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A Nondestructive Testing Technique: Nail Penetration Test

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This study presents a practical nondestructive testing (NDT) method: the nail penetration test (NPT). The major tools of the test technique are a gas nailer with 130 J (95.88 ft-lbf) power, concrete nails, and a gas nailer cell. The study covers three different limestone aggregate types. Six concrete mixtures were prepared from each aggregate type. Five nail shots were performed on each concrete mixture (or grade) and the average value was obtained.

The average nail penetration depths were correlated with the compressive strength of concrete. Other NDT techniques, such as the Schmidt rebound hammer (SRH), ultrasonic pulse velocity (UPV), and Windsor probe (WP), were also applied to concrete samples. The measured compressive strength values were compared with those obtained from the empirical relationships using the data from the NPT, SRH, UPV, and WP. It was found that the reliability of the NPT to estimate the compressive strength of concrete is very high. The tool employed in the investigation covers a relatively wide range of compressive strength of concrete. This testing tool is proposed to estimate the compressive strength of in-place concrete.

Keywords: compressive strength; nail penetration test; nondestructive testing; Windsor probe.

INTRODUCTION

The compressive strength of concrete is the most common measure used by engineers to determine the actual strength of the concrete. The most effective way of determining the compressive strength of concrete is to measure it by breaking cylindrical or cubic concrete specimens in a compression testing machine. While this test method appears to be relatively simple, it is destructive, costly, and time-consuming. In addition, the compressive strength of cylindrical or cubic concrete specimens prepared in a laboratory does not represent the strength of in-place concrete. Therefore, the standard method is mostly chosen to determine the potential compressive strength of in-place concrete. Some difficulties exist concerning high-quality coring samples due to densely reinforced bars or fragile units. For these reasons, the general trend in estimating the compressive strength of concrete is to use nondestructive testing (NDT) methods, such as the Schmidt rebound hammer (SRH), ultrasonic pulse velocity (UPV), and penetration test (PT). These NDT methods are lightweight, quick, cost-effective, and completely nondestructive.[1]

The SRH (also called the Swiss hammer), principally a surface hardness tester, is extensively used in evaluating the compressive strength of concrete due to its simplicity, portability, low cost, and nondestructive applications.[2] Some common applications of the SRH can be divided into the following categories: verification of uniformity of concrete quality, estimation of modulus of elasticity, abrasion resistance classification, and estimation of the flexural strength of concrete.[2-4] Although this testing device offers great advantages because of its aforementioned properties, the SRH values are affected by a number of factors, such as the size of the specimens, age of the sample, surface and internal moisture conditions of the concrete, type of coarse aggregate, type of cement, carbonation of the concrete surface, and orientation of the hammer.[2] In addition to the drawbacks of SRH, the SRH values obtained are very sensitive to local changes in concrete[5] and reflect the outer surface of concrete and a depth of 1.2 to 2.0 in. (30 to 50 mm).[6,7] According to many researchers, there is a general correlation between the compressive strength of concrete and the rebound number; however, there is a wide degree of disagreement among various researchers concerning the accuracy of the estimation of strength from the rebound readings and the empirical relationship.[8] The probable accuracy of estimation of concrete strength in a structure is ±25%. Carette and Malhotra[9] pointed out that the SRH was not a satisfactory method for reliable estimates of the strength of concrete at early ages. Aydin and Saribiyik[10] reported that the use of the SRH method on existing buildings is not suitable to estimate the strength of old concrete. The general opinion among many concrete technologists is that SRH tests are best suited for use as a means of checking the uniformity of concrete quality.[7,8]

UPV is another NDT technique to predict the compressive strength indirectly. The method consists of measuring the time of travel of an ultrasonic pulse passing through the concrete. Knowing the direct path length between the transducers and the time of travel, the pulse velocity through the concrete can be obtained. The test results are very sensitive to the mixture ratio, moisture content, aggregate properties, pores and fractures, surface conditions, and the location of steel reinforcement in the concrete.[11] Steel reinforcement is a particular problem because the pulse velocity through steel is approximately 40% greater than that through concrete.[8] UPV testing has great potential for concrete conditions, particularly for establishing uniformity and detecting pores or fractures.[12] The usability of this test for predicting strength is much more limited[13,14] because of the large number of variables affecting the relation between strength and pulse velocity.

PTs and pin penetration tests (PPTs) are widely used to determine the strength of concrete. In penetration techniques, the concrete strength is estimated by forcing a steel probe with explosive capsules into the concrete surface and measuring the exposed length of the probe on the concrete. The commercial equipment used in PTs is known as a Windsor probe (WP).[15] This technique yields more reliable results than the SRH.[2] Also, the PT is less affected by surface conditions (texture, moisture content, and surface irregularities) than the SRH.[2,8] One of the main factors that

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Fig. 1—(a) Nail PT apparatus and its application; and (b) external and (c) internal appearance. (Note: 1 mm = 0.0394 in.)

will influence the depth of penetration of the probe is the type of coarse aggregate used in the concrete. In an effort to account for this, the manufacturers of the test equipment suggest that the Mohs scale of hardness should be used to classify the different types of coarse aggregate. On the other hand, researchers have suggested that results obtained with respect to aggregate type are not reliable.[2] Although the WP is called an NDT technique, the application of the thick probe (0.24 in. [6.3 mm] in diameter) to the concrete with an explosive capsule causes a fracture zone on the concrete surface. When the probe is removed from the concrete, a conical space generally forms in the fracturing concrete.[2,8] Applying only one explosive-loaded capsule for a probe is another restriction in the applications. All of these are setbacks for the repetitive performance of the technique. Also, the use of explosive capsules and probes is not economical.

A smaller-scale version of this test was also developed by Nasser and Al-Manaseer.[16,17] The PPT is similar in principle to the PT, with a spring-loaded hammer being used to drive a steel pin. The main difference between the two tests is that the PPT requires considerably less energy (approximately 1.5% of the energy delivered by the WP). Owing to the low energy, the penetration of the pin is greatly reduced if the pin encounters a coarse aggregate particle. Thus, the test is intended as a PT of the mortar fraction of the concrete. The sensitivity of the pin penetration to changes in compressive strength decreases for a concrete strength greater than 4 ksi (28 MPa).[18] For this reason, the PPT system is not recommended for testing concrete with a compressive strength greater than 4 ksi (28 MPa).[8]

The goal of this investigation is to propose a practical NDT method for concrete. The major tool in the proposed technique is a gas nailer produced for concrete. Kayabali and Selcuk[19] used the nail penetration test (NPT) to indirectly determine the compressive strength of intact rocks. The application of the gas nailer to estimate the compressive strength of concrete is a novel subject. A relationship between nail penetration depth and the compressive strength of concrete was sought. This investigation also includes some other NDT techniques, such as the SRH, UPV, and PT to comparatively demonstrate the superiority of the proposed method.

RESEARCH SIGNIFICANCE

NDT methods are widely used to determine the compressive strength of concrete. The reliability and accuracy of the NPT to assess compressive strength indirectly and quantitatively seem to be higher than those of the SRH and PT. The proposed testing tool has the main advantages of portability, robustness, quickness, low cost, and nondestructiveness, depending on the use. In addition to the substitution with the SRH and PT (WP) in many applications requiring determination of the compressive strength of concrete, the proposed equipment would be considered for long-term changes of in-place concrete strength to investigate the uniformity and quality of in-place concrete. The authors believe that the method has the potential to be a standard index test to estimate concrete strength.

NPT

The major tool for the proposed technique is a gas nailer produced for concrete (Fig. 1). Nails ranging from 1.2 to 1.8 in. (30 to 45 mm) long are applied to the concrete with the nail gun. Nails are usually driven by compressed air (pneumatic), highly flammable gases such as butane and propane, or powder. The variation of the driving power is ± 0.01 for pneumatic nailers.[20] The gas nailer used in this study uses a gas cell containing compressed gas. Because the gas supply is constant, by repeated nailer action, the nail is driven into the material under a constant pressure.

The depth of penetration of the nails is an indicator of the concrete strength—that is, the weaker the concrete, the deeper the nail penetration should be, and vice versa. The nail gun operates with a gas cartridge exerting as much as 95.88 ft-lbf (130 J) on 0.1 in. (2.6 mm) diameter pointy nails.

Table 1—Mechanical and physical properties of aggregates

Properties			HSN limestone	KTL limestone	KYM limestone
Mechanical	Compressive strength, ksi (MPa)		9.6 (65.9)	10.4 (71.9)	8.9 (61.1)
	Schmidt rebound test R_{ort}		51.8	56.3	49.4
	Ultrasonic velocity test, mile/s (km/s)		3.87 (6.2)	4.1 (6.6)	3.6 (5.8)
	Point load strength test, ksi (MPa)		0.5 (3.6)	0.6 (4.1)	0.5 (3.2)
Physical	Density, lb/ft^3 (g/cm^3)	0 to 4	167.30 (2.68)	167.93 (2.69)	167.30 (2.68)
		4 to 11.2	167.93 (2.69)	167.93 (2.69)	167.93 (2.69)
		11.2 to 22.4	168.55 (2.70)	166.68 (2.67)	168.55 (2.70)
	Water absorption, %	0 to 4	0.50	0.76	0.65
		4 to 11.2	0.40	0.40	0.64
		11.2 to 22.4	0.31	0.28	0.58

Notes: 1 ksi = 6.89 MPa; 1 lb/ft^3 = 0.016 g/cm^3; 1 mile/s = 1.61 km/s.

Table 2—Chemical, physical, and mechanical characteristics of cement used

<table>
<tr><th colspan="2">Chemical composition, %</th><th colspan="4">Physical properties</th></tr>
<tr><td>SiO_2</td><td>20.35</td><td colspan="3">Fineness, in.^{2}/lb (cm^2/g)</td><td>11.4 (3350)</td></tr>
<tr><td>Al_2O_3</td><td>5.98</td><td colspan="3">Soundness, in. (mm)</td><td>0.04 (1)</td></tr>
<tr><td>Fe_2O_3</td><td>3.06</td><td colspan="3">Temper water, %</td><td>27.2</td></tr>
<tr><td>CaO</td><td>63.35</td><td colspan="3">Initial set, minutes</td><td>106</td></tr>
<tr><td>MgO</td><td>1.89</td><td colspan="3">Final set, minutes</td><td>189</td></tr>
<tr><td>SO_3</td><td>2.89</td><td colspan="3">Density, lb/ft^3 (g/cm^3)</td><td>193.5 (3.1)</td></tr>
<tr><td>Na_2O</td><td>0.58</td><td rowspan="3">Mechanical properties</td><td>Day</td><td>Compressive strength, ksi (MPa)</td><td>Flexural strength, ksi (MPa)</td></tr>
<tr><td>K_2O</td><td>0.88</td><td>7</td><td>5.9 (40.8)</td><td>1.1 (7.3)</td></tr>
<tr><td>Loss on ignition</td><td>0.50</td><td>28</td><td>7.5 (51.9)</td><td>1.5 (10.1)</td></tr>
</table>

Notes: 1 ksi = 6.89 MPa; 1 lb/ft^3 = 0.016 g/cm^3; 1 in. = 25.4 mm.

A single gas cartridge provides approximately 700 shots serially. The NPT is similar to the PT, except that the nail impacts the concrete with less energy than the probe of the PT (WP test). Owing to the low energy level and small diameter of the steel nails, the penetration does not create any fracture zone or hole in the surface of the concrete.

The gas nailer can be held in any position. It should be at nearly a right angle to the concrete (or in-place concrete) surface. Shots deviating significantly from perpendicularity cause chiseling of the concrete surface and bending of the nails outside the concrete. In this case, the test should be rejected as invalid.

The gas nailer provides some security systems. The gas nailer does not allow the nails to be fired unless the operator does not compress the muzzle on the surface of the concrete. This works well when the operator does not develop the right touch to let the gun recoil. Also, the goggles and earplugs offer safety to the operator in applications. In addition to the advantages of this method, gas nailers have been widely used in the construction industry to make fastenings into concrete, masonry, and structural steel without predrilling holes, and authorized gas nailer distributors offer complete training programs for end users.

EXPERIMENTAL STUDY

Materials

Three different crushed limestone aggregates were used in the investigation. Limestone aggregates were collected from quarries in Hasanoglan, HSN (Ankara, Turkey); Kutludugun, KTL (Ankara, Turkey); and Kaymaz, KYM (Eskisehir, Turkey). The limestones used have a compact texture and fine grain size. The mechanical and physical properties of the limestone aggregate rocks were determined by a variety of laboratory tests in accordance with the procedures given by ASTM International. The compressive strength, Schmidt rebound number, ultrasonic velocity, point load strength index, density, and water absorption ratio of the aggregate rocks are presented in Table 1.

Type CEM I 42.5 R portland cement was used for the production of concrete. The chemical, physical, and mechanical characteristics of the cement are shown in Table 2. To produce high-strength concrete with a low water-cement ratio (*w/c*), a Type F high-range water-reducing admixture additive was used, which is consistent with ASTM C494/C494M-99ae1.[21]

Method

Six concrete mixtures were prepared for each limestone aggregate type. The *w/c* and cement amount were kept constant in each concrete mixture of the limestone aggregate types, as shown in Table 3. Nine cubic concrete samples with dimensions of 5.9 x 5.9 x 5.9 in. (150 x 150 x 150 mm) and one plate concrete sample with dimensions of 19.6 x 19.6 x 5.9 in. (500 x 500 x 150 mm) were cast from each concrete mixture. A total of 162 cubic samples and 18 plate samples were prepared with the same dimensions using three different aggregate types. All of these samples were cured in lime-saturated water for 28 days and then dried in a large oven at 221 ± 41°F (105 ± 5°C) for 24 hours. Four uniaxial compression tests and five NPTs were performed on nine separate cubic samples to determine the average compressive strength and nail penetration values of each concrete mixture

Table 3—Mixing ratios of concrete

Mixture marking	Cement, lb/ft^3 (kg/m^3)	Water, lb/ft^3 (kg/m^3)	*w*/*c*	High-range water-reducing admixture, lb/ft^3 (kg/m^3)	Groups 0 to 4, lb/ft^3 (kg/m^3)	Groups 4 to 11.2, lb/ft^3 (kg/m^3)	Groups 11.2 to 22.4, lb/ft^3 (kg/m^3)	Total, lb/ft^3 (kg/m^3)
HSN 1	19.9 (318.8)	13.7 (220)	0.69	—	44.2 (709.2)	32.6 (523.4)	32.8 (525.6)	143.4 (2297.0)
HSN 2	22.8 (366.7)	13.7 (220)	0.60	—	43.2 (692.5)	31.9 (511.1)	32.0 (513.2)	143.8 (2303.6)
HSN 3	25.4 (407.4)	13.7 (220)	0.54	—	42.3 (678.4)	31.3 (500.7)	31.4 (502.7)	144.2 (2309.2)
HSN 4	32.7 (523.8)	13.7 (220)	0.42	—	39.8 (637.8)	29.4 (470.8)	29.5 (472.7)	145.2 (2325.1)
HSN 5	37.1 (594.6)	13.7 (220)	0.37	0.4 (5.9)	38.3 (613.2)	28.3 (452.6)	28.3 (454.4)	145.7 (2334.8)
HSN 6	42.9 (687.5)	13.7 (220)	0.32	0.6 (10.3)	36.3 (580.9)	26.7 (428.7)	26.8 (430.5)	146.7 (2351.0)
KTL 1	19.9 (318.8)	13.7 (220)	0.69	—	43.8 (702.6)	32.8 (526.6)	32.8 (527.0)	143.2 (2295.0)
KTL 2	22.8 (366.7)	13.7 (220)	0.60	—	42.8 (686.1)	32.1 (514.2)	32.1 (514.6)	143.6 (2301.6)
KTL 3	25.4 (407.4)	13.7 (220)	0.54	—	41.9 (672.1)	31.4 (503.7)	31.4 (504.1)	144.0 (2307.2)
KTL 4	32.7 (523.8)	13.7 (220)	0.42	—	39.4 (631.9)	29.5 (473.6)	29.5 (473.9)	145.0 (2323.3)
KTL 5	37.1 (594.6)	13.7 (220)	0.37	0.4 (5.9)	37.9 (607.5)	28.4 (455.3)	28.4 (455.6)	145.6 (2333.0)
KTL 6	42.9 (687.5)	13.7 (220)	0.32	0.6 (10.3)	35.9 (575.5)	26.9 (431.3)	26.9 (431.6)	146.6 (2349.3)
KYM 1	19.9 (318.8)	13.7 (220)	0.69	—	44.4 (710.5)	32.7 (524.8)	32.5 (520.7)	143.3 (2294.8)
KYM 2	22.8 (366.7)	13.7 (220)	0.60	—	43.3 (693.8)	31.9 (512.5)	31.7 (508.4)	143.6 (2301.4)
KYM 3	25.4 (407.4)	13.7 (220)	0.54	—	42.4 (679.6)	31.3 (502.0)	31.1 (498.0)	144.0 (2307.0)
KYM 4	32.7 (523.8)	13.7 (220)	0.42	—	39.9 (639.0)	29.4 (472.0)	29.2 (468.3)	145.0 (2323.1)
KYM 5	37.1 (594.6)	13.7 (220)	0.37	0.4 (5.9)	38.3 (614.3)	28.3 (453.8)	28.1 (450.2)	145.6 (2332.9)
KYM 6	42.9 (687.5)	13.7 (220)	0.32	0.6 (10.3)	36.3 (581.9)	26.8 (429.8)	26.6 (426.4)	146.6 (2349.0)

Note: 1 lb/ft^3 = 16.01 kg/m^3.

(or grade). The plate samples were prepared for the WP test as one plate for each mixture. SRH and UPV tests were carried out on all concrete samples prior to the application of the NPT, PT, and uniaxial compressive test.

The maximum aggregate size D_{max} value of the aggregate used in the concrete samples was selected as 0.88 in. (22.4 mm), which consists of three groups of 0 to 0.15, 0.15 to 0.44, and 0.44 to 0.88 in. (0 to 4, 4 to 11.2, and 11.2 to 22.4 mm). The aggregate grain size distribution was computed as suggested by Fuller and Thompson[32] and used as suitable for ASTM C33-03.[22] The mixing ratios of the designed concrete are given in Table 3.

Experiments performed on samples

Five testing techniques were employed in this investigation. They include the uniaxial compressive strength in accordance with ASTM C39/C39M-05e2,[23] the PT in accordance with ASTM C803/C803M-03,[24] the SRH in accordance with C805/C805M-08,[25] the UPV in accordance with ASTM C597-02,[26] and the NPT proposed as a novel technique for indirect determination of concrete strength. The details of each testing method are explained in the following paragraphs.

A 675 kip (3000 kN) capacity machine was used to measure the compressive strength of the concrete. Concrete blocks of different strengths for each aggregate type were subjected to compression with a loading speed of 540 lbf/s (2.4 kN/s), and the average compressive strength was obtained.

ASTM C805/C805M-08[25] was employed for SRH applications. To avoid orientation corrections, the hammer was held downward at a right angle to the concrete surface. Prior to the experiments, concrete samples were set on a smooth floor against any disturbance during SRH applications. Ten single impacts were performed on each concrete cube sample with dimensions of 5.9 x 5.9 x 5.9 in. (150 x 150 x 150 mm). Then, the average rebound hardness value for each concrete mixture was determined. Once the SRH test was complete, the two surfaces of cube samples were prepared for the UPV test as described in ASTM C597-02.[26] The time was measured on each of the two opposing surfaces and the average was recorded.

The WP shown in Fig. 2 has a diameter of 1/4 in. (6.3 mm) and length of 2.9 in. (73.7 mm). Three shots were carried out on each plate sample with the dimensions of 19.6 x 19.6 x 5.9 in. (500 x 500 x 150 mm). The applications were carried out such that the shot points were sufficiently far from the edges of the plate to prevent disintegration. The exposed lengths of the probes were determined using a depth gauge. At the end, the mean values were calculated from three exposed lengths of probes.

The literature review revealed that the gas nailer has never been applied to concrete for determining the compressive strength of concrete. The applications were carried out such that the shot points were at least 1.96 in. (50 mm) from the edges of the concrete samples to prevent disintegration. A total of five shots were performed on five separate cubic samples with dimensions of 5.9 x 5.9 x 5.9 in. (150 x 150 x 150 mm) for each concrete mixture.

Only one NPT was performed on each concrete sample owing to the limitation with dimensions. The surfaces of the concrete blocks were smoothed against any possible disturbance during nail penetration. This precaution also helped the operator to place the nailer in a proper position on the upper surface of the concrete samples. To reduce any possible movement of the concrete sample, a further precaution was taken by securing the concrete sample on the floor and tightly pressing the nailer on the sample. Nails 1.8 in. (45 mm) long were used on each concrete sample. The length of the nail outside the concrete sample was measured by a digital caliper (sensitivity of 0.01 mm) and the penetration depth was obtained after deducting this length from the total length of the nail. The average of five shots was rounded to the nearest tenth.

Regarding the repeatability of the proposed method, a series of NPTs was conducted on a large concrete block. The compressive strength of the concrete was 3.77 ksi (26 MPa). The dimensions of the concrete block using the HSN-2 group aggregate were 39.4 x 39.4 x 5.9 in. (1000 x 1000 x 150 mm). Twenty-five shots made on the concrete block gave mean, minimum, and maximum values of 1.35, 1.28, and 1.42 in. (34.3, 32.6, and 36.1 mm), respectively. The standard deviation was 0.04 in. (1.0 mm). This series of tests demonstrates that the proposed method is repeatable for the gas nailer employed in this investigation.

Fig. 2—Application of Windsor probe test.

RESULTS AND DISCUSSION

The mean values of all five test methods (that is, the uniaxial compressive strength, SRH, UPV, PT [WP], and NPT) are presented in Table 4. A series of regression analyses was carried out to determine the best empirical correlations of all five test methods, as shown in Fig. 3. Regression analyses reveal that an acceptable relationship exists between the compressive strength and the nail penetration depth. The nail penetration depth *d* increases with decreasing compressive strength of concrete, as seen in Fig. 3. The regression coefficients R^2 for the nail penetration depth, WP penetration, and SRH values versus uniaxial compressive strength are found to be 0.95, 0.92, and 0.90, respectively. The regression coefficient between ultrasonic velocity and compression strength is somewhat lower (Fig. 3). In addition to regression coefficients, the correlation coefficients for the nail penetration depth, WP penetration, and SRH values versus uniaxial compressive strength are found to be 0.92, 0.88, and 0.87, respectively.

The following empirical relationship between the nail penetration depth *d* and the uniaxial compressive strength of concrete was established

$$f_c\ (\text{MPa}) = -2.686d + 120 \qquad (1)$$

where *d* is the nail penetration depth, in mm. The measured compressive strength values were compared with those obtained from the empirical relationships using the data from the SRH, UPV, PT, and NPT, as shown in Fig. 4. It

Table 4—Average test results

Mixture type	Compressive strength f_c, ksi (MPa)	COV, %	Schmidt rebound number, R_N	COV, %	UPV, mile/s (km/s)	COV, %	Windsor probe test, in. (mm)	COV, %	NPT d, in. (mm)	COV, %
HSN 1	3.5 (24.4)	1.4	22.0	3.6	2.71 (4.36)	3.6	1.87 (47.5)	6.4	1.38 (35.1)	5.9
HSN 2	3.9 (26.6)	6.1	24.2	2.3	2.73 (4.39)	0.9	1.90 (48.3)	4.3	1.37 (34.8)	7.3
HSN 3	4.5 (31.0)	1.3	24.8	2.0	2.82 (4.54)	0.8	1.93 (49.2)	6.7	1.24 (31.5)	2.0
HSN 4	5.4 (37.0)	0.1	26.9	1.6	2.91 (4.69)	1.2	1.97 (50.1)	3.5	1.18 (30.0)	5.2
HSN 5	7.0 (48.0)	3.7	32.6	1.7	2.93 (4.71)	1.1	1.98 (50.5)	9.2	1.12 (28.5)	3.7
HSN 6	8.9 (61.3)	3.1	32.7	3.0	2.94 (4.73)	0.6	2.04 (51.9)	4.4	0.90 (23.1)	4.2
KTL 1	3.4 (23.5)	5.7	21.0	5.7	2.72 (4.38)	0.02	1.86 (47.3)	1.3	1.41 (36.0)	8.7
KTL 2	4.1 (28.0)	2.9	26.0	2.6	2.77 (4.45)	2.4	1.88 (48.0)	1.9	1.31 (33.5)	6.3
KTL 3	4.4 (30.4)	5.9	24.2	4.8	2.85 (4.60)	0.5	1.91 (48.7)	5.5	1.29 (33.0)	1.5
KTL 4	5.8 (39.9)	3.7	26.5	2.6	2.90 (4.66)	0.7	1.94 (49.3)	8.0	1.14 (29.1)	1.4
KTL 5	6.4 (44.0)	1.9	29.5	5.7	2.93 (4.71)	2.1	1.96 (50.0)	8.2	1.05 (26.8)	8.3
KTL 6	8.6 (59.4)	0.1	34.3	2.8	2.94 (4.73)	0.6	2.01 (51.3)	1.2	0.84 (21.4)	2.6
KYM 1	3.5 (23.9)	1.2	22.2	2.3	2.58 (4.15)	0.3	1.85 (47.1)	9.2	1.45 (37.0)	2.5
KYM 2	3.9 (27.0)	3.1	24.9	4.1	2.67 (4.30)	0.4	1.89 (48.1)	8.6	1.39 (35.4)	4.3
KYM 3	4.9 (33.9)	0.1	26.6	4.1	2.73 (4.40)	1.0	1.92 (49.0)	2.0	1.24 (31.5)	4.1
KTM 4	5.7 (39.0)	0.4	28.2	2.5	2.82 (4.54)	0.3	1.96 (49.9)	2.9	1.13 (28.8)	2.4
KYM 5	7.1 (49.2)	5.0	32.0	4.7	2.84 (4.57)	3.5	1.99 (50.8)	3.0	1.02 (26.0)	5.0
KYM 6	9.4 (64.7)	1.1	33.3	2.0	2.94 (4.73)	3.3	2.03 (51.6)	0.3	0.87 (22.1)	6.3

Notes: UPV is ultrasonic pulse velocity test; NPT is nail penetration test; COV is coefficient of variation of test data; 1 ksi = 6.89 MPa; 1 in. = 25.4 mm; 1 mile/s = 1.61 km/s.

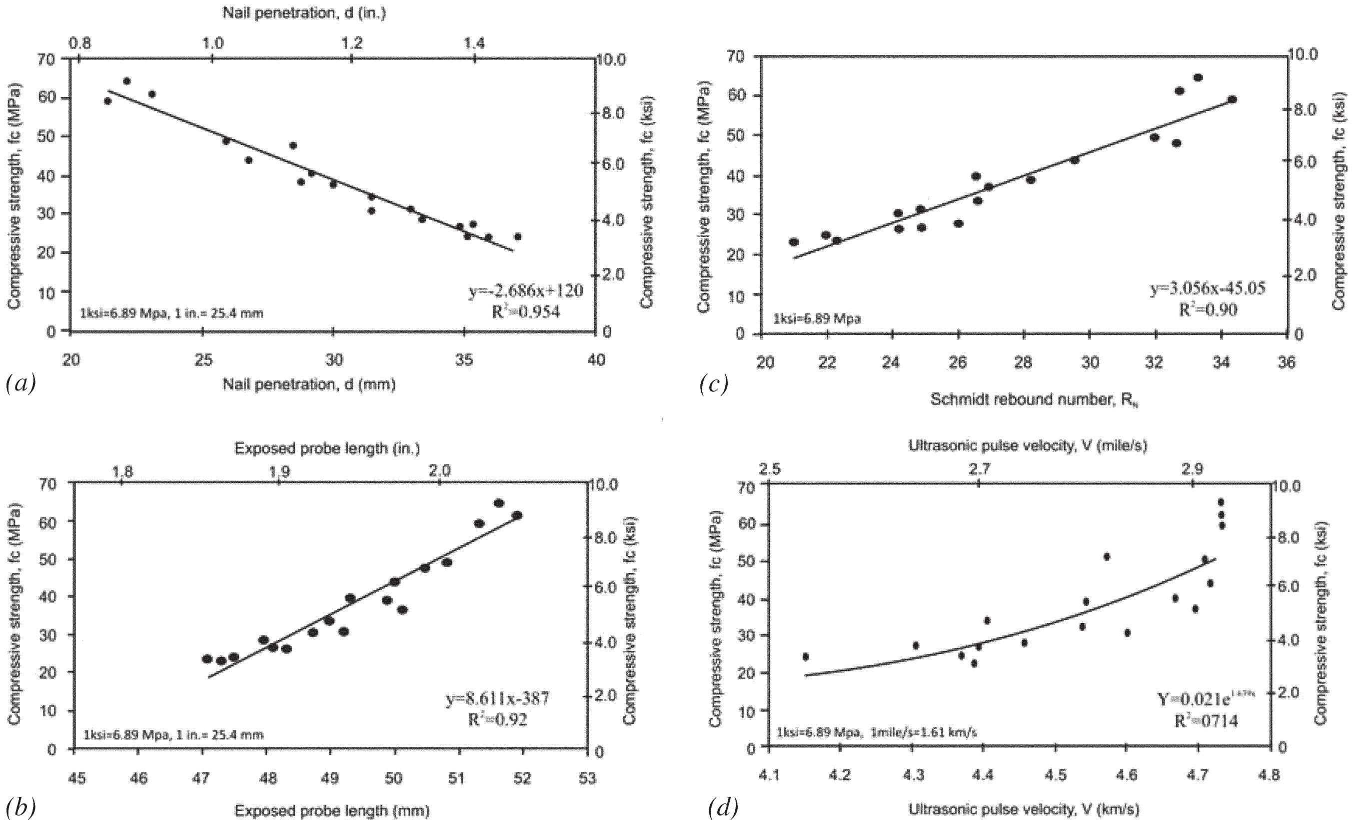

Fig. 3—Relation between: (a) nail penetration test and compressive strength; (b) probe length in penetration test and compressive strength; (c) Schmidt rebound values and compressive strength; and (d) ultrasonic pulse velocity test and compressive strength.

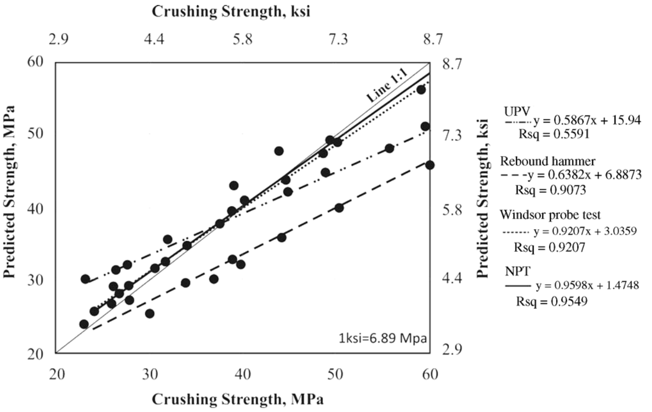

Fig. 4—Comparison of results using various methods.

can be asserted that the reliability of the NPT to estimate the compressive strength of concrete is very high. The absolute relative errors between the measured and estimated strength data were found to be smaller than 10%, as given in Table 5. The range of relative error can be considered reasonably good for the empirical relationship used in this study. The comparison between the measured compressive strength values and the computed compressive strength values using the SRH and UPV techniques (Fig. 4) reveals that the SRH and UPV significantly underestimate the compressive strength of concrete for high-strength concrete, although these testing devices offer great advantages because they are portable, lightweight, cost-effective, and nondestructive.

The type of coarse aggregate used in the concrete influences the depth of penetration of the WP. As the probe penetrates the concrete, some energy is absorbed by friction between the probe and the concrete, and some is absorbed by crushing and fracturing of the concrete. In general, cracks in the fracture zone will be through the mortar matrix and the coarse aggregate particles. Hence, the strength properties of both the mortar and coarse aggregate influence the penetration distance.[8] The WP must be perpendicular to the concrete surface and can be held in any position. The minimum acceptable distance to the edge of the concrete or between the two probes is 1.96 in. (50 mm),[11] whereas the minimum thickness of the concrete is approximately three times the expected depth of penetration.[27] The limitations, such as the type of coarse aggregate, orientation of the probe, edge distances, spacing between impacts, and test specimen size with PT, may also be valid for the NPT. Compared to the SRH, the NPT is less affected by surface conditions, such as the texture, moisture content, and surface irregularities. In addition, because the PT requires high energy with explosive capsules and creates a failure zone or hole in the concrete with some of the energy being absorbed by crushing and fracturing of the concrete, the NPT is superior to the PT in providing nondestructiveness, and the results are more reliable. Concerning the PPT technique, because the sensitivity of the pin penetration to changes in compressive strength decreases for strengths greater than 4 ksi (28 MPa),[18] it is not recommended for testing concretes with compressive strengths greater than 4 ksi (28 MPa). Kayabali and Selcuk[19] indicated that the tool's ability in the NPT is approximately 14.5 ksi (100 MPa) of uniaxial compressive strength.

These findings in the investigation are valid for the limestone aggregates, which are widely used in concrete mixtures. The

Table 5—Measured and estimated strength values of concrete

Mixture type	NPT d, in. (mm)	Compressive strength		Absolute relative error, %
		Measured f_c, ksi (MPa)	Estimated f_c, ksi (MPa)	
HSN 1	1.38 (35.1)	3.5 (24.4)	3.7 (25.7)	5.42
HSN 2	1.37 (34.8)	3.9 (26.6)	3.8 (26.5)	0.27
HSN 3	1.24 (31.5)	4.5 (31.0)	5.1 (35.3)	14.1
HSN 4	1.18 (30.0)	5.4 (37.0)	5.7 (39.4)	6.54
HSN 5	1.12 (28.5)	7.0 (48.0)	6.3 (43.4)	9.48
HSN 6	0.90 (23.1)	8.9 (61.3)	8.4 (57.9)	5.45
KTL 1	1.41 (36.0)	3.4 (23.5)	3.3 (23.3)	0.83
KTL 2	1.31 (33.5)	4.1 (28.0)	4.3 (30.0)	7.21
KTL 3	1.29 (33.0)	4.4 (30.4)	4.5 (31.3)	3.16
KTL 4	1.14 (29.1)	5.8 (39.9)	6.0 (41.8)	4.85
KTL 5	1.05 (26.8)	6.4 (44.0)	6.9 (48.0)	9.12
KTL 6	0.84 (21.4)	8.6 (59.4)	9.0 (62.5)	5.25
KYM 1	1.45 (37.0)	3.5 (23.9)	3.2 (21.5)	9.95
KYM 2	1.39 (35.4)	3.9 (27.0)	3.6 (24.9)	7.72
KYM 3	1.24 (31.5)	4.9 (33.9)	5.1 (35.3)	4.39
KTM 4	1.13 (28.8)	5.7 (39.0)	6.1 (42.6)	9.34
KYM 5	1.02 (26.0)	7.1 (49.2)	7.2 (50.1)	1.95
KYM 6	0.87 (22.1)	9.4 (64.7)	8.8 (60.6)	6.27

Notes: 1 ksi = 6.89 MPa; 1 in. = 25.4 mm.

influence of some of the aggregate characteristics on the strength of concrete has been previously reported by various researchers. The weaker aggregates reduce the strength of concrete and stronger aggregates increase it.[28-31] The strength properties of both the coarse aggregate and mortar influence the penetration distance. This contrasts with the behavior of normal-strength concrete in a compression test, where mortar strength has the predominant influence on measured compressive strength. Nevertheless, the aggregate effects are taken into consideration in regression analyses. In further studies, hard or soft aggregate types used in a concrete mixture should be re-evaluated by a regression analysis and by the findings presented herein.

CONCLUSIONS

The NPT is recommended for the indirect estimation of the compressive strength of concrete. The major equipment used to carry out this test has the main advantages of portability, quickness, low cost, and complete nondestructiveness, depending on the use. In the scope of this experimental study, the following conclusions can be drawn:

1. The reliability and accuracy of the NPT to assess the compressive strength indirectly and quantitatively seem to be higher than those of the SRH and PT. In several applications requiring the determination of the compressive strength of concrete, the proposed test device could be more helpful. These major applications may include determining the strength of critical structural elements, determining decreasing strength due to chemical and environmental impacts on buildings, investigating uniformity of concrete, and investigating actual concrete strength and possible long-term changes in concrete strength. The NPT also has the potential to be a standard index test for the indirect determination of concrete strength.

2. The application of the gas nailer to estimate the compressive strength of concrete is a novel subject. Some of the restrictions for PT and PPT, such as the type of coarse aggregate, orientation of the probe, edge distances, and spacing between impacts and test specimen size, may also be valid for the NPT. Because the PT requires high energy with explosive capsules and creates a fracture zone or indentation in the surface of the concrete with some of the energy being absorbed by crushing and fracturing of the concrete, the NPT is superior to the PT in providing complete nondestructiveness and more reliable compressive strength estimations.

3. The results obtained in this investigation and the proposed testing technique are valid only for the commercial nailer used in this study. The other commercially suitable nailers are expected to give different results unless they have similar characteristics, such as the impact energy and the type of concrete nails.

4. The equipment employed in this investigation covers a relatively wide range of uniaxial compressive strengths of normal-strength concrete (2.9 ksi < f_c < 8.7 ksi [20 MPa < f_c < 60 MPa]). Further research is recommended to include the evaluation of the compressive strength of high-strength concrete (8.7 ksi < f_c < 14.5 ksi [60 MPa < f_c < 100 MPa]) and normal-strength concrete (f_c < 8.7 ksi [f_c < 60 MPa]) using hard and soft aggregate types.

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