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Analytical model for transfer length prediction of 13 mm prestressing strand

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Abstract. An experimental investigation to determine the transfer length of a seven-wire prestressing strand in different concretes is presented in this paper. A testing technique based on the analysis of bond behaviour by means of measuring the force supported by the prestressing strand on a series of specimens with different embedment lengths has been used. An analytical bond model to calculate the transfer length from an inelastic bond stress distribution along the transfer length has been obtained. A relationship between the plastic bond stress for transfer length and the concrete compressive strength at the time of prestress transfer has been found. An equation to predict the average and both the lower bound and the upper bound values of transfer length is proposed. The experimental results have not only been compared with the theoretical prediction from proposed equations in the literature, but also with experimental results obtained by several researchers.

Keywords: bond; concrete; pretensioning; prestress; transfer length; strand; model.

1. Introduction

The behaviour of the pretensioned concrete members depends on the bond mechanism between the strand and the surrounding concrete. The prestressing force in the strand is transferred to the concrete by bond in the prestress transfer operation. At this moment, in the end region of the member the stress in the strand varies from zero at the free end to a maximum value (effective stress) along the distance defined as transfer length (ACI 2005).

The accuracy of the transfer length estimation is important in the design exercise (Russell and Burns 1996, Barnes *et al.* 2003). Several theoretical and experimental research works on bond and transfer length of prestressing strands have been conducted over the years. Bond strength as well as transfer length depend on several factors (CEB 1987, FIB 2000) such as concrete strength at the time of prestress transfer, initial stress of the strand, concrete cover, condition of prestress transfer

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process, strand geometry, strand surface condition, etc. However, there is no consensus on the main parameters to be considered in the equations to calculate the transfer length (Martí 2003). An example of such is the ACI Code 318-05 (ACI 2005) provisions for transfer length which are not a function of concrete strength. On the other hand, the CEB-FIP Model Code 1990 (CEB-FIP 1990) and the Eurocode 2 (CEN 2004) provisions for transfer length consider the concrete properties.

Two methods to experimentally determine the transfer length have been habitually used (Thorsen 1956): measuring the superficial strains of the concrete or measuring the strand end slip. The application of sophisticated measurement procedures that do not disturb the bond phenomena such as the radiographic technique (Evans and Robinson 1955), photoelasticity (Linger and Bhonsle 1963), contact electrical resistivity (Fu and Chung 1998) or ultrasound (Chen and Wissawapaisal 2001), have not been developed sufficiently. Recently, an experimental methodology (ECADA test method) based on the measurement and the analysis of the force supported by the strand in specimen series with different embedment lengths has been conceived (Martí-Vargas *et al.* 2006).

The purpose of this research study is to develop an analytical bond model to predict the transfer length of 13 mm prestressing strand. To this end, an experimental program to determine the average bond stress along the transfer length in twelve concretes of different compositions and properties by means of the ECADA test method has been set up. The experimental results have been compared with other theoretical and experimental researches from the literature.

2. Previous research

Bond stresses along the transfer length are induced by the relative strand slips to the concrete cross sections (Balazs 1993). For prestressing strands, three bond mechanisms can be distinguished (FIB 2000): adhesion, friction and mechanical action. The adhesion is destroyed when a very small slip occurs. Then the friction mechanism and the mechanical action are activated and frictional bond stresses are developed which are caused by the radial compressive stresses around the prestressing strand. These radial compressive stresses are the response of the surrounding concrete to the displacement of the prestressing strand when a slip occurs. Several effects contribute to radial compressive stresses (Den Uijl 1998, FIB 2000).

When the adhesion is destroyed, the transferred bond force is small compared to the prestressing force. As a consequence, the bond of prestressing strand can mainly be adscribed to friction (Den Uijl 1998). Janney (1954) was one of the pioneers in the research of bond characterisation and its relation with the transfer length of prestressing strands. The results obtained by Janney (1954) showed an inelastic response of the surrounding concrete with a radial microcracking along almost the entire transfer length. On the other hand, Guyon (1953) indicates that the hypothesis of uniform bond stress distribution along the transfer zone (inelastic bond behaviour) is an unattainable limit since a portion in the transfer zone that will behave in an elastic way will always exist. Recent research has stated an inelastic response for more than 90% of the transfer length (Barnes *et al.* 2003).

The hypothesis of uniform bond stress distribution along the transfer length has been assumed by several Codes and authors (ACI 2005, CEB-FIP 1990, CEN 2004, Mitchell *et al.* 1993, Mahmoud *et al.* 1999). For the equilibrium of a strand, the transfer bond force over the transfer length must be equal to the force in the prestressing strand

$$U_{t,av} P_p L_t = f_p A_p \tag{1}$$

where

$U_{t,av}$= average bond stress along the transfer length
P_p = perimeter of prestressing strand
L_t = transfer length
f_p = effective stress in prestressing strand
A_p = cross-sectional area of prestressing strand

The current ACI Code provisions on transfer length first appeared in the ACI Code 318-63 (ACI 1963) and were derived from Eq. (1) using (Tabatabai and Dickson 1993)

$U_{t,av}$ = 2.76 MPa
P_p = $4\pi d_b/3$ (d_b is the nominal diameter of prestressing strand)
A_p = $0.725\pi d_b^2/4$
f_p = f_{pe} (effective stress in prestressing strand after allowance of all prestress losses)

resulting in

$$L_t = \frac{f_{pe} d_b}{21} \tag{2}$$

This equation has remained to date in the ACI Code 318-05 (ACI 2005) in spite of a considerable number of proposed modifications which consider concrete strength (Zia and Mostafa 1977, Nijhawam 1978, Mitchell *et al.* 1993, Mahmoud *et al.* 1999). In addition, several authors consider that the use of the term f_{pi} (initial stress in prestressing strand just after prestress transfer) in Eq. (2) for design purposes rather than f_{pe} is more rational considering that the transfer length is established at the release of prestress and does not significantly change with time (Buckner 1995, Shahawy 2001).

An analytical bond model to calculate the transfer length by adopting both plastic and elastic zones along the transfer length was proposed by Cousins *et al.* (1990). This model was also applied by Brearley and Johnston (1990) and Nanni *et al.* (1992), and it is based on the following assumptions

a) The bond stress will be considered proportional to the slip for small slips of the strand relative to the concrete. This region will be called the elastic zone.

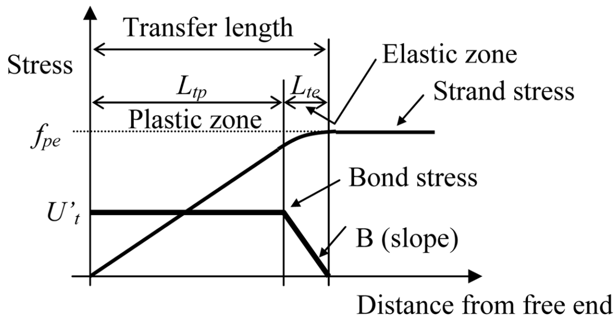

Fig. 1 Bond model for transfer length (Cousins *et al.* 1990)

b) The bond stress maintains a maximum or yield value from the elastic zone to the end of the member. This region will be called the plastic zone.

Fig. 1 shows the variation of both the strand stress and bond stress along the transfer length proposed in this elasto-plastic bond model. The equation proposed by Cousins *et al.* (1990) to predict the transfer length is

$$L_t = L_{tp} + L_{te} = \frac{f_{pe}A_p}{\pi d_b U_t} + 0.5\left(\frac{U_t}{B}\right) \tag{3}$$

where

L_{tp} = length of the plastic zone of transfer length
L_{te} = length of the elastic zone of transfer length
U_t = plastic transfer bond stress
B = bond modulus (slope of bond stress curve in the elastic zone)

In accordance with ACI Code 318-05 (ACI 2005), transfer length appears to be independent of the concrete compressive strength in Eq. (3). However, some early research works on bond observed that transfer length decreased when concrete strength increased (Ratz *et al.* 1958, Zia and Mostafa 1977). Others researchers also indicate that transfer bond stress is proportional to the square root of the concrete compressive strength (Olesniewicz 1975, Nanni *et al.* 1992, Mitchell *et al.* 1993, Barnes *et al.* 2003).

The effect of concrete strength was considered by Cousins *et al.* (1990) by redefining U_t as

$$U_t = U_t' \sqrt{f_{ci}'} \tag{4}$$

where f_{ci}' is the concrete compressive strength at the time of prestress transfer, and U_t' is a plastic transfer bond stress parameter. Eq. (3) can be rewritten as follows

$$L_t = L_{tp} + L_{te} = \frac{f_{pe}A_p}{\pi d_b U_t' \sqrt{f_{ci}'}} + 0.5\left(\frac{U_t' \sqrt{f_{ci}'}}{B}\right) \tag{5}$$

Several equations to predict the transfer length have been proposed by several Codes and researchers from experimental results and theoretical studies. Various equations consider the concrete compressive strength to predict transfer length, and anothers are proposed variants of the ACI provisions. Table 1 shows some of these equations for prestressing steel strands. The equations appear in both their original form and the parametric form according to the structure of Eq. (6).

$$L_t = \frac{f_{px}^n A_p}{(k_1 \pi d_b) U_t} + k_2 \tag{6}$$

The additional notation that appears in Table 1 is

f_{pu} = ultimate tensile strength of prestressing strand
f_{pt} = stress in prestressing strand at the time of tensioning
f_{cci}' = cube compressive strength of concrete at the time of prestress transfer
f_{ctdi} = design tensile strength of concrete at the time of prestress transfer
d_w = nominal diameter of one of the outer wires of a prestressing strand

Table 1 Proposed equations for transfer length from the literature

Reference	Equation number	Equation	$L_t = \frac{f_{px}^n A_p}{(k_1 \pi d_b) U_t} + k_2$ (in MPa and in mm units) (6)				
			f_{px}	n	U_t	k_1	k_2
ACI 1963 ACI 2005	(2)	$L_t = \frac{f_{pe} d_b}{21}$	f_{pe}	1	2.76	4/3	--
Olesniewicz 1975	(7)	$L_t = \Psi d_b \sqrt{\frac{f_{pi}}{f'_{cci}}}$ $\Psi = 10$ for the average value	f_{pi}	0.5	$0.015\ f'^{0.5}_{cci}$	4/3	--
Zia and Mostafa 1977 (sudden release)	(8)	$L_t = 1.5 \frac{f_{pi} d_b}{f'_{ci}} + 117$	f_{pi}	1	$0.097 f'_{ci}$	4/3	117
Zia and Mostafa 1977 (gradual release)	(9)	$L_t = 1.3 \frac{f_{pi} d_b}{f'_{ci}} + 58$	f_{pi}	1	$0.112 f'_{ci}$	4/3	58
Nijhawam 1978	(10)	$L_t = 0.69 \frac{f_{pi} d_b}{f'_{ci}} + 262$	f_{pi}	1	$0.212 f'_{ci}$	4/3	262
Cousins *et al.* 1990	(5)	$L_t = \frac{f_{pe} A_p}{\pi d_b U'_t \sqrt{f'_{ci}}} + 0.5 \frac{U'_t \sqrt{f_{ci}}}{B}$ $A_p/\pi d_b = d_b/4$ for uncoated strands $U_t' = 0.556$ and $B = 0.0815$ MPa/mm	f_{pe}	1	$0.556 f'^{0.5}_{ci}$	1	$3.4 f'^{0.5}_{ci}$
CEN 1991	(11)	$L_t = \beta_b d_b$ $\beta_b = 75 - (f'_{ci} - 25)$ (in Mpa)	--	--	--	--	--
Bruggeling and Huyghe 1991	(12)	$L_t = \frac{7}{12} d_w \frac{f_{pi}}{0.13 f'_{cci}}$ $d_w = 0.33 d_b$ for 12.7 mm 7-wire strand	f_{pi}	1	$0.099\ f'_{cci}$	4/3	--
Balazs 1992	(13)	$L_t = 3.15 d_b \sqrt[5]{\frac{f_{pe}^3}{f'^2_{ci}}}$	f_{pe}	0.6	$0.046 f'^{0.4}_{ci}$	4/3	--

Table 1 Continued

Reference	Equation number	Equation	$L_t = \dfrac{f_{px}^{n} A_p}{(k_1 \pi d_b) U_t} + k_2$ (in MPa and in mm units) (6)				
			f_{px}	n	U_t	k_1	k_2
Shahawy *et al.* 1992 Deatherage *et al.* 1994 Buckner 1995	(14)	$L_t = \dfrac{f_{pe} d_b}{21}$	f_{pi}	1	2.76	4/3	--
Mitchell *et al.*1993	(15)	$L_t = \dfrac{f_{pe} d_b}{21} \sqrt{\dfrac{20.7}{f'_{ci}}}$	f_{pi}	1	$0.674\, f_{ci}'^{0.5}$	4/3	--
Tadros and Baishya 1996	(16)	$L_t = \dfrac{(f_{pe}/0.8) d_b}{21}$	$\dfrac{f_{pe}}{0.8}$	1	2.76	4/3	--
Russell and Burns 1996	(17)	$L_t = \dfrac{f_{pe} d_b}{14}$	f_{pe}	1	1.84	4/3	--
Mahmoud *et al.* 1999	(18)	$L_t = \dfrac{f_{pi} d_b}{\alpha_t f_{ci}'^{0.67}}$ $\alpha_t = 2.4$ for steel strands	f_{pi}	1	$0.350\, f_{ci}'^{0.67}$	4/3	--
CEB-FIB 1990	(19)	$L_t = \alpha_8 \alpha_9 \alpha_{10} \dfrac{A_p}{\pi d_b} \dfrac{f_{pi}}{\eta_{p1} \eta_{p2} f_{ctdi}}$ for 7-wire strands $A_p/\pi d_b = 7d_b/36$ α_8, α_9 and α_{10} account for sudden or gradual release, stress condition and surface condition η_{p1} and η_{p2} account for the tendon type and the tendon position during concreting	f_{pi}	1	$\left(\dfrac{\eta_{p1}\eta_{p2}}{\alpha_8 \alpha_9 \alpha_{10}}\right) f_{ctdi}$ for $\alpha_8 = 1$ (gradual release) $\alpha_9 = 0.75$, $\alpha_{10} = 0.5$, $\eta_{p1} = 1.2$, and $\eta_{p2} = 1$ $3.2 f_{ctdi}$ if sudden release ($\alpha_8 = 1.25$) $2.56 f_{ctdi}$	1	--
CEN 2004	(20)	$L_t = \alpha_1 \alpha_2 d_b \dfrac{f_{pi}}{\eta_{p1} \eta_1 f_{ctdi}}$ α_1 account for sudden or gradual release α_2 is a tendon area factor (for 7-wire strands $\alpha_2 d_b = 7d_b/36$) η_{p1} and η_1 account for the tendon type and the bond conditions	f_{pi}	1	$\left(\dfrac{\eta_{p1}\eta_1}{\alpha_1}\right) f_{ctdi}$ for $\alpha_1 = 1$ (gradual release), $\eta_{p1} = 3.2$, and $\eta_1 = 1$ $3.2 f_{ctdi}$ if sudden release ($\alpha_1 = 1.25$) $2.56 f_{ctdi}$	1	--

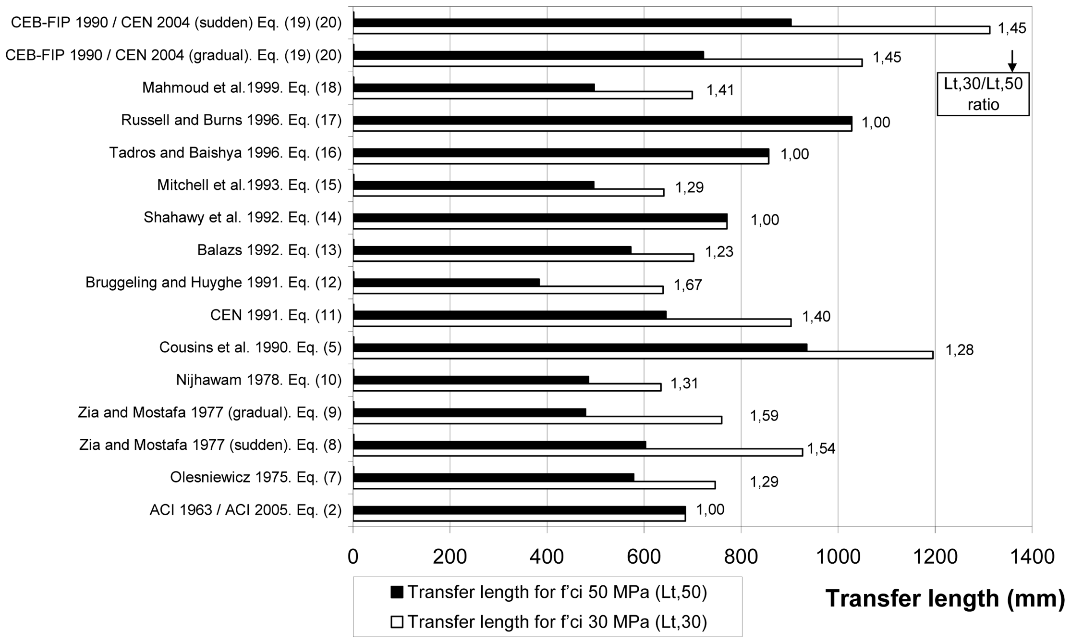

Fig. 2 Graphical comparison between the predicted transfer lengths from several equations in the literature

In order to calculate U_t as a function of concrete strength, the values for today's prestressing strand of $A_p = 0.779\pi d_b^2/4$ and $k_1 = 4/3$ have been considered when they have not been explicitly specified in the equations (Tabatabai and Dickson 1993, Russell and Burns 1996). In addition, U_t = 2.76 MPa for ACI Code 318-05 (ACI 2005) provisions and their variants has been considered, and U_t = 1.84 MPa for Eq. (17) has been adopted by applying a proportional relation between Eqs. (2) and (17).

As it can be observed in Table 1, Eq. (19) (CEB-FIP 1990, MC90) and Eq. (20) (CEN 2004) coincide in their final result, although they do not present the same form. The value α_9 = 0.75 is not explicitly featured in the MC90, but has been introduced by the authors from α_9 = 0.5 and α_9 = 1, established in MC90 for the lower bound and the upper bound values of transfer length, respectively.

The predicted transfer length of a 13 mm prestressing strand from the equations in Table 1 are presented in Fig. 2 for concrete compressive strength at the time of prestress transfer f'_{ci}, which is equal to 30 MPa and 50 MPa. The following relationships have been adopted to calculate the transfer length: $f_{pt} = 0.75f_{pu}$ (f_{pu} = 1860 MPa), $f_{pi} = 0.9f_{pt}$, $f_{pe} = 0.8f_{pt}$, $f'_{cci} = 1.25f'_{ci}$ and f_{ctdi} has been obtained according to the gathered prescriptions in Eurocode 2 (CEN 2004). The different equations provide a wide range of predicted values of transfer length. Fig. 2 illustrates the repercussion from the concrete strength f'_{ci} in transfer length determination according to the different equations. When the transfer length is a function of f'_{ci}, an increase in concrete strength reduces transfer length.

The transfer length design value depends on the design situation. A lower transfer length value should be used for verifications of local stresses at prestress transfer, whereas a higher value should be used for ultimate limit states. The transfer length obtained by means of the equations included in Table 1 is an average value, except Eq. (17), which is recommended for use in design applications as a reasonable limit for the higher values of transfer length by Russell and Burns (1996). Table 2

Table 2 Prediction of lower bound and lower bound values of transfer length

Reference	Equation number	Lower bound value	Average value	Upper bound value	Upper/lower ratio
Olesniewicz 1975	(7)	$\Psi = 7$	$\Psi = 10$	$\Psi = 13$	1.9
CEN 1991	(11)	$0.8L_t$	L_t	$1.2L_t$	1.5
Balazs 1992	(13)	$0.79L_t$	L_t	$1.41L_t$	1.8
CEB-FIB 1990	(19)	$\alpha_9 = 0.5$	$\alpha_9 = 0.75$	$\alpha_9 = 1$	2
CEN 2004	(20)	$0.8L_t$	L_t	$1.2L_t$	1.5

includes the cases of predicting both a lower bound and an upper bound value of the transfer length, in addition to the estimation of the average transfer length value.

3. Experimental program

An experimental program to determine the transfer length of prestressing strand in different concretes has been conducted. The ECADA[1] test method (Martí 2003, Martí-Vargas *et al.* 2006) was used. This test methodology is based on measuring and analysing the force supported by the strand in a series of pretensioned concrete specimens with different embedment lengths. Fig. 3 and Fig. 4 show the layout of the test equipment, consisting of a pretensioning frame with an adjustable strand anchorage and an Anchorage-Measurement-Access (AMA) system. The AMA system is placed at the stressed end of the pretensioning frame to simulate the sectional stiffness of the specimen.

3.1 Materials

Tests were carried out on twelve different concretes with a range of water/cement ratios (w/c) from 0.3 to 0.5, cement content (C) from 350 to 500 kg/m^3 and a compressive strength at time of

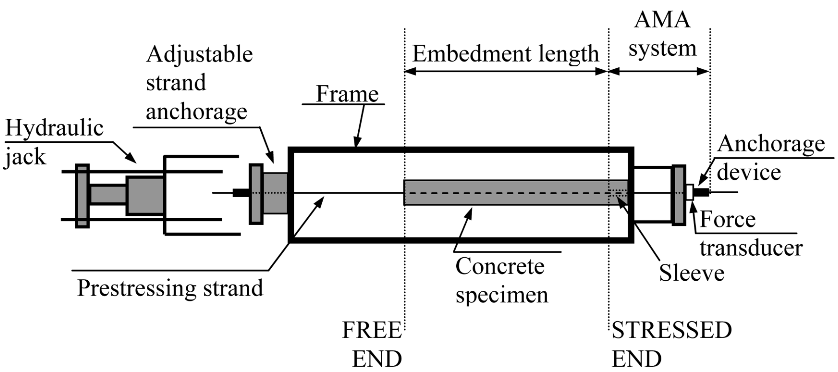

Fig. 3 Test equipment configuration

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

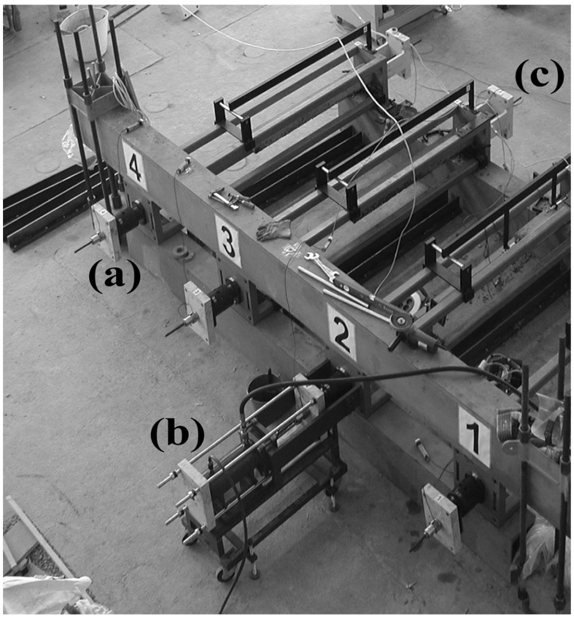

Fig. 4 General view of test equipment. (a) Adjustable strand anchorage, (b) Hydraulic jack, (c) AMA system

Table 3 Concretes mix design from the test program

Designation	Cement (kg/m^3)	*w/c* ratio	Gravel/sand ratio
C350/0.50	350	0.50	1.14
C350/0.45		0.45	
C350/0.40		0.40	
C400/0.50	400	0.50	
C400/0.45		0.45	
C400/0.40		0.40	
C400/0.35		0.35	
C450/0.40	450	0.40	
C450/0.35		0.35	
C500/0.40	500	0.40	
C500/0.35		0.35	
C500/0.30		0.30	

testing f'_{ci} from 24 to 55 Mpa.

The concrete components were: cement CEM I 52.5 R (CEN 2000), crushed limestone aggregate 7/12, washed rolled limestone sand 0/4 and a polycarboxylic ether superplasticiser. The mix design of different tested concretes is shown in Table 3.

The prestressing strand was a low-relaxation seven-wire strand of 13 mm diameter with a guaranteed ultimate strength 1860 MPa, specified as UNE 36094:97 Y 1860 S7 13.0 (AENOR 1997). The main characteristics were taken from the manufacturer: 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 prestressing strand was tested in the as-received condition (free of rust and free of lubricant). The prestressing strand was no treated in any special manner, and it was stored indoor.

3.2 Testing technique

The step-by-step test procedure is explained in detail in Martí (2003) and Martí-Vargas *et al.* (2006), and may be summarised as follows

a) Preparation stage.
1. The strand is placed in the frame.
2. Tensioning of the strand.
3. Anchorage of the strand by an adjustable strand anchorage.
4. The concrete is mixed, placed into the form prepared in the frame, and consolidated.
5. After the concreting, the specimen is cured to achieve the desired concrete properties before the time of testing.

b) Testing stage.
1. The adjustable strand anchorage is relieved using the hydraulic jack.
2. The strand prestress transfer is produced at a controlled speed, and the prestressing force transfer to the concrete is performed. The concrete specimen is supported at the stressed end of the frame.

c) Stabilisation period.

3.3 Test parameters

The specimens were 100 × 100 mm^2 cross section with a concentrical single strand (as received) at a prestress level of 75 percent of nominal ultimate strand strength. All specimens were subjected to the same consolidation and curing conditions. The prestress transfer was gradually performed 24 hours after concreting, and a 2-hour stabilisation period from the prestress transfer was established.

3.4 Instrumentation

The instrumentation used was
- A hydraulic jack pressure sensor to control the tensioning and the prestress transfer operations.
- A hollow force transducer to measure the force supported by the strand at all times during the test.

3.5 Criterion to determine transfer length

With the ECADA test method, the transfer length is determined by testing a series of specimens with different embedment lengths and by measuring the force in the strand at the stressed end during both the prestress transfer process and stabilisation period.

The transferred prestressing force values are ordered according to the specimen embedment length. The obtained curves present a bilinear tendency, with an ascendent initial branch and a practically horizontal branch. The transfer length corresponds to the smaller specimen embedment length that marks the beginning of the horizontal branch (Martí-Vargas *et al.* 2006). The resolution in the determination of the transfer length will depend on the sequence of specimens lengths tested.

4. Results and discussion

4.1 Transfer length determination

For each concrete type, the transfer length is determined from series of specimens of different embedment lengths. Fig. 5 shows the results of transferred prestressing force to the concrete versus the embedment length for some concretes mix design.

Table 4 shows the compressive strength at the time of prestress transfer f'_{ci} for every concrete mix design, the transfer length results and the effective stress in prestressing strand f_{pi}. This effective stress is the average value of the strand stress on specimens with embedment length equal to or greater than the transfer length obtained by the ECADA test method for each concrete mix design after the stabilisation period. An increase in the concrete compressive strength at the time of prestress transfer f'_{ci} results in a decrease of the transfer length, as shown in Table 4.

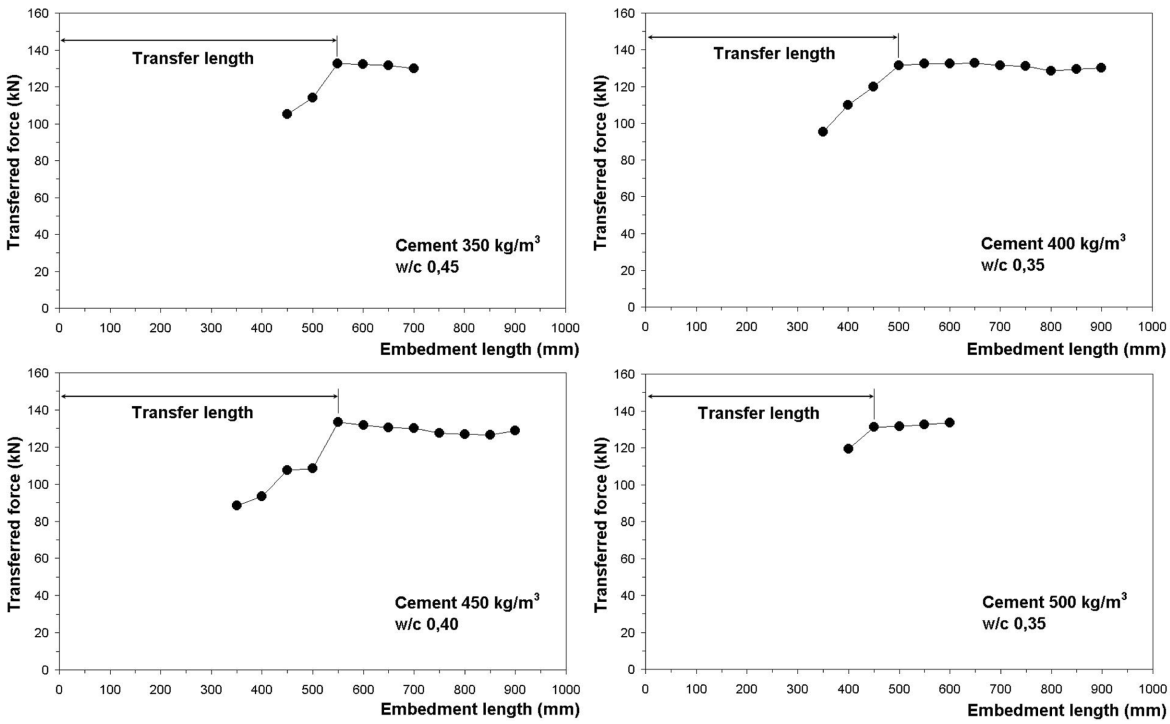

Fig. 5 Test results for some concretes mix design

Table 4 Transfer length test results

Designation	f'_{ci} (MPa)	Transfer length (mm)	f_{pi} (MPa)
C350/0.50	26.1	550	1326
C350/0.45	37.3	550	1316
C350/0.40	46.7	550	1328
C400/0.50	24.2	650	1303
C400/0.45	28.3	550	1337
C400/0.40	41.4	550	1317
C400/0.35	45.3	500	1311
C450/0.40	36.3	550	1299
C450/0.35	46.6	500	1299
C500/0.40	30.8	600	1322
C500/0.35	46.6	450	1290
C500/0.30	54.8	400	1295

4.2 Proposed analytical bond model for transfer length

In the elasto-plastic bond model of Cousins *et al.* (1990), the plastic transfer bond stress U_t can be obtained from the slope of the lineal branch in the strand stress versus distance from free end curve, and the bond modulus B is U_t/L_{te}, where it is necessary to know the elastic zone of transfer length L_{te}. In practice it is difficult to know this curve with accuracy. This is due to the fact that a direct measurement of stress in the strand disturbs bond phenomena.

In order to determine the transfer length, U_t and B, the longitudinal strain on the outside surface of the concrete method was used through gage points (Cousins *et al.* 1990). However, the derivation

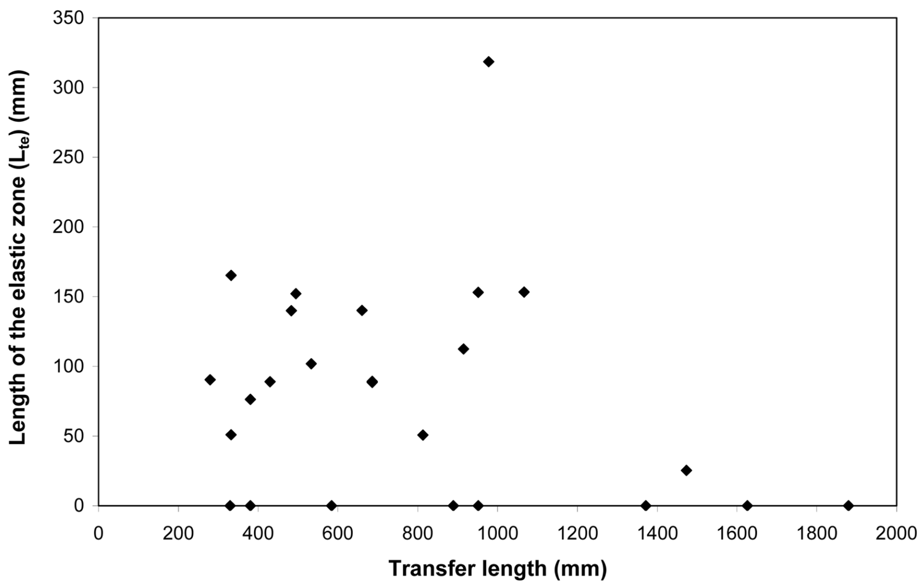

Fig. 6 Length of the elastic zone of transfer length (results from Cousins *et al.* 1990)

of the transfer length from this method presents two difficulties (Den Uijl 1998). Firstly, these strains indicate the length over which the prestressing force is built up and linearly distributed across the concrete section, rather than the transfer length. Secondly, it is difficult to define the exact point where all the prestress has just become present. Consequently, the determination of the elastic zone of transfer length L_{te} is affected by these two difficulties.

Fig. 6 illustrates the elastic zone of transfer length versus the transfer length from the experimental results of Cousins *et al.* (1990). A wide range of the elastic zone of transfer length values between 0 and 318 mm is observed. In some cases, the elastic zone of transfer length was not detected.

An elastic zone included in the transfer length has not been observed in the results of the tests made with the ECADA test method. The variation of the transferred prestressing force with the embedment length is practically linear (see Fig. 5), as detected by Bruggeling and Huyghe (1991) for the case of strands, which corresponds with a uniform distribution of the bond stress (exclusive inelastic response).

The analytical bond model following the structure of the Eq. (6) that is proposed considers an inelastic bond behaviour, where the transfer length is obtained as

$$L_t = \frac{f_{pi}A_p}{(4/3)\pi d_b U_{t,av}} \tag{21}$$

As a generalisation of Eq. (4), the effect of the concrete strength on the average bond stress along the transfer length $U_{t,av}$ may be illustrated redefining $U_{t,av}$ as

$$U_{t,av} = U_t'(f_{ci}')^{\alpha} \tag{22}$$

In order to determine the plastic transfer bond stress parameter U_t' and the appropiate α exponent from the measured transfer lengths in this study, several regression analyses of the test results have

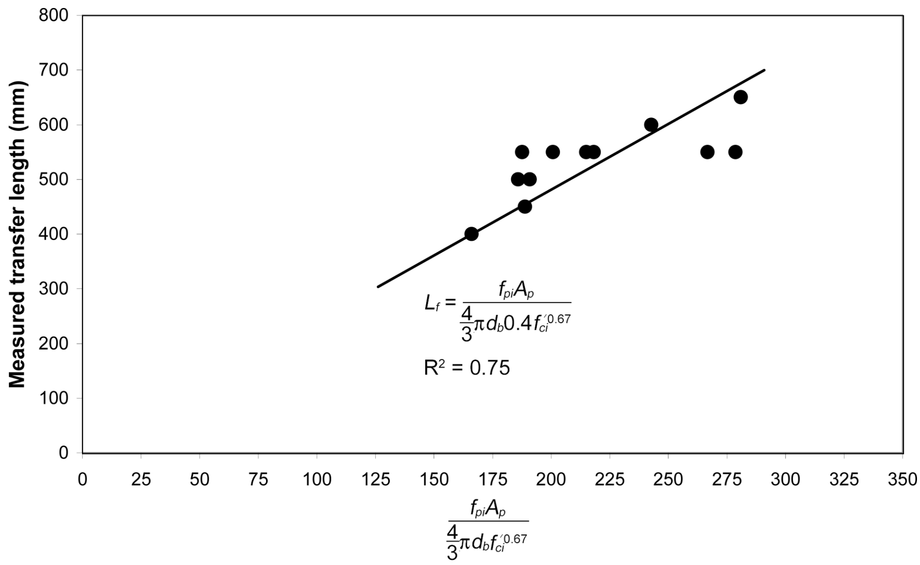

Fig. 7 Transfer length regression analysis based on test results

been made by substituting $U_{t,av}$ in Eq. (21) by Eq. (22). Several values of α among 0 and 1 (0.15, 0.25, 0.4, 0.5, 0.67, 0.7, 0.725, 0.75, 0.775, 0.8 and 1) have been considered. $\alpha = 0.67$ and $U_t' = 0.4$ are the best adjustment obtained by regression analyses (Fig. 7). Therefore, the proposed equation for transfer length for the test results of this study is

$$L_t = \frac{f_{pi} A_p}{(4/3)\pi d_b 0.4 f_{ci}'^{\,0.67}} \tag{23}$$

4.3 Comparison with experimental transfer lengths from other researchers

Some researchers have reported experimental transfer length results in similar test conditions to this study: nominal strength of the strand (1860 MPa), diameter of the strand (from 12.5 to 13 mm) and prestress level (70 to 80% of the nominal strength). Table 5 summarises these results, and Fig. 8 shows the measured transfer length versus the concrete compressive strength at the time of prestress transfer for these research works. Table 5 and Fig. 8 also include the test results of this study.

It can be observed that the range of concrete strength f_{ci}' of the concretes mix design analysed in this study covers the wide range of concrete compressive strengths used by the rest of researchers (Fig. 8). A tendency of reduction of transfer length when f_{ci}' increases is observed. The range of measured transfer lengths is very ample for a single concrete compressive strength. Furthermore, the range of concrete compressive strength values varies considerably for a single transfer length. The high results of transfer length obtained by Cousins *et al.* (1990) is an anomaly in relation to the test results which may be caused by additional unreported factors.

The application of the proposed Eq. (23) to predict transfer lengths (except those of Cousins *et al.* 1990) shows a good estimation of the average value (Fig. 9): 53.3 percent of the experimental values are greater than the prediction, and 46.7 percent are less. The regression analysis of all test data results in a value of $U_t' = 0.39$. In addition, both the lower and upper bound values of U_t' have been obtained for 95 percent and 5 percent of the experimental values, resulting in $U_{t0.95}' = 0.26$ and

Table 5 Test results from several researchers

Reference	Number of tests	Reported transfer lengths (mm)			$L_{t,\max}/L_{t,\min}$ ratio
		Minimum ($L_{t,\min}$)	Average	Maximum ($L_{t,\max}$)	
Cousins *et al.* 1990	20	813	1262	1880	2.3
Deatherage *et al.* 1994	16	457	602	914	2.0
den Uijl 1995	8	297	436	608	2.0
Dorsten *et al.* 1984	8	533	683	864	1.6
Holmberg and Lindgren 1970	4	318	502	673	2.1
Mitchell *et al.* 1993	14	330	499	710	2.2
Mahmoud *et al.* 1999	8	350	469	600	1.7
Oh and Kim 2000	36	434	606	898	2.1
Rose and Russell 1997	30	213	392	714	3.4
Russell and Burns 1996	34	406	748	1118	2.8
Shahawy *et al.* 1992	12	749	765	813	1.1
Test results	12	400	533	650	1.6

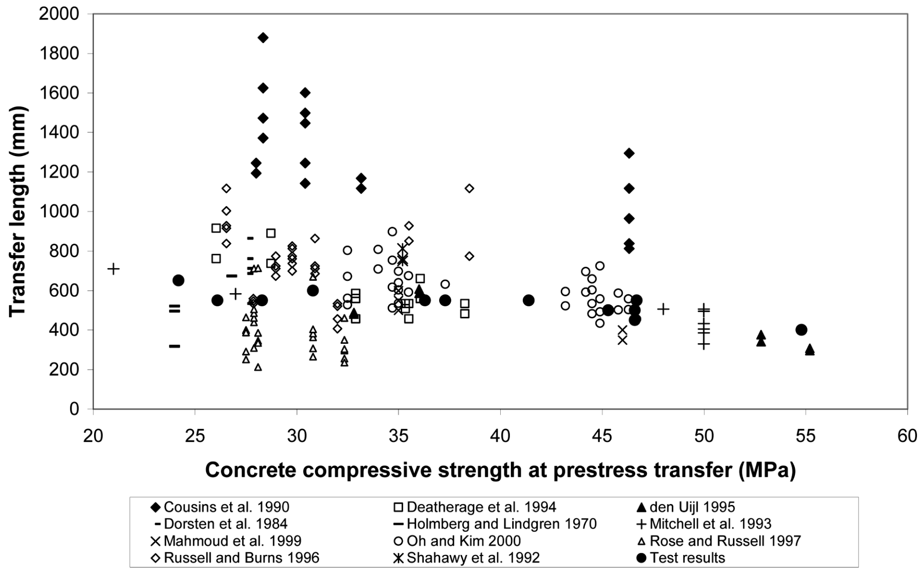

Fig. 8 Measured transfer length versus concrete strength by several researchers

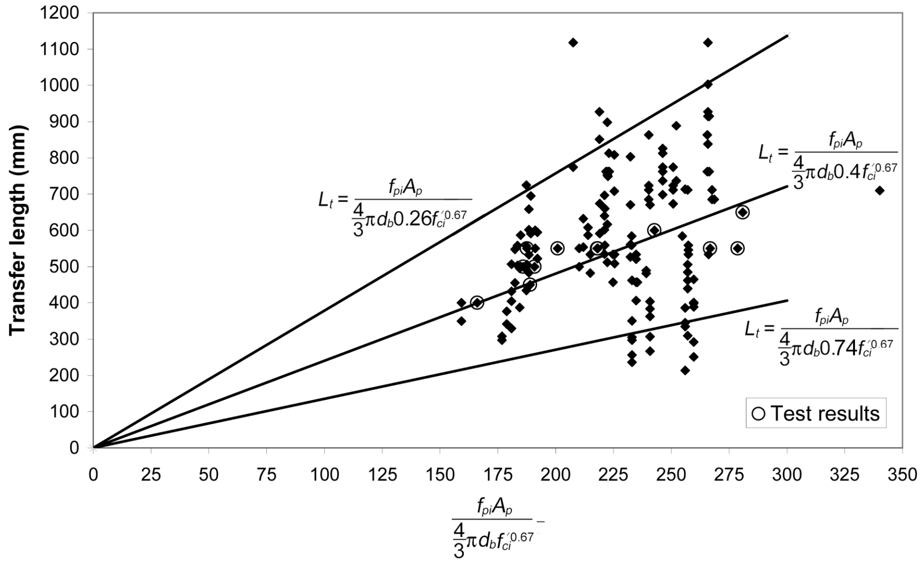

Fig. 9 Transfer length regression analyses based on several researchers' results

$U'_{t0.05} = 0.74$, respectively.

Therefore, the proposed equation for transfer length of 13 mm prestressing strand can be expressed as

$$L_t = \lambda \frac{f_{pi} A_p}{(4/3)\pi d_b 0.4 f_{ci}'^{\,0.67}} \tag{24}$$

where
λ = 1 for the average value of transfer length
λ = 0.5 for the lower bound value of transfer length ($U_t'/U_{t0.05}'$ = 0.39/0.74 = 0.53)
λ = 1.5 for the upper bound value of transfer length ($U_t'/U_{t0.95}'$ = 0.39/0.26 = 1.50)

By susbstituting $A_p = 0.779\pi d_b^2/4$ and d_b = 12.9 mm in Eq. (24), this equation can be expressed as

$$L_t = \lambda \frac{4.7 f_{pi}}{f_{ci}'^{\,0.67}} \tag{25}$$

The [upper bound/lower bound] ratio for this study is 1.5/0.5 = 3, greater than that derived by some individual proposed equations in the literature which proposed ratios between 1.5 and 2 (Table 2), although within the [maximum transfer length/minimum transfer length] ratios obtained for some individual experimental transfer lengths results from several researchers with ratios between 1.1 and 3.4 (Table 5).

The obtained value of λ = 1.5 to predict the upper bound value of transfer length coincides with the relationship between the transfer length prediction from the equation proposed by Russell and Burns (1996) and the ACI Code 318-05 provisions (ACI 2005), that is, L_t (Eq. (17))/L_t (Eq. (2)) = 1.5.

4.4 Comparison of test results with others authors and Codes provisions

In Fig. 10, the experimental results obtained in this study have been compared with the theoretical predictions from the equations included in Table 1 and the proposed equation. The minimum,

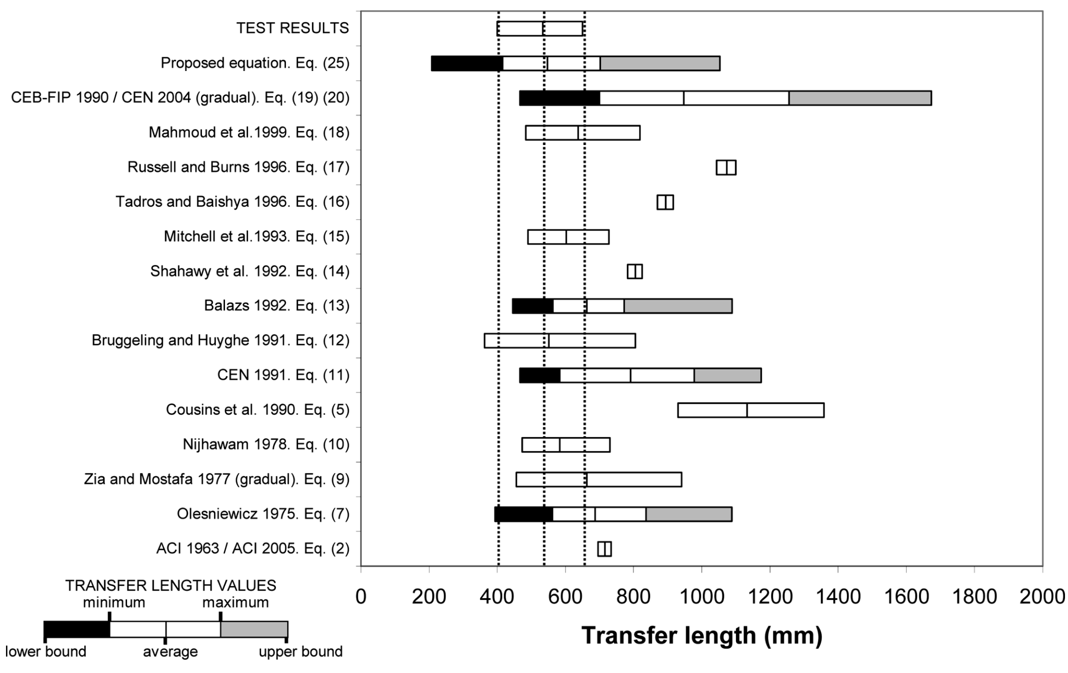

Fig. 10 Prediction of transfer lengths test results from several equations in the literature

average and maximum value of the transfer length obtained by applying the equations to the analysed test condition (f'_{ci} and f_{pi}) have been represented. Moreover, both the lower and upper bound values are illustrated in the prediction from equations with this option. A prestress loss of 20 percent was assumed to obtain f_{pe} (Tabatabai and Dickson 1993), a relationship $f'_{cci} = 1.25 f'_{ci}$ was adopted to calculate transfer length with Eqs. (7) and (12), and f_{ctdi} was obtained according to the gathered prescriptions in Eurocode 2 (CEN 2004) to calculate transfer length with Eqs. (19) and (20).

Fig. 10 illustrates how the predictions give transfer length values which vary considerably and are very different to each other. The prediction of transfer length from the equations in which f'_{ci} is not accounted for (Eqs. (2), (14), (16) and (17)) includes a restricted interval, as it is only influenced by the effective stress in the prestressing strand, which varies slightly among the different concrete mix designs. In addition to the proposed Eq. (25), which evidently predicts the measured transfer lengths well, Eq. (12) also provides a good prediction of the minimum and average transfer lengths measured in this study. Generally, the measured transfer length is overestimated by the remaining equations, with predictions that give transfer length values that more than double the measured transfer lengths (Eqs. (5) and (20)). On the other hand, the Eq. (17) proposed by Russell and Burns (1996) gives a good prediction of the upper bound value of the transfer length derived from the test results according to Eq. (25), as shown above. However, this is not a good prediction with any equation of the lower bound value of the transfer length. Therefore, situations in which a short transfer length is unfavourable are neglected, as are the verifications of local stresses at prestress transfer.

5. Conclusions

The conclusions from this study are as follows

1. An experimental program to analyse the influence of concrete compressive strength on the transfer length of 13 mm prestressing strand has been conducted by means of the ECADA test method.
2. An increase in the concrete compressive strength at the time of prestress transfer results in a decrease of the transfer length.
3. The test results show that the variation of the transferred prestressing force with the embedment length is practically linear, which corresponds to a uniform distribution of the bond stress. An elastic zone in the transfer length has not been observed.
4. An inelastic bond model has been obtained considering the average bond stress along the transfer length ($U_{t,av}$) as a function of the concrete compressive strength at the time of prestress transfer (f'_{ci}) according to the relationship $U_{t,av} = 0.4 f'^{0.67}_{ci}$.
5. With this relationship, the estimation of the transfer length offers a good prediction of the experimental transfer lengths reported by several authors.
6. The following equation is proposed to predict the transfer length of 13 mm prestressing strand

$$L_t = \lambda \frac{4.7 f_{pi}}{f'^{0.67}_{ci}}$$

where $\lambda = 1$ for the average value of transfer length, $\lambda = 0.5$ for the lower bound value of transfer length and $\lambda = 1.5$ for the upper bound value of transfer length.

7. The test results obtained in this study have been compared with the theoretical predictions from different proposed equations by several authors to determine transfer length. The predictions give transfer length values which vary considerably and are very different to each other.
8. Generally, predicted transfer lengths are greater than measured transfer lengths. Therefore, usually it is not had an adequate lower value of transfer length for verifications of local stresses at prestress transfer.

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