- Technical Report -

IN-PLACE TEST METHOD WITH PENETRATION RESISTANCE FOR LOW-STRENGTH CONCRETE

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ABSTRACT

This study involves a proposal of an in-place testing approach for concrete with a penetration resistance device. The existence of low-strength concrete (≤ 9 MPa) in buildings in Bangladesh requires a rapid evaluation of concrete compressive strength which is possible by an easy in-place test method with the penetration resistance device. Three types of pins of different diameters and shapes were used among which 2.5 mm diameter sharp pin gave the best relationship. The effect of surface roughness on the penetration depth results is also investigated which was found negligible for 2.5 mm diameter pins.

Keywords: In-place test, penetration resistance, low-strength concrete, compressive strength, surface roughness.

1. INTRODUCTION

Bangladesh is a developing country in Southeast Asia located in a tectonically active region but has not been exposed to any large magnitude earthquake within the last 150 years [1]. The collapse of reinforced concrete (RC) buildings without the occurrence of an earthquake have been encountered owing to the use of substandard materials [2]. Mainly brick aggregate is used instead of stone aggregate for making concrete due to ease of availability in Bangladesh, the former being the weaker aggregate. Moreover, the unavailability of construction regulations after the country's independence in 1971 until the publication of the first building code, Bangladesh National Building Code (BNBC) 1993 may be a reason for leading to catastrophic failure of RC buildings [3].

Prevention of future loss of lives associated with building collapses makes it necessary to identify the buildings with low-strength concrete, those have a higher risk probability of collapse. Previously executed studies show the existence of concrete compressive strength lower than 10 MPa [2]. However, due to the existence of an enormous number of buildings in the capital city of the country, Dhaka, it is not possible to perform a detailed seismic investigation to all existing buildings [4]. Moreover, the available guidelines within the country for seismic evaluation and retrofit of the existing buildings, discards the buildings having concrete compressive strength lower than 9 MPa because very low concrete strength lead too vulnerable structure to retrofit. Therefore, as a first step, easy and rapid non-destructive test methods can be useful to identify these buildings to make it easier for the responsible authority to decide the fate of these buildings. Although historically these tests that do not cause damage to the concrete are called non-destructive, new methods have emerged that result in superficial local damage [5]. The terminology in-place tests can be used for those that do not alter the concrete and result in minor surface damage. In this study, the chosen testing method is resistance to penetration, performed by a device with a pin shooting process like the Windsor pin method [5]. The targeted concrete strength range is low-strength concrete, lower than 9 MPa, thus smaller impact energy is suitable to be used on such low-strength concrete.

This study involves experimental procedures performed with a penetration probe device to obtain regression equations and explores the suitability of the device for evaluating concrete compressive strength for screening the low-strength concrete buildings in Bangladesh.

2. OVERVIEW OF IN-PLACE TEST METHODS

2.1 Conventional method of in-place tests

The purpose of in-place testing is to evaluate the compressive strength of concrete in the structure accompanied by a known relationship between the result of the test and the strength of the concrete. The significant characteristic of such tests is to estimate compressive strength indirectly. Generally, drilled cores are extracted from the existing structure at selected locations to establish a relationship empirically. In-place test methods can supplement coring and allows more economical evaluation of the concrete in structures.

The critical step in such applications is to develop a valid relationship to use the in-place test results [5]. Laboratory specimens that represent the similar properties of the targeted concrete can be used to develop

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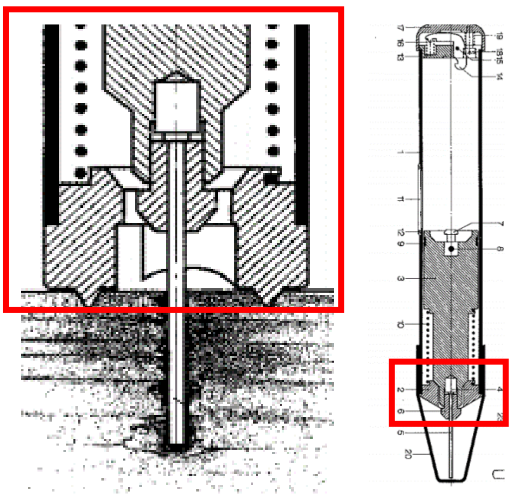
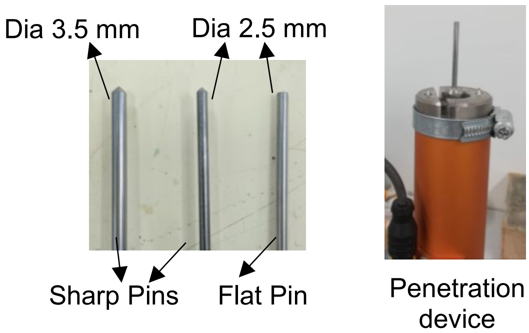
an empirical relationship between the in-place test result and the compressive strength of cylinders. The purpose of such in-place test to evaluate mortar not the whole concrete. Mortar strength can be related with concrete strength with the assumption that the aggregates do not affect concrete strength. Even the most popular in-place test method such as rebound hammer evaluates only the near surface property instead of the whole concrete. In case of penetration test, strength properties of both mortar and aggregate affects the penetration depth because the probe can travel through the mortar and aggregate in the fracture zone. For example, softer aggregate may allow greater penetration depths. Because this study deals with the very initial development of concrete strength evaluation procedure with a new penetrating device, the effect due to the difference in aggregate is not considered.



(a) Cross section of the device



(b) Types of pins

(c) Digital penetration depth measuring device

Fig. 1 Employed penetration resistance device.

2.2 Description of the penetration resistance device

The employed penetration resistance device is a handheld instrument that was originally developed in Switzerland to collect quantitative data on the degree of soft rot in wooden poles [6]. The cross section of the device is shown in Fig. 1(a.) The test involves injecting a spring-loaded pin into the target surface of concrete by shooting and reading the depth of needle penetration from a scale on the body of the instrument or in a digital device as shown in Fig 1(c). The essence of the test involves the initial kinetic energy of the pin and the energy absorbed by concrete. When the pin penetrates the concrete, some energy is absorbed by the friction of the pin and the concrete, and some of the energy is absorbed by the crushing and fracturing of the concrete.

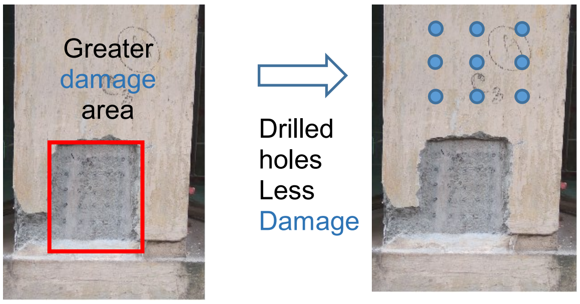
The employed penetration resistance device as shown in Fig. 1(b) has 3 types of striker pins with an impact energy of 6 J [7]. The three pins are 2.5 mm diameter sharp pin, 2.5 mm diameter flat pin and 3.5 mm diameter sharp pin. The use of the device requires contact of the concrete surface of which the compressive strength is unknown. Then the pin is driven into the concrete by a preloaded spring with a known force. The depth of the pin penetration is directly correlated to the compressive strength of the concrete. The maximum penetration depth can be automatically measured by the device itself. The measurement capacity is 40mm with an accuracy of 0.1 resolution [7]. Some of the advantages of the employed penetration resistance device includes, skilled labor is not necessary and quantitative data is available. It weighs 900 grams and easy to carry. The body is 345 mm in length with 50 mm diameter. Unlike the popular Windsor pin test, it is cheaper because the pin of employed penetration resistance device is not damaged easily when it hits an aggregate during the test due to smaller impact energy [5].

3. EXPERIMENTAL PROGRAM

3.1 Proposed method of test using the employed penetration resistance device

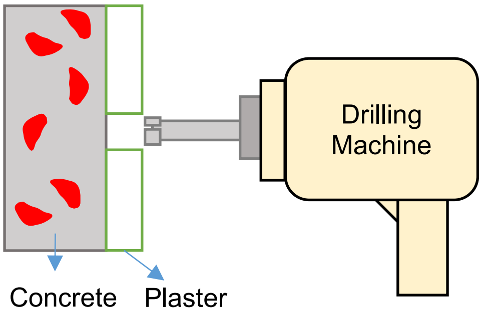
In developing countries like Bangladesh, the structural members, columns and beams, have a plaster mortar layer of 10-20 mm thickness for finishing over the actual concrete surface (shown in Fig 2). Using the in-place testing device on the plaster mortar layer will impart misguiding results. Therefore, it is necessary to peel off the surface layer first to perform the tests on the bare concrete surface. In this case, the amount of damage taking place is not less as shown in Fig. 2(a). A rough surface is exposed with visible aggregates after peeling off the upper plaster mortar layer. Mostly the red brick aggregate is found. Arranging the position of the pin becomes easier when the aggregate is visible to avoid directly hitting the aggregate. Also, to observe the effect of surface roughness on the result of the penetration resistance test, prism specimens were made with varying degrees of roughness in this study.

However, to avoid the peeling off the concrete

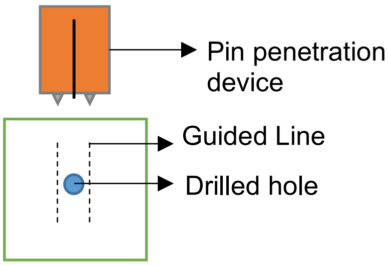


(a) Bare concrete

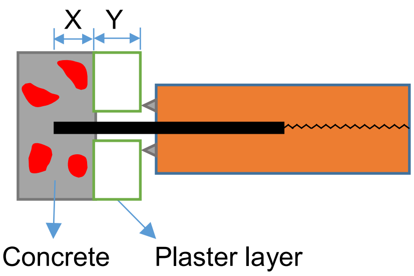
(b) Location of drilled holes



(c) Drrilling through the plaster



(d) Guidied lines to hit through the hole

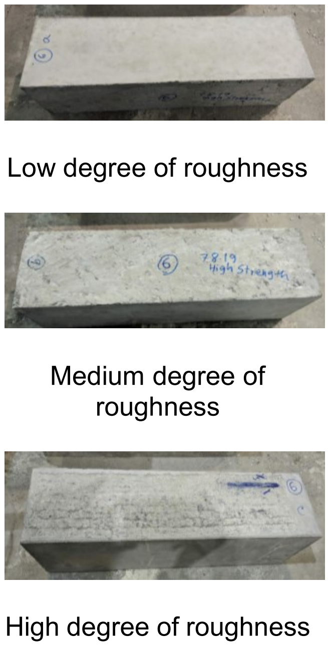


(e) Measuring penetration depth after pin penetration

Fig. 2 Schematic diagram for using penetration resistance device through the plaster mortar layer

surface holes can be drilled through the layer as shown in Fig. 2(b-c). This can reduce the amount of damage before the in-place test methods. With the use of proper guided lines in Fig. 2(d) drawn on the plaster mortar layer the device needs to be held in place and then shot through the small drilled hole. In the case of a drilled hole, the concrete surface may be disturbed and the possibility of directly hitting the aggregate remains. In this method to obtain the actual penetration depth, the thickness of the plaster mortar layer needs to be subtracted from the total penetration depth recorded as shown in Fig. 2(e). The kinetic energy of the penetrating needle may be consumed during the flight within the plaster thickness of 20 mm. However, the manufacturer claims this consumed energy is negligible for the flight of 20 mm thickness and not considered in the study.

(a) Pin penetration test on cylindrical specimen



(b) Prism specimens with different degrees of roughness

(c) Prism specimen with holes through plaster mortar layer

Fig. 3 Specimens for pin penetration test

3.2 Materials and properties

Table 1 represents the mix proportions of the specimens. Keeping in mind the abundant use of bricks in Bangladesh low-strength brick aggregate cylinders were made. Prism specimens consisting of stone aggregate were cast to observe the effect of surface roughness. Plaster mortar was applied on one of the prism specimens to perform the penetration test through holes. Considering these cases experimental procedures are done in 3 steps.

- Cylindrical specimens made of crushed brick chips as aggregate with varying water cement ratios Fig. 3(a).
- Prism specimens with different degree of surface roughness as shown in Fig. 3(b).

Table 1 Mix proportions of specimens

Specimen Shape	Type of Aggregate	W/C ratio	Water (kg/m^3)	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Limestone powder (LSP) (kg/m^3)
Cylinder	Brick	0.6	210	350	730	825	0
		1.0	210	210	730	825	110
		1.5	225	150	730	825	150
		2.0	235	118	716	807	160
		2.1	354	169	584	662	68
Prism	Stone	0.30	170	577	726	882	
		0.54	175	324	832	971	
		0.55	180	328	808	978	
		0.56	178	318	842	947	
		0.67	209	310.6	797.7	931	
		1.0	188.5	188.5	700	1292.4	

- Prism specimen with holes through a plaster mortar layer as shown in Fig. 3(c).

3.3 Penetration resistance test and compressive strength test

The penetration resistance device is hit on the concrete surface of each specimen; cylindrical and prism, for 5 or more times. Nine cylindrical specimens with brick aggregate were hit with 2.5 mm diameter flat pins vertically downwards on the flat concrete floor. In case of stone aggregate prism specimens, the instrument was shot both vertically and horizontally. While hitting horizontally, the prism specimens were kept against a wall so that it does not move during the test. While performing the penetration, resistance test a cone shaped region in which the concrete is heavily fractured is created. The mean penetration value after excluding penetration depths greater than +20% and smaller than -20% of the first calculated mean, is considered in results. In this way the results obtained by directly hitting on aggregate is excluded which is required for penetration resistance test methods according to the standard ASTM C803. To know the compressive strength the same cylinders of 100 mm diameter and 200 mm length were tested according to ASTM C39. However, in case of the brick aggregate cylinder specimens the penetrated surface were made smooth in a grinder machine before performing the compressive strength test on the same specimen. The 2.5 mm diameter pins became blunt and damaged after approximately 95 times of hitting on concrete strength below 40 MPa.

3.4 Measurement of surface roughness

The surface roughness measurement is done according to ISO-25178. A 3D scanning device as shown in the Fig 4(a) is used. A mean is considered on the height screen for the measurement area specified. While calculating the deviation of height distribution the height of the reference surface is considered 0. The arithmetic mean height *Sa* is calculated as follows;

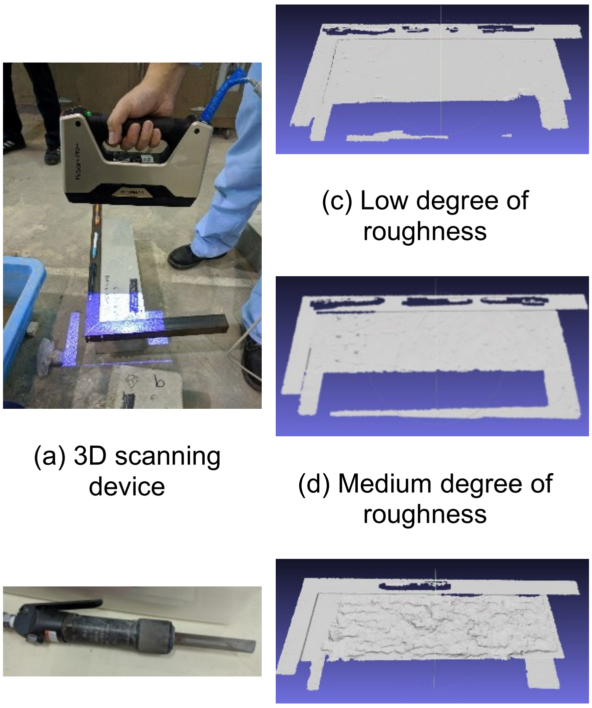
$$Sa = \frac{1}{A}\iint_A |z(x,y)|\, dxdy \qquad (1)$$

Where, A is the number of measurement points along area A, $z\,(x, y)$ is height at position (x, y)

On each prism specimen 3 type of surfaces were made as shown in Fig. 4 (c), (d) and (e). Depending on the value of *Sa* the degree of roughness is defined as low, medium and high. The higher the *Sa* value the rougher the surface. The three surfaces are:

- Surface attached to the steel mold (low roughness, smooth surface)
- Surface at the casting side above the mold covered with polyethylene (medium roughness, moderate surface)
- Surface made rough using an air compressor chipper shown in Fig. 4(b) (high roughness, rough surface)

Plaster layer was applied on one of the prism specimens.



(a) 3D scanning device

(b) Air compressor chipper

(c) Low degree of roughness

(d) Medium degree of roughness

(e) High degree of roughness

Fig. 4 Measurement of surface roughness with 3D scanning

4. RESULTS AND DISCUSSION

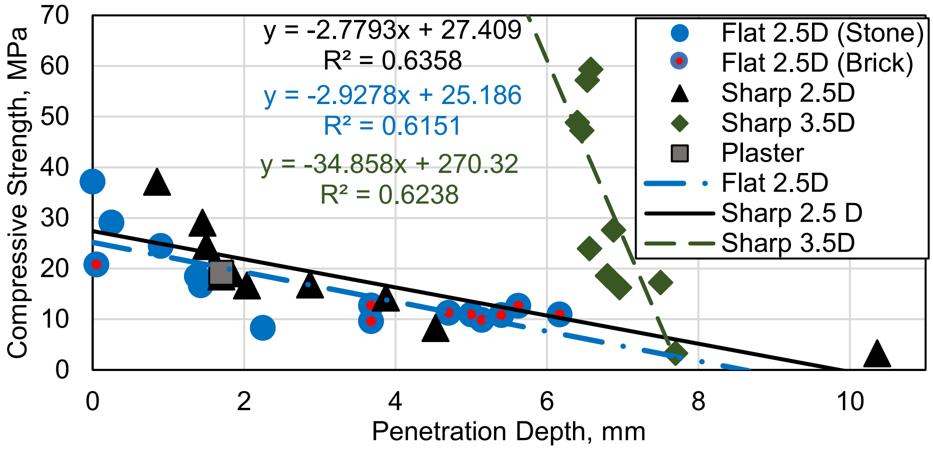
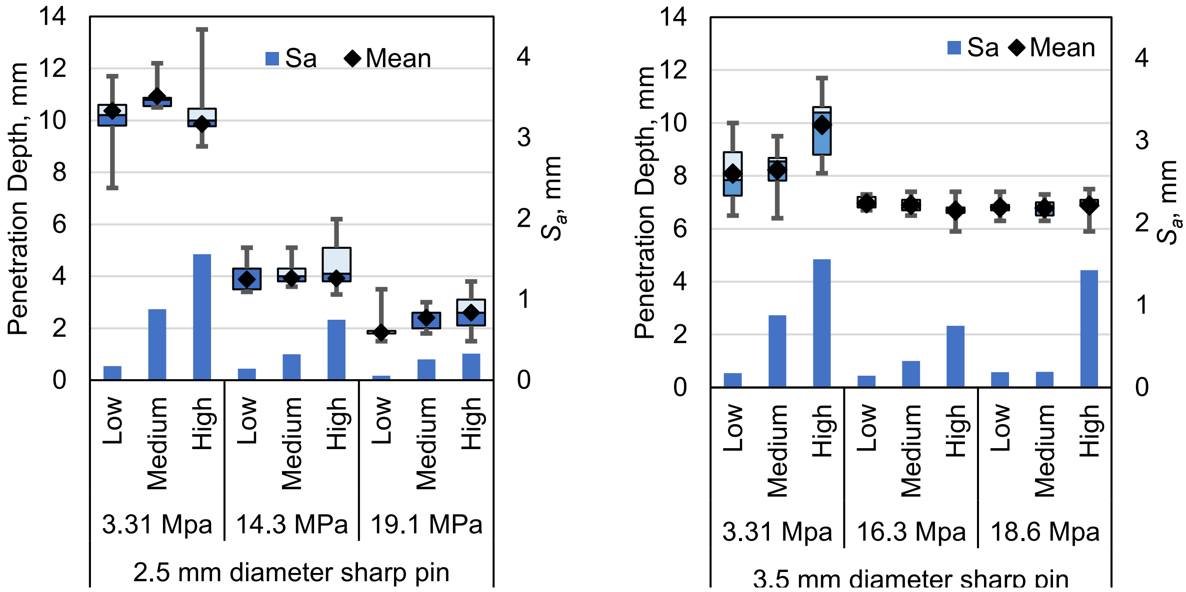


Fig. 5 Results of penetration tests



(a) Results for 2.5 mm diameter sharp pin (b) Results for 3.5 mm diameter sharp pin

Fig. 6 Results of penetration depths and surface roughness

In Fig 5 the penetration depths of the penetration resistance device with compressive strengths are shown. Linear relationships are chosen which give the highest R^2 values than other relationships, for example, power, exponential, etc. The shape of the pin is indicated by flat or sharp and the diameter of the pin is indicated by 2.5D (2.5 mm diameter) or 3.5D (3.5 mm diameter).

The regression curve for 2.5D flat pins is shown as the blue dot dashed line. Basically, all the blue round legends including the ones with the red points are used to derive this curve. The red points on the blue round legends represent the 9 results from brick aggregate cylinders and other blue round legends show results from stone aggregate specimens. The brick aggregate low-strength concrete cylinders show higher penetration depths than the result obtained from the stone aggregate specimen. The brick aggregate cylinders were of lower compressive strength thus no bending or bluntness was observed even when the pin hit on the aggregate.

The black triangular legends are used to formulate the regression curve of 2.5D shown as the black solid line. The square ash colored legend shows the result through the plaster using the 2.5 mm diameter sharp pin. The closer alignment of this result with the formulated regression curve of 2.5D proves that the sharp pin can be used through plaster mortar layer with the proposed methodology. This result through the plaster mortar layer is not used to obtain the regression curve of 2.5D. Both the thinner pins of 2.5 mm diameter, flat and sharp, give relationships with flatter slope. Thus, it is easier to determine the compressive strength for specific penetration depth with these two pins. On the other hand, the sharp 3.5D pin gives a relationship which has a very steep slope as shown by the dashed green line. This regression curve is obtained using the green diamond legends that represents the results obtained using 3.5 mm diameter pins. Because of the steep slope, it is difficult to differentiate the compressive strength for specific penetration depth. In other words, the penetration depth is found similar, within 7mm – 8mm of penetration depth for compressive strength 18.6 MPa and 59.4 MPa. In the case of, 3.31 MPa the sharp 2.5 mm diameter pin has a penetration depth greater than the sharp 3.5 mm diameter pin. Due to the poor bonding between the cement matrix and aggregate in the low-strength concrete specimen the thinner shaped pin was able to penetrate more than the thicker pin.

The results of the penetration resistance device for varying degrees of roughness, low, medium and high, are shown in Fig 6. Results of the arithmetic mean height S_a is also shown on the secondary Y-axis. A higher value of S_a indicates a high degree of roughness and a lower value of S_a indicates a low degree of roughness. The distribution of the data set for a specific specimen and degree of roughness is shown by the error bars and box plots. The highest and lowest point of error bars indicate the maximum and minimum penetration depths. The first quartile, median and third quartile are shown by the lowest point of the box, line across the box and highest point of the box. The mean penetration depths are calculated considering the penetration depths within ±20% of the first mean obtained on 3 types of surfaces. The obtained mean penetration depths for 3.31 MPa with 2.5 mm diameter pins are 10.36 mm, 10.93 mm and 9.86 mm, which are very close to each other. Also, the mean penetration depths obtained from 14.3 MPa and 19.1 MPa specimen are very close to each other in spite of the distance between maximum and minimum penetration depths. In the case of very low-strength concrete, 3.31 MPa, aggregates were observed to fall when the pin hit the rough concrete surface. During the preparation of rough surface with an air compressor chipper, the aggregates were also observed to loosely bonded with the cement matrix due to the lean concrete mix. This contributed to higher penetration depths on the surface of high roughness than the penetration depth obtained on the surface of a low degree of roughness with the thicker pin. ACI also specifies a smooth surface layer with trowel finish can result in low penetration values which is the case for the surface having a low degree of roughness [5].

In Fig 6(b) the penetration depths obtained from the 3.5 mm diameter pin on various surface roughness are obtained. In the case of 3.31 MPa, the surface having a high degree of roughness shows a penetration depth value of 9.92 greater than the mean penetration depths from the low and medium degree of roughness which are 8.1 mm and 8.2 mm consecutively. However, the mean penetration depths are similar where no significant difference in penetration depths are observed with the difference in surface roughness for 16.3 MPa and 18.6 MPa specimens, therefore, the effect of surface roughness can be neglected for both type of pins when the mean penetration depth is calculated considering the values within ±20% of the first mean penetration depth. Also, from Fig 5 and Fig 6, it can be stated that the 2.5 mm diameter sharp pin is the most suitable pin to use among the three pins used in this experiment. In Fig 5 when the penetration depth is greater than 6.6 mm the penetration depth indicates low-strength concrete (≤ 9 MPa).

5. CONCLUSIONS

This study describes the in-place testing approach with the proposed penetration resistance device and examines its suitability to use on the concrete of stone and brick aggregate with pins of different diameters and shapes. A method to perform in-place tests through plaster with the device is proposed. The obtained penetration depth result through the plaster hole shows good alignment with the obtained regression line of 2.5 mm diameter pin. The thinner diameter pin of 2.5 mm diameter is found suitable over the thicker diameter pin of 3.5 mm diameter for the low-strength concrete and a regression equation is proposed for the former. Finally, the surface roughness of the bare concrete surface in existing structural members is also considered, and the effect of roughness is found negligible when the mean penetration depth is calculated by considering the penetration depths of ±20% of the first mean of all collected penetration depths.

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