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FOR TENSILE STRENGTH OF CONCRETE

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by
T. A. Colgrove¹ and W. F. Chen²

ABSTRACT

The tensile strength of concrete is most commonly measured using the indirect split-cylinder test. Recently a new test, the double punch test, has been proposed. The new test method has undergone preliminary experimental study to determine the testing procedure which would yield the most reliable and consistent results. However, further study was needed. Using the previously recommended procedure, the effect of several additional parameters on the tensile strength was studied.

These parameters include the rate of stressing during the test, and the effect of lightweight as well as regular concrete. Also being studied is the effects of the molds, machine lubricant, and testing machine. The analysis of these results has led to a more thorough understanding and greater applicability of the new tensile test.

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1. INTRODUCTION

The tensile strength of concrete can be obtained from several different tests, such as direct pull tests on briquettes, flexural tests on beams, and splitting tests on cylinders. The most common is the indirect split cylinder test (Brazilian test). In countries where the compressive strength is determined from cubes rather than from cylinders, the tensile strengths have been obtained using a split cube or a cube specimen tested diagonally. However, there are drawbacks connected to each of these tensile tests. Recently, a new alternative test for concrete, the double-punch test has been developed [1]. Preliminary work has been conducted and has resulted in the determination of a standard procedure for the test [2]. The purpose of the work represented here was to further investigate experimentally the results of varying several parameters, including the rate of stressing during the test, and the effect of lightweight as well as regular concrete. Also observed was whether the new test accurately reflected changes in molds, machine lubricant, and testing machine. This study has led to a more thorough understanding and greater applicability of the test. The ultimate goal in this study is to prepare this test for acceptance into the specifications of the American Society of Testing and Materials.

2. TEST PROCEDURE

The double punch test consists of a 6 x 6 in. (15.30 x 15.30 cm.) concrete cylinder placed vertically between the loading platens of the testing machine and compressed by two 1 2 in. (3.80 cm.) diameter steel
punches placed concentrically on the top and bottom surfaces of the cylinder (Fig. 1). No plywood bearing discs between the punch and specimen surface are needed provided the surfaces of the specimen are relatively smooth [2]. The sample splits across many vertical diametral planes similar to the split cylinder test (see Fig. 2), but the double punch technique requires a much simpler testing procedure.

The tensile strengths arrived at by this method show a good correlation with the split-cylinder method. The coefficients of variation, when compared, are similar or much lower as in the case of lightweight concrete.

3. STRESS DISTRIBUTION AND MODE OF FAILURE

The compressive loading transferred to the specimen through the steel punches produces a stress distribution which has been shown [1] to give an average tensile strength over all of the cracked diametral planes represented by the following formula:

\[ f'_t = \frac{Q}{\pi(1.20 \ bH - a^2)} \]

where \( f'_t \) = tensile stress
\( Q \) = applied load
\( b \) = radius of cylinder
\( H \) = height of cylinder
\( a \) = radius of punch

Valid for \( b/a \leq 5 \) or \( H/2a \leq 5 \). For any ratio \( b/a > 5 \) or \( H/2a > 5 \), the limiting value \( b = 5a \) or \( H = 10a \) should be used.
The ideal failure mode for the double punch test is for the specimen to fail in many radial cracks. Since the strength is an average value, the greater the number of these radial cracks, the more accurate the value of the strength. Many cracks also indicates more even stress distribution in the test specimen. Where the specimen's top and bottom surfaces are very rough or not parallel to each other the specimen may fail in only two cracks, and usually at a significantly lower load (Fig. 3). Most specimens fail in three or four cracks.

4. EXPERIMENTAL DETAILS

4.1 Materials

Throughout the experiment two types of coarse aggregate were used: a 3/4 in. (1.9 cm.) maximum size crushed stone for all regular concrete specimens, and a 3/4 in. (1.9 cm.) maximum size expanded shale commercially called Nytralite for all lightweight concrete specimens. The same sand, fineness modulus 2.95, and ordinary type I Portland cement was used in all cases. Darex was used as an air entraining agent for the lightweight batches.

4.2 Test Apparatus

The loading punches were made from No. 1018 cold rolled steel and were 1\(\frac{1}{2}\) in. (3.80 cm.) in diameter and 1 inch (2.55 cm.) thick. All surfaces were machined, and the ends parallel. Two plywood discs, 6 in. (15.30 cm.) in diameter with a 1.5 in. (3.80 cm.) diameter hole in the center, were used as templates to center the punches on the concrete specimen and then between the loading platens of the machine.
A 300 kip (340 metric tons) Baldwin hydraulic testing machine was used for all compression, split cylinder, and double punch tests except where noted otherwise. In those cases either a 120 kip (136 metric tons) Tinius-Olsen mechanical machine or a 60 kip (68 metric tons) Baldwin hydraulic machine was used.

4.3 Mix Design

Mix proportions for the various mixes of concrete used in this work are given below in Table 1.

Table 1 Mix Proportions of Concretes (All Quantities Pound Per Yd.³)

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>w/c Ratio</th>
<th>Water</th>
<th>Cement</th>
<th>Fine Aggregate</th>
<th>Coarse Aggregate</th>
<th>Darex</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.40</td>
<td>340</td>
<td>850</td>
<td>1080</td>
<td>1680</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>0.50</td>
<td>340</td>
<td>680</td>
<td>1220</td>
<td>1680</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>0.60</td>
<td>340</td>
<td>565</td>
<td>1320</td>
<td>1680</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>0.70</td>
<td>340</td>
<td>485</td>
<td>1390</td>
<td>1680</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>0.60</td>
<td>285</td>
<td>480</td>
<td>1350</td>
<td>955</td>
<td>5½ oz.</td>
</tr>
<tr>
<td>6</td>
<td>0.44</td>
<td>292</td>
<td>658</td>
<td>910</td>
<td>955</td>
<td>5½ oz.</td>
</tr>
<tr>
<td>7</td>
<td>0.53</td>
<td>292</td>
<td>550</td>
<td>996</td>
<td>955</td>
<td>5½ oz.</td>
</tr>
</tbody>
</table>

Each batch was mixed in a rotary mixer and specimens were cast in accordance with ASTM Standard Methods for Making and Curing Concrete Test Specimens in the Laboratory (C192).

Cylinders used for double punch testing had a diameter and height of 6 in. (15.20 cm.). The cylinders, unless specified otherwise were cast in wax coated, disposable cardboard molds, meeting the
requirements of ASTM Specifications for Single-Use Molds for Forming 6 by 12 in. Concrete Compression Test Cylinders (C470). These molds were cut to 6 in. (15.30 cm.) in height for double punch specimens. Cube specimens were 6 in. (15.30 cm.) on edge and cast in either plywood or steel molds.

Immediately after casting, the samples were covered with plastic sheets for a period of 24 hours. The molds were then stripped from the samples, and the samples were placed in a moist curing room, ASTM Specifications for Moist Cabinets and Rooms Used in the Testing of Hydraulic Cements and Concretes (C511), for the remaining 27 days. Lightweight specimens were removed from the moist curing room after 7 days and covered with wet burlap and plastic for the remaining 21 days.

Standard control specimens were cast for each mixture.

5. RESULTS

5.1 Control Tests

Control tests were made for each mix and the values are shown in Table 2 below.
Table 2 Results of Control Specimens

<table>
<thead>
<tr>
<th>Mix</th>
<th>Water Cement Ratio, w/c</th>
<th>Simple Compression a, f' c (MN/m²)</th>
<th>Split Cylinder b, f' c (MN/m²)</th>
<th>Coefficient of Variation, %</th>
<th>Double Punch c, f' c (MN/m²)</th>
<th>Coefficient of Variation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.4</td>
<td>5396 (37.21)</td>
<td>505 (3.48)</td>
<td>2.16</td>
<td>376 (2.60)</td>
<td>4.89</td>
</tr>
<tr>
<td>2</td>
<td>.5</td>
<td>4907 (33.83)</td>
<td>506 (3.49)</td>
<td>3.17</td>
<td>394 (2.71)</td>
<td>6.96</td>
</tr>
<tr>
<td>3</td>
<td>.6</td>
<td>4176 (28.79)</td>
<td>461 (3.18)</td>
<td>9.76</td>
<td>373 (2.57)</td>
<td>1.79</td>
</tr>
<tr>
<td>4</td>
<td>.7</td>
<td>3634 (25.06)</td>
<td>398 (2.74)</td>
<td>9.68</td>
<td>354 (2.44)</td>
<td>3.76</td>
</tr>
<tr>
<td>5</td>
<td>.6</td>
<td>3749 (25.85)</td>
<td>374 (2.58)</td>
<td>7.38</td>
<td>261 (1.80)</td>
<td>2.18</td>
</tr>
<tr>
<td>6</td>
<td>.44</td>
<td>4100 (28.26)</td>
<td>427 (2.95)</td>
<td>9.63</td>
<td>331 (2.28)</td>
<td>6.40</td>
</tr>
<tr>
<td>7</td>
<td>.53</td>
<td>4556 (31.42)</td>
<td>440 (3.04)</td>
<td>6.04</td>
<td>321 (2.22)</td>
<td>3.20</td>
</tr>
</tbody>
</table>

a Average of 3 tests.
b Average of 3 tests mixes 1-4, 8 tests mixes 5-7.
c Average of 3 tests mixes 1-4, 5 tests mixes 5-7.

The double punch test gave more consistent results in many cases as shown by the lower coefficients of variation in the Table.

In Fig. 4 the double punch strengths closely parallel the strengths given by the split cylinder tests in the regular concrete region (mixes 1-4). However, the relationship was not quite as good in the lightweight concrete (mixes 5-7).

In the split cylinder test the plane of failure of the specimen is predetermined. That is, it will crack vertically whether that plane happens to be the strongest or weakest area of the specimen. In contrast to this, the double punch test does not predetermine the failure plane.
and so will fail in the weakest planes. This explains the consistently lower strengths obtained.

5.2 Effect of Molds

The purposes of this experiment were to investigate any effects on the double punch test strengths due to different types of molds and to see whether these effects, if any, are comparable to those reflected in the split cylinder testing procedure.

In split cylinder testing cylinders cast in cardboard molds give specimens with lower strengths and higher variability than specimens cast in steel molds [3].

Regular and lightweight concrete specimens were cast in both cardboard and steel cylinder molds. Standard 12 in. (30.50 cm.) cardboard molds were cut to 6 in. (15.20 cm.) heights and false bottoms were made for the steel molds. Cube specimens were also cast in both plywood and steel molds.

The results in Table 3 show the double punch test consistently reflects greater strengths and lower coefficients of variation in the case of steel molds. This therefore indicates the sensitivity of the double punch method to record these changes.
Table 3 Effect of Mold Type on Specimen Strength

<table>
<thead>
<tr>
<th></th>
<th>Cylinder</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cardboard</td>
<td>Steel</td>
</tr>
<tr>
<td>Mix 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular</td>
<td>Strength</td>
<td></td>
</tr>
<tr>
<td></td>
<td>psi (MN/m²)</td>
<td>333 (2.30)</td>
</tr>
<tr>
<td></td>
<td>Coefficient of Variation</td>
<td>5.98</td>
</tr>
<tr>
<td>Mix 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lightweight</td>
<td>Strength</td>
<td></td>
</tr>
<tr>
<td></td>
<td>psi (MN/m²)</td>
<td>261 (1.80)</td>
</tr>
<tr>
<td></td>
<td>Coefficient of Variation</td>
<td>2.18</td>
</tr>
</tbody>
</table>

*a Average of 4 tests

5.3 Effect of Stressing Rate

The influence of the stressing rate was measured by testing mixes 3 and 5 each at 7 and 28 days. Regular concrete (mix 3) showed a gradual decrease in the strength with an increased rate (Fig. 5). Lightweight concrete (mix 5) was found to be more sensitive to the rate. Beyond 200 psi/min. the strength rose steeply to around 500 psi/min. then fell off. The 28 day strengths are also given in Table 4.

Table 4 Effect of Stressing Rate

<table>
<thead>
<tr>
<th>Rate psi/min. (MN/m²/min)</th>
<th>Mix 3</th>
<th></th>
<th>Mix 5</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Strength</td>
<td>Coefficient of Variation, %</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>psi (MN/m²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 (0.69)</td>
<td></td>
<td>379 (2.62)</td>
<td>2.74</td>
<td></td>
</tr>
<tr>
<td>200 (1.38)</td>
<td></td>
<td>390 (2.69)</td>
<td>4.14</td>
<td></td>
</tr>
<tr>
<td>300 (2.07)</td>
<td></td>
<td>364 (2.51)</td>
<td>7.23</td>
<td></td>
</tr>
<tr>
<td>500 (3.45)</td>
<td></td>
<td>368 (2.54)</td>
<td>4.18</td>
<td></td>
</tr>
<tr>
<td>1000 (6.89)</td>
<td></td>
<td>362 (2.50)</td>
<td>14.00</td>
<td></td>
</tr>
</tbody>
</table>

*a Average of 6 test results at 28 days.
5.4 Effect of Testing Machine

Testing machine conditions may significantly affect the measured strength of concrete. Care must be taken to accurately align the punches and specimen in the testing machine. Each of the testing machines used was fitted with a spherical bearing block on the upper platen. Tests were made on the type of lubricant used on the upper platen. With a poor lubricant, the platen is able to move initially but then breaks down under load and becomes effectively fixed. With a high pressure lubricant the spherical bearing block is able to adjust throughout the loading.

In this test a low grade all-purpose grease was compared to a high pressure graphite lubricant. Again, as with the mold test, the double punch test was sensitive to this condition and able to accurately reflect the changes. In the case of the high pressure graphite lubricant the strength was significantly higher due to the more evenly distributed load and the coefficient of variation was sharply lower than with the poor lubricant.

Table 5 Effect of Two Types of Lubricant on Measured Strengths

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Strength$^a$ (psi (MN/m²))</th>
<th>Coefficient of Variation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>High pressure lubricant</td>
<td>361 (2.49)</td>
<td>1.69</td>
</tr>
<tr>
<td>Poor lubricant</td>
<td>329 (2.27)</td>
<td>11.3</td>
</tr>
</tbody>
</table>

$^a$Average of 3 test results
It was also decided to investigate the effect, if any, of the size of testing machine used. The results are given in Table 6.

Three machines, a 300 kip (340 metric tons) Baldwin hydraulic machine, a 120 kip (136 metric tons) Tinius-Olsen mechanical machine, and a 60 (68 metric tons) Baldwin hydraulic machine were used for this test. The measured double punch tensile strength of concrete is seen to be insensitive to the size of testing machine.

Table 6
Effect of Three Types of Testing Machine on the Measured Strengths

<table>
<thead>
<tr>
<th>Strength Mix 4</th>
<th>60 kip(^a)</th>
<th>120 kip(^a)</th>
<th>300 kip(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>psi (MN/m(^2))</td>
<td>361 (2.49)</td>
<td>362 (2.50)</td>
<td>358 (2.47)</td>
</tr>
<tr>
<td>Coefficient of Variation, %</td>
<td>1.49</td>
<td>1.61</td>
<td>3.10</td>
</tr>
</tbody>
</table>

\(^a\)Average of 3 tests
\(^b\)Average of 6 tests

5.5 Curing Rate

This test was undertaken to determine if specimens tested by the double punch method reflected the same strength changes throughout its curing period as those tested by the split cylinder test method. As before, both regular (mix 2) and lightweight (mix 5) concrete were studied. Figure 6 shows the parallel correlation between the two tests for both types of concrete. This therefore indicates the sensitivity of both methods to record the strength changes with time.
6. ADVANTAGES OF THE DOUBLE PUNCH TEST

There are four primary advantages of the double punch test over the split cylinder test. These are:

1. It gives an average tensile strength which exists over all of the failure planes, and a "truer" strength than the split cylinder test because of the weak link theory.

2. It is much simpler to perform than the split cylinder test method.

3. Because the ultimate load needed for failure is much lower (20-30 kips compared to 40-60 kips), a smaller machine can be used. This makes the test more attractive for field tests with portable machines.

4. For those countries which use cubes for compression tests, the double punch method is much easier than the diagonal split cube procedure.

7. CONCLUSIONS

1. Control Tests

The strengths of concrete obtained by the double punch test are generally more consistent than those obtained by the split cylinder test method.

2. Molds

The double punch procedure showed that the use of steel molds for casting specimens gave higher strengths with lower variability than those in cardboard molds, and is therefore sensitive to the type of mold used.
3. **Stressing Rate**

Increasing the stressing rate for the double punch test gives lower strengths for regular concrete specimens and higher strengths in the case of lightweight concrete samples.

4. **Testing Machine**

The double punch tensile strength of concrete test specimens is independent of the size testing machine used. However the type of lubricant used on the upper platen does affect the measured strength. A good (high pressure) lubricant results in higher and less variable tensile strengths.

5. **Curing Rate**

The double punch test and the split cylinder test reflect comparable increases in tensile strength throughout the curing period of test specimens.

8. **RECOMMENDATIONS**

In order to standardize test procedure and therefore make results reproducible from laboratory to laboratory it is recommended, based on the past [2] and present studies, that:

1. To use 6 in. by 6 in. concrete cylinders;
2. To use 1\(\frac{1}{2}\) in. diameter steel punches;
3. No plywood bearing discs are needed;
4. To use a stressing rate of 100-200 psi per minute;
5. To use high pressure lubricant on the spherical bearing block for lower testing variability during the double punch test.
9. ACKNOWLEDGMENTS

The research reported herein was supported by the National Science Foundation under Grants GY-9989 and GK-14274 to Lehigh University.

10. REFERENCES


Fig. 1 Test Set-Up for the Double Punch Test
Fig. 2 Example of Double Punch Failure Mode
Fig. 3 Improper Failure Mode in Double Punch Test Due to Very Rough or not Parallel Top and Bottom Surfaces
Fig. 4 Relationship of Double Punch to Split Cylinder Strengths in the Various Mixes Used
Fig. 5 Results of 28 Day Tensile Strength vs. Rate of Loading

- Regular Concrete

- Lightweight Concrete
Fig. 6 Comparison of Split Cylinder and Double Punch Tests Throughout Curing Period