Influence of concrete composition on anchorage bond behavior of prestressing reinforcement

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ABSTRACT:

An experimental research addressing the effects of concrete composition and strength on anchorage bond behavior of prestressing reinforcement is presented to clarify the effect of material properties that have appeared contradictory in previous literature. Bond stresses and anchorage lengths have been obtained in twelve concrete mixes made up of different cement contents (C) –350 to 500 kg/m^3– and water/cement (w/c) ratios –0.3 to 0.5–, with compressive strength at 24 hours ranging from 24 to 55 MPa. A testing technique based on measuring the prestressing force in specimens with different embedment lengths has been used. The results show that anchorage length increases when w/c increases, more significantly when C is higher; the effect of C reveals different trends based on w/c. The obtained anchorage bond stresses are greater for higher concrete compressive strength, and their average ratio of 1.45 with respect to transmission bond stresses implies a potential bond capacity.

KEYWORDS:

concrete, cement, reinforcement, strand, bond, anchorage, development, pretensioned, precast

1. INTRODUCTION

In pretensioned prestressed concrete, prestressing reinforcement stresses vary along the member length and through time. Two main stages must be considered –prestress transfer and loading– which require setting up two lengths [1]: transmission length (transfer length [2]), defined as the distance along which the prestress is built up in the prestressing reinforcement after prestress transfer, and anchorage length (development length [2]), defined as the distance required to transfer the ultimate tension force to the concrete. Fig. 1 illustrates these lengths and the idealized profile of the prestressing reinforcement force at the end of a member.

Estimation of transmission and anchorage lengths from the required bond stress is important in design [3]. Different experimental methodologies to characterize bond and to determine transmission and anchorage lengths have been proposed based on push-in test [4], pull-out test [5,6], push-pullout test [7], reinforcement end slip [8], and longitudinal concrete strain [9]. However, no consensus exists regarding a standard testing method for bond properties determination [2] and there are no minimum requirements for bond performance of prestressing reinforcements in [1,2], or in standards like in [10,11]. Recently, an experimental methodology has been developed, the ECADA[1] test method [12], which is based on the measurement of the prestressing reinforcement force by analyzing specimens series with different embedment lengths. Its feasibility has been verified in short [13,14] and long time analyses [15,16].

As exposed in the background section, and particularly concerning the effect of concrete composition variations, additional knowledge about bond behavior of prestressing

[1] ECADA is the Spanish acronym for "Ensayo para Caracterizar la Adherencia mediante Destesado y Arrancamiento"; in English, "Test to Characterize the Bond by Release and Pull-out".

reinforcement is required for a better determination of transmission and anchorage lengths in precast pretensioned concrete members.

Regarding transmission length, a first study on the effects of concrete composition was carried out at the Institute of Concrete Science and Technology at Universitat Politècnica of València [17]. In this context, and as a complementary part of that first study, the purpose of this paper is to present the experimental results addressing the effects of concrete composition on anchorage bond behavior of seven-wire prestressing strands. To this end, an experimental program to determine anchorage lengths, as well as the average bond stress along these lengths in twelve concretes of different composition –varying cement contents and with different water-to-cement (w/c) ratios– and properties, by means of the ECADA test method, has been carried out.

2. BACKGROUND

Bond strength, as well as transmission and anchorage lengths, are function of a large numbers of factors [1]: concrete strength at the time of the prestress transfer, initial reinforcement stress, concrete cover, prestress transfer procedure, reinforcement size and geometry, surface condition, concrete strength at the time of loading, etc. The mechanisms associated with bond are still being studied [18]. Several equations to calculate both transmission and anchorage lengths have been proposed [3,19]. However, no consensus has been reached concerning the main parameters to be considered in these equations. Some authors and code provisions for anchorage length propose equations in which concrete properties are not a parameter [2,20]. Only concrete compressive strength is included when concrete properties are considered [21,22].

Several experimental works about bond and transmission, and on anchorage lengths of prestressing reinforcement, have been conducted over the years. There have been different and conflicting observations about the effect of important parameter on anchorage length in previous literature. Regarding concrete compressive strength, several authors [21,23,24] have concluded that transmission and anchorage lengths decrease when concrete compressive strength increases. Furthermore, [25] points out that the influence of concrete compressive strength on bond capacity of prestressing reinforcement is not clear.

Cement content and w/c ratio are important parameters of the concrete mix design. Nevertheless, few studies [26,27] have been undertaken regarding their influence on bond properties. According to [26], bond strength decreases when the w/c ratio increases. However, according to [27] bond strength improves when the w/c ratio increases. On the other hand, bond strength has been found to be higher when cement content is increased [26], whereas other authors [28] have concluded that increasing cement content produces a reduction of bond strength.

The aforementioned first study [17] showed that the influence of w/c ratio on transmission length is very small for concretes with low cement contents, but the influence of w/c ratio was highly significant when cement content is high. Also, the effect of cement content on transmission lengths revealed different tendencies based on w/c ratio.

Recent studies on the effects of varying concrete composition on bond properties have focused on self-compacting concrete [29,30], ultra-high strength concrete [31], and steel fiber reinforced concrete [6].

On the other hand, in addition to the anchorage length definition in terms of stress (or force) [1,2], the maximum stress in the prestressing reinforcement must be achieved by preventing reinforcement end slip [32]. However, a limitation or an account for reinforcement slip is not addressed in the main design codes [2,33,34].

Consequently, researchers have suggested defining anchorage length based on two different assumptions [35]: without prestressing reinforcement slip at the free end of the member during the loading stage (anchorage length –without slip–, L_A), and accepting prestressing reinforcement slips at the free end when a prestressed concrete member is loaded (anchorage length with slip, L_S). These two anchorage length modes have been considered in this experimental study.

3. EXPERIMENTAL STUDY

3.1. Test equipment and instrumentation

The ECADA test method [12,36] has been used in this experimental study. This test method is based on the measurement of the prestressing reinforcement force at a simulated cross section of a pretensioned prestressed concrete member. To this end, a prestressing frame is required to test specimens as a part of one end of the member, as shown in Fig. 2. An adjustable reinforcement anchorage is placed at one end (free end) of the prestressing frame –to facilitate the tensioning and release operations– and an Anchorage-Measurement-Access (AMA) system at the other end (stressed end). The AMA system serves as anchorage for the prestressing reinforcement, it simulates the sectional rigidity of the specimens, it allows the measurement of the prestressing reinforcement force, and it allows to increase the prestressing reinforcement force by pull out. A detailed description of the test method and the AMA system requirements is available in [12, 36].

The test equipment is completed with a hollow hydraulic jack of 300 kN of capacity that can be placed at each end of the prestressing frame. The force in the reinforcement is controlled at all times during the test by means of a hollow force transducer HBM C6A located in the AMA system. A pressure transducer completes the instrumentation and is used to control the hydraulic jack. No internal measuring devices are used in the specimens tested in order not to interfere bond phenomena.

As a complement for this experimental study, a displacement transducer at the free end of the specimen is used allowing the prestressing reinforcement end slip to be measured during loading. Therefore, according to the two anchorage length modes, the criterion to determine L_A is based on the force achieved immediately before prestressing reinforcement end slip occurs, and only the prestressing reinforcement force achieved is considered in determining L_S.

3.2. Specimen testing procedure

This test method allows the characterization of bond of prestressing reinforcement in concrete by means of the sequential release of the prestress transfer (detensioning) and the pull-out (loading) operation on the same specimen test. Testing a specimen consists of the following stages: preparation, prestress transfer (release), and anchorage capacity (loading) analysis, as follows.

Preparation stage:

- Alignment of the reinforcement in the prestressing frame.
- Reinforcement tensioning by means of the hydraulic jack which is coupled at the free end of the frame.
- Anchoring of the reinforcement by means of the adjustable anchorage; the hydraulic jack is relieved (and it can be coupled to other frame for a new operation).
- Casting of the specimen: concrete is mixed, placed into the moulds in each frame, and consolidated; specimens remain under the selected conservation conditions until the time of prestress transfer.

Prestress transfer stage:

- Release: the hydraulic jack is remounted on the free end and the adjustable anchorage is removed; the hydraulic jack is gradually unloaded, triggering the transfer of the actual prestressing force (P_0) to concrete.
- Measuring: the prestressed concrete specimen is supported at the end plate of the prestressing frame included in the AMA system; the hydraulic jack is relieved; after a stabilization period, the prestressing reinforcement force (P_T) is measured.

Loading stage:

- Preliminary: the hydraulic jack is anew coupled to the frame at the stressed end; a displacement transducer is placed at the free end of the test specimen.
- Loading: the force in the prestressing reinforcement is increased by loading the hydraulic jack which pulls the AMA system from the pretensioning frame.

- Measuring: the maximum force achieved during the pull-out operation before reinforcement slip at the free end (P_A) and the maximum force achieved during the pull-out operation (P_S) is measured. Testing is complete when the prestressing reinforcement fractures, the concrete splits, or there is reinforcement slippage without reinforcement force increase.

3.3. Transmission and anchorage lengths determination

With the ECADA test method, the determination of transmission and anchorage lengths requires testing a series specimens with different embedment lengths. After the specimens have been tested, both the transmission and the anchorage lengths are determined by plotting the measured prestressing reinforcement forces –at the prestress transfer and loading stages– vs the specimen embedment length. Fig. 3 shows an idealization of what these plots look like.

For the transferred prestressing force values (P_T), the curves are expected to present a bilinear trend (see Fig. 3), with an ascendent branch followed by a practically horizontal branch corresponding to the effective prestressing force (P_E, maximum prestressing force value determined by strain compatibility between the prestressing reinforcement and concrete). The transmission length (L_T) corresponds to the specimen embedment length that marks the beginning of the horizontal branch. As shown in Fig. 3, this is the point where $P_T = P_E$.

For the pull-out forces values (P_A and P_S), the curves are expected to show an increasing trend (see Fig. 3). A reference force (P_R) was established to analyze the anchorage behavior. The anchorage length (L_A) corresponds to the shortest embedment length among the tested specimens in which P_R is achieved in the pull-out operation without reinforcement slip at the free end of the specimen, that is, to the first specimen of the series with $P_A \geq P_R$. The anchorage length with slip (L_S) corresponds to the shortest embedment length of the test specimens in which P_R is achieved in the pull-out operation, that is, to the first specimen of the series with $P_S \geq P_R$.

3.4. Bond stress determination

Based on the uniform bond stress distribution hypothesis which is generally accepted by several Codes [2,33,34] and authors [7,37,38], the average bond stress values are obtained by balancing the prestressing reinforcement force with the resultant of induced bond stresses at the different testing stages, as follows:

$$U_T = \frac{P_E}{\left(\frac{4}{3}\pi\phi\right)L_T} \quad (1)$$

$$U_A = \frac{P_A}{\left(\frac{4}{3}\pi\phi\right)L_A} \quad (2)$$

$$U_S = \frac{P_S}{\left(\frac{4}{3}\pi\phi\right)L_S} \quad (3)$$

Where:

U_T = average bond stress along the transmission length

U_A = average bond stress along the anchorage length

U_S = average bond stress along the anchorage length with slip allowed

P_E = effective prestressing force

P_A = maximum force reached during the pull-out operation before reinforcement slippage

P_S = maximum prestressing reinforcement force anchored during the pull-out operation

ϕ = nominal diameter of prestressing reinforcement

L_T = transmission length

L_A = anchorage length

L_S = anchorage length with prestressing reinforcement end slippage

3.5 Program

Twelve concretes mixes with w/c ratios ranging from 0.3 to 0.5, cement contents from 350 to 500 kg/m^3 and compressive strength at the age of testing f_{ci} from 24 to 55 MPa have been tested. This range was selected as representative of most of the cases in precast prestressed concrete industry, as pointed out by the companies partaking in this study and according with the Spanish code provisions [39] for prestress transfer (concrete stress after prestress transfer must not exceed 0.6f_{ci}). Concrete components were: cement CEM I 52.5 R [40], crushed limestone aggregate 7/12 mm, washed rolled limestone sand 0/4 mm and a polycarboxylic ether-based high range water reducer. All concrete mixes were designed with a constant gravel/sand ratio of 1.14.

The prestressing reinforcement used was low-relaxation, seven-wire steel strand of 13 mm nominal diameter. The strand had a guaranteed ultimate strength 1860 MPa, specified as UNE 36094:97 Y 1860 S7 13.0 [10]. The manufacturer provided the following main characteristics: diameter 12.9 mm, section 99.69 mm^2, nominal strength 192.60 kN, yield stress at 0.2% 177.50 kN, and modulus of elasticity 196.70 GPa.

The testing parameters were:

- Specimens were 100 x 100 mm^2 cross-sectioned (to avoid splitting failure) with a centered prestressing strand.
- Prestressing strands were tested in as-received conditions, free of rust and free of lubricant, and were not treated in any special way.
- The strand prestress level was of 75 percent of specified strand strength (maximum level of prestress according to the Spanish code provisions [39] for pretensioning).
- All specimens were subjected to the same consolidation and curing conditions, and they were conserved under laboratory conditions.
- The release was performed 24 hours after concreting gradually at a controlled speed of 0.80 kN/s (to simulate the gradual release method as used by the companies partaking in this study).
- The loading stage was also gradually performed after the stabilization period (2 hours in this study).
- Series of embedment lengths followed increments of 50 mm.
- For the anchorage analysis, the pull-out loading was performed to achieve a reference force (P_R) of 158 kN which was established as representative in this experimental study of the force that can be applied to the strand before failure.
- The anchorage length (L_A) was assumed for a strand slip of 0.1 mm.

Some aspects of the experimental study are shown in Fig. 4: a specimen when casting (a), a general view of the prestressing frames (b) and some series of tested specimens (c).

4. TEST RESULTS AND DISCUSSION

For each specimen, the prestress transfer and the pull-out operations performed by means of the ECADA test method have been carried out sequentially following the same sequence of operations in all cases. For each concrete mix, transmission length (L_T) and anchorage lengths (L_A and L_S) have been determined from a series made up of 6 to 12 specimens with different embedment lengths.

Table 1 provides the main results for all the concrete mix designs, including concrete compressive strength at the age of testing, tested specimen embedment lengths, measured prestressing strand forces and obtained lengths. The effective prestressing force P_E is the average value of the force in the prestressing strand in those specimens with an embedment length equal to or longer than the transmission length obtained by the ECADA test method for each concrete mix design after the stabilization period. P_A and P_S values are the measured values in the corresponding specimens.

As observed in Table 1, L_T values range from 400 to 650 mm, L_A from 600 to 850 mm, and L_S from 300 to 700 mm. As reference values, transmission and anchorage lengths calculated according to the 12-4 equation of ACI 318-11 [2] are provided. They are 810 mm –for effective prestressing force of 130.8 kN, the average value for the analyzed concretes– and 1320 mm –for 158 kN, the P_R–, respectively. These values do not depend on concrete properties [2]. A reference value for L_S is not available, because this length constitutes a new concept and there is no equation for it in literature. Calculated lengths overestimate experimental values between 125% and 200% in the case of L_T and between 155% to 220% in the case of L_A.

As observed in Table 1, and according to the transmission and anchorage length definitions, all L_A values are greater than the corresponding L_T. However, it is worth noting that almost all L_S values are shorter than the corresponding L_T, and the difference between them is bigger when concrete compressive strength is higher. This proves that higher bond stresses can be achieved from the mechanical action exerted by developing strand end slip. In addition, obtained L_A values prove to be dependent on concrete properties and composition, and it is remarkable that they are lower than the provided values according to ACI 318-11 [2]. An overestimation of the measured anchorage lengths by ACI 318-11 provisions has also been detected in other experimental studies [13,21].

Several studies have addressed the influence of parameters like concrete compressive strength, strand diameter or bond strength. Some predictive equations to obtain the transmission and anchorage lengths have been proposed [3,19]. However, no equations involving concrete mix design parameters, such as w/c ratio or cement content are found in previous literature. It was not the objective of this study to come to a new design equation, but only to assess the influence of concrete composition on anchorage lengths.

The parameters w/c ratio, cement content, and concrete compressive strength have been considered as separate parameters in the analyses carried out. These parameters are correlated and they therefore constitute a multi-variable system, as can be observed in Fig. 5. The obtained concrete compressive strengths for all concrete mixes are being related with w/c ratio (Fig. 5a) and cement content (Fig. 5b). As expected, concrete compressive strength decreases when w/c ratio increases. The slopes of the curves appear to be comparable in Fig. 5a. However, in Fig. 5b it appears different tendencies based on different free water contents remaining in concrete after casting. It is worth noting that these correlations do not necessarily implies that the effects of concrete compressive strength, w/c ratio, and cement content on anchorage bond behavior are also correlated or follow the same trends. This justifies to perform separate analyses for each parameter.

The results of transmission length were presented and analyzed in [17]. The following sections provide the discussion of the two modes of anchorage length. In addition, as the transmission length is also part of the anchorage length, some analyses regarding the whole of results and their relations are also included.

4.1. Influence of concrete compressive strength

Fig. 6 shows the results of the anchorage length (L_A) vs concrete compressive strength at the age of testing f_{ci}. The anchorage length decreases when f_{ci} increases. The results are fitted to the linear tendency according to Eq. (6) with a R^2 = 0.50.

$$L_A = 922.2(w/c) - 5f_c \tag{6}$$

Fig. 7 provides the results of anchorage length with slip (L_S) vs concrete compressive strength. It is observed that the higher concrete compressive strength is, the lower the L_S values obtained. The results are fitted to a linear tendency according to Eq. (7) with a R^2 = 0.68.

$$L_A = 843(w/c) - 7.8f_c \tag{7}$$

4.2. Influence of w/c ratio

Fig. 8 shows the results of anchorage length (L_A) vs w/c ratio. It is observed that the greater the w/c ratio, the greater the anchorage length obtained. The results are fitted to the linear trend according to Eq. (4) with a coefficient of correlation (R^2) of 0.41.

$$L_A = 916.2(w/c) + 307.8 \qquad (4)$$

Fig. 9 provides the results of anchorage length with slip (L_S) vs w/c ratio. It is observed that anchorage length with slip is greater for greater w/c ratio. Scatter of results tends to increase when w/c ratio increases. The results are fitted to the linear trend according to Eq. (5) with a R^2 = 0.53.

$$L_S = 1041(w/c) - 101.2 \qquad (5)$$

4.3. Influence of cement content

Fig. 10 provides the results of the anchorage length (L_A) vs the cement content used in each concrete mix design. It can be observed that L_A depends as much on cement content as on w/c ratio. If the w/c ratio is high (0.50), L_A strongly increases when cement content increases; if the w/c ratio is medium (0.45-0.40), L_A slightly increases when cement content increases; and if the w/c ratio is low (0.35-0.30), L_A does not vary irrespectively of cement content increases. Finally, it is observed that L_A for concretes with 350 kg/ m^3 cement content practically does not vary, irrespectively of w/c ratio.

Fig. 11 shows the results of the anchorage length with slip (L_S) vs the cement content used in each concrete mix design. The tendencies observed are similar to those observed for L_A: they depend as much on cement content as on w/c ratio, except for concretes with 350 kg/ m^3 cement content, whose L_S values practically coincide, irrespectively of the w/c ratio. For the rest of the concrete mix designs, L_S strongly increases when cement content increases and the w/c ratio is high (0.50); for the other w/c ratios (medium or low, 0.45-0.30), L_S slightly increases when cement content increases.

These tendencies for both L_A and L_S values agree with [28] when the w/c ratio is high: if cement content increases, bond capacity decreases, and the anchorage length increases. The influence of w/c ratios seems to be clear in concretes with high cement content and less obvious when cement content is low. It can be explained by the fact that free water remaining in concrete increases with the cement content, and then the influence of concrete porosity on bond behavior also increases [41]. As this is an effect related to the total free water, w/c ratios are more influent when cement content is high.

The obtained coefficients of correlation (R^2), which range 0.41 to 0.68 for fitted lines in sections 4.1 and 4.2 are comparable to other studies on bond of prestressing strands by applying simple regression models [42] with R^2 ranging from 0.47 to 0.69. However, from the analysis of influence of cement content, the results reveal different tendencies with respect to w/c ratio and a fitted line has not been added because a general trend has not been observed.

4.4. Bond stresses

From the prestressing strand forces and anchorage lengths (L_A and L_S) measured, average bond stresses (U_A and U_S) along both L_A and L_S have been obtained by using Eqs. (2) and (3), respectively. Figs. 12 and 13 show the obtained bond stresses for each concrete mix design. In addition to transmission length results were analyzed in detail in [17], Figs. 12 and 13 also include the U_A/U_T and U_S/U_T ratios –and their average values– for comparison purposes, where U_T is the average bond stress along the transmission length according to Eq. (1). As it can be observed in both figures, generally for same cement content, an increase in the average bond stress is observed when w/c ratio decreases. For the case of the lower cement content (350 kg/m^3), the average bond stresses appears to be independent of w/c ratios.

U_A/U_T values (Fig. 12) are of de order of 1 –average ratio is 0.96–. However, the U_S/U_T ratio (Fig. 13) ranges from 1.13 to 1.78, with an average value of 1.45. This is because the mechanical action exerted by developing strand slips increases bond strength along L_S (anchorage length with slip) when compared to the bond strength along L_A (anchorage length –without slip–). This contribution can enhance the strength and ductility of pretensioned members by improving their bond strength at the end zones after anchorage failure according to L_A occurs.

The effects of concrete compressive strength (f_{ci}) on the average bond stresses U_A and U_S are shown in Fig. 14. It can be observed that both U_A and U_S values increase when concrete compressive strength increases. For the same increase in f_{ci}, U_S improvement is greater than U_A improvement. In this way, the U_S/U_A ratio also increases when f_{ci} increases. From test results, U_S/U_A ratios ranging from 1.15 to 1.93 with an average value of 1.52 have been obtained.

In this experimental study for the bond characterization of 13 mm prestressing steel strands, the loading stage was performed 2 hours after the prestress transfer stage. This fact implies that the concrete compressive strength at loading coincides with f_{ci}. For [f_c (at loading)] > [f_{ci} (at prestress transfer)], U_A and U_S values can be expected to be above the obtained values in this study and to have the same tendencies. In order to obtain equations for design with 95% confidence intervals, additional experimental works on transmission and anchorage lengths should be conducted.

5. CONCLUSIONS

The research program reported herein has analyzed the anchorage bond behavior and has determined the anchorage lengths of pretensioned prestressed concrete specimens in two modes: anchorage length (L_A) –without slip– and anchorage length with slip and (L_S), and their corresponding average bond stresses U_A and U_S. From twelve concrete mixes, with different cement contents and water/cement (w/c) ratios, specimens containing 13-mm seven-wire prestressing steel strand were tested using the ECADA test method. The main conclusions drawn from this experimental study are as follows:

- L_S values are shorter than the corresponding transmission length L_T values, mainly when concrete compressive strength is higher. This proves that higher bond stresses can be achieved due to the mechanical action exerted by the development of strand end slip.
- Anchorage lengths L_A and L_S decrease when concrete compressive strength at the age of testing increases. However, this fact is not considered in the current ACI 318 Code provisions, which are conservative when the results obtained in this study are taken into account.

- Anchorage lengths L_A and L_S increase when w/c ratio increases, more significantly when cement content is higher.
- The effect of cement content reveals different tendencies with respect to w/c ratio:
  - When cement content increases, L_A strongly increases if w/c ratio is high (0.50), slightly increases if w/c ratio is medium (0.45-0.40), and does not vary if w/c ratio is low (0.35).
  - When cement content increases, L_S strongly increases if w/c ratio is high (0.50), and slightly increases if w/c ratio is medium or low (0.45-0.35).
  - For low cement content (350 kg/ m^3), L_A and L_S practically do not vary irrespectively of the w/c ratio.
- Except for low cement content (350 kg/m^3), an increase in the average bond stresses U_A and U_S is observed for same cement content when w/c ratio decreases.
- U_A and U_S as well as U_S/U_A ratios increase when concrete compressive strength at the age of testing increases.
- U_S/U_T values range from 1.13 to 1.78, with an average value of 1.45. This is because the mechanical action exerted by developing strand slips increases bond strength along L_S (anchorage length with slip) when compared to the bond strength along L_A (anchorage length –without slip–). This contribution can enhance the strength and ductility of pretensioned members by means a potential bond capacity at the end zones after anchorage failure according to L_A occurs.

New results directly related to the influence of concrete composition on anchorage bond behavior of prestressing reinforcement have been presented in this paper. The conclusions obtained have pointed out that other aspects in addition to concrete strength can affect bond phenomena in pretensioned concrete. Regarding the reasons for the observed behavior, further researches should be addressed including experimental techniques to characterize concrete immediately surrounding the reinforcement-concrete interface.

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REFERENCES

[1] FIB. Bond of reinforcement in concrete. Bulletin d'information nº 10. Lausanne: Fédération Internationale du Béton; 2000.

[2] ACI Committee 318. Building code requirements for reinforced concrete (ACI 318-11). Farmington Hills, MI: American Concrete Institute; 2011.

[3] Martí-Vargas JR, Serna P, Navarro-Gregori J, Pallarés L. Bond of 13 mm prestressing steel strands in pretensioned concrete members. Eng Struct 2012;41:403-412.

[4] Rose DR, Russell BW. Investigation of standardized tests to measure the bond performance of prestressing strand. PCI J 1997;42:56-80.

[5] Moustafa S. Pull-out strength of strand and lifting loops. Technical Bulletin 74-B5. Washington: Concrete Technology Corporation; 1974.

[6] Baran E, Akis T, Yesilmen S. Pull-out behavior of prestressing strands in steel fiber reinforced concrete. Constr Build Mater 2012;28:362-371.

[7] Hegger J, Bülte S, Kommer B. Structural behavior of prestressed beams made with self-consolidating concrete. PCI J 2007;52(4):34-42.

[8] Martí-Vargas JR, Arbeláez CA, Serna-Ros P, Castro-Bugallo C. Reliability of transfer length estimation from strand end slip. ACI Struct J 2007;104(4):487-494.

[9] Russell BW, Burns NH. Measured transfer lengths of 0.5 and 0.6 in. strands in pretensioned concrete. PCI J 1996;41:44-65.

[10] AENOR. UNE 36094:1997 Alambres y cordones de acero para armaduras de hormigón pretensado. Madrid: AENOR; 1997.

[11] ASTM. A416/A416M-10 Standard specification for steel strand, uncoated seven-wire for prestressed concrete. West Conshohocken, PA: American Society for Testing and Materials; 2010.

[12] Martí-Vargas JR, Serna-Ros P, Fernández-Prada MA, Miguel-Sosa PF, Arbeláez CA. Test method for determination of the transmission and anchorage lengths in prestressed reinforcement. Mag Concr Res 2006;58:21-29.

[13] Martí-Vargas JR, Arbeláez CA, Serna-Ros P, Fernández-Prada, MA, Miguel-Sosa PF. Transfer and development lengths of concentrically prestressed concrete. PCI J 2006;51(5):74-85.

[14] Martí-Vargas JR, Serna-Ros P, Arbeláez CA, Rigueira-Victor JW. Bond behaviour of self-compacting concrete in transmission and anchorage. Mater Constr 2006;56(284):27-42.

[15] Caro LA, Martí-Vargas JR, Serna P. Time-dependent evolution of strand transfer length in pretensioned prestressed concrete members. Mech Time-Depend Mater 2012. http://dx.doi.org/10.1007/s11043-012-9200-2.

[16] Caro LA, Martí-Vargas JR, Serna P. Prestress losses evaluation in prestressed concrete prismatic specimens. Eng Struct 2013;48:704-715.

[17] Martí-Vargas JR, Serna P, Navarro-Gregori J, Bonet JL. Effects of concrete composition on transmission length of prestressing strands. Constr Build Mater 2012;27:350-356.

[18] Briere V, Harries KA, Kasan J, Hager Ch. Dilation behavior of seven-wire prestressing strand – The Hoyer effect. Constr Build Mater 2013;40:650-658.

[19] Floyd RW, Howland MB, Hale WM. Evaluation of strand bond equations for prestressed members cast with self-consolidating concrete. Eng Struct 2011;33:2879-2887.

[20] Shahawy M, Moussa I, Batchelor B. Strand transfer lengths in full scale AASHTO prestressed concrete girders. PCI J 1992;37:84-96.

[21] Mitchell D, Cook WD, Khan AA, Tham Th. Influence of high strength concrete on transfer and development length of pretensioning strand. PCI J 1993;23:52–66.

[22] Martí-Vargas JR, Hale WM. Predicting strand transfer length in pretensioned concrete: Eurocode versus North American practice, ASCE J Bridge Eng 2013. http://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000456 .

[23] Mahmoud ZI, Rizkalla SH, Zaghloul ER. Transfer and development lengths of carbon fiber reinforcement polymers prestressing reinforcing. ACI Struct J 1999;96:594-602.

[24] Ramirez JA, Russell BW. Transfer, development, and splice length for strand/reinforcement in high-strength concrete. NCHRP Report 603. Washington DC: National Cooperative Highway Research Program, Transportation Research Board; 2008.

[25] Gustavson R. Experimental studies of the bond response of three-wire strands and some influencing parameters. Mater Struct 2004;37:96-106.

[26] Lorrain M, Khelafi H. Contribution a l'etude de l'endommagement de la liaison armature-beton de haute performance. Mater Struct 1989;22:127-138.

[27] Fu X, Chung DDL. Improving the bond strength between steel rebar and

concrete by increasing the water/cement ratio. Cem Concr Res 1997;27:1805-1809.

[28] Król M, Szerafin J. Dynamics of bond development in permanently compressed concrete. In: Bond in concrete: from research to practice. Riga: Ed. Riga Technical University and CEB; 1992, p. 2.47-2.57.

[29] Sfikas IP, Trezos KG. Effect of composition variations on bond properties of self-compacting concrete specimens. Constr Build Mater 2013;41:252-262.

[30] Pop I, Schutter G, Desnerck P, Onet T. Bond between powder type self-compacting concrete and steel reinforcement. Constr Build Mater 2013;41:824-833.

[31] Hegger J, Bertram G. Verbundverhalten von vorgespannten litzen in UHPC. Beton- und Stahlbetonbau 2012;107(1):23-31.

[32] Buckner CD. A review of strand development length for pretensioned concrete members. PCI J 1995;40:84-105.

[33] CEN. European standard EN 1992-1-1:2004:E: Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. Brussels: Comité Européen de Normalisation; 2004.

[34] FIB. Model Code 2010. First complete draft - Volume 1." Fib Bulletin nº55. Lausanne: Fédération Internationale du Béton; 2010.

[35] Martí-Vargas JR, Serna P, WM Hale. Strand bond performance in prestressed concrete accounting for bond slip. Eng Struct 2013;51:236-244.

[36] Martí-Vargas JR, Caro LA, Serna P. Experimental technique for measuring the long-term transfer length in prestressed concrete. Strain 2013;49:125-134.

[37] Pozolo A, Andrawes B. Analytical prediction of transfer length in prestressed self-consolidating concrete girders using pull-out test results. Constr Build Mater 2011;25:1026-1036.

[38] Martí-Vargas JR, Arbeláez CA, Serna-Ros P, Navarro-Gregori J, Pallarés-Rubio L. Analytical model for transfer length prediction of 13 mm prestressing strand. Struct Eng Mech 2007;26:211-229.

[39] Ministerio de Fomento. Instrucción de hormigón estructural (EHE-08). Madrid: Ministerio de Fomento; 2008.

[40] CEN. European standard EN 197-1:2000: Cement. Part 1: Compositions, specifications and conformity criteria for common cements. Brussels: Comité Européen de Normalisation; 2000.

[41] Fu X, Chung DDL. Effects of water-cement ratio, curing age, silica fume, polymer admixtures, steel surface treatments, and corrosion on bond between concrete and steel reinforcing bars. ACI Mat J 1998;95(6):725-734.

[42] Kose MM, Burkett, WR. Formulation of new development length equation for 0.6 in. prestressing strand. PCI J 2005;50(5):96-105.