Influence of Casting Position on Anchorage Strength of Steel Reinforcement

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1. BACKGROUND

It is widely recognised that bond strength of bars cast near the top of a pour is weaker than that of bars cast near the bottom. The lesser strength of top cast bars is attributed to two factors:

a) the increase in w/c ratio towards the top of a pour as a result of consolidation of fluid concrete prior to setting; and
b) formation of voids beneath bars as solids in fluid concrete settle when the bar is restrained from vertical movement.

This project was initiated from a rigorous Literature Review drafted earlier by Dr John Cairns in which an analysis of results from tests on lapped joints within the ACI 408 bond test database suggested the 0.7 factor for "top cast" bars, i.e. bars in a 'poor' casting position as defined by EC2 (see, for example, Figure 1), was somewhat conservative. On the other hand, several more recent studies which employed pull-out type specimens with short bond lengths in which bars were rigidly restrained against vertical displacement show a markedly greater top cast effect than that currently given in major design Codes.

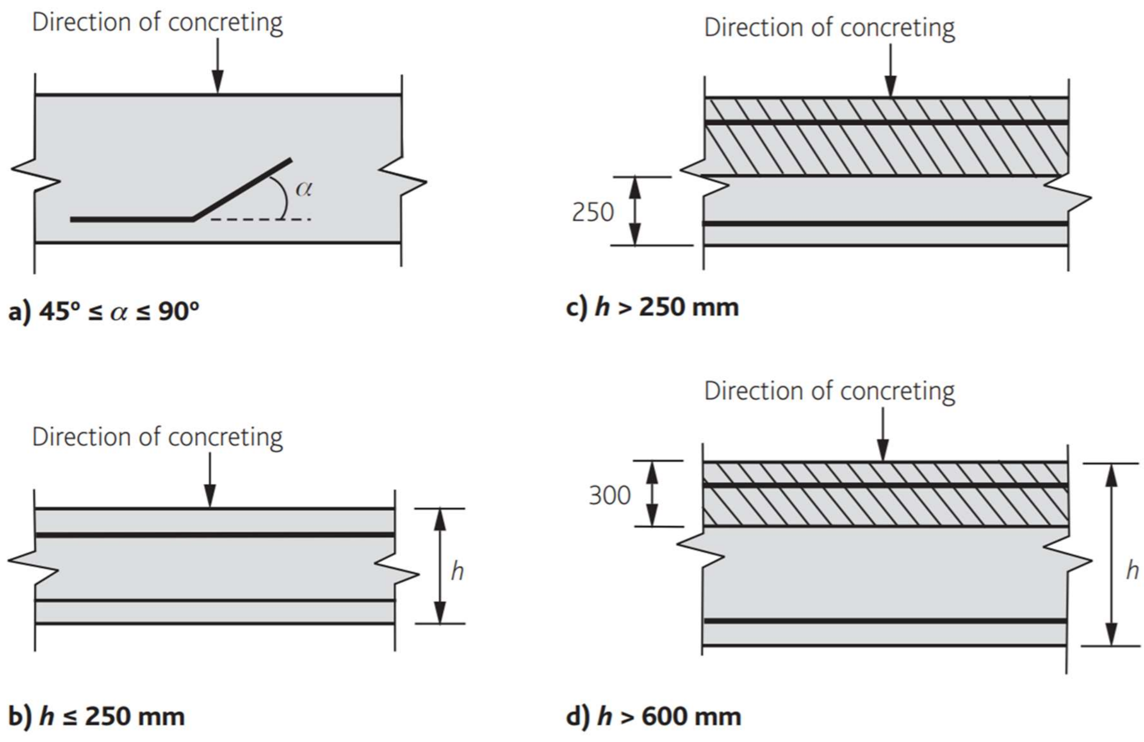


Figure 1 Description of bond conditions to BS EN1992-1-1.

The aim of this project is to develop recommendations for the casting position factor η_1 used in the determination of basic bond strength of reinforcement in EC2. The value of the coefficient and the classification of criteria for good/poor bond conditions are both considered.

Subsidiary aims necessary to achieve this overall objective are:

(1) To evaluate the importance of the stiffness of support to the bars while fluid concrete consolidates;
(2) To assess the variation in anchorage capacity with bond length;
(3) To assess the sensitivity of anchorage capacity to characteristics of the concrete mix;
(4) To assess the validity of the Rilem Pullout test (PoT) (BS EN 10080 Annex D); and
(5) To assess the influence of the head of concrete above the bar on resistance of bottom cast bars.

2. EXPERIMENTAL PROGRAMME

An experimental programme was undertaken in the Structures Laboratory at Heriot-Watt University in Edinburgh to study influence of casting position on the bond strength of embedded steel in concrete. Test parameters in the experiments include:

- the distance of the bar from the bottom of the pour
- the distance of the bar from the top of the pour
- height of test specimens
- concrete strength and consistency
- restraint to vertical displacement of bar following compaction of fresh concrete

(Note that the first three items are inter-related).

1.1 Test specimens

Four series of test specimens with 16 mm diameter reinforcing bars provided in both faces were fabricated. Each series contained:

(1) Tall specimen with an overall height of 1500 mm;
(2) Medium specimen with an overall height of 450 mm;
(3) Short specimen with an overall height of 250mm; and
(4) Modified RILEM pull-out specimen (BS EN 10080 Annex D), with an overall height of 1500 mm.

Specimens (1)-(3) had plan dimensions of 360×400mm^2 whereas the modified RILEM specimen had plan dimensions of 160×160mm^2. The specimens were constructed with Grade C25/30 and C35/45 concretes. In each concrete grade, the effect of slump was also studied: S2 (low) slump and S5 (high) slump. The dimensions of the test specimens are shown in Figure 2.

In the low-strength series (C30), the bars on the two faces in the Tall/Medium/Short specimens had a central bond length of 200 mm and two unbonded lengths of 80 mm at both ends, giving a total length of 360 mm. The central bond length was reduced to 125 mm in the high-strength series (C45) to ensure that bar yielding did not govern the failure. These unbonded lengths were provided prior to casting by means of plastic pipes (see Figures 2(a)-(c), 3(a)). In the C30 series, six bars were provided on the two faces of the Tall specimen, three bars on the top with vertical centre-to-centre (c/c) distance of 150 mm (see Figures 2(a)-(c)) hereinafter referred to as the top cast bars and three others on the bottom with the same vertical distance referred to as the bottom cast bars. The C45 series had the same bar configuration but with two additional bars provided under the top cast bars on each face, thereby giving a total of eight bars in each face. The 150 mm spacing was provided to ensure that cracking generated during testing will have no influence on the bond strength of the adjacent bar.

The Medium specimen had only three bars on each face with the same vertical distance as above (i.e. 150 mm) whereas the Short specimen had only two bars on each face. Due to the limited height of the Short specimen, the vertical centre-to-centre distance of the bars was shortened to 120 mm.
In the Tall/Medium/Short specimens, bars in one face of each specimen were placed in round holes to provide a rigid support to the bars, whereas bars in the opposite face were placed in slot holes and secured in place with removable supports. These temporary supports were released immediately after compaction to allow the bars to displace vertically as concrete consolidated.

In addition to these primary test bars, the C30 specimens had two 8 mm diameter vertical links which were provided at a c/c distance of 100 mm to simulate the presence of shear links/transverse reinforcement in practice. The C45 specimens had only one 8 mm diameter link provided at the centre of the bonded length. The vertical links were tied to 16 mm bars by soft iron tying wire as in practice. Tying to links provided the only vertical restraint to test bars in slotted holes after temporary support was released.

In the C30 series, the modified RILEM specimen had a bond length of 80 mm and an unbonded length over the other half to minimise the restraint effects at the loaded end. The unbonded length was provided using a plastic pipe as in the other test specimens. The c/c distance of the bars in this specimen follows that in the Tall specimen (see Figures 1(a) and (d)). In the C45 series, the bond length was reduced to 48 mm to avoid bar yielding. In this series, two additional top bars were provided on each face following the bar configuration in the Tall specimen (see Figure 2(d)).

All specimens were cast with the 16 mm bars positioned horizontal. Grade 500C high-strength reinforcing bars were used throughout. Figure 3(a) displays the rib pattern of the reinforcing bars used in this experimental programme. The bars were used 'as delivered' – their condition was generally clean, with some experiencing only superficial rust in a few places.

It should be noted that the bond length shown in the schematics in Figures 2(a) – (d) is only for the C30 series. As stated earlier, the bond length in C45 series was reduced to 125 mm (Figures 2(a)-(c)) and 48 mm in Figure 2(d).

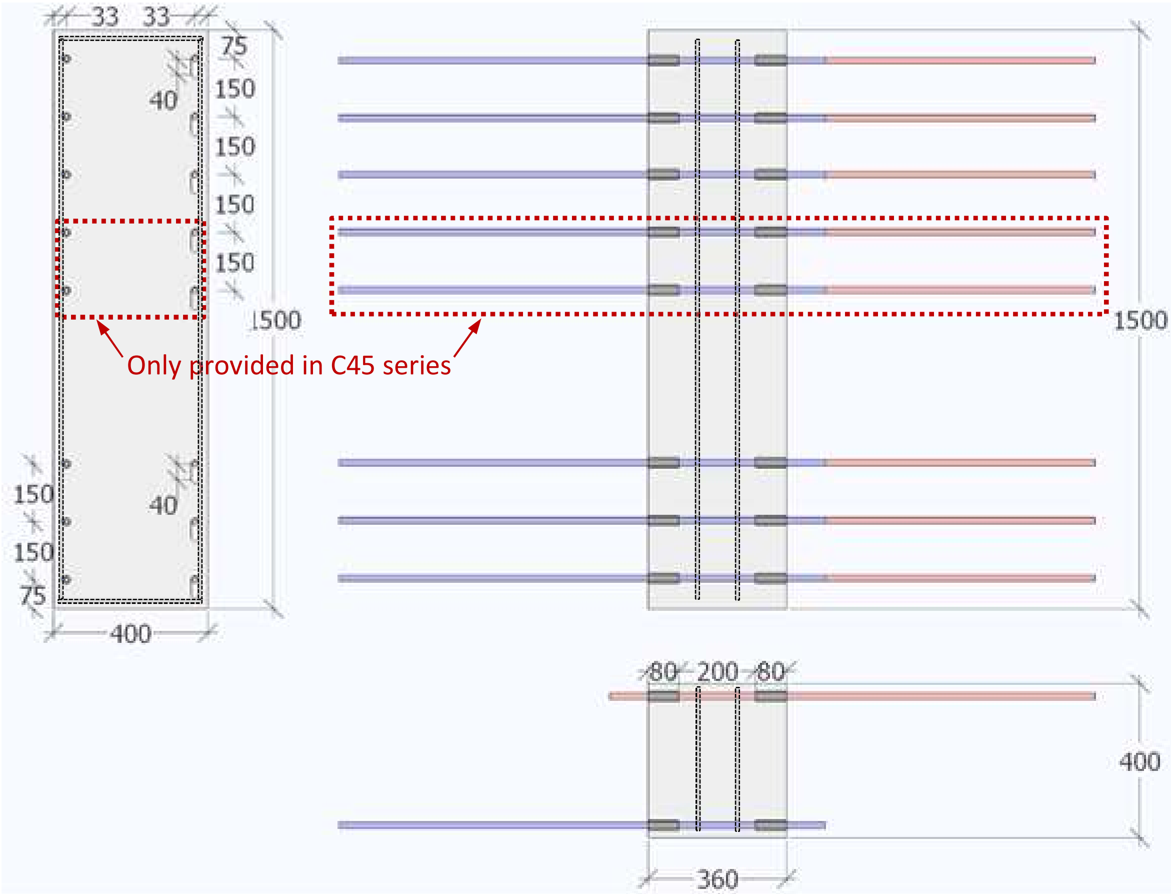


Figure 2 (a). Schematic of the Tall specimen showing overall dimensions in mm, the configuration of the primary test bars (outside and inside the specimen), the configuration of the transverse links for C30 specimens (for C45 specimens, only one link was provided at the centre), the location of round and slot holes and the position of the plastic pipes inside the specimen. The top sketches show the elevation views while the bottom shows the plan view.

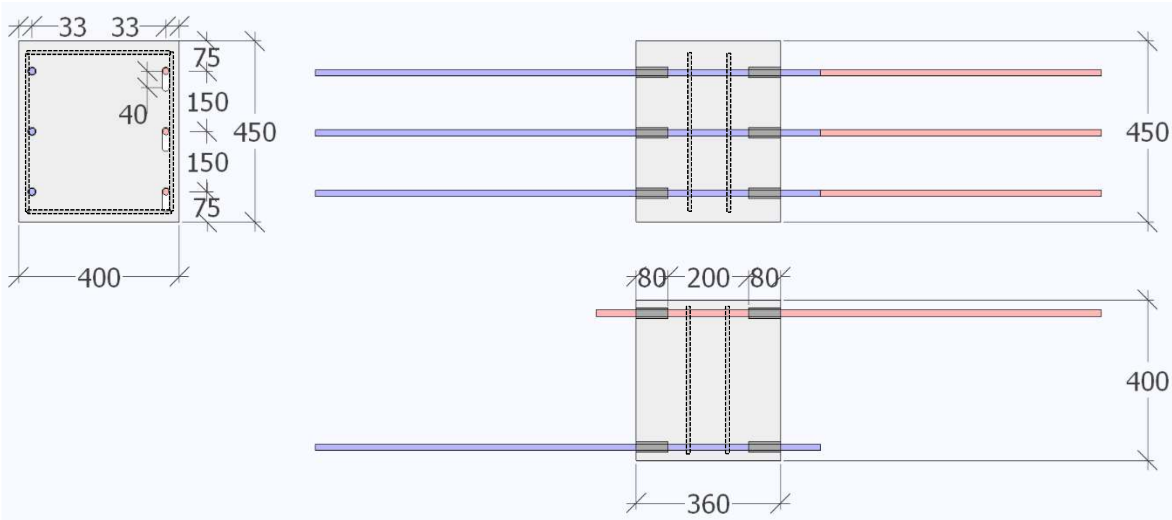


Figure 2 (b). Schematic of the Medium specimen showing overall dimensions in mm, the configuration of the primary test bars (outside and inside the specimen), the configuration of the transverse links for C30 specimens (for C45 specimens, only one link was provided at the centre), the location of round and slot holes, and the position of the plastic pipes inside the specimen. The top sketches show the elevation views while the bottom shows the plan view.

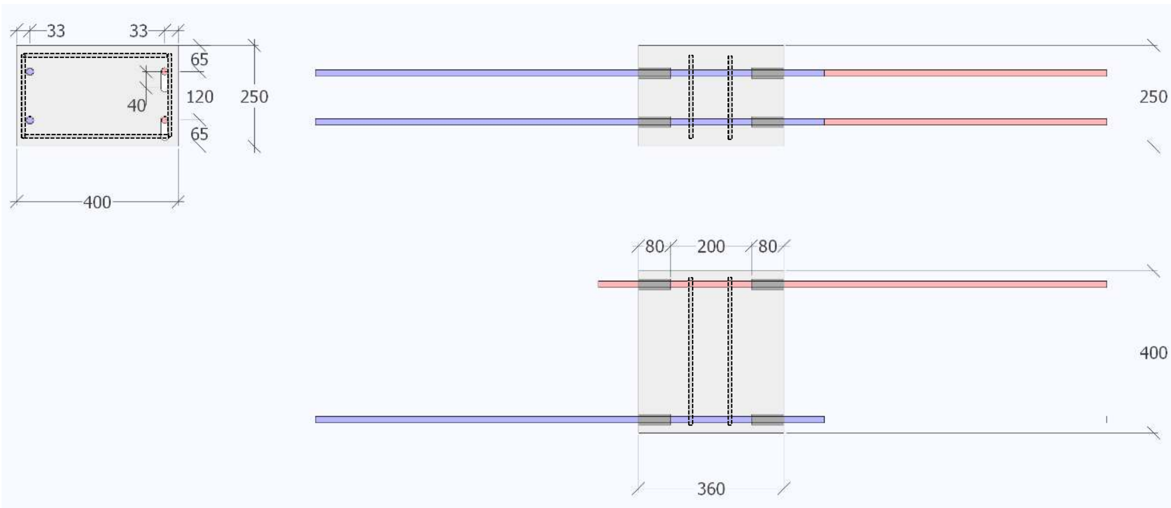


Figure 2 (c). Schematic of the Short specimen showing overall dimensions, the configuration of the primary test bars (outside and inside the specimen), the configuration of the transverse links for C30 specimens (for C45 specimens, only one link was provided at the centre), and the location of round and slot holes. The top sketches show the elevation views while the bottom shows the plan view.

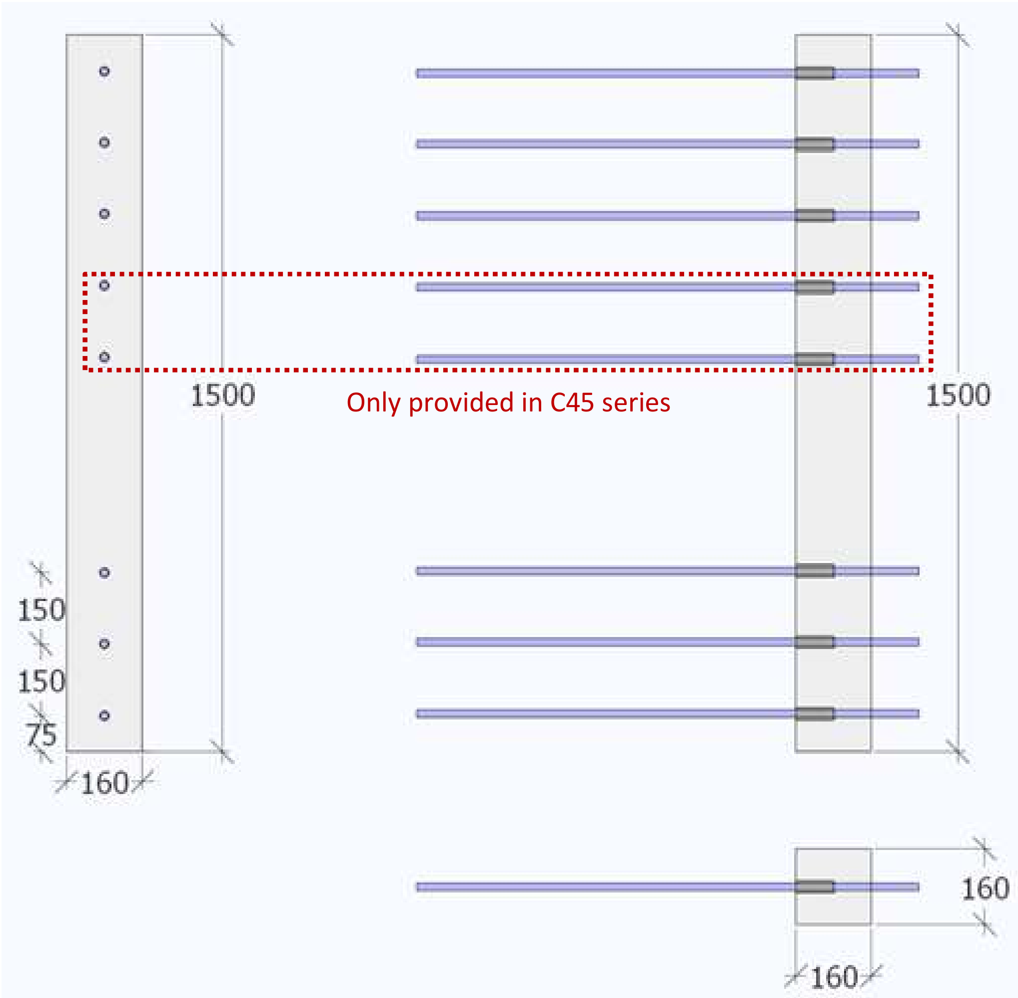


Figure 2 (d). Schematic of the modified RILEM specimen showing overall dimensions and bar configuration. The top sketches show the elevation views while the bottom shows the plan view.

Figure 3 Typical rib pattern of the 16 mm reinforcing bar.

1.2 Specimen preparation

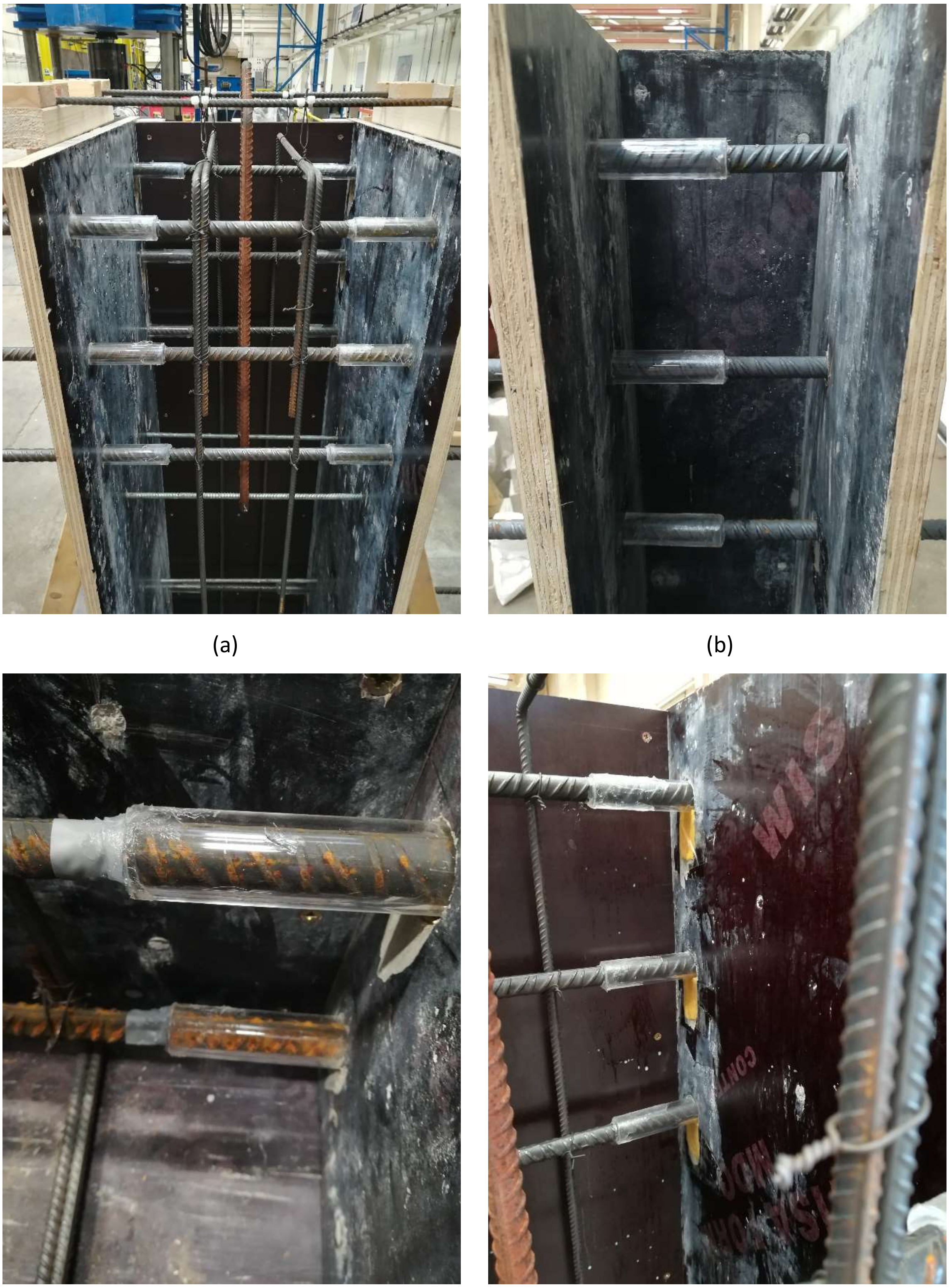
Timber formwork was prepared in-house using phenolic film faced plywood panels. Prior to casting, all 16mm bars were slotted into the designated (round/slot) holes on one pair of opposing sides in each formwork, with bar ribs oriented sideways (see Figures 4(a), (b) and (d)). Two plastic pipes were provided at both ends of each bar (see Figures 2(a)-(c), 4(a)), to negate the influence of boundary effects on bond strength. Plastic cable ties (see Figure 5) were provided on the bars at the outer face of the formwork to secure the bars against longitudinal movement during preparation, casting and compaction.

Each bar was tied to the vertical links, with bars on the round holes being tied securely using a plier and bars on the slot holes being tied securely by hand. The vertical links were then tied to two bars on the top (see Figures 4(a) and 5) rather than supported by a rebar spacer at the bottom, in order to avoid vertical restraint. The vertical links were provided in all specimens, with the exception of the RILEM specimen which also only had one plastic pipe (at one end) instead of two. A lifting hook (see Figures 4(a) and 5) was provided in each specimen to enable ease of lifting and positioning in the laboratory using an overhead crane.

Once the bars had been arranged in the designated position, the opposing ends of the central portion (next to the plastic pipes) were covered by insulation tapes (see Figure 4(b)), before sealing the end of the plastic pipes (next to the tapes) with silicone. The tapes were removed after one day. Covering the bars in this fashion not only ensured that no silicone would cover the designated bond length, but also allowed a neat/clear cut to the silicone thereby ensuring accuracy with respect to the bond length provided.

The bars in the slot holes were supported by removable supports (see Figure 5), which were released immediately after compaction to allow the 16 mm bars to displace vertically as concrete consolidated. The slot holes were filled by sponge flush with the internal face of the formwork. The sponges were covered by plastic tapes to minimise water absorption from the fresh concrete. Four tie bars were provided in the Tall specimen to minimise bulging of formwork, with each pair positioned at a distance of approximately 500 mm and 1000 mm from the top pour.

Once the bar preparation had been completed, the internal face of the formwork was given a coating of a proprietary release agent, with extra care being given on application to ensure that the release agent did not contaminate the main (16 mm) bars.



(a) (b) (c) (d)

Figure 4. (a) Bar arrangement for the tall specimen (C30 series), showing the 16mm bars, vertical links tied to the temporary support, plastic pipe at each end, lifting hook tied to tension ties. (b) Plastic pipes inside the Rilem specimen. (c) Insulation tapes and silicone. (d) Plastic pipe sealed with silicone after the removal of the insulation tape. Also shown are the sponges placed inside the slot holes.

(a)

(b)

(c)

(d)

Figure 4 (continued). Bar arrangement in (e) Tall and (f) Rilem specimens of C45 series. (g) close-up of the bonded length; and (h) cable ties used in the fabrication.

Figure 5. Close-up of the removable support on the slot holes.

Each bar was then secured in placed using cable ties to ensure movement during casting and compaction (see Fig. 4(h)).

1.3 Specimen fabrication

The concrete mixes used to fabricate the test specimens are presented in Table 1. The binders comprised CEM I to BS EN197-1 blended with ground granulated blast-furnace slag (GGBS) to BS EN15167-1 at a replacement ratio of 50%. The water/binder (w/b) ratio was varied to achieve the two different target strengths. 4/20mm crushed basalt aggregate from the Duntilland Quarry and 0/4mm sand from the Levenseat Quarry were used throughout. To achieve the required consistency, a high-range water reducer (MasterGlenium 126) conforming to BS EN934-2 was added. The high slump concrete, S5, was achieved by increasing the binder and water contents and the HRWR amount. Both concrete mixes were supplied by a local ready-mix company, Aggregate Industries, from their Ratho plant in Edinburgh.

The specimens were cast in timber formwork along with fifteen standard 100 mm cubes for compressive strength control tests. The concrete in the specimens was compacted using an internal vibrating poker, whereas the cubes were compacted on a vibrating table. Each mix was prepared in one batch to minimise variation in mechanical properties. The concrete slump was checked prior to casting to ensure consistency (see Figures 7(a) -(d)). It is clear that there were some variations in the measured slumps, with C30-S2 mix measured at 60 mm, C30-S5 mix at 175 mm, C45-S2 at 85 mm, and C45-S5 mix at 220 mm. Compared to the classifications in BS EN 8500-1, the slump values for both S2 series mixes were within the specified range (i.e. 40 – 100 mm). Consistency of the mix referred to here as C45 S5 mix fits into the S5 classification (i.e. slump >210 mm), whereas the C30-S5 mix fell just below the recommended limit for S5 and came at the top end of the S4 category (i.e. 150 – 220 mm).

Figure 6. Concrete casting and compaction.

Table 1. Concrete mix design provided by the local ready-mix company.

Source Plant: **Ratho Minimix**

C25/30 20mm CIIIA WRA S2		**Quantity / UOM**
Cemex EN 197-1 Cem I 52,5N Leith Dock		140.000 KG
GGBS BS EN 15167-1 Lafarge/Holcim		140.000 KG
4/20 Conc. Graded Basalt EN12620/PD6682-1TC1 Duntilland	Aggregate Industri Duntilland	1106.000 KG
0/4 Conc. Sand MP Gravel EN12620/PD6682-1 (Levenseat)		858.000 KG
Glenium 126 BASF	BASF	1.580 KG
Water (Cold)		

A/C Ratio	7.014	Actual WCR	.625
% Fines	43.686	Alkali (kg/m3)	
Total Cementitious (kg/m3)	280.000	Chlorides	

Source Plant: **Ratho Minimix**

C25/30, 20mm, CIIIA S5 + S/Plast		**Quantity / UOM**
Cemex EN 197-1 Cem I 52,5N Leith Dock		165.000 KG
GGBS BS EN 15167-1 Lafarge/Holcim		165.000 KG
4/20 Conc. Graded Basalt EN12620/PD6682-1TC1 Duntilland	Aggregate Industri Duntilland	1116.000 KG
0/4 Conc. Sand MP Gravel EN12620/PD6682-1 (Levenseat)		808.000 KG
Glenium 126 BASF	BASF	2.420 KG
Water (Cold)		

A/C Ratio	5.830	Actual WCR	.530
% Fines	41.996	Alkali (kg/m3)	
Total Cementitious (kg/m3)	330.000	Chlorides	

Source Plant: **Ratho Minimix**

C50/60, 20mm, CIIIA, S2 + WRA		**Quantity / UOM**
Lafarge/Holcim Cem I 52,5N EN197-1 Glasgow		218.000 KG
GGBS BS EN 15167-1 Lafarge/Holcim		217.000 KG
4/20 Conc. Graded Basalt EN12620/PD6682-1TC1 Duntilland	Aggregate Industri Duntilland	1125.000 KG
0/4 Conc. CRF CP Basalt EN12620/PD6682-1 TD1Duntilland		374.000 KG
0/4 Conc. Sand MP Gravel EN12620/PD6682-1 (Levenseat)		374.000 KG
Glenium 126 BASF	BASF	2.460 KG
Water (Cold)		

A/C Ratio	4.306	Actual WCR	.471
% Fines	39.936	Alkali (kg/m3)	
Total Cementitious (kg/m3)	435.000	Chlorides	

Source Plant: **Ratho Minimix**

C50/60, 20mm, CIIIA, S5 + S/P		**Quantity / UOM**
Lafarge/Holcim Cem I 52,5N EN197-1 Glasgow		218.000 KG
GGBS BS EN 15167-1 Lafarge/Holcim		217.000 KG
4/20 Conc. Graded Basalt EN12620/PD6682-1TC1 Duntilland	Aggregate Industri Duntilland	1074.000 KG
0/4 Conc. Sand MP Gravel EN12620/PD6682-1 (Levenseat)		374.000 KG
0/4 Conc. CRF CP Basalt EN12620/PD6682-1 TD1Duntilland		374.000 KG
Water (Cold)		
Glenium 126 BASF	BASF	2.460 KG
Master Glenium 315C BASF		.960 KG

A/C Ratio	4.189	Actual WCR	.437
% Fines	41.054	Alkali (kg/m3)	
Total Cementitious (kg/m3)	435.000	Chlorides	

(a) (b)

(c) (d)

Figure 7. Measured concrete slumps: (a) C30 S2 slump; (b) C30 S5 slump; (c) C45 S2 slump; and (d) C45 S5 slump concretes.

The concrete for the Short and Medium specimens was poured in a single lift before being compacted with the poker for approximately 60 sec, whereas the concrete for the Tall and RILEM specimens was poured in two lifts, with the same duration of vibration to each lift. It took approximately 45 minutes from the first arrival of the truck at site to the completion of compaction. It is approximated that the delivery and mixing time from the local plant took about 60-90 minutes, so altogether the completion of compaction was approximately 2 hours from initial gauging. Figure 7 presents the condition of the test specimens after casting.

Figure 8. Specimens after casting

1.4 Curing and preparation

On demoulding at approximately 48 hours, each test specimen was wrapped in damp paper towel and a heavy-duty polythene sheeting. The specimens were left in the laboratory and wetted on a daily basis until required for testing, which in this experimental programme, was between the 26^{th} and 38^{th} days after casting. Three cubes were tested on a weekly basis to obtain the strength development with time.

Figure 9. Specimens wrapped with wet cloth and plastic during curing. The cubes were stored under the blue polyethylene sheet and regularly wetted.

1.5 Load testing

Testing was undertaken between the 26th and 38th day after casting. Each specimen was firstly unwrapped and then positioned in a specially designed test rig. Figure 9 displays the schematic of the test setup used for testing the Short/Medium/Tall specimen, with the photos provided in Figures 11(a)-(d) for clarity. To provide transverse (vertical) restraint and avoid uplift at the back (free end) as the bar at the loaded end was pulled, each specimen was clamped vertically using one (or two) removable hollow (yellow) square steel section(s), with the contact on the specimen provided by either one or two steel plate(s) with dimensions of 300×300×25 (thick) mm. The steel plates were positioned clear of the test bars and did not bear directly over the test bar. The hollow steel section(s) were oriented along the direction of the test bars and were secured in position with two 12 mm threaded bars at each end. In addition to this vertical restraining mechanism, one 60×60×6 mm L-shape section was provided at the lower portion of the back face of the specimen to provide a horizontal restraining mechanism, in order to prevent the specimen from rotating during testing. The L section was secured in position using two 16 mm bolts which were connected to the base plate. Four 150 mm high triangular-shape steel sections were also provided at the lower portion of the front face to provide longitudinal restraint against the applied load. A 12 mm thick plywood was inserted between these steel stoppers and the specimen to avoid local compression failure which would affect the results of the bars on the opposing face. As the depth of the Short specimen is less than the total width of the four stoppers, an additional 25 mm thick spreader plate was provided to spread the reaction forces uniformly against these four stoppers – see Figure 10 for the location of the spreader plate.

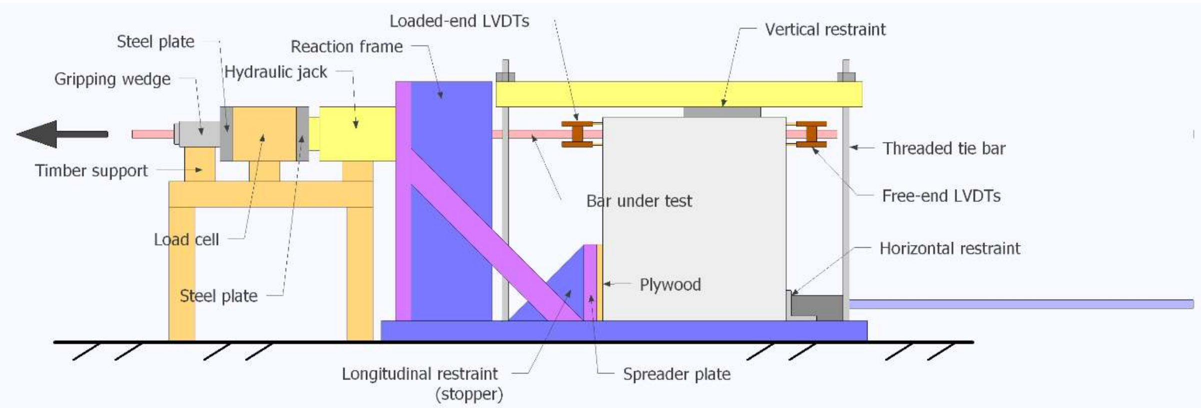


Figure 10. Test setup for Short/Medium/Tall specimen. Note that the spreader plate was only used when testing the Short specimen.

Loading was applied using a hand operated hydraulic jack initially at two 25 kN increments to 50 kN, followed by 20 kN increments up to peak load. Loading was continued beyond the peak load to the maximum travel of the displacement transducers used in this work, which was approximately 10 mm. A wedge grip was provided at the end of each bar to facilitate loading. As detailed above, each specimen was restricted in movement at three locations:

(i) at the back of the top face to prevent uplift (vertical restraint);

(ii) at the lower portion of the back face to prevent rotating (horizontal restraint); and

(iii) at the lower portion of the front face of the specimen (longitudinal restraint).

The applied load was monitored using a 200kN hollow load cell inserted onto the reinforcing bar at the loaded end, with a 20 mm thick steel plate provided between the hydraulic jack and the load cell, as well as between the load cell and the gripping wedge (see Figure 10), in order to ensure that uniform pressure would be applied to the load cell. The loaded-end bar displacement and the free end slip were each measured by a pair of linear variable displacement transducers (LVDTs), with each pair placed on the front and the back the specimen, respectively. Test data were monitored continuously using an 8-channel data acquisition unit which was interfaced to a signal amplifier and controlled by a Desktop PC, using a DAQami software. The sampling rate was set constant at 10Hz throughout.

Figure 11 (a). Short specimen with the 1st bar ready for testing.

Figure 11 (b). Medium specimen with the 2nd bar ready for testing.

Figure 11 (c). Tall specimen with the 1st and 6th bars ready for testing.

Figure 11 (d). RILEM specimen with the 2nd bar ready for testing.

The RILEM specimen did not require the use of a testing rig. Prior to testing, the specimen was positioned on two steel rigid supports. The hand operated hydraulic jack and the load cell were then inserted directly to the bar at the loaded end (see Figure 11(d)), with the same intermediate steel plates provided as before to ensure uniform pressure. To reduce the effect of platen restraint to a minimum, two additional plates (150mm square 30mm-thick hollow steel plate and 18 mm-thick plywood) were provided between the load cell and the specimen, with the plywood inserted first (in contact with the specimen). Both plates had a centre hole of diameter of approximately 30 mm. Loading was then initiated using the same test protocol as before.

In addition to the main test series, the concrete compressive strength (control) tests were conducted using a 3,000kN Avery-Denison testing machine at a rate of 240 kN/min.

3. TEST RESULTS

In the following sections, the results of bond tests are presented and discussed. Overall, it was observed that all bars in the Modified RILEM specimens exhibited pull-through mode of failure, whereas all bars in other (beam-end Tall/Medium/Short) specimens exhibited splitting failure.

3.1 Results of Modified RILEM specimens

Figures 12 (a), (c), (e) and (g) display the bond stress, τ (MPa), versus end-slip relation measured from all RILEM specimens, with the bond strength being obtained through the relationship,

$$\tau = \frac{P}{\pi \phi \ \mathrm{d}} \qquad (1)$$

where *P* is the applied load in the bar (N); l_b and ϕ are, respectively, the bond length and diameter of the bar (in mm). It should be noted that the bond length for M1 (C30) and M2 (C45) mixes was 80 mm, whereas for M3 (C45) and M4 (C45) it was 48 mm. In these Figures, each bar was labelled according to the following: concrete strength (30: C30, 45: C45); target slump class (2: S2, 5: S5); type of specimen (R: Rilem; S: Short; M: Medium; and T: Tall); type of hole (S: Slot; R: Round) and the end digits represent the depth of concrete from the bar centreline to the top cast surface (in mm).

To better understand the variation in bond strength against depth of casting, bond strengths at various depths were normalised against the mean bond strength of the bottom cast bars for each of the four casts; the results of which are presented in Figures 12 (b), (d), (f) and (h), together with the reduction factor η_1 representing the 'good' and 'poor' bond conditions to BSEN1992-1-1:2004. For clarity, this top/bottom cast ratio is presented in Table 1.

It is clear from the Figures and Table 1 that cast position has a significant influence on bond strength, generally showing a decreasing tend in bond strength with increasing distance to the top surface. It is postulated that there are some synergistic and opposing effects such as

(i) an increase in w/c toward the top of the pour as a result of bleeding;

(ii) formation of voids beneath bars but this effect would possibly diminish with increasing depth due to increasing hydrostatic pressure; and

(iii) better concrete consolidation with increasing depth which may, in turn, increase the concrete strength.

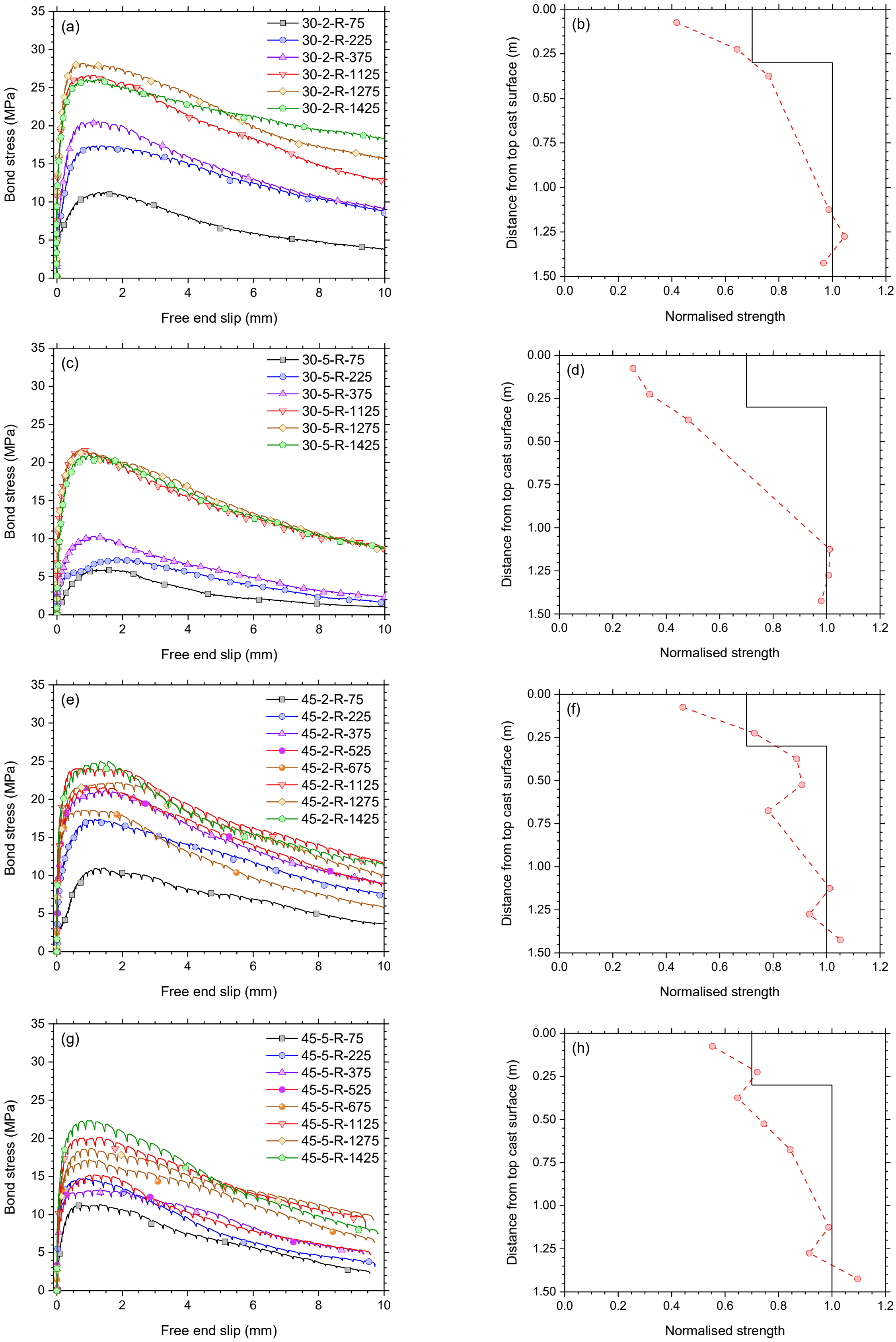


Figure 12: (a), (c), (e), (g) Bond stress vs free end slip. (b), (d), (f) and (h) The depth of concrete cast above bar centreline vs the normalised bond strength. Also plotted by the continuous black line is the EC2 reduction factor η_1.

Table 1: Normalised bond strength observed in the Modified RILEM specimens.

Depth (mm)	30-2	30-5	45-2	45-5
75	0.42	0.28	0.46	0.55
225	0.64	0.34	0.73	0.72
375	0.76	0.48	0.89	0.65
525	-	-	0.91	0.75
675	-	-	0.78	0.84
1125	0.99	1.01	1.01	0.99
1275	1.05	1.01	0.94	0.92
1425	0.97	0.98	1.05	1.10

3.2 Results of Short specimens

Figures 13 (a), (c) and (e) display the bond stress versus end-slip relation measured from all Short specimens, with the bond stress obtained using equation (1).

It should be noted that the bond length for M1 (C30) and M2 (C45) mixes was 200 mm whereas for M3 (C45) and M4 (C45) was 125 mm. The specimen labelling was as before. Again, to study the variation in bond strength against the depth of casting, normalised bond strengths are also presented in Figures 3 (b), (d) and (f) together with the definition of 'good' bond condition to BS EN1992-1-1. The normalised bond strength is listed in Table 2 for clarity.

It is evident from Figures 13 (a), (c), (e) and (g) that the bond strength of the slot-hole bars is generally higher than the corresponding round-hole bars. As the degree of compaction and consolidation for these two series of bars is similar, this could be attributed to the fact that the slot-hole bars had a less rigid support allowing the bars in the slot-hole to displace vertically with the concrete during early hardening.

Table 2: Normalised bond strength observed in the beam-end Short specimens.

Depth	30-2		30-5		45-2		45-5		Mean	Mean	Overall
(mm)	Slot	Round	Slot	Round	Slot	Round	Slot	Round	Slot	Round	Mean
65	0.66	0.70	0.95	0.77	0.95	1.15	0.87	0.72	0.86	0.84	0.85
185	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

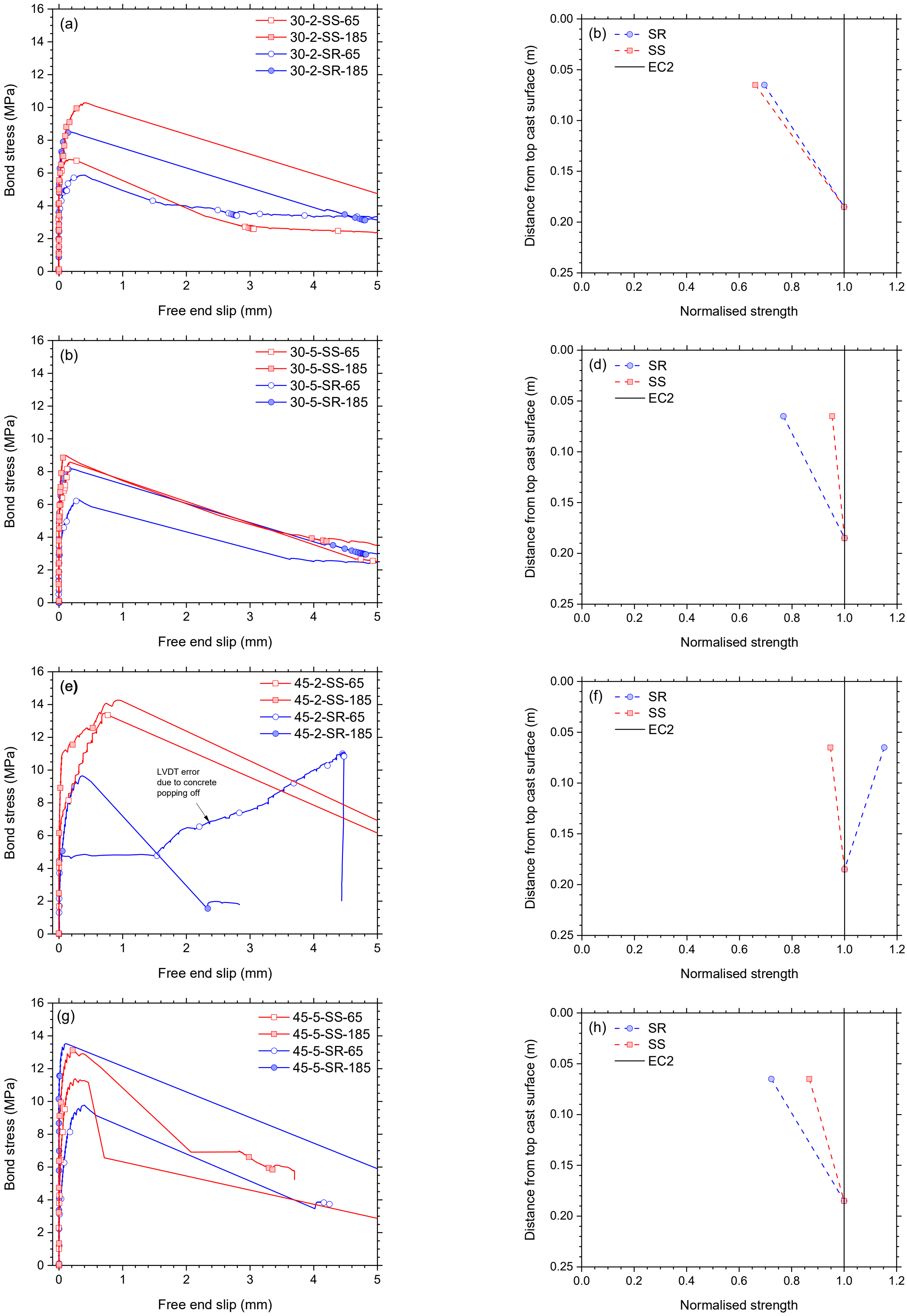


Figure 13: Short specimens: (a), (c), (e) and (g) bond stress vs free end slip. (b), (d), (f) and (h) the distance from the top cast surface plotted against the normalised bond strength.

Taking the bond strength of the bottommost bar as a reference, Figures 13 (b), (d), (f) and (h) display the normalised bond strength of the bars, as also summarised in Table 2. It is apparent that slot-hole top cast bars cast in S5 slump concretes display consistently less reduction factor when compared to bars cast in round holes. The opposite trend was observed in mix C45-S2, while the difference was minimal for C30-S2. An overall mean of 0.85 is obtained.

3.3 Results of Medium-height specimen

Figures 14(a), (c), (e) and (g) display the bond stress versus end-slip relation for all Medium specimens. The specimen labelling was as before. To reiterate here that R stands for round hole and S stands for slot hole, and the final digits represent the depth of concrete above the bar centreline. As before, the normalised bond strength is plotted against the depth in Figures 14 (b), (d), (f) and (h), together with the casting position factor used in BSEN1992-1-1:2004, following the 'good' and 'poor' bond classification. The mean strength of the two bottommost bars was taken as a reference. A summary of the normalised strength is presented in Figure 14 and summarised in Table 3 for clarity. In general terms, it is apparent from Figures 14(b), (d), (f) and (h) and Tales 3 that the normalised bond strengths of the slot- and round-hole bars are comparable and in general agreement with the existing definition of the 'good' and 'poor' bond classification, and also the top-cast ratio. However, the normalised strength still does not take into account some of the aspects listed in Section 3.1; the discussion on these aspects (i.e. surcharge effects) is provided in Section 4.5 followed by a more accurate assessment of the top cast ratio in Section 4.6.

Table 3: Normalised bond strength observed in the beam-end Medium specimens.

Depth (mm)	30-2		30-5		45-2		45-5	
	Slot	Round	Slot	Round	Slot	Round	Slot	Round
75	0.86	0.86	0.78	0.64	0.77	0.73	0.62	0.76
225	1.08	1.04	1.10	1.10	1.05	0.98	0.98	1.03
375	0.92	0.96	0.90	0.90	0.95	1.02	1.02	0.97

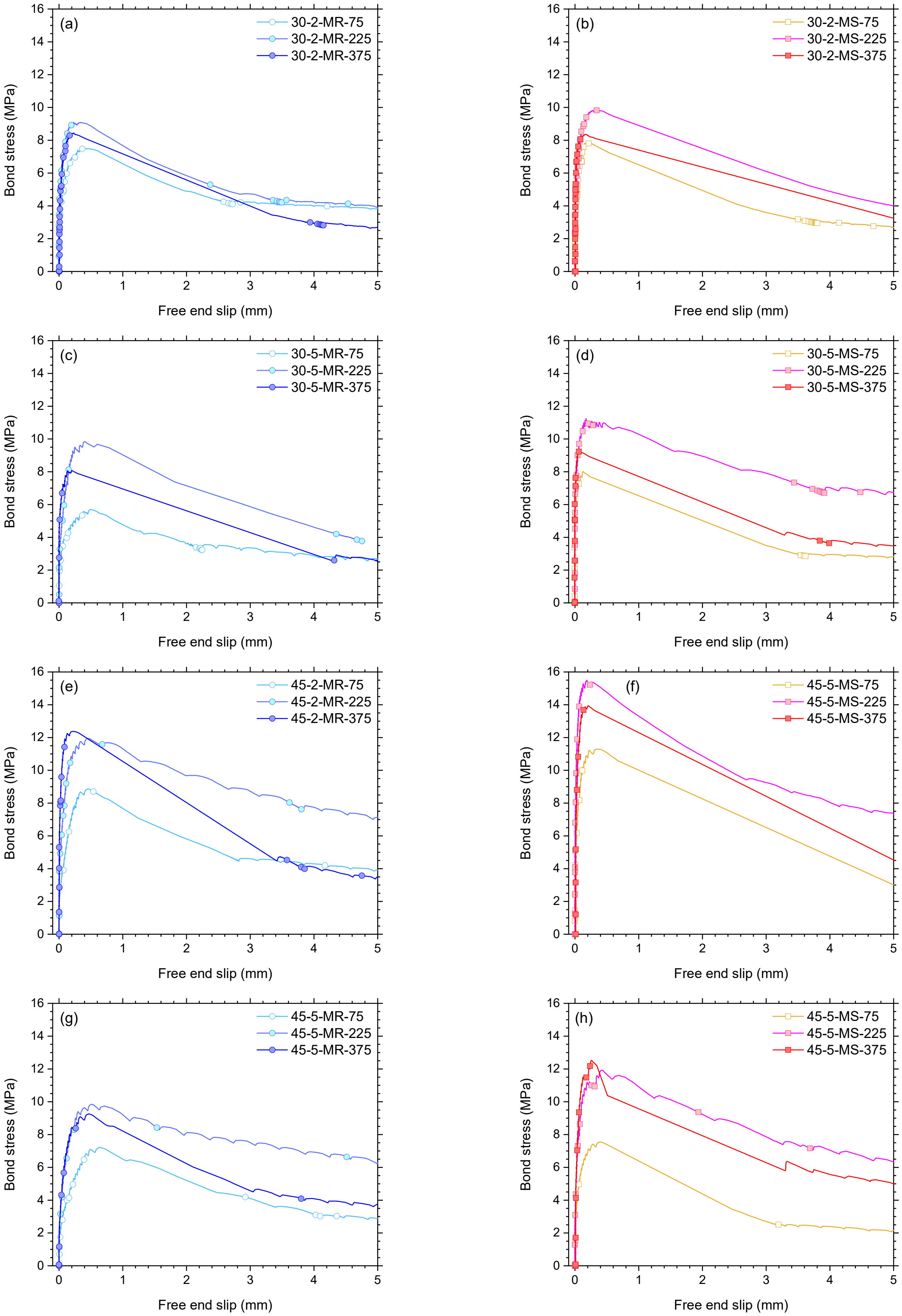


Figure 14: Medium height specimens: (a), (c), (e) and (g) bond stress vs free end slip for bars cast in round holes. (b), (d), (f) and (h) the corresponding response for bars cast in slot holes.

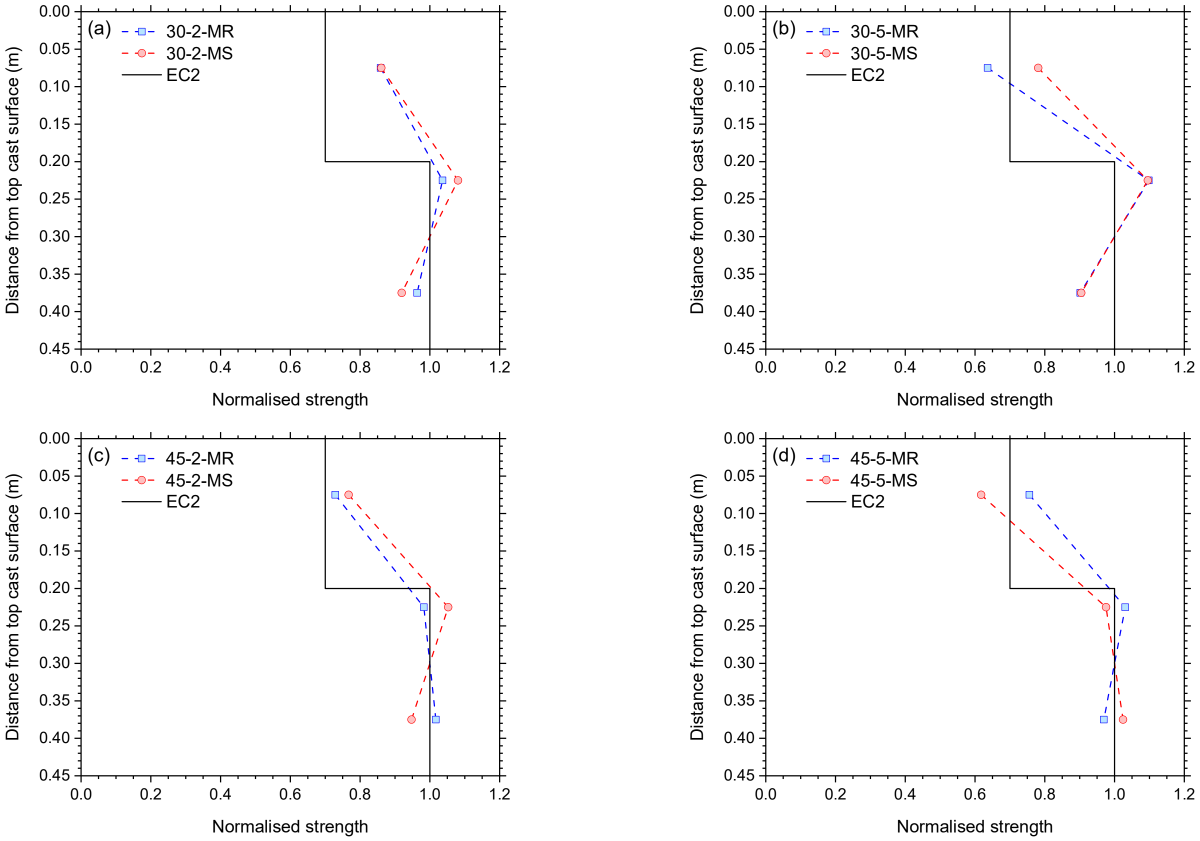


Figure 15: The distance from the top cast surface plotted against the normalised bond strength for all medium height specimens.

3.4 Results of the Tall-height specimens

Figures 16 (a)-(h) display the bond stress versus end-slip relation for all Tall specimens. The bond stress, τ (MPa), was obtained using equation (1) and as before, S stands for slot hole, R stands for round hole, and the number that follows represents the depth of concrete above the bar centreline.

Again, as before, the normalised bond strength is plotted against the depth in Figures 16, together with the casting position factor used in BSEN1992-1-1:2004, following the 'good' and 'poor' bond classification. The mean strength for all available results within the bottom 400 mm (bottom cast bars) was taken as a reference. It is apparent from the Figure that the bond strengths of the slot- and round-hole bars in the first three series (C30 S2, C30 S5 and C45 S2) are generally comparable. There appears to be a greater reduction in bond strength in the last series (C45 S5) with the reduction varying linearly with specimen depth. This could be attributed to the largest slump value of the concrete, but this would require further investigation.

It is noteworthy that as in the Medium specimens, the normalised strengths still include some of the aspects listed in Section 3.1; the discussion on these aspects (i.e. surcharge effects) is provided in Section 4.5, with a better assessment of the top cast ratio in Section 4.6.

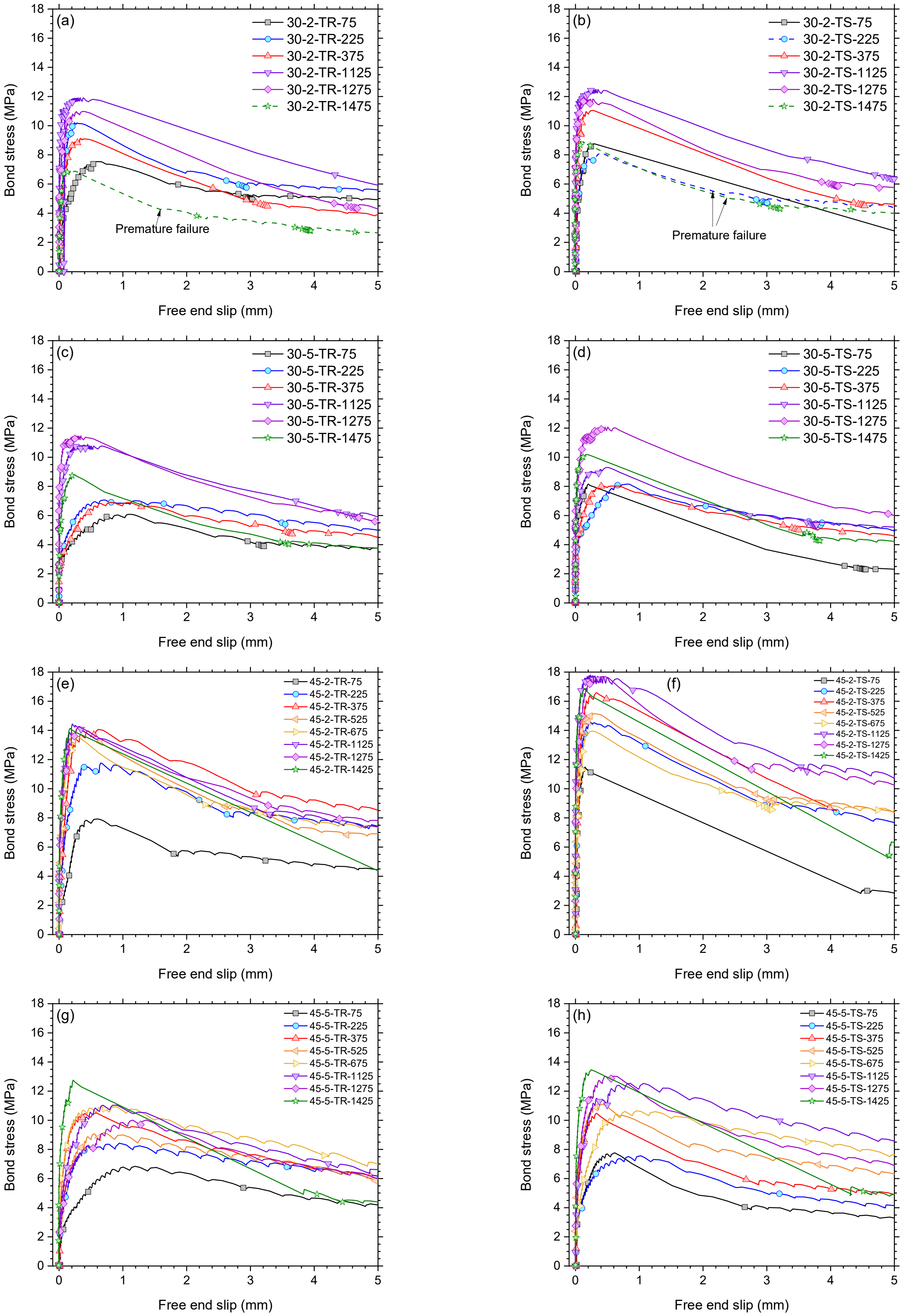


Figure 16: Tall height specimens: (a), (c), (e) and (g) bond stress vs free end slip for bars cast in round holes. (b), (d), (f) and (h) the corresponding response for bars cast in slot holes.

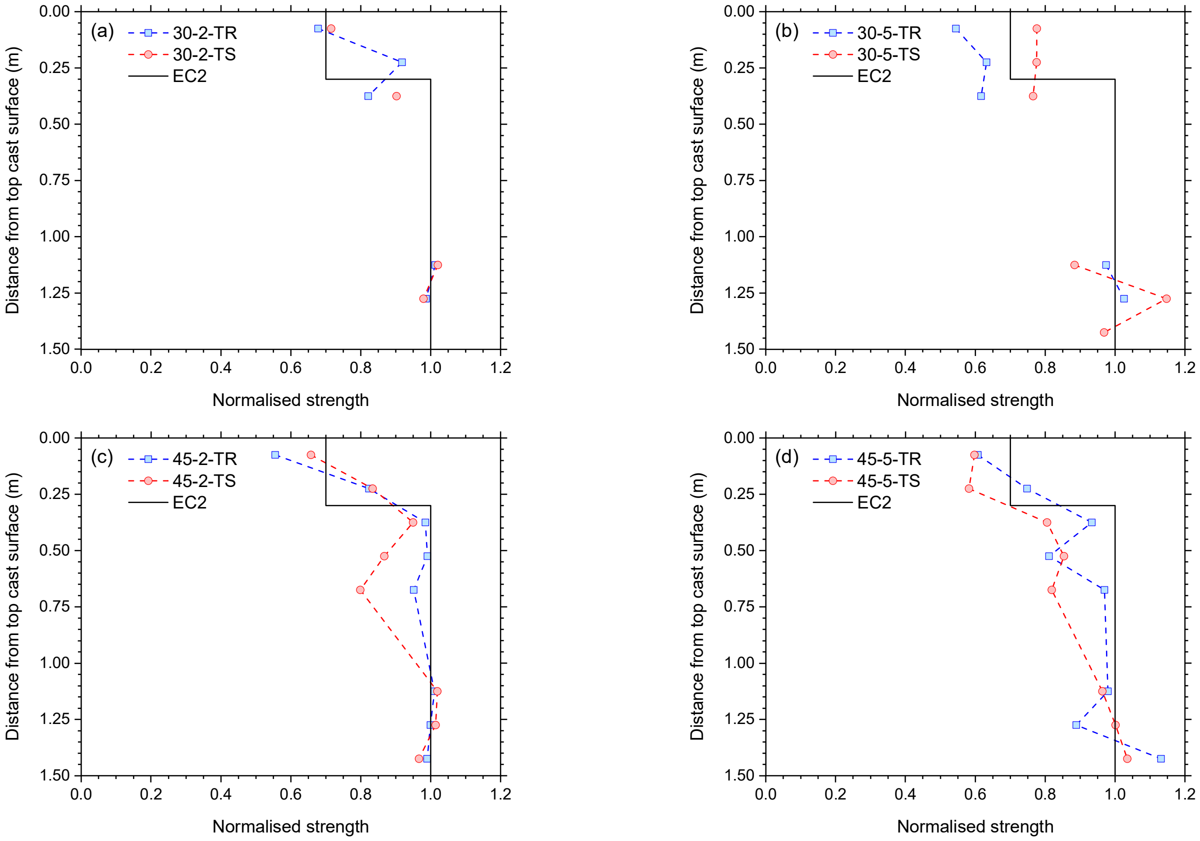


Figure 17: The distance from the top cast surface plotted against the normalised bond strength for all Tall height specimens.

Table 4: Normalised bond strength observed in the beam-end Tall specimens.

Depth (mm)	30-2		30-5		45-2		45-5	
	Slot	Round	Slot	Round	Slot	Round	Slot	Round
75	0.72	0.68	0.78	0.54	0.66	0.56	0.60	0.61
225	-	0.92	0.78	0.63	0.83	0.82	0.58	0.75
375	0.90	0.82	0.77	0.62	0.95	0.98	0.81	0.93
525	-	-			0.87	0.99	0.85	0.81
675	-	-			0.80	0.95	0.82	0.97
1125	1.02	1.01	0.88	0.97	1.02	1.01	0.96	0.98
1275	0.98	0.99	1.15	1.03	1.01	1.00	1.00	0.89
1425	-	0.68	0.97		0.97	0.99	1.03	1.13

4. ANALYSIS OF RESULTS

In this section, the influence of key parameters considered within the experimental programme is presented and discussed.

4.1 Test method

Table 5 presents the mean normalised bond strengths for all mixes based on the values presented earlier in Tables 1 and 4. In general terms, it is evident that the RILEM PoT is more sensitive to the top bar effect. The top cast ratios observed in PoT specimens both this investigation and in those reviewed by Cairns are markedly lower (i.e. show a stronger influence) than in lap joint specimens, hence it can be concluded that RILEM type PoTs greatly exaggerate the influence of casting position. It is postulated that this is due to the short bond length inherent in the RILEM PoT test configuration, in combination with the effect of the mechanism of stress transfer (and hence the mode of failure). All bars in the RILEM Pot specimens tested here experienced pull-though mode of failure and they would rely primarily on the mechanical bond between the steel and the surrounding concrete. On the other hand, all bars in the Tall specimens exhibited splitting mode of failure and the bond strength of the bars in these specimens depend not only on the mechanical bond but also on the tensile strength of the concrete cover. It is anticipated that the influence of bleeding and void formation under the bars (see (i) and (ii) effects in Section 3.1), which will have a direct influence on bond, are more prominent in the RILEM Pot specimens and hence the exaggeration of the top cast effect experienced by this test method, particularly the top cast bars where more bleeding and void formation effects could be expected.

Table 5: Comparison of the normalised bond strength observed in the Modified RILEM Pot and Tall specimens (values less than 1 highlighted in red).

Depth (mm)	RILEM PoT	Tall-Slot	Tall-Round	Tall-Mean
75	0.43	0.69	0.60	0.64
225	0.61	0.73	0.78	0.76
375	0.70	0.86	0.84	0.85
525	0.83	0.86	0.90	0.88
675	0.81	0.81	0.96	0.89
1125	1.00	0.97	0.99	0.98
1275	0.98	1.04	0.98	1.01
1425	1.03	0.99	0.93	0.96

4.2 Concrete mix

To investigate the effect of concrete mix, Tables 6-8 list the mean top/bottom ratio for Short, Medium and Tall specimens in each series and the ranking order of the mean ratio, with the summary of the mean top/bottom ratios for Medium and Tall specimens in Table 9, together with the minimum and maximum values. In general terms, it is apparent from Table 9 that the high slump mixes exert a greater influence on top cast effect than the low slump mixes. No clear influence of concrete strength is apparent.

Table 6: Effect of concrete mix on the mean normalised bond strength in Short specimens.

Depth (mm)	30-S2	30-S5	45-S2	45-S5
65	0.68	0.86	1.05	0.79
Rank	4	2	1	3

Table 7: Effect of concrete mix on the mean normalised bond strength in Medium specimens.

Depth (mm)	30-S2	30-S5	45-S2	45-S5
75	0.86	0.71	0.75	0.69
Rank	1	3	2	4

Table 8: Effect of concrete mix on the mean normalised bond strength in Tall specimens.

Depth (mm)	30-S2	30-S5	45-S2	45-S5
75	0.70	0.66	0.61	0.60
Rank	1	2	3	4
225	0.86	0.70	0.83	0.66
Rank	1	3	2	4
375	0.86	0.69	0.97	0.87
Rank	2	4	1	3

Table 9: Overall effect of concrete mix on the mean, max, and min normalised bond strengths in Medium and Tall specimens over the top 375 mm of depth.

Type	30-S2	30-S5	45-S2	45-S5
Mean	0.82	0.69	0.79	0.71
Rank	1	4	2	3
Max	0.86	0.71	0.97	0.87
Min	0.70	0.66	0.61	0.60

4.3 Support condition

Based on the measured absolute values of the bond strength (see Appendix B), it was found that bars in round holes averaged 13% weaker than those in slotted holes. A similar difference is measured on short, medium and tall specimens. The difference is largely independent of bar height in tall specimens. It therefore seems most unlikely that this difference is attributable to consolidation of concrete or to migration of water towards the top of the specimen.

The test arrangement and procedure for round and slotted hole bars were identical. Bars in round holes were tested first, the specimen then turned over and bars in slotted holes subsequently tested. The relative weakness of bars in round holes therefore cannot be attributed to damage from earlier tests.

Specimens were cured when wrapped in polythene, and curing conditions would therefore have been identical.

There is no obvious reason why bars cast in round holes should be consistently weaker than those cast in slotted holes. The only possibility that is suggested is that the different forms of support may have produced a different response to vibration during compaction, but at this time this is purely conjecture. The following analyses are based on comparison between bars within each group with results for bars supported in slotted holes and those in round holes treated independently.

To investigate the influence of support condition on casting position, the values presented in Table 9 is broken down with respect to the different casts for both round and slotted bars and the results of which are presented in Table 10. It is apparent that support condition does not significantly alter the ranking observed earlier with regard to the effect of concrete slump, as discussed in Section 4.2. Table 10 also shows that the difference between the mean top cast factors in the low slump mixes is only marginal indicating negligible effect of support condition. A greater influence of support condition can be seen from one of the high slump mixes (Mix C30-5). For example, by making the support condition more rigid (slot to round hole), it decreases the top cast factor from 0.77 to 0.61. This is consistent with results for RILEM PoT where the support on a very short bond length would have been even more rigid (hence the larger top cast effect seen in Table 5). An opposite trend is however evident from Mix C45-5 and the reason behind this phenomenon is still not clear.

Table 10: Overall effect of support condition and concrete mix on the normalised mean, max, and min bond strengths in Medium and Tall specimens over the top 375 mm of depth.

	Slot bars					Round bars				
Type	30-2	30-5	45-2	45-5	Mean	30-2	30-5	45-2	45-5	Mean
Mean	0.82	0.77	0.80	0.65	0.76	0.82	0.61	0.77	0.76	0.74
Rank	1	3	2	4	-	1	4	2	3	-
Max	0.90	0.78	0.95	0.81	-	0.92	0.64	0.98	0.93	-
Min	0.72	0.77	0.66	0.58	-	0.68	0.54	0.56	0.61	-

The top/bottom ratio for bars in round holes across all 4 series averages only 2% lower than that for companions in slotted holes overall, although the difference is not statistically different.

4.4 Surcharge effects

The normalised bond strength discussed in the previous sections should not be used as a direct measure of the top cast effect as this parameter is dependent not only upon the top cast effect itself, but also on the variations in concrete strength (hence the bond strength) with the head of concrete above the bar (or specimen height; see Section 3.1). To investigate the influence of top cast effect alone, the effect of the variation in bond strength needs to be removed.

Figures 18(a) and (b) display the relationship between specimen height and the bond strength observed from the bottom cast bars from all specimens, with the bond strength in each specimen normalised against the bond strength of the bottom most bar in the corresponding short specimen and presented in Figures 18(c) and (d). Note that the mean strength of the bottom cast bars in the medium specimen represents the mean strength of two bottom most bars, whereas in the tall specimens, it corresponds to the mean strength of three bottom most bars.

In general terms, it is evident from Figures 18(c) and (d) that the normalised mean strength in all except one series (45-5) exhibits a general increasing trend with increasing specimen height due to the surcharge effect. The reason behind the anomaly observed in the last series of data is not clear; from Figure 18(b), it is apparent that the anomaly is due to the overly high bond strength of the short specimens. Accordingly, for the purpose of data analysis in the following sections, it is assumed that the surcharge effect in this series (45-5) is comparable to the other S5 series (30-5).

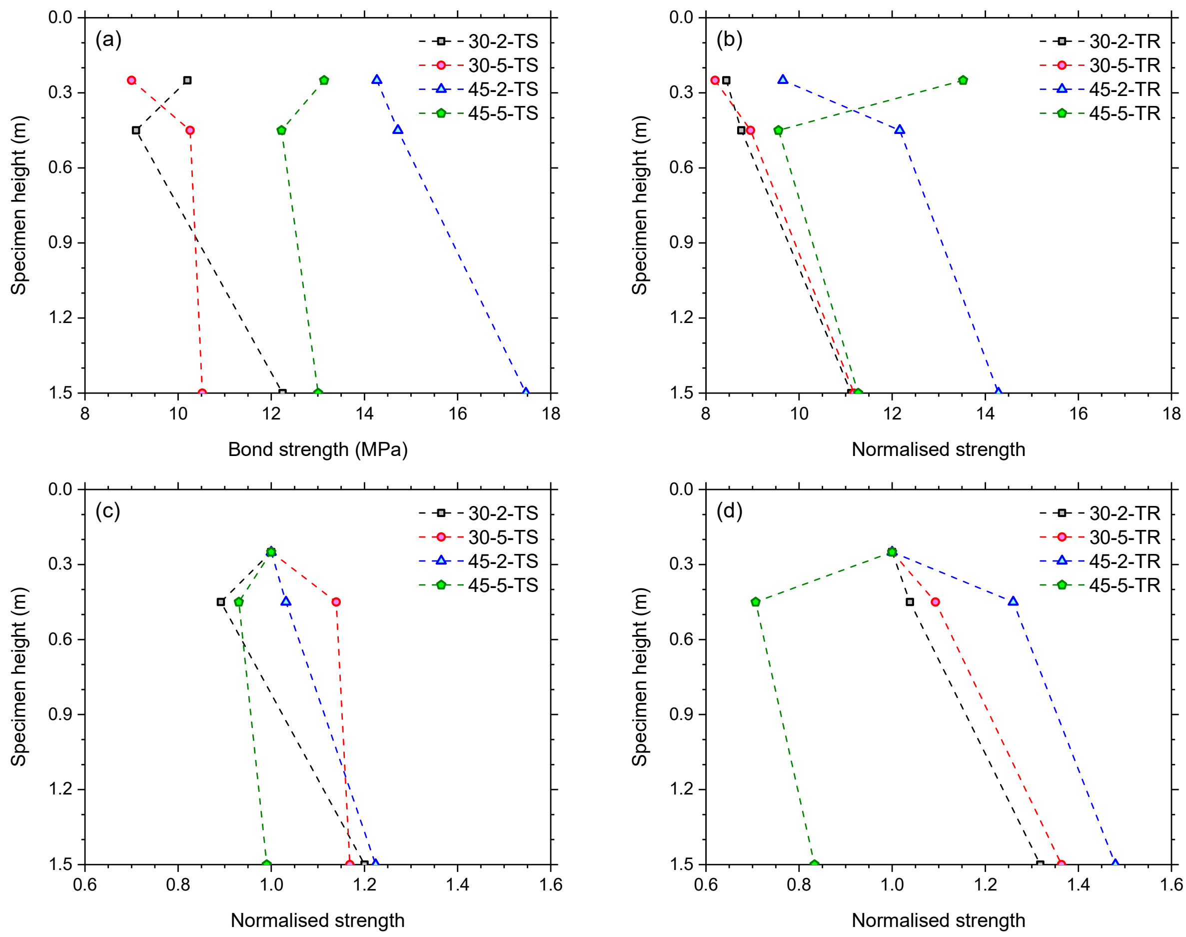


Figure 18: Surcharge effects observed in all (a) slot- and (b) round-hole bars, presented as specimen height plotted against the bond strength. The corresponding normalised strengths are presented in (c) and (d) to account for differences in concrete strength.

4.5 Revised Evaluation of top cast effect

To better assess the top cast effect, the bond strengths of bars in the Tall specimens were normalised against:

(i) two bottom cast bars in the corresponding medium specimen; and

(ii) one bottom cast bar in the corresponding short specimen.

These normalised bond strengths are presented in Figures 18-21 together with the current EC2 reduction factor and the definition of 'good' and 'poor' bond conditions. These results can be compared with those presented earlier in Figures 17(a)-(d) with no consideration of surcharge effects (i.e. the bond strength was normalised against the strength of two/three bottom cast bars within the same specimen).

In general terms, it is apparent that the existing provisions of the definition of 'good'/'poor' bond condition in BSEN1992-1-1 could be used as is, whereas the top cast factor appears to be too conservative. To investigate this aspect in more details, a summary of the revised top/cast ratios is presented in Tables 11 and 12. Furthermore, since the difference in the surcharge effect between the short and medium specimen is small, the average top cast ratio is presented in Table 13, with the bond strength normalised against the average of the bottom cast bars in both Short and Medium specimens.

With reference to Table 13, it is evident that concrete consistency exerts a more significant influence on the top/bottom cast ratio than concrete strength and support condition (slot/round). The results show that greater concrete consistency consistently leads to a greater reduction in top cast factor and a greater depth of concrete influenced by the top cast effect. Concrete strength appears to show a similar trend, although this factor does not seem to affect the depth of concrete influenced by the top cast effect.

The slotted hole bars are considered to be more representative of practical construction where support would be less rigid and can be expected to result in less top cast effect (or greater top cast factor). From the results presented in Tables 11-13, for example, it is evident from the result at 75 mm from the top that by making the support more rigid, this decreases the top cast factor from 0.81 to 0.77, which is line with the above expectation. An opposite trend is however evident from the second depth (i.e. 225 mm) and clearly warrants further investigation (i.e. through further laboratory testing). Due to the variability in tests results, however, it is also not possible to assess the influence of this parameter on the depth of concrete influenced by the top cast effect.

To obtain a top cast factor for the 450 mm high specimens, Table 14 displays the revised top/bottom cast ratio from the Medium specimens, with the bond strengths of the bars normalised against those of the bottommost cast bar in the Short specimen. A similar trend could be observed with respect to the effect of concrete consistency, strength and bar support.

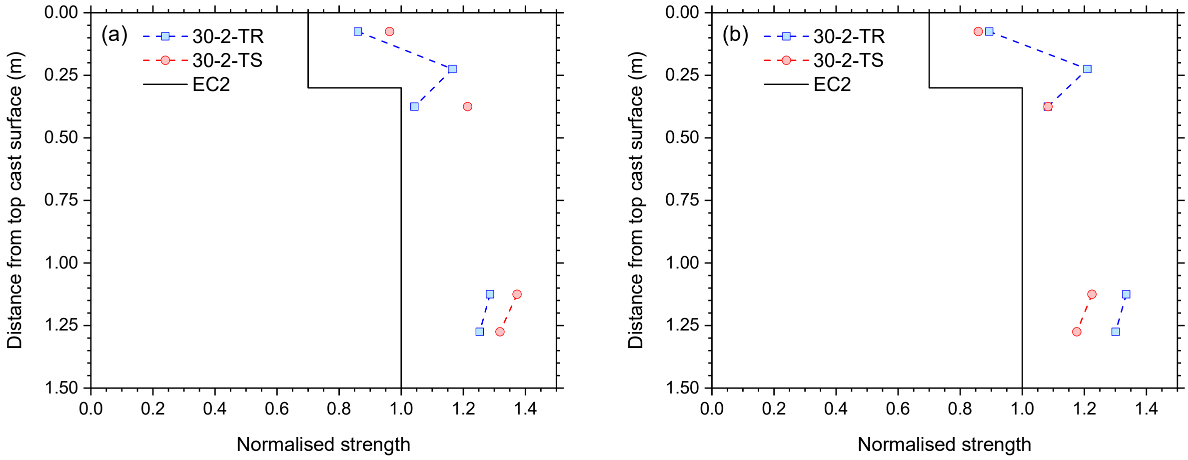


Figure 18: Normalised bond strength in C30 S2 series against the mean strength of: (a) two bottom cast bars in medium specimens; and (b) the bottommost cast bar in short specimens. TR: round hole. TS: slot hole.

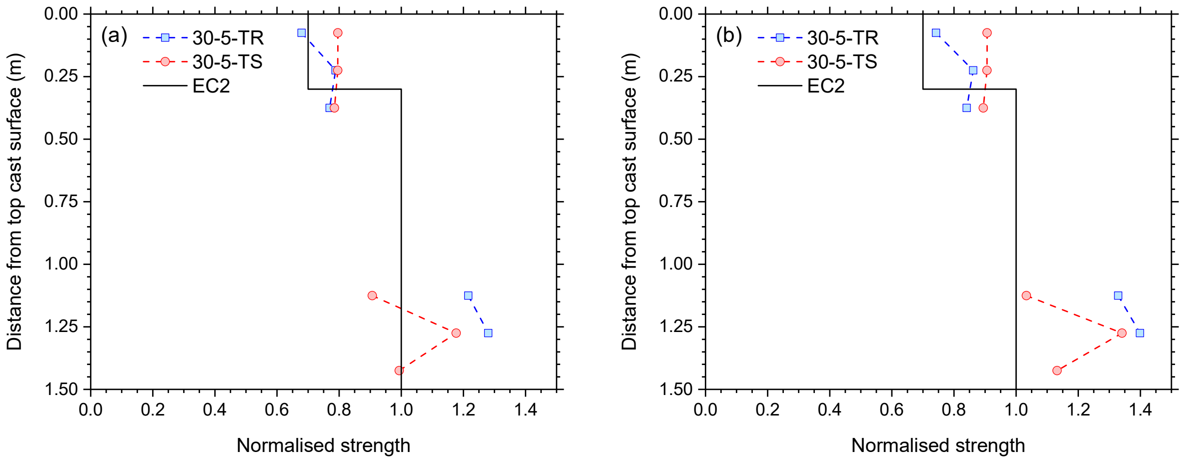


Figure 19: Normalised bond strength in C30 S5 series against the mean strength of: (a) two bottom cast bars in medium specimens; and (b) the bottommost cast bar in short specimens. TR: round hole. TS: slot hole.

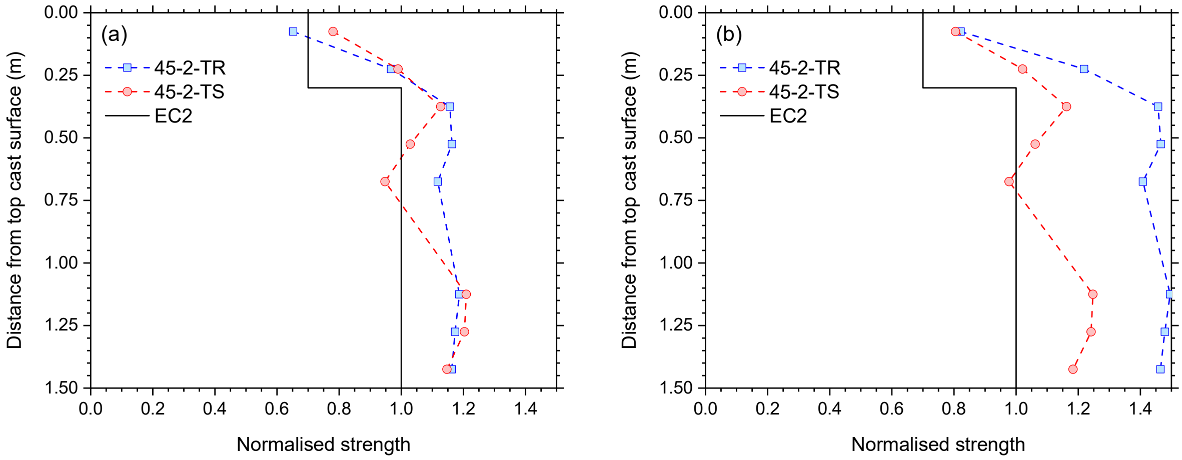


Figure 20: Normalised bond strength in C45 S2 series against the mean strength of: (a) two bottom cast bars in medium specimens; and (b) the bottommost cast bar in short specimens. TR: round hole. TS: slot hole.

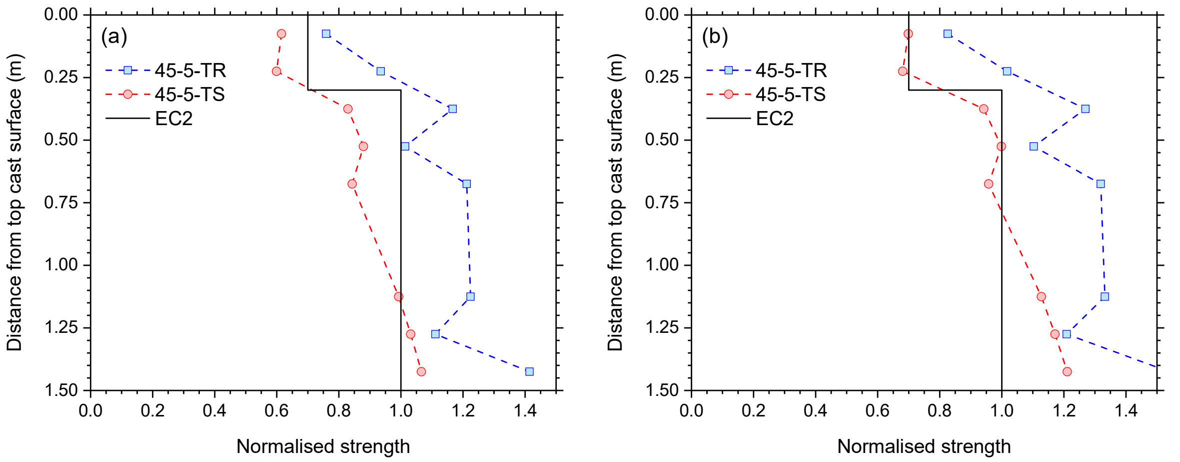


Figure 21: Normalised bond strength in C45 S5 series against the mean strength of: (a) two bottom cast bars of medium specimens; and (b) the bottommost cast bar of short specimens. TR: round hole. TS: slot hole.

Table 11. Top cast factor (normalised against bottom bar in companion short specimen).

Depth	30-2		30-5		45-2		45-5		Mean	Mean	Mean	Mean	Mean	Mean	Overall
mm	Slot	Round	Slot	Round	Slot	Round	Slot	Round	Slot	Round	C30	C45	S2	S5	Mean
75	0.86	0.89	0.91	0.74	0.80	0.82	0.70	0.83	0.82	0.82	0.85	0.79	0.84	0.79	0.82
225	-	1.21	0.91	0.86	1.02	1.22	0.68	1.02	0.87	1.08	0.99	0.98	1.15	0.87	0.99
375	1.08	1.08	0.89	0.84	1.16	1.46	0.94	1.27	1.02	1.16	0.98	1.21	1.20	0.99	1.09
525	-	-	-	-	1.06	1.47	1.00	1.10	1.03	1.28	-	1.16	1.26	1.05	1.16
675	-	-	-	-	0.98	1.41	0.96	1.32	0.97	1.36	-	1.17	1.19	1.14	1.17
1125	1.22	1.34	1.03	1.33	1.25	1.50	1.13	1.33	1.16	1.37	1.23	1.30	1.33	1.21	1.27
1275	1.18	1.30	1.34	1.40	1.24	1.48	1.17	1.21	1.23	1.35	1.30	1.28	1.30	1.28	1.29
1425	-	-	1.13	-	1.18	1.46	1.21	1.54	1.18	1.50	1.13	1.35	1.32	1.29	1.31

Table 12. Top cast factor (normalised against bottom two bars in companion medium specimen).

Depth	30-2		30-5		45-2		45-5		Mean	Mean	Mean	Mean	Mean	Mean	Overall
mm	Slot	Round	Slot	Round	Slot	Round	Slot	Round	Slot	Round	C30	C45	S2	S5	Mean
75	0.96	0.86	0.80	0.68	0.78	0.65	0.64	0.72	0.79	0.73	0.82	0.70	0.81	0.71	0.76
225	-	1.17	0.80	0.79	0.99	0.97	0.62	0.88	0.80	0.95	0.92	0.86	1.04	0.77	0.89
375	1.21	1.04	0.78	0.77	1.13	1.16	0.86	1.10	1.00	1.02	0.95	1.06	1.14	0.88	1.01
525	-	-	-	-	1.03	1.16	0.91	0.96	0.97	1.06	-	1.01	1.10	0.93	1.01
675	-	-	-	-	0.95	1.12	0.87	1.14	0.91	1.13	-	1.02	1.03	1.01	1.02
1125	1.37	1.29	0.91	1.22	1.21	1.19	1.03	1.15	1.13	1.21	1.20	1.14	1.26	1.08	1.17
1275	1.32	1.25	1.18	1.28	1.20	1.17	1.07	1.05	1.19	1.19	1.26	1.12	1.24	1.14	1.19
1425	-	-	0.99	-	1.15	1.16	1.10	1.33	1.08	1.25	0.99	1.19	1.15	1.14	1.15

Table 13. Top cast factor (normalised against companion short and medium specimens).

Depth	Mean	Mean	Mean	Mean	Mean	Mean	Overall
mm	Slot	Round	C30	C45	S2	S5	Mean
75	0.81	0.77	0.84	0.74	0.83	0.75	0.79
225	0.84	1.01	0.95	0.92	1.10	0.82	0.94
375	1.01	1.09	0.96	1.13	1.17	0.93	1.05
525	1.00	1.17	-	1.09	1.18	0.99	1.09
675	0.94	1.25	-	1.09	1.11	1.07	1.09
1125	1.14	1.29	1.21	1.22	1.29	1.14	1.22
1275	1.21	1.27	1.28	1.20	1.27	1.21	1.24
1425	1.13	1.38	1.06	1.27	1.24	1.22	1.23

Table 14. Top cast factor obtained from the medium specimens (normalised against bottom bar in companion short specimen).

Depth	30-2		30-5		45-2		45-5		Mean	Mean	Mean	Mean	Mean	Mean	Overall
mm	Slot	Round	Slot	Round	Slot	Round	Slot	Round	Slot	Round	C30	C45	S2	S5	Mean
75	0.77	0.89	0.89	0.70	0.79	0.92	0.67	0.73	0.78	0.81	0.81	0.78	0.84	0.75	0.79
225	0.96	1.08	1.25	1.20	1.09	1.24	1.06	0.99	1.09	1.13	1.12	1.09	1.09	1.13	1.11
375	0.82	1.00	1.03	0.99	0.98	1.28	1.12	0.93	0.99	1.05	0.96	1.08	1.02	1.02	1.02

Table 13 show that in Tall specimens cast with S2 concrete, the net top cast factor on the bar closest to the top face was 0.85 (rounded to the nearest 0.05), and that (by interpolation), no net reduction was observed for bars more than 200 mm from the top face. The corresponding factor and depth for S5 concrete are 0.75 and 400 mm. Values for intermediate consistencies could, presumably, be interpolated. With regard to Medium specimens, Table 14 show that the same top cast factors can be used (0.85 for S2 concrete and 0.75 for S5 concrete) and this would be applicable to bars more than 250 mm from the bottom face (also determined by interpolation). This is in line with the definition of 'good'/'poor' bond condition in BSEN1992-1-1 for overall depth range 250–600 mm (see Figure 1). However, this range would need to be modified should the definition of 'poor' bond of 200 mm from the top face shown above is used.

Note that Code provisions which make casting coefficient dependent on concrete consistency could be difficult to implement as calculation of bond lengths will precede a decision on concrete consistency in many instances. With reference to Tables 13 and 14, it is evident that the slotted-hole bars closest to the top face exhibit less top cast effect, displaying a net top cast factor of 0.80 (rounded to the nearest 0.05). Given that this condition is believed to be more representative of practical conditions, greater weight should be given to 'slotted' hole results than to round hole results reported in this investigation; hence a constant top cast factor of 0.8 is proposed. Accordingly, based on the results of the slotted hole bars, the existing provisions on the definition of 'good'/'poor' bond condition in BSEN1992-1-1 could also be used as is. Further investigation is, however, required to determine the definition of bond condition in shallow members and the associated value of top cast factor. Based on the results presented in this study, an effective top cast/bottom cast ratio of about 0.85 is evident.

5. CONCLUSIONS AND RECOMMENDATIONS

It is evident both from this investigation and from a review of previous work that the RILEM pull-out test leads to an overestimation of the influence of casting position. The value of this form of test is therefore highly questionable and it is desirable that a reliable standard form of tests to evaluate bond properties of novel concretes be developed.

Surcharge effects have a key role and should be considered when evaluating an appropriate coefficient for the influence of casting position. Neglecting the surcharge effect could result in an overestimation of the top cast effect. Support condition is shown to have an influence of the absolute values of the bond strength.

Concrete consistency appears to exert a more dominant influence on the top/bottom cast ratio than concrete strength and support condition. It is shown that greater consistency consistently leads to greater top cast effect.

Based on the test results obtained to date on 16 mm ribbed bars, there is evidence to suggest that the existing provisions on the definition of 'good'/'poor' bond condition in BSEN1992-1-1 could be used as is. A constant top cast factor of 0.8 is recommended, although further investigation is still required to determine the definition of bond condition in shallow member and the associated value of top cast factor.

Should the effect of concrete consistency be required, a top cast factor of 0.85 could be considered for S2 concrete and 0.75 for S5 concrete for member with overall depth greater than 250 mm; values for intermediate consistencies could, presumably, be interpolated. These recommendations are still subject to revision at a later date when these results have been examined alongside the Literature Review drafted earlier by Dr John Cairns and as new test data exist from further testing (i.e. from different bar diameters and types). Work is continuing in this respect.

ACKNOWLEDGEMENTS

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APPENDIX A

Table A1. Summary of concrete mixes.

THE QUALITY SCHEME FOR READY MIXED CONCRETE ISO 9001 UKAS PRODUCT CERTIFICATION 009

AGGREGATE INDUSTRIES

Concrete Mix Composition

To: **MINIMIX CASH SALE**
Aggregate Industries
Bardon Hill
Coalville
Leicestershire LE67 1TL

Duntilland Quarry
North Lanarkshire ML7 4NZ

Tel: 08450757777
Fax: 01698870590

Site / Contract Address	**Benny Suryento** **Forth Gait** **Heriot Watt University** **Riccarton**	Plant: Contact: Our Ref: Account No: Issue Date: Issued By:	**RATHO MINIMIX** **Diane Leslie** **4744266** **167021** **05/11/18** [signature]

All mixes in accordance with BS 8500-2 (except proprietary mixes) unless otherwise agreed. Batch weight of materials calculated on as SSD basis for 1.0m3 of fresh compacted concrete. Mixes are quality controlled and actual mix proportions may vary in response to control systems.

Source Plant: **Ratho Minimix**

C25/30 20mm CIIIA WRA S2		**Quantity / UOM**
Cemex EN 197-1 Cem I 52,5N Leith Dock		140.000 KG
GGBS BS EN 15167-1 Lafarge/Holcim		140.000 KG
4/20 Conc. Graded Basalt EN12620/PD6682-1TC1 Duntilland	Aggregate Industri Duntilland	1106.000 KG
0/4 Conc. Sand MP Gravel EN12620/PD6682-1 (Levenseat)		858.000 KG
Glenium 126 BASF	BASF	1.580 KG
Water (Cold)		

A/C Ratio	7.014	Actual WCR	.625
% Fines	43.686	Alkali (kg/m3)	
Total Cementitious (kg/m3)	280.000	Chlorides	

Source Plant: **Ratho Minimix**

C25/30, 20mm, CIIIA S5 + S/Plast		**Quantity / UOM**
Cemex EN 197-1 Cem I 52,5N Leith Dock		165.000 KG
GGBS BS EN 15167-1 Lafarge/Holcim		165.000 KG
4/20 Conc. Graded Basalt EN12620/PD6682-1TC1 Duntilland	Aggregate Industri Duntilland	1116.000 KG
0/4 Conc. Sand MP Gravel EN12620/PD6682-1 (Levenseat)		808.000 KG
Glenium 126 BASF	BASF	2.420 KG
Water (Cold)		

A/C Ratio	5.830	Actual WCR	.530
% Fines	41.996	Alkali (kg/m3)	
Total Cementitious (kg/m3)	330.000	Chlorides	

THE QUALITY SCHEME FOR READY MIXED CONCRETE 009

AGGREGATE INDUSTRIES

Proposed Concrete Mix Composition

To: **MINIMIX CASH SALE**
Aggregate Industries
Bardon Hill
Coalville
Leicestershire LE67 1TL

Duntilland Quarry
North Lanarkshire ML7 4NZ

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Site / Contract Address **Benny Suryento** **Forth Gait** **Heriot Watt University** **Riccarton**	Plant: **RATHO MINIMIX** Contact: **Diane Leslie** Our Ref: **4744266** Account No: **167021** Issue Date: **16/08/19** Issued By:

All mixes in accordance with BS 8500-2 (except proprietary mixes) unless otherwise agreed. Batch weight of materials calculated on as SSD basis for 1.0m3 of fresh compacted concrete. Mixes are quality controlled and actual mix proportions may vary in response to control systems.

Source Plant: **Ratho Minimix**

C50/60, 20mm, CIIIA, S2 + WRA			**Quantity / UOM**
Lafarge/Holcim Cem I 52,5N EN197-1 Glasgow			218.000 KG
GGBS BS EN 15167-1 Lafarge/Holcim			217.000 KG
4/20 Conc. Graded Basalt EN12620/PD6682-1TC1 Duntilland	Aggregate Industri	Duntilland	1125.000 KG
0/4 Conc. CRF CP Basalt EN12620/PD6682-1 TD1Duntilland			374.000 KG
0/4 Conc. Sand MP Gravel EN12620/PD6682-1 (Levenseat)			374.000 KG
Glenium 126 BASF	BASF		2.460 KG
Water (Cold)			

A/C Ratio	4.306	Actual WCR	.471
% Fines	39.936	Alkali (kg/m3)	
Total Cementitious (kg/m3)	435.000	Chlorides	

Source Plant: **Ratho Minimix**

C50/60, 20mm, CIIIA, S5 + S/P			**Quantity / UOM**
Lafarge/Holcim Cem I 52,5N EN197-1 Glasgow			218.000 KG
GGBS BS EN 15167-1 Lafarge/Holcim			217.000 KG
4/20 Conc. Graded Basalt EN12620/PD6682-1TC1 Duntilland	Aggregate Industri	Duntilland	1074.000 KG
0/4 Conc. Sand MP Gravel EN12620/PD6682-1 (Levenseat)			374.000 KG
0/4 Conc. CRF CP Basalt EN12620/PD6682-1 TD1Duntilland			374.000 KG
Water (Cold)			
Glenium 126 BASF	BASF		2.460 KG
Master Glenium 315C BASF			.960 KG

A/C Ratio	4.189	Actual WCR	.437
% Fines	41.054	Alkali (kg/m3)	
Total Cementitious (kg/m3)	435.000	Chlorides	

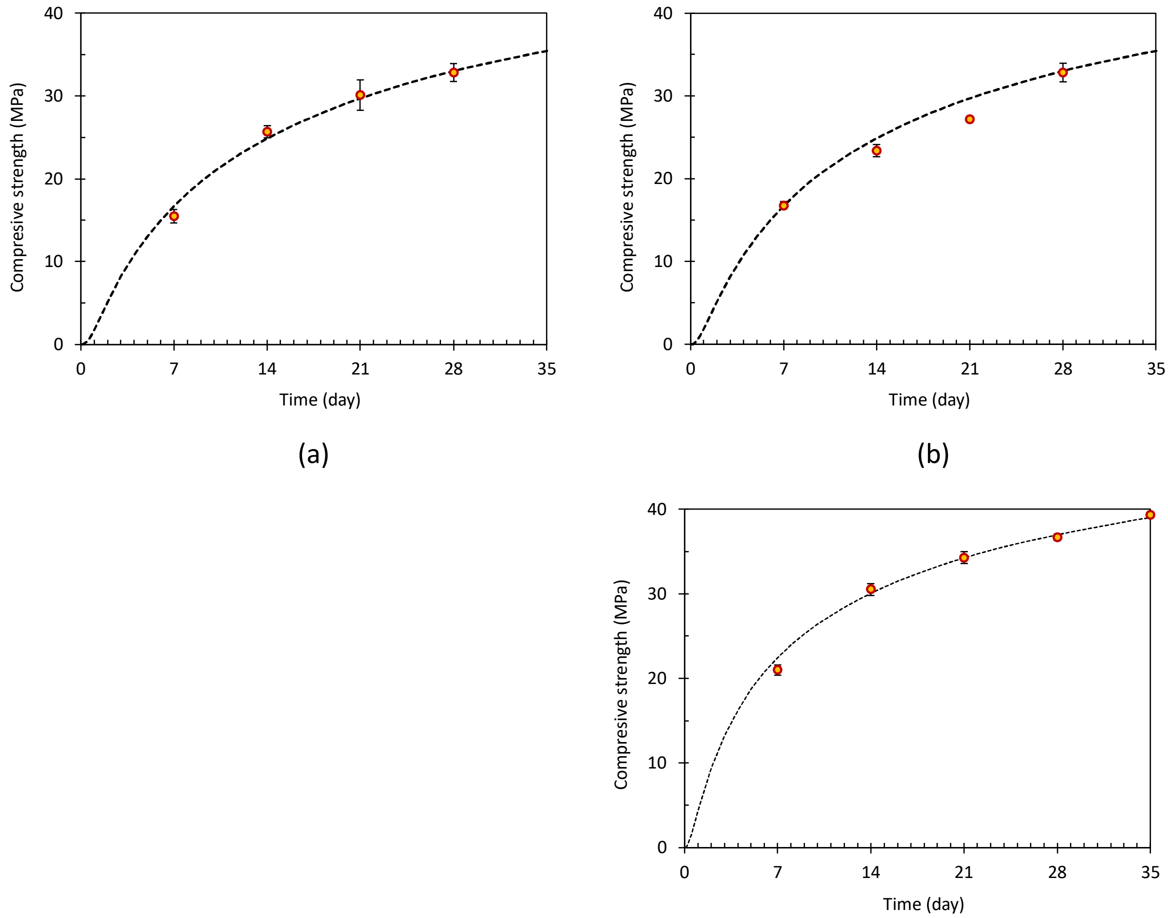
(a) (b)

(c) (d)

Figure A1. Measured concrete slumps: (a) Mix C30-2; (b) Mix C30-5; (c) Mix C45-2; and (d) Mix C45-5.

Mechanical properties: compressive strengths

Figure A2 displays the measured concrete cube compressive strengths for the C25/30 S2 mix, each determined on 100 mm cubes during the curing period, together with the predicted strength obtained using the expression in BSEN1992-1-1:2004, the range of the concrete strengths during the test period, and error bars representing ±1 standard deviation. It is evident from the Figure that over the initial two weeks, there is an initial rapid gain in strength, followed by a more gradual increase with no sign of a plateau even at 28-day, which reflects on-going hydration and pozzolanic activity. This is attributed to the relatively high cement replacement level (50%). However, as the concrete strength during the four days test period (Day 26th to Day 29th) increases at a much slower rate and the difference in strength was less than 4%, it can be assumed that during this relative short period of time, the concrete strength was constant. At 28 days, the concrete attains a cube compressive strength of 32.8 MPa (standard deviation of 1.1 MPa) which is equivalent to a cylinder strength of approximately 27.1 MPa. The mean splitting tensile strength was found to be 2.9 MPa, with a standard deviation of 0.2 MPa.



(c)

(d)

Figure A2: Predicted and measured concrete strength for all concrete mixes (a) M1 (S2); (b) M2 (S5); (c) M3 (S2) – data not available; and (d) M4 (S5) during the initial five weeks of curing.

APPENDIX B – BOND STRENGTH (MPa)

Short specimens

Depth	30-2		30-5		45-2		45-5	
mm	Slot	Round	Slot	Round	Slot	Round	Slot	Round
65	6.75	5.87	8.58	6.29	13.50	11.11	11.39	9.77
185	10.20	8.44	9.00	8.20	14.27	9.65	13.13	13.52

Medium specimens

Depth	30-2		30-5		45-2		45-5	
mm	Slot	Round	Slot	Round	Slot	Round	Slot	Round
75	8.76	7.52	8.01	5.70	11.29	8.87	7.55	7.23
225	-	9.08	11.24	9.84	15.49	11.95	11.92	9.85
375	11.05	8.44	9.28	8.08	13.94	12.37	12.52	9.26

Tall specimens

Depth	30-2		30-5		45-2		45-5	
mm	Slot	Round	Slot	Round	Slot	Round	Slot	Round
75	8.76	7.54	8.16	6.08	11.48	7.93	7.77	6.84
225	-	10.21	8.16	7.06	14.57	11.76	7.56	8.43
375	11.05	9.13	8.05	6.89	16.58	14.07	10.47	10.52
525	-	-	-	-	15.15	14.15	11.10	9.14
675	-	-	-	-	13.95	13.59	10.65	10.93
1125	12.49	11.27	9.30	10.89	17.80	14.44	12.53	11.04
1275	11.99	10.98	12.07	11.47	17.71	14.27	13.02	10.02
1425	-	-	10.19	-	16.88	14.14	13.46	12.75

RILEM PoT specimens

Depth mm	30-2	30-5	45-2	45-5
75	10.57	5.90	10.99	11.27
225	16.29	7.22	17.35	14.69
375	19.28	10.33	21.11	13.19
525	-	-	21.58	15.19
675	-	-	18.58	17.20
1125	24.96	21.63	24.05	20.14
1275	26.44	21.55	22.25	18.66
1425	24.45	20.96	24.99	22.34