A NONDESTRUCTIVE TESTING TECHNIQUE FOR HIGH STRENGTH CONCRETE：EXPLOSIVE-LOADED NAIL PENETRATION TEST

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The traditional nondestructive techniques (NDT) may be insufficient to estimate the compressive strength of high strength concrete used widely in modern architecture engineering. This paper adopts the penetration test for this purpose with some advantages. This method is more convenient and more efficient than the traditional ones. The explosive-loaded nail penetration test (ENPT) can widen the testing rage of NDTs which are used to estimate the compressive strength of high strength concrete. Experimental results shown a good relationship between the compressive strength of concrete specimen (30-80MPa) and the results obtained from the ENPT. Other NDT techniques like Schmidt rebound hammer (SRH) and ultrasonic pulse velocity (UPV) were also applied to concrete specimens as comparisons and the results shown that the ENPT is more reliable. Since the penetration depth is closely related to the large-scale compressive strength obtained from indoor and field tests, the new test method is considered to be effective.

Keywords: *Compressive strength; In-situ test; High strength concrete; Nondestructive testing (NDT); Explosive-load nail penetration test (ENPT).*

1. Introduction

A great number of NDT methods have been proposed for the estimation of in-site actual strength of concrete structures and, among all the parameters, the compressive strength is the most commonly measured one. The NDT methods such as SRH, UPV, and penetration test (PT) [1] can establish correlation curves between physical parameters, such as surface hardness, velocity, density, and compressive strength without damage to concrete structures. However, the estimation of compressive strength by methods above may be different from the actual strength because of their deficiencies and limitations.

The SRH can only provide a crude estimate for the compressive strength because the SRH numbers reflect only the characteristics of the outer surface but not the whole [2]. Besides, the SRH results can be affected by a great number of factors such as the carbonization content and moisture content of samples, the age and size of the specimens, and the ingredient proportion of concrete etc. [3]. The UPV results are sensitive to fractures while can be badly affected by steel reinforcement, moisture content, and surface conditions [4]. Therefore researchers prefer it for integrality checking rather than compressive strength evaluating [5]. The PT with thick probe may destroy the weak specimens with low compressive strength while the pin penetration tests (PPT), driving a much thinner steel pin with a spring-loaded hammer, may have a relatively lower accuracy of estimated strength and therefore unsuitable for high-strength concrete due to the relatively lower energy and the shorter and thinner pins[6]. The advent of plenty of skyscrapers and large-scale public buildings indicates a great need of high strength concrete (above 50MPa) and as a result, a simple in- situ test method is proposed to replace these methods above.

The nail penetration test (NPT) [7] is a novel NDT method which is loaded by compressed air or explosive. Kayabali and Selcuk [8] used the NPT method to indirectly determine the compressive strength of intact rocks and noted that the air-loaded NPT is particularly applicable to weak rocks. They then analyzed the impacts of nail diameters and the driving energy and developed an empirical equation relating compressive strength to nail penetration depths obtained by apparatus with different energy and nail diameters [9]. Palassi [10] utilized a new testing apparatus for NPT and pointed out that this apparatus has a good potential for standardization and universal use especially for the in-situ estimation of the rock strength. Selcuk etl. [7] used the NPT method to estimate the compressive strength of concrete and verified its reliability. Iwaki etl. [11] applied the NPT for the estimation of shotcrete strength and non-uniformity checking of lining. Bae [12] estimated the compressive strength of shotcrete in Korea with NPT and pointed out that the feasibility of NPT method decreases with the increase of hardening strength. The researches

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above indicate that there is a relationship between compressive strength and penetration depth. However, the feasibility of NPT on high strength concrete is still unverified since the high strength concrete is too difficult to penetrate.

Based on the considerations above, this study is to propose a NDT method that suitable for those high strength concrete structures (more than 50MPa). An explosive-loaded NPT (ENPT) method as a simple in-situ test method was applied to concrete specimens with the strengths ranging from 30MPa to 80MPa and the nails were quenched so that they can penetrate into high strength concrete. The relationship between compressive strength and penetration depth obtained by the ENPT was sought in this investigation and the results of SRH and UPV were also included to comparatively demonstrate the superiority of ENPT. Moreover, the effectiveness and reliability of the ENPT was verified through the in-site tests. The application of the ENPT to estimate the compressive strength of high strength concrete is a novel subject and can achieve more accurate results than conventional ones. Besides, the ENPT method can be easily performed by a trained technician with low cost and the simplicity of the ENPT make it superior when applied to structures that requiring a great number of tests. The ENPT method can be conducted as frequently as required and the strength development at any age can be determined.

2. Test Procedure

2.1 Specimen preparation

The concrete cubes with compressive strengths ranging from 30 to 80 MPa were casted in consideration of the discreteness of the compressive strength. The fine aggregate is consist of crushed stones ranging from 2-4.75mm and the ordinary sand with density of 2.5t/m^3 , while the coarse aggregate is consist of crushed stones ranging from 5-20mm and the particle size distribution of aggregate used in the tests is suitable for ASTM C33[13] . All these concrete specimens were cured under the same natural conditions with rain-cloth protecting from rain and sunlight.

A total of 114 concrete specimens of 4 different ages and 6 different design strengths (24 groups) with dimensions of 150mm×150mm×150mm were employed during tests. The details of the distribution of concrete specimens are shown in Tab.1.72 concrete specimens were broken by a compression testing machine and the average of the three in each group represents the compressive strength of the specimens in that group. 18 cubic specimens were prepared to determine the optimal amount of shooting points for the ENPT, which can describe the compressive strength of specimen accurately at the lowest cost. 24 concrete specimens with different compressive strengths and ages were tested by the NDT methods in order of the UPV, the SRH and the ENPT and thereby achieving the empirical relationships respectively. The concrete specimens used for the NDT methods were fixed by a compression testing machine during testing as shown in Fig.2.

2.2 Explosive-loaded NPT apparatus

The ENPT apparatus used in this study is consist of an explosive-loaded nailer (Fig.1a) and quenched nails (Fig. 1b) about 45mm in length. The quenched nails can widen the range of strength estimation and the qualities of nails such as material, strength and surface finish conform to JIS A 5529. The penetration depth is measured with a digital depth gauge as shown in Fig.1c. With the precisely controlled amount of powder, nails are driven into concrete specimens under a constant pressure and therefore, the depth the nails penetrating into these cubes can indicate the compressive strength of the concrete specimens.

Table 1

Details of the distribution of concrete specimens

Design concrete Strength (MPa)	Age at testing (days)								
	14		28			60		90	
	NDTS	CS	NDTS	COVs	CS	NDTS	CS	NDTS	CS
30	1	3	1	3	3	1	3	1	3
40	1	3	1	3	3	1	3	1	3
50	1	3	1	3	3	1	3	1	3
60	1	3	1	3	3	1	3	1	3
70	1	3	1	3	3	1	3	1	3
80	1	3	1	3	3	1	3	1	3

PS: CS is the short of Compressive strength

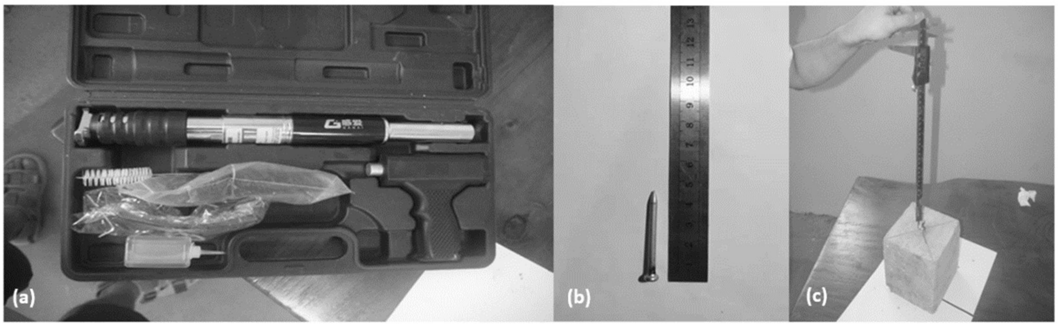

Fig.1 - The ENPT apparatus (a) the explosive-loaded nailer, (b) the quenched nails and (c) the digital depth gauge


Fig.2 - Tested specimen in a compression testing machine

What calls for special attention during tests is that the users must be trained before operating the apparatus.

2.3 Test procedure

This experiment is consistent of three series of tests and a total of 114 cubic specimens with dimensions of 150mm×150mm×150mm are tested. Series A is used to determine the compressive strength of cubic specimens in accordance with ASTM C39/C39M-05e2 [14]. Series B is used to determine the optimal amount of shooting points for the ENPT mainly based on the coefficient of variation (COV) of the penetration depth of nails on a specimen. Series C is used to establish the relationship between compressive strength and the average of penetration depth. The SRH and the UPV are employed in this test as comparisons and the SRH is employed in accordance with C805/C805M-08 [15], the UPV is employed in accordance with ASTM C597-02 [16].

Series A: A total of 72 concrete specimens of 6 different design strengths and 4 different ages are prepared for this series. The details of the distribution of these concrete specimens are shown in Tab.1. All these concrete specimens are broken by a compression testing machine (Fig.2) and the critical compressive strength when specimens begin to break is recorded. The 72 concrete specimens are divided evenly into 24 groups according to their age and design strength and the average of the compressive strength of the three in a group represents the compressive strength of the specimens in that group.

Series B: A total of 18 concrete specimens are prepared for this series and they are divided evenly into 3 groups as shown in Tab.2. Four nails are shot on one surface of a specimen in group 1, five nails are shot on one surface of a specimen in group 2 and six nails are shot on one surface of a specimen in group 3. Every specimen has four surfaces to be shot and the exposed lengths of nails are measured and the COV of penetration depths is obtained after calculating. With the analysis of results obtained from these three groups, the optimal amount of shooting points is determined and the ENPT method with the optimal amount of shooting points can accurately estimate the compressive strength of concrete specimens at a lower cost.

Series C: The UPV method, the SRH method and the ENPT method are applied in sequence to the remaining 24 concrete specimens.

Table 2

Details of the distribution of specimens and nails

Design concrete Strength (MPa)	Group 1		Group 2		Group 3	
	The amount of specimens	nails/surface	The amount of specimens	nails/surface	The amount of specimens	nails/surface
30	1	4	1	5	1	6
40	1	4	1	5	1	6
50	1	4	1	5	1	6
60	1	4	1	5	1	6
70	1	4	1	5	1	6
80	1	4	1	5	1	6

PS: All the specimens are cured for 28 days

Table 3

Mean penetration depth and their COV

Compressive Strength (MPa)	Group 1		Group 2		Group 3	
	The mean penetration depth (mm)	COV,%	The mean penetration depth (mm)	COV,%	The mean penetration depth (mm)	COV,%
34.8	32.7	6.3	33	5.8	31.5	4.2
41.3	30.8	5.2	31.5	8.3	30.2	5.0
54.5	28.1	4.0	27.8	2.6	28.5	5.7
62.3	24.5	4.2	24.1	5.5	25.2	6.3
73.1	23.1	1.8	23.9	4.1	24.1	3.7
81.2	21.6	5.9	22	6.2	22.5	2.8

PS: All the specimens are cured for 28 days

The UPV method is employed prior to the other NDT methods. A pulse velocity is obtained after the two transducers are put on the opposing surfaces of a concrete specimen and the transit time pulses used for traversing between these two transducers are measured. The velocity obtained from this pair of surfaces is in accordance with ASTM C597-02 [16] and the average obtained from the three pairs of a specimen is recorded as the final velocity. After the UPV method is completed, the SRH method is applied on the same specimen according to C805/C805M-08 [15]. The average of the four mean rebound numbers obtained from four surfaces will be recorded as the final number. Once the application of the SRH method is finished, surfaces should be prepared smoothly for the application of the ENPT method. The procedures of ENPT method are as following.

Step1: Inspect the concrete specimen visually and then smooth the surface to make sure the tested specimen is intact and free of any disturbance. Draw a certain number of shooting points distributed evenly on the smooth surface.

Step 2: Shoot the nails into the concrete specimen at the shooting points and ensure that the nails are perpendicular to the smooth surface.

Step 3: Measure the exposed lengths of these nails with a depth gauge and then calculate the average of these penetration depths.

Step 4: Repeat step1 to step 3 on the other three surfaces and calculate the average of penetration depths of the four surfaces as final penetration depth.

3. Results and discussions

3.1 The COV and the optimal amount of shooting points

The concrete specimens used for the determination of optimal amount are all cured for 28 days and are divided evenly into 3 groups. The amount of nails shot into specimens in each group is different, so that the COV of penetration depth in different groups can indicate the optimal amount of shooting points. The mean penetration depth and their COV are shown in Tab.3

According to Table 3, the COVs in three different groups are all small enough to indicate the feasibility of the ENPT method. The acceptable COV in three groups indicate that the average of four penetration depths can be as well as the average of five penetration depths and the average of six penetration depths. The analysis of test results reveals that four shooting points are the optimal amount and the average of four penetration depths can accurately estimate the compressive strength of concrete specimens at a lower cost.

3.2 Relationship between the compressive strength and the measurements

A series of regression analyses is carried out to determine the empirical relationship between the compressive strength and the penetration depth. All of the relationships described by linear equation, polynomial equation and exponential equation in Fig.3a indicate that the penetration depth decreases with the increasing of the compressive strength. The best-fitting empirical equations for rebound number and velocity are shown in Fig.3b and Fig.3c respectively and their results are in accordance with that of penetration depth.

The best-fitting relationship between the penetration depth and the estimated strength of all specimens is approximated to a curve of polynomial equation and the empirical equation is described as

$$\mathrm{Y} = 271.66 - 11.74\mathrm{X} + 0.14X^2 \qquad (1)$$

Where X is the average of the 16 penetration depths on a concrete specimen, and Y is the estimated compressive strengths of the corresponding specimen.

The regression coefficient for the ENPT, the SRH and the UPV is 0.975, 0.89 and 0.72, respectively. One of the reasons for higher regression coefficient of the ENPT might be due to the relatively stronger quenched nails. The quenched nails are stronger than conventional ones, which make them easier to penetrate into concrete specimens without affections from aggregate and thereby more suitable for high strength concrete. Another reason might be due to the capacity of describing the inherent characteristic of specimens. The penetration depth is mainly affected by factors like aggregate and cement and is less sensitive to factors like moisture content and external environment, making the ENPT able to describe the inherent characteristic of specimens and thereby more suitable for strength estimating. The reason for a lower regression

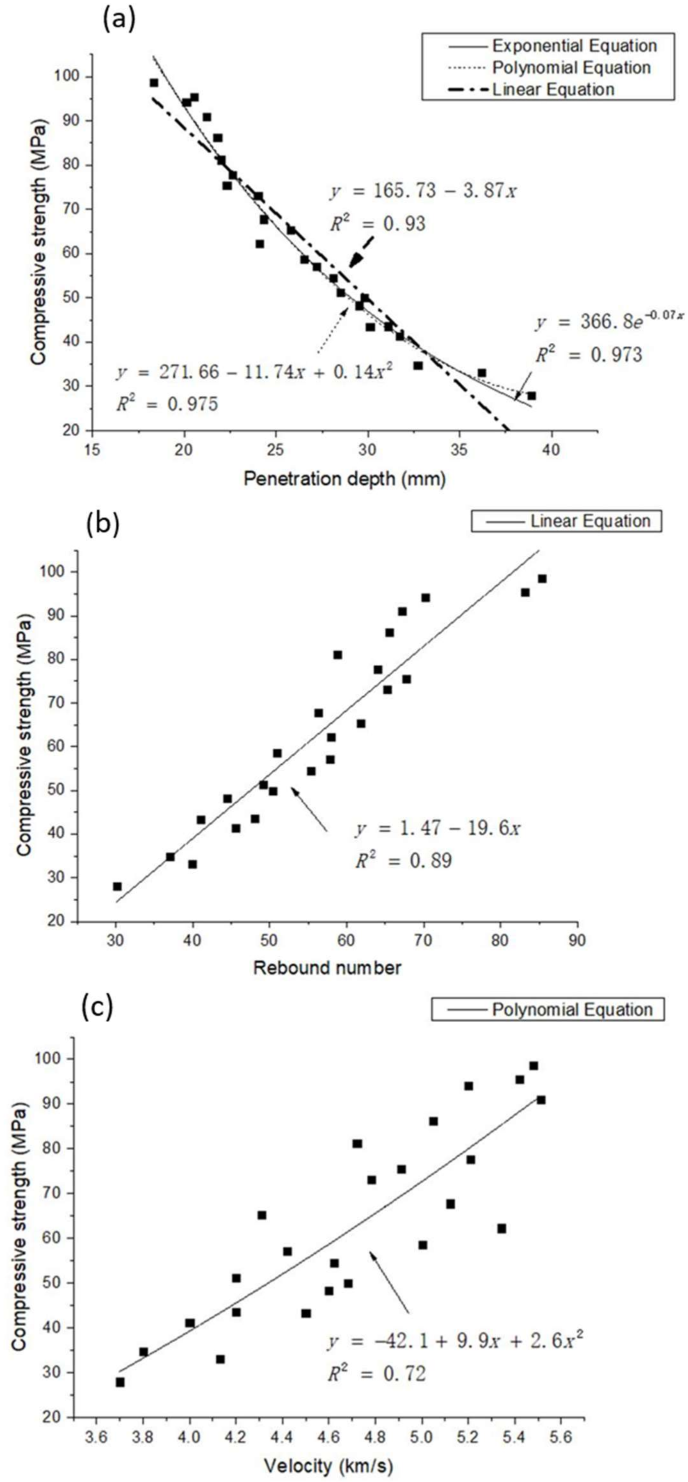

Fig.3 - Relationships between compressive strength and (a) penetration depth, (b) rebound number, (c) velocity

coefficient of the SRH may because of the susceptibility. The values of the SRH are sensitive to factors such as carbonization content and moisture content. Besides, the SRH reflect only the characteristics of the outer surface but not the whole, making it less suitable for strength estimating. The regression coefficient for the UPV is much lower than that for the ENPT and the SRH since the velocity of the UPV is affected by aggregate, moisture content and fractures badly, making the UPV less reliable for strength estimating.

3.3 In-site verification of ENPT

The reliability and accuracy of the ENPT is verified by compressive strength of drilling cores obtained from a newly built building and a 12-year old bridge, respectively. The in-site test for the existing building is performed on testing zones with dimensions of 400mm×400mm locating at pillars and beams on different floors and a total of 10 testing zones are included in this test, as shown in Fig.4a. The in-site test for the existing bridge is performed on testing zones with dimensions of

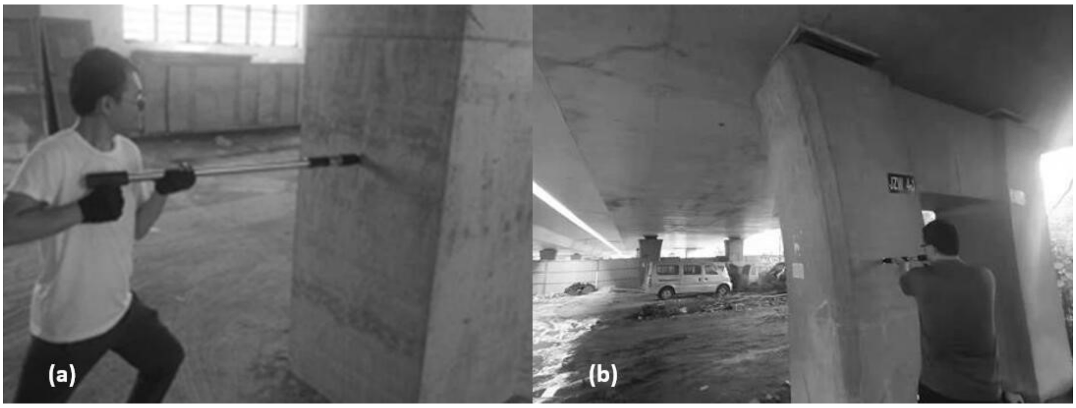

Fig.4 - In-site verification of the ENPT applied on an (a) existing building and an (b) existing bridge

Table 4

Comparison between real strength and calculated strength of the newly built building

Zone number	Mean crushing strength (MPa)	Penetration depth (mm)				Mean Penetration depth (mm)	Mean calculated strength (MPa)
		1	2	3	4		
1	35.8	34.1	33.1	33.5	32.2	33.2	36.2
2	27.7	37.9	38.5	39.1	37	38.1	27.6
3	26.4	39.4	37.9	38.5	39.6	38.9	26.8
4	30.5	34.7	36.2	35.8	36.1	35.7	31
5	36.2	33.3	32.5	32.8	34.1	33.2	36.2
6	38.7	32.2	31.8	33.5	31.7	32.3	38.5
7	48.2	29.6	28.8	29.3	28.5	29.1	48.6
8	45.6	30.2	28.9	30.8	29.5	29.9	45.8
9	47.3	29.5	29.1	30.2	28.9	29.4	47.5
10	50.2	28.1	28.4	29.2	29.3	28.8	49.7

Table 5

Comparison between real strength and calculated strength of the old bridge

Zone number	Mean crushing strength (MPa)	Penetration depth (mm)				Mean Penetration depth (mm)	Mean calculated strength (MPa)
		1	2	3	4		
1	73.7	23.2	24	23.8	23.5	23.6	72.6
2	71.7	22.9	24.6	23.9	23.7	23.8	71.5
3	66.4	25.6	23.7	24.9	25.3	24.9	66.1
4	70.5	25.3	23.4	24.2	23.9	24.2	69.5
5	75.2	22.7	24.3	22.6	22.5	23	75.7

400mm×400mm locating at piers and a total of 5 testing zones are included in this test, as shown in Fig.4b. Four nails are shot on a testing zone and the average of the exposed length is then calculated. Make sure the nails are not shot on bars. After the nails are shot, two drilling cores with dimensions of 100mm×100mm (diameter× height) are drilled off the testing zone and then the crushing strength is measured. The average of the two crushing strength indicates the compressive strength of this testing zone.

The compressive strength estimated by the ENPT is compared with the real compressive strength measured by the average of crushing strength, as shown in Tab.4 and Tab.5. The comparison demonstrates that the ENPT is available for the estimation of compressive strength of high strength concrete structures.

4. Conclusions

The ENPT is an available nondestructive method for the prediction of the compressive strength of high strength concrete structures. The following conclusions were drawn in the scope of this experimental study:

(1)There is a correlation exists between the penetration depth of the ENPT and the compressive strength of concrete specimens. That is, the lower the penetration depth is, the stronger the compressive strength is.

(2)The ENPT is reliable and stable for the estimation of compressive strength compared with the results obtained by the SRH and UPV. The regression coefficient R^2 for the ENPT is 0.975 while the regression coefficient for the SRH and UPV is 0.89 and 0.72, respectively. Therefore, for the concrete specimens used in the tests, the reliability of ENPT is better than the SRH and UPV. Besides, the experimental results show a good COV of penetration depth, which also indicates the stability and reliability of the ENPT on estimation of compressive strength.

(3)Two in-site tests were performed on a newly built building and a 12-year old bridge, respectively. Both of the two tests show the agreement of real crushing strength and calculated compressive strength estimated by the ENPT, proving the feasibility of the ENPT on in-site testing.

(4)The ENPT has an advantage over the SRH and UPV at higher strength. The application of the quenched nails and higher energy makes the ENPT more powerful to penetrate into concrete structures without causing fracture zones and the enough energy also makes ENPT less sensitive to the effect of coarse aggregate, extending the rage of NDTs to high strength concrete. With the penetration of nails, the ENPT can reflect the internal characteristics of concrete structures, making the calculated compressive strength much closer to the real strength. However, it should be noted that the nails must be perpendicular to the surface in order to achieve the accurate compressive strength. Another negative aspect is that a trained technician is necessary for the operation of the ENPT since the apparatus is driven by explosive and accidents may happen because of improper operation.

(5)Further research is recommended to analysis the influence of parameters like diameters of the nails and the size of specimens on the estimation of compressive strength. The impacts of admixture and environment will also be taken into account.

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