COMPRESSIVE STRENGTH OF CONCRETE USING INNOVATIVE IN-SITU SHEAR TESTING METHOD

SUHANG YANG[1,2], ZHIFENG XU [2,3,4], ZHENGNING BIAN[1*]
[1] School of Civil Engineering, Changzhou Institute of Technology, Changzhou 213032, PR China.
[2] Key Laboratory of concrete and prestressed concrete structure, Ministry of education, Southeast University, Nanjing 211189, PR China.
[3] College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao 266590, PR China.
[4]Shandong Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology, Qingdao 266590, P.R. China.

Shear strength is the essential mechanical property of structural concrete, especially for complex stress analysis and finite element analysis. Laboratory core double shear testing (LDST) is considered time-consuming and expensive testing for the measurement of the in-situ shear strength of concrete. The object of this paper is to introduce an innovative in-situ shear test (IST) method for the measurement of the shear strength of partial concrete cores. According to the principle of the clamping mechanism, the time required for field testing was reduced to less than 30 minutes. The core samples in different diameters and lengths were compared by IST and LDST. Student's t-tests of shear strength results obtained by using LDST and IST showed an evident difference between the two methods. The shear strength of the core increases with the decrease of the core length and increases with the core diameter. The standard deviation of the results was considered as an increase with a reduction of core diameter for both LDST and IST. Since no extraction of core specimen is needed, and the core length is less than that of tested using LDST, and the specimens can be easily carried and quickly performed in-situ with less damage to the structure. The shear strength of concrete measured by IST is inferior to that of obtained by the LDST method, and correction efficiency must be adopted to adjust IST test results to that LDST. A good correlation between concrete IST strength and cube compressive strength is proposed in the paper.

Keywords: *Concrete; compressive strength; shear strength; Laboratory core double shear testing (LDST); In situ shear testing (IST); compressive strength*

1. Introduction

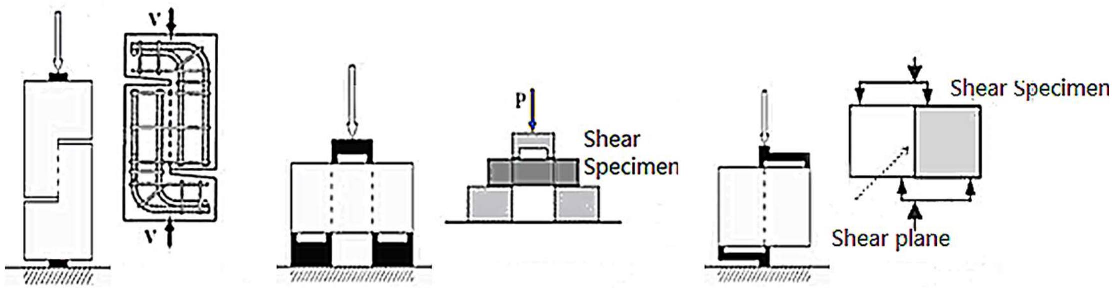
When the strength of existing structures is in doubt, it is necessary to measure the strength of the in-situ concrete. In addition to the tensile strength and compressive strength of structural concrete, its shear strength is also the basic mechanical property. In the complex stress analysis and finite element analysis of concrete, its shear strength parameters are vital.

There are several test methods to measure shear strength, such as the push-off specimen (Figure 1a) [1], JSCE method (Figure 1b) [2, 3], and FIP standard method (Figure 1c) [4]. Push off test method is a simply designed one for shear testing, with the characteristics of simple design, casting and testing. Some researchers concluded that the test results obtained with the push-off test for L-shaped specimens are about 90% of those derived with the FIP method and 70% of those yielded with the JSCE method. The test and finite element analysis show that the JSCE method can give more accurate shear strength results than other test methods [5]. The pure shear failure of concrete is caused by the principal tensile stress, which occurs from the middle of the section. This implies that greater shear stresses are obtained for the corresponding test method the closest the shear test conditions are to the pure shear state.

The majority of concrete consultants will prefer to conduct a suitable core test in accordance with the relevant specification. The local double-shear testing method (LDST) using a double shear test mechanism to estimate the shear strength of concrete core is proposed by Yang et al [6]. The core can be tested after being extracted from the concrete structure without much preparation. The mechanisms of the DSTM are fairly straightforward, as illustrated in Figure 5a, which is similar to those of the JSCE method. The failure mode of the specimen tested with LDST initiates from within the core, eliminating the effects of drilling for damage and allowing for more accurate test results.

Recent numerous studies have thus been made on the compression strength result in analysis of core samples extracted from sites [7-12], but such research is rather scarce on concrete cores testing on site. The purpose of this study is to investigate the applicability of a newly developed portable in-situ single shear test (IST) apparatus for in-situ core testing to determine the shear strength of cores. Core testing of LDST involves core cutting in-situ and transportation of core specimen from the site to a laboratory. The objective of IST described in this paper is to avoid these processes, which may cause time delays and errors, by using a newly developed IST machine that can test cores in-situ and provide results within 30 min. In-situ

* Autor corespondent/*Corresponding author*,
E-mail: bian27@163.com



(a) L-type push-off test (b) JSCE test (c) FIP shear test

Fig. 1 - Sketch of different shear test.

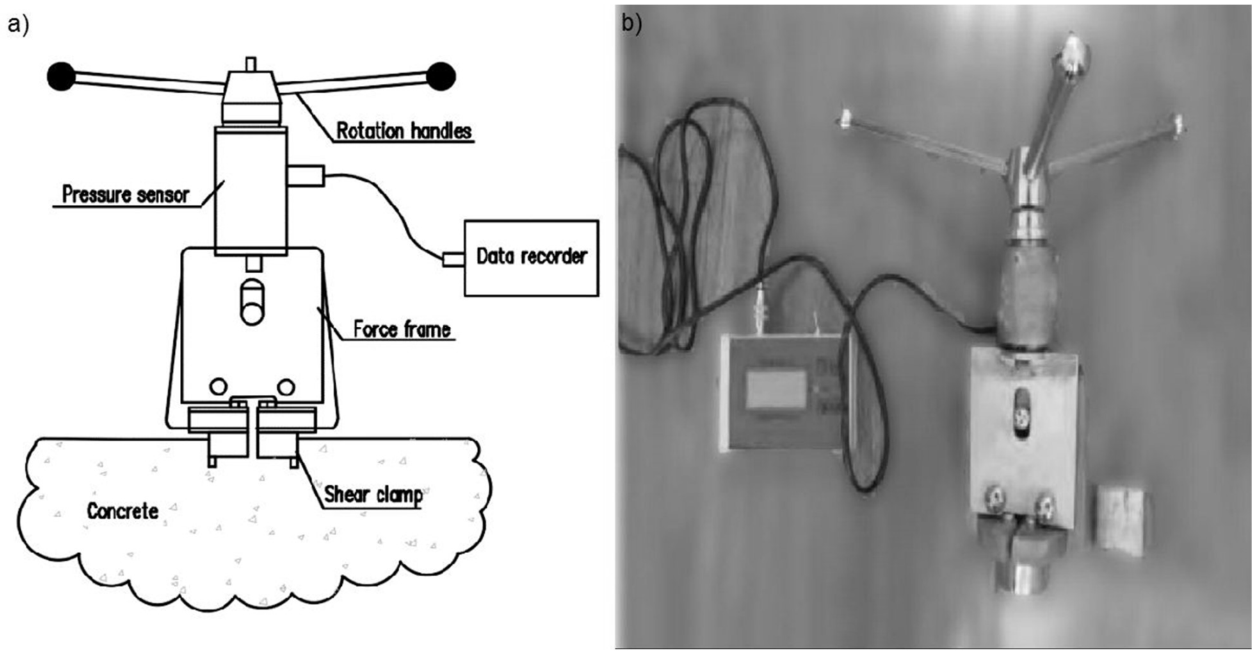


Fig 2 - Sketch of IST apparatus. (a) Component of IST apparatus; (b) Photo of IST apparatus.

shear tests were performed on cores in different diameters and lengths, and the results were compared with those obtained with the LDST. The special testing machine is not needed for the shear testing, which is easily and quickly carried out on site, and the core length is shorter than that for LDST.

2.Materials and methods

2.1. Specimen preparation

The concrete cube of C40 cast to 150 mm was used in this test and the strength of the cube tested after 28 d curing was 42.57MPa in accordance with BS EN 12390-3 [13]. The different mixtures are mixed in a drum-type mixer, cast horizontally from the top of the 150 mm cube steel mold and compacted on a shaking-table. The fine aggregate was made of ordinary sand with the density of 2.5 t/m^3 and the coarse aggregate was small aggregates with the particle size of 2~4.75 mm, interspersed with aggregates with the maximum aggregate size of 5~20 mm. The particle size distribution of aggregate is specified to ASTM C33 [14]. The effect on the tensile strength of the concrete is small when the maximum aggregate size is lager than 16 mm and the maximum aggregate size is not considered in the research.

3.Description of IST machine (IST)

Figure 2 shows a schematic of the IST apparatus. The apparatus consists of a forcing frame, a shear clamp, a pressure sensor and a rotary handle for turning. The principle of IST is to test the shear strength of small diameter un-extracted cores in-situ. The apparatus is placed inside the concrete to ensure that the clamp is accurately positioned in the core cut seam and remains in the concrete. Once the apparatus is fixed, the shear load is applied through the rotation handle to the concrete core and transfers the shear force to the clamp through the force frame.

The mechanism of IST is simple, as illustrated in Figure 3. Figure 3a illustrates the internal structure of the IST apparatus. The shear force is loaded according to the principle of theoretical mechanics. When the rotary handle is turned clockwise, the corresponding pressure load is transmitted to the pressure sensor connected to the rotary handle, and then fragment A moves down accordingly. Component A transmits pressure to component B through hinged bars at

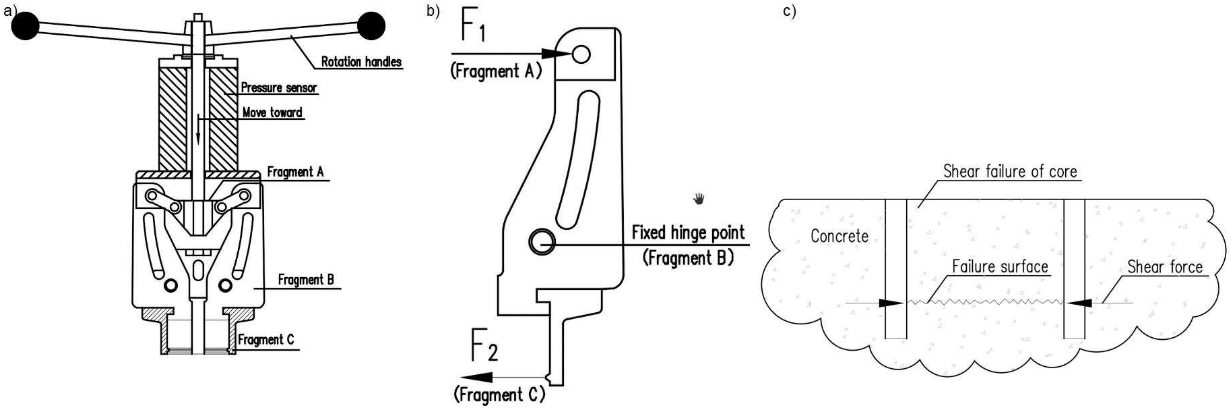


Fig. 3 - Mechanism of IST apparatus. (a) Internal structure of IST apparatus, (b) Clamping of IST, (c) Single shear of IST.

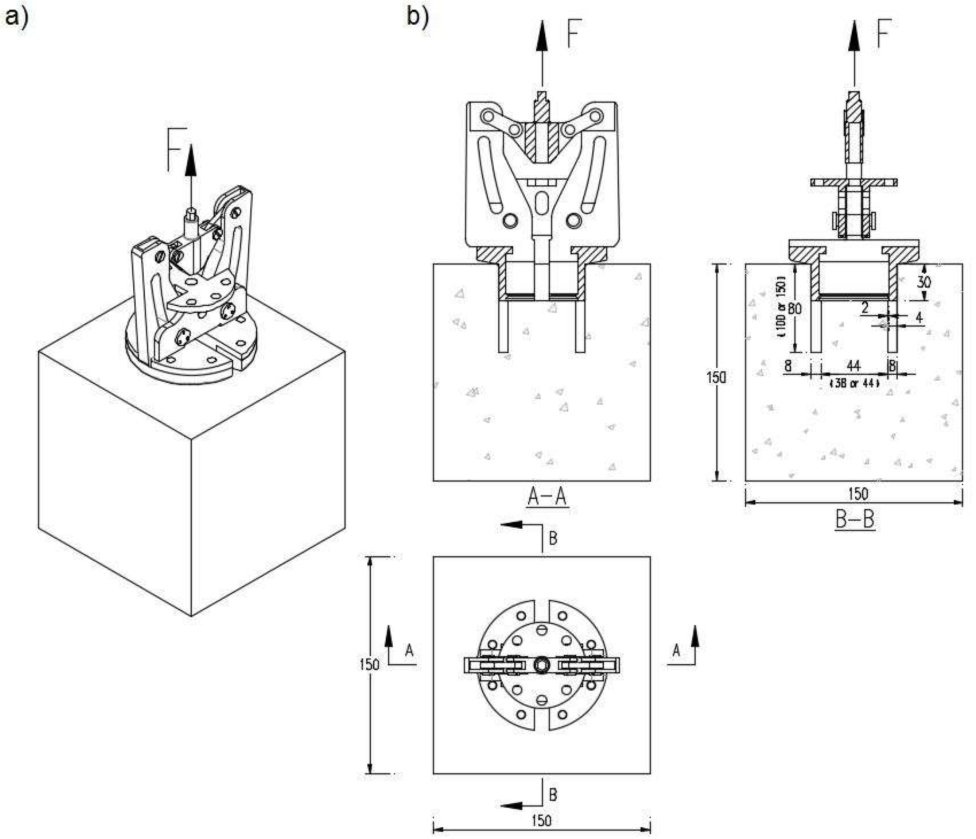


Fig. 4 - Structure of IST apparatus. (units: mm) (a) 3-D diagram of IST apparatus, (b) Detail size of IST apparatus.

both ends, and Part B acts as a lever. The rotating handle is finally converted into the shear force acting on the core sample. The pressure sensor was pre-calibrated to show the load transferred to shear force. The detail of the IST apparatus is illustrated in Figure 4. It could be noted that the annular protruding teeth are at the bottom of the clamp.

Then, The effective peak load values for the failure mode of the specimen in the IST device are acquired, accurate to 1 N. IST shear strength is calculated by $x=P/3.14D^2$ (x=the shear strength achieved by failure, MPa; P=the maximum load applied to the test core, N and D = the diameter of the core specimen, mm). For testing with this method, there is no need to transfer core samples from the field to the laboratory and the shear strength of concrete core samples can be measured in time in situ.

4.Methodology

4.1. Laboratory double shear test of core (LDST)

Core samples of different diameters (38, 44 and 49 mm) and lengths (80, 100 and 150 mm) were drilled from concrete cubes at selected locations using the drilling-machine (Figure 5a). The diameters of the cores (D) in the shear

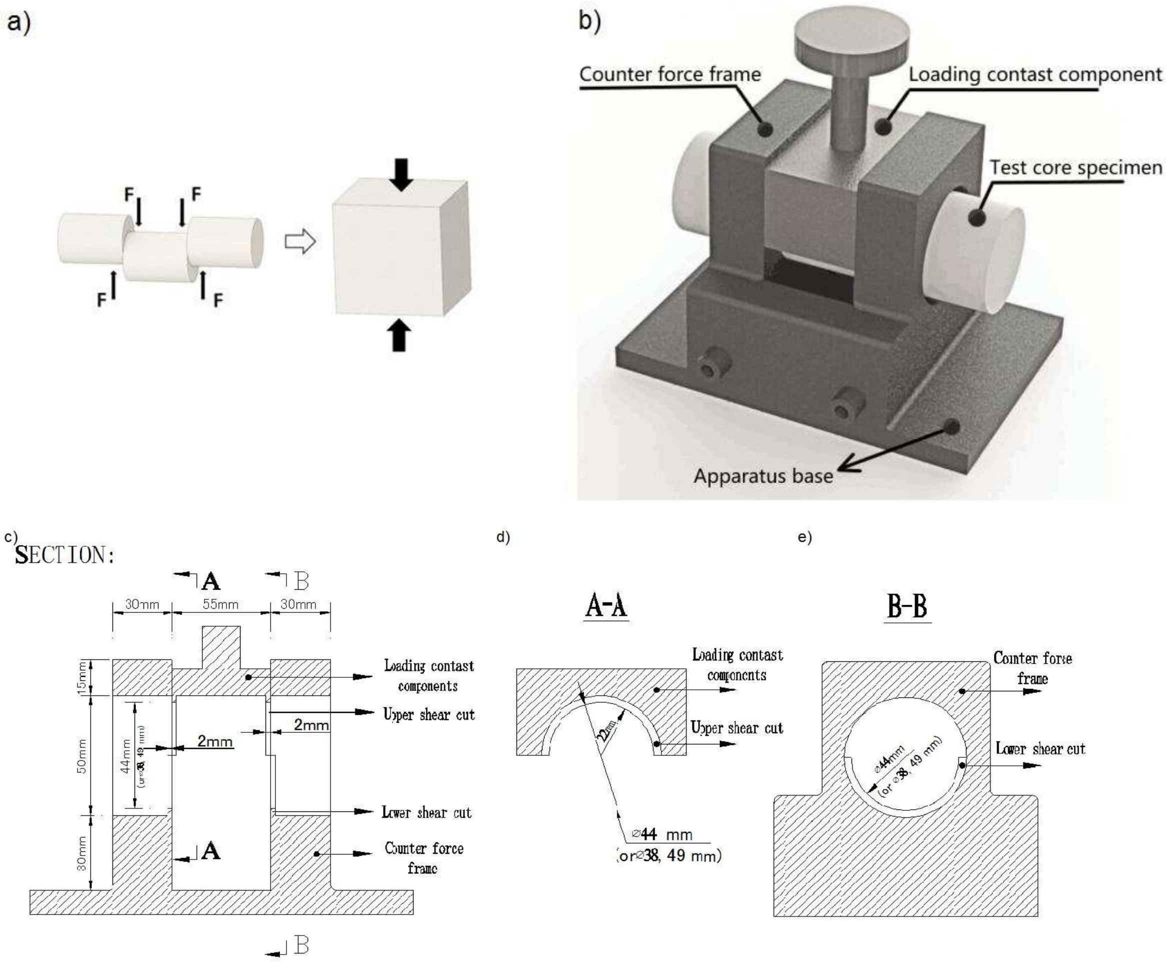


Fig. 5 - Schematic diagram of the apparatus for LDST. (units: mm) (a) LDST mechanism, (b) 3D schematic diagram of LDST, (c) Size of apparatus, (d) Loading contact components, (e) Counter force frame.

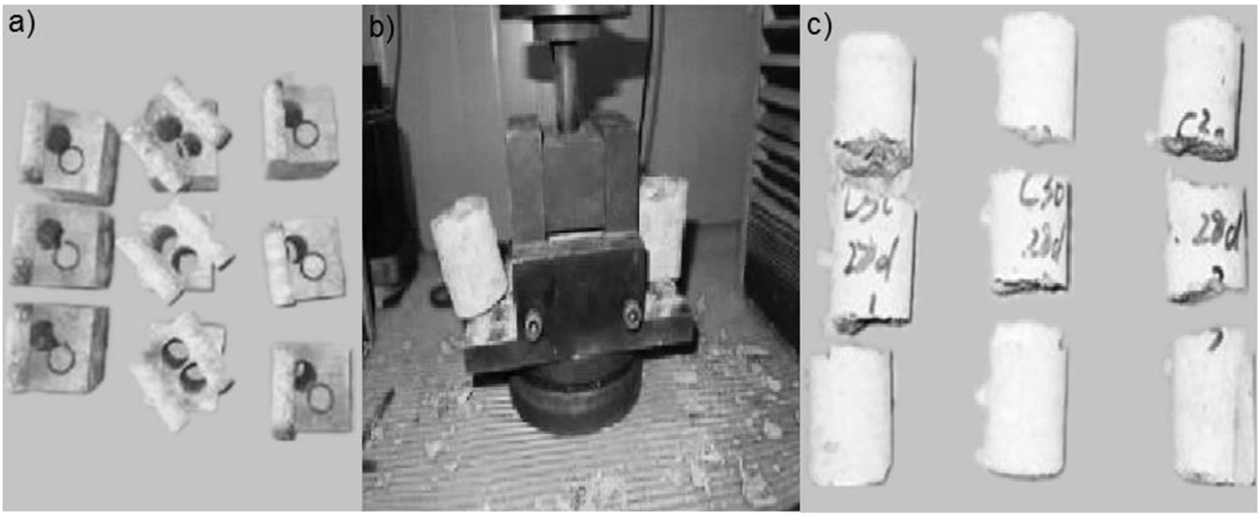


Fig. 6 - Procedure of LDST. (a) Concrete core, (b) Tested core, (c) Failure mode LDST.

positions are recorded for the mean value calculation (Figure 5b). The specimen is placed on the test apparatus and the ends of the specimen are ensured to be exposed to the outside of the apparatus in equal lengths. Apply load at a constant rate of 0.05 N/mm^2/s, and obtain the effective peak shear load values. Effective peak load for the failure mode of the specimen obtained from the DSTM apparatus, accurate to 1 N. LDST shear strength is calculated by $x=2P/3.14D^2$ (x=the shear strength achieved by failure, MPa; P=the maximum load applied to the test core, N and D=the core specimen diameter, mm). Typical failure mode after LDST is shown in Figure 6.

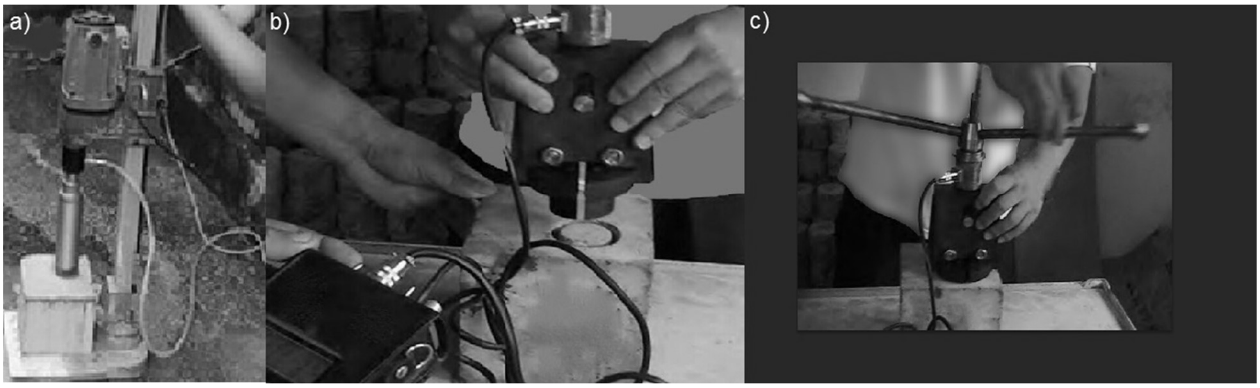


Fig. 7 - Procedure of IST. (a) Drill the core, (b) Position the IST, (c) IST testing.

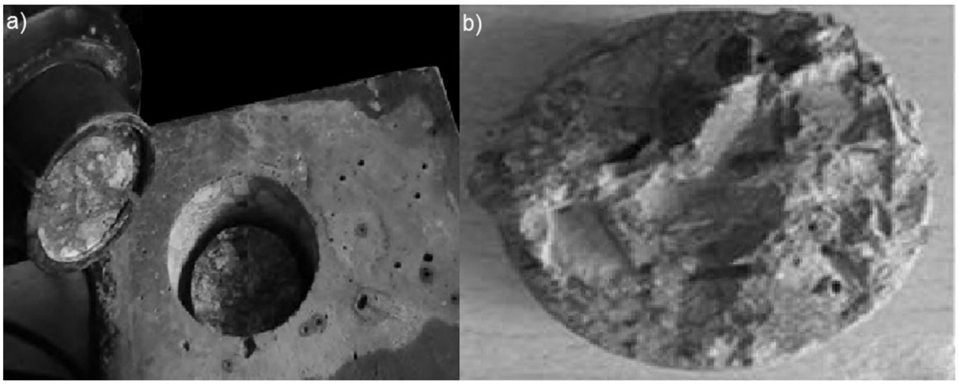


Fig. 8 - Failure section of IST.(a) Finished core, (b) Failure section.

4.2. In-situ single shear test of core (IST)

For IST, the same number of cores in different lengths (80, 100 and 150 mm) and diameters (38, 44 and 49 mm) are tested for LDST. Before the IST apparatus is fixed to the concrete core, the test area must be separated from the remaining part of concrete using a water-cooled coring machine, as shown in Figure 7, and the sizes (diameter and length) of the partial core must be carefully checked. By replacing the clamp of IST with the same diameter as the measured core, the shear test of core samples with different diameters was carried out.

Position the apparatus on the partial core sample so that the loading ram was centrally placed. Apply load on the core specimen gradually and measures the load when the failure of the specimen occurred. Figure 8 displays the typical failure mode after the IST test, which demonstrates that the failure surface parallels the concrete surface and appears as interfacial damage between the slurry and the aggregate. Then, trend charts were drawn founded on the experimental results obtained.

Concrete cubes were cured indoors and covered with a wet cloth.All cubes the specimens were cured under the same environmental conditions. Testing of concrete cores in 49 mm diameter and 80 mm length was carried out to determine the IST strength at the specified curing ages (7, 28, 60 and 180). The compressive strength of concrete in various sizes of 150 mm cubes was tested according to BS EN 12390-3 (BSI 2009). Cube compressive strength range from 10 to 60 MPa. And the relationship between the IST test values and the compressive strength of cubes was obtained by regression analysis of the data irrespective of the ages. Three cubes were selected from concrete cubes of each design strength at each test age. Four IST tests were conducted on each concrete cube to obtain the average value.

5. Results and discussion

5.1. Comparison of LDST and IST results

Figure 9 shows the strength of both methods and the trend lines, which are almost the same for both LDST and IST results. The mean shear strength of the cores in diameter of 38 mm and length of 80 mm is 8.52 MPa by LDST method and 7.72 MPa by the IST method. The values are 7.92 MPa and 7.29 MPa for cores in diameter of 44 mm, and 7.65 MPa and 7.06 MPa for cores in diameter of 49 mm. Such trend was found similar to the strength of cores in other lengths. The results of shear strength measured by LDST and IST are a bit different.

To better compare the two methods, the obtained test data are also analyzed by t-test. The comparison of LDST and IST results of the core groups in different diameters and lengths is shown in Table 1. The T-stut values of all combinations were less than the corresponding critical P-value

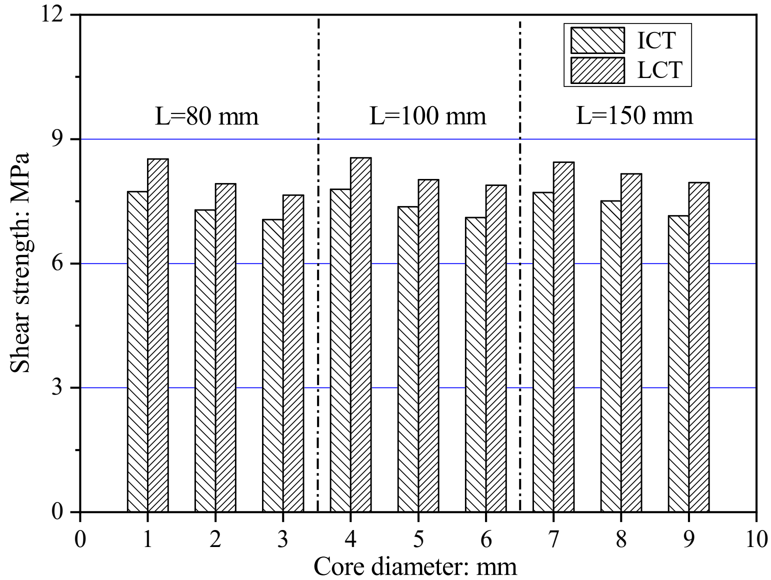


Fig. 9 - Core shear strengths measured by IST and LDST.

Student's t-test values between core shear strengths obtained by the LDST and IST **Table 1**

L: mm	**D: mm**	**Shear strength: MPa**						**Student's test (t_{stut})**	**t_{stut} < 0.05**	**MV of LDST/ MV of IST**
		LDST			**IST**					
		Shear strength values	**Mean value**	**SD**	**Shear strength values**	**Mean value**	**SD**			
80	38	8.4 8.9 9.1 8.0 8.2 8.2	8.5	0.387	7.2 8.5 8.3 7.6 7.5 6.9	7.7	0.560	0.026	Yes	1.104
	44	8.3 8.2 7.6 7.6 7.7 8.0	7.9	0.283	6.9 8.0 7.5 6.4 7.3 7.4	7.2	0.484	0.031	Yes	1.088
	49	7.5 7.7 7.6 7.3 7.5 7.9	7.6	0.193	6.5 7.3 7.4 6.5 7.2 7.2	7.0	0.367	0.010	Yes	1.084
100	38	9.0 8.4 8.7 8.6 8.3 8.0	8.5	0.327	7.3 8.4 8.5 7.6 7.5 7.2	7.7	0.519	0.020	Yes	1.0976
	44	8.0 8.4 7.7 7.9 7.7 8.1	8.0	0.239	7.1 8.2 7.5 6.8 7.3 7.1	7.3	0.433	0.016	Yes	1.088

Table continues on next page

		8.1			6.6					
		7.6			7.3					
	49	7.8	7.8	0.163	7.4	7.1	0.351	0.001	Yes	1.110
		8.0			6.5					
		7.8			7.2					
		7.7			7.3					
		8.5			7.1					
		8.7			8.4					
	38	8.3	8.6	0.289	8.2	7.8	0.445	0.009	Yes	1.098
		8.6			7.4					
		8.2			7.6					
		9.1			8.0					
		8.0			7.0					
		8.2			8.1					
150	44	8.0	8.1	0.228	7.3	7.5	0.374	0.007	Yes	1.087
		8.5			7.8					
		7.8			7.4					
		8.3			7.2					
		8.2			6.6					
		7.8			7.3					
	49	7.7	7.9	0.188	7.4	7.1	0.298	0.0005	Yes	1.112
		8.1			6.7					
		7.9			7.2					
		7.8			7.3					
Mean value										1.096
SD										0.0096

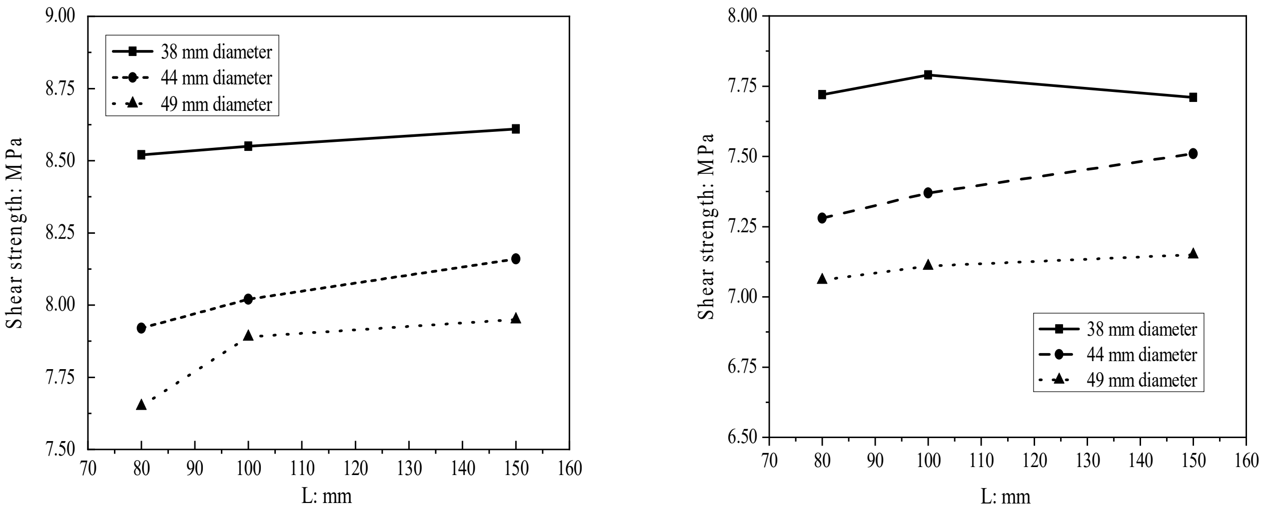


Fig. 10 - Core shear strengths tested by LDST (a) and IST, (b) plotted against core length.

of 0.05, indicating a remarkable variation in the means of the two methods. It shows that IST can be used for in-situ testing.

The shear strength obtained with IST should be multiplied by a correction factor and converted to the shear strength obtained using LDST, and the mean value of correction factor equal to 1.096. It could be interpreted that the two shear planes on the specimen of LDST make the stress uniformity better than that of IST, though shear strength tested by LDST is slightly higher than that of IST.

5.2.Effect of length of core on shear strength

The possible trend of core strength relative to core length was analyzed by using the data obtained. Average core strength results obtained by LDST and IST methods and core length are plotted in Figure 10. The data show that core shear strength increases with length increasing in case of given diameter for both the LDST and IST methods.

The shear strength of cores (d=38 mm) with lengths of 80, 100 and 150 mm determined by LDST were 8.52, 8.55 and 8.61 MPa, respectively. For LDST, the results show that core strength increases slightly as the length increases from 80 to 150 mm, increased by about 1.0 %.

The results of cores (d=38 mm) with lengths of 80, 100 and 150 mm tested by IST were 7.72, 7.79 and 7.84 MPa, respectively. Similar trends were observed with both LDST and IST methods for strengths of cores in diameters of 44 and 49 mm. But for cores with 38 mm diameter, the shear strength increased by about 0.9% and then decreased by 1%. This small difference is believed to be of no practical significance for the shear strength of an existing structure.

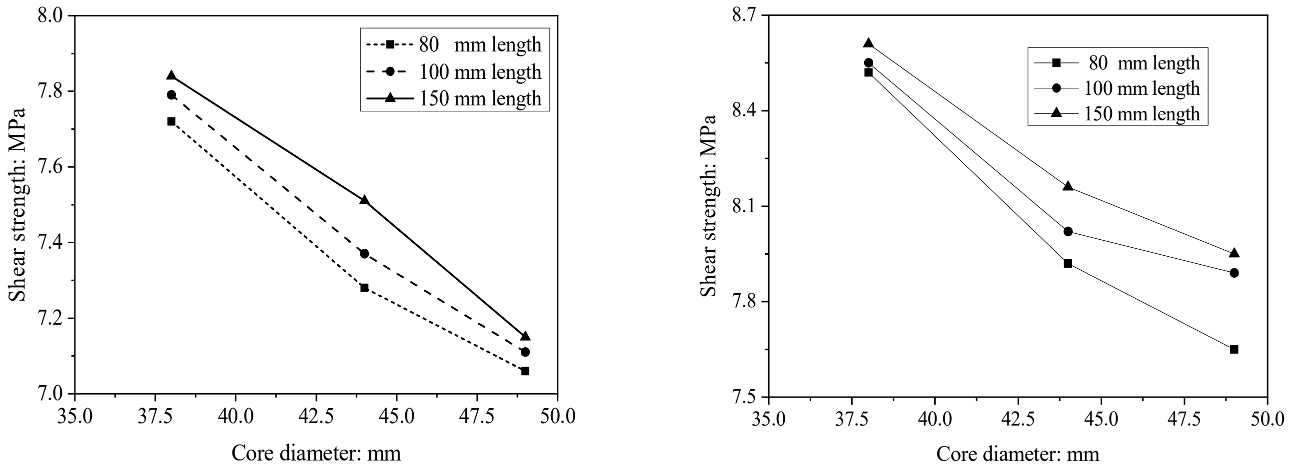


Fig. 11 - Core shear strengths measured by LDST (a) and IST, (b) plotted against core diameter.

To simplify the experiment in-situ, the length of core suitable for IST should be as shorter as possible, and a length of 80 mm could be selected as the standard test length of core samples.

5.3. Diameter effect on core shear strength

The average test results of shear strength for LDST and IST were compared to understand the possible trend of core shear strength relevant to diameters. The trends are clearly shown in Figure 11, where the core strength is inversely proportional to the core diameters. The experimental data suggest that the shear strength of the core decreases with the increase in core sample diameter.

For cores in diameters of 38, 44 and 49 mm, the average strength of L=80 mm by LDST method are 8.52, 7.92 and 7.65 MPa, respectively. Corresponding strength obtained by IST is 7.72, 7.29 and 7.06 MPa, respectively. The lengths of core with the l=100 and 150 mm follow similar trends in LDST and IST. Previous studies for compression test of drilling-core suggested that the larger the core diameter, the smaller the strength is because the size effect said that the larger the sample diameter, the higher the probability of defects is, and the lower the strength is. It can not only avoid the excessive decrease of the shear strength, but also ensure the ideal shear failure of the specimen [8].

5.4. Variation of test results

Figure 12 displays the histogram of SD values of LDST and IST methods as a function of diameter and length. The results demonstrate that the SD value increases with the decrease of core diameter and length. At the core in diameters from 38 to 49 mm and length of 80 mm, the standard deviation of core strength measured by the LDST method ranges from 0.193 to 0.387. The corresponding SDS values measured by IST are 0.367-0.560. A similar trend appears for SDs of cores with L=100 and 150 mm, the SD of cores with the same length decrease with the increase in diameter. Coefficients of variation for the IST and LDST range from 4.2 to 7.3 % and 2.4 to 4.5 %, respectively. The dispersion of IST is slightly larger than that of LDST. Compared with other in-situ strength testing methods, the reported values for break-off testing [15], pull-off testing [16], pull-out testing [17] and point-load testing [18] are 10.0, 8.0, 10.0 and 9.0 %, respectively. For this investigation, the COVs of LDST and IST are always lower than the pull-off test results. This indicates that the IST could obtain reliable and repeatable test results and eliminate defects of data scatter caused by other test methods and small core compression test [19, 20].

For further studies covering concrete with compressive strengths of 10 to 100 MPa, test data should be accumulated to improve the accuracy of in-situ tests and empirical factors. And the effect of aggregate types and sizes should also be investigated. Since the dispersion of shear strength test results is lower than that of the core compression test, further work is also needed to find some correlations existing in the concrete compressive strength and shear strength and to estimate the concrete compressive strength by a pre-calibrated relationship graph.

6. Relationship between IST strength and concrete cube strengths

Figure 13 illustrates the most appropriate relationship derived after the regression analysis of the data. A line of best fit was adopted to represent this relationship as the regression type $y=ax^b$, which describes the relationship between tensile and compressive strength and is also consistent with previous studies. The relationship of the increases in compressive strength for the concrete cube with the change in LST strength is provided in this Figure 13. The correlation coefficient (R^2) is 0.965. The relationship between the LST strength x and the cubic compressive strength y of concrete is expressed in Eq. 1.

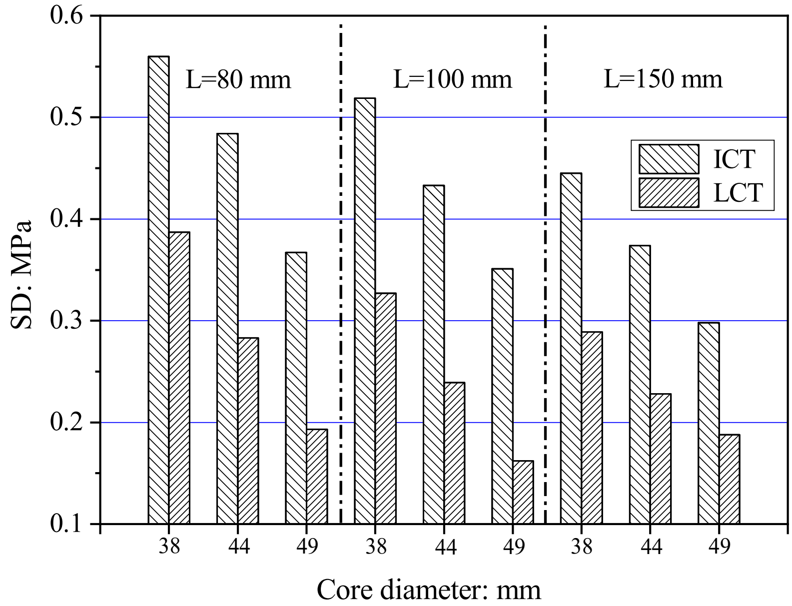


Fig. 12 - SD of results tested by LDST and IST plotted against core diameter.

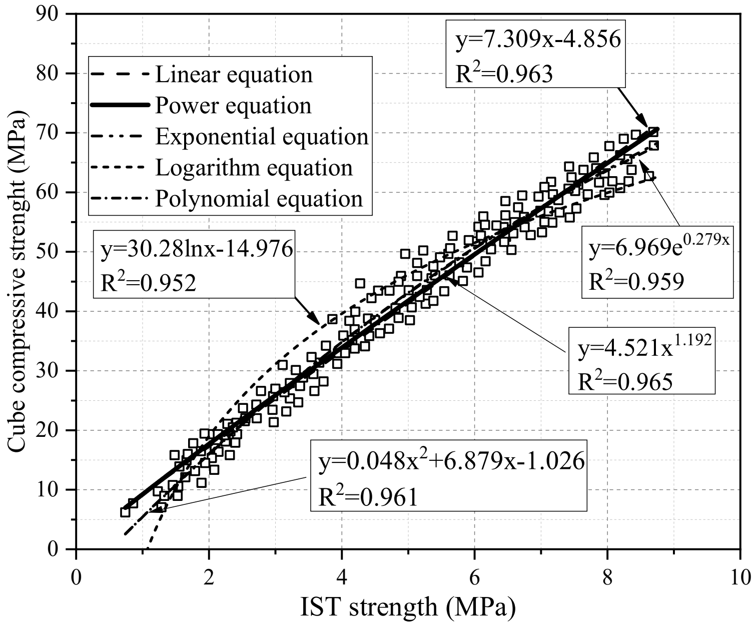


Fig. 13 - Relationship between test value and cube compressive strength.

$$y = 4.521x^{1.192} \quad (1)$$

where x = IST strength of concrete, in MPa; and y = compressive strength of concrete cube, in MPa.

7.Summary and Conclusions

The developed in-situ test method is simple, convenient and time-saving since some processes involved in the LDST method are not needed. The principle of the IST is to test the un-extracted core with lesser diameters within site for its shear strength. The following points are drawn:

(1) The results from IST are satisfactorily similar to those from the LDST method. Student's t-test values indicate that there is no significant difference between the two methods at the 95% confidence interval. The shear strength obtained with IST is multiplied by a correction factor and converted to that obtained using LDST, the mean value of the correction factor equal to 1.096.

(2) The IST results vary slightly to those from the LDST method of the core with different length and diameter, and the core strength increases with a decrease in diameter and grows with an increase in core length. A length of 80 mm could be selected as the standard test length of core samples.

(3) The SDs of cores gained by IST is found to be higher than that of LDST, and the SDs decreased with the increase of core length for both LDST and IST. Cores in larger diameter are thus

recommended because of less variation in the results.

(4) The clamping mechanism is utilized to apply the shear force on cores for the IST apparatus. The reliability and accuracy of the IST are higher than those of the SRH and pull-off tests. The IST can provide a reliable and alternate test method for the measurement of the concrete shear strength.

(5) Regression analysis shows that there is a good correlation between compressive strength and IST strength. The regression coefficient (R^2) is 0.965.

Data Availability Statement
Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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