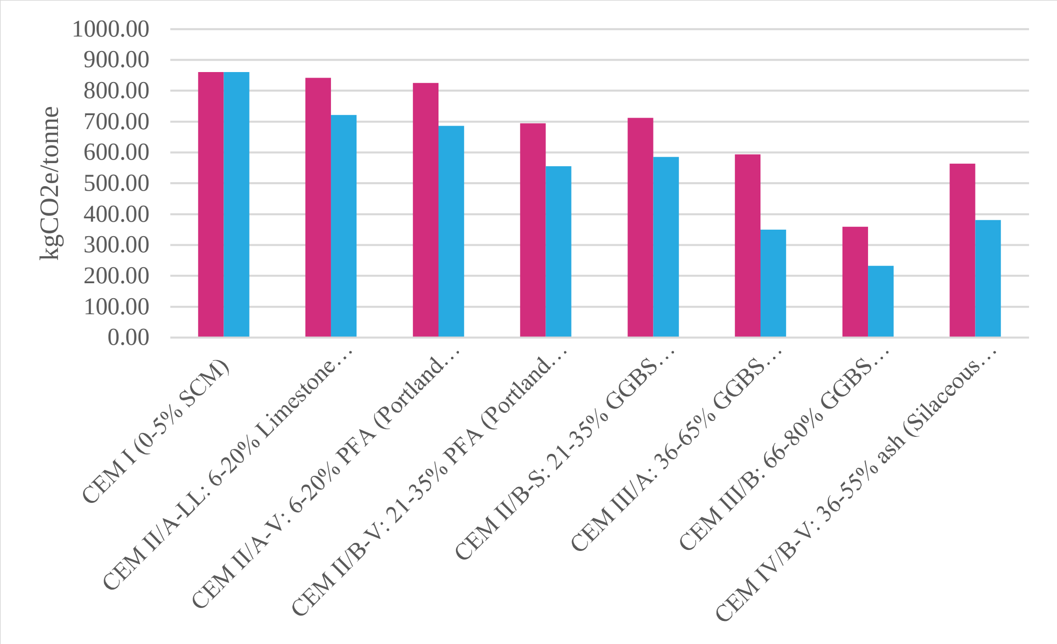


**Figure 1: Comparison of embodied carbon for different Supplementary Cementitious Material replacement levels (MPA, 2015)**

**Figure 1** compares the estimated embodied carbon per tonne of cements/cement blends containing different replacement levels of SCMs (MPA, 2015). It can be seen that incorporating up to 80% GGBS in the cements can potentially reduce the embodied carbon of the cement by about 70% from around 860 kg$CO_2$e/tonne to approximately 240 kg$CO_2$e/tonne. Therefore, incorporating GGBS at high replacement levels could significantly reduce the carbon footprint of sprayed concrete.

The use of SCMs in sprayed concrete has hitherto been relatively limited compared to other cast in situ applications. This is mainly because they react more slowly compared to CEM I, hence have slower strength development – critical for sprayed concrete linings and tunnelling. Higher accelerator dosages are therefore required. There is also the problem of a lack of compatibility of GGBS with aluminium sulfate and sodium aluminate liquid accelerators that are typically employed in sprayed concrete construction (Salvador et al., 2019).

## 1.2 Knowledge and experience gaps

Typical current sprayed concrete practice is to use predominantly CEM I rich mixes. The sustainability benefits derived from the use of high-volume replacement with SCMs such as GGBS (as employed in other concrete placement methods) have not yet been realised in sprayed concrete tunnel linings. There are some examples of the use of low volume replacement with PFA in Asia (Ishida et al., 2009); there is also a relatively recent trend in Europe to use more limestone filler in sprayed concrete (Galobardes et al., 2015), but these are isolated examples. In addition, some European standards such as NF EN 206 limit the GGBS replacement level to

50% (Armengaud et al., 2018). There is also a lack of published literature on the understanding of the early hydration mechanisms of sprayed concrete incorporating high volume GGBS replacement levels of 70-80% with set accelerators.

Historically, liquid alkaline accelerators based on sodium aluminate and sodium carbonates (Zhang et al., 2020) and more recently, alkali free accelerating admixtures based on aluminium sulfate solution (Maltese et al., 2007) have been used in sprayed concrete. Alkali free accelerators have become the more favoured option due to health and safety concerns with the alkaline alternatives (Salvador et al., 2016) and the lower risk of an alkali silica reaction with the aggregate (Zhang et al., 2020). The differences in the chemical composition between the alkaline and alkali free accelerators means that the hydration mechanisms and kinetics are different. However, both result in a reduction in setting time and increase in early age strength development (Salvador et al., 2016).

The older liquid alkali free accelerators were typically used at a dosage of 8-10% although newer formulations allow this to be dropped to around 5-7%. When used at this dosage in sprayed concrete containing predominantly CEM I, these admixtures have been shown to provide the requisite setting time and early age strength development (Zhang et al., 2020). However, when large volume replacement with SCMs such as GGBS are used, say 70%, the hydration mechanisms change. The result of this is that the setting time and early age strength development are significantly slowed down (Korde et al., 2019).

The development of Calcium Aluminate (CA) and Calcium Sulfoaluminate (CSA) based powdered accelerators has the potential to offer greater SCM use in sprayed concrete. PFA has been used in a number of tunnelling projects in Japan with replacement levels up to around 27% and accelerated with a calcium aluminate based powdered accelerator (Ishida et al., 2009) There has also been some use of GGBS in tunnel applications in Japan using CSA accelerators. However, this has been relatively limited 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. Ishida et al., (2009) suggested that most of the existing CSA based accelerators available at the time of the study could only allow the replacement levels for GGBS of up to around 45%.

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 insufficient knowledge on powdered accelerators, a lack of industry experience, and insufficiently developed dosing and spraying machines. This is also compounded by industry standard specifications for large infrastructure projects in the UK which typically stipulate liquid alkali free accelerators. This can hamper the development and adoption of alternative technologies such as CSA based powdered accelerators with the potential to provide equivalent performance.

## 1.3 Aims and objectives

The main aim of this IStructE research project was to establish whether new CSA based powdered accelerators can provide the setting and early age strength development required when sprayed concrete contains GGBS at a replacement level of between 70% and 80% and to evaluate the impact on the durability of the resultant sprayed concrete. The laboratory testing stage has been completed but the spraying trials are yet to be completed at the time of compiling this report. The samples from the spraying trials will be assessed against the typical requirements of specifications for sprayed concrete in tunnel linings for a large infrastructure project in the UK, in this case HS2.

The objectives of the project were to:

- Evaluate how the setting time changes as the GGBS content of cement pastes accelerated with a conventional liquid alkali free liquid accelerator based on an aluminium sulfate solution is increased from 0 to 80%;
- Evaluate how the setting time changes as the GGBS content of cement pastes accelerated with the new CSA based powdered accelerators is increased from 0 to 80%;
- Establish the early hydration mechanisms in cement pastes accelerated with the new CSA based powdered accelerators;
- Evaluate the early age strength development and long-term strength of sprayed concrete containing between 70 and 80% GGBS;
- Evaluate the durability of sprayed concrete containing 70-80% GGBS.

# 2 Trials

## 2.1 Laboratory trials

The research programme included a series of laboratory trials which sought to understand the chemical reactions and microstructural changes that take place during the early stages of hydration when different accelerators are added to blended cements. The following materials were used in the trials:

- CEM I 52.5N to BS EN 197-1 provided by Shotcrete Services Limited (SSL);
- GGBS supplied by Ecocem;
- Alkali free aluminum sulfate solution based liquid accelerator with a solids to water ratio of 55 to 45 provided by SSL;
- Two CSA based powdered accelerators supplied by Ecocem.

As the cement paste is the component of the sprayed concrete that governs the reactions, the laboratory phase of the study has focused primarily on the cement pastes.

The first part of the laboratory trials was carried out at Loughborough University between February and May 2021. This stage involved setting time measurement in cement pastes containing different levels of GGBS replacement ranging from 0 to 80%. GGBS content levels of 0%, 25%, 50%, 70% and 80% were selected.

The initial and final setting times were measured using Vicat apparatus to BS EN 196-3. The admixture dosage was 8% and the testing was carried out at 20°C. **Table 1** presents the details of the cement paste combinations used in the setting time measurements:

| Paste Designation | w/c ratio | Accelerator Type | Accelerator Dosage (%) | CEM I content (%) | GGBS content (%) |
|---|---|---|---|---|---|
| P_0_0 | 0.3 | None | 0 | 100 | 0 |
| P_8A_0 | 0.3 | Alkali free liquid | 8 | 100 | 0 |
| P_8B_0 | 0.3 | CSA Powder 1 | 8 | 100 | 0 |
| P_8C_0 | 0.3 | CSA Powder 2 | 8 | 100 | 0 |
| P_8A_25 | 0.5 | Alkali free liquid | 8 | 75 | 25 |
| P_8B_25 | 0.5 | CSA Powder 1 | 8 | 75 | 25 |
| P_8C_25 | 0.5 | CSA Powder 2 | 8 | 75 | 25 |
| P_8A_50 | 0.5 | Alkali free liquid | 8 | 50 | 50 |
| P_8B_50 | 0.5 | CSA Powder 1 | 8 | 50 | 50 |
| P_8C_50 | 0.5 | CSA Powder 2 | 8 | 50 | 50 |
| P_8A_70 | 0.5 | Alkali free liquid | 8 | 30 | 70 |
| P_8B_70 | 0.5 | CSA Powder 1 | 8 | 30 | 70 |
| P_8C_70 | 0.5 | CSA Powder 2 | 8 | 30 | 70 |
| P_8A_80 | 0.5 | Alkali free liquid | 8 | 20 | 80 |
| P_8B_80 | 0.5 | CSA Powder 1 | 8 | 20 | 80 |
| P_8C_80 | 0.5 | CSA Powder 2 | 8 | 20 | 80 |

**Table 1: Cement paste combinations investigated**

In the paste designation system adopted in Table 1:

- The P denotes a paste;
- The first number (0 or 8) is the accelerator dosage as a percentage of the cement or cement blend;
- The letters A, B or C denote the accelerator type. Accelerator A is the liquid alkali free accelerator, B and C are CSA Powdered Accelerators 1 and 2 respectively;
- The last number 0, 25, 50, 70 or 80 is the GGBS content as a percentage of the cement blend.

The second part of the laboratory trials involved materials characterisation and was completed at the University of Leeds between June and August 2021. This included X-ray fluorescence (XRF) spectrometry to determine the chemical composition of the CEM I, GGBS and powdered accelerators.

## 2.2 Spraying trials

SSL are a sprayed concrete subcontractor and Ecocem are suppliers of low carbon concrete and constituents. Between 2017 and 2019, they conducted a series of spraying trials on panels using a machine prototype capable of using the CSA based powdered accelerators with concrete mixes containing up to 70% GGBS (Reddy et al., 2018) . **Figure 2** shows a panel from the spraying trials.

**Figure 2: Sprayed concrete panels from Ecocem and Shotcrete trials**

The trials sought to establish the performance of new calcium sulfoaluminate cement based powdered accelerators against more conventional aluminium sulfate solution based liquid alkali free accelerating admixture. The trials evaluated the following mechanical properties:

1. Early age strength measurements using a needle penetrometer in the first hour after spraying and a nail pull test typically between 6 and 24 hours after spraying;
2. Compressive strength testing on cubes at 7, 28 and 56 days;
3. Compressive strength testing on cores at 1, 7, 28, 56 and 90 days;
4. Fibre content determination;

5. Flexural strength testing using a notched beam test;
6. Water penetration tests;
7. Bond strength between layers sprayed 4 hours apart;
8. Shrinkage.

The trials also involved the following durability tests:

1. Carbonation testing: both natural carbonation over 730 days and accelerated carbonation at a $CO_2$ concentration of 1%, at 20±2 °C at 60±10 % RH for 72 days;
2. Free-thaw resistance: accelerated scaling test in a sodium chloride (NaCl) solution;
3. Sulfate resistance: BRE procedure based on BRE Report 164 where cubes are stored in varying sulfate solutions;
4. Fire resistance: exposure to the Eurocode hydrocarbon curve;
5. Alkali-silica reaction desk study.

These trials and results were not part of this IStructE study but provided important supporting and contributory data and findings to support this current research work.

# 3 Results and discussions

## 3.1 Laboratory trials

The initial and final setting times are summarised in **Table 2**, **Figure 4** and **Figure 4**:

| **Group** | **GGBS Replacement Level (%)** | **Mix Designation** | **Test successfully completed (Y/N)** |
|---|---|---|---|
| Reference Group: no accelerator | 0 | P_0_0 | Y |
| | | | |
| Group A: Alkali Free Liquid Accelerator @8% | 0 | P_0_8A | Y |
| | 25 | P_25_8A | Y |
| | 50 | P_50_8A | Y |
| | 70 | P_70_8A | Y |
| | 80 | P_80_8A | Y |
| | | | |
| Group B: CSA Powdered Accelerator 1 @ 8% | 0 | P_0_8B | Y |
| | 25 | P_25_8B | Y |
| | 50 | P_50_8B | Y |
| | 70 | P_70_8B | Y |
| | 80 | P_80_8B | Y |
| | | | |
| Group C: CSA Powdered Accelerator 2 @8% | 0 | P_0_8C | Y |
| | 25 | P_25_8C | N |
| | 50 | P_50_8C | N |
| | 70 | P_70_8C | N |
| | 80 | P_80_8C | N |

**Table 2: Summary of setting time tests successfully completed**

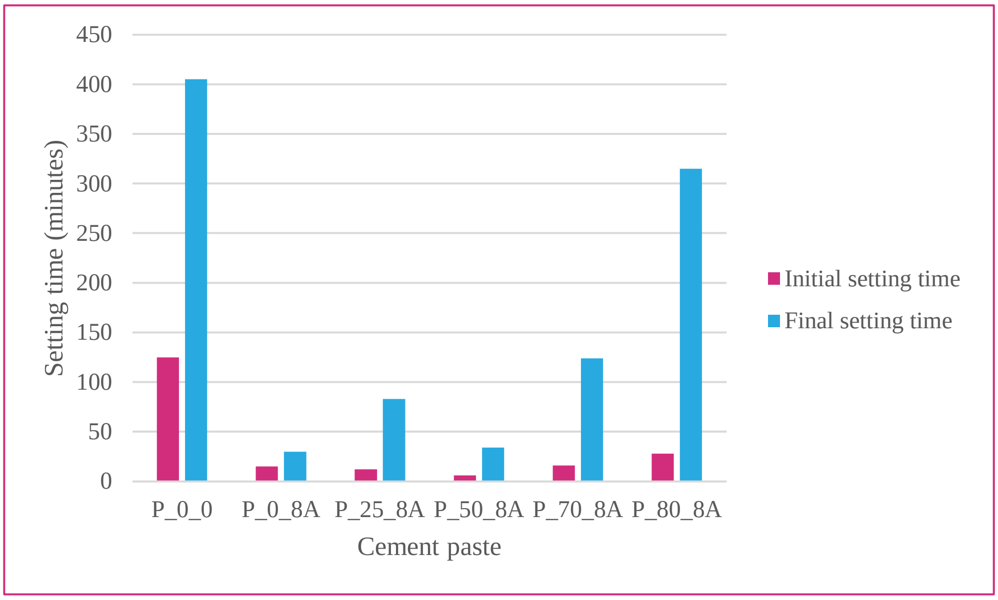


**Figure 3: Setting times for pastes accelerated with liquid alkali free accelerator**

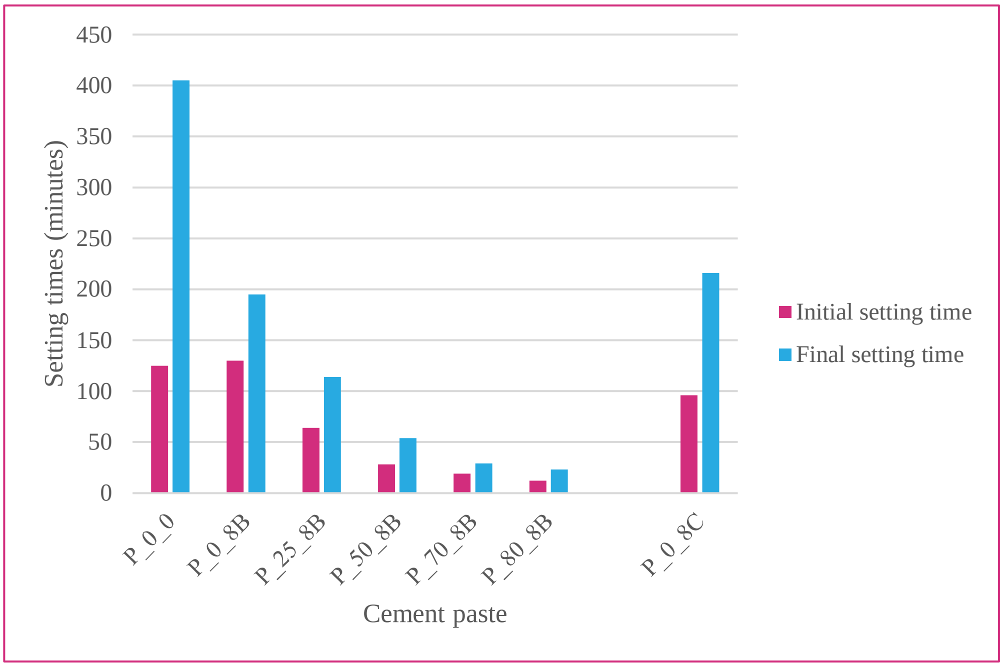


**Figure 4: Setting times for pastes accelerated with CSA powdered accelerators**

From **Figure 4** and **Figure 4**, the following comparisons can be made between the performance of the three accelerators:

- For the CEM I cement pastes with 0% GGBS, the liquid alkali free accelerator provided the quickest initial and final setting time;

- At GGBS contents of 25% and above, CSA Powdered Accelerator 2 provided the quickest setting time although this was difficult to quantify due to the rapid setting of the pastes;
- At GGBS contents of 0 to 25%, the alkali free liquid accelerator yielded quicker setting times than the CSA Powdered Accelerator 1;
- At GGBS contents of 70% and above, the CSA Powdered Accelerator 1 yielded significantly faster setting times than the alkali free liquid accelerator.

## 3.2 Materials characterisation: XRF

The XRF was completed on both CSA powdered accelerators, the GGBS and the CEM I. Due to commercial sensitivities, the full oxide composition of the powdered accelerators cannot be disclosed here. Nonetheless, it has been noted that both powdered accelerators are CSA based. CSA Powdered Accelerator 2 has a significantly higher content of alkalis compared to CSA Powdered Accelerator 1. CSA Powdered Accelerator 1 has a higher $Na_2O$ and $Fe_2O_3$ content than CSA Powdered Accelerator 2 but CSA Powdered Accelerator 2 has a significantly higher CaO content than CSA Powdered Accelerator 1.

As expected, a notable difference in the composition of the GGBS and CEM I is the significantly higher content of of $Al_2O_3$ compared to CEM I: approximately 13% in the GGBS compared to approximately 5% in the CEM I.

## 3.3 Discussion of laboratory results

From **Figure 4** and **Figure 4**, it can be observed that in the CEM I pastes, the liquid accelerator in paste P_8A_0 significantly reduces the setting time compared to the reference paste P_0_0. However, in the pastes accelerated with the CSA powders, pastes P_8B_0 and P_8C_0, the effect is much smaller. This indicates a low compatibility between the powdered CSA accelerators and the CEM I compared to that between the same cement and the liquid alkali free accelerator.

From **Figure 3**, it can be observed that the initial and final setting times increase as the GGBS content is increased in the cement pastes accelerated with the liquid alkali accelerator. However, from **Figure 4**, the converse is generally true for the pastes accelerated with the CSA powdered accelerators.

The explanations provided below may help explain the trends observed. Proske et al. (2018) notes that alkali conditions are necessary to facilitate the hydration of GGBS to form calcium silicate hydrates. The alkali free liquid accelerators are typically stabilised in an acidic solution and therefore have a low pH. However, the CSA powdered accelerators have a high alkali content with CSA Powdered Accelerator 2 having a significantly higher CaO content than CSA Powdered Accelerator 1. This may explain the difference in the reaction as the GGBS content is increased. The higher pH environment brought about by the alkalis in the CSA accelerators create conditions that are conducive to the hydration of GGBS.

A reason for the difference in the reactivity between CSA Powdered Accelerator 1 and 2 may be explained by the difference in their sodium contents. CSA Powdered Accelerator 1 has higher $Na_2O$ content than the 2. Zajac et al., (2016) noted that sodium based compounds can be used to retard CSA cements by inhibiting the nucleation of ettringite. This may be a reason for the difference in the reactivity observed. It may be that the higher $Na_2O$ content retards some of the reaction of the CSA Powdered Accelerator 1 leading to a lower reaction than the CSA Powdered Accelerator 2 which has a very low $Na_2O$ content.

Adu-Amankwah et al. (2017) and Panesar and Zhang (2020) have noted the effect of limestone filler in providing nucleation sites which aid in the precipitation of hydration products. It is not clear if the GGBS could be performing a similar role here by providing a suitable substrate for ettringite precipitation but that may be a hypothesis also worth investigating. The fineness of the GGBS used in comparison to that of the CEM I influences this nucleation effect (Scrivener et al (2015).

At GGBS contents of 70% and 80%, the setting times in the cement pastes accelerated with the CSA Powdered Accelerator 1 are comparable to the CEM I pastes accelerated with the liquid alkali free accelerator. As the liquid accelerator used in the trials is regularly used in sprayed concrete tunnelling applications, this result may also indicate that both CSA powder accelerators could potentially provide the requisite setting time for a sprayed concrete for underground construction with a GGBS content of 80%. However, it is worth noting that the high pH of these powdered accelerators could pose health and safety risks for operators on site and therefore the materials handling procedures adopted for the use of CSA powdered accelerators would need to address this.

## 3.4 Spraying trials

Ecocem had conducted spraying trials previously to this work using the CSA Powdered Accelerator 2. The trials included a mix containing 70% GGBS and the testing was carried out against the requirements of the Thames Tideway project specification. Below is a summary of the results of the testing.

### 3.4.1 Early age strength development

The results of the needle penetrometer typically between 6 and 60 minutes after spraying and the nail pull-out tests between 6 and 24 hours after spraying indicate that at 70% replacement with GGBS, the early age strength is above the J2 curve from BS EN 14487.

### 3.4.2 Compressive strength

100mm diameter cores were cut from the sprayed panels and tested for compressive strength. 6 cores were taken from each of the panels sprayed and the mean 28-day compressive strength was 75 MPa with the minimum strength observed of 68.7 MPa which was greater than required in the Thames Tideway specification.

### 3.4.3 Flexural strength

Three-point notched beam tests to determine the flexural strength. Three beams were tested and these yielded limit of proportionality results of 7.8, 4.0 and 7.2 MPa and $f_{R,3}$ values of 2.2, 2.1 and 1.9 MPa respectively which were greater than the requirement for a minimum $f_{R,3}$ value of 1.75 MPa for the Thames Tideway specification.

### 3.4.4 Bond strength

The spraying trials included a bond strength test panel where the second layer was sprayed four hours after the first. Three cores were tested yielding values 2.35, 1.28 and 2.75 MPa which were greater than the minimum requirement 0.5 MPa

### 3.4.5 Water penetration

The results of water penetration on three no. 150mm diameter cores showed depths of penetration of 9, 13, and 10mm which were less than the maximum depth of penetration of 50mm stipulated.

### 3.4.6 Carbonation resistance

The maximum depths of carbonation were not stipulated in the specification. However, this was still evaluated using a natural carbonation test and an accelerated carbonation test. In the natural carbonation resistance test, the phenolphthalein tests indicated a mean depth of carbonation of 1.3mm after 180 days and 1.4mm after 365 days.

The accelerated carbonation tests were carried out in an atmosphere containing 1% $CO_2$, at a temperature of 21±2 °C and a relative humidity of 60±10 %. The mean depth of carbonation at the end of the trials at 72 days was 7.6mm.

### 3.4.7 Freeze-thaw resistance

The freeze-thaw resistance was carried out in accordance with PD CEN/TS 12390-9. The test involved subjecting 150 x 150 x 50mm specimens to repeated cycles of freezing and thawing in a 3mm deep solution of sodium chloride. The resistance is measured in the amount of scaled material in $kg/m^2$.

The maximum measurement of scaled material from an individual sample after 56 cycles was 0.511 $kg/m^2$. UK standards do not include a maximum limit but that the equivalent Dutch standard stipulates a maximum of 1$kg/m^2$.

### 3.4.8 Sulfate resistance

These tests are still on-going. The testing conducted is an in-house one developed by BRE. 100mm concrete cubes are stored in varying sulfate solutions. At certain intervals, the cubes are removed from the solution and the length of the diagonal is measured. The change in the length of the diagonal provides a measure of the resistance to sulfate attack.

BRE state that the final stage is when the cubes are reduced to a sphere. There was no discernible change in the shape of the cubes after 180 days of immersion. The change in the length of the diagonal in the cubes tested was between 1 and 4 mm. At 365 days, the change in the lengths of the diagonals was still between 1 and 4mm. The 730-day results have not yet been received.

### 3.4.9 Fire testing

The fire testing involved subjecting three no. 100mm diameter and 100mm length cylinders to the Eurocode hydrocarbon curve for a period of 60 minutes and measuring the change in mass. The starting mass for all three samples was 1.7 kg and the post-test mass for all three samples was 1.4 kg. BRE also made some observations that there was no evident explosive spalling.

### 3.4.10 Alkali silica reaction

This was a desk study carried out by BRE. The results of the study suggests that the risk of alkali-silica reaction from the cement and aggregates used in this trial is fairly low. However, this result is only applicable to the combination of materials used in these trials. If the aggregate source or cement is changed, then that could also affect this risk.

# 4 Key conclusions and recommendations for further work

## 4.1 Key conclusions

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

- CSA based powdered accelerators can allow the incorporation of 70% GGBS in sprayed concrete whilst 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 can successfully meet the long-term strength and durability requirements of typical industry standard infrastructure specifications such as Thames Tideway.

## 4.2 Recommendations for further work

The results from the laboratory trials indicate that the CSA powdered accelerators could provide the required setting time in sprayed concrete containing 80% GGBS. However, further sprayed concrete trials would need to be conducted to establish the feasibility of increasing the GGBS content to 80%.

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 should also seek to address the health and safety concerns with the highly alkaline CSA powders. The trials could also evaluate the amount of waste from rebound as well as the amount of dust generated.

# 5 Acknowledgements

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