Enhancing bond performance by functional grading of concrete

Philipp Preinstorfer[1,2*[0000-0001-5189-5375]] and Janet M. Lees[1[0000-0002-8295-8321]]

[1] Department of Engineering, University of Cambridge, Cambridge CB3 0FA, UK
[2] Institute of Structural Engineering, TU Wien, 1040 Vienna, Austria
philipp.preinstorfer@tuwien.ac.at

Abstract. The concrete industry is seeking solutions to reduce the carbon footprint of concrete structures. The carbon impact of concrete is mainly driven by the cement clinker content. Typically, the concrete grade is selected according to the most stringent requirements throughout the structure, even though these requirements will vary spatially. Thus, regions exist within structures where concretes with a lower performance would be sufficient. This inefficiency in cement usage can be remedied by functionally grading the concrete according to local requirements to thereby reduce the carbon footprint of the structure. The presence of concrete layers, however, increases the complexity of the design. In this study, the bond performance of layered concrete structures is investigated. Pull-out tests on single mix samples with varying concrete cover were performed using low-strength or high-strength concrete. In a second step, companion functionally graded specimens were tested. In the graded samples, a 15 mm layer of high-strength concrete was placed on the outer face, while the remainder of the sample was cast with low-strength concrete. The failure of the specimens was in all cases initiated by a splitting of the concrete. The failure load, however, was governed by the splitting resistance of the concrete enclosing the reinforcement bar and, for the parameters tested here, appeared to be independent of the layer thickness. This suggests that the splitting resistance of functionally layered concrete can be controlled in a targeted manner. In this way, the overall concrete consumption of a structural element can be reduced using concrete layers with different performance requirements.

Keywords: Functionally graded concrete (FGC); layered concrete; bond performance; pull-out test; splitting resistance.

1 Introduction

Functional grading of concrete is a promising pathway to increase the performance of concrete structures [1], [2] and to lower carbon emissions [3] by tailoring the concrete mix design according to the specific requirements within a structure [4], [5]. To enhance durability, for example, a thin layer of highly durable concrete can be placed as an outer protective layer of a structure. Corrosion of the reinforcement, e.g. due to carbonation of the concrete, can then be delayed [6]. This outer layer of durable concrete may not only allow the usage of concrete with lower performance inside the structure but also a decrease in the concrete cover thickness. However, a minimum limit on the concrete cover thickness exists in current standards (e.g. EN 1992-1-1 [7]), to avoid a splitting failure due to bond action. The question arises whether the bond performance of specimens with a small concrete cover is affected by a thin layer of high-strength, highly durable concrete, and the possible impact on concrete cover thickness limits in layered concrete. An initial literature review revealed that there is no relevant literature available on this specific matter. This paper therefore aims to shed light on this topic by investigating the bond performance of reinforcement embedded in specimens with homogeneous concrete grades and compare it to the bond performance of specimens with an outer high-strength concrete layer. The concrete cover is chosen so that a splitting failure can be expected.

2 Experimental programme

2.1 Materials

Two different concrete mixes were used in the study. The mix designs are listed in **Table 1**. In Mix A, CEM II/A-LL was used as binder, while CEM I was used for mix B. Mix A and Mix B are subsequently referred to as “Low-Strength” and “High-Strength” Mix, respectively. To improve workability, 1% superplasticiser (SP) was used in mix design B. Also, 15 kg/m³ red dye was added in Mix B to distinguish between the two concretes in the hardened state when layered.

Table 1. Mix design of concrete Mix A and B

Type	CEM I [kg/m³] 52.5 N	CEM II [kg/m³] 32,5 R	Water [kg/m³]	Fine agg. [kg/m³] 0-4 mm	Coarse agg. [kg/m³] 4-10 mm	SP [kg/m³]
Mix A	-	297	226	1078	718	-
Mix B	550	-	180	830	855	5.5

In the following sections, series H refers to samples with a homogenous layout, while in series L layered specimens were prepared. In total, two batches of each mix design were cast. The material properties of these four batches are listed in **Table 2**. In case of series L, the material properties were also tested on samples with homogenous concrete (for the low-strength and high-strength mix each). Cubes with dimensions 100 × 100 × 100 mm were used to measure the compressive strength. The splitting tensile strength was tested on cylinders 100/200 mm (diameter/height). Series L generally shows a lower strength, which might be attributed to a different mixer used. The reinforcement was made of steel B500 with a yield strength of 500 MPa.

Table 2. Material properties of the concrete (mean values after at least 28 days of hardening)

	$f_{cm,cube,100}$ [Mpa]	$f_{ctm,sp}$ [Mpa]
Series H – Low strength	27.2 (±1.1)	2.4 (±0.2)
Series H – High strength	93.2 (±3.8)	4.9 (±0.3)
Series L – Low strength	21.7 (±0.9)	2.0 (±0.1)
Series L – High strength	82.5[1]	4.3 (±0.3)

[1]only one specimen tested

2.2 Test setup and specimen preparation

To investigate the splitting cracking behaviour pull-out tests with varying concrete cover were conducted. The chosen test setup is similar to studies from the literature [8], however, only specimens with homogenous concrete grades were tested there. Reinforcement bars with a 12 mm bar diameter ($\varnothing_s$) were placed in the specimens and with a free length of $5 \cdot \varnothing_s$ that protruded from the lower surface to measure the slip and a free length of $50 \cdot \varnothing_s$ above the upper surface to be clamped into the testing machine. The reinforcement bar was fully bonded along the whole embedment length. The distance from the bottom face of the specimen to the centre line of the tested reinforcement was increased by $0.42 \cdot \varnothing_s$ (5 mm) for every sample and ranged from $0.42 \cdot \varnothing_s$ (5mm) to $2.5 \cdot \varnothing_s$ (30 mm; see **Fig. 1**). All six specimens per set were cast at once in a single formwork and cut afterwards to give a pull-out test specimen width of 240 mm. The area of interest was at the bottom side of the specimens. To avoid a splitting crack from propagating throughout the whole specimen, two reinforcement bars Ø12 were placed on the top side of the specimens with a concrete cover of 15 mm to each side before casting. In the case of the specimens with a homogenous concrete grade (series H), the whole formwork was filled at once without any pour delay. For the layered specimens of series L, high-strength concrete (red colour) was filled into the formwork until a layer thickness of $1.25 \cdot \varnothing_s$ (15 mm) was achieved. The rest of the formwork was then filled with the low-strength concrete after a pour delay of approximately 30 min.

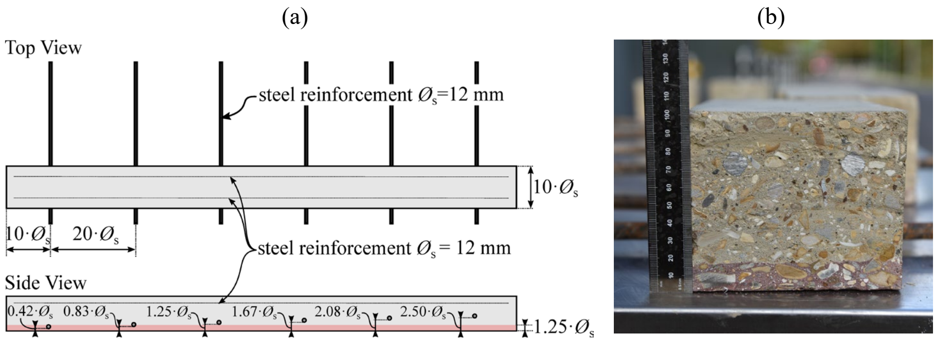

Fig. 1. Specimen preparation: (a) Six specimens were cast within one formwork. The concrete cover ranged from $0.42 \cdot \varnothing_s$ (5 mm) to $2.5 \cdot \varnothing_s$ (30 mm) and (b) the specimens were cut after hardening and the actual layer thickness was measured.

The cutting was done after a hardening time of at least 28 days with a water-cooled saw. The resulting width of the specimens was 240 mm ($20 \cdot Ø_s$) so that the reinforcement bars were located at the centre of the test specimens. After cutting, the actual layer thickness was measured for each specimen on both cutting faces.

To test the specimens, they were flipped 90 degrees so that the reinforcement bar was upright and could be clamped into the brackets of an Electromechanical Universal Testing System with a capacity of 150kN. The specimen was supported at a distance of 100 mm on the top of the specimen. Eventually, the specimens were fixed by a steel plate with a hole in the middle and four threaded rods to the bottom of the Instron machine. The loading was applied using displacement control with a velocity of 1 mm/m until a displacement of 20 mm was reached or no load could be transferred anymore. To measure the slip, Linear Variable Differential Transformers (LVDT) were placed on the reinforcement to measure the displacement to the top and bottom sides of the specimens during testing. To observe any splitting cracks on the front face of the specimens, measurements with digital image correlation (DIC) were carried out. Therefore, a stochastic pattern of black dots was sprayed on the specimens after the front face was painted white. During testing, a single-lens reflex camera was used to take photos with a frequency of 0.2 Hz. The load was measured by a load cell in the testing machine.

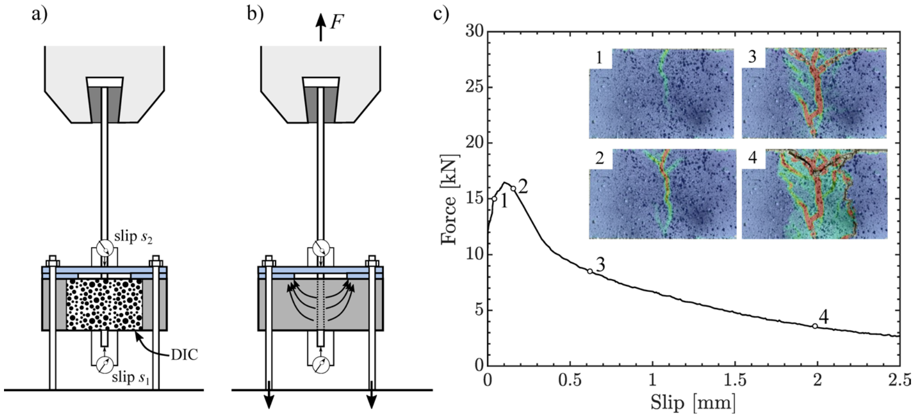

Fig. 2. Test setup for the bond performance tests: (a) two LVDTs measure the slip at the bottom and top face, DIC measurements are carried out to track crack propagation, (b) test-related load path during loading and (c) typical bond-force slip response of the tests with crack propagation at different load stages.

A typical bond-force slip (bottom slip) response of the tests is depicted in **Fig. 2**c. After a splitting crack initiates (1; not visible to the naked eye), the bond stiffness decreases. The crack propagates and widens when the loading is increased (2) and eventually the peak bond strength is reached, followed by a distinct decrease in transmittable bond force (3). In the final stage of the test, a concrete cone forms at the top side of the specimen (4) due to the test-related load transfer depicted in **Fig. 2**b.

3 Results

3.1 Bond performance of homogenous specimens

The bond-force slip-response of series H (homogenous concrete grade) can be seen in **Fig. 3**. The slip measurements are given up to 2.5 mm (left column). A detailed view up to 0.25 mm is given in the right column for better comparison. In all cases, a splitting crack occurred. Hence the bond strength increases with increasing ratio of concrete cover *c* to reinforcement diameter $\varnothing_s$. However, with increasing $c/\varnothing_s$ ratio, a higher fracture toughness becomes visible, especially in the case of the low-strength mix. In general, it can be stated that the lower-strength concrete showed a more ductile behaviour compared to the high-strength mix, where there was a distinct drop in transmittable bond force once the peak bond strength was surpassed. The bond capacity of the high-strength mix was approximately twofold compared to that of the low-strength mix, which corresponds to the difference in splitting tensile resistance of the mixes (4.9 and 2.4 MPa, respectively; see **Table 2**).

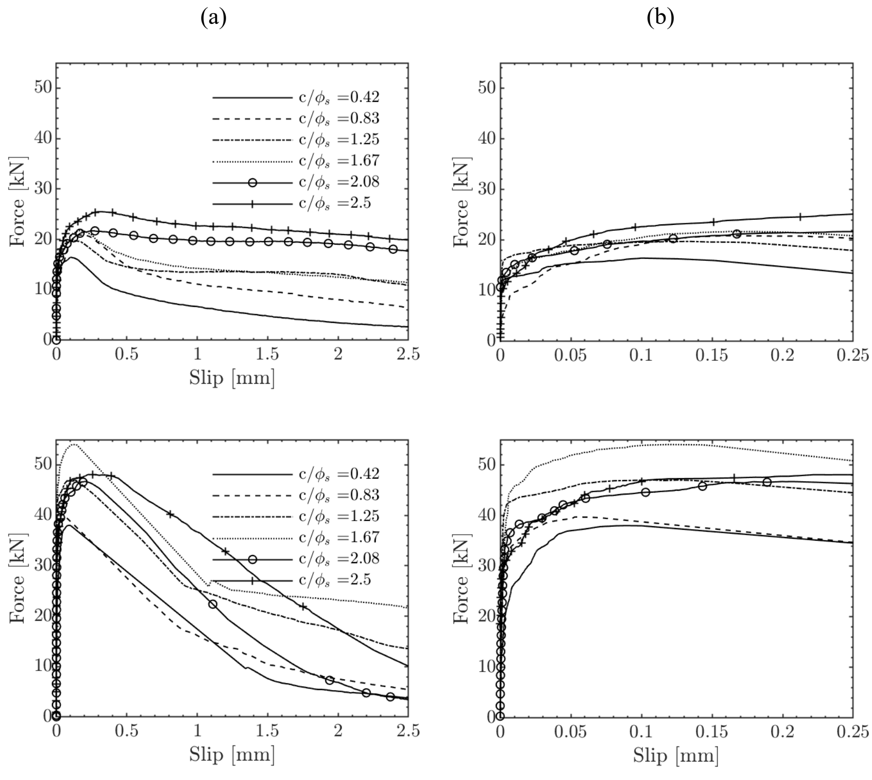

Fig. 3. Bond Force-slip response of homogenous specimens: low-strength concrete (top) and high-strength concrete (bottom). In the left column (a), the measured slip is depicted up to 2.5 mm, while in the right column (b), the slip is limited to 0.25 mm.

3.2 Bond performance of layered specimens

The bond-force slip response of series L is depicted in **Fig. 4**. In the case of small $c/Ø_s$ ratios up to 0.83, a similar brittle behaviour as for the high-strength mix in series H was observed. However, the higher $c/Ø_s$ ratio of 0.83 resulted in smaller peak bond strength when compared to a $c/Ø_s$ ratio of 0.42. For $c/Ø_s > 0.83$, the behaviour became more ductile again, comparable to the behaviour of the low-strength mix of series H.

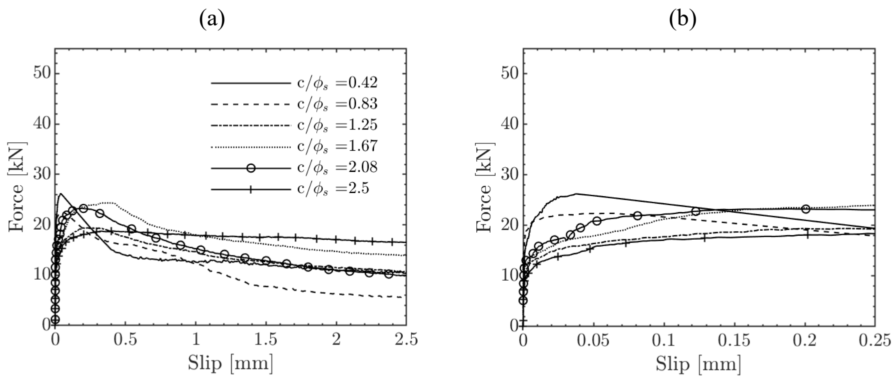

Fig. 4. Bond Force-slip response of layered specimens. In the left column (a), the measured slip is depicted up to 2.5 mm, while in the right column (b), the slip is limited to 0.25 mm.

Fig. 5 depicts the specimens with a $c/Ø_s$ ratio of 0.42-1.67 after the tests. Specimens with a $c/Ø_s$ ratio of 2.08 and 2.50 showed a similar behaviour to that shown in **Fig. 5**c-d for a $c/Ø_s$ ratio of 1.25-1.67, and so are not depicted here. A splitting crack became visible in all specimens. In the case of the specimen with a $c/Ø_s$ ratio = 0.83, an interfacial failure between the two concrete mixes occurred, which led to the complete spalling of the high-strength layer. Noticeably for this specimen, the centre line of the reinforcement coincided with the interface between the two concrete mixes.

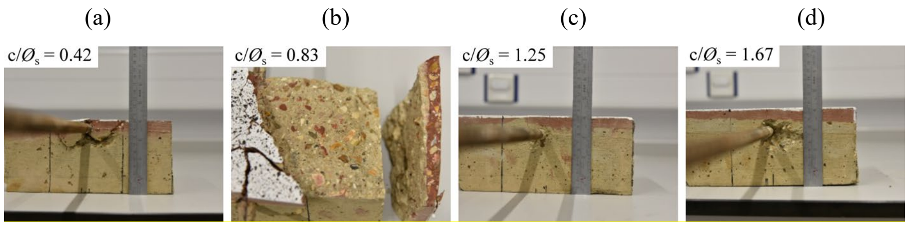

Fig. 5. Picture of the specimens after the test was completed: $c/Ø_s$ = 0.42 (a), $c/Ø_s$ = 0.83 (b), $c/Ø_s$ = 1.25 (c) and $c/Ø_s$ = 1.67 (d)

3.3 Comparison of bond performance

To compare the bond performance of the homogeneous and layered specimens, the peak bond strength f_b for both series is depicted in **Fig. 6**a as a function of the $c/Ø_s$ ratio. The bond strength f_b is obtained by dividing the measured bond force F by the surface area of the bonded reinforcement to the concrete. It is noticeable that in the case of the graded specimens, only for a very small $c/Ø_s$ ratio of 0.42, the peak bond strength is considerably higher than for the homogenous specimens made of low-strength concrete. In the range $0.83 < c/Ø_s < 2.5$, the obtained bond strengths of the graded specimens somewhat match the values obtained from the low-strength mix.

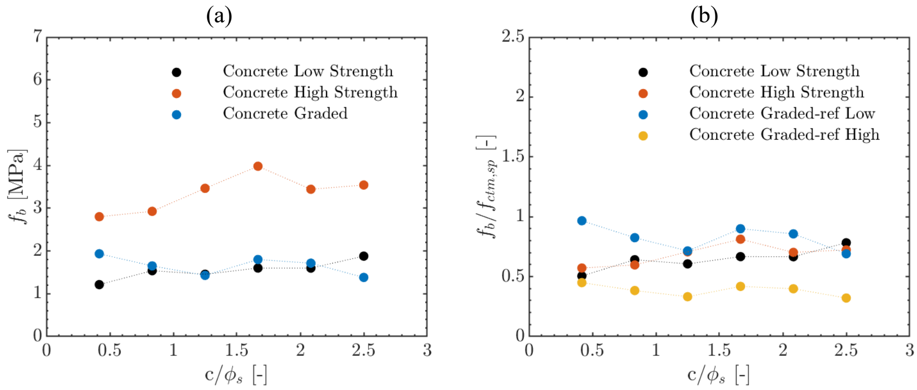

Fig. 6. Comparison of the bond performance of Series H and L: peak bond strength f_b in dependency of the $c/Ø_s$ ratio (a) and normalised bond strength $f_b/f_{ctm,sp}$ in dependency of the $c/Ø_s$ ratio. The results of the layered specimens are normalised by the splitting tensile resistance of the low-strength (blue line) and the high-strength mix (yellow line).

It must be considered, however, that the series L concretes in general exhibited a lower splitting tensile strength. Therefore, the normalised bond strength is given in **Fig. 6**b, where the bond strength f_b is divided by the splitting tensile strength $f_{ctm,sp}$. In the case of the layered specimens, the bond strength is normalised by the splitting tensile resistance of the low-strength (blue line) or the high-strength mix (yellow line). Again, the same trend becomes visible for the layered specimens, where for a small $c/Ø_s$ value of 0.42, the bond strength normalised by the high-strength mix matches the results of series H. For larger $c/Ø_s$ values, normalisation by the splitting tensile resistance of the low-strength mix better matches the results of series H.

4 Conclusions

This paper describes the results of a study on the bond performance of reinforcement embedded in layered concrete specimens. As a reference, a series of specimens with homogenous concrete grades, namely a low-strength mix and a high-strength mix, were tested using a pull-out test on samples with varying concrete cover ($0.42 < c/Ø_s < 2.50$). In the second step, a series where a concrete layer of 15 mm was cast with the high-strength concrete mix, while the rest of the specimen was cast with the low-strength mix was undertaken. The following conclusions can be drawn from this study:

1. The occurrence of splitting cracks governed the bond performance in all samples. As expected, the bond performance increased with increasing $c/Ø_s$ ratio in samples with homogenous concrete grades.
2. In the case of the samples with a homogenous concrete grade, the peak bond strength of the high-strength mix was approximately twofold compared to the low-strength mix. This correlates with the difference between the splitting tensile resistance (4.9 > 2.4) of the two mixes, indicating that the bond performance of the tested samples is a function of the splitting resistance of the concrete. The post-peak behaviour, however, is different, with the low-strength mix showing a more ductile behaviour.
3. In the case of the layered specimens, the reinforcement bar was fully or partly enclosed up to the centre line of the reinforcement bar by the high-strength mix for $c/Ø_s$ = 0.42 and $c/Ø_s$ = 0.83, respectively. However, it was only in the case of $c/Ø_s$ = 0.42 that the bond strength could be correlated with the splitting resistance of the high-strength mix. For the sample with $c/Ø_s$ = 0.83, a spalling of the high-strength layer was observed. This was attributed to a relatively weak interface between the two layers of concrete, even though the pour delay was only 30 minutes. It is likely that the splitting forces due to bond action, which were orientated perpendicular to the interface for this sample, then caused the spalling of the cover.
4. For $c/Ø_s$ > 0.83, where the reinforcement is not enclosed by the high-strength mix, it was observed that a layer of high-strength concrete did not or only marginally influenced the splitting resistance and hence the bond performance of the specimens. Hence, a layer of high-strength concrete does not act as a crack stop, as it was to some extent expected at the beginning of the study.

In this paper, the influence of a layer of high-strength concrete on the bond performance of steel reinforcement was studied. It is concluded that if this layer fully encloses the reinforcement, the splitting resistance and hence the bond performance of concrete samples with small cover thickness can be enhanced. Because higher-strength concrete typically also shows higher resistance against chemical and mechanical aggression, the overall cover thickness in structures can be reduced, thus saving material. Whether this also entails a reduction in carbon emissions has to be assessed in each individual case, as high-strength concrete normally also contains higher cement content. On the other hand, if the layer does not enclose the reinforcement, only the splitting resistance of the lower-strength mix can be considered. Further studies, however, are needed on concretes with higher ductility, e.g. fibre-reinforced concrete.

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