APULOT test: a tool for concrete’s quality control based on bond performance

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ABSTRACT: The APULOT test, or bottle test, is a cheap and simple alternative to cylindrical specimens for those regions where conventional quality control is difficult to introduce. By casting concrete into an empty plastic bottle (the mould), bottle-shaped concrete specimens with an embedded rebar are produced. The rebar is simply pulled out of the concrete specimen and bond strength is the outcome used for quality control. It has been investigated how different parameters affect bond strength values in the APULOT test, and their relation to compressive strength of concrete in order to compare the reliability of the bottle test with the conventional quality control strategy by means of cylindrical specimens. The best configuration of the parameters considered for an eventual standardization has been examined, and expressions have been found as a tool to translate bond strength values to concrete compressive strength values that can be monitored.

1 INTRODUCTION

The APULOT test, or bottle test, was first thought of at Université de Toulose and is being developed in co-operation by different universities in Brazil and other countries (Lorrain 2008, do Vale Silva 2010, Lorrain 2010, do Vale Silva 2011, Nguyen 2011).

The APULOT test is carried out on concrete specimens which are produced using a plastic bottle as a mould, the bottom having been cut and removed, and with an embedded reinforcing bar. At the age of control, i.e. 28 days after casting, the rebar is pulled out and the bond strength value obtained is the control parameter. It is therefore a very particular variation of the pull out test. By having the bond strength value obtained to concrete's compressive strength, as shown in Figure 1, the APULOT test can constitute an alternative to cylindrical specimens for concrete's quality control.

This test is proposed as a low-cost and simple alternative to conventional quality control of concrete that can be applied where technical means are not widely available. As a consequence, it can be an easy way of introducing quality control at regions where it is not usually performed because of technical limitations.

2 OBJECTIVES

The main objective of this and other ongoing studies in relation to the APULOT test is to arrive at an acceptable initial proposal susceptible of being standardized as an informative or orientative quality control test for concrete which can be applied extensively to concrete production as well as concrete reception. The research reported herein had two particular goals contributing to the aforementioned general objective.

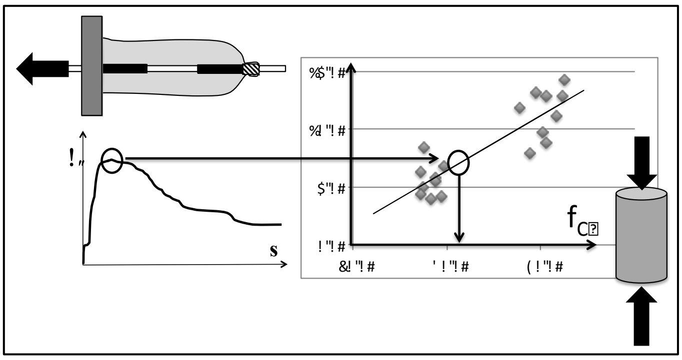

Figure 1. Bond strength as a parameter for concrete's quality control in the APULOT test.

The first particular objective was to analyze how certain variables related to the definition of the test itself affect the test output, i.e. bond strength, and its relation to compressive strength of concrete evaluated by means of cylindrical 150x300mm specimens.

The second particular objective was to study the feasibility of the test as a quality control test for compressive strength of concrete, by assessing the variability of its outcome and comparing it to that of cylindrical specimens data.

3 EXPERIMENTAL PROGRAM

3.1 Variables Considered

The variables considered in the research reported herein as well as their different values are summarized in Table 1. Rebar diameter, state of the rebar surface, and type of bottle are variables related to the definition of the test itself, and their effect on the test outcome is to be analyzed in order to give recommendations concerning how the test is to be performed. In addition, three different mix designs have been considered, i.e. with different w/c ratios, their average compressive strength being used to relate bond strength values obtained from the APULOT test to compressive strength values as evaluated by means of cylindrical specimens.

Table 1. Variables considered in this research.

Variable	Values
Mix design - w/c - f_C	A - 0.46 - 56.5 MPa B - 0.60 - 39.8 MPa C - 0.70 - 28.2 MPa
Rebar diameter	8 mm 10 mm 12 mm
Rebar surface	Clean Corroded Greasy
Bottle mould type	1 2 3

Mix designs considered have been defined with the intention of focusing the analysis on low- and middle-strength concretes. The test is most likely to be useful to monitor production and reception of low-strength concrete. However, the need of extending the research to middle-strength mix designs is justified by the need of knowing what happens when the concrete produced or received is better than initially intended. There is no point in considering higher compressive strengths.

All rebars considered are made with steel type B500SD (in agreement with EN 10080).

No rebar diameters greater than 12 mm have been considered since it was preferable to have radial microcracking controlled and therefore minimizing the likeliness of splitting. As a consequence, the process which determines the peak load required to have the bar pulled out is triaxial compression of concrete between ribs (FIB 2010). This favours a clear relation to be established between bond strength values obtained and compressive strength of concrete. Greater rebar diameters would decrease the cover/diameter ratio, and this would be likely to favour a greater dispersion in the bond strength values.

The variable describing the state of rebar surface has been included because rebars available at construction sites can be found in different states of conservation. Since bond of rebars to concrete may not be the same if rebars are significantly corroded or if their surface is greasy (circumstances modifying friction in the interface between rebar surface and surrounding concrete), the results of the APULOT test may be sensitive to such circumstances.

By means of considering a variable corresponding to the state of rebar surface as in this research, conclusions concerning the effect of corrosion can be drawn by comparing the cases 'corroded' vs 'clean', and also in relation to the effect of the rebar being greasy by comparing the cases 'greasy' vs 'clean'.

3.2 Design of the Experiment

Not all possible combinations of the levels considered for the variables in this research (Table 1) have been tested. The combinations tested are listed in Table 2 and were selected on the statistical basis of Design of Experiments techniques with the help of orthogonal arrays and derived factorial plans (Montgomery 2009). As a consequence, the number of combinations to be tested becomes affordable without affecting the reliability of conclusions to be drawn from the experimental results.

Table 2. Combinations tested.

Id	Mix design	Rebar diameter	Rebar surface	Bottle type
L1	A	8	Clean	1
L2	A	10	Greasy	2
L3	A	12	Corroded	3
L4	B	8	Corroded	2
L5	B	10	Clean	3
L6	B	12	Greasy	1
L7	C	8	Greasy	3
L8	C	10	Corroded	1
L9	C	12	Clean	2

Three batches were produced for each combination, and three bottle specimens and three cylindrical specimens were cast from each batch. That is to say, 9 bottle specimens and 9 cylindrical specimens were produced and tested for each combination. This had two objectives: to make conclusions more reliable, and to have the possibility to better estimate variance values for both bond strength (bottle specimens) and compressive strength (cylindrical specimens) in order to compare their feasibility for quality control of concrete. As a consequence, values of bond strength as obtained from the bottle test as well as compressive strength for each one of the combinations tested are well defined, analyses are carried out on a set of highly reliable data, and the quality of statistical inference to come to conclusions is assured.

3.3 Materials and Mix Designs

Mix designs used are summarized in Table 3. Limestone crushed sand and crushed coarse aggregate were used, and the cement used was class CEM I 42.5R (in agreement with EN 197-1) in all cases. Limestone filler and a high range water reducing admixture were also used, and their amounts were adjusted in each case to have self-compacting mixes.

Table 3. Mix designs used in this research (kg/m^3).

	A	B	C
Cement	420	325	325
Total water	194	195	227
Coarse aggregate (7/12 + 12/20)	721+0	528+348	503+332
Sand	957	977	933
Limestone filler	72	55	55
Superplasticizer	8.8	2.75	1.33

This might seem in contradiction with the circumstances in which the APULOT test is conceived to be applied. However, the objective of this research was to explore how the variables considered affect bond strength values as obtained from the APULOT test and their relation to compressive strength. Since differences regarding the mix compactness might have interfered with the conclusions regarding the effects of the variables considered, it was decided to minimize the risk of having unknown, uncontrolled effects by using only self-compacting mixes.

Obviously, the next step is going to be having the test applied to not self-compacting mixes. Accordingly, recommendations concerning compaction of concrete when poured into the bottle moulds are to be taken into account in future research.

3.4 Definition and Casting of Bottle Specimens

Figure 2 shows the general dimensions of bottle specimens.

At the section where the tap was, the rebar must be fixed as well as possible in order to prevent fresh concrete to escape through the space between the rebar and the plastic bottle at this section, and to have the bar relatively centered along the longitudinal axis of the bottle. To do so, adhesive tape can be used, rolling it around the rebar many times. A length of at least 80 mm of free rebar is recommended.

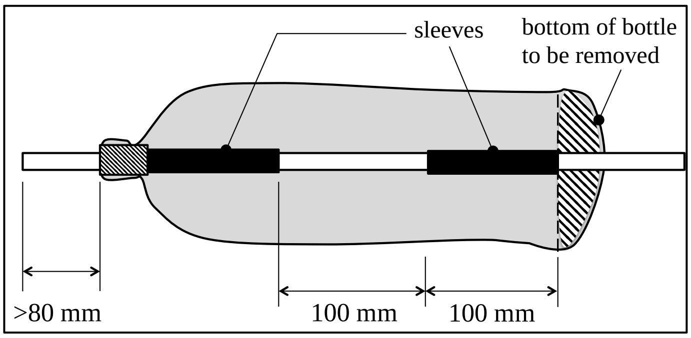

Figure 2. General scheme of a bottle specimen

Sleeves are used as indicated in Figure 2 for different reasons. The main purpose of sleeves is to have the embedded length of the rebar limited at a certain value, in the case of this research it was 100 mm, though other possibilities have been proposed (do Vale Silva 2010), this particular requiring further investigation in the future. Using sleeves is also justified by the need of minimizing the effect of compressive reactions on the bottom of the bottle specimen: the length of this sleeve has been fixed to 100 mm. Finally, a second sleeve is used for the remaining length of the rebar, its purpose being to prevent the development of bond stresses in those sections where concrete cover is highly variable due to the shape of the bottle.

Due to the particularities of the bottle specimens (their shape, their having a rebar), it was necessary to find a setup and methodology for casting the concrete not much sophisticated but which could guarantee the verticality of the bottle during the casting (so that the bottom surface of the bottle specimen was perpendicular to the rebar) and the rebar being positioned along the longitudinal axis of the bottle mould.

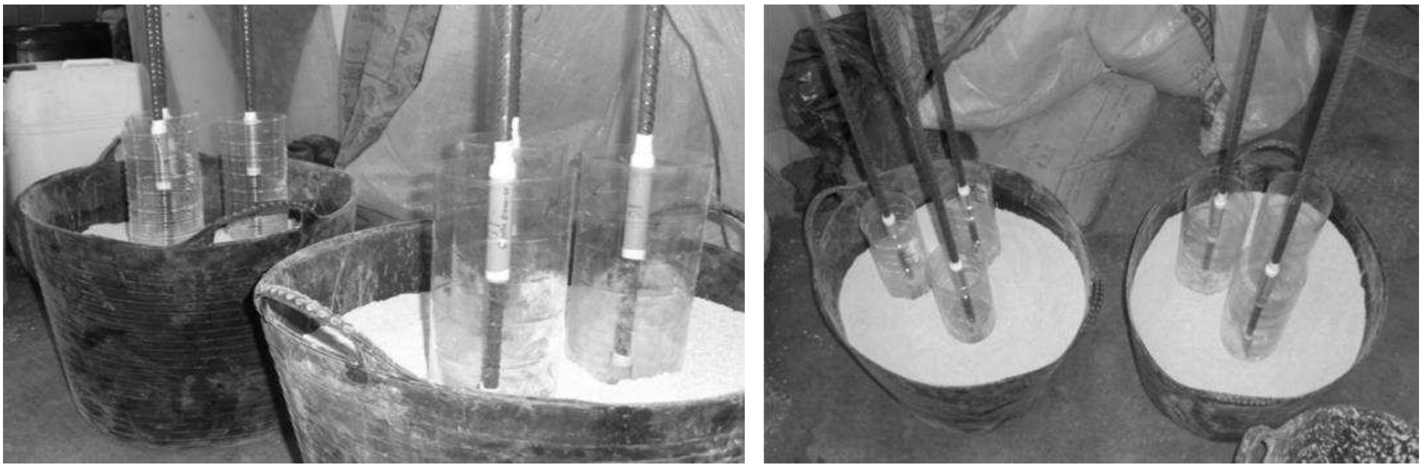

Figure 3. Bottle moulds and rebars prepared and right before casting.

Although other methodologies can also be valid as long as they comply with the aforementioned requirements, in the case of this research plastic baskets, wooden blocks, and sand were used, as shown in Figure 3.

Wooden blocks with holes in them were used for the rebars to be fixed into them. They were put into plastic baskets and then the baskets were filled with sand. This way, the sand fixes the position of the bottle moulds and the wooden blocks, with 80 mm of rebar inserted in the holes, keep the rebar in the desired vertical position. With this simple system, the worker has hands free to cast the concrete into the bottles.

Production of concrete was carried out in all cases by following exactly the same sequence and by controlling the time for all operations. Components were added to the mixture following this sequence: aggregates, cement, water, and high-range water-reducing admixture.

Concrete must be poured with care and must be properly compacted. In the case of the specimens for this research, this was avoided by using self-compacting mixes: any unknown interference with test results due to bad compaction had to be avoided in this study.

3.5 Testing of Bottle Specimens

All tests (i.e. both APULOT test and compressive strength tests of control cylindrical specimens) were carried out 28 days after casting.

During the pull out tests (see Figure 4), load/time ratio was kept between 2 to 4 kN/min before the peak load was reached, and after the peak load slip/time ratio was kept between 0.4 to 0.6 mm/min.

Figure 4. APULOT test carried out on one bottle specimen.

Relative displacements (slip values) were measured at the loaded end of the rebar by means of a linear variable differential transformer (LVDT). This was interesting in order to have bond stress-slip curves for all cases and retain them for further analysis, though having slips monitored is not part of the APULOT test, i.e. it is not at all part of the proposed methodology to have it implemented at construction sites.

A piece of teflon was used to improve the contact between the support plate and the bottle specimens in order to minimize the effect of compressive stresses at the loaded end. Using teflon with this purpose was thought to be highly convenient given the unlikeliness of having surface specimen perfectly perpendicular to the rebar, given the difficulties of having a very well smoothed surface as a result of having the rebar in the center and the peculiarities of the moulds position during casting.

4 RESULTS AND DISCUSSION

4.1 Analysis of Results: Methodology

Table 4 summarizes the test results. In some cases the bottle specimens tested where the rebar was not pulled out in a typical way because either yielding of rebar was reached or splitting occured. In such cases the bond stress-slip curve obtained is not a complete one and there is no bond strength as such. Logistic binary regression has been applied to take advantage of the information regarding the mode of failure observed to try to predict under what circumstances yield of the rebar occurs or a bottle specimen is likely to experience splitting when the rebar is pulled out.

Table 4. Summary of the test results obtained.

	Mode of failure			Bond strength	f_C
Id	PO	Yield	Splitting	τ_{BOT}, MPa	MPa
L1	0	9	0	-	55.4
L2	1	8	0	12.4	56.8
L3	0	1	8	-	57.4
L4	0	9	0	-	39.8
L5	1	8	0	13.8	41.0
L6	9	0	0	11.4	40.4
L7	9	0	0	5.6	28.3
L8	8	1	0	12.6	28.1
L9	8	1	0	12.2	28.3

After that, combinations corresponding to splitting or yielding of the rebar are discarded, and multiple linear regression (MLR hereafter) has been applied to relate compressive strength values, f_C, to bond strength values obtained from the APULOT test, τ_{BOT}, by taking into account the modifying effect of the different variables considered. But there is much more than simply a predictive equation, because variables that do not have a statistically significant effect can be identified and removed, i.e. simplifying the adjusted model without affecting the accuracy of the equation found. To do so, statistical inference has been made by means of significance tests associated to the coefficients estimated in the construction of the linear model (Hair 2009).

4.2 Variables Determining Mode of Failure

Logistic binary regression (Kleinbaum 2010) has been applied to test results concerning mode of failure to relate the variables considered to the probability that a specimen experiences yielding of the rebar (p) instead of having the bar pulled out. The probability of splitting cannot be properly analyzed on the basis of the results presented herein because it has occured in only one out of the nine combinations tested (see Table 4) and therefore any analysis would conclude that splitting is expected to occur only in that case, which is unlikely.

Since cover/diameter ratio (C/D) is usually assumed to determine mode of failure, a model where the effect of such ratio is affected by any other variables considered (symbolized as Ψ) seems an appropriate point of departure:

$$\frac{p}{1-p} = \exp\left(\beta_0 + \Psi \times \frac{C}{D}\right) \qquad (1)$$

However, concrete cover is not considered as such in this research but the type of bottle determines differences regarding concrete section and particularly concrete cover. As a result, the following equivalent formulation for C/D is proposed:

$$\frac{C}{D} = \left(C_1 + C_2 B_2 + C_3 B_3\right) \times \frac{1}{D} \qquad (2)$$

where D is the rebar diameter, expressed in mm; C_1, C_2, and C_3 are coefficients to be adjusted; B_2 is a Boolean variable which equals 1 when the bottle is type 2, and 0 otherwise; and B_3 is a Boolean variable which equals 1 when the bottle is type 3, and 0 otherwise.

The function Ψ modifies the effect of C/D and is defined in terms of other variables:

$$\Psi = \psi_1 f_C + \psi_2 R + \psi_3 G \qquad (3)$$

where ψ_1, ψ_2, and ψ_3 are coefficients to be adjusted; f_C is the specified compressive strength of concrete, in MPa; R is a Boolean variable which equals 1 when the rebar is corroded, otherwise it equals 0; and G is a Boolean variable which equals 1 when it is greasy, otherwise it equals 0.

Once the model is adjusted to the experimental observations in this research, significance tests are carried out on estimates for the coefficients, and the model is simplified by stepwise regression (Hair 2009) to include only statistically significant effects. The following expression is obtained:

$$\frac{p}{1-p} = \exp\left(10.37 + \frac{3.14 f_C - 52.56G}{D}\right) \qquad (4)$$

When it comes to determine the probability of having yielding of the rebar, the differences between the types of bottle considered are not significant. It has also been detected that having the rebar corroded does not make any difference, while having it greasy does. The accuracy of the model cannot be significantly improved by any other alternative model (p-value for residuals 1.0000 >> 0.05), which is a good result. The two effects considered are significant (p-values 0.0000 in both cases).

Figure 5 shows the probability of rebar yielding vs rebar diameter for three different values of compressive strength, assuming that the bar is not greasy. The choice of what rebar diameter is more convenient to perform the test can be reasoned on the basis of Figure 5, where three hypothetical compressive strength values of 25, 30, and 35 MPa have been considered to illustrate the model which follows expression (4).

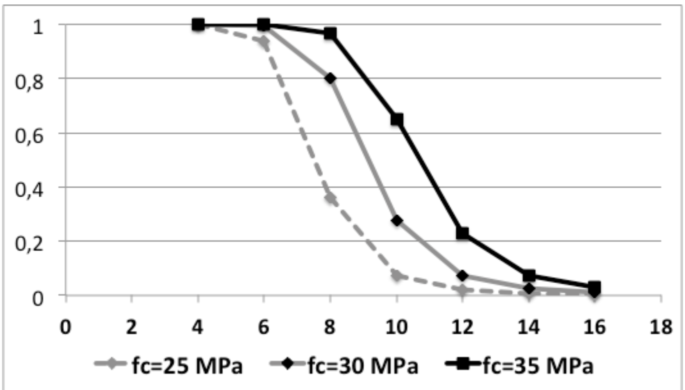

Figure 5. Probability of rebar yielding vs rebar diameter for different compressive strength values (rebar not greasy).

If 8-mm rebars are chosen for the test, when yielding occurs nothing can be clearly said about compressive strength of the concrete batch being tested, since compressive strengths of 25, 30, or 35 MPa are very likely to lead to rebar yielding indistinguishably. Performing the test with rebars of 10 mm implies that, if yielding occurs, a specified compressive strength of 35 MPa can be assumed, though this is going to be false in 35% of cases.

Choosing 12-mm rebars has the advantage of yielding not being very likely and theoretically the occurence of confused cases is no more than 20%. However, the only case where splitting has occured involves a 12-mm rebar (see Tables 2 and 4), and therefore a diameter of 12 mm is probably not a good choice.

As a consequence, performing the APULOT test with 10-mm rebars seems to be the best option, though conservative criteria need to be defined for those control cases where yielding occurs, in order to have a confidence level greater than 65%.

Figure 6, when compared to Figure 5, clearly shows to what extent the situation is different when a greasy rebar is used: at any rate yielding is likely to occur under such circumstances (considering only commercial diameters, the probability of rebar yielding is never greater than 0.05). As a consequence, using greasy rebars might be an alternative to aim at a better classification capacity of the test, though this would require further data to be confirmed.

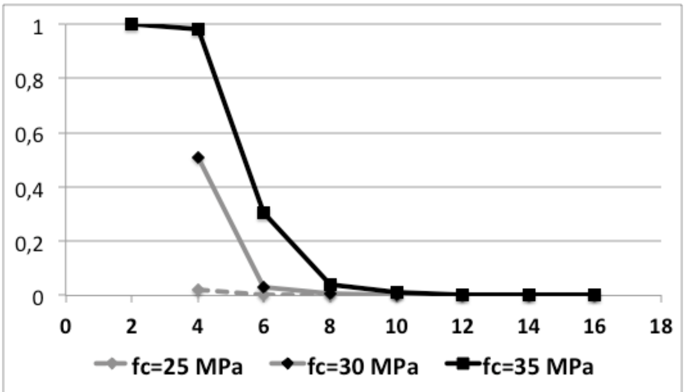

Figure 6. Probability of rebar yielding vs rebar diameter for different compressive strength values (greasy rebar).

4.3 Transforming APULOT test results to concrete compressive strength values.

When no rebar yielding occurs, the output of the APULOT test is the bond strength value obtained when pulling out the rebar, τ_{BOT}, expressed in MPa. In order to have such values related to compressive strength of concrete as obtained from cylindrical specimens, f_C, an expression which follows the general form of (5) has to be found:

$$\tau_{BOT} = \Gamma \times f_C \tag{5}$$

where Γ is a function of several variables different than f_C, thus introducing the idea that the relation between τ_{BOT} and f_C depends on parameters derived from test setup and conditions.

Since cover/diameter ratio (C/D) is of capital importance, it is reasonable to define function Γ as:

$$\Gamma = \beta_0 + (\beta_1 + \beta_2 R + \beta_3 G) \times \frac{C}{D} \tag{6}$$

where R, G are Boolean variables related to the state of the rebar used as defined in section 4.2. As already explained in section 4.2, C/D is expressed in terms of variables used in this research and therefore (6) is rewritten as follows:

$$\Gamma = \beta_0 + (\beta_1 + \beta_2 R + \beta_3 G) \times \frac{C_1 + C_2 B_2 + C_3 B_3}{D} \tag{7}$$

Once the model is adjusted to the experimental observations in this research, i.e. coefficients estimated by least squares fitting, significance tests are carried out on these estimates. The model is then simplified by stepwise regression (Hair 2009) to include only statistically significant effects, and the following expression is obtained:

$$\frac{\tau_{BOT}}{f_C} = K \quad \frac{2.278}{D} \tag{8}$$

where D is the rebar diameter expressed in mm, and K is a constant whose value depends on the state of the rebar used: 0.606 for clean rebar, 0.474 for greasy rebar, and 0.678 for rusty rebar.

The fitted model is highly accurate, having a R-squared value of 90.12%. Therefore, equation (8) represents a very simple and quite accurate way of estimating concrete's compressive strength (f_C) from the bond strength value obtained in the APULOT test (τ_{BOT}), which is a step forward to the implementation of the latter as an alternative to the former.

However, the aforementioned R-squared value is calculated for the parameter that equation (8) predicts, i.e. the relation of observed vs predicted values of the ratio τ_{BOT}/f_C. If equation (8) is applied to the dataset this analysis is based upon, pairs of predicted f_C vs observed f_C are obtained. They are shown in Figure 7, together with the 95%-confidence limits (dotted lines).

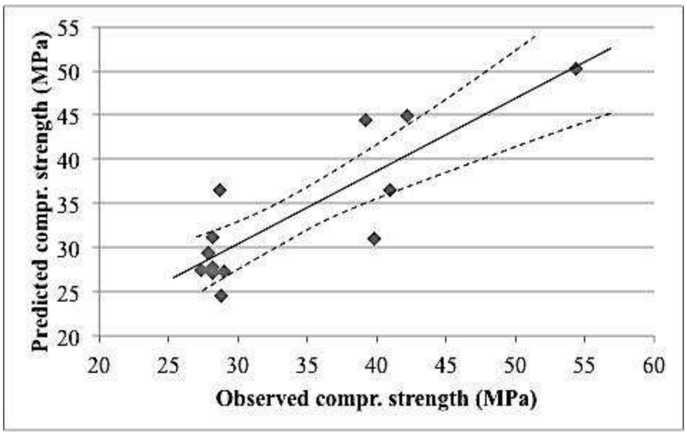

Figure 7. Predicted vs observed values for compressive strength of concrete.

The R-squared value corresponding to the regression line in Figure 7 which relates predicted and observed values of compressive strength of concrete is 73.66%, which stands for a more direct measure of the accuracy of equation (8) as a tool for quality control than the R-squared measuring the accuracy of prediction in terms of τ_{BOT}/f_C ratio.

This can be judged from another point of view as well. The mean squared error obtained for predicted f_C values in relation to the line fitted in Figure 6 is 18.07, and therefore an estimate for the standard deviation of predicted f_C values with respect to observed f_C values is $18.07^{0.5}$ = 4.25 MPa. Since the average of the observed f_C values is 33.6 MPa, it follows that the relative standard deviation of predicted f_C values with respect to their corresponding observations is 12.6%. Since values up to 11% for the coefficient of variation of concrete compressive strength are considered satisfactory for most situations (ACI Committee 214 2011), it can be considered that the bottle test together with equation (8) constitute as accurate a tool for concrete's quality control as the testing of cylindrical specimens.

5 SUMMARY & CONCLUSIONS

- The APULOT test, or bottle test, is an economical and simple alternative to conventional quality control of concrete. It is based on relating bond strength to concrete compressive strength.
- A particular methodology for the test has been proposed concerning general dimensions of bottle specimens, mounting of bottle moulds, fixing of rebars, and casting of concrete.
- A series of tests have been performed to study the effect that rebar diameter, the state of its surface (clean, rusty, or greasy) and the use of different bottles as moulds have on bond strength values as obtained in APULOT test.
- No differences have been found among the three different types of bottle considered in this research.
- Rebar yielding prevents any relation from being established to concrete compressive strength. Therefore the discriminatory power of the test is lost when rebar yielding occurs.
- An expression to predict the probability of rebar yielding has been obtained. It has been found that it is affected by rebar diameter and the state of the rebar surface.
- An expression which accurately relates bond strength in the bottle test (τ_{BOT}) to concrete compressive strength (f_C) has been obtained.
- Together with the expression obtained to relate τ_{BOT} to f_C, the bottle test proves to be as reliable a tool as testing cylindrical specimens for quality control of concrete.

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