Martí Vargas, JR.; Serna Ros, P.; Navarro Gregori, J.; Bonet Senach, JL. (2012). Effects of concrete composition on transmission length of prestressing strands. Construction and Building Materials. 27(1):350-356. doi:10.1016/j.conbuildmat.2011.07.038.

Effects of concrete composition on transmission length of prestressing strands

J.R. Martí-Vargas*, P. Serna, J. Navarro-Gregori, J.L. Bonet
ICITECH, Institute of Concrete Science and Technology
Universitat Politècnica de València, 4G, Camino de Vera s/n, 46022, Valencia, Spain
e-mail: jrmarti@cst.upv.es; pserna@cst.upv.es; juanagre@cst.upv.es; jlbonet@cst.upv.es
*Corresponding author: Tel.: +34 96 3877007 (ext. 75612); Fax: +34 96 3877569;
e-mail address: jrmarti@cst.upv.es (José R. Martí-Vargas)

ABSTRACT:

The bond behaviour of prestressing strands in precast pretensioned concrete members, and its transmission length, depends on several factors. However, no consensus exists on the main parameters to be considered in the expressions to predict the transmission length. Usually when the concrete properties are considered, only the concrete compressive strength is included. This study analyzes the influence of concrete composition made up of different cement contents and water/cement ratios on the bond behaviour in transmission of seven-wire prestressing strands. The bond properties and the transmission lengths have been determined. The results show that the influence of the water/cement ratio is very small for concretes with lows cement contents, but the influence of the water/cement ratio on the transmission lengths is highly significant when cement content is high. The effect of cement content in the transmission lengths can reveal different tendencies based on the level of the water/cement ratio.

KEYWORDS:

bond, concrete, cement, transmission, transfer, reinforcement, strand, precast, pretensioned

1. INTRODUCTION

The manufacturing process of pretensioned concrete members consists of three stages: first the prestressing reinforcement is tensioned; next, the concrete member is cast around the prestressing reinforcement; and finally, the prestressing reinforcement is released, and the prestressing force is transferred to the concrete by bond. After this, the force in the reinforcement will vary from a zero value at the ends of the member to a constant maximum (effective prestressing force) in the central zone (Fig. 1). Transmission length (L_T) is defined as the distance required to develop the effective prestressing force in the prestressing reinforcement [1,2].

The transmission length estimation is important in the design exercise [3]. According to the codes [1,2], transmission length must be experimentally determined, and different methodologies have been proposed (for example strand pullout test, strand slip, concrete strain [4]). Although a considerable amount of experimental research has been carried out, no consensus exists on a standard test method for bond properties determination [2]. Recently, an experimental methodology (the ECADA[1] test method) based on the measurement and the analysis of the force supported by the reinforcement in specimen series with different embedment lengths, has been conceived [5], and its feasibility has been verified [6].

The industry of precast prestressed concrete members aims to obtain products in the shortest possible time. For this reason, an early age usually fixed by the concrete compressive strength

---

[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".

is required at prestress transfer. However, some authors and code provisions for transmission length propose expressions in which concrete properties are not a parameter [1,7-10]. Only the concrete compressive strength is included when concrete properties are considered [2,11-17].

Several authors [3,11,12,15-17] conclude that the concrete strength at prestress transfer has a clear influence on the transmission length. For other authors [18] the influence of concrete strength on the transmission length obtained was found no systematic. Furthermore, [19] indicates that the influence of the concrete compressive strength on the bond capacity of strands is not clear.

The cement content and the water/cement (w/c) ratio are important parameters of the concrete mix design. Nevertheless, few studies [20-24] have been undertaken regarding their influence on the bond properties. [20,21] conclude that the bond strength decreases when the w/c ratio increases, and also a bond improvement has been found [22] when the w/c ratio increases. On the other hand, greater bond strength to a larger cement content has been found in [20,21], whereas the authors in [23,24] concluded that an increased cement content produces a diminution of bond strength. Therefore, additional knowledge about the bond behaviour of prestressed reinforcement is required to better design exercise in precast pretensioned concrete members.

In this paper, an experimental study to analyze the influence of the concrete composition of concretes made with varying cement contents and with different water/cement ratios on the bond behaviour in transmission of seven-wire prestressing strands is presented.

2. EXPERIMENTAL STUDIES

2.1. Test procedure

The test method used (ECADA test method) is based on the measurement and analysis of the force supported by the prestressing reinforcement in pretensioned concrete members with different embedment lengths [5]. For this purpose, specimens with different embedment lengths (the embedment length is a test variable) were prepared in prestressing frames 2000 mm in length, like that shown in Fig. 2. The experimental setup includes an anchorage-measurement and access system (AMA system) at one of its ends (stressed end). The AMA system has been designed to guarantee the anchorage of the prestressing reinforcement at the stressed end, simulating the sectional rigidity of the concrete specimen. The force supported by the prestressing reinforcement is controlled at all times during the test by means of a hollow force transducer HBM C6A located in the AMA system. An adjustable anchorage is placed at the opposite end (free end) of the prestressing frame to facilitate the tensioning and to release operations of the prestressing reinforcement. A hollow hydraulic jack of 300 kN of capacity completes the test equipment.

A detailed description of the ECADA test method is included in [5]. The test procedure can be summarized as follows:

Preparation stage:

- Alignment of the reinforcement in the prestressing frame.
- Reinforcement tensioning.

- Anchoring the reinforcement by the adjustable anchorage; the hydraulic jack is relieved.
- Casting the specimen: the concrete is mixed, placed into the moulds of each frame, and consolidated; the specimens remain under the selected conservation conditions until the time of testing.

Testing stage:

- Release: the hydraulic jack is remounted on the free end and the adjustable anchorage is removed; the hydraulic jack is unloaded, triggering the transfer of the prestressing force to the concrete.
- Stabilization: after a stabilization period (two hours in this study), the loss of force supported by the reinforcement after release (ΔP) is measured (see Fig. 3).

Although it is not included in this study, the test can continue with a pull-out operation of the reinforcement from the stressed end to analyze the anchorage length.

2.2. Transmission length determination

For each transmission length determination a series of specimens with a variable embedment length are casted and tested with the ECADA test method.

Fig. 3 shows an example of a specimen test result; the evolution of the force applied by the hydraulic jack and that supported by the prestressing reinforcement over time. The represented force in the reinforcement corresponds to the variation of force registered during the testing stage (release and stabilization). The force loss ΔP depends on the specimen embedment length.

If the embedment length of a specimen is greater than the transmission length, the force loss ΔP is perceptibly constant and independent of the embedment length. In these cases, the force loss is due to the compatibility of strains between the concrete and prestressing reinforcement, and the prestressing force which transferred P_T coincides with the effective prestressing force.

If the specimen embedment length is lesser than the transmission length, the force loss ΔP noted in the reinforcement at the AMA system after the stabilization period includes bond failure effects. This loss will be greater when the specimen embedment length is lower. The prestressing force transferred to the concrete P_T will be lower than the effective prestressing force.

The transmission length can be determined with the ECADA test method by attempting series specimens with different embedment lengths and by classifying the individual results of each test (ΔP) according to the embedment length.

The transmission length is determined as the shortest specimen embedment length in that it reaches the minimum value of ΔP of the series (Fig. 4). The resolution in the determination of the transmission length depends on the sequence of the specimen embedment lengths tested. The feasibility and the reliability of the test method have been verified in [5,6].

2.3. Bond stress determination

The average bond stress (U_T) developed along the transmission length characterizes the prestress transfer phenomenon, and is expressed by Eq. (1):

$$U_T = \frac{P_T}{\frac{4}{3}\pi\phi L_T} \qquad (1)$$

Where U_T is the average bond stress (MPa), P_T is the prestressing force transferred (N), L_T is the transmission length (mm), and ϕ is the nominal diameter of prestressing strand (mm).

2.4 Test programme

Four families of concrete were analyzed. Each family was characterized by its cement content (350, 400, 450 and 500 kg/m^3) and was composed of concretes with different w/c ratios (between 0.3 and 0.5). All concretes were designed with a constant gravel/sand ratio of 1.14. The additive was dosed for the purpose of obtaining a consistency adapted for the manufacture of the specimens. A total of twelve concrete mix designs were manufactured. Table 1 shows the analyzed mix designs with a range of concrete compressive strength (f_{ci}) at the time of release (24 hours from concreting) from 24 to 55 MPa. This range has been established as representative of the precast prestressed concrete industry according with the requirements of the collaborating companies in this study and according with the Spanish code provisions [25] for prestress transfer (concrete stress after prestress transfer must not exceed 0.6 f_{ci}). Table 1 also includes the tested embedment lengths for each concrete mix design.

The materials used for the manufacture of concretes were: cement was an ordinary portland cement type “CEM I 52.5R” according with the European standard EN 197-1:2000 [26] with a guaranteed 52.5 N/mm^2 strength grade, 7/12 (mm) crushed limestone coarse aggregate, and rolled and washed 0/4 (mm) limestone sand. A polycarboxylic ether-based high range water-reducing admixture (2% of cement content) was included in the mixes.

The prestressing reinforcement was a 13 mm diameter seven-wire prestressing steel strand with a guaranteed 1860 N/mm^2 ultimate strength typified as “Y 1860 S7 13.0” according with the Spanish standard UNE 36094:97 [27]. According to the supplier’s quality certificate, its main specifications were: section, 99.69 mm^2; ultimate load, 192.60 kN; 0.2% elastic limit, 177.50 kN; modulus of elasticity, 196.70 kN/mm^2.

The testing parameters were:

- Specimens were 100 x 100 mm^2 cross-sectioned (to avoid splitting failure) with a concentrically prestressing strand.
- The prestressing strand was tested in the as-received condition, and was 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 [25] for pretensioning).
- 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 used by the collaborating companies in this study).

3. TEST RESULTS AND DISCUSSION

For each concrete mix design, the transmission length is determined from a series of 6 to 12 specimens with different embedment length. As an example of the process of transmission length determination following the criterion of the ECADA test method Fig. 5 shows the loss of force registered, based on the embedment length of each specimen test for the C-350-0.50 concrete. Table 2 provides the results of the transmission lengths and the average value and the standard deviation of the effective prestressing force obtained in specimens with embedment length equal to or greater than the transmission length for all concrete mix designs.

The transmission length has been calculated with the 12-4 equation of ACI 318-08 [1] as a reference value. For an average effective prestressing force of 130.8 kN for the analyzed concretes, a transmission length of 810 mm is obtained (the effect of the standard deviation has been neglected as it is very small). According to the ACI 318-08 [1], this value do not depends on the concrete properties.

Most of the studies analyzing the transmission length are orientated on the influence of parameters like the concrete compressive strength, strand diameter or bond strength. Several studies have proposed predictive formulas to obtain the transmission length [17]. However, there are not found in the literature any expression from transmission length involving the concrete mix design parameters as cement content or w/c ratio. It was not the objective of this study to found a new design formula, but only to point out the influence on the transmission length of the concrete composition. To this end, linear regression analyses were performed taking as singles variables parameters the concrete dosage or strength.

3.1. Influence of the w/c ratio

Fig. 6 illustrates the results of transmission length based on the w/c ratio. It is observed that the greater the w/c ratio, the greater the transmission lengths obtained. The results adjust to a linear tendency according to Eq. (1) with a $R^2 = 0.63$. The obtained tendency agrees with [20,21], as opposed to [22].

$$L_T = 860.6(w/c) + 184.5 \tag{2}$$

3.2. Influence of the concrete strength

Fig. 7 shows the results of the transmission length based on the concrete compressive strength at testing time f_{ci}. The transmission length decreases when f_{ci} increases. The results adjust to a linear tendency according to Eq. (2) with a $R^2 = 0.68$. The obtained tendency agrees with [3,11,12,15-17] (an extensive literature review and comparisons on proposed equations for transmission length of 13 mm prestressing steel strands is available in [17]).

$$L_T = 746.7 - 4.4 f_{ci} \tag{3}$$

3.3. Influence of cement content

Fig. 8 illustrates the results of the transmission length based on the cement content used in each concrete mix design. It is observed that the transmission length is of 550 mm for all concretes with 350 kg of cement by m^3, irrespectively of the w/c ratio. The transmission length for the rest of the concrete mix designs depends as much on the cement content as on the w/c ratio. If the w/c ratio is high, the transmission length increases when the cement content increases; if the w/c ratio is low, it diminishes when the cement content increases.

These tendencies agree with [20,21] when the w/c ratio is low (if the cement content increases, the bond capacity increases, and the transmission length decreases), and with [23,24] when the w/c ratio is high (if the cement content increases, the bond capacity decreases, and the transmission length increases).

3.4. Influence of water content

Fig. 9 shows the variations of the transmission length based on the effective water content of the concrete. A general tendency is that the transmission length increases when the water content increases. An important increase of the transmission length is detected for concretes with highly effective water contents (200 l/m^3). When the effective water content is very low (140 l/m^3), transmission lengths greater than which would correspond to the general tendency are noted. It is likely that this is owing to the fact that in the compaction conditions used, that is, in those concrete mix design with water content that are so adjusted, the attainment of a correct compaction is hardly evident.

As a consequence a multiple variable effect of the concrete composition parameters is evident. A more complete analysis was performed concerning the bond strength in the next section.

Finally, the fact that the obtained transmission lengths, other than depending on the concrete properties and composition, they are lower than the transmission length obtained according to ACI 318-08 [1] can be emphasized. An overestimation of the measured transmission lengths by ACI 318-08 provisions also has been detected in several experimental studies [4,15,28].

3.5. Bond stress

Fig. 10 illustrates the average bond stress values in transmission of the analyzed concretes obtained according to Eq. (1). In order to obtain this value for each concrete mix design, the effective prestressing force considered is the average value of results of the prestressing force transferred on those specimens whose embedment length is equal to or greater than the transmission length. For same cement content, a reduction in the average bond stress is observed when the w/c ratio increases.

The influence of the w/c ratios seems to be clear in concretes with high cement content and less obvious when cement content is low. It must be explained by considering that the remaining free water in concrete increases as the cement content, and then the concrete porosity influencing the bond behavior also increases. As this is an effect related with the total free water, the w/c ratios is more influent when cement content is high.

Fig. 11 shows the average bond stress values in transmission based on the concrete compressive strength f_{ci}. When f_{ci} increases, an increase of the average bond stress in the transmission takes place. This tendency can be explained with greater clarity if the combined effect of the concrete strength and the cement content is analyzed. Thus, a linear slope tendency is evaluated differently when the results corresponding to concretes with fixed cement content in the mix are analyzed separately. Table 3 shows the expressions of the obtained lines of tendency for each cement contents.

Once an interaction between the composition variables was detected, in order to consider the influence of this interaction, a linear multiple regression analysis on the experimental results was performed. It is evident that cement and water content are not independent with the w/c ratio or compressive strength. That is why we selected as independent parameters the cement content (C, kg/m^3) and the concrete compressive strength (f_{ci}, MPa) as they are the best known parameters when casting and producing concrete. To include the interaction effect in the study an additional parameter ($C \cdot f_{ci}$) was considered. The obtained expression is show in Eq. (4). A $R^2 = 0.87$ was found that demonstrates a very good correlation.

$$U_T = \frac{0.43Cf_{ci} - 144f_{ci} - 20C}{1000} + 11.08 \tag{4}$$

The validity of Eq. (4) has been verified for 13 mm prestressing strand by comparing its predictions with the experimental results of different researchers available in the scientific literature (Fig. 12). The selection of the results to be included in the comparison was conditioned to the availability of the data necessary to calculate the average bond stress (transmission length, effective prestressing force, cement content and concrete strength), and that the test conditions (i.e. strand diameter, prestress level, gradual release) were similar to those of this study.

Fig. 12 presents the results of the tests performed by each author for each test condition characterized by concrete strength and cement content. The value of the calculated transmission length is obtained from Eq. (1) by taking the result of applying the experimental parameters of each author to Eq. (4) as the average bond stress (U_T).

The specimens that were tested in similar conditions to those of this study were seen to fit to the theoretical value, as in the case of the tests in [15] -2A and 2B-. The discrepancies in the results correspond to different test conditions. Thus, the slow or gradual release of rough strands are shown for lesser transmission lengths than for the theoretical transmission length [29] -1A- and [30] -4A and 4B-, whereas the smooth strands with a sudden release present greater transmission lengths [8] -3C and 3D-.

6. CONCLUSIONS

The conclusions from this study are as follows:

- The increases in the w/c ratios, particularly if they are obtained with high water contents, along with the logical reduction in concrete strength, entail a clear increase of the transmission lengths.
- For concretes with low cement contents (350 kg/m^3), the influence of the w/c ratio is very small, and the transmission lengths are practically constant. However, if the cement content is

high (500 kg/m^3), the influence of the w/c ratio in the transmission lengths is highly significant.

- The variations in the cement content for constant w/c ratios show different tendencies based on the level of the w/c ratio at which it works. If the w/c ratio is high, an increase in the cement content leads to increases in the transmission lengths; for a low w/c ratio however, an increase in the cement content entails a reduction of the transmission length.
- The application of the provisions to determine the transmission length according to ACI 318-08 is conservative for the results obtained in this study.
- A relationship between the average bond stress in transmission (U_T), and the variables cement content (C) and concrete compressive strength at release (f_{ci}), has been found.
- The validity of this obtained expression has been verified by comparing its predictions with the experimental results of different authors. A good adjustment for the tests performed in similar conditions to those of this study has been found. It has, however, been observed that the superficial conditions of the prestressing strand or varying release methods can cause significant variations in the transmission length values.

ACKNOWLEDGEMENTS

The content of this article forms a part of research that the Universitat Politècnica de València’s Institute of Concrete Science and Technology (ICITECH) is presently conducting in conjunction with PREVALESA and ISOCRON. This study was funded by the Ministry of Education and Science and ERDF (Project BIA2006-05521). The authors wish to thank the above companies as well as the concrete structures laboratory technicians at the Universitat

Politècnica de València for their cooperation. Also, the authors wish to pay their respects to C.A. Arbeláez.

REFERENCES

[1] ACI Committee 318. Building code requirements for reinforced concrete (ACI 318-08). Farmington Hills (MI): American Concrete Institute; 2008.

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

[3] Barnes RW, Grove JW, Burns NH. Experimental assessment of factors affecting transfer length. ACI Struct J 2003;100:740-748.

[4] Shing PB, Cooke DE, Frangopol DM, Leonard MA, McMullen ML, Hutter W. Strand development and transfer length tests on high performance concrete box girders. PCI J 2000;45:96-109.

[5] 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.

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

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

[8] Deatherage JH, Burdette E, Chew ChK. Development length and lateral spacing requirements of prestressing strand for prestressed concrete bridge girders. PCI J 1994;39:70-83.

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

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

[11] Olesniewicz A. Statistical evaluation of transmission length of strand. Varsaw: BISTYP; 1975.

[12] Zia P, Mostafa T. Development length of prestressing strands. PCI J 1977;22:54-65.

[13] Bruggeling ASG, Huyghe GF. Prefabrication with Concrete. Netherlands: Ed. A.A. Balkema/Rotterdam/Brookfield; 1991.

[14] Balázs G. Transfer control of prestressing strands. PCI J 1992;37:60-71.

[15] 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.

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

[17] 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.

[18] Kaar PH, LaFraugh RW, Mass MA. Influence of concrete strength on strand transfer length. PCI J 1963;8:47-67.

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

[20] Armstrong WEI. Bond in prestressed concrete. Civil Eng J 1949;33:19-40.

[21] 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.

[22] 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.

[23] Tulin LG, Al-Chalabi M. Bond strength as a function of strand tension and cement paste content for lightweight aggregate concrete. ACI J 1969;66:840-848.

[24] 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. 5.62-5.67.

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

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

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

[28] 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.

[29] Holmberg A, Lindgren S. Anchorage and prestress transmission. Stockholm: National Swedish Building Research; 1970.

[30] Uijl JAd. Transfer length of prestressing strands in HPC. Progr Concr Res 1996;4:75–90.