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Bond of self-compacting concrete incorporating silica fume: Top-bar effect, effects of rebar distance from casting point and of rebar-to-concrete relative displacements during setting

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HIGHLIGHTS

- The top-bar effect is eliminated for SCC incorporating 8.9–10.6% silica fume.
- No bond loss was observed in SCC up to 1.60 m from the single casting point.
- The bond variation is comparable between SCC and NVC.
- Setting depends on superplasticizer content, regardless of the concrete type.
- Rebar displacements during setting similarly affect SCC and NVC bond.

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ABSTRACT

This study investigates the effect of different silica fume levels of cement replacement on the bond capacity of Self-Compacting Concrete (SCC).

Specifically, the top-bar effect, the bond variation as a function of the rebar distance from the casting point and the effect of a rebar-to-concrete relative displacement during setting on bond are examined. Vertical and horizontal specimens with transverse rebars distributed over height (600 mm) and length (1780 mm), respectively, were cast and tested by pull-out. Six SCC mixtures with various replacement levels were investigated and compared to one reference SCC mixture (without silica fume) and three Normally Vibrated Concrete (NVC) mixtures of different workability classes.

It was found that the top-bar effect of SCC mixtures incorporating silica fume is less intense than in NVC and it is almost eliminated for replacement levels between 8.9% and 10.6% (by weight). No bond loss is evident up to at least 1.60 m from the casting point. Finally, the effect of a rebar-to-concrete relative displacement during setting on bond is similar between SCC and NVC. Although higher initial setting times are observed in SCC, bond is not prone to reduction due to a rebar-to-concrete relative displacement during this period.

1. Introduction

The increased reinforcement requirements that have been adopted by major building codes [1–2] during the last three decades have led to considerably high congested concrete members. As a result of the required dense reinforcement, significant difficulties have been encountered, regarding the correct application and the effectiveness of the mechanical compaction, in order to adequately fill the formworks, without leaving any surface or hidden voids. Thus, the uniformity of the final material during the execution of Normally Vibrated Concrete (NVC) structures has been put into question, up to some extent.

In the late 1980's, Self-Compacting Concrete (SCC) had been universally introduced [3–6] as a revolutionary material that had the ability to easily flow under its own weight and adequately fill highly congested concrete members, without requiring any compaction. Since then, the enhanced rheological properties of SCC have been admired in practice by the construction industry and its use has been widely extended. Concurrently, a great number of researchers on a worldwide scale have been motivated to further investigate the effects of using SCC on several hardened concrete properties, such as mechanical strength and durability.

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Bond to reinforcement steel is considered to be one of the most crucial mechanical properties, as it is directly associated with the ability of reinforced concrete to act as a composite material by ensuring the cooperation between steel and the surrounding concrete. Previous research has already provided sufficient data to give confidence in the bond behaviour of SCC. Specifically, it has found that the normalized bond strength of SCC is, in general, similar or higher than of NVC [7–14] and it usually presents a lower scatter [11,13–16]. However, limited attention has yet been given to the effect of the specific composition properties on the resulting bond, whilst a further investigation on more specialized bond issues is also potentially critical.

The incentive of the present study is to supplement previous literature on the effect of SCC composition on advanced aspects of bond. Specifically, the impact of (i) the rebar position over height (top-bar effect), (ii) the rebar distance from the casting point and (iii) a rebar-to-concrete relative displacement during setting, as a result of possible unintentional formwork displacements, on bond was examined in six SCC mixtures, produced with various silica fume levels of cement replacement. The results were compared to the corresponding bond characteristics of one reference SCC mixture (without silica fume) and three typical NVC mixtures.

2. Theoretical approach

2.1. Effect of composition

As it has been formerly reported [8,12,14,17–19], the quality of concrete, in terms of its composition, its production process and its placing method, may significantly affect bond capacity. It is considered [7,14,19–23] that any changes in composition that affect the morphology of the concrete matrix may lead to considerable effects in bond characteristics. Such composition changes include variations in the content of cement, water or any supplementary inert, pozzolanic or hydraulic materials (type I or II additions), the latter being frequently used for the production of rheologically enhanced and stable SCC mixtures.

For silica fume in NVC, the bond-enhancing effect has been previously discussed in several studies [18,20,24–27]. The enhanced bond has been attributed to both the chemical reaction between CH crystals and the pozzolanic material (pozzolanic reaction) and the filling effect (physical action) that are considered to significantly densify the concrete-steel transition zone and, thus, reduce the accumulation of free water due to bleeding under the horizontally placed rebars. Combined with the usually lower water content of SCC mixtures, the achieved denser capillary network is expected to reduce the water accumulation beneath all rebars, thus enhance bond behaviour.

2.2. Effect of rebar position over height (top-bar effect)

For deep concrete members and apart from the concrete composition, the role of reinforcement, and, specifically, the effect of the rebar orientation and position on the resulting bond capacity, is considered to be significant. For NVC, major building codes [1–2] have adopted a correction factor that decreases the value of bond strength in the higher parts of the deep concrete members.

This correction factor aims to confront the phenomenon, known as the ‘top-bar effect’, whose mechanism can be summarized as follows. Prior to the final setting (stiffening) of concrete, the heavier constituent materials (cement, aggregates) tend to settle due to gravity (plastic settlement), thus forcing the lighter water to move upwards, through the capillary network, to the higher parts of the concrete members and, finally, their free surface (bleeding phenomenon). Along this path, part of the water is trapped underneath the horizontal reinforcement bars, thus reducing the quality of the interface zone, in terms of the bonding between steel bars and the surrounding concrete. This water accumulation is higher in the upper parts of deep concrete members. In addition to this mechanism, the air entrapment underneath the reinforcement bars and between their ribs due to the vibration process of NVC is also known to further negatively influence the resulting bond.

As explained previously (Section 2.1), the more densified capillary network of SCC, due to the incorporation of both inert and/or pozzolanic additions, leads to a reduction of the water accumulation beneath bars, and, therefore, the top-bar effect is expected to be less significant.

This significance has been previously investigated by several researchers [10–12,15–17,21,22,27–30] and it has been reported that SCC behaviour is either equal or better than NVC for high elements and the top-bar effect is less intense for SCC mixtures. Furthermore, many researchers implied that the provisions of EN 1992-1-1 (2004) [1] for NVC appear to be adequate for SCC [9,11,14,21,27]. However, it has been also reported [9,15] that the bond reduction with height exceeded these provisions in some SCC and NVC specimens, up to some extent. It should be noted that each of these studies focuses on different parameters (concrete strength, rheology characteristics, cover thickness, bond length, etc.) and they should not be directly compared.

2.3. Effect of distance from the casting point

Another major issue that has yet been limitedly investigated is the effect of the rebar distance from the casting point on bond characteristics. The ability of SCC to flow over considerably greater distances (compared to NVC) with insignificant or no signs of obvious segregation, offers the advantage of reducing the required casting points during the execution of a structure. In ACI 237R (2007) [31], the concrete discharge at one single casting point is suggested until either the concrete member is completely filled (beams) or the fresh mixture has flown as far as possible, before moving the point of discharge (slabs).

Given the satisfactory segregation resistance of properly designed SCC mixtures, an insignificant bond loss across length should be expected, yet there is only limited research work to validate this assumption. Previous work [13,29] has shown that some issues may arise especially for lower slump-flow values and for greater distances from the casting point. Still, it is considered that the dominant cause of the reduced bond is not a local deterioration in the concrete-steel interface zone but the unsuccessful embedment of rebars, in terms of the reduced steel cover in remote regions due to the decreasing slope of the final surface. In both studies, the low concrete cover in higher distances led a great number of rebars to fail by splitting, instead by pull-out.

2.4. Effect of rebar displacements during concrete setting

During concrete setting, a possible local differential settlement of formwork’s scaffolding or a horizontal formwork displacement due to a seismic event or a blast load may result in a relative displacement between the embedded rebars and the surrounding concrete. The effect of such a rebar-to-concrete relative displacement on the particle interlocking of aggregates within the concrete matrix may be reflected on bond; however no previous research work has been conducted on the subject.