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Compression Tests on Hardened Concrete in Tension
--Manuscript Draft--

Manuscript Number:	10423
Full Title:	Compression Tests on Hardened Concrete in Tension
Article Type:	Manuscript
Section/Category:	Manuscript Submission
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Science Education Title: Tension Tests on Hardened Concrete

Overview:

In a previous laboratory focused on concrete in compression, we observed that concrete can withstand very large stresses under uniaxial compressive forces. However, the failures observed were not compressive failures but failures along shear planes where maximum tensile forces occur. Thus, it is important to understand the behavior of concrete in tension and particularly its maximum strength as that will govern both its ultimate and service behavior. From the ultimate standpoint, combinations of tension and shear stresses will lead to cracking and immediate and catastrophic failure. For that reason, concrete is seldom if ever used in an unreinforced condition in structural applications; most concrete members will be reinforced with steel so that these cracks can be stopped and the crack widths limited. The latter is important from the serviceability standpoint because controlling crack widths and distribution are the key to durability, as this will impede deicing salts and similar chemicals from penetrating and corroding the reinforcing steel.

The objectives of this experiment are threefold: (1) to conduct tensile split cylinder tests to determine concrete tensile strength, (2) to conduct beam tests to determine concrete tensile strength, and (3) to demonstrate the influence of steel reinforcement on behavior by comparing the behavior of lightly reinforced beam with an unreinforced one.

Principles:

The tensile capacity (f_t) of a brittle composite material like concrete is often in the range of 1/10 of its compression capacity (f'_c). This behavior is driven by the existence of a very weak layer, called the interfacial transition zone (ITZ), between the mortar and the aggregate (Figure 1). This very thin layer (only about 40 μ m or so) contains less unhydrated cement and calcium silicates hydrates (C-S-H) than the mortar, but more large oriented crystals of calcium hydroxide (C-H) as well as trisulfate hydrates (or ettringite, the long needle-like structures in the transition zone in Figure 1). Both of these factors contribute to a larger porosity in this layer and thus to a lower strength. In addition, the fact that the average spacing between aggregate particles is only 2 to 2.5 times the thickness of the ITZ, means that a very significant amount of the mortar, by some estimates up to 40%, is made up of this weaker material.

Figure 1 – Interface transition zone (adapted from Mehta, P.K. and Monterio, P.J.M., Concrete: Structure, properties and Materials, 2nd Ed., Prentice-Hall, 1993).

The brittle behavior of concrete is driven by the growth of microcracks that propagate from stress concentrations that occur between the aggregate and mortar. Figure 2 illustrates conceptually the state of stress around an idealized round aggregate particle as a compressive load is applied. As the compression tries to “flow” around the particle and the force vector becomes inclined, tensile forces develop in the horizontal direction.

These forces are higher at the interface due to stress concentrations. The combination of large tensile forces and a weak ITZ lead to preferential cracking in this area.

As the compressive stress increases in a cylinder test, these cracks begin to grow and propagate as the result of the transverse tensile stresses, existing initial microcracks and the presence of the weak ITZ. The crack growth will become unstable as the concrete reaches its maximum strength, and the concrete will lose its ability to maintain strength very rapidly as cracks propagate at great speed. This results in overall brittle behavior for concrete, as well as for many similar ceramic materials with weak interface zones.

Figure 2 – Idealization of the state of stress around a round aggregate particle (adapted from Mindess, S., Young, F.J., and Darwin, D., Concrete, 2nd Ed., prentice Hall, 2003)

The characteristic low tensile capacity of concrete also makes a direct tension test very difficult to conduct, as conventional tensile specimens tend to fail at the grips due to stress concentrations. An elegant solution around this problem is to test cylinders on their side (Figure 3). This method is called the split cylinder, or Brazilian test. Figure 3 shows the elastic stress distribution in the horizontal direction through the depth of the cylinder. As one moves away from the loading heads, where there is a complex state of stress, a uniform horizontal tensile stress field will develop. Since the concrete is weak in tension, this will lead to a vertical crack and the splitting of the cylinder. From statistical studies, the split cylinder test is expected to give tensile capacities on the order of $6\sqrt{f'_c}$.

Figure 3 – Stress distribution over the diameter of a cylinder loaded in compression

Another indirect way of testing concrete in tension is to use a short beam specimen in a four-point bending test configuration (Figure 4). The central portion of the beam is under constant moment and zero shear, and thus a simple relationship can be derived between the failure load, the geometric properties and the tensile strength of the beam using elastic theory principles. The beam will fail suddenly as soon as a crack forms at the bottom and have no residual strength. Although it is well known that at failure the distribution of strains across the depth of the concrete beam does not quite follow those of the elastic theory, this inconsistency is generally considered to have little influence on the final results. From statistical studies, the beam tensile test is expected to give tensile capacities on the order of $7.5\sqrt{f'_c}$.

Figure 4 – Typical beam test configuration for determining tensile capacity of concrete.

The sudden and brittle failure observed in the concrete beam test would be unacceptable in any practical application, where ductility and residual strength to carry at least gravity loads is needed. Steel reinforcement is added at the bottom (or tensile side) of the beam to prevent such sudden failures; as the concrete begins to crack, the steel will begin to take up the tensile forces (Figure 5). The technique works as long as the bars, which have surface deformations to help them transfer forces from the concrete, are properly anchored. In the case of a short beam like the one that will be tested here, this will be accomplished by providing a hook at the end of the bars. In addition, because diagonal shear cracks can occur near the mid depth of the beam, vertical stirrups are generally provided. Finally, because of the indeterminate nature of reinforced concrete structures, it is hard to know for sure where tension and compression will be on a beam under a particular set of loads. For that reason, bars will also be placed at the top, resulting in the typical steel cage (Figure 5) that is seen in most beams in reinforced concrete structures.

Figure 5 – Typical reinforcement in a concrete beam.

Procedure:

Split Tension Test

- 1.1 For each test, obtain two thin strips of balsa wood or similar (about 1/8" thick x 1" wide x 8' long) to help distribute the loads on the cylinders.
- 1.2 Measure the dimensions of the two cylinders. Draw a line along the diameter on each end of the specimen bisecting the cylinder.
- 1.3 Center one strip along the center of the lower bearing block of the testing machine.
- 1.4 Place the cylinder on the strip and align so that the lines marked on the ends of the specimen are vertical and centered over the strip.
- 1.5 Place a second strip lengthwise on the cylinder.
- 1.6 Lower the upper loading head of the testing machine until the assembly is secured in the machine (Figure 6).

Figure 6 – Placement of specimen for split tension test (adapted from Mehta, P.K. and Monterio, P.J.M., Concrete: Structure, properties and Materials, 2nd Ed., Prentice-Hall, 1993)

- 1.7 Estimate the maximum loading the specimen can take assuming the tensile strength is $6\sqrt{f'_c}$, where f'_c is the nominal concrete compressive strength.
- 1.8 Apply the compressive load slowly (at around 100 psi to 200 psi per min.) and continuously until the specimen fails in split tension.
- 1.9 Record the maximum applied load.
- 1.10 Examine the fracture surface and estimate the percentage of aggregate that has fractured.

Beam Tension Test

- 2.1. Construct two concrete beams with a 6 in. x 6 in. cross section and 30 in. in length.
- 2.2. Install a 4-point bending test apparatus in the testing machine (Figure 4).
- 2.3. Carefully lift the beam and install it into the test set up.
- 2.4. Turn on the testing machine and activate the software to read load and deformations
- 2.5. Estimate the maximum loading the specimen can take assuming the tensile strength is $7.5\sqrt{f'_c}$ and apply the compressive load slowly (at around 100 psi to 200 psi per min.) and continuously until the specimen fails.
- 2.6. Record the maximum applied load.
- 2.7. Examine the fracture surface and estimate the percentage of aggregate that has fractured

Reinforced Beam Test

- 3.1. Construct one concrete beam with a 6 in. x 6 in. cross section and 30 in. in length and two #3 bars (3/8 in. diameter) to the bottom side.
- 3.2. Install a 4-point bending test apparatus in the testing machine.
- 3.3. Carefully lift the beam and install it into the test set up.
- 3.4. Turn on the testing machine and activate the software to read load and deformations.
- 3.5. Estimate the maximum loading the specimen can take assuming the tensile strength is $7.5\sqrt{f'_c}$ and apply the compressive load slowly (at around 100 psi to 200 psi per min.) and continuously until the specimen fails.
- 3.6. Record the applied load and deformations as the test progresses.

Results:

The split tensile strength (σ_t) is computed as:

$$\sigma_t = 2P_{\max}/(\pi DL)$$

where D is the diameter (inches), L is the length (inches), and P_{\max} is the maximum compressive load (lb.) reached during the tensile test. For these tests, the average was xxxx psi with a standard deviation of xxx psi. Typically, the tensile strength is related to the compressive strength by a formula of the type $f_t = k\sqrt{f'_c}$, where $k \cong 6.0$ and f'_c is in psi. However, there is usually considerable scatter in the tensile strength results, and this formula should only be seen as a rough guide rather than an absolute value.

The split tensile strength (σ_t) is computed as:

$$\sigma_t = P_{\max}L/(bd^2)$$

where d is the depth (inches), b is the width, L is the length (inches), and P_{\max} is the maximum compressive load (lb.) reached during the tensile test. This formula is valid for the case where the loads are applied at the third points. For these tests, the average was xxxx psi. The tensile strength from a beam test is related to the compressive strength by a formula of the type $f_t = k\sqrt{f'_c}$, where $k \cong 7.5$ and f'_c is in psi. There is considerable scatter in the test result as seen in Figure 7.

Figure 7 – Scatter in tensile strength results from beam tests as a function of compressive strength.

The load-deflection curve for the unreinforced and reinforced concrete beams is shown in Figure 8. The unreinforced beam likely followed the same load path initially, but failed as soon as the initial cracking occurred. The reinforced one shows a slight discontinuity when the initial cracking occurred and a slightly lower stiffness as it begins to pick up load again in its cracked condition. The load continues to increase until the concrete begins to yield, when the curve begins to flatten. However, because the steel is very ductile and strain-hardens, the load will continue to increase slightly and failure will occur at very large deformations when the concrete on top crushes.

Figure 8 – Comparison of load-deflection curves for unreinforced and reinforced concrete beams.

Commented [MOU1]: Note that we will need to wait for the actual tests that will be filmed to enter this data; otherwise it will all seem contrived.

Summary:

The test demonstrated the brittle nature of tensile failures in concrete and showed that the tensile strength is only a fraction ($1/8$ to $1/12$) that of the compressive strength. Brittle failures of this type could have catastrophic consequences for human safety, and thus all concrete structures need to be reinforced with steel (or similar) bars to take tensile forces. A comparison of the load-deformation curve for the unreinforced and reinforced beams indicate not only that the latter possesses greater strength but also large deformation capacity.

Applications:

The key to the safety and long-term performance of concrete structures is to provide steel reinforcement in areas of high tensile and shear stresses. In general, the amount of steel necessary to reach this goal is small, on the order of 1%-1.5% of the area of the concrete cross section. This small amount means that concrete structures can be economical, safe and provide good serviceability. In addition, the ability to cast concrete into any desired form gives architect great leeway in developing aesthetically pleasing structures (Figure 9).

Figure 9 – Virginia Tech Stadium (Blacksburg, VA)

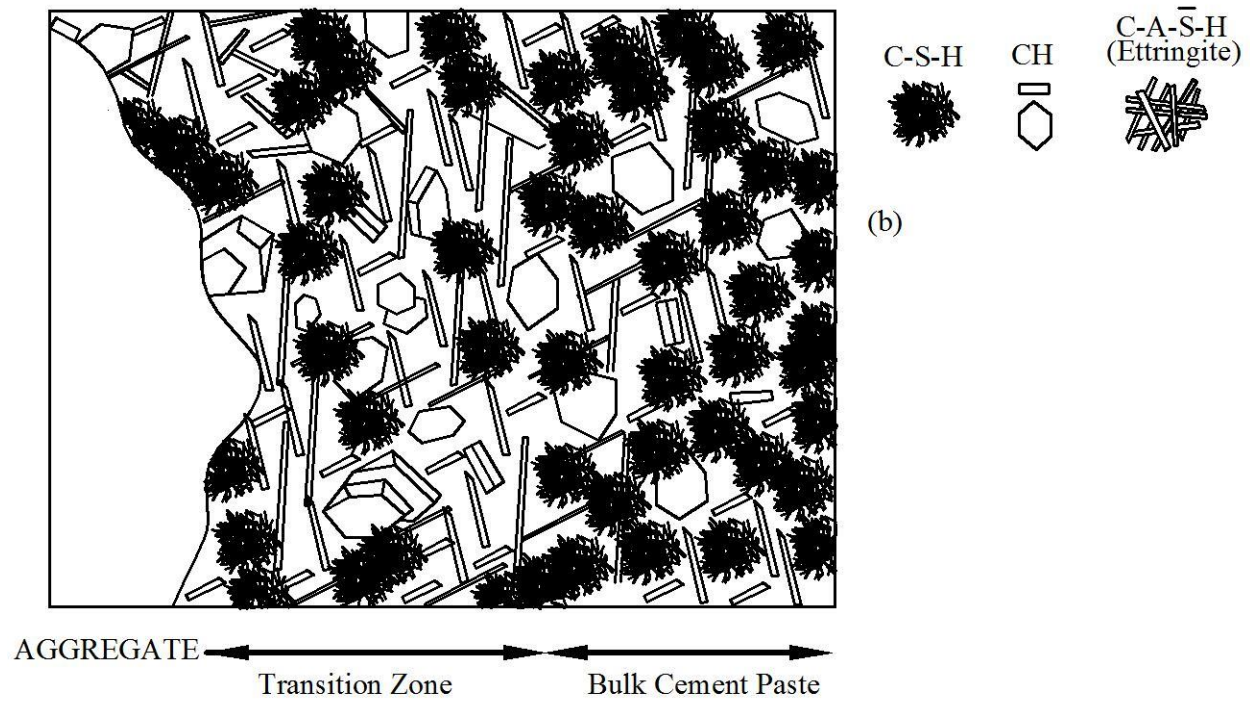


Figure 1 – Interface transition zone (adapted from Mehta, P.K. and Monterio, P.J.M., *Concrete: Structure, properties and Materials*, 2nd Ed., Prentice Hall, 1993)

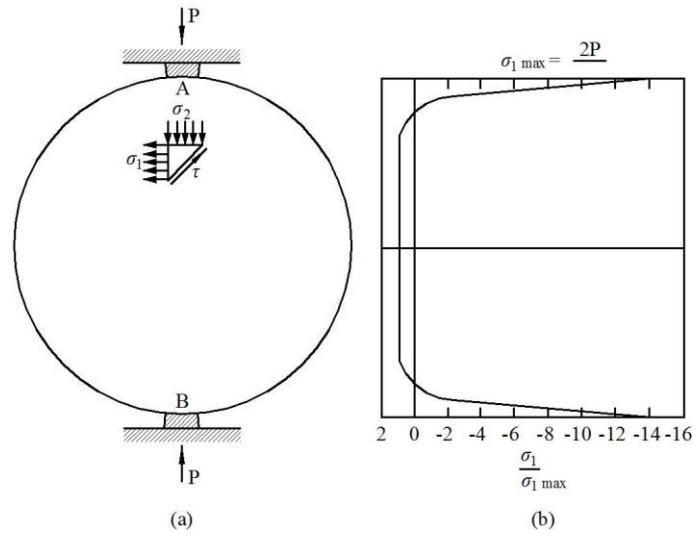
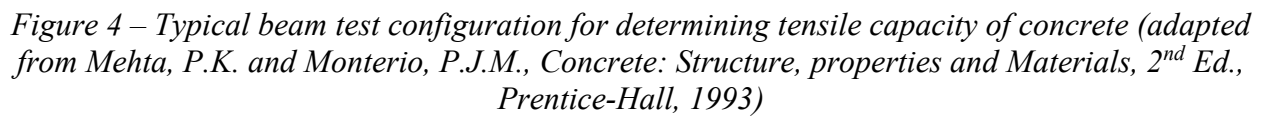


Figure 3 – Stress distribution over the diameter of a cylinder loaded in compression
(adapted from Mindess, S., Young, F.J., and Darwin, D., *Concrete*, 2nd Ed., Prentice Hall, 2003)



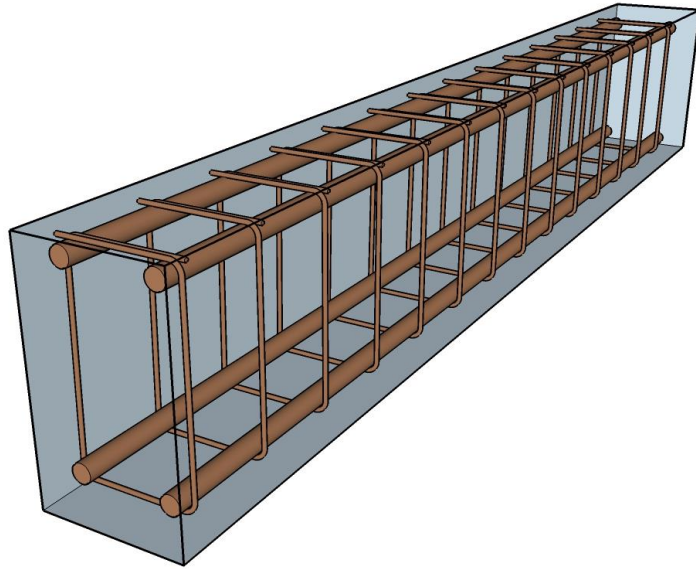


Figure 5 – Typical reinforcement in a concrete beam

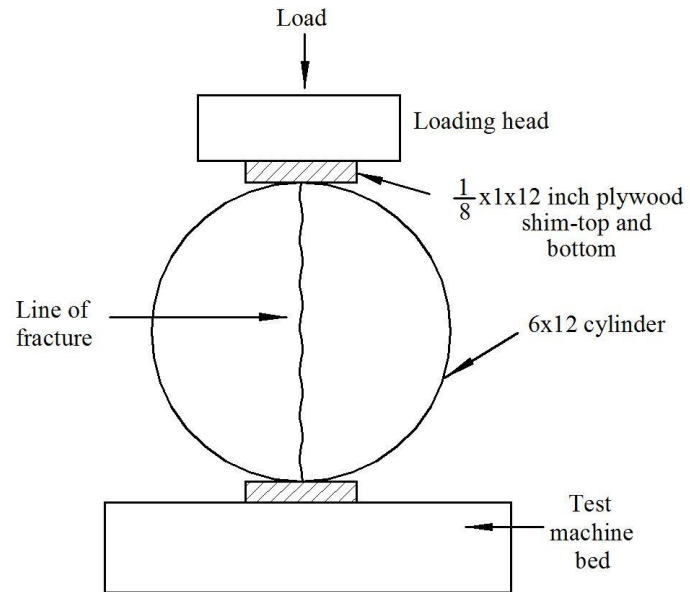


Figure 6 – Placement of specimen for split tension test (adapted from Mehta, P.K. and Monterio, P.J.M., Concrete: Structure, properties and Materials, 2nd Ed., Prentice-Hall, 1993)

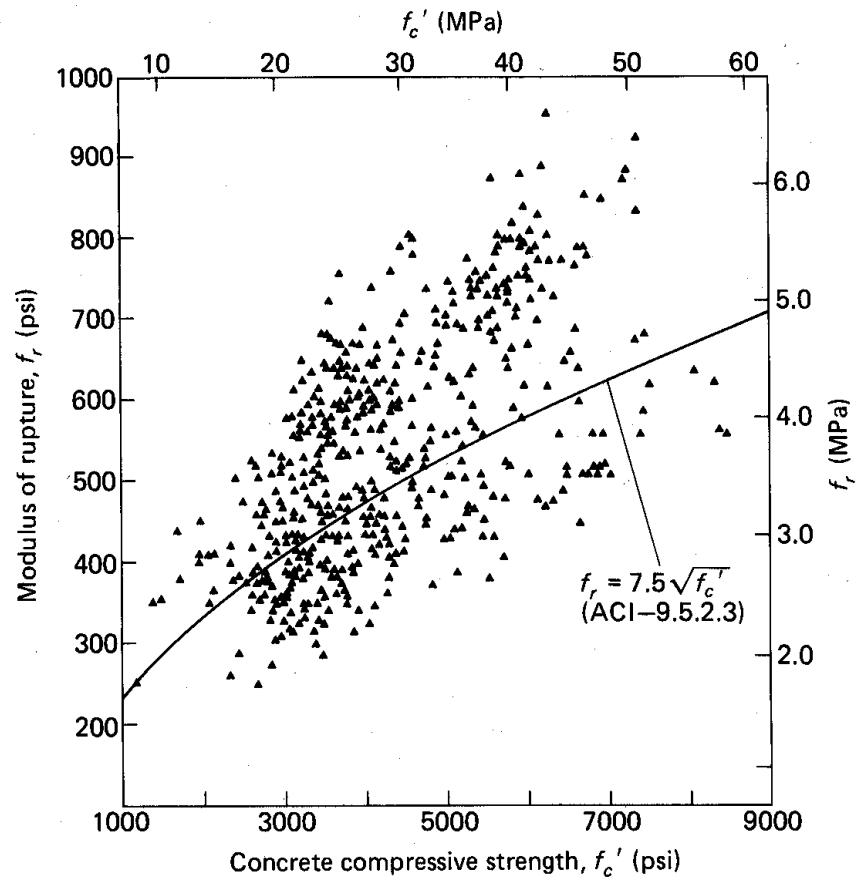


Figure 7 – Scatter in tensile strength results from beam tests as a function of compressive strength

Figure 8 – Comparison of load-deflection curves for unreinforced and reinforced concrete beams.

(to be added when the tests are filmed)



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