Low carbon multi-component cements for UK concrete applications

Summary

The MPA with the help of the IEEA has developed new low carbon cements for the UK cement industry. These types of cement break from tradition as they utilise limestone powder in combination with fly ash or ground granulated blast furnace slag (ggbs) to substitute clinker (the energy intensive component in cement). Not only do these cements perform better in concrete, but they also allow for further reductions in embodied carbon through improved material efficiency. The performance of 22 different multi-component cements was evaluated in generic concrete mixes over a period of two years. The cements were shown to meet the minimum performance criteria to allow specification using current concrete technical guidance, with up to 60% reduction in CO_2 emissions vs CEM I (the market leader). These results have been presented to the British Standards Institution (BSI) and a revision of BS 8500 to include the new cements has been approved. A total of five cements were chosen for a precast concrete demonstration, providing further confidence that the new cements perform as well as the traditional references. This IEEA project will accelerate the deployment of these low carbon cements into the UK market, enabling the UK cement industry to maintain pace with industry decarbonisation goals.

The Industrial Energy Efficiency Accelerator (IEEA)

The IEEA programme supports the development of innovative technologies that will help industry reduce energy consumption and cut carbon emissions. It focuses on innovations with large potential cross-sector energy and carbon reduction impact - either new technologies or established technologies applied to new sectors. Over £15 million in public and private funding has been committed to develop solutions through partnerships between technology developers and industrial companies willing to test technologies on-site. The programme is funded by the UK government (BEIS) and managed by the Carbon Trust, with support from Jacobs.

Introduction

In the UK, Portland cement CEM I is utilised in either its pure form or blended with secondary materials to produce low carbon cements. CEM I consists mostly of Portland cement clinker, which is high in embodied carbon. Recent Government research into the UK cement industry has highlighted that supplies of secondary materials such as fly ash and ground granulated blast furnace slag (ggbs) are diminishing. However, limestone, another secondary material for cements, is abundantly available. The Mineral Products Association (MPA) identified that limestone remains underutilised in the UK and could be combined with ggbs or fly ash in new low carbon multi-component cements. The use of limestone in these cements would lessen the burden on supplies of fly ash and ggbs without compromising performance. Through optimised grinding and blending of the materials, the carbon footprint may be further reduced compared with traditional low carbon cements.

Currently 79% of the UK cement market sales is CEM I, with a total market of 10 million tonnes per annum. It has been calculated that a clinker-ggbs-limestone cement could potentially achieve a reduction in carbon of up to 60% vs Portland cement CEM I. If fully deployed this would result in a reduction in direct emissions from cement production of over 4 million tonnes of CO_2 every year (Figure 1). In this project, MPA and project partners developed, manufactured and demonstrated 22 new clinker-fly ash-limestone and clinker-ggbs-limestone cements. All cements completed rigorous laboratory testing in concrete and five cements were selected for a precast concrete manufacturing trial and installation. Following this, a proposal to revise the British standard for concrete (BS 8500) was made to the British Standards Institution and accepted.

About the innovation

Multi-component cements are defined as cements containing more than one secondary ingredient. In this project, focus was given to two main groups of multi-component cements: clinker-ggbs-limestone and clinker-fly ash-limestone. These cements have no history of use in UK concrete applications. To optimise multi-component cements for the UK market, careful attention needs to be paid to the grinding of the individual components as well as the proportions of components in the blend. This was investigated for both clinker-ggbs-limestone and clinker-fly ash-limestone (Figure 2). The candidate cements and their constituents are shown in Annex A. Cement compositions 19-22 (designated CEM VI) were calculated to have 60% less embodied carbon compared with Portland cement CEM I.

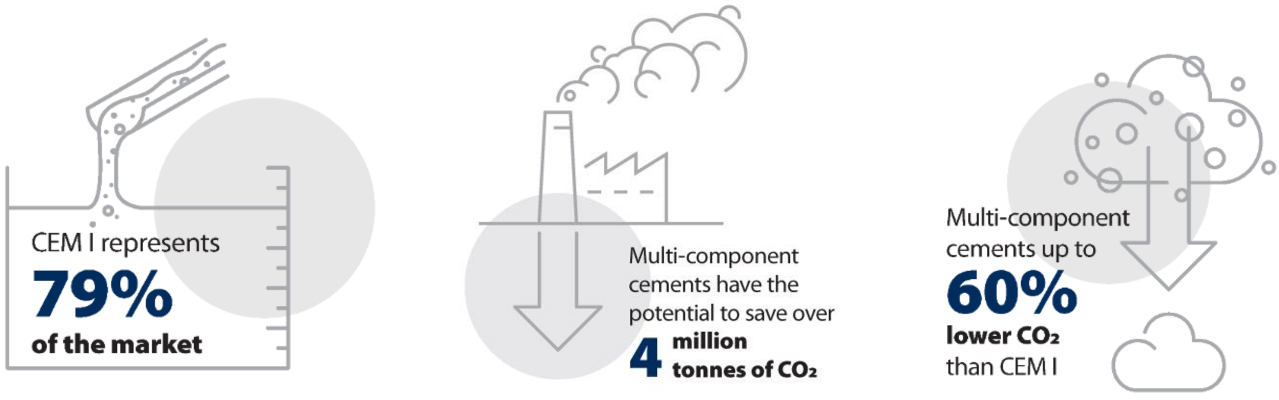


Figure 1 – CEM I production and potential CO_2 savings with multi-component cements

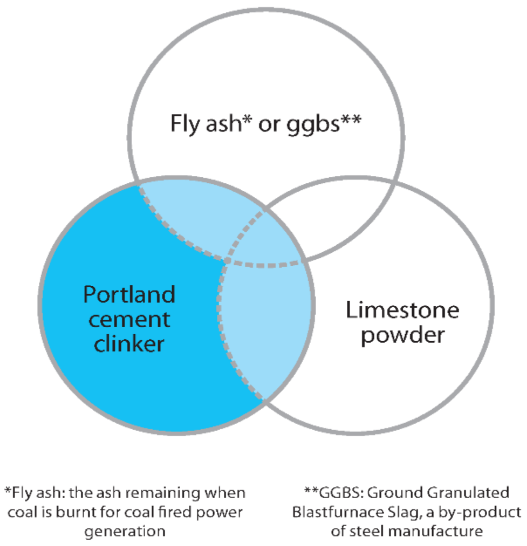


Figure 2 - Design concept for low-carbon multi-component cements

The UK Construction Industry prefers tried and tested materials with a long history of good performance to ensure standards are maintained and structures are fit for purpose. Unfortunately, this prudent approach is a hurdle for new and innovative materials and means that their uptake can be slow to grow. Therefore, to influence the relevant standards and guidance, demonstration of 'fitness for purpose' of any non-traditional material is necessary usually through rigorous testing or industry trials. While testing in a laboratory may provide sufficient evidence for the revision of standards, additional evidence from manufacturing trials may be key for increasing confidence amongst designers, specifiers and clients. In addition to a laboratory test programme, it was proposed to carry out a full-scale manufacturing trial of precast concrete elements and to install in a challenging exposure environment (i.e., soil containing high levels of sulphates). MPA believes that this combined approach (i.e., laboratory + field) will enable rapid acceptance of these new cement materials for the UK construction sector.

To examine possible variations in performance from different constituent materials, several candidate cements were replicated but with varied constituents. These were:

Group A (different sources of fly ash)

Group B (varying fineness of limestone)

Group C (different sources of CEM I)

Group D (different sources of GGBS)

Group E (different sources of limestone)

The cements were proportioned and produced at Hanson Cement's laboratory in Scunthorpe using a large-scale laboratory blender, to produce approximately 50 kg of each cement. The effect of different source materials was studied by testing the compressive strength of standard mortar prisms manufactured using the relevant cements from each group where proportions were fixed, but source materials were changed.

The demonstration

One of the challenges in this project was to identify suitable test methods to evaluate the durability performance of each of the cements in concrete. MPA carried out a review and presented a proposal to the British Standards Institution (BSI) committee responsible for BS 8500. The BSI committee endorsed the test programme as suitable for multi-component cements to be included in all exposure classes in BS 8500, subject of course to satisfactory results. A series of trial concrete mixes were carried out at the BRE laboratory using each of the new cements to meet the minimum requirements for two generic concretes – one normal strength and one high strength. These two concrete mixes also used parameters which met the minimum BS 8500 requirements for Design Chemical Classes 2 and 4 (DC-2 and DC-4) for established cements CEM II/B-V + SR and CEM III/A + SR at the recommended consistence class S3. In addition to compressive strength, a suite of durability tests were carried out which include: dimensional stability (BRE in-house prism method), natural carbonation resistance, sheltered exposure (BS EN 12390-10:2018), accelerated carbonation resistance (prEN 12390-12), sulfate resistance (BRE in-house method), chloride Migration (prEN 12390-18), accelerated freeze-thaw resistance (scaling test) (PD CEN/TS EN 12390-9:2016) and alkali silica reaction (amended version of BS 812-123:1999).

Five of the 22 cements were selected to produce five reinforced concrete retaining wall elements (Figure 4-5). An additional three reference retaining walls were produced with the three reference cements (CEM I, CEM II/B-V + SR and CEM III/A + SR). Eight precast concrete retaining walls with overall dimensions 1m (w) x 1m (d) x 2m (h) were designed and manufactured for installation on concrete blinding with restraint brackets used to join the units (See Figures 3-6). The retaining wall units were backfilled with sulphated soil. Brief access to the site has been arranged every 3-5 years to extract small samples (cores) from the concrete units for chemical analysis. The data obtained from the demonstration phase will be compared with the laboratory programme to further validate the performance of the new multi-component cements for UK concrete applications.

Figure 3 - Photo of the BRE concrete carbonation testing facilities (clockwise from left: splitting the concrete prism, applying indicator solution and sheltered outdoor storage of concrete prisms)

Figure 4 - Sequence of backfilling retaining walls with sulphated soil (clockwise from top left)

Figure 5 - Completed demonstration at the HS2 South Portal site

Results

All new cements successfully demonstrated that they meet the minimum strength requirement of 20 MPa at 28 days for normal strength concrete and 40 MPa at 28 days for high strength concrete. Durability performance of the new cements in generic BRE concrete mixes was successfully characterised and understood. A good relationship between compressive strength and carbonation depth was observed. This is in keeping with the relationship already established for traditional UK cements. All cements, except for one outlier, have shown excellent resistance to chlorides, freeze-thaw and alkali-silica reaction. The visual assessment of normal strength (DC-2) and high strength (DC-4) concrete mixes subjected to two years of cycling in aggressive sulphate solutions made it possible to identify the minimum levels of ggbs or fly ash required to resist damage from sulphates.

Figure 6 illustrates the benefits of cements with multi-components. The compressive strength for MCC1 demonstrated was identical to the reference (CEM III/A). This demonstrates clearly that limestone powder saves on ggbs without any compromise in performance. MCC2 demonstrates the material efficiency at work whereby performance is slightly improved with less clinker in the cement.

MPA has verified that multi-component cements can reduce the embodied carbon of concrete by up to 60% vs. Portland cement CEM I, the current market leader. Calculations are based on the established values of embodied carbon for each of the multi-component ingredients. The methodology for calculating the embodied carbon of the tested cements is the same methodology as used in the MPA published Factsheet 18.

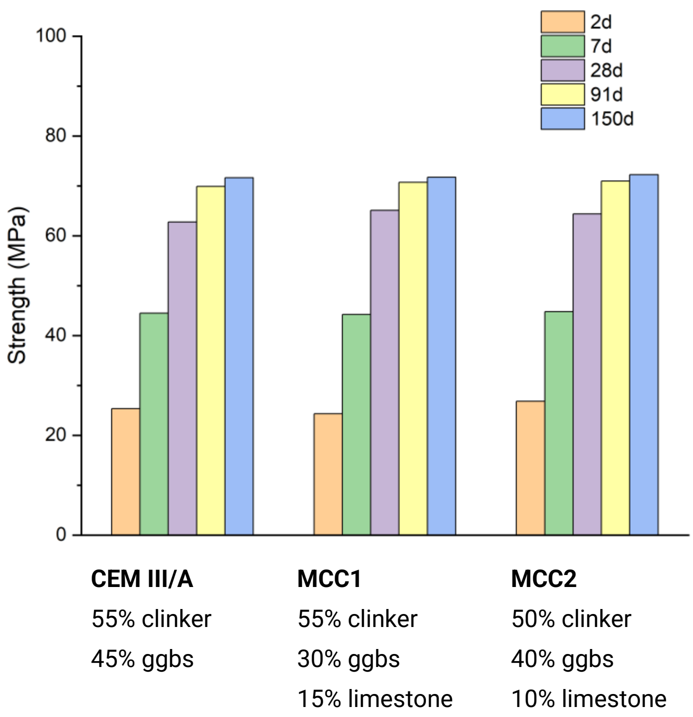
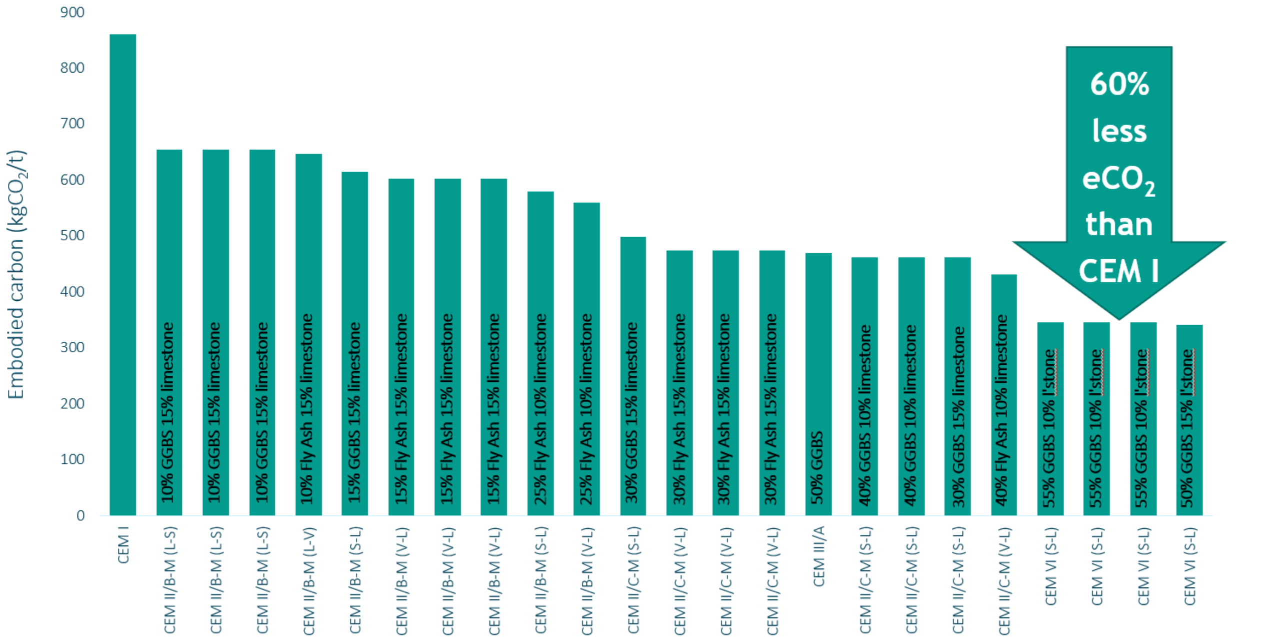


Figure 6 – Compressive strength test data for multi-component cement concretes vs. the reference CEM III/A



[MPA Cement Factsheet 18, 2019]

Figure 7 - calculated values of embodied CO2 of the tested cements versus Portland cement CEM I

Future impact

Following the outcome of the laboratory and demonstration programme, a series of recommendations were made to BSI to enable the new multi-component cements to be specified in generic concrete applications. Based on the rigorous and wide-ranging test data, MPA completed a revised list of the 'permitted' cements for the UK concrete standard (BS 8500). The new multi-component cements are identified by the CEM II-M and CEM VI designations. Sulphate resisting cements are identified by the "+SR" designation. BSI has accepted the MPA proposals to revise the standard with a target of December 2022 for publication. Following publication, the UK concrete industry will roll out the new cements at scale. The concrete industry is encouraged by the results which has shown that performance is identical or improved at lower levels of clinker, when compared to well-established cements. A major attraction is the saving on fly ash and ggbs that can be achieved while maintaining or further reducing clinker levels. The main customers of the new cements are the major UK concrete producers who have informed MPA that they will prioritise the deployment of high fly ash and high ggbs multi-component cements as soon as they are available on the market. These will replace traditional cements such as CEM II/B-V and CEM III/A.

Beyond the IEEA project, MPA will continue to communicate the benefits of multi-component cements with designers, specifiers and producers through seminars, conferences and industry guidance. The testing carried out in this project set out to validate the performance of the new cements in all concrete applications, thus, enabling the cements to be used in place of the market leader, CEM I. If the new cements are fully adopted in the UK, up to four million tonnes of direct CO_2 emissions could be saved every year - the equivalent of taking 2.2 million cars off the road. Assuming that cement production remains the same in the UK for the next 10 years, this would lead to a cumulative CO_2 saving of over 20m tonnes of CO_2 after five years and over 40m tonnes of CO_2 after 10 years.

Innovation lessons

In this project a high bar was set to ensure that a TRL level of 9 could be reached for each of the 22 cements studied. Early work focused fully on the manufacturing and testing work, with work on the demonstration site not happening until later in the programme. Finding a suitable demonstration site proved to be challenging, and significant delays resulted. Fortunately, BEIS allowed some flexibility to the programme and the demonstration went to plan. MPA would encourage future participants to plan the demonstration as early as possible to avoid delays later in the programme.

Contact information

Who to contact for more information

Tel: +44 (0) 20 7963 8000

Email: info@mineralproducts.org

www.mineralproducts.org

Industrial Energy Efficiency Accelerator delivered and supported by:

Department for Business, Energy & Industrial Strategy

CARBON TRUST

Jacobs

Disclaimer

BEIS, the Carbon Trust, and Jacobs give no warranty and make no representation as to the accuracy of this report, and accept no liability for any errors or omissions.

Annex A – Table of candidate cements and their constituents

Group	Ref	Designation	Sources	Proportions	Comp strength	Dim stab	Nat carb		Accel carb	Chloride migration	Freeze thaw	ASR	Sulfate		Precast demo
					DC4	DC4	DC2	DC4	DC4	DC4			DC2	DC4	
A	1	CEM II/B-M (V-L)	Hope/Drax/Trucarb 298	K65/V25/L10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	2	CEM II/B-M (V-L)	Hope/Drax/Trucarb 298	K70/V15/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	3	CEM II/B-M (V-L)	Hope/Tilbury/Trucarb 298	K70/V15/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	4	CEM II/B-M (V-L)	Hope/Tudela/Trucarb 298	K70/V15/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	5	CEM II/B-M (L-V)	Hope/Drax/Trucarb 298	K75/V10/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
B	6	CEM II/B-M (S-L)	Buxton/Port Talbot/Trucarb 298	K65/S25/L10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	7	CEM II/B-M (S-L)	Buxton/Port Talbot/Trucarb 298	K70/S15/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	8	CEM II/B-M (L-S)	Buxton/Port Talbot/Trucarb 270	K75/S10/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	9	CEM II/B-M (L-S)	Buxton/Port Talbot/Trucarb 285	K75/S10/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	10	CEM II/B-M (L-S)	Buxton/Port Talbot/Trucarb 298	K75/S10/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
C	11	CEM II/C-M (V-L)	Rugby/Drax/Trucarb 298	K50/V40/L10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	12	CEM II/C-M (V-L)	Rugby/Drax/Trucarb 298	K55/V30/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	13	CEM II/C-M (V-L)	Cauldon/Drax/Trucarb 298	K55/V30/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	14	CEM II/C-M (V-L)	Buxton/Drax/Trucarb 298	K55/V30/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
D	15	CEM II/C-M (S-L)	Ketton/Port Talbot/Trucarb 298	K50/S40/L10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	16	CEM II/C-M (S-L)	Ketton/Ecocem/Trucarb 298	K50/S40/L10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	17	CEM II/C-M (S-L)	Ketton/FF Tudela/Trucarb 298	K50/S40/L10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	18	CEM II/C-M (S-L)	Ketton/Port Talbot/Trucarb 298	K55/S30/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
E	19	CEM VI (S-L)	Rugby/Port Talbot/Trucarb 298	K40/S45/L15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	20	CEM VI (S-L)	Rugby/Port Talbot/Trucarb 298	K35/S55/L10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	21	CEM VI (S-L)	Rugby/Port Talbot/Betacarb	K35/S55/L10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	22	CEM VI (S-L)	Rugby/Port Talbot/FF filler	K35/S55/L10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
References	23	CEM II/B-V	Hope/Drax	K73/S27	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	24	CEM III/A	Ketton/Port Talbot	K55/S45	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	25	CEM I	Rugby	K95	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓