Construction and Building Materials 169 (2018) 678–688

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Bond strength of reinforcing bars encased with shotcrete

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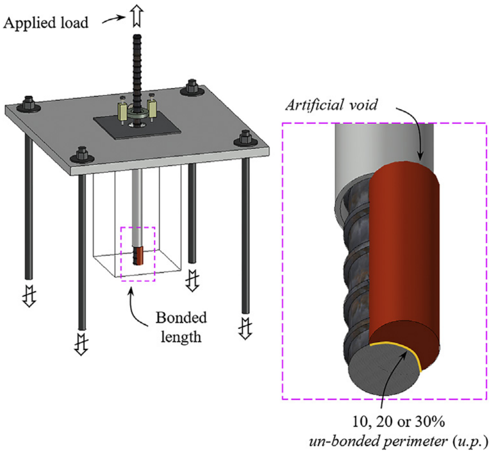
HIGHLIGHTS

- Concrete sprayed properly offers better *slip stiffness* than cast-in-place concrete.
- Shotcrete voids were recreated using *artificial voids* made of silicone.
- A void's transversal length of approximately 20% sets a bond performance threshold.
- The height of the voids does not greatly influence the bond strength of a bar.
- The optimal combination between the *consistency* and the airflow rate must be sought.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 August 2017
Received in revised form 11 January 2018
Accepted 28 February 2018

Keywords:
Shotcrete
Sprayed concrete
Consistency
Voids
Artificial voids
Encapsulation
Bond strength
Hypothesis testing

ABSTRACT

As the use of shotcrete (sprayed concrete) to build full-depth structural elements increases in North America, the encapsulation quality of reinforcing bars has become a subject of growing concern. In this investigation, the influence of the mixture *consistency* and the size of imperfections (created deliberately) behind reinforcing bars on the bond strength of the bars was studied using shotcrete "pull-out" specimens sprayed with the *dry-mix* process. However, as the desired range of the imperfection sizes could not be obtained, cast-in-place "pull-out" specimens were built with artificially created voids. This strategy allowed to study the reduction of the bond strength by knowing the precise size of the voids. The results suggest that the best bond performance of a bar is obtained, given an appropriate spraying technique, when the optimal combination between the mixture *consistency* and the airflow rate is used. Moreover, reinforcing bars encased with shotcrete slip less, relative to concrete, than those encased with cast-in-place concrete because of the high compaction with which the mixture is placed. Additionally, a void's transversal length (in contact with the bar) of about 20% of the bar's nominal perimeter was found to be the threshold beyond which an important change of the bond performance occurs.

1. Introduction

Shotcrete is a method of concrete placement in which the mixture is sprayed at high velocity onto a surface using compressed air. Nowadays, its use in North America has increased substantially

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https://doi.org/10.1016/j.conbuildmat.2018.02.218
0950-0618/

and structural elements such as shear walls [1], columns [2], girders [3] and shells [3,4] are being built entirely with it, mostly, because little formwork (if any) is needed. However, concerns regarding the encapsulation quality of the reinforcing bars have been raised due to the "shadow" zone existing behind the bars. To avoid the creation of imperfections[1] in that area, good practice guidelines state that an appropriate spraying technique, in combination with an adequate mixture *consistency*, needs to be used [5–9]. Nozzle operators (often called nozzlemen) are required to, among others, continuously move the nozzle in small circles, stand at the right distance from the receiving surface and hold the nozzle at the right angle relative to the receiving surface while spraying the concrete [5]. Albeit this is true for both process of shotcrete available (*dry*- and *wet-mix*), the peculiarity of the *dry-mix* process is that the nozzlemen control the flow of water and thus, their experience plays a more important role than in the case of the *wet-mix* process regarding the encapsulation of reinforcing bars [6]. With the *dry-mix* process, mixtures sprayed "too wet" (with high water content) will probably slough off the surface before the desired buildup thickness is attained whereas mixtures sprayed "too dry" (with low water content) will lack sufficient plasticity to flow around the bars and voids behind them may be created. Nonetheless, for a given *consistency* above the optimal, voids created by experienced nozzlemen will be smaller than those created by unskilled nozzlemen [6]. In general, it has been suggested to spray *dry-mix* shotcrete at its *wet-test stable consistency* which refers to a mixture having the maximum amount of water before it sloughs off the receiving surface [6,10]. For *dry-mix* process mixtures with an 8–10% cement replacement with silica fume, a *consistency* ranging between 0.5 and 1.4 MPa should be sought [7] to avoid excessive rebound (the mass of un-adhered particles expressed as a percentage of the total mass of the sprayed mixture) and to maximize the buildup thickness. Unfortunately, recommendations regarding the optimal mixture *consistency* to achieve the proper encapsulation of reinforcing bars in combination with their best bond performance have not been suggested.

Despite the use of the proper *consistency* and spraying technique, imperfections may also be created, among others, due to heavily congested zones of reinforcing bars within members, difficult conditions at the job site or the use of set-accelerators (mostly when using the *wet-mix* process). In these cases, the bond strength of the bars is expected to decrease since the bond stress will not be transferred uniformly to the bar from the surrounding concrete. Indeed, it has been shown that the ultimate bond strength of a bar will drastically decrease as the size of the imperfections behind it (which were qualitatively characterized) increases for a given concrete compressive strength [8]. In contrast with cast-in-place concrete, the height of the concrete below the bars should not cause an additional reduction of the bond strength (unless the mixture is sprayed "too wet" and plastic settlement occurs) because less bleeding is observed in shotcrete [11]. Nonetheless, detailed information about the dimensions, type, and distribution of the imperfections and their effect on the bond strength and the slip performance of the bars is almost inexistent in the literature. To the knowledge of the authors, only the transversal length of a void has been investigated in the past [12]. The results showed how the bond strength of plain round bars decrease linearly and proportionally, regardless of the concrete compressive strength, as the transversal length of a void increases. The purpose of this paper is to assess the impact of the mixture *consistency* and of the transversal dimensions of imperfections on the bond strength of deformed reinforcing bars encased with shotcrete. The results will ultimately be useful to set acceptance criteria for the evaluation of cores taken from shotcrete pre-construction panels[2] and even for the future development of guidelines regarding the detailing of the reinforcement during the design phase of a structure.

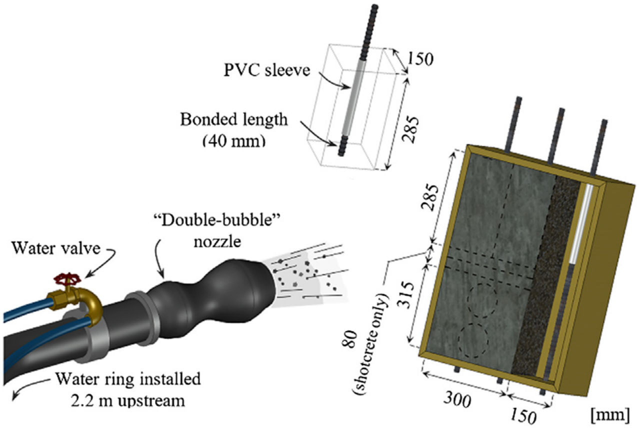

Fig. 1. Representation of the spraying operation.

2. Experimental program

2.1. Test specimens

Shotcrete "pull-out" specimens were built in the laboratory using the *dry-mix* process so the nozzlemen could intentionally change the water added to the mixture and create a wide range of reinforcing bar encapsulation qualities. The mixture was sprayed into wooden rectangular panels as the one shown in Fig. 1 in which all of the reinforcing bars were positioned with their longitudinal ribs facing the sides of the panels.

Two nozzlemen (referred henceforth as N1 and N2) sprayed the concrete using an ALIVA® 246.5 spraying machine with the water ring installed 2.2 m upstream from a "double-bubble" nozzle. Both nozzlemen were asked to spray the concrete using three different flows of water ranging from high (the "wettest" *consistency*) to low (the "driest" *consistency*) without changing the chosen rate of airflow and using a proper spraying technique. In that manner, only the ability of each nozzleman to specify the appropriate rate of airflow before shooting and to choose the mixture *consistency* would influence the creation of imperfections. However, as the desired range of imperfection sizes could not be obtained, cast-in-place specimens (using the same pre-bagged shotcrete mixture) in which the voids were recreated using silicone were built. Such strategy allowed to better correlate the measured bond strength to the known void sizes by overcoming the difficulties related to spraying. Moreover, similar mixture properties from one specimen to another were obtained. In such cases, the concrete was placed and consolidated in accordance with the ASTM C192/C192M-16a standard [13].

The blocks were stripped 1 day after the spraying or the casting operations and were subsequently cured for one week using wet burlap. The blocks were then cut following the dotted lines shown in Fig. 1 over the mold to obtain three specimens per panel. Each specimen consisted of a 150 × 150 × 285 mm prism with a single 16 mm nominal diameter (d_b) reinforcing bar concentric with the longitudinal axis of the prism as shown in Fig. 1. The initial length of the reinforcing bar was protected with a 245 mm long PVC sleeve to leave a 40 mm (2.5d_b) bonded length (the portion of the bar in contact with concrete) at the opposite end of the specimen from which the bar was pulled. The relatively short bonded length was chosen to avoid the yielding of the reinforcing bars during the tests and did not contain any grade or manufacturer markings.

2.2. Artificial and shotcrete voids

Artificial voids were made of silicone and were used in combination with cast-in-place specimens only. First, the fresh silicone was inserted into hollow plastic tubes to create voids' nominal transversal lengths, referred to as *un-bonded perimeters* (or *u.p.*) henceforth, of 10, 20 and 30% (refer to Fig. 2a); the *un-bonded perimeters* are expressed as a percentage of the nominal perimeter of the bar. The hardened silicone was then extracted from the plastic tubes, whose only objective was to act as molds, and were subsequently cut longitudinally in two halves. The resulting pieces were then glued over the entire bonded length of the reinforcing bars using the same material.

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[1] Imperfections may take the form of entrapped aggregates (*sand lenses*) or voids.

[2] Panels often used in complex shotcrete projects to recreate the challenging parts of the actual structure.