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DESIGN CONSULTANT FRAMEWORK CONTRACT C122 – BORED TUNNELS

LOW CARBON CONCRETE (CEMFREE) TRIALS

Document Number: C122-OVE-C-RGN-CR146-50002

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Contents

1 Introduction

As part of an Innovation Initiative Crossrail are desirous of incorporating ultra low carbon concrete into the works subject to the results of a rigorous testing regime and a review of compliance with current standards and functional requirements.

A potentially suitable product known as Cemfree which has been developed by the David Ball Group has been identified for testing. Details of the product are subject to a Confidentiality Agreement.

Cemfree is to be tested for its physical properties, workability and future durability.

The trials were carried out in two phases with the first phase consisting of block trials on three different mixes and then a full trial panel using a mix chosen on the basis of the results of the block trials.

The parties involved in the trials are:

Client: Crossrail (CRL)

Specialist Concrete Developer: David Ball Group (DBG)

Main Contractor: Vinci Construction UK, also known as Taylor Woodrow (VCUK)

Main Contractors Technical Advisers: The Technology Centre (TC)

Crossrail C122 Bored Tunnels Framework Design Consultant: Arup-Atkins JV (AADT)

Main Contractors Testing House: Environmental Scientifics Group (ESG)

Concrete Supplier: Hanson Products Europe Ltd

The report also considers the impact of designing infrastructure using the concrete.

2 General Principles of Ultra Low Carbon Concrete

Cemfree utilises an activator that combines with cement substitutes to produce an alkali-activated binder.
Alkali-activated binders have many cost and durability benefits. Their manufacture uses less energy and produces less carbon dioxide than conventional Portland cement. They are based on minimally processed industrial by-products, which significantly reduces the carbon footprint of concretes made from them.

3 Testing Regime

The additional potential benefits that are subject to testing are:

- Long term strength retention
- Creep & shrinkage

The unknown characteristics which will be subjected to testing are:

- Rate of strength gain
- Resistance to sulfates
- Appearance
- Protection of reinforcement against carbonation and chlorides
- Sensitivity to curing
- Heat of hydration
- Reinforcement bond strength
- Modulus of elasticity

No fire tests have been carried out on Cemfree to date and none are incorporated in the test regime.

An understanding of the workability of the concrete is required. Cemfree has previously been used in concrete mixes using either a skip or directly from the delivery vehicle chute, i.e. consistence class S3. DBG confirmed that a mix has not yet been perfected for pump pouring, i.e. consistence class S4. The trials are therefore limited to consistence class S3.

DBG have confirmed that the causticity of Cemfree is similar to other concretes and will declare any additional hazards due to the activator.

DBG have stated that good curing of the concrete is required and are to advise of any special curing needs.

A full schedule of tests to be carried out is located in Appendix C. This was subsequently reduced in scope due to cost controls. The initial list was issued in response to PTR C315-RFI-001346 and amended in response to PTR C315-RFI-001364.
This list was subsequently adapted by PTR C315-RFI-001474 as shown in Table 1:

Table 1 Trial Panel Testing

Test	Frequency
Carbonation	2No. 100 x 100 x 400mm specimens and 3No. cubes for each of the 3 tests required (2No. in the slab & 1No. in the wall)
Modulus of elasticity	1No. 75 x 75mm prism and 3No. cubes for each of the 3 tests required to be carried out at 28 days (2No. in slab & 1No. in wall)
Heat of Hydration	Data logger to be provided by ESG to measure temperature in the base slab every 30 minutes for 3 days.
Aggregate segregation	On site plastic concrete sampling test based on ASTM C1610 but adjusted for cylinder compaction.
Workability	Slump tests: 1No at batching plant, 1No on site arrival, 1No at pour finish, 1No at 1 hour, 1No at 1.5 hours for both the base slab and wall pours.

4 Trial Mix Designs

The following block trial mixes were considered:

With reference to Oliver Greet (DBG) email 24th January 2013:

Initial Mix

CemFree: 400 kg/m3, Sand: 801 kg/m3, Gravel 4-20mm: 1079 kg/m3, Water: 120 l/m3

Admixture: Sika VC10: 4.4 L/m3

Binder 1

5% CemFree Activator, 5% CEM 1, 90% GGBS

Binder 2

5% CemFree Activator, 5% CEM 1, 55% GGBS, 35% PFA

Binder 3

5% CemFree Activator, 95% GGBS

Binder 4

5% CemFree Activator, 60% GGBS, 35% PFA

At the Start-Up meeting held on 23rd October 2013 attended by CRL/DBG/VCUK/TC and AADT

Binder 5 (New mix proposed at): DJB to advise further.

5% CemFree Activator, 5% CEM 1, 90% PFA

It was concluded that Binders 3, 4 and 5 would be block trialled. DJB considered that Binders 1 and 2 not worth testing as they will add little value. However, Binder 3 contained CEM 1.

Martin Liska (DBG) email dated 25th October 2013

Binder 3: 5% Cemfree Activator + 95% GGBS

Binder 4: 5% Cemfree Activator + 55% GGBS + 40% PFA

Binder 5: 5% Cemfree Activator + 95% PFA

5 Compliance

DBG confirmed at the meeting of 26th October 2013 that the proposed mix is currently not in accordance with BS8500-1[1]. DBG were to investigate alternate international standards that compliance can be obtained from, for example ASTM C1157. The European cement standard, EN 197-1[2], has been checked on the basis of 5% PC and 90% GGBS may comply with CEM IIIC but it would seem that, because of the inclusion of the activator, it does not as there is no allowance in the standard for an activator.

Compliance is considered further in Section 9 of this report.

6 Block Trials

The initial trials were based on 1m x 1m x 0.8m high blocks agreed at the Start-Up meeting of 26th October 2013. The block trials were carried out on 21st November 2013 with the following present:

[redacted] (CRL), [redacted]DBG) (first pour only)

[redacted] (DBG)

[redacted] (CRL)

[redacted] (CRL)

[redacted] (DBG)

[redacted] (VCUK)

[redacted] (VCUK)

[redacted] (C122)

Photographs of the block trial are contained in Appendix A of this report.

<u>First Trial: Binder 3: 5% Cemfree Activator + 95% GGBS (Mix 1)</u>

Batched at approximately 08:30 but due to a vehicle non-compliance the pouring commenced much later than planned.

The slump test carried out at approximately 09:50 was 140mm and was an unusual collapse as the top of the sample moved sideways.

Pouring commenced 10:00 and was completed 10:15. The recorded slump at 10:30 was 70mm.

The fresh concrete was viscous and continued to slump gradually unlike a normal concrete.

The poker did not expel much air due to the viscous nature of the concrete.

If the formwork had been higher the mix would have failed to deliver freely via the chute.

The aggregate was clearly visible on the top surface when floated due to the binder paste forming a meniscus around the aggregate.

Only 34 of the required 48 cubes were taken as the mix became unworkable. It was agreed that wet cure tests were not required at 1 day as the concrete would not have set and that the 2 samples required for the 1,2, 3,7,14 and 28 day air tests need not be tested as the information could be extrapolated form the cores to be taken.

Second Trial: Binder 4: 5% Cemfree Activator + 55% GGBS + 40% PFA (Mix 2)

The mix arrived on site at approximately 12:00.

The recorded slump was 230mm. Bleed water from the slump sample concrete was noted.

Pouring commenced 12:15 and was completed 12:30. The recorded slump on completion of pouring was 230mm.

Compaction was achieved using vibrating poker but use was limited due to the fluid nature of the mix.

The mix was coarse but viscous. Following compaction, the mix bubbled and was not hard enough to be trowelled.

The top 75mm approximately did not contain large aggregate and segregation problems were likely.

Third Trial: Binder 5: 5% Cemfree Activator + 95% PFA (Mix 3)

The mix arrived on site at approximately 14:00.

The recorded slump was 260mm.

Compaction was achieved using vibrating poker but again use was limited due to the fluid nature of the mix.

Pouring commenced 14:10 and was completed 14:15. The recorded slump on completion of pouring was 250mm.

The mixed bubbled slightly but the effect was not as pronounced as Mix 2. Slight bubbling was observed after floating. The variation in slumps taken at the beginning and end of pouring was better than for Mix 1, therefore it is likely to last longer on site, otherwise it behaved as Mix 1.

7 Trial Panel

The trial panel consisted of a section of Surface Rail track support slab and vehicle restraint wall. Details of the panel are shown on drawing C315-VIN-C-DWG-CR146_ST003-50018 contained in Appendix D. C315-RFI-001453-01 confirmed that the buttress detail, holding down bolts, couplers and dowel bars were not required. It also confirmed that the wall finish on the outside face was to be F3 and on the inside to be F2. The slab finish was to be U2.

The following information is to be provided by the Contractor:

- Time of batching, delivery, slumping, pouring and ambient temperature for the base pour.
- Details of the plasticiser and the quantities and timing of the addition of water and plasticiser.
- Details of the mix design if changed from the Block Trials.
- Method of batching.

7.1 Trial Panel Base Pour

The base trial pour was carried out on 4th April 2014. The trial was not fully witnessed by C122 due to a clash of commitments.

The concrete was placed using a skip and trunking and it was evident relatively early on in the pour that blockages were occurring in the trunking. These were dislodged by vibrating the trunking. It is understood that water was added to the mix later on in the pour as it was not possible to release the blockage in the trunking by vibration alone. It is understood that the David Ball Group were not aware of the intended method of pouring and the workability of the batched concrete was selected to suit a chute pour directly from the delivery vehicle.

Comments on Low Carbon Concrete – Trial Panel Report document number C315-VIN-C-RGN-CR146_ST003-53521[10] records the following summary of workability (slump) tests.

120mm at 20 minutes from batching

90mm at 40 minutes from batching

30mm at 60 minutes from batching

The pour was completed within 1 hour and no further slump testing could be carried out beyond 60 minutes due to the mix setting by this time.

7.2 Trial Panel Wall Pour

The wall trial pour was carried out on 14th April 2014. Concrete arrived at 09:05, pouring commenced at 9:15 and was completed at 09:27.

The ambient air temperature 12.9°C and the concrete temperature was 19.0°C.

The concrete was placed using a skip and trunking. Trunking was more necessary on this pour as the concrete had to be placed between the wall reinforcement to avoid segregation. There were similar issues with the relatively rapid loss of workability and David Ball Group added a controlled amount of Sika Viscocrete plasticiser in the second skip.

The mix performed reasonably well under vibration and did not appear to segregate.

Comments on Low Carbon Concrete – Trial Panel Report document number C315-VIN-C-RGN-CR146_ST003-53521 records the following summary of workability (slump) tests.

240mm at 10 minutes from batching (collapsed slump)

220mm at 40 minutes from batching (collapsed slump)

Pouring was completed within 40 minutes of batching and no more slump testing could be carried out beyond this point due to the concrete setting without it being agitated within the wagon.

8 Results

The results are based on Cement Free Concrete - Initial Testing Report document number C315-VIN-C-RGN-CR146_ST003-53110 Revision 1.0[9] by VCUK.

The results are summarised in Appendix B of this report.

8.1 Mix 1

8.1.1 Compressive Strength

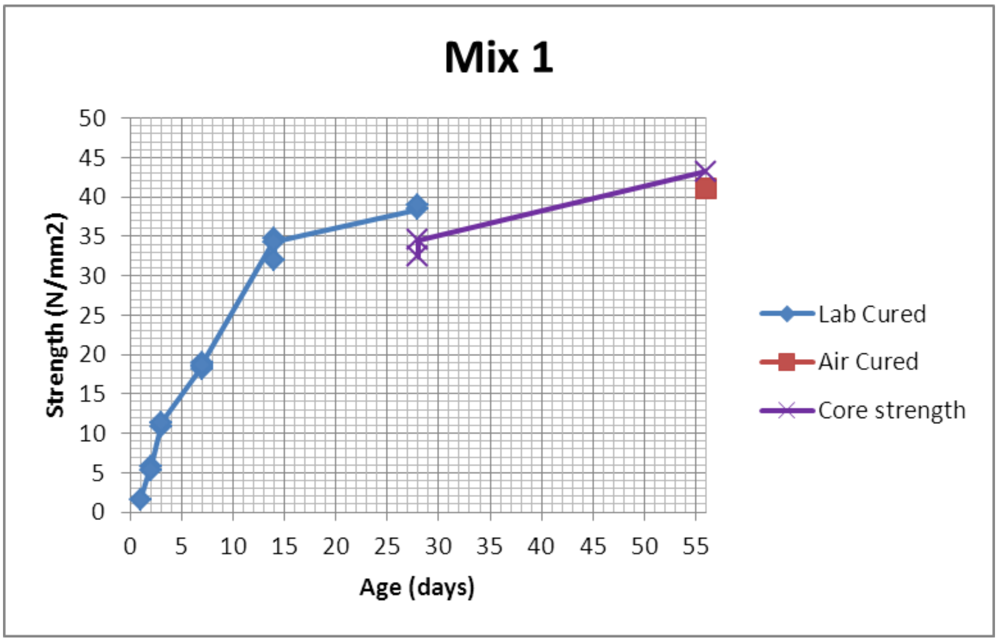

Figure 1 Mix 1 Compressive Strength Results

The mix had not achieved the required cube strength of 40N/mm^2 at 28days. The average 28 day strength was 38.7 N/mm2 based on two samples.

The insitu core strengths which have been corrected to suit insitu cube strength are lower than lab cured cube strength.

Lab cured cubes were not available to compare with air cured cubes but the air cured cubes are only slightly weaker than the insitu core strengths which have been corrected to suit insitu cube strength at 55 days.

8.1.2 Static Modulus of Elasticity

The average static modulus of elasticity of Mix 1 was 30,750 N/mm^2 based on two results.

8.1.3 Tensile Splitting strength on Concrete

The average tensile splitting strength was 3.23 N/mm^2 based on three results.

8.2 Mix 2

8.2.1 Compressive Strength

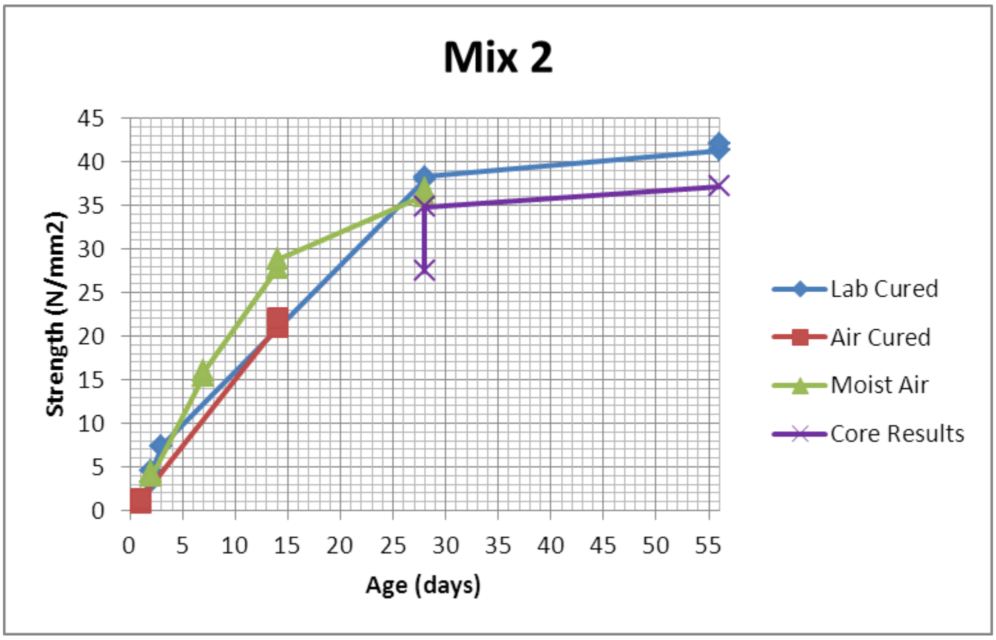

Figure 2 Mix 2 Compressive Strength Results

The mix had not achieved the required cube strength of 40N/mm^2 at 28days.The average 28 day strength was 38.1 N/mm^2 based on two samples.

The insitu core strengths which have been corrected to suit insitu cube strength are lower than lab cured cube strength.

There are no Lab cured cubes between 4 and 27 days to make meaningful comparison with moist air and air Cured conditions, other the lab cured cubes were stronger at 3 and 28 days.

8.2.2 Static Modulus of Elasticity

The static modulus of elasticity of Mix 2 was 29,000 N/mm^2 based on two results.

8.2.3 Tensile Splitting strength on Concrete

The average tensile splitting strength was 2.93 N/mm^2 based on three results.

8.3 Mix 3

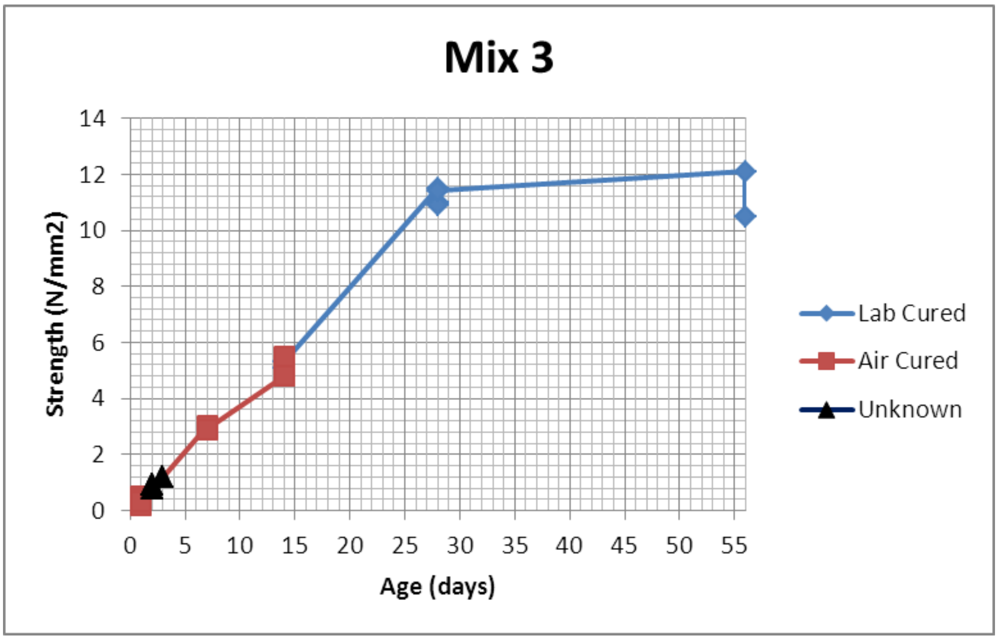

Figure 3 Mix 3 Compressive Strength Results

8.3.1 Compressive Strength

The mix had not achieved the required cube strength of 40N/mm^2 at 28days and was well below 40N/mm^2 at 56 days. This mix is therefore not suitable for further comparison.

8.4 Trial Panel Base Pour

8.4.1 Compressive Strength

Table 2 Trial Panel Base Compressive Strength Results

Laboratory Test Specimen	Mean Compressive strength (N/mm^2)	Location	Age at test	Saturated Density (kg/m3)
23061247	24.5	Base	7	2450
23061248	35.1	Base	28	2460
23061249	25.5	Base	28	2430

Mix 1 used for the block trials had not achieved the required cube strength of 40N/mm^2 at 28days. The average 28 day strength was 38.7 N/mm^2 based on two samples.

Laboratory Test Specimen 23061249 appears to be a rogue result; otherwise Laboratory Test Specimen 23061248 strength corresponds reasonably with the block trial results.

8.4.2 Accelerated carbonation testing

(Awaiting results)

8.4.3 Heat of hydration

Table 3 Heat of Hydration

Date	Time	Temperature (°C)
4th April 2014	10:45	21.1
4th April 2014	12:30	21.8
4th April 2014	16:00	22.2
5th April 2014	09:30	19.7

8.4.4 Modulus of elasticity

All testing carried out on the base was at 28 days

Table 4 Modulus of Elasticity

Laboratory Test Specimen	Static Modulus of Elasticity (N/mm^2)	Mean Compressive strength (N/mm^2)	Saturated Density (kg/m^3)
EE 7796/1	36500	35.5	2430
EE 7796/2	35500	35.5	2430
EE 7808/1	41500	41.3	2475
EE 7808/2	38000	41.3	2475

Results do not appear to be consistent as EE 7808/2 appears to be relatively low.

The average static modulus of elasticity of Mix 1 for the block trials was 30750 N/mm^2 based on two results. The average based on the results above is 37,875 N/mm^2 representing a 23% increase in the value for the Block Trial.

8.4.5 Aggregate segregation

(Awaiting results)

8.5 Trial Panel Wall Pour

8.5.1 Compressive Strength

Table 5 Mix 1 Compressive Strength Results

Laboratory Test Specimen	Mean Compressive strength (N/mm^2)	Location	Age at test	Saturated Density (kg/m^3)
23071010	39.9	Wall	28	2470
23071011	40.2	Wall	28	2490
23071012	42.0	Wall	28	2480
23071006	41.0	Wall	28	2480
23071007	41.6	Wall	28	2470

Mix 1 used for the block trials had not achieved the required cube strength of 40N/mm^2 at 28days. The average 28 day strength was 38.7 N/mm^2 based on two samples.
The average compressive strength result for the Trial Panel Wall is 40.9 N/mm^2 at 28days.

8.5.2 Accelerated carbonation testing

(Awaiting results)

8.5.3 Modulus of elasticity

(Awaiting results)

8.6 Summary of Test Results

The third trial consisting 5% Cemfree Activator + 95% PFA (Mix 3) achieved less than third of the required design strength and should therefore not be considered further.

Both the first trial consisting of 5% Cemfree Activator + 95% GGBS (Mix 1) and the second trial consisting of 5% Cemfree Activator + 55% GGBS + 40% PFA (Mix 2) failed to achieve the 28 day target laboratory cube compressive strength of 40N/mm^2. However both the average 28 day results for mixes results exceeded 38 N/mm^2 and based on further testing it may be possible to attribute 35N/mm^2 strength to both mixes.

The static modulus of elasticity of Mix 1 was 6% higher than that of Mix 2. Mix 1 therefore provides a greater structural stiffness once cast which will benefit in reducing mid span deflections for beams.

The tensile splitting strength of Mix 1 was 10% higher than that of Mix 2. Mix 1 will therefore offer a greater degree of crack control and more favourable bond strength on the basis of the limited number of results obtained in these trials as, at this stage, there is no indication of the variability of results.

On the basis of the above and the performance of each mix whilst being poured, it was recommended that Mix 1 consisting of 5% Cemfree Activator + 95% GGBS is used for the trial panel.

The Trial Panel Compressive Strength test results demonstrated that the target strength of 40N/mm^2 at 28days using Mix 1 was not achieved in all cases.

The heat of hydration of Mix 1 used in the Trial Panel looks acceptably low.

The Modulus of Elasticity results showed a 23% increase between the Block Trials and the Trial Panel.

Complete results are awaited for the Trial Panel Accelerated carbonation, Aggregate Segregation and Modulus of Elasticity tests.

9 Design Considerations

9.1 Standards and Compliance

The requirements are as follows:

BS EN 197: Cement -Part 1: Composition, specifications and conformity criteria for common cements[3].

National foreword

This British Standard does not include in its scope: the additional special properties of low heat Portland cement, conforming to BS 1370 or of sulfate-resisting Portland cement, conforming to BS 4027; or high slag blastfurnace cement, previously specified in BS 4246 or the low early strength classes of Portland blastfurnace cements, specified in BS 146, or pozzolanic pulverized-fuel ash cement, conforming to BS 6610; or other types of cement whose hardening is not primarily due to the hydration of calcium silicates, i.e. high alumina cement, conforming to BS 915-1, and supersulfated cement, conforming to BS 4248. It is intended that cements from within this range will be specified in further parts of BS EN 197 or in other standards.

Foreword to amendment A1

Very low heat special cements are dealt with in EN 14216.

3.4 Definition of a minor additional constituent

Specially selected inorganic material used in a proportion not exceeding a total of 5 % by mass related to the sum of all main and minor additional constituents.

Table 1 — The 27 products in the family of common cements

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EN 197-1:2000

Table 1 — The 27 products in the family of common cements

Main types	Notation of the 27 products (types of common cement)		Composition [percentage by mass [a]]										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		
						natural	natural calcined	siliceous	calca-reous				
			K	S	D [b]	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	–	–	–	–	–	–	–	–	–	0 to 5
CEM II	Portland-slag cement	CEM II/A-S	80 to 94	6 to 20	–	–	–	–	–	–	–	–	0 to 5
		CEM II/B-S	65 to 79	21 to 35	–	–	–	–	–	–	–	–	0 to 5
	Portland-silica fume cement	CEM II/A-D	90 to 94	–	6 to 10	–	–	–	–	–	–	–	0 to 5
	Portland-pozzolana cement	CEM II/A-P	80 to 94	–	–	6 to 20	–	–	–	–	–	–	0 to 5
		CEM II/B-P	65 to 79	–	–	21 to 35	–	–	–	–	–	–	0 to 5
		CEM II/A-Q	80 to 94	–	–	–	6 to 20	–	–	–	–	–	0 to 5
		CEM II/B-Q	65 to 79	–	–	–	21 to 35	–	–	–	–	–	0 to 5
	Portland-fly ash cement	CEM II/A-V	80 to 94	–	–	–	–	6 to 20	–	–	–	–	0 to 5
		CEM II/B-V	65 to 79	–	–	–	–	21 to 35	–	–	–	–	0 to 5
		CEM II/A-W	80 to 94	–	–	–	–	–	6 to 20	–	–	–	0 to 5
		CEM II/B-W	65 to 79	–	–	–	–	–	21 to 35	–	–	–	0 to 5
	Portland-burnt shale cement	CEM II/A-T	80 to 94	–	–	–	–	–	–	6 to 20	–	–	0 to 5
		CEM II/B-T	65 to 79	–	–	–	–	–	–	21 to 35	–	–	0 to 5
	Portland-limestone cement	CEM II/A-L	80 to 94	–	–	–	–	–	–	–	6 to 20	–	0 to 5
		CEM II/B-L	65 to 79	–	–	–	–	–	–	–	21 to 35	–	0 to 5
		CEM II/A-LL	80 to 94	–	–	–	–	–	–	–	–	6 to 20	0 to 5
		CEM II/B-LL	65 to 79	–	–	–	–	–	–	–	–	21 to 35	0 to 5
	Portland-composite cement [c]	CEM II/A-M	80 to 94	<------ 6 to 20 ------>									0 to 5
		CEM II/B-M	65 to 79	<------ 21 to 35 ------>									0 to 5
CEM III	Blastfurnace cement	CEM III/A	35 to 64	36 to 65	–	–	–	–	–	–	–	–	0 to 5
		CEM III/B	20 to 34	66 to 80	–	–	–	–	–	–	–	–	0 to 5
		CEM III/C	5 to 19	81 to 95	–	–	–	–	–	–	–	–	0 to 5
CEM IV	Pozzolanic cement [c]	CEM IV/A	65 to 89	–	<------ 11 to 35 ------>					–	–	–	0 to 5
		CEM IV/B	45 to 64	–	<------ 36 to 55 ------>					–	–	–	0 to 5
CEM V	Composite cement [c]	CEM V/A	40 to 64	18 to 30	–	<------ 18 to 30 ------>			–	–	–	–	0 to 5
		CEM V/B	20 to 38	31 to 50	–	<------ 31 to 50 ------>			–	–	–	–	0 to 5

[a] The values in the table refer to the sum of the main and minor additional constituents.
[b] The proportion of silica fume is limited to 10 %.
[c] In Portland-composite cements CEM II/A-M and CEM II/B-M, in Pozzolanic cements CEM IV/A and CEM IV/B and in composite cements CEM V/A and CEM V/B the main constituents other than clinker shall be declared by designation of the cement (for example see clause 8).

Figure 4 Table 1 of EN 197-1

Summary of BS EN 197 requirements

- CEM III/C is classed as Blastfurnace Cement containing 5 to 19% of Clinker and 81 to 95% of Blast furnace slag.
- Portland Cement (CEM I) consists of 95-100% clinker, therefore the assumption is that the remaining 5% of CEM III/C is CEM I. CEM I is unlikely to consist of 100% clinker therefore the CEM III/C will need to have more than 5% CEM I.
- EN 14216 still refers back to BS EN 197 for cement
- Only cements are referred to in the table. Activators are not mentioned therefore concrete produced using Cemfree activator must contain at least 5% of CEM I to be compliant.

BS 8500-1 Concrete – Complementary British Standard to BS EN 206-1 - Part 1: Method of specifying and guidance for the specifier[1]

Foreword
Relationship with other publications:
BS 8500 contains additional United Kingdom provisions to be used in conjunction with BS EN 206-1. Together they form a complete package for the specification, production and conformity of fresh concrete.

Introduction
The Foreword to BS EN 206-1 sets out the context in which BS EN 206-1 operates in the context of European standards. As BS 8500 is the UK complementary standard to BS EN 206-1, the context in which BS 8500 operates is the same when BS 8500 is used within a suite of European standards. For a number of years, the European Standard design codes will co-exist with the current British Standard design codes.

1 Scope

This part of BS 8500 describes methods of specifying concrete and gives guidance for the specifier.

NOTE The guidance for the specifier is given in Annex A. This annex provides guidance on the concrete quality to specify for selected exposure classes, intended working life and nominal cover to normal reinforcement. It does not give guidance on stainless steel and non-metallic reinforcement. Guidance on nominal cover to reinforcement for structural and fire consideration is available in other publications, e.g. structural design codes of practice.

A.2.3 Environments associated with unreinforced concrete

The classification of exposure for unreinforced concrete is limited to exposure classes X0, ACEC and/or XF. The XC, XD and XS classes are not applicable as they relate specifically to the risk of corrosion of reinforcement.

Exposure class X0 can exist only on its own. An aggressive chemical environment for concrete (ACEC class) can apply on its own or in combination with an XF exposure class. If the unreinforced concrete contains any embedded metal, it should be classified as reinforced and the appropriate limiting values associated with exposure classes XC, XD or XS should be selected.

See BS 8204-2 for guidance on abrasion classes for floors or BS EN 13813 for wear resistance by performance.

Extract from Table 1 for the XO exposure class

Table A.1 **Exposure classes** (*continued*)

Class designation	**Class description**	**Informative examples applicable in the United Kingdom**
XC3 and XC4	Moderate humidity or cyclic wet and dry	External reinforced and prestressed concrete surfaces sheltered from, or exposed to, direct rain
		Reinforced and prestressed concrete surfaces subject to high humidity (e.g. poorly ventilated bathrooms, kitchens)
		Reinforced and prestressed concrete surfaces exposed to alternate wetting and drying
		Interior concrete surfaces of pedestrian subways not subject to de-icing salts, voided superstructures or cellular abutments
		Reinforced or prestressed concrete beneath waterproofing

Figure 5 Table A. 1. BS 8500-1

Section A.4.2

Details of the cements and combinations recommended in these tables are given in Table A.6. In addition to these cements and combinations, there are others that have specialist uses or for which experience of their use in the UK is limited. No specific guidance on the application of these cements and combinations is provided in this British Standard. Such cements are not permitted to be used by a producer except where they are specified or agreed.

Note that BS 8500-1 Table 8 recommends a maximum of 55% ggbs in CEM IIIB cement (or CIIIB combinations) to avoid surface scaling in wearing surfaces.

Table A6

Table A.6 **Cement and combination types** A)

Broad designation B)	**Composition**	**Comprises cement and combination types (see BS 8500-2:2006, Table 1)**
CEM I	Portland cement	CEM I
SRPC	Sulfate-resisting Portland cement	SRPC
IIA	Portland cement with 6% to 20% fly ash, ground granulated blastfurnace slag, limestone, or 6% to 10% silica fume C)	CEM II/A-L, CEM II/A-LL, CIIA-L, CIIA-LL, CEM II/A-S, CIIA-S, CEM II/A-V, CIIA-V, CEM II/A-D
IIB-S	Portland cement with 21% to 35% ground granulated blastfurnace slag	CEM II/B-S, CIIB-S
IIB-V	Portland cement with 21% to 35% fly ash	CEM II/B-V, CIIB-V
IIB+SR	Portland cement with 25% to 35% fly ash	CEM II/B-V+SR, CIIB-V+SR
IIIA D), E)	Portland cement with 36% to 65% ground granulated blastfurnace slag	CEM III/A, CIIIA
IIIA+SR E)	Portland cement with 36% to 65% ground granulated blastfurnace slag with additional requirements that enhance sulfate resistance	CEM III/A+SR F), CIIIA+SR F)
IIIB E), G)	Portland cement with 66% to 80% ground granulated blastfurnace slag	CEM III/B, CIIIB
IIIB+SR E)	Portland cement with 66% to 80% ground granulated blastfurnace slag with additional requirements that enhance sulfate resistance	CEM III/B+SR F), CIIIB+SR F)
IVB-V	Portland cement with 36% to 55% fly ash	CEM IV/B(V), CIVB

A) There are a number of cements and combinations not listed in this table that may be specified for certain specialist applications. See BRE Special Digest 1 [1] for the sulfate-resisting characteristics of other cements and combinations. See IP 17/05 [7] for the use of high ggbs content cements and combinations in secant piling applications.
B) The use of these broad designations is sufficient for most applications. Where a more limited range of cement or combinations types is required, select from the notations given in BS 8500-2:2006+A1:2012, Table 1.
C) When IIA or IIA-D is specified, CEM I and silica fume may be combined in the concrete mixer using the k-value concept; see BS EN 206-1:2000, **5.2.5.2.3**.
D) Where IIIA is specified, IIIA+SR may be used.
E) Inclusive of low early strength option (see BS EN 197-4 and the "L" classes in BS 8500-2:2006+A1:2012, Table A.1).
F) "+SR" indicates additional restrictions related to sulfate resistance. See BS 8500-2:2006+A1:2012, Table 1, footnote D.
G) Where IIIB is specified, IIIB+SR may be used.

Figure 6 Table A. 6. BS 8500-1

A.7.5

In exposure classes XF3 and XF4, it is recommended that the aggregates are specified as freeze-thaw resisting. In BS 8500-2:2006, 4.3, requirements are given in terms of a performance in the magnesium sulfate soundness test carried out in accordance with BS EN 1367-2. Such a test is not sufficiently discriminating when used on certain porous flint aggregates and the only guide in this case is experience with concrete made with the aggregate in question after several years' exposure to freeze-thaw conditions.

Summary of BS 8500-1 requirements

- BS 8500 takes precedence over BS EN 206.

- The British Standard does not provide guidance for the use of stainless steel reinforcement.
- There is no risk of corrosion attack if mass concrete or reinforced concrete in dry conditions is used as defined by the XO class.
- CEMIIIC is not included in BS8500 and no guidance is provided.
- Frost resistance is largely dependent on the provision of either an adequate entrained air void system or sufficient strength. Aggregates need to be frost resistant in the more onerous freeze-thaw conditions.
- BS EN 206 / BS8500 are dependent on BS EN 197

EN 1992-1-1: Design of concrete structures Part 1-1: General rules and rules for buildings[4]

1.2.2 Other reference standards

EN 197-1: Cement: Composition, specification and conformity criteria for common cements

EN 206-1: Concrete: Specification, performance, production and conformity

2.1.3 Design working life, durability and quality management

(1) The rules for design working life, durability and quality management are given in EN 1990 Section 2.

3.1.2 Strength

(1)P The compressive strength of concrete is denoted by concrete strength classes which relate to the characteristic (5%) cylinder strength fck, or the cube strength fck,cube, in accordance with EN 206-1.

The requirements of BS EN 206 with regards to strength are as follows:

5 Requirements for concrete and methods of verification

5.1 Basic requirements for constituents

5.1.1 General

(1) Only constituents with established suitability for the particular intended use of the concrete conforming to this European Standard shall be used.

(2) Where there is no European Standard for a particular constituent which refers specifically to the use of this constituent in concrete conforming to this standard, or where there is an existing European Standard which does not cover the particular product or where the constituent deviates significantly from the European Standard, the establishment of suitability may result from:

- a European Technical Assessment which refers specifically to the use of the constituent in concrete conforming to this standard;

- provisions valid in the place of use of the concrete which refers specifically to the use of the constituent in concrete conforming to this standard.

NOTE 1 Where general suitability is established for a constituent, this does not indicate suitability *in every intended use of the concrete and for every concrete composition.*

NOTE 2 European Technical Assessments for constituents establish their general suitability for the use in concrete conforming to this standard. EN 206 is not a harmonised European Standard and the durability provisions for concrete are given in provisions valid in the place of use. Therefore to establish specific suitability, it is necessary to assess the "Product" against the durability provisions valid in the place of use.

(3) Constituents shall not contain harmful ingredients in such quantities as may be detrimental to the durability of the concrete or cause corrosion of the reinforcement and shall be suitable for the intended use in concrete.

Section 4 Durability and Cover To Reinforcement

4.1 General

(1)P A durable structure shall meet the requirements of serviceability, strength and stability throughout its design working life, without significant loss of utility or excessive unforeseen maintenance (for general requirements see also EN 1990).

(2)P The required protection of the structure shall be established by considering its intended use, design working life (see EN 1990), maintenance programme and actions.

(3)P The possible significance of direct and indirect actions, environmental conditions (4.2) and consequential effects shall be considered.

(4) Corrosion protection of steel reinforcement depends on density, quality and thickness of concrete cover (see 4.4) and cracking (see 7.3). The cover density and quality is achieved by controlling the maximum water/cement ratio and minimum cement content (see EN 206-1) and may be related to a minimum strength class of concrete.

4.2 Environmental conditions

(1)P Exposure conditions are chemical and physical conditions to which the structure is exposed in addition to the mechanical actions.

(2) Environmental conditions are classified according to Table 4.1, based on EN 206-1.

(3) In addition to the conditions in Table 4.1, particular forms of aggressive or indirect action should be considered including chemical attack, arising from e.g.

- solutions of acids or sulfate salts (EN 206-1, ISO 9690)

- chlorides contained in the concrete (EN 206-1)

- alkali-aggregate reactions (EN 206-1, National Standards)

physical attack, arising from e.g.

- water penetration (EN 206-1).

(12) Where freeze/thaw or chemical attack on concrete (Classes XF and XA) is expected special attention should be given to the concrete composition (see EN 206-1 Section 6). Cover in accordance with 4.4 will normally be sufficient for such situations.

(13) For concrete abrasion special attention should be given on the aggregate according to EN 206-1.

4.4.1.2 Minimum cover

4.4.1.2 (5) the requirements for structural classification and values of minimum cover due to environmental conditions refers to tables 4.3N, 4.4N and 4.5N.

The National annexe to BS EN 1992-1-1 replaces this with the following requirement:
Use BS 8500-1:2006, Tables A.5 and A.11 for recommendations for concrete quality for a particular exposure class and cover reinforcement. For completeness tables A.5 and A.11 are included below.

Table A.5 **Durability [A)] recommendations for reinforced or prestressed elements with an intended working life of at least 100 years** (*continued*)

Nominal cover [B)]	**Compressive strength class where recommended, maximum water-cement ratio and minimum cement or combination content for normal-weight concrete [C)] with 20 mm maximum aggregate size [D)]**										**Cement/combination types**
mm	**15 + Δc**	**25 + Δc**	**30 + Δc**	**35 + Δc**	**40 + Δc**	**45 + Δc**	**50 + Δc**	**55 + Δc**	**60 + Δc**	**65 + Δc**	
XD3	—	—	—	—	—	—	—	C45/55[E)] 0.35[F)] 380	C40/50[E)] 0.40 380	C35/45[E)] 0.45 360	CEM I, IIA, IIB-S, SRPC
	—	—	—	—	—	C40/50[E)] 0.35[F)] 380	C35/45[E)] 0.40 380	C32/40[E)] 0.45 360	C28/35 0.50 340	C25/30 0.55 320	IIB-V, IIIA
	—	—	—	—	—	C32/40[E)] 0.40 380	C28/35 0.45 360	C25/30 0.50 340	C25/30 0.55 320	C25/30 0.55 320	IIIB, IVB-V
XS3	—	—	—	—	—	—	—	—	C45/55[E)] 0.35[F)] 380	C40/50[E)] 0.40 380	CEM I, IIA, IIB-S, SRPC
	—	—	—	—	—	C40/50[E)] 0.35[F)] 380	C35/45[E)] 0.40 380	C32/40[E)] 0.45 360	C28/35 0.50 340	C25/30 0.55 320	IIB-V, IIIA
	—	—	—	—	—	C32/40[E)] 0.40 380	C28/35 0.45 360	C25/30 0.50 340	C25/30 0.50 340	C25/30 0.50 340	IIIB, IVB-V

A dash (—) indicates that greater cover is recommended.

A) Where appropriate, account should be taken of the recommendations to resist freeze-thaw damage (see **A.4.3**, Table A.8), aggressive chemicals (see **A.4.4**, Table A.11) and abrasion (no guidance provided).

B) Expressed as the minimum cover to reinforcement plus an allowance in design for deviation, c, e.g. to allow for workmanship. Check the appropriate design code to see whether it is recommended that the minimum cover to prestressing steel is adjusted by a factor $\Delta c_{dur,\gamma}$.

C) Also applies to heavyweight concrete. For lightweight concrete the maximum w/c ratio and minimum cement or combination content applies, but the compressive strength class needs to be changed to a lightweight compressive strength class (see BS EN 206-1:2000, Table A.8 and **A.4.1**, Note 2) on the basis of equal cylinder strength if designing to BS EN 1992.

D) For adjustments to cement content for different maximum size of aggregate, see Table A.7.

E) If the concrete is specified as being air entrained in accordance with the XF2 or XF4 recommendations in Table A.8, the minimum compressive strength class for corrosion induced by chlorides may be reduced to C28/35.

F) In some parts of the UK it is not possible to produce a practical concrete with a maximum w/c ratio of 0.35.

Figure 7 Table A. 5. BS 8500-1

Table A.11 **Limiting values of composition and properties for concrete where a DC-class is specified**

DC-class	Max. w/c ratio	Min. cement or combination content (kg/m³) for max. aggregate size				Cement and combination types	Grouping used in BRE SD1: 2005 [1]
		⩾40 mm	20 mm	14 mm	10 mm		
DC-1 A)	—	—	—	—	—	All in Table A.6	A to G
DC-2	0.55	300	320	340	360	IIB-V+SR, IIIA+SR, IIIB+SR, IVB-V	D, E, F
	0.50	320	340	360	380	CEM I, SRPC, IIA-D, IIA-Q, IIA-S, IIA-V, IIB-S, IIB-V, IIIA, IIIB	A, G
	0.45	340	360	380	380	IIA-L or LL ⩾42,5	B
	0.40	360	380	380	380	IIA-L or LL 32,5	C
DC-2z	0.55	300	320	340	360	All in Table A.6	A to G
DC-3	0.50	320	340	360	380	IIIB+SR	F
	0.45	340	360	380	380	IVB-V	E
	0.40	360	380	380	380	IIB-V+SR, IIIA+SR, SRPC	D, G
DC-3z	0.50	320	340	360	380	All in Table A.6	A to G
DC-4	0.45	340	360	380	380	IIIB+SR	F
	0.40	360	380	380	380	IVB-V	E
	0.35	380	380	380	380	IIB-V+SR, IIIA+SR, SRPC	D, G
DC-4z	0.45	340	360	380	380	All in Table A.6	A to G
DC-4m	0.45	340	360	380	380	IIIB+SR	F

A) If the concrete is reinforced or contains embedded metal, the minimum concrete quality for 20 mm maximum aggregate size is C25/30, 0.65, 260 or designated concrete RC25/30.

Figure 8 Table A. 11. BS 8500-1

Summary of EN 1992-1-1 requirements

- EN 1992-1-1 requirements are based on EN 206-1. It has previously been established that BS 8500 takes precedence over BS EN 206.
- The National Annexe to BS EN 1992-1-1 allows the use of the Concrete Society Guide for stainless steel and (indirectly) Highways Agency guidance. The National Annexe to BS EN 1992-1-1 has a higher status than BS 8500/EN 206. Therefore the requirements for stainless steel should be based on compliance with cover from the National Annexe to BS EN 1992-1-1 and minimum concrete quality from BS8500.

Extracts from relevant reports are as follows:

Cemfree - The Development of Non-Portland Cement Based Concretes Prof Peter Hewlett & Dr Martin Liska[5]

Introduction:

Standards and specifications are tolerant of rather than committed to using alternatives to PC with practical examples not exceeding 50:50 GGBS:PC with the occasional exception.

For instance BS 8500 and BS EN 197-1:2000 and BS 4246: 1996 do not recognise 100% replacement of PC by GGBS notwithstanding potential good durability and high chemical resistance reduced chloride and sulphate intrusion, but some results are contradictory.

It is relevant and perhaps telling that ASTM have produced a performance based standard – C1157 that is not dependent on defined materials, so opening up the prospect of showing conformity to one of the stated performance categories that should allow specifiers to recognise the role of non PC based concretes and mortars. Additionally, the American Concrete Industry, building code requirements for structural concretes allows that the use of hydraulic cements conforming to ASTM C1157 in lieu of Portland cement.

It is usual but not necessary to incorporate some PC when making GGBS based concretes. For instance BS EN 197 allows up to 95% GGBS but with a minimum of 5% PC (but rarely if ever specified). PC is added to generate some alkali that acts as a stimulant to the hydraulic latency of the GGBS. Some 5% "minor constituents" are also allowed but not at the expense at the PC. It is the chemical stimulation of the GGBS and the level of structure building that controls the strength/time/temperature properties of the resulting concretes and to some extent its durability. It is the comparison with the Portland cement concretes that has limited the applications and committed development of alternatives. However, is such a comparison entirely justified if one is genuinely concerned about reducing clinker use, and making best use of the environmental legacy of such materials as GGBS?

Durability Considerations

The long term performance as well as performance in aggressive environments of any binder is always of paramount importance for widespread acceptance to occur. Very often a design life of 120 years is required. However, such stringent, but understandable, requirements often hinder innovation as it is not possible to realistically test novel systems in all possible scenarios for the required amount of time. Accelerated testing is often questionable due to yielding results which in fact do not represent the real long term behaviour of the tested system.

In order to overcome this shortcoming, we decided to compare the hydration products to a well established binder system such as Portland cement with high GGBS content. There is a plethora of evidence that such blends exhibit markedly improved durability when compared to pure Portland cement. The durability of a system depends partially on the physical characteristics of the concrete (i.e. porosity and permeability) and also on the chemical speciation of the system (i.e. presence of compounds which readily take part in expansive reactions, such as Portlandite and sulphates). Given the close similarity of the hydration products of Cemfree (including the dense nature of the paste) and the PC-GGBS blend it is not unreasonable to assume that their long term behaviour would be very similar as well.

Summary

- Challenges the British Standards which do not cover all materials.
- Indicates some (but not all) test results are positive
- Refers to ASTM which are not recognised in the Eurocodes

Alkali Activated Materials State-of-the-Art Report, RILEM TC 224-AAM L.S.-C. Ko et al[6].

Section 7 AAM Concretes: Standards for Mix Design/Formulation and Early-Age Properties

7.5.5 EN 206-1: Concrete – Part 1: Specification, Performance, Production and Conformity

Due to the definitions and wording in EN 206-1, it could be possible to use AAM binders in concretes which comply with this standard; it appears that there is not an explicit and strict requirement for cements to comply with EN 197-1, as the words "general suitability" and "should" are used. However, this lack of an explicit requirement has not been legally tested. In addition, European Technical Approvals (for products which do not conform to any other existing standard) and National Standards/Regulations are allowed to extend the range of binder materials, as is the case in the Swiss National Appendices to these standards, which offer scope for a broader range of binders including alkali-activated materials.

Summary

- The lack of an explicit requirement for cement to comply with EN 197-1 has not been legally tested.

BRE Information Paper IP 4/11 Alkali-activated binders Concretes in Construction[7]

Standards and Regulatory Framework

Standards for cement and concrete have been developed and refined over the past century around practice and experience based primarily on PC binders. Over the past two decades, the move away from prescriptive (recipe- based) to performance-based standards has opened the door to PC formulations containing greater proportions of other binder materials (such as pfa and ggbs) that can meet or exceed the performance requirements of 'pure' PC concretes. At first sight, it would seem a small step to move to zero-PC formulations such as activated binder systems.

However, the main standard in the European Union (EN 197) and related cement and concrete standards are based on the presence of some PC in the formulation. In the southern hemisphere, some major stakeholders (manufacturers, designers, purchasers and insurers) have been willing to accept alkali-activated binder concrete products containing no PC as long as they meet the same performance standards as PC concrete. This position has been reached through dialogue and building trust among the parties. The payback is a commercial advantage and environmental 'edge' for manufacturers, consulting engineers and clients. In isolation, such an approach is unlikely to be acceptable in the EU, where a route to standardisation and wider acceptance is likely to also involve establishing a track record of proven performance based on:

- *low criticality applications such as landscaping products and foundations*
- *applications where standardisation is based on the performance of the final product irrespective of its ingredients (for example, block pavers).*

Summary

- The main standard in the European Union (EN 197) and related cement and concrete standards are based on the presence of some PC in the formulation.
- Wider acceptance is likely to also involve establishing a track record.

Overall Summary of Standards and Compliance

The design process is illustrated by the flow charts shown in Figures 9 and 10. A number of dispensations would be required in order to provide the design for a typical structure.

The dispensations are summarised as follows:

- The minimum clinker content is not in accordance BS EN 197
- CEM IIIC mixes are not recognised by BS 8500-1
- There is no basis to justify a design life of 120 years.

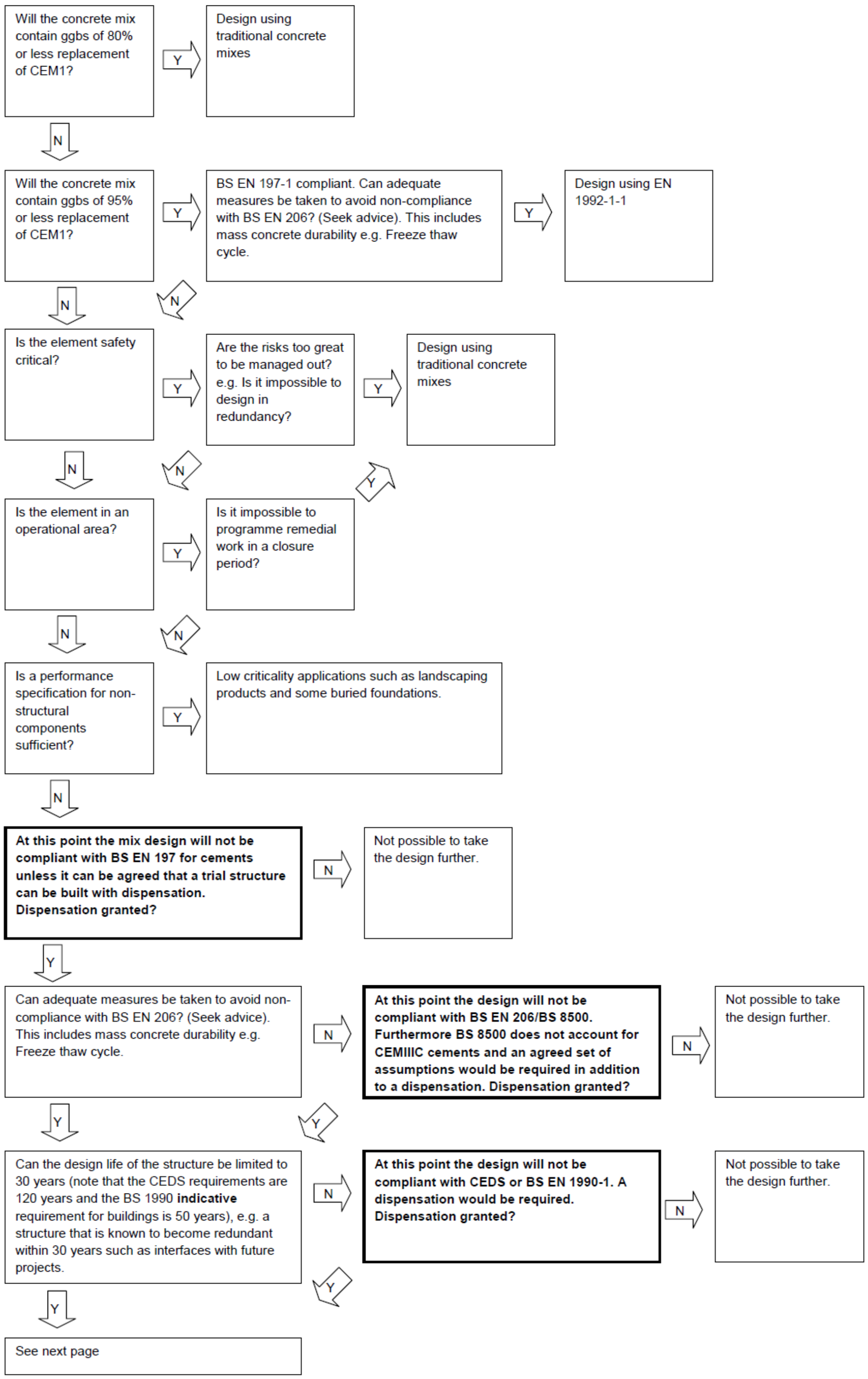

Figure 9 Design Flow Chart (Part 1 of 2)

Continued from previous page.
Dispensations are required for BS EN 197 and potentially BS EN 206/BS 8500

Structure is limited to:

Safety and operationally non - critical

30 year design life

Additional measures are in place for durability and visual inspection.

Additional notes

There is insufficient fire testing to confirm if the concrete could be used in fire conditions. It must therefore be assumed that any examples are either not subject to fire, are redundant enough not to warrant a safety risk and at a low level not to cause injury due to disintegration or a fire can be effectively controlled prior to the concrete being heated.

Creep: not assessed.

Y

Consider the use of stainless steel reinforcement?

Y

The National Annexe to BS EN 1992-1-1 allows the use of the Concrete Society Guide for stainless steel and (indirectly) Highways Agency guidance. The National Annexe to BS EN 1992-1-1 has a higher status than BS 8500/EN 206 so compliance with cover from the National Annexe to BS EN 1992-1-1 and minimum concrete quality from BS8500 is the requirement.

N

Design using mass concrete or using non-stainless steel reinforcement, using previous dispensation for BS EN 206 cement type.

Y

Design using stainless steel reinforcement, using previous dispensation for BS EN 206 cement type.

Conclusion

Dispensations are required for BS EN 197 and BS EN 206/BS 8500 and BS EN 1992-1-1.

Structure is limited to:

- A 30 year design life
- Consist of mass concrete only
- Are not subject to freeze-thaw conditions
- Are not subject to fire
- Are not in Operational Railway areas
- Are not safety critical
- Can be accessed for inspection and can be subjected to a more frequent inspection and maintenance regime.

Limited use of stainless steel reinforcement

Figure 10 Design Flow Chart (Part 2 of 2)

9.2 Carbonation Resistance

For concrete mixes containing EN 197-1 cements, steel embedded in concrete is protected against corrosion by the alkalinity of the cement paste within the concrete mix. Despite the reduction in calcium hydroxide resulting from the incorporation of GGBS, the pH of the cement paste remains at an adequately high level to protect steel. Carbonation can reduce the alkalinity and protection to steel.

Extracts from relevant reports are as follows:

BRE Information Paper IP 5/11 Durability of alkali-activated binder concretes[8]

Table 4 shows carbonation test results (determined using phenolphthalein in water/ethanol solution)[7] for three different exposure conditions. In contrast with the normal behaviour with Portland cement-based concretes, depths of carbonation for each of the AA binder mixes could be ranked in the order indoors > outdoors (exposed) > outdoors (sheltered). Carbonation depths were also significantly higher in the AA binder concretes compared with the PC control mix. With Portland cement-based concrete, the general carbonation behaviour for a given concrete is indoors > outdoors (sheltered) > outdoors (exposed). In the latter exposure environment, the presence of liquid water in pores is thought to slow the rate of CO2 ingress. In Portland cement-based concretes, embedded reinforcement is protected/passivated by the high-pH conditions associated with the calcium-rich phases, and AA binder concretes are also believed to offer a similar degree of protection to reinforcement[9]. With Portland cement-based concretes, the phenolphthalein test is widely accepted to indicate when carbonation has reached the steel and it is no longer protected from corrosion, but it is not clear whether this durability failure mode applies in the same way as with AA binder concretes. This aspect has been identified as a priority topic for further study. Monitoring by BRE of concrete specimens (including concrete specimens with embedded reinforcement) is expected to continue to gather long-term performance data. Each measurement is the mean of two specimens (with 20 individual measurements per specimen). Freshly broken surfaces were sprayed with phenolphthalein indicator solution and the depth of carbonation (indicated by colour change) determined using a gauge before calculating mean values.

Summary

- *The rate of carbonation (as measured using phenolphthalein indicator) was greater than expected and this may have implications for protection of reinforcement*

Cemfree - The Development of Non-Portland Cement Based Concretes Prof Peter Hewlett & Dr Martin Liska[5]

<u>Depth of Carbonation</u>

The depth of carbonation (in mm) was measured on two Cemfree and two Portland cement concretes. The measured values after 6 months of exposure to ambient conditions are shown in Table 3. They demonstrate a similar behaviour of all the concretes with high GGBS content (8.5 – 9mm). No carbonation was seen for CEM III(A) mix (50:50) at this stage of testing. Accelerated carbonation (1%) indicates similar performance up to 28 days - further testing in hand.

Cemfree White	Cemfree Super	CEM III (A)	CEM III (C)
8.5	9	0	10

Figure 11 Cemfree in-house testing of carbonation

Summary

- Indications are that the carbonation rates for Cemfree concretes are greater than for equivalent PC based concretes including those with moderate (50%) content of ggbs
- Internal AAM concretes and equivalent PC based concretes appear to be most affected most by carbonation. The outdoor sheltered condition for AAM concretes is better than the outdoor exposed condition and the converse applies to equivalent PC based concretes.

Alkali Activated Materials State-of-the-Art Report, RILEM TC 224-AAM L.S.-C. Ko et al[6].

13.1.2 Durability

• AAMs show limited carbonation resistance in conventional laboratory tests; this contrasts field performance, which does not seem to show major problems. Some steps towards elucidating the reasons for this discrepancy are beginning to become evident.

Overall Summary of Carbonation Resistance

- Tests are still being carried out to determine performance relative to PC based concretes.
- The rate of carbonation appears to be greater in internal conditions than external conditions. This is true of all cement types but is usually not a problem because of insufficient moisture to support significant reinforcement corrosion rates.

9.3 Freeze–thaw resistance

Concrete which is saturated with water can be damaged by repeated cycles of freezing and thawing, and the use of de-icing salts greatly exacerbates the likelihood of attack. Freeze-thaw damage usually shows up as scaling of the surface, exposing the underlying coarse aggregates.

Extracts from relevant reports are as follows:

BRE Information Paper IP 5/11 Durability of alkali-activated binder concretes[8]

Figure 8 shows expansion data for concrete specimens immersed in water and subjected to 70 freeze–thaw cycles. The results for AA binder concretes indicate little or no expansion with slight surface erosion. The control concrete (which had not been designed to be frost resistant) expanded by more than 0.4% and was severely cracked and spalled. Freezing and thawing can be deleterious to concrete. It is associated with the expansion on freezing of water in the concrete pores and controlled air entrainment is normally applied with PC concretes to minimise the risk of damage. The AA binder concretes have performed well, and this is believed to be associated with the dense microstructure commonly developed by these binder systems[10, 11].

Summary

- Indications are that the AA binder concretes perform better in freeze-thaw conditions than for equivalent PC based concretes.

Alkali Activated Materials State-of-the-Art Report, RILEM TC 224-AAM L.S.-C. Ko et al[6].

The report contains a number of case studies but does not reach any definite conclusion. However the following is stated:

11.11 Demonstration Projects and Applications in Building and Civil Infrastructure Conclusions

The case studies presented display that, in general, the alkali-activated concretes which have been placed into service have been able to serve the purposes for which they were designed, without evident problems related to carbonation, freeze-thaw resistance, mechanical or chemical stability, acid resistance, protection of reinforcing steel, alkali-silica reaction, or any other forms of degradation. In general, the measured strengths of products taken from service after a period of a decade or more have been significantly above the initial design strength requirements.

Summary

- Performance indications are that the AA binder concretes perform satisfactorily in freeze-thaw conditions.

Cemfree - The Development of Non-Portland Cement Based Concretes Prof Peter Hewlett & Dr Martin Liska[5]

Freeze-Thaw

Non air entrained Cemfree concretes are not expected to perform differently to non-air entrained PC concretes. However, work is in hand to establish the performance relative to both types as well as the compatibility with air entraining admixtures.

Overall Summary of Freeze-Thaw resistance

- Tests are still being carried out to determine performance relative to PC based concretes.

9.4 Chloride Resistance

One of the major causes of deterioration of reinforced concrete structures is chloride-induced corrosion of the reinforcing steel, therefore the properties of the concrete surrounding the reinforcement will determine the extent to which this can occur.

Extracts from relevant reports are as follows

Cemfree - The Development of Non-Portland Cement Based Concretes Prof Peter Hewlett & Dr Martin Liska[5]

Chloride Ion Penetration Test

The chloride penetration test is an important parameter for the protection of the reinforcing steel. The parameter was determined using ASTM 1202-12. The authors are aware that the test has been criticised when used in concretes where part of the binder was replaced with GGBS. However, this test is still widely used. It was found that the passed charge of 196 Coulombs corresponds to a very high resistance of the concrete to chloride penetration as shown in Table 2. This suggests a beneficial environment for the protection of the reinforcing steel.

At time of writing this paper, alternative test procedures are being considered

Alkali Activated Materials State-of-the-Art Report, RILEM TC 224-AAM L.S.-C. Ko et al[6].

13.1.2 Durability

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• *AAMs seem to show good chloride resistance, acid resistance, fire resistance, leaching resistance and sulfate resistance; under exposure to MgSO4 in some 'sulfate exposure' tests, it is* *the Mg 2+ rather than the SO 4 2− that has been identified as the cause of the lower than anticipated results.*

Overall Summary of Chloride Resistance

- The indications based on the above reports are promising but further tests are required however ASTM C1202 is entirely unsuitable as it relies on the electrical conductivity of the pore solution which is not comparable between these materials and more conventional cement concrete. No confidence should be placed in the results obtained.

9.5 Fire Resistance

Alkali Activated Materials State-of-the-Art Report, RILEM TC 224-AAM L.S.-C. Ko et al[6].

12.4.5 Fire Resistance

A comparative test of alkali silicate activated fly ash concrete and high strength OPC based concrete demonstrated that the AAM concretes have significant advantages over OPC at high temperature [78 , 103]. It was concluded [78] that the more porous nature of the low-calcium AAM binder facilitated the release of steam pressure during heating, which greatly reduced spalling when compared to OPC concretes of similar initial compressive strength.

Where the references are:

[78] Zhao, R., Sanjayan, J.G.: Geopolymer and Portland cement concretes in simulated fire. Mag. Concr. Res. 63 (3), 163–173 (2011)

And

[103] Van Riessen, A., Rickard, W., Sanjayan, J.: Thermal properties of geopolymers. In: Provis, J.L., van Deventer, J.S.J. (eds.) Geopolymers: Structures, Processing, Properties and Industrial Applications, pp. 317–344. Woodhead, Cambridge (2009)

Overall Summary of Fire Resistance

- The indications are promising.

9.6 Summary of Design Considerations

This summary is based on information from relevant reports and the trials carried out by Crossrail.

Extracts from relevant reports are as follows:

BRE Information Paper IP 5/11 Durability of alkali-activated binder concretes[8]

This limited study highlights the potential of AA binder concretes. The BRE studies showed good performance of these concretes in the following respects, with performance in some exposure environments significantly better than conventional concretes:

1. The AA binder concretes showed good compressive strength development when cured under moist (sealed) conditions although specimens stored in air or water developed lower strength than sealed specimens, particularly those stored in air.

2. The AA binder concretes showed better resistance than the control concrete (Mix 4) to both organic acid (citric acid) and sulfates. The resistance of the AA binder concretes to freeze–thaw cycles was excellent, even without the use of air entrainment.

3. AA binder concretes have similar handling and strength development properties to Portland cement based concretes and they could realistically be used as replacements to conventional concretes in some applications.

4. The rate of carbonation (as measured using phenolphthalein indicator) was greater than expected and this may have implications for protection of reinforcement

Alkali Activated Materials State-of-the-Art Report, RILEM TC 224-AAM L.S.-C. Ko et al[6].

13.1.2 Durability

AAM concretes have been observed to perform well in service in a range of applications, from civil construction and infrastructure to niche applications such as waste immobilisation.

• AAMs can show drying problems if exposed to low humidity at early age as the gel does not strongly bind water of hydration, so curing is an important challenge. In practice, drying conditions during placement and in the early stages of curing may lead to shrinkage and surface micro-cracking.

• Rigorous drying, as required by many durability testing procedures, is known to be challenging with regard to the stability of AAM gels, which may influence the outcomes of the tests.

• AAMs seem to show good chloride resistance, acid resistance, fire resistance, leaching resistance and sulfate resistance; under exposure to MgSO4 in some 'sulfate exposure' tests, it is the Mg 2+ rather than the SO 4 2− that has been identified as the cause of the lower than anticipated results.

• AAMs show limited carbonation resistance in conventional laboratory tests; this contrasts field performance, which does not seem to show major problems. Some steps towards elucidating the reasons for this discrepancy are beginning to become evident.

• Corrosion of steel in AAM concrete is not understood, so it cannot be predicted just based on alkalinity; this is an important field that requires research.

13.3 Conclusions

Summarising the preceding discussion in a very general sense, to enable large scale deployment of alkali-activated binders in concrete production, the following are required:

(a) broad scale, field experience in non-structural applications;

(b) advanced trial experience in structural applications;

(c) international engagement on performance standards, and

(d) quality research focused on analysis and prediction of long term in-service performance.

- Current Standards severely restrict compliant design using Cemfree Concrete. This will not only be an issue for designers but will also apply to those carrying out the design check. There appears to be no evidence to suggest that a 120 year design life can be achieved.

- The indications are that the AA binder concretes perform better in freeze-thaw conditions than for equivalent PC based concretes. However, Cemfree concretes have not been tested for this.
- The Cemfree chloride diffusion test results from C315 have not yet been received. Early indications of good chloride resistance based on migration testing (ASTM C1202) should be treated with caution because of the likely difference in pore solution chemistry which could distort results.
- The indications are that fire resistance will be promising based on evidence provided in technical papers. However Cemfree concretes have not been tested.
- The trials demonstrate that the target strength has not been achieved in all instances therefore consideration would need to be given to adopting a reduced design strength.

Based on the above and on the understanding that dispensation can be granted for non-compliance to BS EN 197 the applications are likely to be limited to those that:

- have a 30 year design life
- consist of mass concrete only
- are not subject to freeze-thaw conditions
- are not subject to fire
- are not in operational railway areas
- are not safety critical
- can be accessed for inspection and can be subjected to a more frequent inspection and maintenance regime.

Further dispensations would be required if stainless steel reinforcement was to be adopted in the design to provide greater corrosion resistance in order to minimise the impact of possible reduced chloride and carbonation resistance.

The applications are likely to be limited to those stated above for mass concrete and

- reducing the risk of carbonation by using in external structures only
- providing additional protective measures to reduce chloride attack.

It is unlikely that a structure which accommodates these requirements will be a useful Crossrail asset.

10 Construction Considerations

The concrete temperature should not fall below 5°C. There is no lower limit on ambient temperature if appropriate precautions are taken over the period which concrete temperature should be maintained above 5°C (ideally above 10°C). A characteristic of Cemfree is the almost total lack of heat of hydration, in cold weather the reaction will slow or cease until it warms up again.

The location of use of the concrete on a construction site is limited until a mix that can be pumped has been perfected.

The trials demonstrated that there are problems with maintaining consistence. DBG advised that the discharge time from batching for their previous trials was between 30-40 minutes. It should be noted that some applications will require this to be longer. A short term measure is to introduce additives on site to maintain consistence, however this needs to be strictly controlled by qualified personnel who may not be available for every site pour. It is understood that DBG will be carrying out further trials in this respect.

It also understood that the variability of maintaining consistence could be due to various sources of GGBS. It is understood that DBG trials have previously been successful using Hanson supplied GGBS, however a commitment to using only one supplier may geographically limit the use of such concrete on site.

It was also noted that, unlike traditional concretes, the Cemfree mix continued to slump for a noticeable period after the removal of the cone. If the slump test is to be used as measurement of workability then some thought needs to be given to fixing the time at which the slump is measured.

Given the issues of maintaining consistence, the concrete is best used under controlled factory conditions. This would also benefit control on curing. Use in Precast Concrete may therefore be a viable option, however the industry often relies on high strength and early strength gains to maintain production rates. The target strength of Cemfree concrete is limited to 40N/mm^2 at 28 days and the test results demonstrate that this is not always achieved.

11 Conclusions

The Block Trial test results confirmed that Mix 1 consisting of 5% Cemfree Activator + 95% GGBS was the most appropriate mix to be used for the Trial Panel. Both the Block Trial and The Trial Panel Compressive Strength test results demonstrated that the target strength of 40N/mm^2 at 28 days using Mix 1 was not achieved in all cases. The heat of hydration of Mix 1 used in the Trial Panel looks acceptably low. The Modulus of Elasticity results were not consistent between the Block Trials and the Trial Panel. Complete results are awaited for the Trial Panel Accelerated carbonation testing, Aggregate Segregation and Modulus of Elasticity tests.

Current Standards severely restrict compliant design using Cemfree Concrete. This will not only be an issue for designers but will also apply to those carrying out the design check. There is limited long term test information within the industry related to carbonation resistance, freeze-thaw conditions, chloride resistance and fire resistance which are indicators of design life. Dispensation for non-compliance with BS EN 197 as a minimum would be required before applications in mass concrete alone could be considered. Further dispensations would be required if stainless steel reinforcement was to be adopted and even then it is unlikely that a useful Crossrail asset could be designed. Ideally any future trials need to be identified before the design stage.

The location of use of the concrete on a construction site is limited until a mix that can be pumped has been perfected. Cold weather can slow down the reaction and the rate of gain of strength. The trials demonstrated that there are problems with maintaining consistence throughout a concrete pour. If the slump test is to be used as measurement of workability then some thought needs to be given to fixing the time at which the slump is measured. Use in the Precast Concrete may be a viable option, subject to target strengths being achieved.

It should be noted that this report has been limited to a review of Cemfree concretes only whilst referring to reference material for Alkali-activated binders in general. Consideration should also be given to:

- Alternative Alkali-activated binders under development
- The availability of GGBS and the consequences on industry of abandoning CEM1 altogether
- The use of concretes with high slag contents and minimum CEM1 content, particularly if stainless steel reinforcement is used.

References

1. BS 8500-1 Concrete – Complementary British Standard to BS EN 206-1 - Part 1: Method of specifying and guidance for the specifier
2. EN 197-1 Cement: Composition, specification and conformity criteria for common cements
3. BS EN 197: Cement -Part 1: Composition, specifications and conformity criteria for common cements.
4. EN 1992-1-1: Design of concrete structures Part 1-1: General rules and rules for buildings
5. Cemfree - The Development of Non-Portland Cement Based Concretes Prof Peter Hewlett & Dr Martin Liska
6. Alkali Activated Materials State-of-the-Art Report, RILEM TC 224-AAM L.S.-C. Ko et al.
7. BRE Information Paper IP 4/11 Alkali-activated binders Concretes in Construction
8. BRE Information Paper IP 5/11 Durability of alkali-activated binder concretes
9. Cement Free Concrete - Initial Testing Report document number C315-VIN-C-RGN-CR146_ST003-53110 Revision 1.0
10. Comments on Low Carbon Concrete – Trial Panel Report document number C315-VIN-C-RGN-CR146_ST003-53521

Appendix A: Photographs

	**Photograph 01** First Block Trial formwork 21st November 2013
	**Photograph 02** Second Block Trial formwork 21st November 2013
	**Photograph 03** Third Block Trial formwork 21st November 2013

	**Photograph 04** Block Trial formwork 21st November 2013
	**Photograph 05** Block Trial formwork. 21st November 2013
	**Photograph 06** Block Trial formwork 21st November 2013

	**Photograph 07** Block Trial formwork, base 21st November 2013
	**Photograph 08** Block Trial formwork 21st November 2013
	**Photograph 09** Block Trial Concrete sampling facilities 21st November 2013

Photograph 10
Block Trial Concrete sampling facilities
21st November 2013

Photograph 11
Block Trial Concrete sampling facilities
21st November 2013

Photograph 12
First Block Trial, chute condition.
21st November 2013

	**Photograph 13** Block Trial formwork 21st November 2013
	**Photograph 14** Block Trial Concrete sampling facilities 21st November 2013
	**Photograph 15** First Block Trial, concrete on chute 21st November 2013

	**Photograph 16** First Block Trial, concrete on chute 21st November 2013
	**Photograph 17** First Block Trial, sample for slump testing 21st November 2013
	**Photograph 18** Second Block Trial, slump prior to pouring 21st November 2013

Photograph 19
First Block Trial, slump prior to pouring
21st November 2013

Photograph 20
First Block Trial, slump prior to pouring
21st November 2013

Photograph 21
First Block Trial, discharge and placing
21st November 2013

	**Photograph 22** First Block Trial, discharge and placing 21st November 2013
	**Photograph 23** First Block Trial, discharge and placing 21st November 2013
	**Photograph 24** First Block Trial, slump following concreting 21st November 2013

Photograph 25
First Block Trial, finish following floating
21st November 2013

Photograph 26
Second Block Trial, sample for slump testing
21st November 2013

Photograph 27
Second Block Trial, sample for slump testing
21st November 2013

	**Photograph 28** Second Block Trial, slump prior to pouring 21st November 2013
	**Photograph 29** Second Block Trial, slump prior to pouring 21st November 2013
	**Photograph 30** Second Block Trial, slump prior to pouring 21st November 2013

Photograph 31
First Block Trial; Finish during Second Trial
21st November 2013

Photograph 32
Second Block Trial, discharge and placing
21st November 2013

Photograph 33
Second Block Trial, discharge and placing
21st November 2013

	**Photograph 34** Second Block Trial, discharge and placing 21st November 2013
	**Photograph 35** Second Block Trial, discharge and placing 21st November 2013
	**Photograph 36** Second Block Trial, float finish not applied as too workable. 21st November 2013

Photograph 37
Second Block Trial, float finish not applied as too workable.
21st November 2013

Photograph 38
First Block Trial, finish during Third Trial
21st November 2013

Photograph 39
Third Block Trial, sample for slump testing
21st November 2013

	**Photograph 40** Third Block Trial, sample for slump testing 21st November 2013
	**Photograph 41** Third Block Trial, slump prior to pouring 21st November 2013
	**Photograph 42** Third Block Trial, slump prior to pouring 21st November 2013

	**Photograph 43** Third Block Trial, slump prior to pouring 21st November 2013
	**Photograph 44** Third Block Trial, discharge and placing 21st November 2013
	**Photograph 45** Third Block Trial, discharge and placing 21st November 2013

	**Photograph 46** Second Block Trial, Finish during Third Trial 21st November 2013
	**Photograph 47** Third Block Trial, float finish being applied 21st November 2013
	**Photograph 48** Third Block Trial, post pour slump 21st November 2013

	**Photograph 49** Third Block Trial, post pour slump 21st November 2013
	**Photograph 50** Second Block Trial, formwork struck and sampled for testing. 4th April 2014
	**Photograph 51** Second Block Trial, surface finish after casting. 4th April 2014

	**Photograph 52** First Block Trial, formwork struck and sampled for testing. 4th April 2014
	**Photograph 53** First Block Trial, formwork struck and sampled for testing. 4th April 2014
	**Photograph 54** First Block Trial, formwork struck and sampled for testing. 4th April 2014

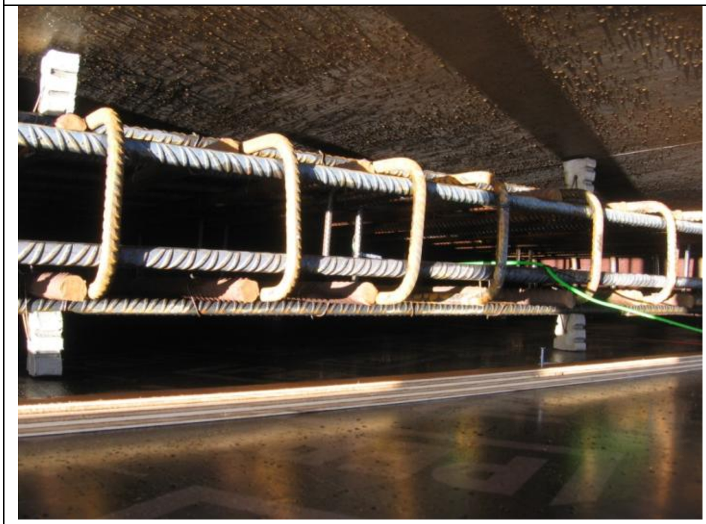
Photograph 55
First Block Trial, formwork struck and sampled for testing.
4th April 2014

Photograph 56
Trial Panel Base Pour concreting.
4th April 2014

Photograph 57
Trial Panel Base Pour concreting.
4th April 2014

	**Photograph 58** Trial Panel Base Pour concreting. 4th April 2014
	**Photograph 59** Trial Panel Base Pour concreting. Second concrete delivery. 4th April 2014
	**Photograph 60** Trial Panel Base Pour concreting. Surface finish 4th April 2014

	**Photograph 61** Trial Panel Base Pour concreting. Surface finish 4th April 2014
	**Photograph 62** Trial Panel Base Pour concreting. Surface finish 4th April 2014
	**Photograph 63** Trial Panel Base Pour concreting. Surface finish 4th April 2014

	**Photograph 64** Trial Panel Base Pour concreting. Finish on kicker. 4th April 2014
	**Photograph 65** Trial Panel Wall Pour concreting. Pre-pour inspection. 14th April 2014
	**Photograph 66** Trial Panel Wall Pour formwork. Pre-pour inspection. 14th April 2014

Photograph 67
Trial Panel Wall Pour concreting.
14th April 2014

Photograph 68
Trial Panel Wall Pour initial slump test.
14th April 2014

Photograph 69
Trial Panel Wall Pour concreting.
14th April 2014

	**Photograph 70** Trial Panel Wall Pour concreting. 14th April 2014
	**Photograph 71** Trial Panel Wall Pour initial slump test. 14th April 2014
	**Photograph 72** Trial Panel Wall Pour final slump test. 14th April 2014

	**Photograph 73** Trial Panel Wall Pour final slump test. 14th April 2014
	**Photograph 74** Trial Panel Wall Pour struck concrete quality 6th May 2014
	**Photograph 75** Trial Panel Wall Pour struck concrete quality 6th May 2014

Appendix B: Results

Block Trial Cube Results

Vinci Report	Laboratory Report	Mix	Lab Ref	Curing	Age	Compressive strength (N/mm^2)
Rev 1.0	UXB22921337_22	1	22921340	Air	56	41.1
Rev 1.0	UXB22921310_22	1	22921310	Lab	1	1.5
Rev 1.0	UXB22921310_22	1	22921311	Lab	2	5.7
Rev 1.0	UXB22921319_22	1	22921319	Lab	2	5.3
Rev 1.0	UXB22921310_22	1	22921312	Lab	3	10.8
Rev 1.0	UXB22921328_22	1	22921328	Lab	3	11.3
Rev 1.0	UXB22921319_22	1	22921320	Lab	3	11.3
Rev 1.0	UXB22921310_22	1	22921313	Lab	7	18.4
Rev 1.0	UXB22921328_22	1	22921329	Lab	7	19
Rev 1.0	UXB22921337_22	1	22921337	Lab	7	18.2
Rev 1.0	UXB22921319_22	1	22921321	Lab	7	18.7
Rev 1.0	UXB22921328_22	1	22921330	Lab	14	34.7
Rev 1.0	UXB22921337_22	1	22921338	Lab	14	32
Rev 1.0	UXB22921319_22	1	22921322	Lab	14	34.3
Rev 1.0	UXB22921328_22	1	22921331	Lab	28	38.4
Rev 1.0	UXB22921337_22	1	22921339	Lab	28	39
Rev 1.0	UXB22921342_22	2	22921342	Air	1	1.1
Rev 1.0	UXB22921342_22	2	22921343	Air	1	0.9
Rev 1.0	UXB22921342_22	2	22921344	Air	1	1
Rev 1.0	UXB22921342_22	2	22921345	Air	1	1.3
Rev 1.0	UXB22921366_22	2	22921366	Air	14	21.1
Rev 1.0	UXB22921366_22	2	22921367	Air	14	22.1
Rev 1.0	UXB22921350_22	2	22921352	Lab	2	3.2
Rev 1.0	UXB22921350_22	2	22921353	Lab	2	4.5
Rev 1.0	UXB22921358_22	2	22921358	Lab	3	7.3
Rev 1.0	UXB22921358_22	2	22921359	Lab	3	7.4
Rev 1.0	UXB22921374_22	2	22921376	Lab	28	37.9
Rev 1.0	UXB22921374_22	2	22921377	Lab	28	38.3
Rev 1.0	UXB22921382_22	2	22921382	Lab	56	41.3
Rev 1.0	UXB22921382_22	2	22921383	Lab	56	42.1
Rev 1.0	UXB22921350_22	2	22921350	Moist Air	2	4.4
Rev 1.0	UXB22921350_22	2	22921351	Moist Air	2	3.9
Rev 1.0	UXB22921358_22	2	22921360	Moist Air	7	15.5
Rev 1.0	UXB22921358_22	2	22921361	Moist Air	7	16
Rev 1.0	UXB22921366_22	2	22921368	Moist Air	14	27.8
Rev 1.0	UXB22921366_22	2	22921369	Moist Air	14	28.8
Rev 1.0	UXB22921374_22	2	22921374	Moist Air	28	36.1
Rev 1.0	UXB22921374_22	2	22921375	Moist Air	28	37
Rev 1.0	UXB22921390_22	3	22921390	Air	1	0.5
Rev 1.0	UXB22921390_22	3	22921391	Air	1	0.4
Rev 1.0	UXB22921390_22	3	22921392	Air	1	0.2

Vinci Report	Laboratory Report	Mix	Lab Ref	Curing	Age	Compressive strength (N/mm^2)
Rev 1.0	UXB22921390_22	3	22921393	Air	1	0.3
Rev 1.0	UXB22921406_22	3	22921408	Air	7	3
Rev 1.0	UXB22921406_22	3	22921409	Air	7	2.9
Rev 1.0	UXB22921414_22	3	22921414	Air	14	4.8
Rev 1.0	UXB22921414_22	3	22921415	Air	14	5.5
Rev 1.0	UXB22921414_22	3	22921416	Lab	14	5.1
Rev 1.0	UXB22921414_22	3	22921417	Lab	14	5.3
Rev 1.0	UXB22921422_22	3	22921422	Lab	28	11.5
Rev 1.0	UXB22921422_22	3	22921423	Lab	28	11
Rev 1.0	UXB22921422_22	3	22921424	Lab	28	10.9
Rev 1.0	UXB22921422_22	3	22921425	Lab	28	11.4
Rev 1.0	UXB22921430_22	3	22921430	Lab	56	12.1
Rev 1.0	UXB22921430_22	3	22921431	Lab	56	10.5
Rev 1.0	UXB22921398_22	3	22921398	Unknown	2	0.9
Rev 1.0	UXB22921398_22	3	22921399	Unknown	2	0.8
Rev 1.0	UXB22921398_22	3	22921400	Unknown	2	0.9
Rev 1.0	UXB22921398_22	3	22921401	Unknown	2	0.9
Rev 1.0	UXB22921406_22	3	22921406	Unknown	3	1.2
Rev 1.0	UXB22921406_22	3	22921407	Unknown	3	1.2

Block Trial Core Results

Vinci Report	Lab Report	Mix	Date of Coring	Age	Core Compres sive strength	Corrected In situ Cube Strength (N/mm^2)
Rev 1.0	UXB0242724/401/S1	1	12/12/2013	28	31	32.4
Rev 1.0	UXB0242724/*403/S1	1	12/12/2013	28	33	34.5
Rev 1.0	UXB0242724/*405/S1	1	12/12/2013	56	41.3	43.2
Rev 1.0	UXB0242724/*416/S1	2	12/12/2013	28	26.3	27.5
Rev 1.0	UXB0242724/*418/S1	2	12/12/2013	28	33.3	34.8
Rev 1.0	UXB0242724/*420/S1	2	12/12/2013	56	35.6	37.2

Block Trial Static Modulus of Elasticity

Vinci Report	Lab Report	Sample Reference	Mix	Date sample Received	Age	Mean Compressive strength (N/mm^2)	Static Modulus of Elasticity (N/mm^2)
Rev 1.0	M7009C53	EE7722/1	1	19/12/2013	28	31.4	30500
Rev 1.0	M7009C53	EE7722/3	1	19/12/2013	28	31.4	31000
Rev 1.0	M7009C53	EE7722/4	2	19/12/2013	28	29.8	29000
Rev 1.0	M7009C53	EE7722/6	2	19/12/2013	28	29.8	29000

Block Trial Tensile Splitting strength on Concrete

Vinci Report	Lab Report	Sample	Mix	Date sample Received	Surface Condition	Age	Tensile Splitting strength (N/mm^2)
Rev 1.0	UXB 0242724-3	22956395	1	12/12/2013	Surface wet	28	2.9
Rev 1.0	UXB 0242724-3	22956396	1	12/12/2013	Surface wet	28	3.35
Rev 1.0	UXB 0242724-3	22956397	1	12/12/2013	Surface wet	28	3.45
Rev 1.0	UXB 0242724-4	22956400	2	12/12/2013	Surface wet	28	2.8
Rev 1.0	UXB 0242724-4	22956398	2	12/12/2013	Surface wet	28	2.95
Rev 1.0	UXB 0242724-4	22956399	2	12/12/2013	Surface wet	28	3.05

Appendix C: Testing Regime

Testing regime for Cemfree Concrete (PTR C315-RFI-001361, 06/12/13)

Property	Test	Number of Samples	Testing House	Comments
Visual Inspection	Inspect for: Cracks, Compaction, Colour and anomalies.		C122/CRL	General: A programme is required to show when samples are to be taken and tests are to be carried out.
Strength development and Long term strength retention	100mm x 100mm cube compressive tests. Minimum of 2No samples of trial each, to be tested at 1, 2, 3, 7, 14, 28, 56, 90 days and as long as permitted by the duration of the test programme. Sampling and testing to be in accordance with BS EN12350-1, BS EN 12390-2 & BS EN 12390-3 and to include density in accordance with BS EN 12390-7. Separate sets to be cured in each of three conditions: (i) Sealed against water loss or gain (ii) Air-dry (iii) Wet cure in accordance with BS EN 12390-2	3x2x8x3=144	ESG	ESG to supply 2 Technicians. The required number of cube moulds are available. The one day test using wet cure conditions will not be practicable, test to be carried out following curing in air dry conditions. *Only 34 of the required 48 cubes taken as the mix became unworkable. Agreed that wet cure tests not required at 1 day as the concrete would not have set and that the 2 samples required for the 1,2, 3,7,14 and 28 day air tests need not be tested as the information could be extrapolated form the cores to be taken.* *NB Dry store cubes were included because of the reported negative effect of water storage on cube strength*
In situ Density and strength	Minimum of 2No 100mm diameter 100mm long cores from each trial in accordance with BS EN 12504-1 to test in situ density in accordance with BS EN 12390-7 and strength in accordance with BS EN 13791. The cores shall be taken at appropriate ages to allow testing at ages of 28, 56 and 90 days after a period of air storage in accordance with BS EN 13791.	3x2x3=18	ESG	ESG are satisfied that the tests can be carried out to the specified standards.
Tensile strength	The concrete shall be tested for indirect tensile strength at an age of 28 days in accordance with either BS EN 12390-5 or BS EN 12390-6, for each of the three curing regimes above. 2 No 100mm diameter cores per sample, length to suit test method.	3x2x3=18	Vinci Technology Centre	ESG are satisfied that the tests can be carried out to the specified standards.
Creep and Shrinkage	The concrete shall be tested for drying shrinkage in accordance with BS ISO 1920-8 and wetting expansion using the same procedure but with specimens continuously stored under water, for which 75mm x 75mm prisms shall be prepared. The concrete shall be tested for creep in accordance with BS ISO 1920-9 using 100mm diameter cores. Tests shall be continued for as long as permitted by the duration of the test programme.	3 9	Vinci Technology Centre	ESG propose that the tests are carried to ASTM C157 and C341. This is a departure from the specification and ESG are to advise of the advantages. The samples to be taken are cylinders instead of cores. ESG have the cylinder moulds. C122 to liaise with C122/CRL Materials Consultants to confirm that the proposed testing is acceptable. *Drying shrinkage - BS ISO 1920-8 says start drying at 7 days, ASTM says 28 days. Drying conditions are almost the same 55% RH for the BS, 50% for the ASTM. C122 preference is still for the BS but if the ASTM is used the 28 day testing is required.* *Creep – initial loading takes place after 28 days for both BS ISO 1920-9 and ASTM C512 (NB ASTM C341 is not the creep test, it's just how to measure the length of the specimens)*
Absorption	The concrete shall be tested for durability properties by means of absorption and capillary suction (sorptivity) tests, as described below. i) Absorption tests shall be carried out in the testing laboratory on 75mm diameter cores cut at an age of 24 to 28 days to enable the absorption tests to be carried between 28 to 32 days in accordance with BS 1881-122. Alternatively, tests may be carried out on 75mm x 75mm prisms cast for the purpose. The upper acceptance limit for absorption after 30 min shall be 3%. ii) Tests for capillary absorption shall be carried out in	3x2=6	Vinci Technology Centre	ESG are proposing that the tests are carried to ASTM. They will advise of the ASTM number. The tests are tom be carried out using cylinders. C122 to liaise with C122/CRL Materials Consultants to confirm that the proposed testing is acceptable.

Testing regime for Cemfree Concrete (PTR C315-RFI-001361, 06/12/13)

Property	Test	Number of Samples	Testing House	Comments
	accordance with BS EN 480-5 Tests to determine the penetration of water under pressure shall be carried out in accordance with BS EN 12390-8. The acceptable limits for penetration shall be 30mm for concrete likely to come into contact with aggressive media and 50mm for slightly aggressive media. In each case the mean from the results obtained for three specimens shall be taken.			
Oxygen and Chloride Diffusion Tests	Two sets of three 100mm diameter x 100mm long cores, which shall include the cured surface shall be taken from the panel. One set of cores for oxygen diffusion tests and one set for chloride diffusion tests at 28 days and 56 days. For oxygen diffusivity, the samples shall be conditioned at 55% Relative Humidity and 20°C for seven days prior to testing. The samples shall be tested using test procedures and equipment as supplied by Imperial College, London or Leeds University or similar qualified laboratory. The concrete shall have a maximum oxygen diffusion coefficient at 28 days of 5 x 10-8m²/s.	3x6=18	Vinci Technology Centre	ESG are proposing that the tests are carried to ASTM. They will advise of the ASTM number. The tests are to be carried out using cylinders. *C122 need to know what is proposed - if it is the ASTM C1202 rapid chloride permeability test then that is not acceptable.*
Protection of reinforcement against carbonation	Accelerated carbonation tests in accordance with BS 1881-210. Allow for 3 tests in the trial panel only.	3 in trial panel only	ESG	ESG to check BS 1881-210 for requirements to achieve accelerated results.
Heat of hydration	Thermocouple to be located in the centre and at mid height of the main trial pour.	1 in trial panel only.	ESG	No reference standards available. C122 to mark up trial panel drawing showing location.
Modulus of elasticity	The concrete shall be tested for static modulus of elasticity in accordance with BS 1881-121	Allow for 3 tests in the trial panel only.	ESG	ESG suggest tests to be carried out at 7 and 28 days using 100mm diameter cores.
Workability	The meeting agreed that consistence class S4 should be targeted. DBG have successfully poured the concrete using skip and chute but have not perfected the mix for pump pouring. It was recognised that a pump mixes were an essential part of the development of the mix and DBG were going to carry out further tests. Tests to BS EN 12350-2 Note that slump may not be the most appropriate test due to strange rheological properties – maybe just consider ability to handle/pump, place and compact. Slump testing to be carried out for information on the three block trials and the trial panel.	8	ESG	ESG will slump test.
Aggregate segregation	Ad-hoc test based on ASTM C1610 for self-compacting concrete but adjusted to include vibration – this has been a problem with high ggbs concrete on several jobs.	1 test in the trial panel only.	ESG	ESG are to research the test and report back.
Alkali-aggregate reactivity	Test method to be decided	Allow for 3 tests in the trial panel only.	This will be outsourced by ESG	ESG suggest petrographic analysis. *No, petrography mainly looks at the reactivity of the aggregates and will not be experienced with this cement type – C122 need an expansion test with a known reactive aggregate to see if the reaction kicks off or not. (On Hold)*

Appendix D: Drawings

C315 – Connaught Tunnel Refurbishment & Surface Rail Works

GA and RC Detail Drawings of TRIAL PANEL for TRACK SUPPORT SLAB

CRL Document Number C315-VIN-C-DWG-CR146_ST003-50018

(Replacing C315-VIN-C-RSP-CR146_ST003-50016)

Contract MDL reference: C08.090

1. Contractor Document Submittal History:

Revision:	Date:	Prepared by:	Checked by:	Approved by:	Reason for Issue:
Rev 1	27/04/12	[redacted]	[redacted]	[redacted]	For Construction
		[redacted]	[redacted]	[redacted]	

2a. Stakeholder (LU/NWR/DLR/RfL/Other* (delete* as applicable)) review required? YES ☐ NO ☐

(If NO, strike out sections 2a & 2b and go to section 3)

This document has been reviewed by _______________ in the capacity of _______________ for coordination, compliance, integration, and acceptance as a safe system of work, output, control, sequence. This document is acceptable for transmittal to _______________ for no objection to the works being executed as described.

Sign: _______________ Name: __________________ Date: _______________

2b. Review by Stakeholder (if required):

Stakeholder Organisation	Job Title	Name	Signature	Date	Acceptance
					☐
					☐
					☐

3. Acceptance by *Crossrail*

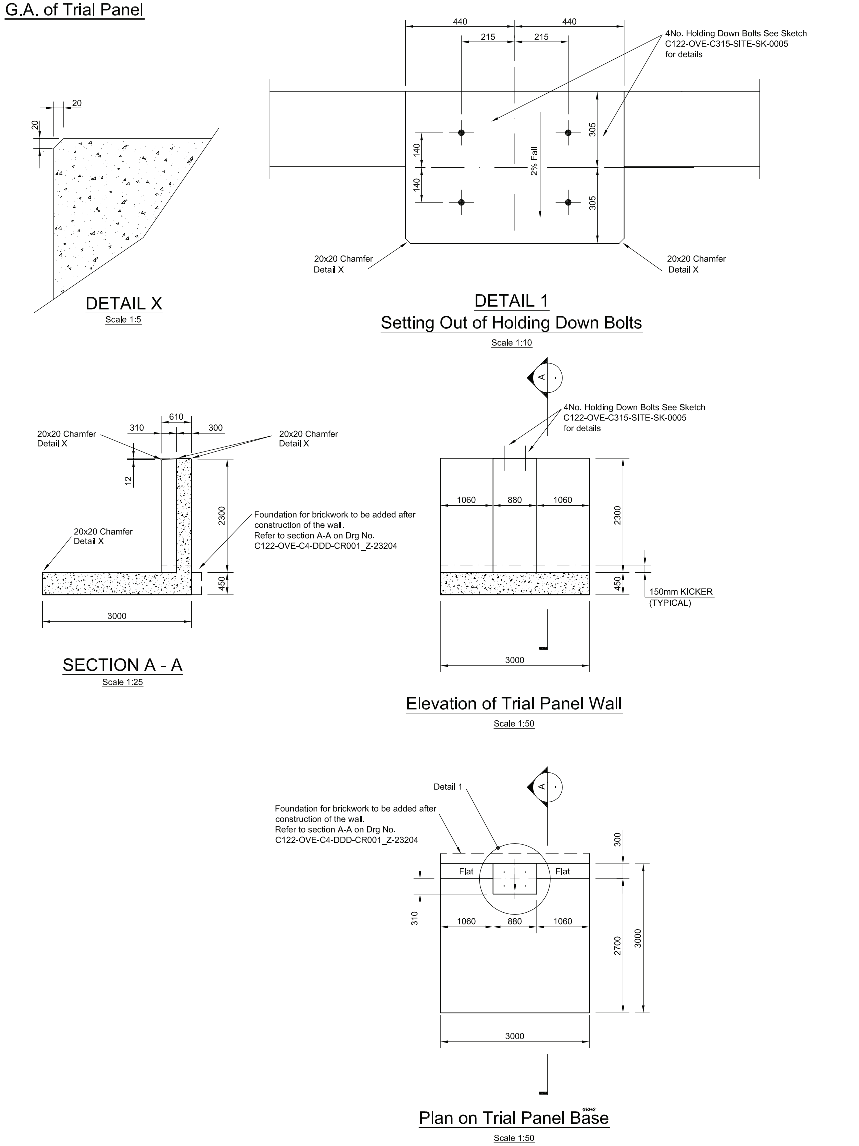
Crossrail	***Crossrail* Review and Acceptance Decal** This decal is to be used for submitted documents requiring acceptance by *Crossrail*.	
☑	Code 1.	Accepted. Work May Proceed
☐	Code 2. indicated	Not Accepted. Revise and resubmit. Work may proceed subject to incorporation of changes
☐	Code 3.	Not Accepted. Revise and resubmit. Work may not proceed
☐	Code 4.	Received for information only. Receipt is confirmed

Reviewed/Accepted by:(signature)	Print Name:	Position:	Date:
[redacted]	[redacted]	[redacted]	21/6/12

Acceptance by *Crossrail* does not relieve the designer/supplier from full compliance with their contractual obligations and does not constitute *Crossrail* approval of design, details, calculations, analyses, test methods or materials developed or selected by the designer/supplier.

NOTE THE PROPERTY OF THIS DRAWING AND DESIGN IS VESTED IN (DESIGNER) AND MUST NOT BE COPIED OR REPRODUCED IN ANY WAY WITHOUT THEIR WRITTEN CONSENT

G.A. of Trial Panel

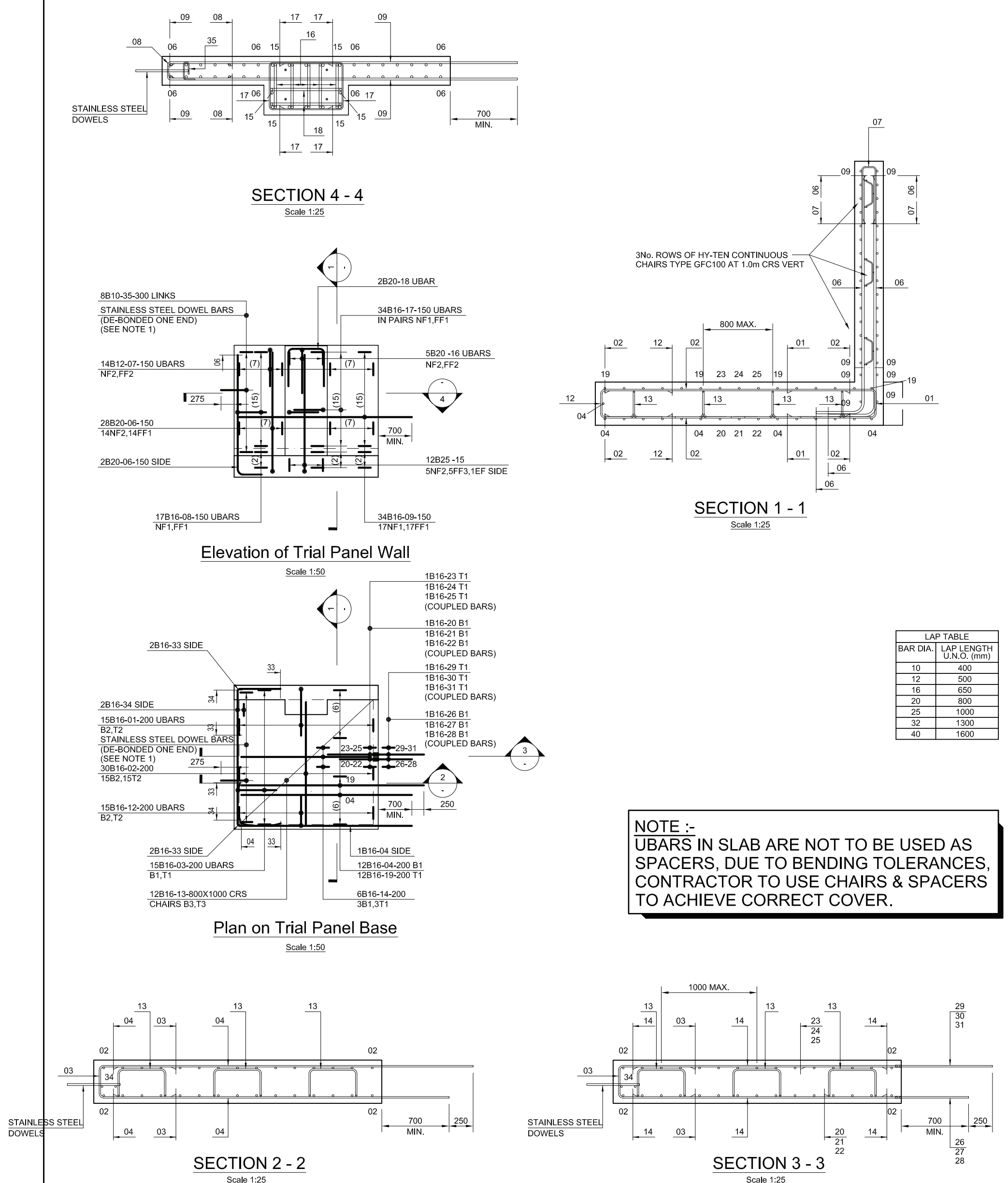


SCALE 1 : 50 (0 – 1000 – 2000 – 3000 – 4000 – 5000mm)

SCALE 1 : 25 (0 – 500 – 1000 – 1500 – 2000 – 2500mm)

Safety, Health and Environmental Information
For S.H.E information - see drgs C122-OVE-C-DDA-CR001_Z-31100 & 31101

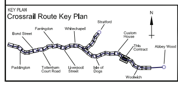
R.C. Details of Trial Panel



LAP TABLE	
BAR DIA.	LAP LENGTH U.N.O. (mm)
10	400
12	500
16	650
20	800
25	1000
32	1300
40	1600

NOTE :-
UBARS IN SLAB ARE NOT TO BE USED AS SPACERS, DUE TO BENDING TOLERANCES, CONTRACTOR TO USE CHAIRS & SPACERS TO ACHIEVE CORRECT COVER.

KEY PLAN
Crossrail Route Key Plan



SAFETY HEALTH AND ENVIRONMENTAL INFORMATION BOX

Construction Notes	Maintenance/cleaning Notes	Demolition/adaptation Notes
SEE ABOVE	SEE ABOVE	SEE ABOVE

NOTES & MODEL REFERENCE FILES
1. This Drawing to be read in conjunction with the following:-
   Drawing C122-OVE-C4-CR001_Z-22200 : General Notes
   Materials and Workmanship Specification KF10
   - Insitu concrete C122-OVE-Z4-RSP-CR001-0023.
2. All dimensions are in millimetres unless specified otherwise.
3. Reinforcement is listed on B.B.S. No.s C315-00-XX-C-VCUK-SH-0001/01-05
4. Cover to be as follows :-
   Slab - 55mm
   Wall - 55mm
5. Concrete Strength C32/40.

ISSUED FOR CONSTRUCTION						
S.R.	25.04.12	M.S.	25.04.12	W.D.	25.04.12
FOR CLIENT APPROVAL						
S.R.	27.03.12	M.S.	27.03.12	W.D.	27.03.12
DRAWN BY	D_DATE	CHECKED BY	C_DATE	APPROVED BY	A_DATE

SCALES @ A1: 1:50 @ A1
ISSUING OFFICE: SITE OFFICE
PROJECT NUMBER: VA0004
STATUS: S10 FIT FOR CONSTRUCTION
SIGN OFF: A - NO COMMENTS; B - MINOR COMMENTS; C - DO NOT USE

VINCI Construction UK Ltd
Astral House, Imperial Way, Watford, Hertfordshire WD24 4WW
Tel: +44 (0)1923 233 433

PROJECT: C315 Connaught Tunnel

TITLE: Trial Panel
G.A. & R.C. Details

CLIENT: Crossrail Limited, 25 Canada Square, Canary Wharf, London E14 5LQ, © Crossrail, www.crossrail.co.uk

DRAWING NUMBER: C315-XX-C-VCUK-DR-001
REV: 2

Project: C315
CONNAUGHT TUNNEL

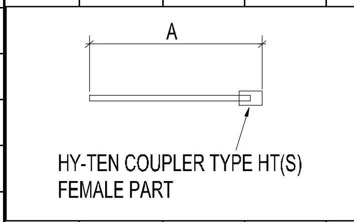
VINCI CONSTRUCTION UK

Revision : 2

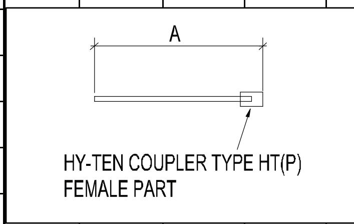
Drawing: C315-XX-C-VCUK-DR-001
Title : R.C. DETAILS TRIAL PANEL

Schedule Ref: C315-XX-C-VCUK-SH-001/01
Date prepared: 23/02/2012 **Date Revised:** 25/04/2012
Prepared by: SR **Checked by:** MS

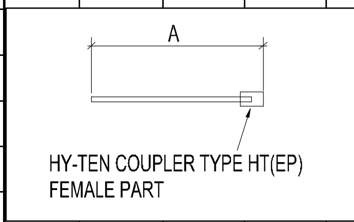
Member	Bar Mark No.	Type	Size	No. of Memb.	No. in Each	Total no.	Length (mm) †	Shape Code	Bending dimensions * in accordance with BS 8666 A mm	B mm	C mm	D mm	E/R mm	Weight (kg)	REV
BASE	01	B	16	1	15	15	2250	21	1000	290	(1000)			53	
	02	B	16	1	30	30	2550	00						121	
	03	B	16	1	15	15	1875	21	800	330	(800)			44	
	04	B	16	1	13	13	3550	00						73	
		A													
	14	B	16	1	6	6	2700	00						26	
	12	B	16	1	15	15	1850	21	800	290	(800)			44	
	13	B	16	1	12	12	1500	98	500	260	300	(300)		28	
	19	B	16	1	12	12	3800	00						72	
	20	B	16	1	1	1	1000	9901	1000					2	



Member	Bar Mark No.	Type	Size	No. of Memb.	No. in Each	Total no.	Length (mm) †	Shape Code	A mm	B mm	C mm	D mm	E/R mm	Weight (kg)	REV
	21	B	16	1	1	1	1000	9901	1000					2	



Member	Bar Mark No.	Type	Size	No. of Memb.	No. in Each	Total no.	Length (mm) †	Shape Code	A mm	B mm	C mm	D mm	E/R mm	Weight (kg)	REV
	22	B	16	1	1	1	1000	9901	1000					2	



Type, Shape Code and Bending Dimensions are in accordance with BS 8666 2005

Diameter	mm	**6**	**8**	**10**	**12**	**16**	**20**	**25**	**32**	**40**	**50**
Weight	kg	0	0	0	0	466	0	0	0	0	0

ALL BARS THIS SHEET	
TOTAL (kg)	**466**

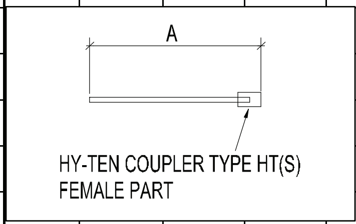
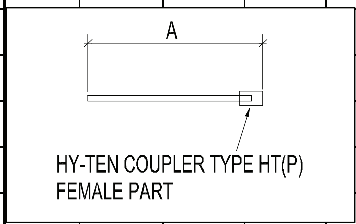
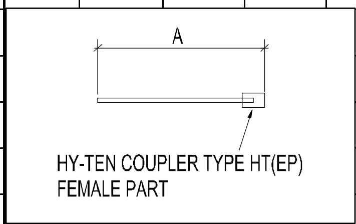
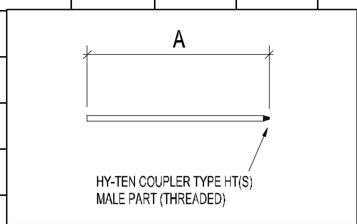
† Specified in multiples of 25mm.
* Specified in multiples of 5mm.

Issue	First issue	Rev 2	Rev 3	Rev 4	Rev 5	This schedule is
Date	27.03.12	25.04.12				Sheet 1 of 5
Status		For Construction				

Project:	C315 CONNAUGHT TUNNEL
Drawing:	C315-XX-C-VCUK-DR-001
Title :	R.C. DETAILS TRIAL PANEL

Revision : 2

Schedule Ref:	C315-XX-C-VCUK-SH-001/02		
Date prepared:	23/02/2012	**Date Revised:**	25/04/2012
Prepared by:	SR	**Checked by:**	MS

Member	Bar Mark No.	Type	Size	No. of Memb.	No. in Each	Total no.	Length (mm) †	Shape Code	Bending dimensions * in accordance with BS 8666 A mm	B mm	C mm	D mm	E/R mm	Weight (kg)	REV
BASE	23	B	16	1	1	1	1400	9901	1400					2	
CONT.															
	24	B	16	1	1	1	1400	9901	1400					2	
															
	25	B	16	1	1	1	1400	9901	1400					2	
															
	26	B	16	1	1	1	800	9902	800					1	
															

Type, Shape Code and Bending Dimensions are in accordance with BS 8666 2005

Diameter	mm	**6**	**8**	**10**	**12**	**16**	**20**	**25**	**32**	**40**	**50**
Weight	kg	0	0	0	0	8	0	0	0	0	0

ALL BARS THIS SHEET	
TOTAL (kg)	**8**

† Specified in multiples of 25mm.
* Specified in multiples of 5mm.

Issue	First issue	Rev 2	Rev 3	Rev 4	Rev 5	This schedule is
Date	27.03.12	25.04.12				Sheet 2 of 5
Status	Fit for Construction					

Project: C315
CONNAUGHT TUNNEL

Drawing: C315-XX-C-VCUK-DR-001

Title : R.C. DETAILS TRIAL PANEL

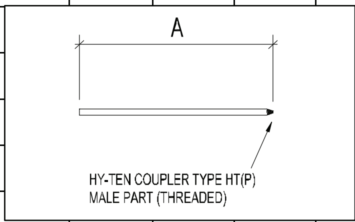
Revision : 2

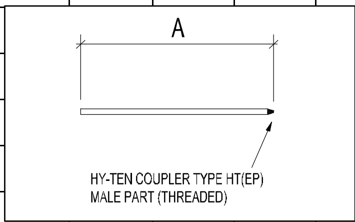
Schedule Ref: C315-XX-C-VCUK-SH-001/03

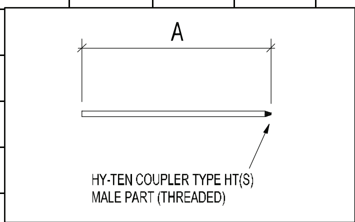
Date prepared: 23/02/2012 **Date Revised:** 25/04/2012

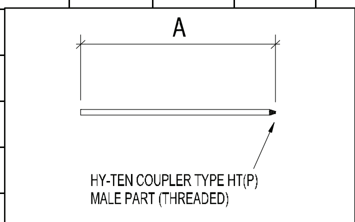
Prepared by: SR **Checked by:** MS

Member	Bar Mark No.	Type	Size	No. of Memb.	No. in Each	Total no.	Length (mm) †	Shape Code	Bending dimensions * in accordance with BS 8666 A mm	B mm	C mm	D mm	E/R mm	Weight (kg)	REV
BASE	27	B	16	1	1	1	800	9902	800					1	
CONT.															
	28	B	16	1	1	1	800	9902	800					1	
	29	B	16	1	1	1	1000	9902	1000					2	
	30	B	16	1	1	1	1000	9902	1000					2	









Type, Shape Code and Bending Dimensions are in accordance with BS 8666 2005

Diameter	mm	6	8	10	12	16	20	25	32	40	50
Weight	kg	0	0	0	0	6	0	0	0	0	0

ALL BARS THIS SHEET	
TOTAL (kg)	6

† Specified in multiples of 25mm.
* Specified in multiples of 5mm.

Issue	First issue	Rev 2	Rev 3	Rev 4	Rev 5	This schedule is			
Date	27.03.12	25.04.12				Sheet	3	of	5
Status	Fit for Construction								

Project: C315
CONNAUGHT TUNNEL

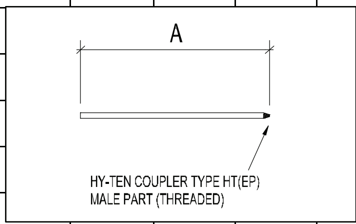
Drawing: C315-XX-C-VCUK-DR-001
Title : R.C. DETAILS TRIAL PANEL

VINCI CONSTRUCTION UK

Revision : 2

Schedule Ref: C315-XX-C-VCUK-SH-001/04
Date prepared: 23/02/2012 **Date Revised:** 25/04/2012
Prepared by: SR **Checked by:** MS

Member	Bar Mark No.	Type	Size	No. of Memb.	No. in Each	Total no.	Length (mm) †	Shape Code	Bending dimensions * in accordance with BS 8666 A mm	B mm	C mm	D mm	E/R mm	Weight (kg)	REV
BASE	31	B	16	1	1	1	1000	9902	1000					2	
CONT.															
	33	B	16	1	4	4	1775	11	900	(900)				11	
	34	B	16	1	2	2	2750	00						9	



Type, Shape Code and Bending Dimensions are in accordance with BS 8666 2005

Diameter	mm	6	8	10	12	16	20	25	32	40	50
Weight	kg	0	0	0	0	21	0	0	0	0	0

ALL BARS THIS SHEET	
TOTAL (kg)	21

† Specified in multiples of 25mm.
* Specified in multiples of 5mm.

Issue	First issue	Rev 2	Rev 3	Rev 4	Rev 5	This schedule is			
Date	27.03.12	25.04.12				Sheet	4	of	5
Status	Fit for Construction								

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Revision : 2

Project: C315
CONNAUGHT TUNNEL

Schedule Ref: C315-XX-C-VCUK-SH-001/05

Drawing: C315-XX-C-VCUK-DR-001

Date prepared: 23/02/2012 **Date Revised:** 25/03/2012

Title : R.C. DETAILS TRIAL PANEL

Prepared by: SR **Checked by:** MS

Member	Bar Mark No.	Type	Size	No. of Memb.	No. in Each	Total no.	Length (mm) †	Shape Code	Bending dimensions * in accordance with BS 8666 A mm	B mm	C mm	D mm	E/R mm	Weight (kg)	REV
WALL	06	B	20	1	30	30	3275	11	800	(2525)				242	
	07	B	12	1	14	14	1400	21	650	145	(650)			17	
	08	B	16	1	17	17	1825	21	850	180	(850)			49	
	09	B	16	1	34	34	3625	00						195	
	15	B	25	1	12	12	2975	11	500	(2525)				138	
	16	B	20	1	5	5	2350	21	1000	450	(1000)			29	
	17	B	12	1	34	34	1850	21	700	490	(700)			56	
	18	B	20	1	2	2	2625	21	1000	725	(1000)			13	
	35	B	10	1	8	8	425	22	120	180	60	(120)		2	

Type, Shape Code and Bending Dimensions are in accordance with BS 8666 2005

Diameter	mm	6	8	10	12	16	20	25	32	40	50
Weight	kg	0	0	2	73	244	284	138	0	0	0

ALL BARS THIS SHEET	
TOTAL (kg)	741

† Specified in multiples of 25mm.
* Specified in multiples of 5mm.

Issue	First issue	Rev 2	Rev 3	Rev 4	Rev 5	This schedule is			
Date	27.03.12	25.04.12				Sheet	5	of	5
Status	Fit for Construction								