Post-installed screws for in-situ assessment of mortar strength

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ABSTRACT: For capacity evaluation, the structural assessment of existing structures is necessary. Concrete strength is an important parameter for such assessment. Non-destructive tests (NDTs) are used along with the traditional approach of core testing for strength assessment of concrete in existing structures. The low reliability of NDT results leads to uncertainty in assessing concrete strength. A new method of non-destructive testing is presented in this paper with the aim of achieving better reliability and reducing uncertainty in the assessment of mortar strength. This approach is based on a modified pullout of post-installed screw anchors. The technique involves a pushin mechanism for a steel screw inside the mortar where a void underneath the screw is left to allow for the uninterrupted movement of the screw inside the concrete. The failure pattern involves local crushing of concrete between the threads of the screw. This paper investigates the load bearing behaviour of threaded screws installed in cement mortar under compressive loading. The results supports the application of the technique in the assessment of compressive strength of mortar. The main parameters affecting the pushin behaviour are presented and their effects are discussed. It is planned to extend the test program to concrete in the future.

1 INTRODUCTION

Concrete is a highly non-homogenous composite material. It can be prepared with wide combination options of suitable materials. Quality control of production and its treatment afterwards highly influence the final properties of concrete. To measure in-place properties of concrete for quality assurance and for evaluation of existing condition, assessment of concrete strength is a must. Concrete strength assessment in existing structures is a major challenge in civil and structural engineering.

The direct determination of strength assessment of concrete requires concrete specimens to be taken from the structure that can be tested destructively. Core testing is the most direct and reliable method to estimate concrete strength in a structure. For strength assessment in existing concrete, different in-situ test methods have been developed. In-place tests are performed on concrete within the structures and are used along with core test to minimize the number of cores to be taken and to reduce the uncertainty in compressive strength assessment across the structure. Among the in-situ tests, some are completely non-destructive while others are partially destructive which cause limited surface damage without having effects on the structural integrity. Ultrasonic pulse velocity (UPV) test, rebound hammer test, maturity test, resonance frequency test etc. can be considered as non-destructive test. Tests such as pullout test, cut and pullout (CAPO) test, pull off test, break off test, penetration resistance test are partially destructive. Historically, all in-situ tests are called non-destructive tests (NDTs) even though some of the test methods offer some superficial damage to concrete surface. Therefore, the term “NDT” is used as a generalized category which include in-place testing methods with no damage or limited surface damage. The significant characteristic of most of the tests is that NDTs do not directly measure the compressive strength of concrete in a structure, they measure some other property that can be correlated to compressive strength (Popovics 1998). Therefore, NDT methods cannot yield direct values of concrete strength. Core testing may not always be possible at all parts of the structure. In addition, core testing is a costly exercise. Therefore, advantages of using NDT in strength assessment is that NDT allows the collection of data in a short time at a low cost. NDTs are be used in determining the statistically most reliable results of core tests with limited expenses and time. Several standards, design manuals and specifications provide methodologies on reliable use of NDTs and strength assessment of concrete from NDT methods (ACI 228.1R 2003, I.S. EN 13791 2007, ISO 1920-7 2004, NRA BA 86 2014).

NDTs for strength assessment of concrete are influenced by several factors, many of which are uncontrolled. The limitation of each of these NDTs and their domain of application can be found in (Sourav et al. 2016). Most NDTs are useful in checking the uniformity and consistency of concrete in structures and in detecting the weak spots. Table 1 summarizes the merits of the NDTs used for strength assessment of concrete.

Table 1. Non-Destructive Test Methods and their relative merits (Bungey 2006).

Test method	Cost	Speed of test	Damage	Representativeness	Reliability
Rebound hammer	Very Low	Fast	Unlikely	Near surface	Poor
UPV	Low	Fast	None	Good	Poor
Maturity	High	Continuous	Minor	Good	Good
Resonance frequency	High	Moderate	None	Good	Poor
Pullout	High	Fast	Minor	Near surfaces	Good
CAPO	High	Fast	Minor	Near surface	Moderate
Penetration Resistance	Moderate	Fast	Minor	Near surface	Low
Pull off	Moderate	Moderate	Minor	Near surface	Low
Break off	Moderate	Moderate	Minor	Near surface	Low

It can be observed from Table 1 that the NDTs with low cost and high speed of testing produce low reliability in the assessment. As a result, there is usually a high level of uncertainty in assessing concrete compressive strength. This explains the limitation of the use of NDTs in the practical field. As an alternative, and with the aim of achieving better level of accuracy and reducing uncertainty in strength assessment of in-situ concrete, a new simplified test approach is presented in this paper. The technique was investigated for cement mortar as the first step towards using the method in assessing the compressive strength of concrete. This approach is based on a modified pullout of post-installed screw anchors. The technique involves a pushin of a steel screw inside the mortar. The screw is first torqued in a drilled hole. The screw is torqued to a level short of the hole end to allow for the uninterrupted movement of the screw inside the mortar during the pushin process. The pushin mechanism of the screw results in a similar failure mechanism to that of a pullout failure. The failure pattern involves local crushing of mortar between the threads of the screw. This paper investigates the load bearing behaviour of the screw under compressive loading with the aim of assessing compressive strength of mortar. The parameters affecting the failure mechanism in pushin testing of screw studied in this research were the mortar compressive strength and age of loading.

2 CURRENT PRACTICE OF NDT

2.1 *General overview*

NDTs are considered to be advantageous to supplement the core test as the number of core that can be taken from a structure is usually limited. NDTs allow more economical evaluation of concrete in the structures. As NDTs measure compressive strength of concrete indirectly, a valid relationship between test result and compressive strength must be established following a valid statistical procedure.

European Standard (EN 13791 2007) gives methods and procedures for the assessment of the in-situ compressive strength of concrete in structures by coring and provides guidance on the use of NDTs for the strength assessment. Use of NDTs with limited number of cores introduces two sources of uncertainty. One is due to the calibration that is performed from a limited number of cores and another is due to the lack of precision of NDTs. EN 13791 offers two approaches; Alternative 1-Direct correlation with cores and alternative 2-Calibration with cores for a limited strength range using an established relationship. Alternative 1 requires minimum of 18 cores where at least 9 pairs of data is required for alternative 2. According to ACI 228.1R 2003, use of NDTs in the practical field should be preceded by the preparation of calibration curve from the same concrete that is under investigation (ACI 228.1R. 2003).

Many of the NDTs have been standardized: rebound hammer (EN 12504-2, ASTM C805), UPV (EN 12504-4, ASTM C597), pullout and CAPO (EN 12504-3, ASTM C900), penetration resistance (ASTM C803), pull off (ASTM C1583).

The most widely used NDTs are the rebound hammer and UPV. These tests are suggested for checking uniformity and quality of concrete under investigation (Sourav et al. 2016). Pullout and CAPO test are identical in loading and failure mechanism. Pullout instrument has to be inserted in fresh concrete whereas CAPO test has post-installed feature for hardened concrete. Even though limited to the outer concrete layer of the structures, CAPO test provides greater level of accuracy in assessing in-situ concrete strength than other NDTs. For CAPO test, a general correlation for any concrete can be used which allows assessment of concrete strength with a specific level of uncertainty (Bungey & Soutsos 2001, Petersen 1997). The CAPO test is complex due to the required equipment and particular insert geometry, and also expensive as the instrument is patented. In recent years, much researches and studies are carried out where several NDT methods are combined. Several researchers published the successful use of combination of NDTs for strength estimation (Shariati et al. 2011, Arioĝlu et al. 2001, Martinez-Molina et al. 2014, Qasrawi 2000, Pucinotti 2007, Pucinotti 2015, Hannachi 2012, Cristofaro et al. 2012). The most widely used techniques for combined method is Son-Reb method (from UPV and Rebound hammer). The combination will be a success when the purpose of combination are correctly (Breysse et al. 2008). Breysse et al. 2008 concluded "the combination of two NDTs can provide additional information only if the sensitivity to the two parameters is different for the two techniques". ACI 228.1R 2003 reported on the marginal improvement of estimation with combined method. Many researchers proposed generalized regression models that were claimed to be useful for any concrete under investigation (Qasrawi 2000, Arioĝlu et al. 2001, Nash't et al. 2005, Amini et al. 2016). Combination may not always lead to improved results (Breysse 2012, Carvalho, et al. 2014). Carvalho et al. 2014 found lack of consistency in the obtained results during the use of rebound hammer and UPV for evaluation of concrete strength of bridges.

A large number of relationship has been proposed for strength assessment of concrete from NDT results (for individual or combined method). Calibration models with different mathematical functions and high variability in their coefficients are observed in the literature. The quality of estimates of strength of concrete by NDTs depends on the errors and uncertainty associated with the testing methods. Sources of uncertainties arise at various level such as: by testing methods, by material intrinsic variability, by environmental effects, by human factor, and by model error or misinterpretation of data. The major cause of uncertainty is the effect of factors other than strength that influence NDT measurement. Breysse et al (Breysse et al. 2008) noted, "any parameter that can be measured using NDTs depends on several material and environmental parameters whose effects are very difficult to uncouple".

In-situ strength assessment of concrete in existing structure is an active field of research in recent years. Researchers focus on the development of NDTs or of data processing for better assessment. Most researches aim at generalizing the relationship of NDTs with compressive strength which can be used for all concrete. Interpretation of the effects of influencing factors is a challenge for the use of NDTs as many of the factors are uncontrolled. In practical field, structures may have high spatial variability due to the variability of material received, their properties and sporadic quality control. The major challenge is to differentiate the effect of strength on the NDT results from all other effects.

3 BOND STRENGTH OF DEFORMED BAR IN CONCRETE

Bond of deformed bar in concrete is a complicated mechanism. Force transfers from a deformed bar to the surrounding concrete by chemical adhesion between the surface of the bar and concrete, friction caused by the roughness of the interface, and mechanical bearing of the deformation against the concrete (ACI 408 2003, Mendis & French 2000). Figure 1 demonstrates the bond force mechanism in concrete.

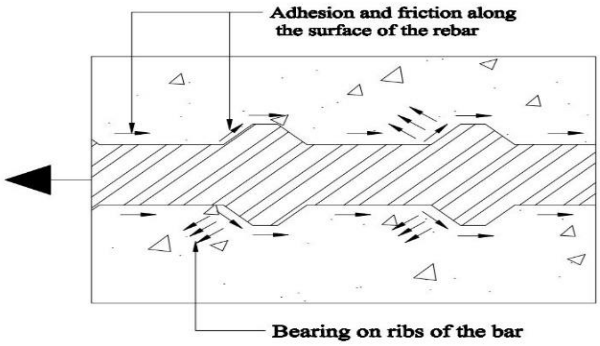

Figure 1: Bond force mechanism in concrete (ACI 408 2003)

When a force starts to act on the deformed bar, initiation of slip of bar with respect to concrete occurs. At this stage, adhesion is lost and friction force is reduced. From that stage on, the bearing mechanism becomes the principle mechanism of force transformation (Brown et al. 1993, Mo & Chan 1996). This bearing force is mostly influenced by the geometry of the deformation of the bar. Two types of failure occur in concrete during the interaction of deformation of rebar with the surrounding concrete; splitting failure and complete pullout failure. In splitting failure, failure occurs by propagation of tensile cracks and is accompanied by little or no crushing of concrete under the deformation. With sufficient level of confinement surrounding the bar, failure pattern is dominated by pullout failure characterized by crushing of concrete under the deformation of the bar. In case of complete pullout failure, ultimate failure load is affected by compressive strength of concrete indicating a close relationship between bond strength and compressive strength of concrete (B. V. Silva et al. 2014a, B. D. V. Silva et al. 2014b, Lorrain & Barbosa 2011).

4 POST-INTALLED SCREWS IN CONCRETE

4.1 *Pullout behaviour of post-installed screw*

Post-installed concrete screw anchors are a relatively new fastening system. They are gaining acceptance in construction practice as they are reliable fastening elements with high capacities. Furthermore, they can be easily installed. Mechanical interlocking principle is adopted in the use of this type of anchors. During installation, concrete screw cuts threads into the concrete providing mechanical interlock (Figure 2).

Installation operation involves drilling a hole in the concrete, cleaning the hole and application of torque for installation of a screw. As the screw is torqued inside the hole, its threads cut a path in the concrete of the hole through a combination of cutting and compressive actions (Stuart et al. 2010).

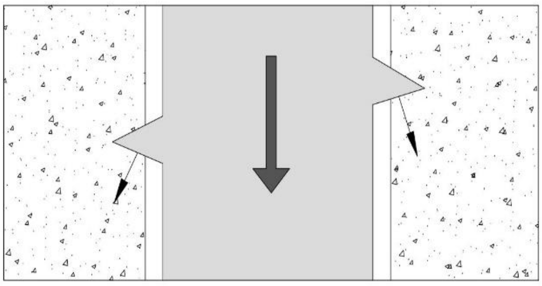

Figure 2: Mechanical interlock principle

When a force is applied on the screw, the ultimate load is mainly influenced by the degree of undercut of the thread in the concrete and the embedment depth (Olsen et al. 2012). A screw with larger undercut will have a higher ultimate load. High level of undercut also increase installation difficulty. Load transfer mechanism is similar to that of the deformed reinforcing bars cast into concrete. as the screw threads act in a similar manner as the ribs of the reinforcing bar (Kuenzlen & Eligehausen 2002). Failure occurs via different modes: steel failure, concrete cone failure, pullout failure and combination of cone and pullout failure. Pullout failure is similar to the pullout failure of deformed bar in concrete that occurs during bond strength test (as discussed in Section 3). Depth of embedment contribute to the load carrying capacity and governs failure pattern. Screws with deep embedment and small undercut will be governed by pullout failure. Screws at shallow embedment depth with high degree of undercut will be controlled by concrete cone failure over the entire length of the screw.

As discussed in Section 3, pullout failure involves crushing of concrete under the threads as the screw pullout progresses. With the increase of load, threads of the screw exerts local bearing pressure on the concrete. Movement of the screw inside the concrete occurs due to gradual crushing of concrete in front of the threads. A complete shearing-off occurs in concrete at the outer edges of the threads at the last stage of loading. Available literature on the post-installed screw anchors focuses on the concrete cone failure. Concrete cone failure occurs due to the exceedance of the tensile strength of concrete in the failure cone. In case of pullout failure, Olsen et al. 2012 stated “ultimate load needs to be evaluated based on the actual test results in accordance with screw anchor qualification standards” as failure load is influenced by the individual design of each screw anchor

4.2 *Pushin mechanism of concrete screw*

Pushin mechanism of screw involves application of compressive loading on the screw installed in a drilled hole in concrete. A void underneath the screw is left to allow the movement of the screw without creating direct bearing between the screw tip and concrete. Figure 3 shows the arrangement for pushin mechanism of screw inside the concrete.

In pushin mechanism, the screw threads exert bearing pressure on the surrounding concrete through mechanical interlock. The state of stress in pushin mechanism is the same as that of pullout mechanism. Local crushing of concrete under the threads of the screw occurs as is the case in pullout failure.

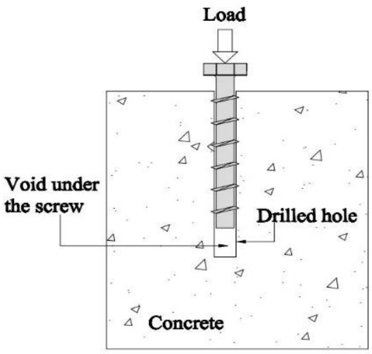

Figure 3: Pushin mechanism of screw inside concrete

5 FAILURE INVESTIGATION UNDER PUSHINMECHANISM

To investigate the failure mechanism resulting from a pushin test, the screw designated TIMco 8x75 supplied by (TIMco) (showed in Figure 4) was pushed inside the cement mortar samples in 8 different stages. 150 mm cube samples were used in the investigation. Details of the screw are given in Table 2.

Table 2: Details of concrete screws.

Type of screw	TIMco 8x75
Market Name	Multi-Fix Bolt Hex Head (TIMco 2013)
Length (mm)	75
Outer Diameter (mm)	10.40
Inner Diameter (mm)	7.60
Type of threads	High and low parallel threads with concave thread configuration (Figure 5.a)
Pitch between thread (mm)	9.50
Thickness of threads (mm)	1.50 (for high threads)

The followings steps were undertaken in the installation of the screw inside the mortar samples.

1. 65 mm deep hole was drilled inside the mortar sample with 8.5 mm drill bit. Drill bit diameter was selected such that no splitting failure of the sample would develop, hence ensuring the complete mortar shearing off along the outer edge of the threads.
2. The diameter of the dilled hole for top 10 mm depth was expanded using 10 mm drill bit to avoid any breakage of mortar due to stress concentration during the screw installation.
3. The drilled holes were cleaned by blowing compressed air.
4. The screw was torqued manually inside the sample up to 40 mm depth of the hole from the top. A depth of 40 mm was selected to ensure the verticality of the installed screw. This resulted in a void of 25 mm underneath the bottom of the screw for its movement along the drilled hole. Figure 5 shows the arrangement of the screw inside the sample.
5. The screw was then loaded using a compression machine with controlled displacement. The loading arrangement is shown in Figure 6.

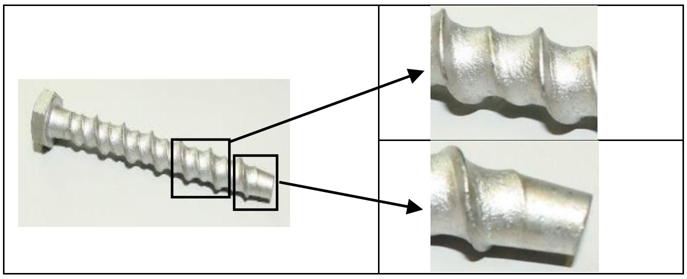

Figure 4: Concrete screw used in the experimental program

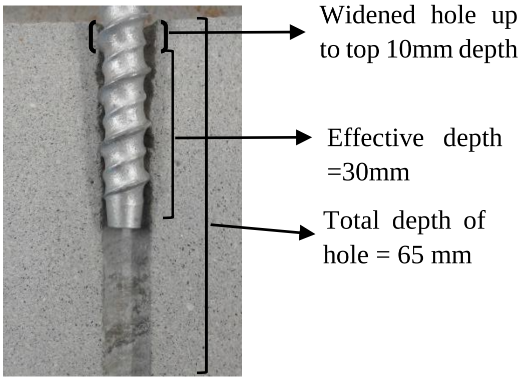

Figure 5: Arrangement of screw inside the sample

In the first stage (stage 1), the screw was pushed by 2 mm, the second by 4 mm, and so on up to 16 mm for stage 8. Stages 1 and 2 show little crushing of mortar under the threads. Each stage showed gradual movement of screw in the mortar during load application. Stage 4 (a movement of up to 8 mm) showed that almost all mortar under the threads at the top has sheared off and the spalled mortar has accumulated under the threads at the bottom.

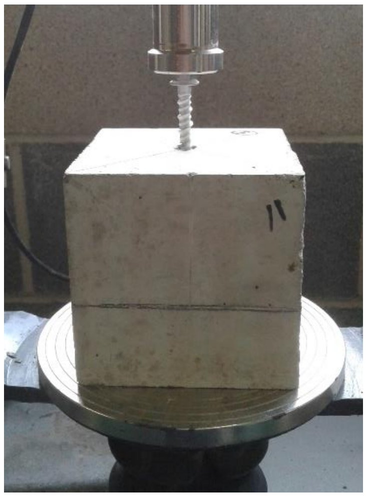

Figure 6: Loading arrangement in pushin mechanism

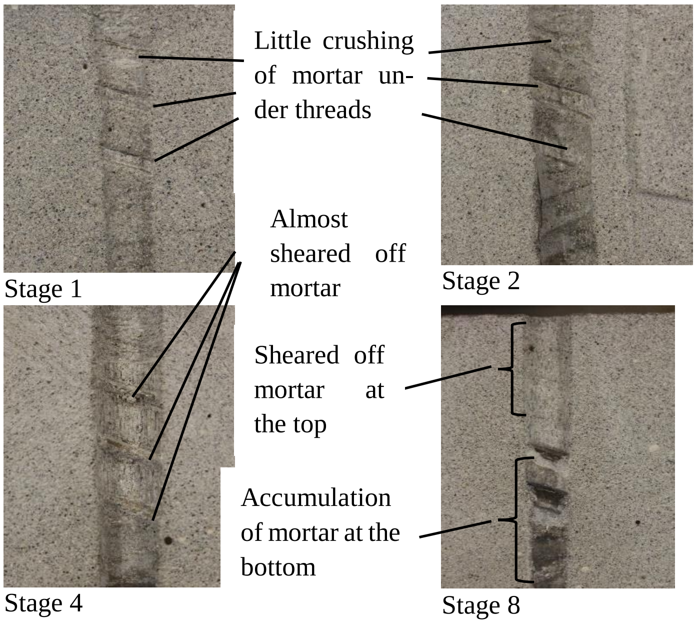

Figure 7: Investigation of failure mechanism in mortar

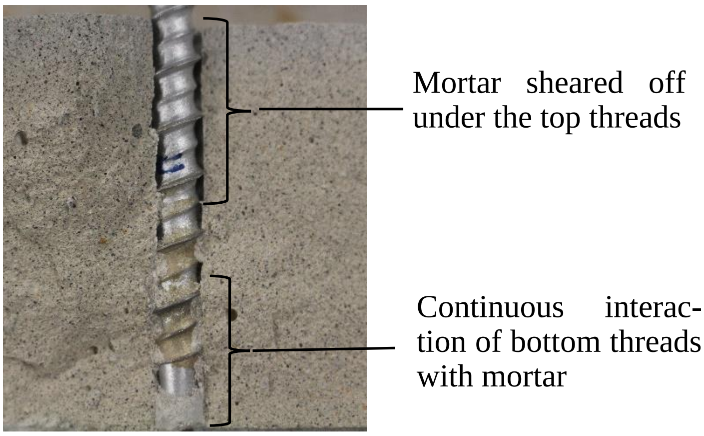

Figure 8: Screw in concrete loaded up to 20 mm

This shearing-off is related to the distance between the threads of the screw. As the mortar sheared-off under the top threads, mortar particles accumulated under the bottom threads. Figure 7 shows selected stages of movement of the screw in the mortar. The figure shows the movement of screw loaded with up to 20 mm of displacement inside the mortar. The mortar under the threads at the top were found to be sheared off and the threads at the bottom continued to interact with the surrounding mortar until the screw came into contact with the bottom of the drilled hole, Figure 8.

6 LOAD CARRYING BEHAVIOUR OF CONCRETE SCREW

An experimental test program was designed to understand the load carrying behaviour of the concrete screw under compressive loading. Samples prepared from two cement mortar mixes were tested (Table 3). The maximum particle size of sand was 0.60 mm. Samples of 150 mm cube were tested at different ages.

Table 3: Details of mortar mixes.

Mortar		Mix 1	Mix 2
w/c		0.40	0.50
Cement/sand		1.0	1.0
Strength	7 day	43.17	31.99
(MPa)	14 day	47.89	38.66
	28 day	52.24	43.63

The experimental program was carried out in two sets. In the first set of test program, screws were installed inside the samples following the same procedure used in the failure investigation (section 5). The screw threads cut into the mortar for 30 mm inside the sample with a number of turns of the threads cutting into mortar of 2.64. Four samples were tested at each age. The compressive strength was obtained by averaging the compressive strengths of three 100 mm cube samples prepared from the corresponding mix. The load displacement curves for mix 2 at the age of 7 and 14 days are shown in Figure 9.

In second set of test, step 4 (in section 5) was modified. The screws were torqued for the full length of the drilled hole and then partly unscrewed to obtain the same insertion depth of 40 mm. The partial unscrewing was carried out to ensure the consistency of mortar shearing-off and to reduce the interaction of bottom threads with the surrounding mortar. In this set, 55 mm deep holes were drilled inside the sample. The 55 mm depth was chosen instead of 65 mm as all the mortar under the threads was observed to be crushed at around 9 mm of screw displacement. This value is similar to the pitch between the threads. The effect of this change was to alter the tail part of the load-displacement curve which is related to the interaction of the bottom threads and mortar at high displacements. The load-displacement curves for test set 1 and 2 are compared in Figure 10. The results obtained from the test programs were compared in table 5.

Table 5: Summary of results.

Test program	Mortar mix	Age (days)	Average Peak load (KN)	Co-efficient of variation (%)
1	1	7	10.11	12.84
		14	11.03	4.37
		28	14.89	6.18
	2	7	8.11	7.61
		14	8.90	18.57
		28	10.32	7.91
2	1	28	12.74	7.63
	2	28	10.49	4.69

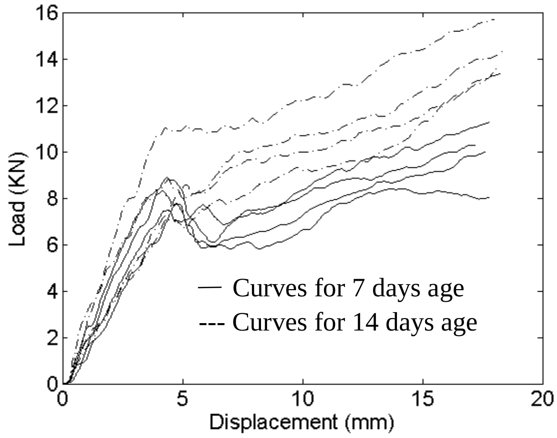

Figure 9: Typical load displacement curve for test program 1 for mix 2.

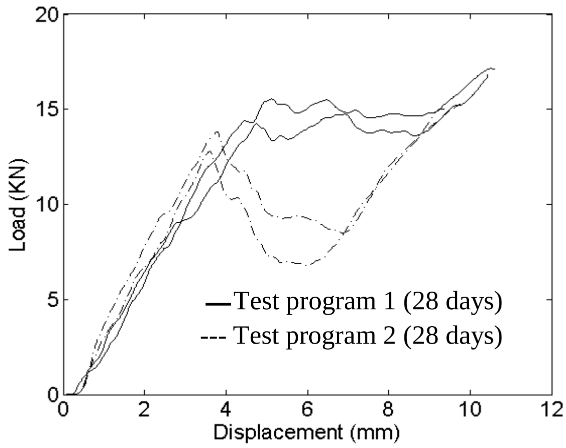

Figure 10: Typical load displacement curve for test program 2 for mix 1.

7 *DISCUSSION OF RESULTS*

The undertaken test programs were designed in a way to result in a bond failure and to avoid any splitting cracks in the mortar. In all the tested samples, the failure mode was always a bond failure and no splitting of the cubes was observed.

The load-displacement curve, Figure 9, shows that a peak load was reached at around 5 mm of displacement. Beyond that displacement (particularly for the 7 days age of mortar), a decrease in the load was observed. This load decrease is related to the decrease of mortar resistance after nearly half the mortar between the threads (nearly 5 mm) is lost. It can also be observed that with further displacement, the load starts to increase again. This can be related to the fact that as the screw continued to be pushed inside the mortar, the bottom threads continued to interact with the surrounding intact mortar. The peak load value for the mortar at 14 days of age is not clear. It is thought that this is related to the complex interaction between the screw end and surrounding intact mortar.

Another observation is that the initial stiffness (slope of the load-displacement curve) was nearly linear at the initial loading stages. Beyond that stage, several changes of slope can be observed. These can be attributed to the crushing of mortar and later interaction with the intact mortar at the screw end.

Test program 2 was designed to reduce the interaction mentioned earlier. A comparison between the results at 28 days obtained from test programs 1 and 2 is shown in Figure 10. As described earlier, test program 2 involved a partial unscrewing operation which was intended to reduce the screw-mortar interaction at large displacements. The results clearly indicate that the revised method adopted in test program 2 managed to reduce the interaction and resulted in a distinctive peak in the load-displacement curve. In test program 1, such a distinctive peak value was absent, particularly when mortar strength is high. The partial unscrewing operation after screwing managed to reduce the effect of continuous interaction of the bottom threads. The presence of predefined failure planes that were created beforehand ensured the failure of mortar surrounding the threads. This resulted in sufficient amount of drop in load after the peak that occurred at around 4-5 mm of displacement. The unscrewing operation also contributes to the slightly lower peak value of test program 2 compared to that of test program 1. The resistance contribution of the bottom threads was reduced by the unscrewing operation. Also, it is possible that slightly more damage to the mortar can happen due to the unscrewing operation. In general, the results of test program 2 were more consistent that those obtained from test program 1. The co-efficient of variation of peak load in test program 2 was found to be lower than that found in test program 1 as shown in Table 5.

In undertaken the experimental program, the failure under the screw threads was thought to be related to the compressive strength of the mortar. A trend of increased peak pushin load was observed with the increase of compressive strength of the mortar, Figure 10. In spite of the limited data available at this stage, the trend of increased peak load with increased mortar strength is clear. Due to the limited available test results, the peak loads obtained in test program 1 were considered for the preparation of demonstration of relationship of peak load and compressive strength. Figure 11 shows the deviation of calculated strength using obtained relation from actual measured strength. A deviation of less than 5 MPa was observed.

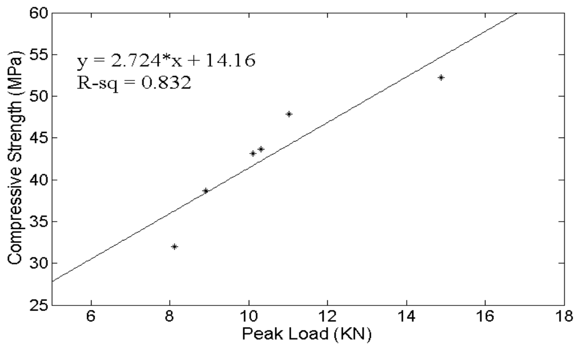

Figure 10: Relationship between peak load and compressive strength of mortar.

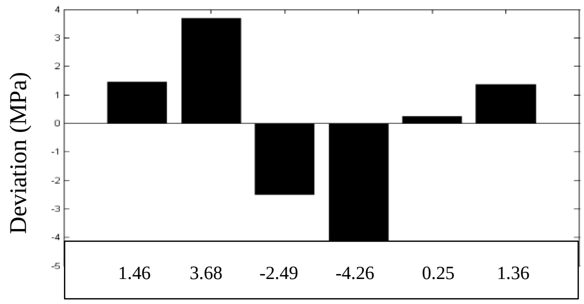

Figure 11: Deviation of calculated strength from actual strength.

8 CONCLUSION

The paper introduces a new simple test method for the assessment of compressive strength of mortar which can be extended to the field of in-situ concrete strength assessment. Commonly used methods used for in-situ strength assessment of concrete such as rebound hammer and UPV are affected by the physical properties such as hardness (in case of rebound hammer), density, cracks, and/or void (in case of UPV). This newly developed method allows to use the mechanical properties of cement mortar in the prediction of compressive strength. The paper addresses the mechanical interaction of cement mortar with screw threads subjected to loading under pushin mechanism. As the pushin mechanism subjects the mortar to crushing failure under the threads of the screw, the increase of peak load is found to be related to the increase of compressive strength. The technique shows that the estimation of compressive strength is reasonably accurate. The creation of failure plane beforehand reduces the effect of the interaction of bottom threads with mortar which results in improved results with low value of co-efficient of variation. The test program demonstrated the new technique as an alternative to currently used NDTs. It can be applied easily, quickly, and with limited cost. The proposed test has the potential to be applied in the assessment of compressive strength of concrete which will contribute to the reduction of uncertainty in the assessment of the concrete compressive strength in existing structures. It is intended to extend the test program to concrete in the future.

9 ACKNOWLEDGEMENTS

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