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Experimental Research on Concrete Strength Prediction by Limpet Pull-off Test in China

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Abstract: Using Limpet pull-off test for concrete strength prediction has now been accepted in standards of the UK, North America, Holland and some other countries. For its application in China, pull-off tests were carried out by using the Limpet in this study. Concrete specimens with four different mixtures and strength classes were cast, representing the normal and the high performance concretes commonly used in China. After different ages, the pull-off tensile strength was determined by using the Limpet and the compressive strength was obtained by carrying out cube crushing test using a WE-100 Universal Testing Machine. To reflect the correlation between the pull-off tensile strength and the cube compressive strength, two types of curve were used for regression, $y = ax^b$ and $y = ae^{bx}$ respectively. The regression efficiency of the two curves was compared.

Keywords: Limpet; pull-off tensile strength; compressive strength; correlation curve

1. Introduction

Pull-off test as a means of predicting the compressive strength of concrete was originally developed at Queen’s University Belfast by Professor A.E. Long (Long, 1979). The pull-off method involves bonding a circular steel probe to the surface of the concrete under test, by means of an epoxy resin adhesive. Two basic approaches can be used (see Fig. 1). One is where the metal disc is attached directly to the concrete surface. The second approach is where partial coring of the surface is used for concrete surface which is carbonated or altered and, therefore, having different physical properties compared with the interior. A slowly increasing tensile force is then applied to the probe and, so long as the tensile strength of the bond strength in adhesive is greater than the tensile strength of concrete, the latter will eventually fail in tension. The amount of overbreak is usually small so the area of failure can be taken as being equal to that of the probe. From this area and the force applied at failure it is possible to calculate a nominal tensile strength for the concrete specimen (Bai, Basheer, Cleland, and Long, 2009).

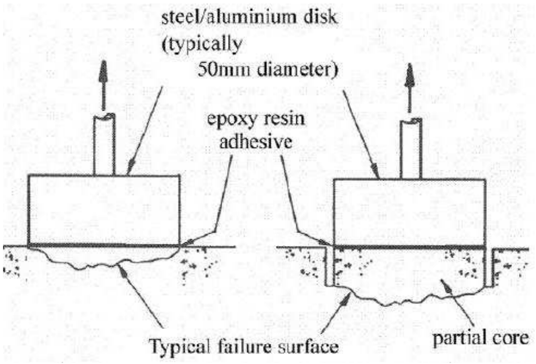

Figure 1. Method of test [2]

Substantial continuous developments and verifications (Long and Murray,1981) have taken place since then. Finally the currently available commercial pull-off equipment, 'Limpet', was developed. In this equipment the force was applied through the rotation of a handwheel and digital readout was added to record the maximum force. This test has now been accepted in British Standards, BS 1881-207:1992 (British Standards Institution,1992) for assessing the in-situ concrete strength in structures and BS EN 1542:1999 (British Standards Institution, 1999) for assessing the bond strength between overlays and substrate concrete in patch repairs. In addition, BS 1881-201:1986 (British Standards Institution, 1986) recommends it for quality control and long term monitoring of hardened concretes. It has also been accepted in North America (ASTM C1583-04), Holland and some other countries for similar applications (Bai, Basheer, Cleland, and Long, 2009).

These standards are not, however, directly transferrable to China. British Standards stipulate that a correlation between pull-off tensile strength and concrete compressive strength must be established for a given concrete before near-surface concrete strength predictions can be established. As concrete is a local material, it is not appropriate to apply the correlation curve recommended in the British Standards to structures constructed in China. As such, the main objective of this research is to establish appropriate correlation curves using local Chinese methods and materials and, in so doing, establish the LIMPET pull-off test as a standard test in China.

In this article, a correlation curve between pull-off tensile strength and compressive strength for typical concretes used in China was established. Further, some significant conclusions were drawn to lay a foundation for the introduction of LIMPET to Chinese standard for concrete strength prediction.

2. Experimental program

2.1 Materials and mix proportions

The cement used for concrete mixtures was ordinary Portland cement produced by Qianchao Group Co., Ltd, Zhejiang, China. Ordinary yellow sand with a specific gravity of 2.60 was used as fine aggregate, while crushed stone with maximum particle size of 20mm and specific gravity of 2.75 was used as coarse aggregate. The mineral admixtures used in this study were fly ash (FA) and ground slag (GS). Fly ash of Ⅰ degree produced in Huarun Power Plant, Anhui, China was used and the ground slag used was produced by Deqing Hengxiang Group Co., Ltd, Zhejiang, China. A naphthalene sulphonate water reducer produced in Muhu Admixture Co., Ltd., Beijing, China, was used to obtain the desired workability.

To represent for typical concrete used in China, four mixtures were designed and their mixture proportions are shown in Table 1.

Table 1. Mixture proportions for concrete (in kg/m^3)

Strength grade	Mix designation	W/B	C	W	S	G	FA	GS	Water reducer	Slump (mm)
C30	30C	0.50	390	195	635	1180	—	—	—	40
C40	40C	0.43	453	195	596	1156	—	—	—	40
C40	40F	0.35	320	161	724	1080	140	—	3.0	170
C40	40G	0.35	184	161	724	1080	—	276	1.8	175

Note: W/B is the water to binders ratio; C, W, S, G, FA, and GS denote cement, water, sand, gravel, fly ash and ground slag respectively.

2.2 Specimens

The coarse aggregate, fine aggregate, cement, and mineral admixtures were first mixed dry for a period of 2 min. The water reducer dissolved in water was then mixed thoroughly for a period of 1 min.

For each mixture, 30 specimens of dimension 150mm×150mm×150mm were cast. The specimens were covered in damp hessian immediately after casting and sprayed with water once every day for 28 days.

2.3 Test methods

Specimens of four mixtures were all tested for compressive strength and pull-off tensile strength at different ages of 2d, 4d, 7d, 28d, 90d and 180d. For each specimen, the LIMPET test was performed first on two opposite faces that were perpendicular to the casting face, and then the cube-compressive-strength test using WE-100 Universal Testing Machine was carried out on the remaining two opposite surfaces of the same specimen (see Fig. 2). For each scenario, i.e. the specimens of the same mixture at the same age, four specimens were cast and tested. Test results of three specimens were used to establish the correlation curve between the pull-off tensile strength and the compressive strength. The remaining data were used to check the curve by error analysis.

It should be noted that before the LIMPET test the circular steel probe should be bonded to concrete surface by means of an epoxy resin adhesive. In this study, the metal disc was attached directly to the concrete surface, as shown in Figure 3. The adhesive should be enough to make sure that the tensile strength of the bond strength in adhesive was greater than the tensile strength of concrete. Otherwise the failure would occur in the adhesive between the probe and the concrete, but not in the concrete.

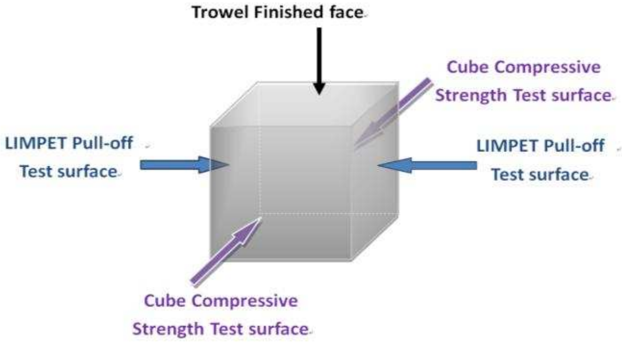

Fig. 2 The test surfaces of the specimens

Figure 3. Metal disc bonded on the surface of specimen

a. Pull-off tensile test by using LIMPET

b. Cub Compressive strength test byusing universal machine

Fig. 4 Test of strength

3. Results and discussion

3.1 Failure mode of Limpet test

The failure surface of specimen after pull-off test is shown in Figure 5. It can be seen that the area of failure is almost equal to that of the probe, therefore, it is possible to calculate the pull-off tensile strength by using the area of the probe. Also the damage to specimen is minimal, so the influence of this local damage on compressive strength test on the two neighboring opposite surfaces can be neglected. Some coarse aggregates in the concrete were found to have damaged hence the failure could be considered to have been caused by tension. All the above observations agreed with the previous studies (Long, 1979; Bai, Basheer, Cleland, and Long, 2009; Long and Murray,1981; British Standards Institution,1992) that studied the application of Limpt for British concrete. Consequently, we regard that Limpet is suitable for testing Chinese concrete as well.

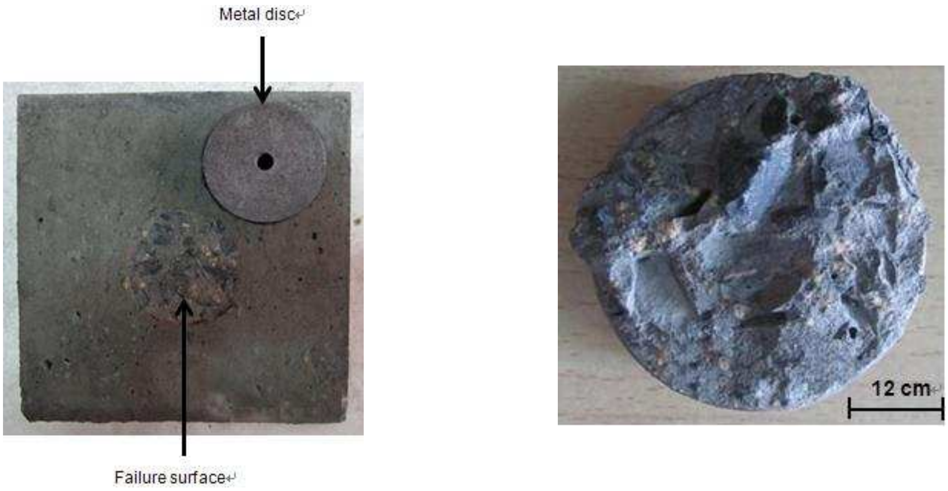

Figure 5. Failure surface of the specimen

3.2 Influence of concrete types, strengths and ages

For each scenario, i.e. the specimens of the same mixture at the same age, four specimens were tested. All data results were used to analyze the influence of concrete types, strength classes and test ages on the correlation curve. Based on the test data, the pull-off tensile strength data was plotted against the cube compressive strength date, Figure 6. It can be seen that the influence of concrete type, strength class and test age is insignificant. For the same materials, in spite of the differences of concrete type, strength and test age, a single curve could be sufficient to reflect the correlation between pull-off tensile strength and cube compressive strength.

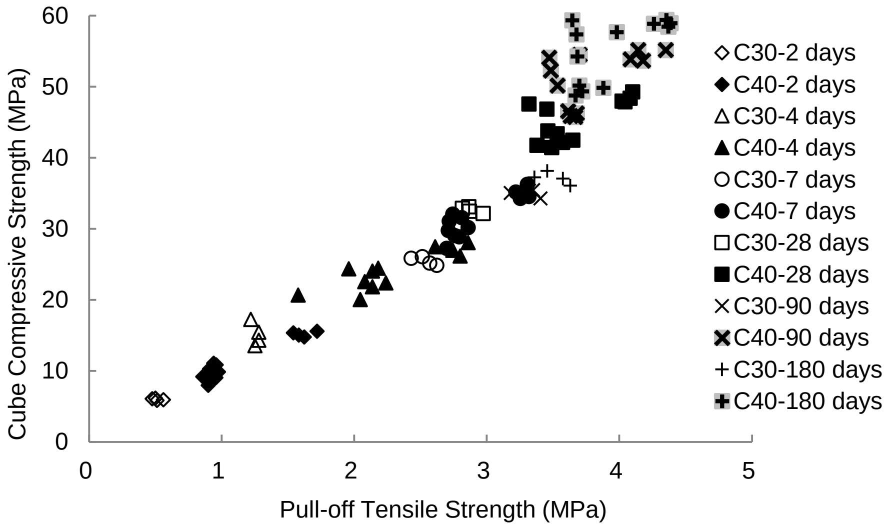

Figure 6. Influence of concrete types, strengths and ages on the relation between the pull-off tensile strengths and the cube compressive strengths

Again, this conclusion agrees well with that in the previous British study (Johnston, 1967). This is also reflected in BS 1881-207: 1992 (British Standards Institution, 1992) in specifying that "in some circumstances, use of a general correlation may be adequate". Consequently, the influence of concrete type, strength and test age to the correlation curve can be neglected.

3.3 Correlation between the Limpet pull-off test and the cube-compressive test

Data results of three specimens were used to establish the regression curve between pull-off tensile strength and compressive strength, while the remaining data was used to check the reliability of the regression curve fitting by error analysis.

3.3.1 Power function fitting

Based on the analysis in section 3.2, a single curve was found to be sufficient to reflect the relationship between the pull-off tensile strength and the cube compressive strength. According to the previous research (Maxwell, 1977; Gawn, 1978; Glass, 1981), the regression form $y = ax^b$ is adequate to represent the relationship. By using the least square method, a regression curve between the pull-off tensile strength and the cub compressive strength was established for concretes commonly used in China, which is given in Fig. 7. The correlation coefficient is 0.911. The regression equation is:

$$f_{c,u} = 8.65 {f_{t,lim}}^{1.29} \tag{1}$$

where $f_{c,u}$ is the cube compressive strength and $f_{t,lim}$ is the pull-off tensile strength. It needs to be pointed out that only three data sets for each scenario were used for the regression analysis, because the fourth data was used for the error analysis of the regression line.

Table 2 reports the errors calculated between the measured data （the fourth data） and the predicted results. It can be seen from Table 2 that the average relative error between the calculated compressive strength by the above regression curve and the measured strength is 9.65%, which is excellent given the large variability of concrete that is normally found between test locations. It may be noted that the relative errors between the calculated value and the measured value for the early-age-strength, i.e. 2 days and 4 days, are higher. It might be due to the fact that the influence of concrete microstructure on tensile strength and compressive strength at these ages may be slightly dissimilar. However, with the development of the concrete strength after 7 days, the relative errors are lower. The average of relative error after 7 days decreases to 6.13%. Therefore, for concrete after 7 days' of curing the precision of strength prediction by the above curve is increased. Furthermore, with a certain degree of caution applied, the LIMPET could be used for predicting the compressive strength of Chinese concretes at their early ages.

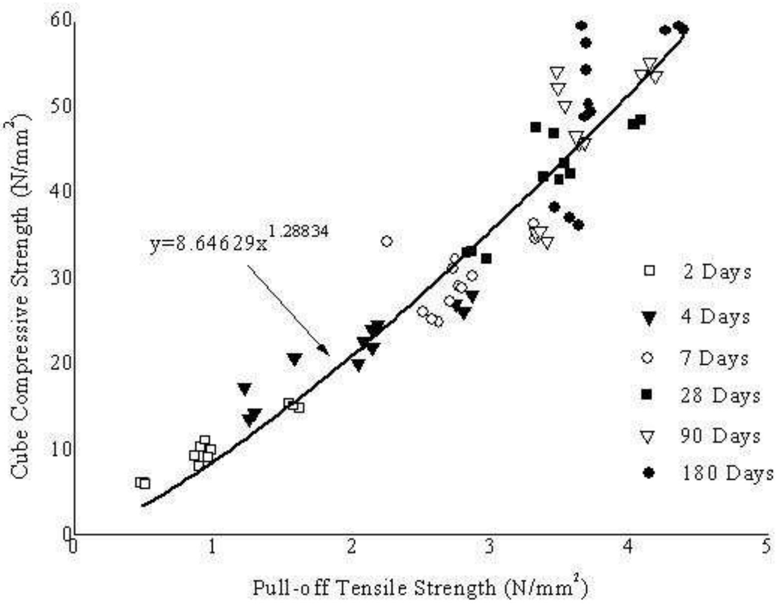

Figure 7. Power function regression line

Table 2. Error analysis of the power function regression line

Strength grade	Designation	Measured tensile strength (MPa)	Measured compressive Strength (MPa)	Calculated compressive strength (MPa)	Relative Error (%)
C30	30C-2-4	0.56	5.95	4.10	31.09
	30C-4-4	1.28	15.45	11.88	23.11
	30C-7-4	2.43	25.85	27.14	4.99
	30C-28-4	2.87	32.45	33.63	3.64
	30C-90-4	3.18	35.05	38.38	9.50
	30C-180-4	3.36	37.25	41.20	10.60
C40	40C-2-4	1.72	15.55	17.39	11.83
	40C-4-4	2.61	27.45	29.76	8.42
	40C-7-4	3.22	35.15	39.01	10.98
	40C-28-4	3.65	42.45	45.84	7.99
	40C-90-4	3.68	46.25	46.33	0.17
	40C-180-4	3.88	49.85	49.6	0.50
C40	40F-2-4	0.96	10.85	8.20	24.42
	40F-4-4	2.24	22.35	24.44	9.35
	40F-7-4	2.71	29.75	31.23	4.97
	40F-28-4	3.46	43.75	42.79	2.19
	40F-90-4	3.70	54.45	46.65	14.33
	40F-180-4	3.98	57.65	51.25	11.10
C40	40G-2-4	0.94	8.85	7.98	9.83
	40G-4-4	1.96	24.35	20.58	15.48
	40G-7-4	2.81	31.55	32.73	3.74
	40G-28-4	4.10	49.25	53.25	8.12
	40G-90-4	4.35	55.15	57.47	4.21
	40G-180-4	4.37	58.45	57.81	1.09

Average relative error (%)	9.65

3.3.2 Exponential function fitting

Due to the particular shape of the Correlation curve between the Limpet pull-off strength and the cube-compressive strength, an exponential function $y = ae^{bx}$ was also used for the regression analysis. By using the least square method, a regression curve between the pull-off tensile strength and the cub compressive strength was established for concretes commonly used in China, which is shown in Fig. 8. The correlation coefficient is 0.906. The regression equation is:

$$f_{c,u} = 8.23e^{0.47 f_{t,lim}} \qquad (2)$$

where $f_{c,u}$ is the cube compressive strength and $f_{t,lim}$ is the pull-off tensile strength. Here also only three data sets for each scenario were used for the regression analysis, because the fourth data was used for the error analysis of the regression line.

The errors calculated between the measured data（the fourth data）and the predicted results are reported in Table 3. It can be seen from Table 3 that the average relative error between the calculated compressive strength by using the above regression curve and the measured strength is 11.74%, which is acceptable. Also, relative errors between calculated value and the measured value of the early-age-strength, i.e. 2 days and 4 days, are higher. The average of relative error after 7 days decreases to 6.02%. Therefore, for concrete after 7 days' of curing the precision of strength prediction by the above regression curve is increased. Consequently, as in the case of the regression relationship given by equation (1), the exponential regression relationship given by equation (2) should be used with caution for predicting the compressive strength of Chinese concretes at their early ages by using the Limpet.

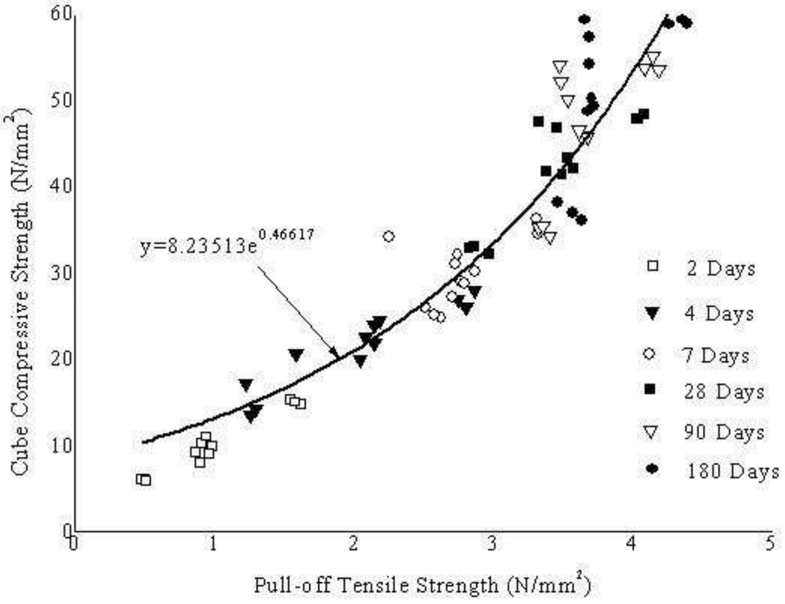

Fig.8 Exponential function regression line

Table 3 Error analysis of the exponential function regression line

Strength grade	Designation	Measured tensile strength (MPa)	Measured compressive Strength (MPa)	Calculated compressive strength (MPa)	Relative Error (%)
C30	30C-2-4	0.56	5.95	10.69	79.69
	30C-4-4	1.28	15.45	14.96	3.20
	30C-7-4	2.43	25.85	25.56	1.10
	30C-28-4	2.87	32.45	31.38	3.28
	30C-90-4	3.18	35.05	36.26	3.46
	30C-180-4	3.36	37.25	39.44	5.87
C40	40C-2-4	1.72	15.55	18.36	18.08
	40C-4-4	2.61	27.45	27.80	1.28
	40C-7-4	3.22	35.15	36.95	5.11
	40C-28-4	3.65	42.45	45.15	6.35
	40C-90-4	3.68	46.25	45.78	1.01
	40C-180-4	3.88	49.85	50.26	0.82
C40	40F-2-4	0.96	10.85	12.88	18.74
	40F-4-4	2.24	22.35	23.40	4.69
	40F-7-4	2.71	29.75	29.13	2.09
	40F-28-4	3.46	43.75	41.32	5.55
	40F-90-4	3.7	54.45	46.21	15.13
	40F-180-4	3.98	57.65	52.66	8.66
C40	40G-2-4	0.94	8.85	12.76	44.22
	40G-4-4	1.96	24.35	20.53	15.67
	40G-7-4	2.81	31.55	30.52	3.27
	40G-28-4	4.1	49.25	55.68	13.07
	40G-90-4	4.35	55.15	62.57	13.45
	40G-180-4	4.37	58.45	63.15	8.05

Average relative error (%)	11.74

3.4 Comparison between the two fitting curves

To reflect the correlation between the pull-off tensile strength and the cube compressive strength, two types of curves were used for regression, $y = ax^b$ and $y = ae^{bx}$ respectively. In this section a comparison between the two regression curves is made. The comparison result is reported in Table 4.

Table 4 Comparison between the two fitting curves

Curve form	Correlation coefficient	Average relative error
$y = ax^b$	0.91116	9.65%
$\mathrm{y = ae^{bx}}$	0.90590	11.74%

It can be seen from Table 4 that, for curve $y = ae^{bx}$ and $y = ax^b$, the correlation coefficient of the former is larger than the latter, while the average relative error of the former is lower than the latter. Consequently, for data in this study, $y = ax^b$ is suggested to be the best form to reflect the correlation between the pull-off tensile strength and the cube compressive strength. This conclusion is in agreement with the previous British studies [8-10], for which the best fit line was of the form $y = ax^b$.

3.5 Feasibility analysis of Limpet application in Chinese standard

Advantages of LIMPET using strength test for concrete are obvious and sufficient. It is low in cost and fast in speed. Besides, it is very light, easy to handle and so is very suitable for site use, even for overhead testing. What's more, consistently accurate and reliable results can be achieved by even unskilled operator and planning in advance of placing the concrete is not required. Also it is supported by internationally accepted research and is widely used and accepted in standard in some countries in the world. Consequently, it is concluded that the Limpet pull-off test is a simple, reliable and easy-to-use method for strength prediction of Chinese concretes both in laboratory and in situ.

Based on this study, the failure mode of Chinese concrete in LIMPET test is the same as that in British. What’s more, the form of correlation curve between the pull-off tensile strength and the cube compressive strength is in agreement with previous British research findings . Therefore, it is feasible for LIMPET to be introduced in Chinese standards.

4. Conclusion

1) The failure mode of Chinese concretes in LIMPET test is the same as that in British. The area of failure is almost equal to that of the probe and the damage to specimen is minimal.
2) In spite of the differences of concrete type, strength and test age, a single curve is sufficient to establish the correlation between the pull-off tensile strength by Limpet and the cube compressive strength.
3) In this study, two types of curve were used for regression, $y = ax^b$ and $y = ae^{bx}$. According to the regression result, $y = ax^b$ is the best form, which is the same as that established by previous British research projects.
4) For Chinese concretes used in this study, it should be cautious to use LIMPET to predict the compressive strength at the early ages before 7 days.
5) With many advantages, such as simple, reliable and easy-to-use, LIMPET can be introduced in China standards in the future.

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