THE EFFECT OF MOISTURE CONTENT ON THE TENSILE STRENGTH PROPERTIES OF CONCRETE

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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This thesis is dedicated to my loving family, my parents, Jingrong Li and Fenghong Liu, and to my loving wife Congxian Jia have offered their support and love throughout this endeavor. It is with the love and support of my family and friends that I am able to reach my goals.

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The objective of this work was to investigate the effect of moisture content on the mechanical properties of concrete, as measured by the pressure tensile strength test. The feasibility and reliability of the gas pressure tensile testing procedure for determining the tensile strength of Portland cement concrete were also examined. A new phenomenon was found during the pressure tensile tests on specimens which had been oven dried for 14 days. A detailed analysis and mechanics based model was formulated and recommendations concerning future research were made.

As part of the reported research, a concise literature review of relevant factors on the mechanical properties of concrete, such as water/cement ratio, temperature and moisture content, was performed.

A series of tests designed for the research were performed. Altogether, 168 specimens were tested, encompassing two water/cement ratios (0.45 and 0.65) and various moisture contents. In order to induce different moisture contents, specimens were

subjected to 28 days of standard moist curing and 28 days of ambient curing, followed by complete immersion for varying periods prior to testing. Immersion periods of 0, 1, 3, 7, and 14 days were used. In addition, a set of specimens was subjected to 14 days of oven drying, with the intent of producing a zero moisture content. For each moisture content, three different tests were performed: uniaxial compressive strength, splitting tensile strength and pressure tensile strength. Finally, a set of 20 specimens was tested after 28 days of standard moisture curing in order to evaluate the statistical variability inherent in the pressure tension test.

Analysis of the collected data suggests that the moisture content in concrete has a significant effect on concrete strength. Regardless of the type of strength (compressive, splitting tensile or pressure tensile), higher moisture contents result in lower strength. By comparing the data from the splitting tensile test to that from the pressure tensile test, it was also established that the latter test procedure possesses great potential for certain specialized applications. For example, oven drying of concrete generates significant damage within the concrete microstructure, which has a significant effect on the mechanical properties and failure mechanisms exhibited by the pressure tension test, as compared to the splitting tension test. Under these conditions, the pressure tension test results no longer correlate well with the results from the splitting tensile tests. A different failure mode resulted and the pressure tension test results showed much more sensitivity to the induced damage.

CHAPTER 1
INTRODUCTION

Portland cement concrete is one of the most common construction materials in use today. It is commonly used as a material for load-bearing components in major structures. The compressive strength of concrete is typically considered to be its most valuable property. It usually gives an overall picture of the quality of concrete because strength is directly related to the structure of the hydrated cement paste. Moreover, the compressive strength of concrete is almost invariably a vital element in structural design and is normally specified for compliance purposes (Neville 1996).

In engineering practice, the strength of concrete at a given age and cured in water at a prescribed temperature is assumed to depend primarily on two factors only: water/cement ratio and degree of compaction. However, in many practical cases, the influence of concrete moisture content, temperature and other factors must also be considered. ASTM C 39, for example, recognizes the effect of moisture content by specifying concrete be tested while “moist.” When concrete bears load under special environmental conditions, such as high humidity or high temperature, the mechanical properties, the load transmission mechanisms, and the failure modes of the concrete may be much different, compared to the standard conditions specified in the various testing standards. Further research must be performed in order to provide a fuller understanding of these behaviors.

The primary objective of this research was to examine the effect of moisture content on the mechanical properties of concrete, especially on the pressure tensile strength, and to relate the more widely accepted splitting tensile strength test to the newer pressure test.

The pressure tensile strength test originated at the Building Research Establishment in the U.K. when researchers attempted to test a standard concrete cylinder in a specially designed apparatus that permitted water pressure to be applied to its bare curved surface (Clayton and Grimer). The surprising results of this test in terms of the ultimate applied stress and the failure mode of the specimens led a well-known American physicist, Percy Bridgman, to study the effect of fluid pressure on the curved surface of solid cylinders of material. He found that under the influence of fluid pressure applied to the curved surface of a cylinder, for a range of brittle and ductile materials, the specimens behave just as though they had been tested in pure uniaxial tension.

In early incarnations of the pressure tension test, water or other fluids were used as the loading medium. This was an inconvenient and messy way to perform such a test. More importantly, the water introduced during the test changed the concrete's original properties, such as water content and pore structure. As a result, the pressure tension test was modified by replacing the fluid with nitrogen as the pressure loading medium.

ASTM Standards require that all concrete test specimens be tested in a "wet" or "moist" condition. This condition has the advantage of being more reproducible than a "dry condition," which includes widely varying degrees of dryness or requires special equipment to create exact values. A moist or saturated moisture content can be easily achieved through immersion.

As far as compressive strength specimens are concerned, testing in a dry condition leads to a higher strength. Thus, testing specimens at the saturated moisture content represents a “worst-case” scenario for strength determination. The loss of strength of due to wetting of concrete is generally attributed to dilation of the cement gel by adsorbed water: the forces of cohesion of the solid particles are then decreased. The objective of this work is to perform research that will illustrate more clearly the effect of moisture content on the mechanical properties of concrete, especially on the pressure tensile strength.

The laboratory portion of the research project focused on the pressure tensile strength test, and the effect of different moisture content on the results. In all, three different tests were performed, including the uniaxial compressive strength test (ASTM C 39/C 39M), the splitting tensile strength test (ASTM C 496), and the pressure tensile strength test. Results were obtained using an MTS 220 kip universal testing machine and a custom built pressure tension tester. Altogether, 168 specimens were tested during the research, comprised of two water cement ratios (0.45 and 0.65) and conditioned to various moisture contents. In order to achieve the desired range of moisture contents, the specimens were immersed in lime-saturated water after a curing regime of 28 days standard moist curing and 28 days ambient curing. Following immersion periods of 0, 1, 3, 7, and 14 days, the specimens were removed and prepared for testing. A final set of specimens was oven-dried for 14 days, after the initial curing regime, in order to induce zero moisture content.

Data analysis of the concrete strength is reported in this paper. In particular, the focus will be on variations in strengths under uniaxial compression, splitting tension, and pressure tension over a range of moisture contents. The splitting tensile strength is compared with, and contrasted to, the pressure tensile strength. Furthermore, a new phenomenon was found during the pressure tension tests on the oven-dried specimens. Detailed analysis is included and recommendations are made concerning further research that should be pursued.

CHAPTER 2
LITERATURE REVIEW

The strength of concrete is commonly considered to be its most valuable property. It usually gives an overall picture of the quality of a concrete because strength is directly related to the structure of the hydrated cement paste. Moreover, the strength of concrete is almost invariably a vital element in structural design and is specified for compliance purposes (Neville 1996).

Strength of Concrete

The strength of concrete originates from the strength of the hardened cement paste, which, in turn, originates from the hydration products. The major portion of these hydration products is in the form of a rigid gel, called cement gel. Although there is no adequate theory yet as to the source of the strength of the cement gel itself, it is reasonable to assume that the bonds of the gel particles to each other, to the aggregate particles, and to other bodies in the concrete are responsible for the strength (Popovics 1998).

There are several significant different ways to measure the strength of concrete, such as compressive strength, tensile strength, shear strength, tensional strength, impact strength, etc. The two standard types of concrete strength of the most interest in research and structural design are compressive strength and tensile strength, as measured by the splitting tensile strength test. Another method for measuring tensile strength is the pressure tension test, which has not yet been standardized.

Compressive Strength

Compressive strength is typically considered to be the most important mechanical property of concrete. In most structural applications, concrete is employed primarily to resist compressive stresses. In those rare cases where other stresses (flexural, etc.) are of primary importance, the compressive strength is still frequently used as the measure of resistance because it is the most convenient to measure. For the same reason, compressive strength is generally used as a measure of the overall quality of a concrete, even when strength itself may be relatively unimportant.

Testing of compressive strength

The compressive strength of concrete or mortar is usually determined by submitting a specimen of constant cross section to a uniformly applied axial compression load, which is increased until failure occurs. The resulting strength is expressed as the ultimate compression load per cross-sectional area, usually in pounds per square inch (psi) or pascals (Pa).

Testing of the compressive strength of concrete started about 100 years ago. Two types of compression test specimens are used: cubes and cylinders. Cubes are used in Great Britain, Germany, and may other countries in Europe. Cylinders are the standard specimens in the United States, France, Canada, Australia, and New Zealand. The standard cylinder is 6 in. in diameter and 12 in. long (if the coarse aggregate does not exceed 2 in.) although the more economical 4 × 8 in. or 3 × 6 in. cylinders are also suitable for many purposes.

Generally, the cylindrical specimens should be removed from their molds about 24 hours after casting and stored in moist conditions at a controlled temperature ($23.0 \pm 1.7^{o}C$) until the time of test. Compressive tests on the specimens should be made as soon as practical after removal from the curing room. Specimens should be tested in a moist condition using a testing machine complying with the specifications of ASTM C39. In addition to being plane, the ends of a cylinder should be normal to its axis, thus guaranteeing that the end planes are parallel to one another. Grinding or capping of the bearing surfaces of the specimen is preferable, though rather expensive.

Another important item is the effect of the test machine itself during testing. The steel loading platens and the rigidity of the test machine will affect the distribution of normal stresses near the ends of the specimens and the failure mode exhibited by the specimens. Figure 2-1(a) indicates schematically the normal stress distribution at the platen-concrete interface when a “hard” platen is used: the compressive stress becomes higher near the perimeter than at the center of the specimen. The same distribution is created when either the specimen or the platen is slightly concave. Conversely, when a “soft” platen is used such as in Figure 2-1(b), the compressive stress is higher near the center of the specimen than around the perimeter. This condition is also produced by a slightly convex specimen face or platen.

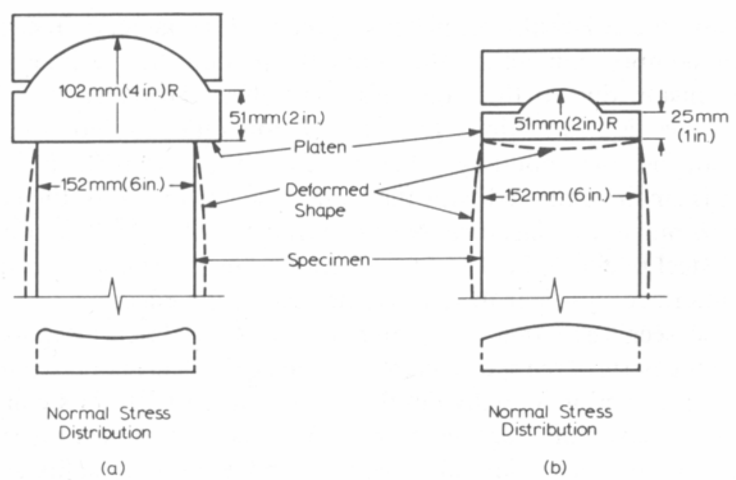

Figure 2-1. Normal stress distribution near ends of specimens when tested in a machine. (a) with hard platens; (b) with soft platens (Neville 1996)

Failure of compression specimens under uniaxial load

Because friction exists between the steel loading platens of the testing machine and the concrete specimen, a rather more complex system of stresses is induced due to the tangential forces being developed between them. The platen restrains the lateral expansion of the concrete in the portions of the specimen near its ends: the degree of restraint exercised depends on the friction actually developed. It is also this tangential force that changes the mode of the concrete specimen's fracture. With friction acting, under normal test conditions, an element within the specimen is subjected to a shearing stress as well as to compression. The magnitude of the shearing stress decreases, and the lateral expansion increases with an increase in distance from the platen. As a result of such restraint, a specimen tested to failure exhibits a relatively undamaged cone or pyramid of height approximately equal to $1/2\,d\sqrt{3}$ (where d is the lateral dimension of the specimen). Sketches of typical fracture modes can be seen in the figure 2-2.

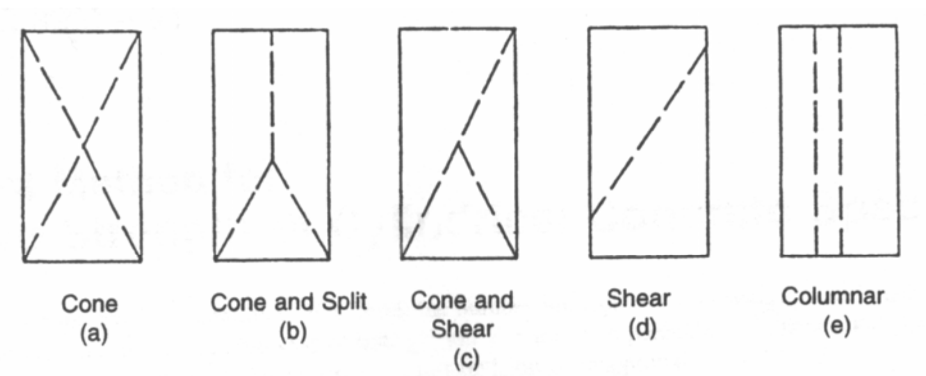

Figure 2-2. Sketches of typical fracture modes (ASTM C39)

This mechanism can be summarized as follows:

1. The typical failure of a concrete specimen in a uniaxial compression test takes place in the middle of the height because the restricting effect of the fractional forces is at a minimum there.

2. The more slender the specimen, the lower the compressive strength measured because the effect of the frictional forces in the middle section becomes smaller.

However, once the specimen is slender enough, a further increase in the slenderness, up to the point where the stability starts controlling the failure, does not cause further significant reduction in the measured strength.

3. If the end friction is reduced, for instance by applying appropriate layers between the loading surfaces, this not only reduces the measured value of the compressive strength but also reduces the variation in strength caused by variations in slenderness of the specimen. This effect is especially spectacular when Teflon layers are applied, due to the low surface friction of this material.

4. The magnitude of the cube strength-cylinder strength ratio is not a constant; it can depend on the type of concrete or aggregate.

The failure mechanism of the specimen is also affected by the design of the machine, especially by the energy stored in it. With a very rigid machine, the high deformation of the specimen under loads approaching the ultimate load is not followed by the movement of the machine head, so that the rate at which the load is applied decreases and a higher strength is recorded. On the other hand, in a less rigid machine, the load follows more nearly the load-deformation curve for the specimen and, when cracking commences, the energy stored by the machine is released rapidly. This leads to failure under a lower load than would occur in a more rigid machine, often accompanied by a violent explosion. Under this condition, tests have to be stopped at the point of the largest load and the decreasing load-deformation curve after that point can not be obtained. The exact behavior depends on the detailed characteristics of the machine. Other than longitudinal stiffness, the machine's lateral stiffness also becomes relevant. Proper and regular calibration of testing machines is essential for a successful test with valid results.

Tensile Strength

The tensile strength of concrete plays a fundamental role in the fracture mechanism of hardened concrete. The actual strength of hydrated cement paste, or of similar brittle materials such as stone, is very much lower than the theoretical strength estimated on the basis of molecular cohesion, and calculated from the surface energy of a solid assumed to be as high as 10.5 GPa. It is an accepted view that fracture in concrete occurs through cracking. This means that concrete fracture is essentially a tensile failure regardless of whether the fracture is induced by compression (or other loading mechanisms), freezing, internal expansion, or by other factors. This theory can be explained by the presence of flaws as postulated by Griffith. These flaws lead to high stress concentrations in the material under load so that a very high stress is reached in very small volumes of the specimen, with a consequent microscopic fracture while the average (normal) stress in the whole specimen is comparatively low. As a result, the mechanical properties of hardened concrete are controlled to a great extent by the fact that its tensile strength is only about one-tenth of its compressive strength.

Mechanism of tensile strength and failure

The tensile strength of concrete is much lower than its compressive strength because of the ease with which cracks can propagate under tensile loads. Tensile strength of concrete is not usually considered in design, in fact it is often assumed to be zero. However, it is an important property since cracking in concrete is generally due to tensile stresses induced by applied loads, deterioration mechanisms, or environmental changes. The failure of concrete in tension is governed by microcracking, associated particularly with the interfacial region between the hydrated cement paste and the aggregate particles (Mindess et al. 2002).

Hydrated cement paste is known to contain numerous discontinuities – pores, microcracks and voids, but the exact mechanism through which they affect overall strength is not known. The voids themselves need not act as flaws, but the flaws may consist of cracks in individual crystals associated with the voids or be caused by shrinkage or poor bond. Considering the heterogeneous nature of concrete and the method of combining the various phases of this composite material into a single whole, this is not surprising.

Although we do not know the exact mechanism of rupture of concrete, it is probably related to the bond between the hydrated cement paste and the aggregates. Griffith's hypothesis postulates microscopic failure at the location of a flaw, and it is usually assumed that the "volume unit" containing the weakest flaw determines the strength of the entire specimen. This statement implies that any crack will spread throughout the section of the specimen subjected to the given stress or, in other words, an event taking place in an element is identified with the same event taking place in the body as a whole. This behaviour can be met only under a uniform stress distribution with the additional proviso that the 'second weakest' flaw is not strong enough to resist a stress $n/(n-1)$ times the stress at which the weakest flaw failed, where n is the number of elements in the section under load, each element containing one flaw (Neville 1996).

As a tensile crack propagates through concrete, its leading edge often consists of multiple branching microcracks that eventually coalesce into a single macrocrack as the tensile displacement increases. Whereas local fracture starts at a point and is governed by the conditions at that point, the knowledge of stress at the most highly stressed point in the body is not sufficient to predict failure. It is also necessary to know the stress distribution in a volume sufficiently extended around this point because the deformational response within the material, particularly near failure, depends on the behavior and state of the material surrounding the critical point, and the possibility of the failure spreading is strongly affected by this state.

Another factor we need consider is the ITZ (interfacial transition zone), because the ITZ typically has less crack resistance than either the aggregate or the hydrated cement paste, and so fracture occurs preferentially in the ITZ, which constitutes the 'weak link' in the concrete. It has been confirmed that fracture usually occurs not right at the physical interface, but about 10-20 um into the ITZ. Although it seems that improving the ITZ, to some extent, can increase the strength of the concrete, unfortunately, for ordinary concretes, improvements in the ITZ are unlikely to lead to major changes in concrete behavior. The modest increases in strength attributable to better paste-aggregate bonding are largely offset by the increasing brittleness of the resulting material (Mindess et al. 2002).

Testing of tensile strength

The case of uniaxial tension is rarely encountered in practice and in laboratory tests can be obtained only with care. However, significant principal tensile stresses may be associated with multiaxial states of stress.

The tensile strength of concrete is most often evaluated using a flexure test, in which plain concrete is loaded in bending, or the split cylinder test, in which a cylindrical specimen is placed on its side and loaded in diametral compression so as to induce transverse tension (this method will be discussed in detail in a later section). In North America, there is no standard test procedure to measure the direct tensile strength of concrete, though a number of approaches (none yet standard) are available to measure the fracture properties of concrete under tension. Exploration of the Pressure Tension method is the main objective of this research.

The most direct way to determine the tensile strength of concrete or mortar is similar to the tensile strength tests of metals and many other materials. The specimen is submitted to a uniformly distributed increasing axial tension load in a suitable testing machine until the specimen breaks into two parts. The strength is expressed as the ultimate tension load per cross-sectional area, usually in MPa.

Though there is no standard American test method for direct determination of tensile strength of concrete. RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures) has prepared a recommendation for direct tension testing of concrete designed primarily for research rather than for routine quality control. This method involves applying direct tension to either cylindrical or prismatic specimens through end plates glued to the concrete. The ends of the specimen must be sawed off to remove surface effects due to casting or vibration. They must be perpendicular to the axis of the specimen within 0.25^{o}. Furthermore, the ends must be carefully cleaned so that the glue (typically a polyepoxy resin) adheres uniformly to the entire surface. Stress is increased at a rate of 0.05 MPa/s until failure occurs. As yet, there is not enough experience with this test method for a proper assessment of its usefulness. The U.S. Bureau of Reclamation also specifies a direct tension test (Procedure 49A) that uses bonded end plates (Mindess et al. 2002). Figure 2-3 consists of a photograph of a typical direct tensile strength test.

There is a common method for estimating the tensile strength of concrete, through an indirect tensile test. The splitting tensile test is the standard method for testing the tensile strength of concrete in North America.

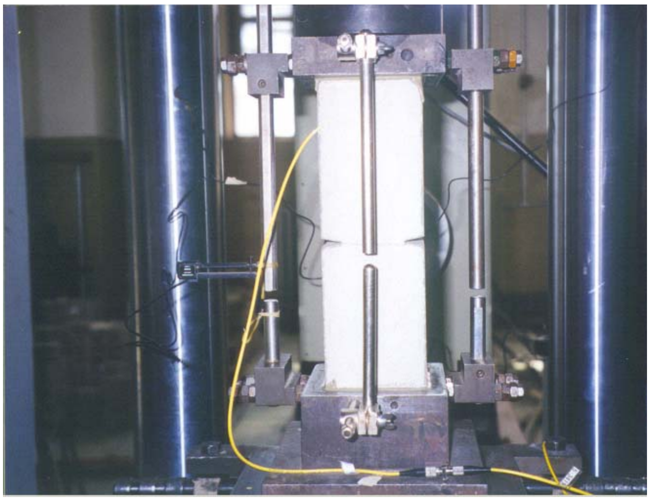

Figure 2-3. Typical direct tensile strength test (Li, 2003)

Splitting Tensile Strength

The Splitting Tensile Strength test has become the most popular test for tensile strength determination. It is carried out on a standard cylinder, tested on its side in diametral compression, as shown in Figure 2-4 (a).

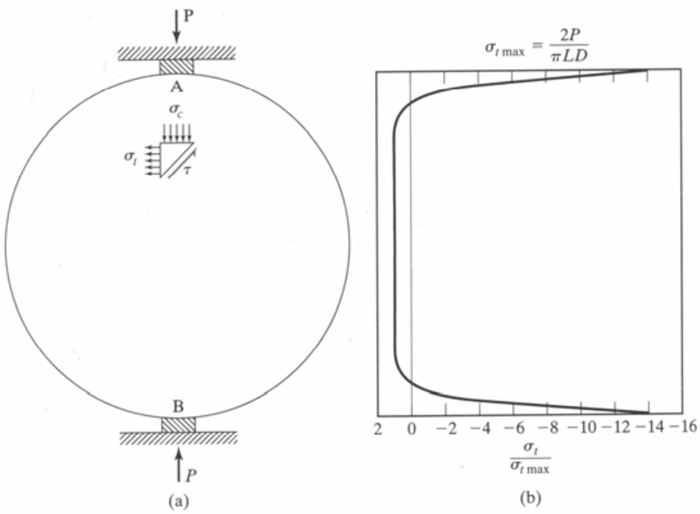

Figure 2-4. Splitting tensile test. (a) splitting tensile Test, (b) the tensile stress distribution along the vertical diameter of the specimen (Mindess et al. 2002)

If the load is applied along the generatrix, then an element on the vertical diameter of the cylinder is subjected to a vertical compressive stress of:

$$\text{Vertical compression} \quad \sigma_c = \frac{2P}{\pi LD}\left[\frac{D^2}{r(D-r)} - 1\right] \tag{2-1}$$

$$\text{Horizontal tension} \quad \sigma_t = \frac{2P}{\pi LD} \tag{2-2}$$

Where P is the applied compressive load, L the cylinder length, D the cylinder diameter, and r the distance of the element from the top of the cylinder.

It is not practical to apply a true 'line' load along the top and bottom of the specimen, partly because the specimen sides are not sufficiently smooth, and partly because this would induce extremely high compressive stresses near the points of load application. Therefore, the load is usually applied through a narrow bearing strip of relatively soft material (Mindess et al. 2002). The distribution of tensile stress along the vertical diameter of the specimen is shown in Figure 2-4 (b). The formulae above are based on the assumption that Hooke's law holds true up to failure in the tested specimen and that a state of plane stress exists. In the case of concrete, however, neither assumption is valid. It has been shown that splitting tensile strength calculated from certain assumptions of the plastic theory are somewhat smaller, while those calculated from other pertinent assumptions are higher than the values calculated from the above formulae (Popvics 1998).

Testing of the splitting tensile strength

In this test, a concrete cylinder is placed between the platens of a testing machine with its longitudinal axis in the horizontal direction and the load is increased until failure by indirect tension in the form of splitting along the vertical diameter. Testing details and results will be talked about in the later chapters.

The greatest advantage of the splitting tension test is that specimen is identical to that used for the compression test. Another advantage is that failure in this test, unlike the flexural test, initiates inside the concrete specimen. Thus, the test is not significantly influenced by the surface conditions of the specimen, such as moisture or temperature, or by minor irregularities in the testing.

The primary disadvantage of this test method is that the tensile stresses only reach their maximum values along a narrow strip within the specimen. Thus, the effects of the critical flaw (i.e., weakest link), as well as the composite nature of the concrete become much less significant in the splitting test than they would be in direct tension testing, or in the concrete making up a structure.

Mechanism of the splitting tensile strength and failure

In direct contradiction to concrete failures under direct tensile load, the fracture plane in the splitting test often passes through the coarse aggregate particles instead of following the ITZ. This may be due to the fact that the tensile stress reaches its maximum value only within a narrow strip along the central vertical plane, essentially forcing failure to occur along this route. Figure 2-5 is a typical failure specimen in the splitting tensile test.

In any case, the strength of the aggregate particles appears to have a sizable influence on the splitting strength of the concrete. For instance, an increase in the maximum particle size causes a greater increase in the splitting strength than in the direct tensile strength (Hannant et al. 1973). Also, when the tensile strength of a cement paste has been increased, for instance by epoxy modification, the splitting strength of the concrete containing this cement paste shows less increase than the flexural or direct tensile strength (Popvics 1998).

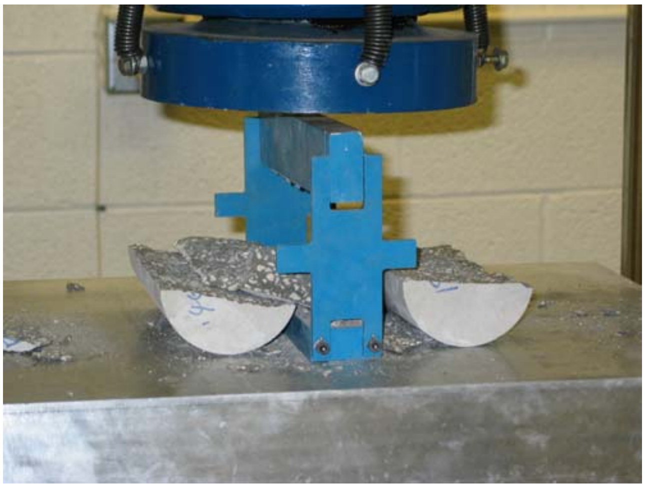

Figure 2-5. Failure specimen in the splitting tensile test

However, the applicability of the splitting tensile strength test for low-strength materials, such as several hour old concrete, is doubtful because such specimens suffer considerable deformation during the test, which alters the distribution of stresses.

The splitting tensile test is a traditional method to test the tensile strength of concrete and is widely used in the construction industry. The method is easy to carry out and provides quick results. Now, a new method that can be used to determine tensile strength has been discovered – the pressure tension test, though it has yet to be standardized and is not yet widely accepted or used.

Pressure Tensile Strength

In the original version of the pressure tension test, a cylindrical specimen was inserted into a specially designed apparatus which permits water pressure to be applied to its curved surface, but not to its ends. That is, the concrete is subjected to an axisymmetrically applied compressive stress using water as the loading medium without the use of an intervening membrane. The results of this test are useful, both in terms of ultimate applied stress and the mode of failure.

It appears that the applied loading is compressive and uniform, using conventional knowledge of concrete, and it is expected that the measured stress at fracture would be high and that fracture would be by crushing or multiple cracking. In fact, the ultimate stress is low and the specimen breaks across a single plane transverse to the specimen axis. The fractured specimen looks as though it had been pulled apart by its ends, as if subjected to applied tension, not compression (Clayton and Grimer, 1979). The water pressure experiment apparatus and details are shown in the Fig 2-6.

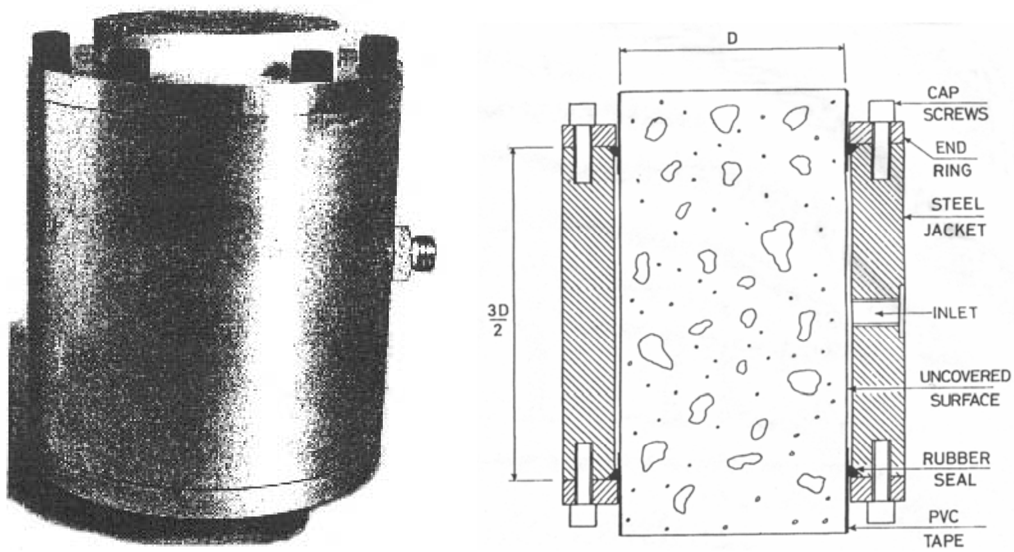

Figure 2-6. Water pressure apparatus. (a) water pressure apparatus, (b) water pressure apparatus schematic (Clayton and Grimer, 1979)

However, using water as the loading medium is not convenient under some conditions, such as when the moisture content in the specimen is a targeted test variable. A new approach to the pressure tension test was introduced by replacing the water with nitrogen gas. This latter form of the test was used throughout the research reported herein.

Mechanics model of pressure tension test

Since the behavior of a concrete cylinder subjected to water pressure is not compatible with the conventional notion of concrete being strong in compression, there should be a rational explanation for this inconsistency.

Since the concrete is permeable to water or gas, the specimen may be pushed apart from within due to internal pore pressures. Based on this assumption, we can state that concrete is strong in compression unless the loading medium enters the concrete, in which case the concrete fails in tension. In other words, subjecting concrete to water pressure is an exceptional type of loading and is not compression at all, but actually tension. Then, the original theory that concrete is strong in compression is left intact. However, it is not so simple. Consider what would happen if fluid pressure were applied to the curved surface of a solid cylinder of material, such as glass or metal, other than concrete? It is clear that no fluid or air would enter the glass or metal. Unfortunately, the same thing happens. Percy Bridgman performed such tests in 1912 and the results showed that, for a range of brittle and ductile materials, the specimens behaved just as thought its ends had been pulled apart. Thus, the assumption made above is weakened; the pore structure and the permeability are not the critical key to this inconsistency, though they may have some effect on fracture strength.

Bridgman formulated an explanation for the pressure tensile strength after a few years of research that provided true insight into the nature of materials.

Application of axisymmetric pressure to a cylindrical specimen is equivalent to a hydrostatic pressure applied to the specimen plus an applied axial tensile stress of the same value. This is shown in Figure 2-7.

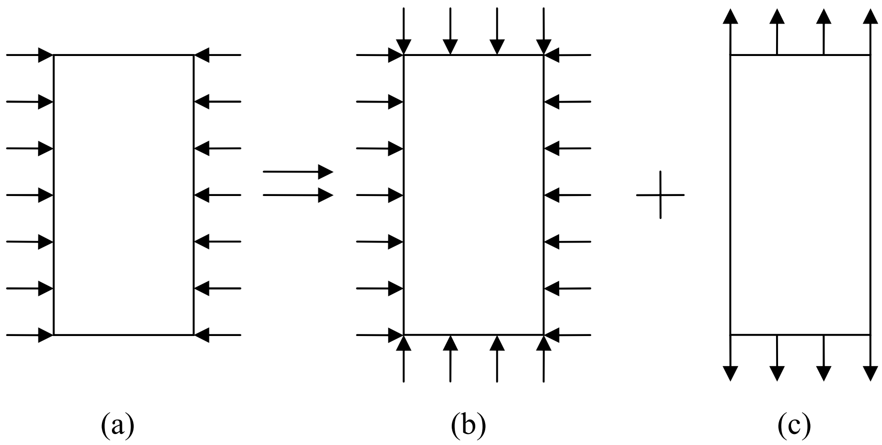

Figure 2-7. Bridgman's model. (a) axisymmetric pressure (biaxial stress), (b) hydrostatic pressure (triaxial stress), (c) axial tensile stress

He further argued that since 'hydrostatic stress does not essentially modify qualitative behaviour', this term in the equation disappears and the required result, that the axisymmetric pressure is equivalent to applying an axial tension, remains. Maybe this can be described in an easier way. Suppose a conventional uniaxial tension test is performed in a high pressure water environment, such as at the bottom of the sea. There is insufficient proof to say that there is any difference between specimen fractures in high pressure water than under atmospheric pressure. This is what Bridgman meant by saying that applying hydrostatic pressure does not change the qualitative behaviour of the material.

However, as shown later, the water content in the concrete will change the test results of the pressure tensile strength test, though it does not change the fracture mode unless the specimen's pore structure has been heavily damaged

Introduction of the diphase model

By analogy, a material may be regarded at each level of consideration as comprising just two phases which are given the general names "Solid" and "Fluid." The solid phase provides the form of the material and is best conceptualized as a finite number of inert, homogeneous particles, each having an indefinitely high strength and stiffness. The scale of these particles depends upon the level at which the material is being considered and can range from that of the specimen itself down to atoms and below. The Fluid phase is the active constituent and provides the pressure which holds the particles of the Solid phase together. In contrast, however, with the conventional view of soils, the Fluid pressure acts externally on the Solid phase. That is, the Solid phase is held together from the outside and this is the manner in which the diphase model represents how a material gains its strength (Clayton and Grimer, 1979).

The diphase view acknowledges that all materials are differentiated. The highest level of differentiation is that of the specimen itself which is clearly distinguishable from its environment. For a specimen, we have two levels of differentiation, dependent upon how we consider the specimen. Clearly, the first level consists simply of the specimen and its environment (water or air surrounding the specimen). We can also subdivide the solid specimen into many particles plus an internal fluid. The second level fluid is consequently both external and internal depending on the level of solid to which reference is being made.

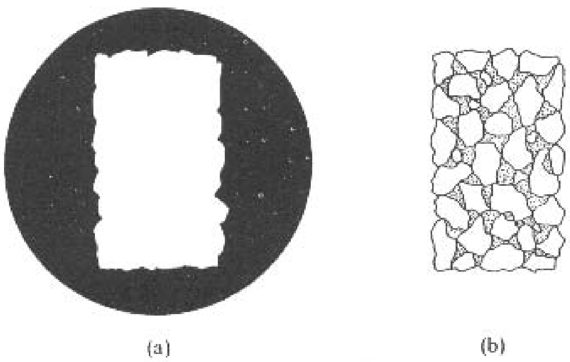

Figure 2-8. Solid level under diphase. (a) first level of differentiation, (b) second level of differentiation (Clayton and Grimer, 1979)

Based on this view, for a specimen under stress, we also have two equally valid views of the same system depending on which of the two alternative viewpoints is adopted. First, we can suppose that the material has a certain strength and the loading is applied from the outside environment, then fracture occurs when the load is higher than the strength. Second, we can suppose that fracture occurs when the resultant compressive stress on the solid is removed. At this point, there is no pressure holding the solid together and the material therefore has no strength. Then, we can recognize that the stress difference is the key problem during fracture and, consequently, fracture of the material can be achieved by two general methods:

1. Decreasing the external stress on the solid phase
2. Increasing the internal stress on the solid phase

Now, we can explain what happened during the pressure tensile test using the diphase concept. Actually, applying fluid pressure to the curved surface of a solid cylinder of material is an effective way of increasing the internal pressure on the solid. In the direction of the applied fluid pressure, the change of internal fluid pressure is counteracted by the change of external fluid pressure, thus maintaining the stress on the solid. In the axial direction of the cylindrical specimen, however, there is no change in external fluid pressure and hence the stress on the solid is reduced due to the increase in internal fluid pressure. As the applied fluid pressure increases, the stress on the solid in the axial direction is steadily further reduced and when this reaches zero, fracture occurs. The mode of fracture is the same as if the specimen had been subjected to an applied axial "tension" because the direction in which the stress on the solid is removed is the same in both cases.

Factors Affecting the Strength of Concrete

We have known that the strength of concrete at a given age and cured in water at a prescribed temperature is assumed to depend primarily on two factors: the water to cement ratio (W/C) and the degree of compaction. In addition to these major factors, there are many other factors that can, and do, influence the strength of concrete to a varying extent. Some of them are:

1. The concrete making procedure, such as batching, mixing, delivering, placing, and consolidating the fresh concrete
2. Testing procedure, including the shape and size of the specimen, end preparation method, type of test machine, and rate of loading
3. Age at testing
4. Effectiveness and duration of curing
5. Curing temperature
6. Air content and porosity
7. Moisture Content

The effects of water/cement ratio, temperature, air content and porosity, and moisture content on the strength of concrete will be dealt with individually.

Water/Cement Ratio

When concrete is fully compacted, its strength is taken to be inversely proportional to its water/cement ratio. This relationship was established by Duff Abrams in 1919 and described by the equation:

$$f_c = \frac{K_1}{K_2^{w/c}} \tag{2-3}$$

where f_c is the compressive strength of the concrete, *w/c* is the water to cement ratio of the mixture (originally taken by volume), an K_1 and K_2 are empirical constants.

However, the range of validity for the water/cement ratio equation is limited due to practical reasons. At very low values of water/cement ratio, the curve deviates from the expected values since full compaction is no longer possible. The actual position of the point of departure depends on the means of compaction available. The general form of the strength versus water/cement ratio curve is shown in Figure 2-9.

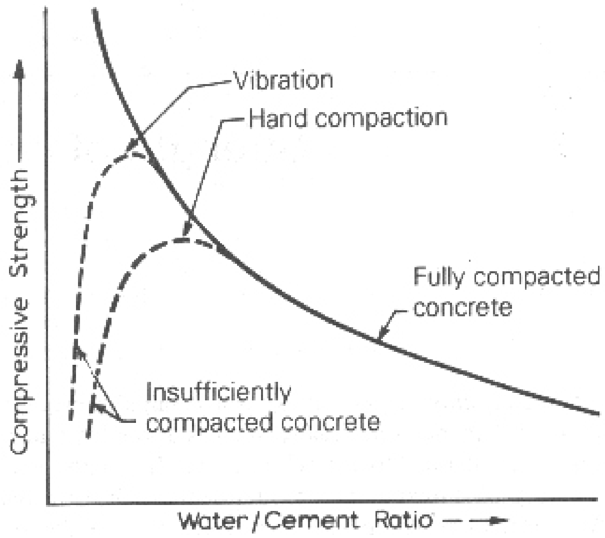

Figure 2-9. The relationship between strength and water/cement ratio of concrete (Neville 1996)

The water/cement ratio also determines the porosity of the hardened cement paste at any stage of hydration, which will directly affect the volume of voids in concrete. In fact, there is a minimum water/cement ratio for the hydration products to form because there is insufficient space at low water/cement ratios. For complete hydration, the water/cement ratio should not be below 0.42 (by weight).

Water/cement ratio is a convenient concept because it means a single variable can be used to estimate many concrete properties, including strength. The relationship between water/cement ratio and concrete strength is only approximate because it can be affected by secondary factors. Fortunately, the approximation is acceptable in most practical cases.

The influence of water/cement ratio on strength does not truly constitute a law because the water cement ratio rule does not include many qualifications necessary for its validity. In particular, strength at any water/cement ratio depends on such factors as; the degree of hydration of the cement and its chemical and physical properties; the temperature at which hydration takes place; the air content of the concrete, the change in the effective water/cement ratio, and the formation of cracks due to bleeding. The cement content of the mix and the properties of the aggregate-cement paste interface are also relevant (Neville 1996).

A better description of the role of water/cement ratio in determining strength was given by Gilkey:

> For a given cement and acceptable aggregates, the strength that may be developed by a workable, properly placed mixture of cement, aggregate, and water (under the same mixing, curing, and testing conditions) is influenced by: (a) ratio of cement to mixing water, (b) ratio of cement to aggregate, (c) grading, surface texture, shape, strength, and stiffness of aggregate particles, (d) maximum size of the aggregate (Gilkey 1961, p 1855).

Temperature and Aging

In this case, the effect of temperature throughout during the curing period will be discussed, not the temperature at testing. However, for reasons that are not fully understood, the temperature of the specimen at the time of testing will affect strength, as shown in Figure 2-10. Higher test temperatures will result in lower strengths, even for concretes that were identically cured in standard conditions. It is likely that at least part of the effect is due to loss of moisture from the specimen while being conditioned to higher temperatures.

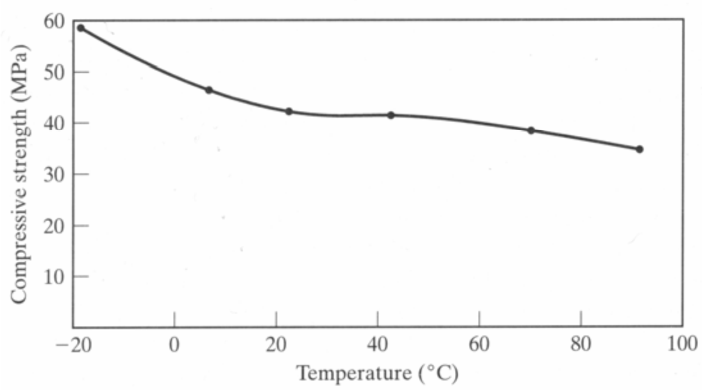

Figure 2-10. Compressive strength as a function of temperature at the time of testing (Mindess et al. 2002)

It has been recognized from the beginning of concrete production that the ambient temperature, especially the curing temperature, has a major effect on the properties of concrete, including strength.

A rise in curing temperature speeds up the chemical reactions of hydration and thus beneficially affects the early strength of concrete without any ill effects on later strength. But increasing temperature during placing and setting may adversely affect the strength from about 7 days onwards because a rapid initial hydration appears to form products of a poorer physical structure, probably more porous, so that a proportion of the pores will always remain unfilled. A high gel/space ratio will lead to a lower strength, compared with a less porous product.

A possible explanation for the inverse correlation between early strength and ultimate strength is that certain strength-affecting properties of the hydration products are modified by a change in the rate of hardening, and the cause of the rate change is secondary at most (Popovics 1998). It was also suggested that the rapid initial rate of hydration at higher temperatures retards the subsequent hydration and produces a non-uniform distribution of the products of hydration within the paste. At the high initial rate of hydration, there is insufficient time available for a uniform precipitation in the interstitial spaces. As a result, a high concentration of the products of hydration is built up in the vicinity of the hydration particles, and this retards subsequent hydration and adversely affects long-term strength (Neville 1996). Figure 2-11 shows the relationship between compressive strength and curing time at different curing temperatures.

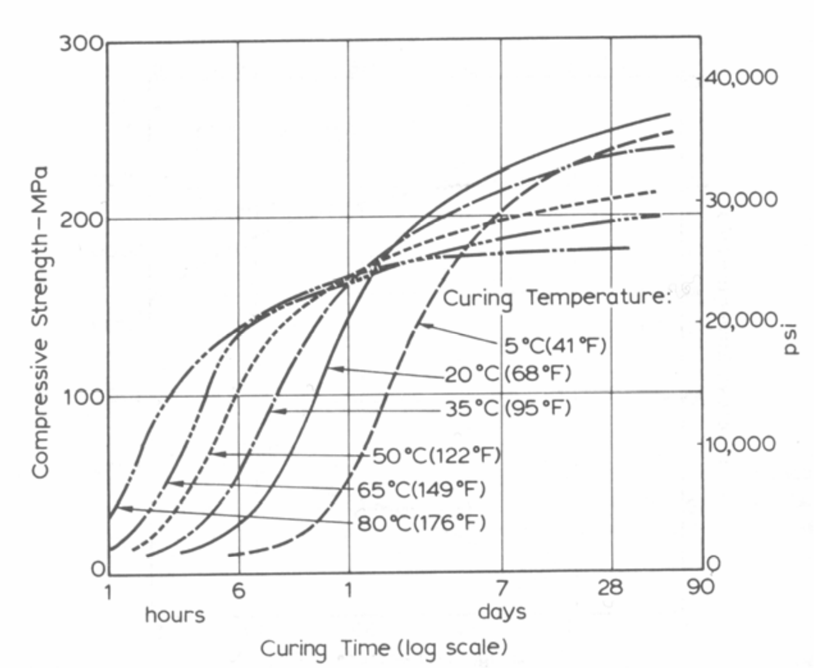

Figure 2-11. Relation between compressive strength and curing time of neat cement paste at different curing temperatures (Neville 1996)

A curing temperature below the freezing point at early ages is also a problem, as it reduces concrete strength. When concrete is frozen immediately after being placed, the compressive strength may decrease 30 to 40%.

In practice, there is a temperature during the early life of the concrete that may be considered optimum with regard to strength at later ages, or more strictly, at comparable degrees of hydration. This temperature is somewhat influenced by cement type (Klieger 1958). This optimum curing temperature was 13^{o}C for Type I cement and 4.5^{o}C for Type III for strengths after 28 days for Klieger's concrete. In general, the best curing temperature for most concretes is the 'normal' temperature, between about 15°C through 40°C (Popovics 1998).

The relationship between water/cement ratio and strength of concrete applies to one type of cement and one age only, and also assumes wet-curing conditions. On the other hand, the strength versus gel/space ratio relationship has a more general application because the amount of gel present in the cement paste at any time is itself a function of age and type of cement. The latter relation thus allows for the fact that different cements require a different length of time to produce the same quantity of gel (Neville 1996). The relative gain in strength with time of concretes with different water/cement ratios is shown in Figure 2-12.

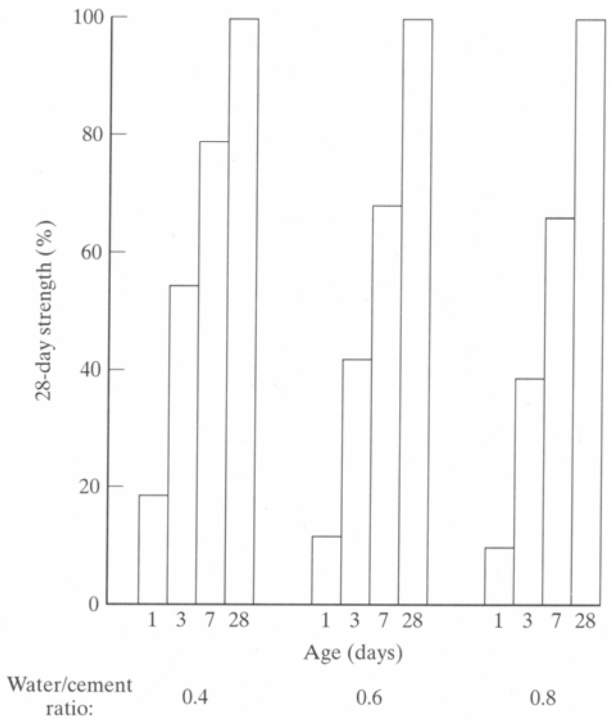

Figure 2-12. Relative gain in strength with time of concretes with different water/cement ratio (Mindess et al. 2002)

Generally, the strength of concrete is characterized by the 28-day value, and some other properties of concrete are often related to the 28-day strength. Although it is known that concrete exposed to water continues to gain strength almost indefinitely, the 28-day strength is widely taken for use during structural design.

Air Content and Porosity

Air content is that portion of the pores in the fresh cement paste portion of concrete that is filled with air. The quantity of liquid-filled pores can be characterized by the water cement ratio of fresh cement paste.

In general, a reduction in porosity within a solid material increases its strength, an axiom particularly applicable to concrete. This was recognized long ago, and is why adobe walls, bricks, and soils were compacted in early times. Later, Roman builders manually compacted their concrete and in the twentieth century various mechanical devices (vibrators, rollers, etc.) were developed for more efficient compaction of concrete. The strength-increasing effect of reducing the water/cement ratio is an example concerning the effect of water filled pores.

There are three basic assumptions that must be made before discussing the effects of air content:

(1) air voids are randomly distributed throughout the matrix, though statistically in a uniform nature,

(2) none of the voids are too large for the size of the concrete specimen, and

(3) the various air voids influence concrete strength to the same extent.

Unfortunately, there are not enough data available at present to establish the definite effects of air content on the strength of concrete. According the Griffith criterion of fracture, larger pores produce less damage than the same total volume of smaller pores of the same void shape. Therefore, the pore size distribution of the pores may also have an effect on the degree of strength reduction. For instance, one may expect that the reduction in load-bearing capacity of a concrete is less when there are a few large holes of controlled shape in it than small pores of uncontrolled shape. Spatial distribution of the pores can also be a factor. It is expected that two pores of the same size would reduce the concrete strength more when they are spaced closely to each other than when they are located far apart (Popovics 1998).

The effect of porosity on the strength of hydrated cement paste has been studied widely. There is no doubt that porosity (defined as the volume of pores larger than gel pores expressed as a percentage of the overall volume of the hydrated cement paste) is a primary factor influencing the strength of the cement paste. A linear relation between strength and porosity, within the range porosities between 5 and 28 per cent, was established by Rossler and Odler (1985). The effect of pores smaller than 20 nm in diameter was found to be negligible. The relationship between the strength of mortar and porosity based on volume of pores larger than 20 nm in diameter is shown in Figure 2-13.

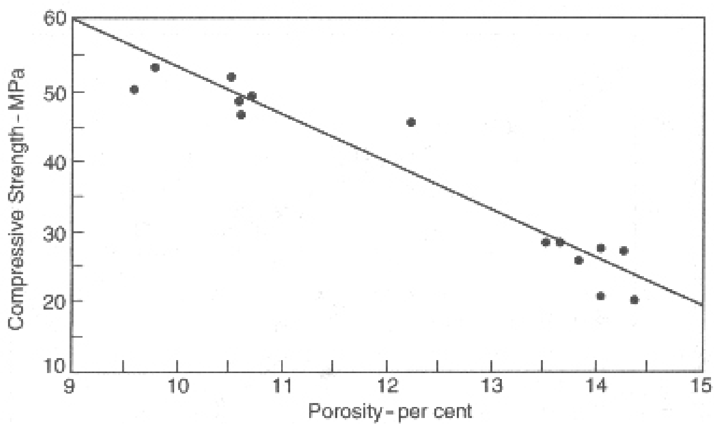

Figure 2-13. Relationship between compressive strength of mortar and porosity calculated from the volume of pores larger than 20 nm diameter (Neville 1996)

Most of experimental work on porosity of hydrated cement paste has been performed on specimens of neat cement paste or mortar, not concrete. In concrete, the pore characteristics of the hydrated cement are somewhat different because of the influence of coarse aggregate particles on the cement paste in their vicinity. It has been confirmed that the difference in porosity between concrete and neat cement paste, at the same water/cement ratio, increases with the progress of hydration and arises from the presence in concrete of some pores larger than those which can exist in neat cement paste.

Whenever the concrete property in question is controlled by the matrix portion of the concrete, one can use the air content as the effective porosity influencing the property. Such is the case, for instance, for the strength of concrete, because the pores in the aggregate particles have scarcely any effect on strength in most normal-weight concrete. However, in other cases, such as the deformability of concrete, the property may be better to use the sum of the air pores in the matrix and the pores in the aggregate particles as effective porosity (Popovics 1998). Realization of this idea should, however, be left for future research.

Moisture Content

Generally, there are two types of water in concrete, free water and chemical water. Here, free water means the water found in the voids and capillary pores which is evaporable, and the chemical water means the water held within the hydration products (gel), which is total ‘solid volume’.

Concrete contains a great number of voids comprising gel pores, capillary pores and flaws. In most conditions, these voids are filled with water and/or air. There are two extreme conditions; all of the voids are filled with water under saturated conditions or the voids are completely devoid of water when the concrete is fully dry. Most concrete specifications, such as ASTM C39 require that the concrete be maintained in a saturated state. However, changes in moisture content caused by wetting or drying have been shown to have a considerable effect on the mechanical properties of concrete and in a variety of ways. Concrete that has been dried has a higher compressive strength and lower static modulus than concrete with a high moisture content taken from the same mix and subjected to an identical curing process.

The reasons for this behavior are not completely understood; it may have something to do with a change in the structure of the C-S-H upon drying, or it may simply represent a change in the internal friction and cohesion on a macroscopic scale; that is, moisture may have a 'lubricating' effect, allowing particles to slip by each other in shear more easily. The lower compressive strength of wet concrete may also be due to the development of internal pore pressure as a load is applied.

Feldman and Sereda (1970) suggested that the Si-O bonds can break more readily to form Si-OH HO-Si bonds in the presence of adsorbed water on the gel particles. When the concentration of water molecules is sufficient to maintain the delivery of moisture to a spreading crack, no further decrease in strength will occur. However, this is disputed by Glucklich and Korin (1975), who question whether enough water can be continuously present at the crack tip to maintain the necessary aggressive environment. Other researchers, including Wittmann and Neville, explained this phenomenon based on combination of the Griffith's fracture criterion and surface free energy theory. It is suggested that changes in strength during adsorption is correlated with surface free energy. When water is absorbed into the gel, the spreading pressure forces the gel surfaces further apart, resulting in a reduction in the Van der Waals forces between gel particles. This leads to a decrease in the surface free energy since the specific surface energy is proportional to the adhesive forces. Thus, using Griffith's criterion, the critical stress decreases as the amount of absorbed water increases (Guo and Waldron 2001).

Popovics (1986) argued that a moisture gradient over the cross-section of a prismatic concrete specimen causes a change in the measured strength. When the moisture level on the outside is lower than that on the inside of a concrete specimen, the outside layer tends to shrink because it is dryer than the core of the specimen. This shrinkage is restrained by the core of the specimen. Consequently, the core is subjected to a lateral biaxial compression, increasing its measured compressive strength in the third direction.

However, tests have shown that well-cured mortar prisms and concrete cores or cylinders, when completely dried, have a higher compressive strength than when tested wet. Since these specimens were not subjected to differential shrinkage, no such biaxial stress system would have been induced and therefore this phenomenon does not explain the increase in strength. Galloway et al. (1979) argued that the presence of water in the concrete may cause a dilation of the cement gel which results in a weakness in cohesion of the solid particles. Another hypothetical explanation has been suggested by Neville, Popovics and Wittman that the water absorbed into the gel pores leads to a transverse bursting effect in the solid matrix of the concrete and this effect increases with an increase in the external compressive load. However, this is purely a conceptual hypothesis without any theoretical model to support it (Guo and Waldron 2001).

However, the experimental evidence is somewhat contradictory, particularly for tensile and flexural strengths. Since concrete has a fairly low diffusion rate, and dries only from the outside, it is very difficult to get perfectly “dry” concrete, or to fully resaturate concrete. Thus, the degree of dryness depends on the size and shape of the specimen. Drying too quickly may also induce tensile cracks due to nonuniform drying (and hence differences in drying shrinkage) of the specimen. These cracks do not have much effect on the compressive strength, but will lower the apparent flexural and tensile strengths. Slow drying, on the other hand, where cracking is prevented, will increase the flexural and tensile strength. Similar effects are sometimes noted when dry specimens are resaturated. The effect of the moisture content on strength becomes an important consideration when testing drilled cores (Mindess et al. 2002).

CHAPTER 3
LABORATORY SPECIMEN TESTING

Experimental laboratory testing made up the bulk of the research discussed in this work. This chapter will present the details of laboratory tests and will include test design and apparatuses, specimen preparation, and experimental procedures.

Test Design

Based on the primary objective of this research, the laboratory tests were designed to obtain the strength of concrete specimens with different moisture contents under different types of loading. Three types of tests were performed: the uniaxial compressive strength test, the splitting tensile strength test and the pressure tensile strength test. All tests were repeated with specimens from two concrete mixtures having different water/cement ratios; 0.45 and 0.65.

Mixture Design

Concrete is among the most complex materials used in the construction industry today. It is a combination of Portland cement, mineral aggregates, water, air, and often includes chemical and mineral admixtures. Unlike other materials used in construction, concrete is usually designed specifically for a particular project using locally available materials (Mindess et al. 2002). The proportioning of concrete mixtures is commonly referred to as mixture design. In the past, there have been two aspects of mix design in which most of the theoretical work has been carried out: water content and aggregate grading. Most of modern empirical design methods depend heavily on these two considerations.

For this research, there were two groups of specimens with different water/cement ratios. Mixture designs for the 0.45 and 0.65 water/cement ratios are shown in Tables 3-1 and 3-2, respectively.

Table 3-1. Mixture design for 0.45 water/cement ratio.

Mix Design 0.45 W/CM Ratio		
Material	**Quantity**	
		kg/m^3
Cement		508
Water		229
Fine Aggregate		855
Coarse Aggregate		733
Admixtures		
Superplasticizer	0.8	L/m3

Table 3-2. Mixture design for 0.65 water/cement ratio.

Mix Design 0.65 W/CM Ratio		
Material	**Quantity**	
		kg/m^3
Cement		350
Water		229
Fine Aggregate		986
Coarse Aggregate		627
Admixtures		
None		

Test Procedure Design

There were two main objectives for this research;

1. Evaluate the effects of concrete moisture content on the mechanical properties of concrete, particularly the pressure tensile strength test results.

2. Relate the splitting tensile strength test to the pressure tensile strength test.

1. Type of tests

Based on these objectives, compressive strength, splitting tensile strength and pressure tensile strength were recorded during the laboratory test.

1. Uniaxial compressive strength test: The standard test described by ASTM C 39 to determine the compressive strength of cylindrical concrete specimens.
2. Splitting tensile strength test: The standard test described by ASTM C496 to determine the splitting tensile strength of cylindrical concrete specimens.
3. Pressure tensile test: Not yet standardized. Used to compare the data with the splitting tensile test.
4. Statistical analysis of the variability exhibited by specimens from different batches (5 randomly selected specimens from each batch after 28-day standard moisture curing).

2. Factor design

There are two significant factors that must be considered during the experimental tests; immersion time and water/cement ratio. In order to obtain the different moisture contents in the concrete specimens, they were replaced in water after 28 days of standard moisture curing and 28 days of ambient curing. The moisture content in the specimens was thus determined by the length of time the specimens were kept in water.

The specimens were tested following re-immersion periods of 0 days, 1 day, 3 days, 5 days, 7 days and 14 days. Therefore, the factor of time had 6 possibilities. A final set of specimens was subjected to 14 days of oven drying. It is reasonable to assume that the free moisture content in these specimens reached zero (creating a 7th moisture content).

Two groups of specimens with different water/cement ratios were cast, with two objectives in mind. The first was to examine the effect of water/cement ratio on the different types of strength for specimens with the same moisture content. The second was to evaluate whether interactions between water/cement ratio and moisture content were significant, whether the water/cement ratio would alter the effects of moisture content on concrete strengths.

3. Specimen sampling procedure

The tests used in this research program required a total of about 100 specimens for each water/cement ratio. Due to capacity restrictions with the available mixer, it was necessary to break this into two batches. In order to minimize the effect of variability between these two batches, half of the specimens for each individual test were taken from each batch. The full specimen testing matrix is shown in Table 3-3.

An MTS Model 810 Material Testing System was used to determine the compressive strength and splitting tensile strength. A custom fabricated pressure tension device designed to test 100 mm diameter by 200 mm long specimens was used to perform the pressure tensile strength tests.

Table 3-3. Test procedure design.

Test Procedures Design													
Factors	**Factor I (Water/Cement Ratio)**												
Factor II (Immersion Period)		**0.45**						**0.65**					
	Test Methods	Uniaxial Compress		Splitting Tension		Air Pressure		Uniaxial Compress		Splitting Tension		Air Pressure	
	Blocks	Block I	Block II	Block I	Block II	Block I	Block II	Block I	Block II	Block I	Block II	Block I	Block II
	0 Day	2	2	2	2	2	2	2	2	2	2	2	2
	1 Day	2	2	2	2	2	2	2	2	2	2	2	2
	3 Day	2	2	2	2	2	2	2	2	2	2	2	2
	5 Day	2	2	2	2	2	2	2	2	2	2	2	2
	7 Day	2	2	2	2	2	2	2	2	2	2	2	2
	14 Day	2	2	2	2	2	2	2	2	2	2	2	2
	Oven Drying	2	2	2	2	2	2	2	2	2	2	2	2

Introduction of Test Apparatus

MTS 810 Testing System

MTS 810 Testing Systems are highly integrated testing packages that can be configured to meet different testing needs. Each includes a Model 318 load unit with integrally mounted actuator and servo valves, a hydraulic power unit, and the MTS TestStar IIs control system, as illustrated in Figures 3-1 and 3-2. The TestStar IIs control system has three major parts: the TestStar system software running on a personal computer, the digital controller, and a remote station control panel. These functions work together to provide fully automated test control. Optional application software packages let you further tailor the system to automate most any standard or custom test procedure.

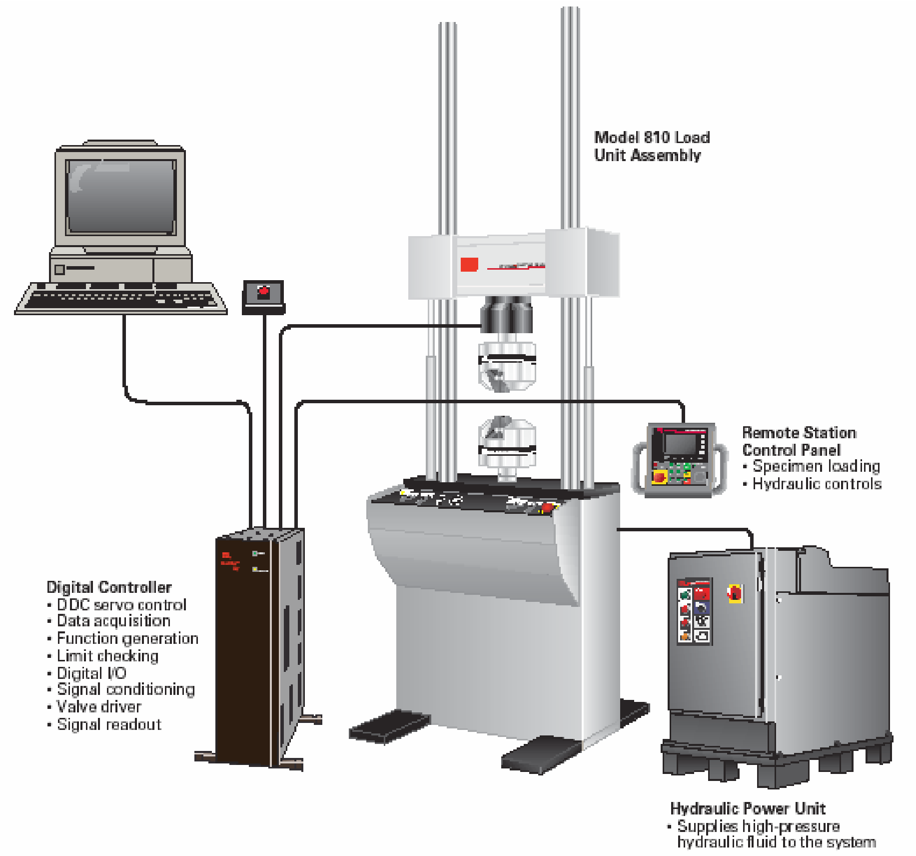

Figure 3-1. MTS 810 material testing system working sketch map.

Figure 3-2 MTS 810 material testing system in UF concrete laboratory.

Pressure Tensile Strength Apparatus

The pressure tension device consisted of a specimen loading sleeve, a nitrogen gas tank, a tank output regulator, a pressure transducer for monitoring loading pressure, and a personal computer for data collection. This apparatus is shown in Figures 3-3 and 3-4.

Figure 3-3. Pressure tensile strength device – specimen loading sleeve.

Figure 3-4 Pressure tensile strength testing system.

Material Preparation

Materials used to cast concrete included coarse aggregate, fine aggregate (sand), cement and water. All of the coarse aggregate, sand and cement were transported to the concrete lab from the Florida Department of Transportation State Materials Office. Both the coarse aggregate and sand were graded for use in concrete. Type I cement, supplied by Rinker Materials, was used in all mixtures. Water was obtained directly from the City of Gainesville drinking water supply.

Concrete Mixing & Casting

Mixing and casting of the concrete specimens took place in the Department of Civil & Coastal Engineering concrete lab at the University of Florida. A total of 200 specimens were cast, all on the same day. Both water/cement ratios were included and each ratio had 100 specimens cast from two batches of 50 specimens each.

First, all of the coarse aggregate was placed into the mixer, along with approximately half of the total amount of water designated in the mixture design. The mixer was then turned on and allowed to run for a few revolutions. The mixer was stopped and the fine aggregate was added, followed by the Portland cement. After all of the remaining dry ingredients were introduced into the mixer, it was turned on and the remaining water was slowly added during mixing. The mixer was left running for about 4 minutes to allow for complete mixing of the concrete. The mixer used in the test is shown in Figure 3-5.

Figure 3-5. Concrete mixer

Curing Procedure

After an initial curing period of 24 hours, the concrete cylinders were removed from their molds. All cylinders were placed into a tank of lime-saturated water and remained submerged in the standard moisture curing environment until reading 28 days of age. A typical curing tank is shown in Figure 3-6.

Figure 3-6. Standard moist curing environment (curing tank).

Following the standard moist curing period, all of the cylinders were removed from the curing tank and exposed to ambient laboratory conditions for 28 days. Cylinders were stored in the MTS testing lab and all strength tests were performed in the same room. Thus, it can be assumed that all specimens were exposed to the same environment. The specimens stored in the MTS lab are shown in Figure 3-7.

Figure 3-7. Specimens stored in ambient laboratory environment after initial curing.

Following 28 days of exposure to the ambient environment, all specimens were re-immersed in the lime-saturated water bath except those which were to be tested at 0 days of saturation and those to be exposed to oven drying. Here, the 0 day exposure means that the specimens had a stable moisture content under the ambient environment. For the oven dried specimens, it was assumed that a moisture content of zero was reached after 14 days at a temperature of 110 ± 5°C. The specimens subjected to oven drying are shown in Figure 3-8.

Figure 3-8. Specimens subjected to oven drying.

Test Procedures

After the various saturating periods were complete (0 days, 1 day, 3 days, 5 days, 7 days, 14 days, and oven dried), the concrete cylinders were tested using the three different strength testing procedures: the compression test, the splitting tension test and the pressure tension test. For each set of moisture content specimens, all three testing procedures were done at essentially the same time, before moisture content could change significantly between tests.

Compressive Strength Test

Two sets of compressive strength tests were performed. The first set was used for the statistical analysis of concrete strength. Twenty cylinders were picked randomly from the four different batches, five from each batch, after the initial 28 day standard moist curing period. The second set of tests was performed to evaluate the compressive strength of the concrete at different moisture contents.

Prior to testing, both ends of the specimens were ground in order to create planar surfaces in accordance with ASTM C-39. Because the grinder used in this research uses a recycling water cooling system, the moisture content of the specimens would be affected if such preparation was done after the final saturation period. To avoid this effect, all specimens used for compression testing were ground after the initial 28 day curing period. The grinder used in the research is shown is Figure 3-9.

Figure 3-9. Cylinder end grinder used to prepare specimens for compression testing.

A total of 56 cylinders were tested in compression by loading until failure in accordance with ASTM C-39. For each moisture content and each water/cement ratio, two cylinders from each batch were tested, for a total of four specimens for each variable set (see Table 3-3).

During testing, the maximum load attained was recorded by the MTS testing system after the cylinder failed. Each specimen was documented (by pictures) before and after failure. A typical specimen failure is shown in Figure 3-10.

Figure 3-10. Typical specimen failure under compression loading.

Splitting Tensile Strength Test

A total of 56 cylinders were also tested under the splitting tensile strength test in accordance with ASTM C-496. A typical specimen failure is shown in Figure 3-11.

Figure 3-11. Typical specimen failure under splitting tensile loading.

Pressure Tensile Strength Test

For this test, the same total number of cylinders (56 specimens) was tested. Duct tape was placed around the circumference at each end of the specimen to provide a better seal at the o-ring locations. The specimens were inserted into the pressure sleeve and the o-rings were placed on either end, on top of duct tape. The end rings of the pressure sleeve were then bolted in place. This procedure is shown in Figure 3-12.

Figure 3-12. Pressure tensile strength test. (a) duct tape application, (b) specimen placed inside pressure sleeve, (c) end rings bolted in place.

During testing, the specimens were loaded at a relatively constant rate. This rate was controlled manually by turning the Nitrogen regulator handle on the gas tank. The pressure within the sleeve was increased at a constant rate by following an inclined line with the actual pressure readout on the computer screen. The pressure was increased until failure occurred. A typical failure is shown in Figure 3-13 and 3-14.

Figure 3-13. Typical specimen failure in the pressure tensile strength test (1/2)

Figure 3-14. Typical specimen failure in the pressure tensile strength test (2/2)

Specimen Failure from the Three Test Procedures

The following pictures (Figures 3-15 and 3-16) show the failed specimens from all three test procedures.

Figure 3-15. Failed specimens from all three strength tests (1/2)

Figure 3-16. Failed specimens from all three strength tests (2/2)

CHAPTER 4
DATA ANALYSIS AND DISCUSSION

Compressive Strength Variability Analysis

Twenty specimens were randomly picked from the two groups of specimens with different water/cement ratios, 10 from each group. Half of the 10 specimens from each group were randomly chosen from each batch and subjected to compressive strength testing. The ends of all specimens were ground prior to testing. All data were collected

Data Analysis

The statistical analyses of uniaxial compressive strength are shown in Tables 4-1 and 4-2.

Table 4-1. Batch compressive strength statistical analysis

Batch	#	Mean (MPa)	Variance (MPa^2)	St. Dev (MPa)	COV (%)
Batch 1 (W/C=0.45)	5	53.1	2.53	1.59	3.0%
Batch 2 (W/C=0.45)	5	55.7	1.70	1.30	2.3%
Batch 1 (W/C=0.65)	5	35.4	4.29	2.07	5.9%
Batch 2 (W/C=0.65)	5	31.9	0.58	0.76	2.4%

Table 4-2. Mixture compressive strength statistical analysis

Mixture	#	Mean (MPa)	Variance (MPa^2)	St. Dev (Mpa)	COV (%)
W/C = 0.45	10	54.4	3.80	1.95	3.6%
W/C = 0.65	10	33.7	5.48	2.34	6.9%

Table 4-1 showed the statistical results for each of the four batches. For batches 1 and 2 with a water/cement ratio 0.45, and batch 2 with a water/cement ratio 0.65, the coefficient of variation was less than 3.9%. The Maximum Acceptable Range of is 3.9 %

for 5 test results according to ASTM C-670 (Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials[1]). The coefficient of variation of batch 2 with a water/cement ratio of 0.65, however, exceeds this 3.9 % limit, though only slightly. We can therefore conclude that the compressive strengths of all four batches of concrete are statistically uniform and they are acceptable for use as specimens for further testing.

Table 4-2 provided the statistical results for the two concrete Mixtures, including both batches in each mixture. The coefficient of variation for the first mixture (with a water/cement ratio of 0.45) was 3.6%, below the Maximum Acceptable Range of 4.5 % for 10 test results according to the ASTM C-670. The other mixture (with a water/cement ratio of 0.65) exhibited a coefficient of variation of 6.9%, only a little higher than the 4.5% limit. Therefore, we can also conclude that the compressive strengths of the two concrete mixtures are statistically uniform and can be considered consistent for future testing.

All specimens had their ends ground immediately following removal from the curing tank and were tested immediately after the grinding operation was completed. Thus, all specimens can be assumed have the same moisture content. Actually, they can also be considered to be in the saturated condition due to their extended immersion period prior to grinding and testing.

The test results for the four batches are shown in Figure 4-1.

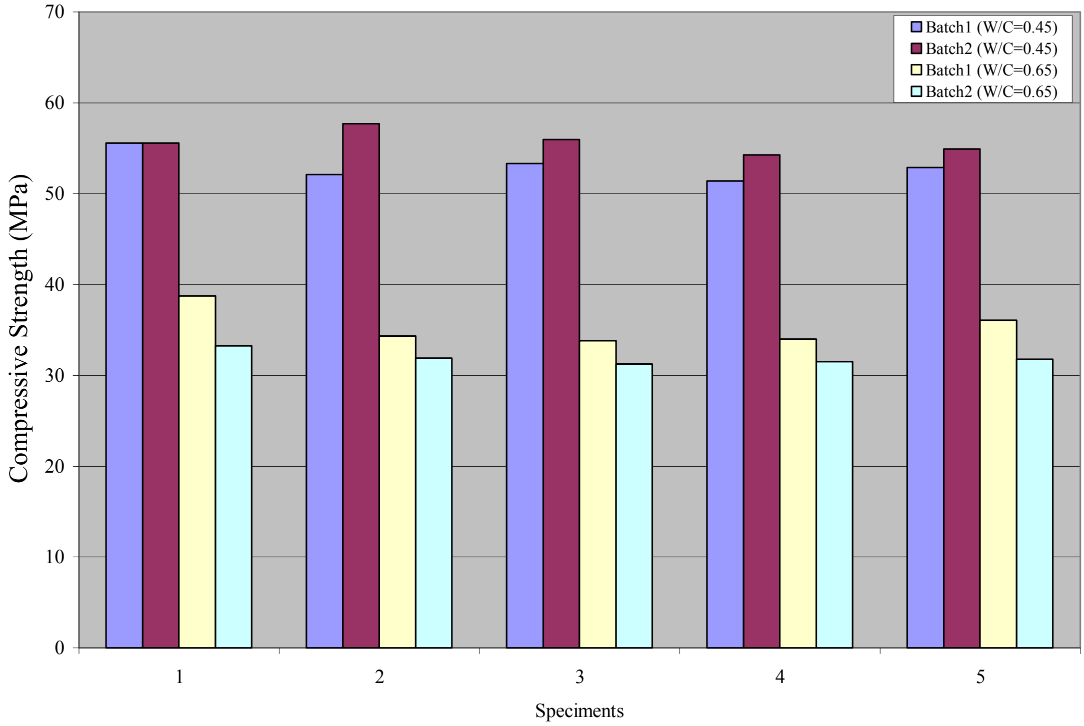

Figure 4-1. Testing Results for strength stability analysis

The remaining specimens were removed from the curing tank and exposed to ambient laboratory conditions. After 28 days, they were replaced in the curing tank, with the exception of those specimens to be tested for 0 days of immersion and those to be oven-dried.

Observations

1. The statistical evaluation of compressive strength showed that the compressive strength of the concrete was stable and acceptable to be used in successive testing.

2. The consistency of the concrete with a water/cement ratio 0.45 was better than that of the concrete with a water/cement ratio 0.65.

3. Water/cement ratio is the primary factor affecting concrete compressive strength. The higher water/cement ratio resulted in a lower compressive strength.

Compressive Strength Analysis

Data Analysis

In total, there were eight specimen groups for each water/cement ratio; 0 days, 1 day, 3 days, 5 days, 7 days, and 14 days of immersion, plus the oven dried specimens at zero moisture content and the standard moist cured (SMC) specimens tested immediately after the initial 28 day curing period. The testing results of different immersion length are shown in Figure 4-2.

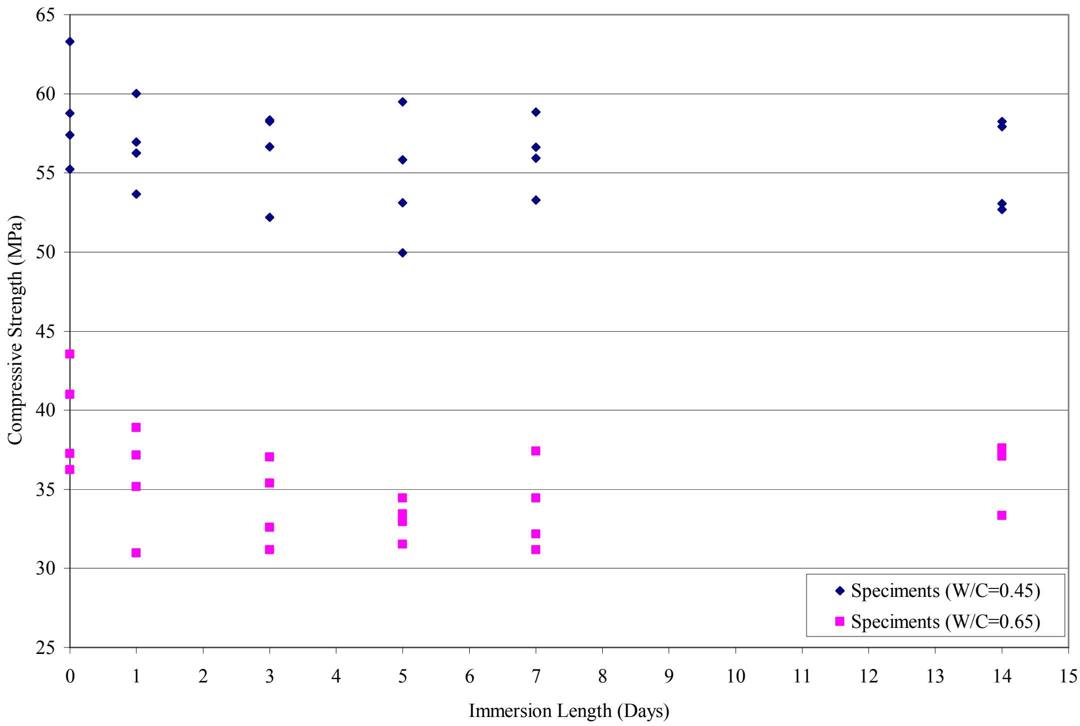

Figure 4-2. Compressive strength test results (individual values).

The mean values of compressive strength for each immersion period are shown in Figure 4-3, while the actual numerical values are provided in Table 4-3.

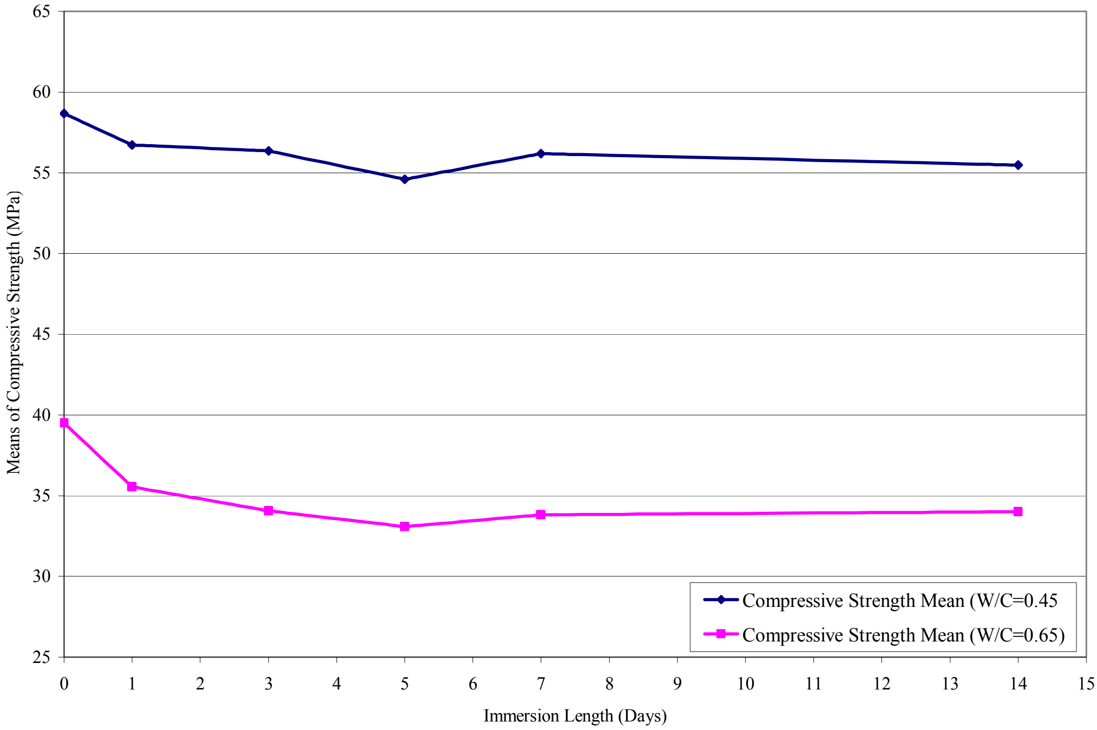

Figure 4-3. Compressive strength test results (mean values).

Table 4-3. Compressive strength test results (mean values).

Immersion Period	W/C = 0.45 Mean (MPa)	W/C = 0.65 Mean (MPa)
0 Day	58.8	39.5
1 Day	56.7	35.5
3 Days	56.4	34.1
5 Days	54.6	33.1
7 Days	56.2	33.8
14 Days	55.5	34.0
Oven Dried	63.2	41.5
28 Day(SMC*)	54.4	33.7

*Standard Moisture Curing

Since the moisture content of the specimens was not measured, the data is presented using immersion period, which should be proportional to moisture content (though not necessarily linear. The longer the specimens cured in water, the higher the moisture content.

Observations

1. Moisture content did affect the compressive strength of the concretes. Comparing the strength levels between 0 days and 14 days of immersion, for example, shows a decrease of about 5.4% and 13.9% for 0.45 and 0.65 water/cement ratio concretes, respectively. The statistics test is shown in Tables 4-4 and 4-5. According to the statistical data analysis, the moisture content did not significantly affect the compressive strength, but the compressive strength did decreased with increasing of moisture content.

Table 4-4. Statistical analysis for compressive strength test (W/C=0.45).

SUMMARY (W/C=0.45)

Groups	Count	Sum	Average	Variance
0 Day	4	234.71	58.68	11.67
1 Day	4	226.88	56.72	6.88
3 Day	4	225.42	56.35	8.28
5 Day	4	218.39	54.60	16.47
7 Day	4	224.70	56.17	5.23
14 Day	4	221.91	55.48	9.05

ANOVA (W/C=0.45)

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	37.68	5.00	7.54	0.79	0.57	2.77
Within Groups	172.74	18.00	9.60			
Total	210.41	23.00				

Table 4-5. Statistical analysis for compressive strength test (W/C=0.65).

SUMMARY (W/C=0.65)

Groups	Count	Sum	Average	Variance
0 Day	4	158.03	39.51	11.42
1 Day	4	142.18	35.55	11.63
3 Day	4	136.22	34.06	7.02
5 Day	4	132.38	33.09	1.49
7 Day	4	135.22	33.80	7.70
14 Day	4	136.03	34.01	19.66

ANOVA (W/C=0.65)

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	110.19	5.00	22.04	2.24	0.09	2.77
Within Groups	176.78	18.00	9.82			
Total	286.97	23.00				

2. Even ambient curing increased the strength of the concrete. Comparing the strength at 0 days of immersion (which is actually 28 days of ambient curing after 28 days of standard moisture curing) to the 28 days of standard moist curing, the strength increased 7.9% and 17.1%, respectively, for the 0.45 and 0.65 water/cement ratio concretes.

3. Oven drying significantly increased the strength of both concretes. Comparing the strength at 0 days of re-immersion to that after similar specimens oven dried for 14 days showd an increase of 7.6% and 5.0%, respectively, for the 0.45 and 0.65 water/cement ratio concretes. Comparing the strength of the 28 day SMC specimens to the oven dried of specimens reveals an increase of 16% and 23% for the 0.45 and 0.65 water/cement ratio concretes, respectively. Statistics tests considering the oven specimens is shown in Tables 4-6 and Table 4-7. According to the P_value, the test is significant.

Table 4-6. Statistical analysis of compressive strength considering oven dried specimens (W/C=0.45).

ANOVA (W/C=0.45)						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	197.72	6	32.95	3.82	0.01	2.57
Within Groups	180.92	21	8.62			
Total	378.64	27				

Table 4-7. Statistical analysis of compressive strength considering oven dried specimens (W/C=0.65).

ANOVA (W/C=0.65)						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	254.07	6	42.34	4.91	0.00	2.57
Within Groups	180.96	21	8.62			
Total	435.03	27				

4. The effect of moisture content on strength change was more pronounced in the concrete with a higher water/cement ratio. This phenomenon can be seen in Table 4-8 and Figure 4-4.

5. Though the compressive strength dropped as moisture content increase, after 7 days of immersion the strength change essentially leveled off. This means that the concrete may have reached a saturated limit state, or at least a point where the outer material is saturated to the point that further ingress slows down dramatically.

Table 4-8. Effect of moisture content on strength change.

	W/C = 0.45		W/C = 0.65	
Immersion Period	Mean (MPa)	Change (%)	Mean (MPa)	Change (%)
1 (0 Day)	58.7	7.65	39.5	5.0
2 (1 Day)	56.7	3.45	35.5	11.1
3 (3 Days)	56.4	0.65	34.1	4.38
4 (5 Days)	54.6	3.22	33.1	2.90
5 (7 Days)	56.2	-2.80	33.8	-2.10
6 (14 Days)	55.5	1.26	34.0	-0.59

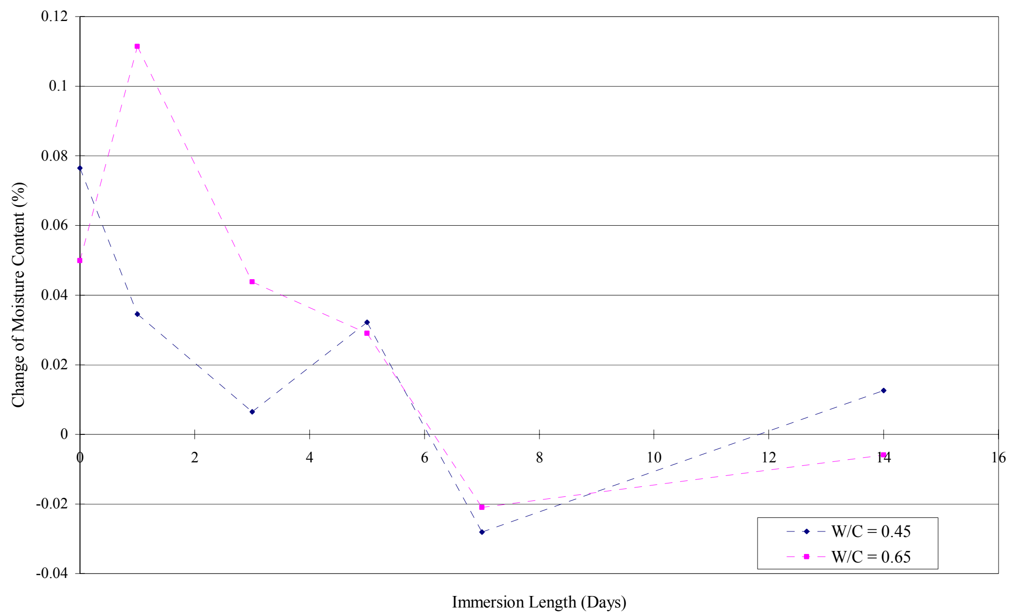

Figure 4-4. The effect of W/C ratio on strength drop due to increasing moisture content.

Splitting Tensile Strength Analysis

Data Analysis

For the splitting tensile strength evaluation, there were seven specimen groups for each water/cement ratio (0 days, 1 day, 3 days, 5 days, 7 days, and 14 days of immersion plus oven dried specimens). The individual test results are shown graphically in Figure 4-5, while the mean values are shown in Figure 4-6. The data for the mean values is tabulated in Table 4-9.

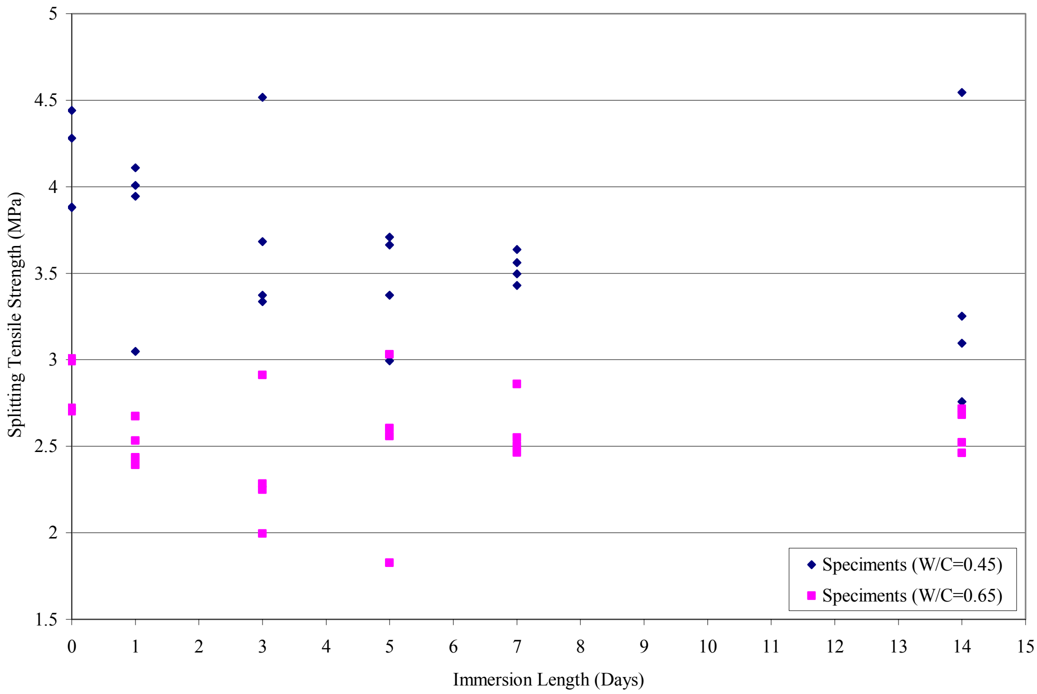

Figure 4-5. Splitting tensile strength test results (individual values).

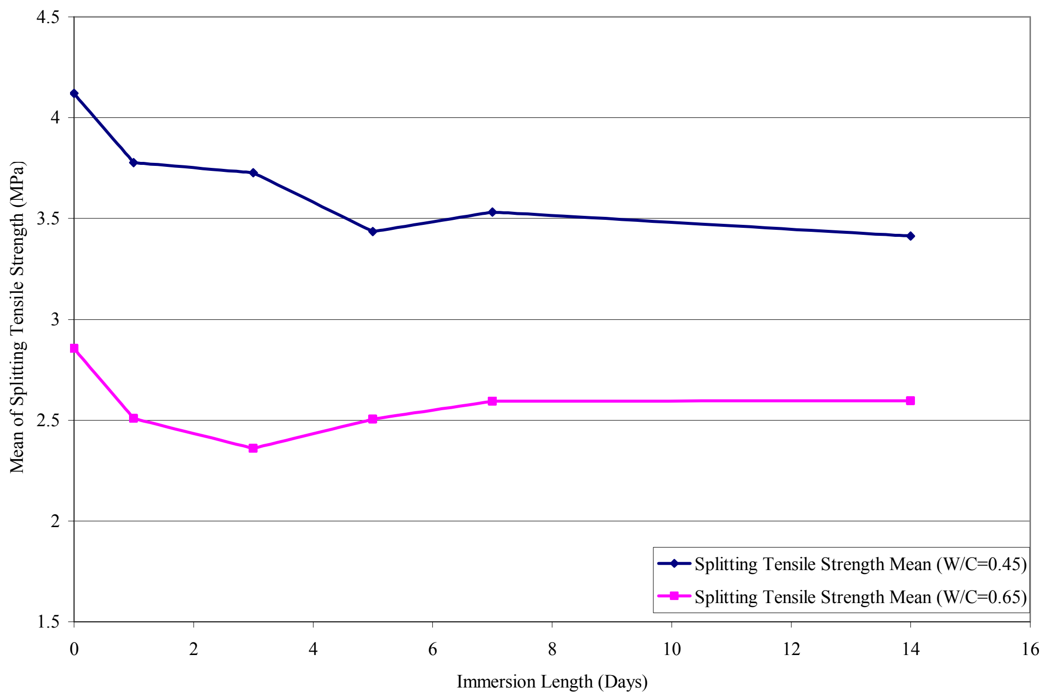

Figure 4-6. Splitting tensile strength test results (mean values).

Table 4-9. Test results for splitting tensile strength (mean values)

Immersion Period	W/C = 0.45 Mean (MPa)	W/C = 0.65 Mean (MPa)
0 Day	4.12	2.86
1 Day	3.78	2.51
3 Days	3.73	2.36
5 Days	3.44	2.51
7 Days	3.53	2.59
14 Days	3.41	2.60
Oven Dried	4.37	3.30

The splitting tensile strength tests were performed at the same times as the compression tests. As discussed in Chapter 2, tensile stress in the splitting test is calculated using;

$$f_t = \frac{2P_c}{\pi l D} \approx \frac{2P_c}{100.5} \quad (4\text{-}1)$$

where; f_t is the tensile stress, P_c is the maximum applied force, l is the cylinder length, and D is the cylinder diameter.

Observations

1. The effect of moisture content on the splitting tensile strength of concrete is not significant. Comparing the strength of 0 day and 14 day immersion specimens, tensile strength decreased 17 % and 9.1%, respectively, for 0.45 and 0.65 water/cement ratio concretes. When comparing the 1 day and 14 day immersion results, however, the tensile strengths decreased 9.7% and -3.5%, respectively. The statistics test results are shown in Tables 4-10 and 4-11. According to the statistical data analysis, the moisture content does not affect significantly splitting tensile strength, but the splitting tensile strength did decrease with increasing moisture content.

Table 4-10 Statistical analysis for splitting tensile strength test (W/C=0.45).

SUMMARY (W/C=0.45)

Groups	Count	Sum	Average	Variance
0 Day	4	16.48	4.12	0.08
1 Day	4	15.11	3.78	0.24
3 Day	4	14.91	3.73	0.30
5 Day	4	13.74	3.44	0.11
7 Day	4	14.13	3.53	0.01
14 Day	4	13.65	3.41	0.61

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.43	5	0.29	1.27	0.32	2.77
Within Groups	4.06	18	0.23			
Total	5.49	23				

Table 4-11. Statistical analysis for splitting tensile strength test (W/C=0.65).

SUMMARY (W/C=0.65)

Groups	Count	Sum	Average	Variance
0 Day	4	11.42	2.86	0.03
1 Day	4	10.04	2.51	0.02
3 Day	4	9.44	2.36	0.15
5 Day	4	10.02	2.51	0.25
7 Day	4	10.38	2.59	0.03
14 Day	4	10.39	2.60	0.02

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.54	5	0.11	1.31	0.30	2.77
Within Groups	1.48	18	0.08			
Total	2.02	23				

2. Actually, it is reasonable to assume that there is no significant effect of moisture content on splitting tensile strength since the strength data fluctuated widely. The variance of the data was high, especially for the 0.65 water/cement ratio mixture, as indicated in Figure 4-7 and Table 4-14.

3. Oven drying increased the tensile strength of the concrete. Comparing the 0 day immersion specimens to the 14 day oven dried specimens, the tensile strength increased 6.03% and 6.12%, respectively, for the 0.45 and 0.65 water/cement ratio

concretes. Statistics test results considering the oven dried specimens are shown in Tables 4-12 and 4-13. According to the P_value, the test is significant.

Table 4-12. Statistical analysis for splitting tensile strength test considering oven dried specimens (W/C=0.45).

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.12	6	0.52	2.39	0.06	2.57
Within Groups	4.57	21	0.22			
Total	7.69	27				

Table 4-13. Statistical analysis for splitting tensile strength test considering oven dried specimens (W/C=0.65).

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.27	6	0.21	2.71	0.04	2.57
Within Groups	1.64	21	0.08			
Total	2.90	27				

4. When a specimen is tested under moist conditions, the outer layer of the specimen is softer than in the dry condition. This will increase the compressive area of this test and may lead to lower estimates of tensile strength. As shown in Figure 4-8, there was typically a slice of concrete remaining after the splitting tensile tests. The specimens did not split into two parts, but three instead.

Table 4-14. Effect of moisture content on strength change.

	W/C = 0.45		W/C = 0.65	
Immersion Period	Mean (MPa)	Change (MPa)	Mean (MPa)	Change (MPa)
1 (0 Day)	4.12	0	2.86	0
2 (1 Day)	3.78	-0.34	2.51	-0.35
3 (3 Days)	3.73	-0.05	2.36	-0.15
4 (5 Days)	3.44	-0.29	2.51	0.15
5 (7 Days)	3.53	0.10	2.59	9.00
6 (14 Days)	3.41	-0.12	2.60	0.002

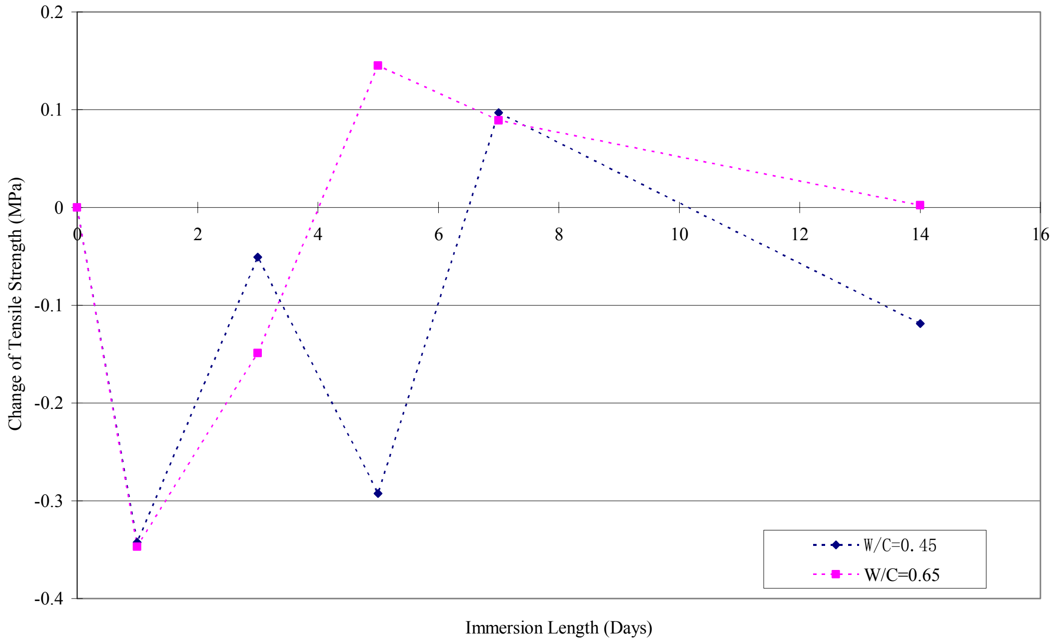

Figure 4-7. The effect of water/cement ratio on the change of strength with varying moisture content.

Figure 4-8. Typical splitting tensile strength test fracture mode.

Pressure Tensile Strength Analysis

Data Analysis

There were seven groups of specimens tested for each water/cement ratio, including 0 days, 1 day, 3 days, 5 days, 7 days, and 14 days of immersion and the oven dried specimens. Individual test results for the pressure tension test are shown in Figure 4-9, while the mean values are depicted in Figure 4-10. Tabulated data of strength means is shown in Table 4-15. Here, each mean represents the average strength from the two batches (each batch consisted of two specimens).

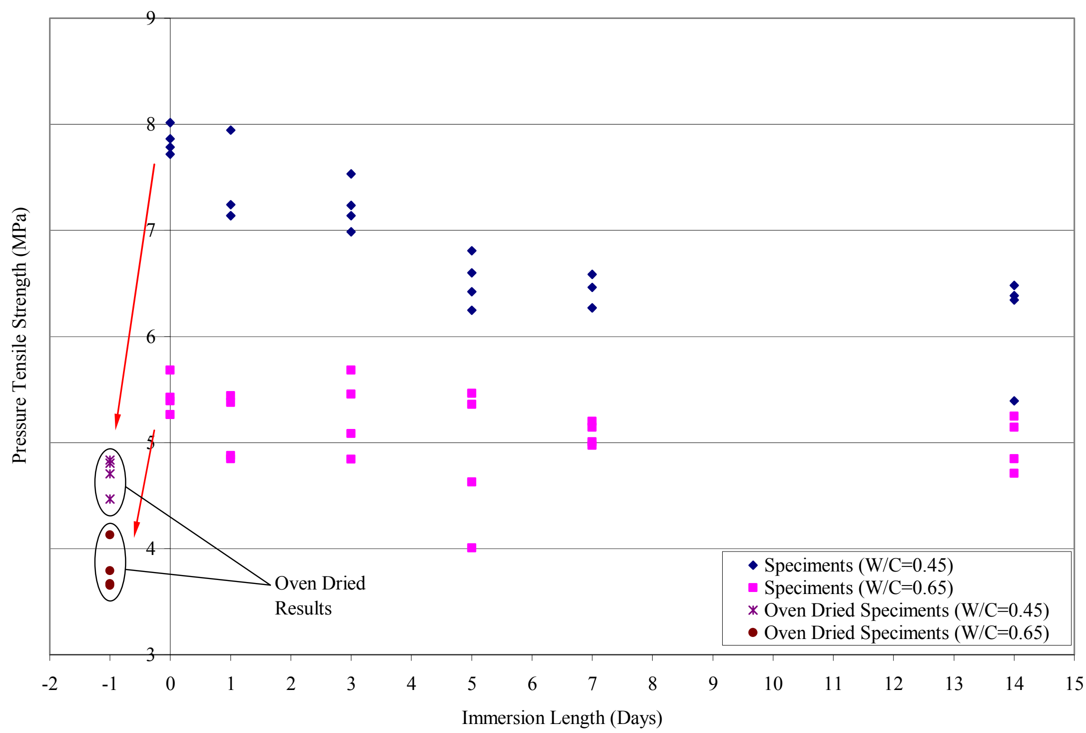

Figure 4-9. Pressure tensile strength test results (individual values).

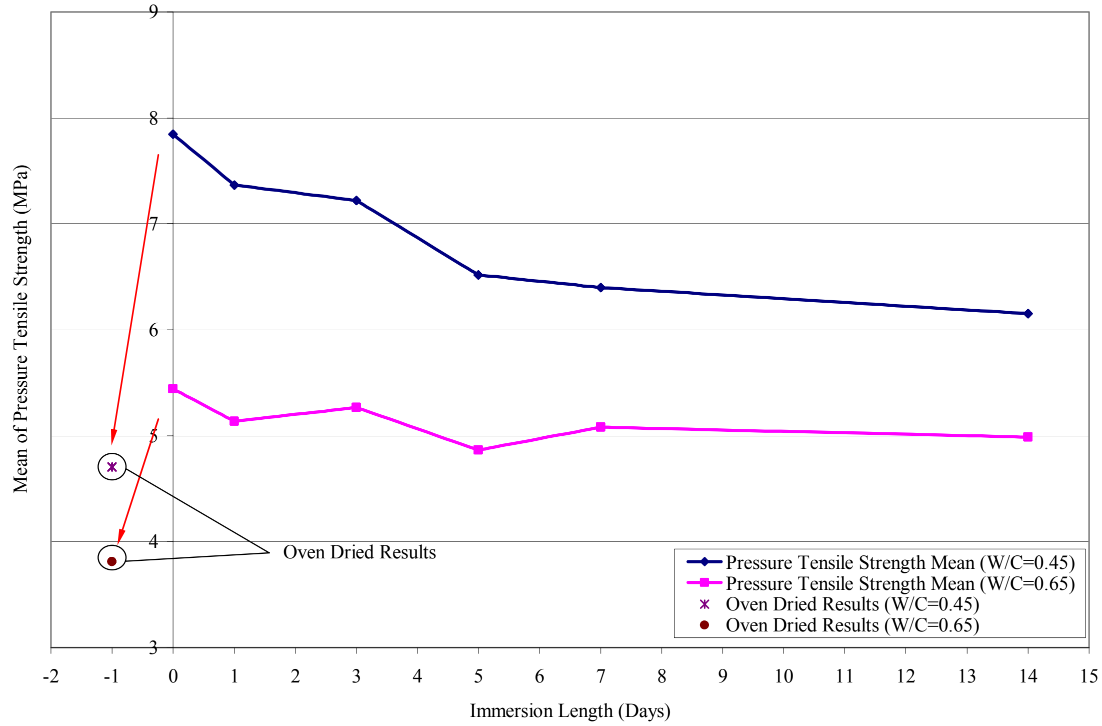

Figure 4-10. Pressure tensile strength test results (mean values).

Table 4-15. Test results for pressure tensile strength (mean values)

Immersion Period	W/C = 0.45 Mean (MPa)	W/C = 0.65 Mean (MPa)
0 Day	7.85	5.44
1 Day	7.37	5.14
3 Days	7.22	5.27
5 Days	6.52	4.86
7 Days	6.40	5.08
14 Days	6.15	4.99
Oven Dried	4.70	3.81

In pressure tensile strength testing, the data is obtained directly in the form of stress, not force. Since the applied pressure during this test was controlled by hand, it is difficult to maintain the exact same load rate throughout the test, and for every specimen. The only way to control the loading rate is to watch the monitor, which plots the applied gas pressure against elapsed time, and to keep the loading curve in a straight line. Because of this, the pressure tension test is not very exact, and there may be some error during testing.

Observations

1. Moisture content has a significant effect on the pressure tensile strength of concrete. Comparing the strength of 0 day and 14 day immersion specimens, the tensile strength decreased 21.58% and 8.33%, respectively, for the 0.45 and 0.65 water/cement ratio concretes. The statistics test results are shown in Tables 4-16 and 4-17. According to the statistical data analysis, the moisture content did affect the pressure tensile strength significantly. The splitting tensile strength decreased with increasing moisture content.

Table 4-16 Statistical analysis for pressure tensile strength test (W/C=0.45).

SUMMARY (W/C=0.45)

Groups	Count	Sum	Average	Variance
0 Day	4	31.38	7.84	0.02
1 Day	4	29.46	7.37	0.15
3 Day	4	28.89	7.22	0.05
5 Day	4	26.08	6.52	0.06
7 Day	4	25.59	6.40	0.02
14 Day	4	24.61	6.15	0.26

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	8.68	5	1.74	18.55	0.00	2.77
Within Groups	1.68	18	0.09			
Total	10.36	23				

Table 4-17 Statistical analysis for pressure tensile strength test (W/C=0.65).

SUMMARY (W/C=0.65)

Groups	Count	Sum	Average	Variance
0 Day	4	21.77	5.44	0.03
1 Day	4	20.54	5.14	0.10
3 Day	4	21.06	5.27	0.14
5 Day	4	19.46	4.86	0.46
7 Day	4	20.32	5.08	0.01
14 Day	4	19.95	4.99	0.06

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.84	5	0.17	1.23	0.33	2.77
Within Groups	2.44	18	0.14			
Total	3.27	23				

2. The result variability for the higher water/cement ratio concrete was greater than for the lower water/cement ratio. This may have been due to variability in the concrete itself, since the 0.65 water/cement ratio concrete had a higher variance in the other tests as well.

3. Oven drying sharply decreased the pressure tensile strength of the concrete. Comparing the strength of 0 day immersion specimens with the 14 day oven dried specimens, the tensile strength decreased 40.04% and 29.94%, respectively, for the 0.45 and 0.65 water/cement ratio concretes. Statistics test results considering the oven dried specimens is shown in Tables 4-18 and 4-19. According to the P_value, the test is significant.

Table 4-18. Statistical analysis for splitting tensile strength test considering oven drying specimens (W/C=0.45).

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	25.48	6	4.25	50.45	0.00	2.57
Within Groups	1.77	21	0.08			
Total	27.24	27				

Table 4-19. Statistical analysis for splitting tensile strength test considering oven drying specimens (W/C=0.45).

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6.78	6	1.13	9.19	0.00	2.57
Within Groups	2.58	21	0.12			
Total	9.37	27				

4. The effect of water/cement ratio on the strength change of concrete is shown in Figure 4-11 and Table 4-20. For the 0.45 water/cement ratio concrete, the strength change is larger than that of the 0.65 water/cement ratio concrete. It appears that this difference grows larger with increasing moisture content.

5. It should be mentioned that loading rate has a large effect on strength results. When similar samples of concrete are loaded at the same rate, they will exhibit similar strength properties. However, if two identical concrete specimens are loaded at different rates, the one loaded with the higher rate will yield a higher strength value The reason for this is that under a high rate of loading, micro-cracks do not have a chance to propagate and follow a path of least resistance to failure as they do when the loading rate is lower. Therefore, the strengths obtained would have errors introduced by the test operator which can not be avoided.

6. Another problem with the pressure tension test is that small leaks may occur during testing that will change the loading rate.

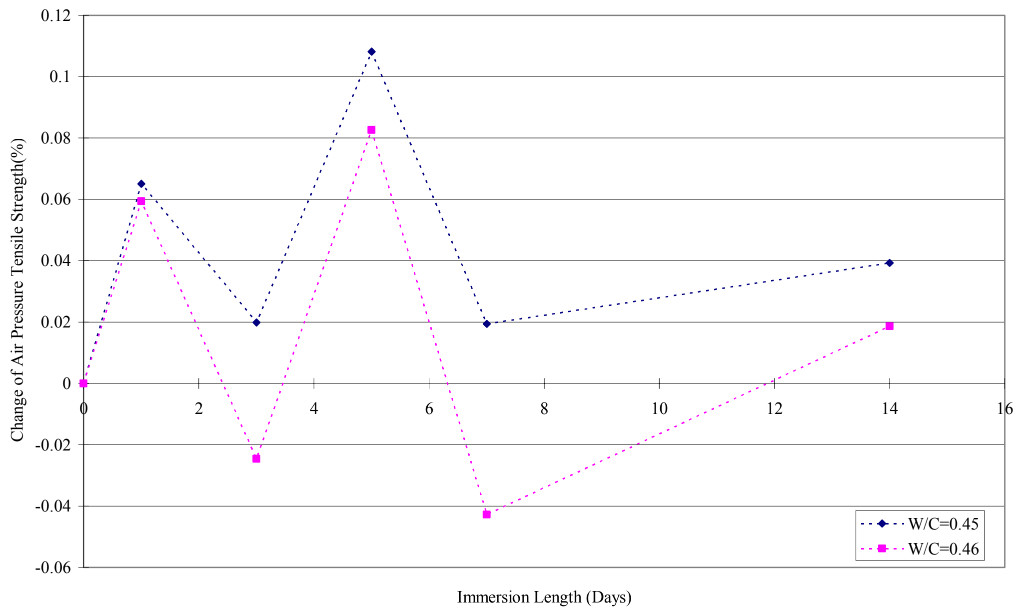

Figure 4-11. The effect of water/cement ratio on strength change with varying moisture content.

Table 4-20. Effect of moisture content on strength change.

	W/C = 0.45		W/C = 0.65	
Immersion Period	Mean (MPa)	Change (MPa)	Mean (MPa)	Change (MPa)
1 (0 Day)	7.85		5.44	
2 (1 Day)	7.37	0.07	5.14	0.06
3 (3 Days)	7.22	0.02	5.27	-0.03
4 (5 Days)	6.52	0.11	4.86	0.08
5 (7 Days)	6.40	0.02	5.08	-0.04
6 (14 Days)	6.15	0.04	4.99	0.02

Comparing Compressive Strength and Splitting Tensile Strength

Both the uniaxial compressive strength test and the splitting tensile strength test are standard test methods supported by ASTM. Typically, there exists stable relationships between compressive strength and splitting tensile strength – the splitting tensile strength is about one tenth of the uniaxial compressive strength for normal strength undamaged concrete.

A number of factors affect the relationship between compressive strength and tensile strength; such as the properties of the aggregates, concrete age, curing conditions etc. A number of empirical formulae relating splitting tensile strength and compressive strength have been suggested, many of them of the type:

$$f_t = k(f_c)^n \tag{4-1}$$

where f_t is the tensile strength, f_c is the compressive strength, k and n are coefficients. Values of n between 1/2 and 3/4 have been suggested.

Here, an attempt will be made to determine whether variations in moisture content of the concrete affects the relation between compressive strength and splitting tensile strength. Tables 4-21, 4-22 show the comparison of results between compressive strength and splitting tensile strength over different immersion periods and water/cement ratios.

Table 4-21. Comparison of compressive strength and splitting tensile strength (W/C=0.45)

Immersion Period	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Ratio
0 Day	58.68	4.12	14.24
1 Day	56.72	3.78	15.01
3 Days	56.35	3.73	15.12
5 Days	54.60	3.44	15.89
7 Days	56.17	3.53	15.91
14 Days	55.48	3.41	16.25
Oven Dried	63.17	4.37	14.46

Table 4-22. Comparison of compressive strength and splitting tensile strength (W/C=0.65)

Immersion Period	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Ratio
0 Day	39.51	2.86	13.83
1 Day	35.55	2.51	14.17
3 Days	34.06	2.36	14.43
5 Days	33.09	2.51	13.21
7 Days	33.81	2.59	13.03
14 Days	34.01	2.60	13.10
Oven Dried	41.48	3.30	13.69

From the tables, we can see that there is no significant change in the ratio between compressive strength and splitting tensile strength over the range of moisture contents examined. For the 0.65 water/cement concrete, the ratio fluctuates but remains constant, while the 0.45 water/cement concrete exhibits a slight increase with increasing immersion time. This means that moisture content does not significantly change the relationship between compressive strength and splitting tensile strength.

The average ratios between compressive strength and splitting tensile strength were 15.27 and 13.64, respectively, for the 0.65 and 0.45 water/cement ratio mixtures. Thus, water/cement ratio is still a critical factor affecting the relationship between compressive and splitting tensile strengths.

Comparing Splitting Tensile Strength and Pressure Tensile Strength

One objective of this research was to relate the more widely accepted splitting tension test to the newer pressure tension approach. Tables 4-23 and 4-24 provide a comparison between the splitting tensile strength test and the pressure tensile strength test over a range of moisture contents and water/cement ratios.

Table 4-23. Comparison of splitting tensile strength and pressure tensile strength (W/C=0.45)

Immersion Period	Splitting Tensile Strength (MPa)	Pressure Tensile Strength (MPa)	Ratio
0 Day	4.12	7.85	1.90
1 Day	3.78	7.37	1.95
3 Days	3.73	7.22	1.94
5 Days	3.44	6.52	1.90
7 Days	3.53	6.40	1.81
14 Days	3.41	6.15	1.80
Oven Dried	4.37	4.70	1.08

Table 4-24. Comparison of splitting tensile strength and pressure tensile strength (W/C=0.65)

Immersion Period	Splitting Tensile Strength (psi)	Air Pressure Tensile Strength (psi)	Ratio
0 Day	2.86	5.44	1.91
1 Day	2.51	5.14	2.08
3 Days	2.36	5.27	2.23
5 Days	2.51	4.86	1.94
7 Days	2.59	5.08	1.96
14 Days	2.60	4.99	1.92
Oven Dried	3.30	3.81	1.26

From this data, it can be shown that there is no significant change in the ratio between the splitting tensile strength and pressure tensile strength over the range of moisture contents examined, with the exception being the oven dried condition. The ratio remains nearly constant. Without considering the oven dried condition, a comparison of these two types of tensile strength is shown in Figures 4-12 and 4-13.

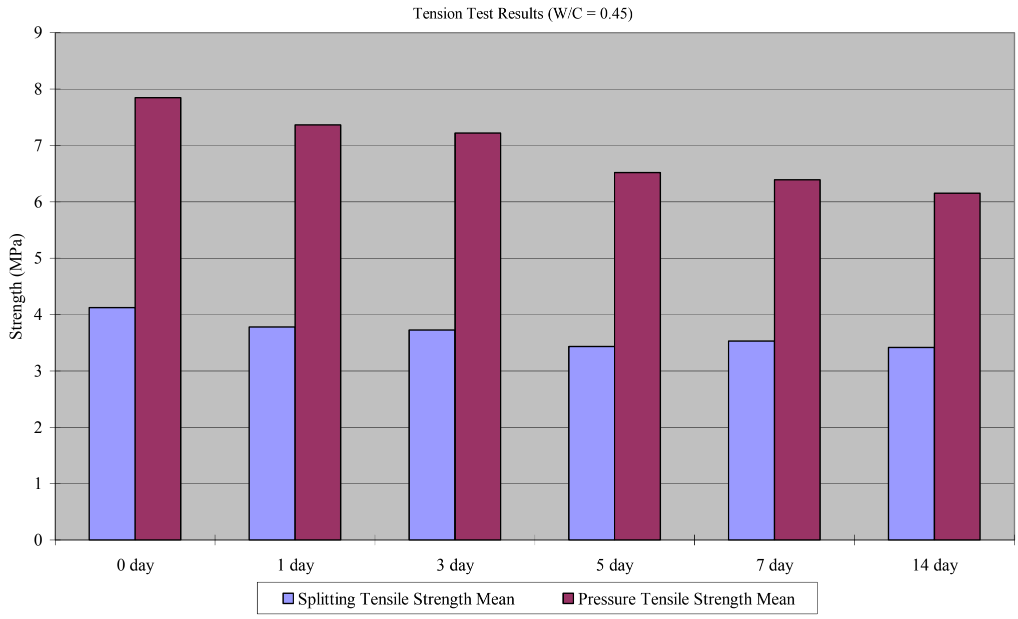

Figure 4-12. Comparison of tensile strength test results (W/C = 0.45)

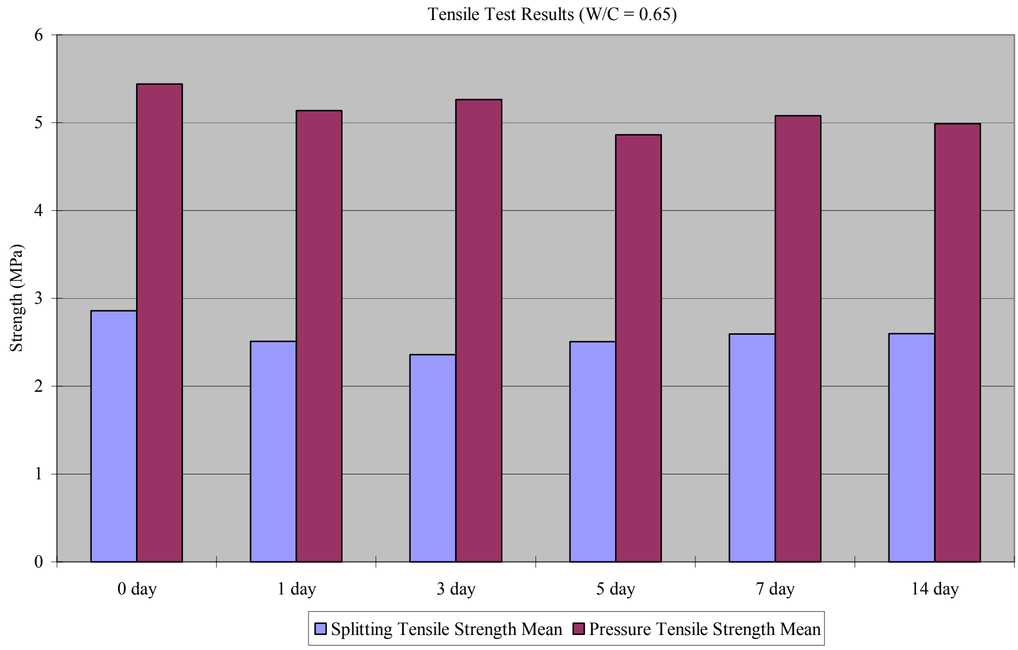

Figure 4-13. Comparison of tensile strength test results (W/C = 0.65)

The average strength ratio for the 0.45 water/cement ratio was 1.88, which rose to 2.00 for the 0.65 water/cement ratio, as shown in Figure 4-14.

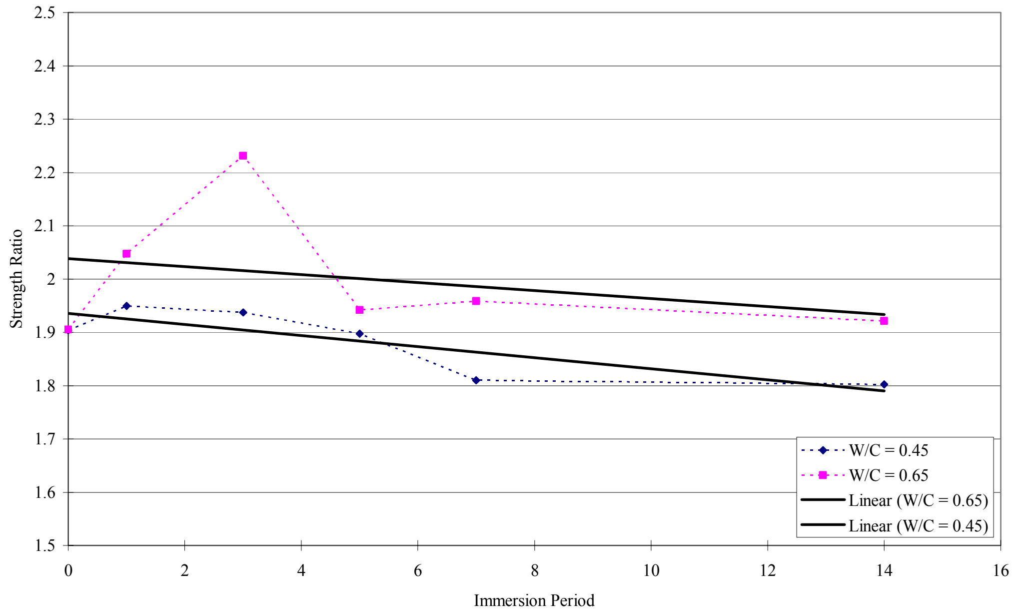

Figure 4-14. Tensile strength ratio at different water/cement ratios.

CHAPTER 5
OVEN DRIED SPECIMEN TESTING

Oven dried specimens were tested in this research. These specimens were stored in an oven for 14 days at 110 ± 5 °C in order to obtain cylinders with zero moisture content. After this procedure, three types of tests were performed – compressive strength, splitting tensile strength and pressure tensile strength.

Properties of Oven Drying Specimens

It has been confirmed that the moisture content of concrete will affect strength. Generally, higher moisture contents result in lower strengths. Therefore, it is reasonable to assume that if the moisture content could be reduced to zero, the highest resultant strength would be obtained. It is common practice to use oven drying to attain zero moisture content. According to this research and lab testing, this assumption holds true for compressive strength and splitting tensile strength. However, the pressure tensile strength results decreased sharply for the specimens that had been oven dried. Due to this phenomenon, the oven dried specimens will be discussed separately from the others.

Microstructure of Oven Dried Specimens

When concrete is dried at a rapid rate, not only is the free moisture content reduced to almost zero, but the microstructure is changed at the same time, leading directly to changes in the mechanical properties of the concrete. Test results confirmed that oven drying generated significant tensile strength loss, which may be attributable to damage of the material's microstructure in the capillary porosity domain.

It is well known that hardened cement-based materials are very sensitive to hydric conditions. Desalutation, desorption, and dehydration phenomena associated with drying may generate damage such as microcracking, capillary porosity evolution, fine pore collapse, and mineralogical transformation. Thus, the removal of evaporable pore water may introduce significant degradation of the pore structure (Galle 2001).

It is widely known that gypsum dehydration begins around 80^{o}C and that the initiation temperature for decomposition of ettringite is about 60^{o}C. Drying is responsible for the structural and physical collapse of hydrates like monosulfoaluminate (AFm) and the Aft phase. The temperature at which the decomposition of C-S-H initiates is not well established but C-S-H is partially dehydrated at 105^{o}C. Concrete pore structure is thus affected.

Previous studies have already suggested that, during drying at 105 ^{o}C, capillary effects are associated with hydrostatic stresses generating damage that can alter the pore structure primarily by rearranging the hydration products. In other words, it is considered that the induced stress is related to surface tension in the fine pores and consequently an increase of the volume of larger pores (M. Moukwa 1988).

Mercury intrusion porosimetry (MIP) has been used for a long time as a convenient means for porous space investigation. C. Galle's work examined the cumulative intruded pore volume and pore accessing diameter distribution for different drying methods and concluded that oven drying is the most damaging preparation method for hardened cement paste pore structures. For concrete, there is an additional damaging effect due to the aggregates, for which thermal expansion may be very different from that of the hardened cement paste. The comparison of pore access diameter for different types of drying methods and different types of cement are shown in Figure 5-1.

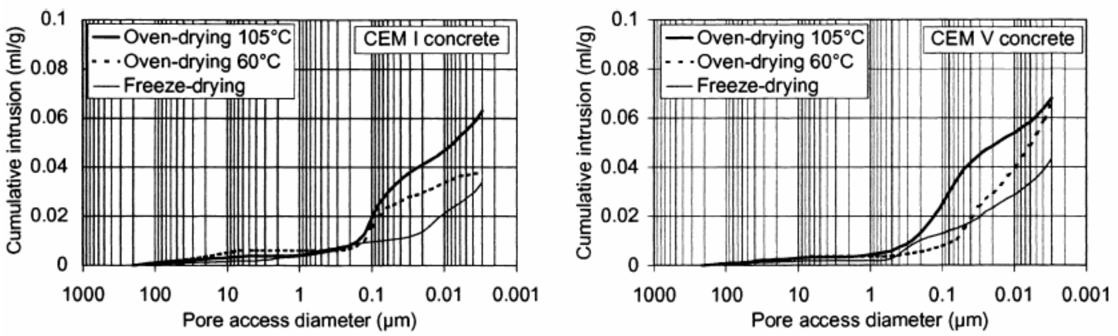

Figure 5-1. Drying technique influence on cumulative intruded pore volume (W/C =0.43) (Galle 2001)

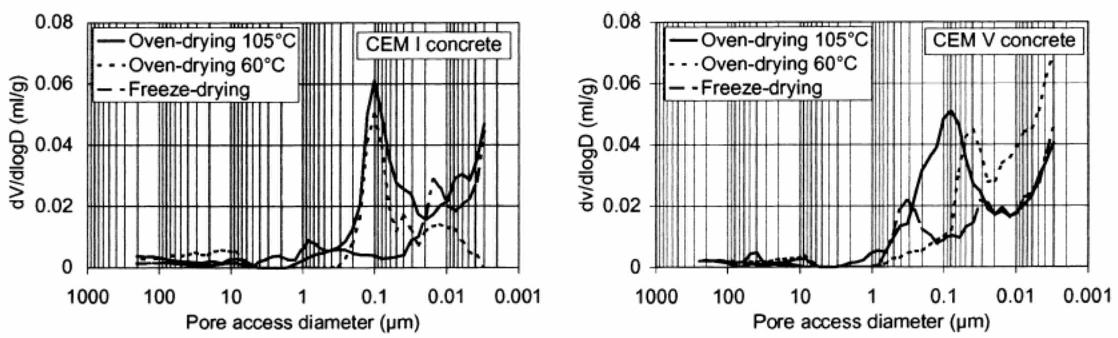

Figure 5-2. Drying technique influence on pore size distribution (W/C =0.43) (Galle 2001)

Galle's experimental results showed that oven drying is responsible for a large increase in capillary porosity that can be attributed to capillary stress, cement hydrate (ettringite, Afm, C-S-H) desiccation and potential microcrack generation related to internal thermohydric stress.

The MIP method is not a truly accurate method in an absolute sense, since it is necessary to assume that larger pores can be intruded from the outside without the mercury having to penetrate through smaller pores first. But, this method is still an effective and convenient way to compare the inner pore structure of cement based materials in a relative sense.

Strength Testing

All of the specimens used for oven dried testing were subjected to 28 days of standard immersion curing and 28 day of air curing under ambient laboratory conditions. The specimens were then placed directly into a drying oven for 14 days at a temperature of 110 ± 5 °C. All specimens were tested immediately upon removal from the oven to prevent rehydration.

Test Results

The test results for all specimens have already been presented in Chapter 4. Here, only the data related to specimens subjected to oven drying, 28 days standard moist curing, and 28 days moist curing followed by 28 days ambient curing are given for comparing the strength change. Test data is shown in Tables 5-1 and 5-2.

Table 5-1. Comparison of compressive strength and tensile strengths (W/C=0.45)

Testing Condition	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Pressure Tensile Strength (MPa)
Oven Dried	63.17	4.37	4.70
28 SMC	58.68	4.12	7.84
28 SMC / 28 Ambient	54.37		

Table 5-2. Comparison of compressive strength and tensile strengths (W/C=0.65)

Testing Condition	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Pressure Tensile Strength (MPa)
Oven Dried	41.48	3.03	3.81
28 SMC	39.51	2.86	5.44
28 SMC / 28 Ambient	33.74		

The test results indicate that both compressive strength and splitting tensile strength increased significantly due to oven drying. For the 0.45 water/cement ratio concrete, the compressive strength increased 16.2%, compared to the standard moist curing condition.

Compared with the 28 day moist curing / 28 day ambient curing specimens, the compressive strength and splitting tensile strength increased 7.7% and 6%, respectively. The pressure tension test, on the other hand, exhibited a strength decrease of 40%.

For the 0.65 water/cement ratio, compressive strength increased 23%, compared with the standard moist curing condition regime. Compared with the 28 day moist curing / 28 day ambient curing specimens, the compressive strength and splitting tensile strength increase 5% and 6. %, respectively. In this case, the air pressure tension test showed a strength decrease of 30%.

The comparison between the oven dried specimens and the 28 day moist curing / 28 day ambient curing specimens is shown in Figure 5-3.

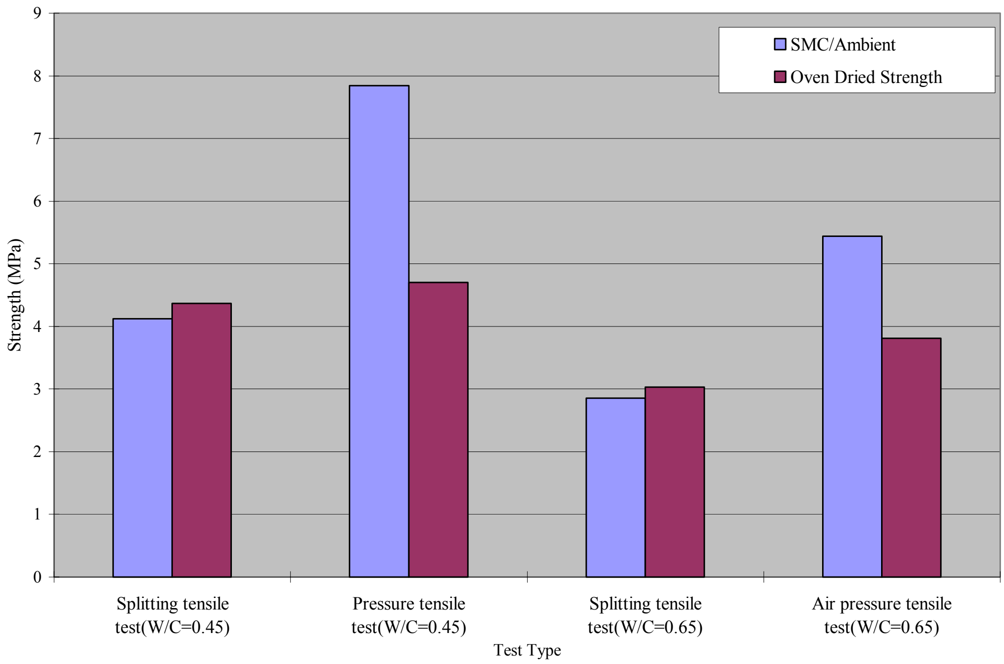

Figure 5-3. Comparison of splitting tensile and pressure tensile strength for oven drying

The comparison of strength change among different type of tests is shown in Figure 5-4. This comparison is also based on the 28 day moist curing / 28 day ambient curing specimens.

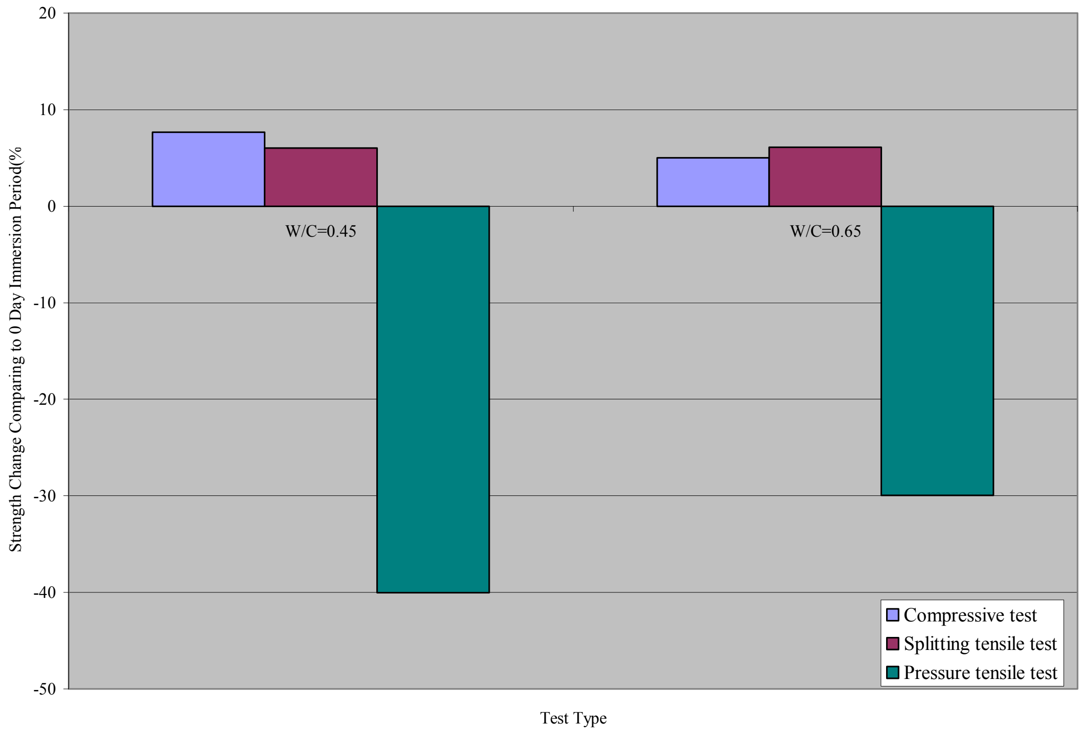

Figure 5-4. Comparison of strength change due to oven drying

Paradox of Oven Dried Specimen Properties

The difference in results between the three tests leads to a number of important questions. What happened to the pressure tension testing results? Why is there a significantly different trend in strength change between pressure tensile strength testing and splitting tensile strength testing or compressive strength testing?

When there is significant moisture present in the concrete, all of the tests exhibited the same trend. But, for the oven dried specimens, pressure tension testing showed a completely different trend than the other two, even though everything was the same for the three test types. Even the pore structure change was the same under oven drying. What lead the pressure tension test to produce this response?

What Happened to the Pressure Tension Testing?

The principals of the pressure tensile strength test have been previously discussed in Chapter 2. Bridgman provided the explanation for the basic mechanism of the test. Application of an axisymmetric pressure to a cylindrical specimen is equivalent to a hydrostatic pressure applied to the specimen plus an applied axial tensile stress of the same value.

As the concrete is permeable to water or air, the specimen may be pushed apart from within due to internal pore pressures. Based upon this assumption, it can be stated that concrete is strong in compression unless the loading medium enters the concrete, in which case the concrete fails in tension. In other words, subjecting concrete to water pressure is an exceptional type of loading and is not compression at all, but actually tension. Then, the original theory that concrete is strong in compression is left intact. However, it seems to be not so simple. Consider what would happen if fluid pressure were applied to the curved surface of a solid cylinder of material, such as glass or metal, other than concrete? It is clear that no fluid or air can enter the glass or metal. Unfortunately, the same thing happened. Percy Bridgman finished these tests in 1912 and the tests results showed that, for a range of brittle and ductile materials, the specimen behaved just as though its ends had been pulled apart. Then, the previous assumption is weakened, that the pore structure and the permeability were not the critical key for this phenomenon, although they may have some effect on the fracture strength.

Is this analysis always right? Is it reasonable to assume that the pore structure and permeability are not the critical keys for the pressure tension test under any condition? However, this seems not so simple again. Consider what specimens Bridgman used, it is easy to find that all the specimens used for pressure tension testing had a general pore structure. This means that most of the pores in the specimens are independent and it is not easy for the pores to connect with each other, at least not extensively. When subjected to a water or gas pressure on the specimen's curved surface the water or air could not easily enter the concrete specimen, to say nothing of the other materials such as glass or metal, which have finer pore structures or waterproof surfaces. Another consideration is that all of the tests were performed over a very short time interval, no more than a few minutes, so the water or the gas could not enter the concrete fully.

What about the oven dried specimens? The pore structure of the concrete specimens has been altered after being oven dried. It confirms that oven drying generates significant damage to the microstructure in the capillary porosity domain. As previously discussed, the cumulative pore volume and average pore diameter are larger. Also, some hydrate components decompose and many microcracks appear inside of the concrete.

Under this condition, not only are pore sizes bigger but they also become connected by the microcracks. When pressure was applied to the specimen's curved surface, the gas could enter the concrete very quickly. Because the directions of the microcracks in the specimen are random, after being loaded the microcracks can develop in any direction. But, concrete is not a uniform material. The pore and microcrack distribution are not evenly distributed, which will lead to the rate a gas entry into the concrete and the microcrack development being uneven. Then, there will be a pressure difference inside the concrete.

Also, there is still space in the tester body between the cylinder and the inner sleeve wall. The cylinder will swell a little before its fracture, which will enhance the damage to the cylinder inside. At this time, the main macro stress still could be seen as tension until fracture occurs. At the point of fracture, the picture will definitely be different. Because the gas inside the concrete will accelerate the development of microcracks, the last fracture mode will not be simple tensile fracture. It will be a composite fracture. The concrete will fracture as if an explosion happened. The concrete specimens will be broken into fragments, which was what happened in the lab testing. Compared with other test fractures, the different fracture modes could be identified easily, as shown in Figure 5-5.

Figure 5-5. Comparison of fracture mode between specimens with moisture content and specimens that were oven dried (pressure tensile testing)

Another question is the difference between compression testing, splitting tension testing and pressure tension testing of the oven dried specimens Most importantly, why did the oven drying not affect the compressive strength and splitting tensile strength? Actually, the different fracture mechanism is the key to this question. In Chapter 2, it was mentioned that heat or high temperature will increase the tested strength of concrete. Under compressive stress, the cement gel is the main source of strength in concrete, the pore structure does not have much affect. Also under compressive stress, most of the microcracks will close and not affect the resulting strength. But, the concrete's brittleness will increase and the fracture will become more sudden after being oven dried. This change in fracture mode can be seen in Figure 5-6.

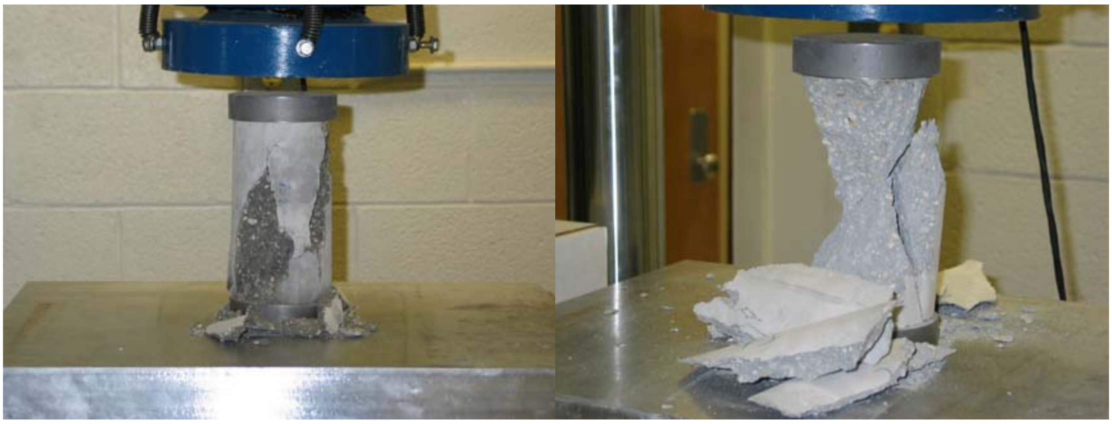

Figure 5-6. Comparison of fracture mode between specimens with moisture content and specimens that were oven dried (compressive testing)

For the splitting tensile strength testing, it also has been mentioned that in contradiction to concrete failure under direct tensile loading, in the splitting test the major part of the coarse aggregate particles are usually broken along the surface of failure. This may be due to the fact that the tensile stresses reach their maximum values in the splitting specimen within a narrow strip along the central vertical plane. This is also why the pore structure and moisture content do not affect the testing strength too much. However, the concrete's brittleness will increase and fracture will be very sudden after being oven dried. This can be seen in Figure 5-7.

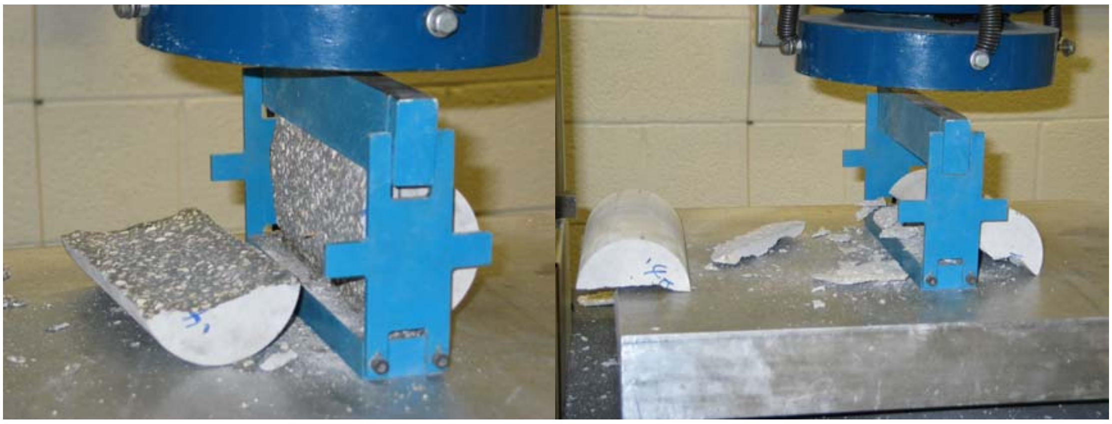

Figure 5-7. Compariso of fracture mode between specimens with moisture content and specimens that were oven dried (splitting tension testing)

Summary

Oven drying generates important damage to the concrete microstructure in the capillary porosity domain and this changes the fracture mode in the pressure tensile strength test. This also leads to a relatively lower strength in the pressure tension test. If the gas was replaced with water as the loading media, this phenomenon may change. At least, the strength should not decrease as much because the water can not enter the concrete as easily and the water will change the moisture content of the specimen. Further research is needed to confirm this hypothesis.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

The effects of concrete moisture content on the mechanical properties of concrete were explored in this research. Testing results, data analysis, observations and recommendations were given.

Conclusions

1. Moisture content in concrete does have a significant effect on the mechanical properties of concrete.

2. Moisture content in the concrete will decrease the compressive strength and pressure tensile strength, but have a much lesser effect on the splitting tensile strength.

3. Oven drying increases the compressive strength and splitting tensile strength, but decreases the pressure tensile strength sharply.

4. Oven drying generates significant damage to the concrete's microstructure and changes the fracture mode exhibited by the pressure tension test.

5. For concretes that are oven dried or that exhibit heavily damaged microstructures, the pressure tension testing appears to be more sensitive to the extent of damage.

Recommendations

1. The exact effects of moisture content in concrete needs to be examined and quantified in future research. The research presented herein only analyzed the trend of the effects and did not investigate the exact relationship between moisture content and mechanical properties of concrete.

2. Theoretical work and numerical models are needed in order to simulate why and how the moisture content affects the mechanical properties of concrete.

3. Chemical property changes resulting from the moisture content should also be examined, related to their affects on the mechanical properties of concrete.

4. The pressure tension test procedure needs to be enhanced, including improvements to the load rate control, before it can be accepted as a standard method for tensile strength testing.

APPENDIX
DATASHEETS

In this appendix, all the data have been collected during the laboratory specimens testing were provided.

Table1. Batch compressive strength statistical analysis data

Batch	1 (MPa)	2 (MPa)	3 (MPa)	4 (MPa)	5 (MPa)
Batch 1 (W/C=0.45)	55.57	52.08	53.32	51.39	52.89
Batch 2 (W/C=0.45)	55.55	57.70	55.98	54.27	54.90
Batch 1 (W/C=0.65)	38.73	34.33	33.82	33.98	36.06
Batch 2 (W/C=0.65)	33.22	31.92	31.26	31.51	31.75

Table 2. Compressive strength testing data (W/C=0.45)

Immersion Period	1 (MPa)	2 (MPa)	3 (MPa)	4 (MPa)
0 Day	57.41	58.76	55.23	63.31
1 Day	53.65	56.25	56.95	60.03
3 Day	52.20	56.65	58.24	58.34
5 Day	49.94	53.12	59.50	55.83
7 Day	53.29	58.84	55.94	56.63
14 Day	53.07	52.69	58.24	57.91
14 Day Oven Drying	62.30	61.92	65.57	62.87

Table 3. Compressive strength testing data (W/C=0.65)

Immersion Period	1 (MPa)	2 (MPa)	3 (MPa)	4 (MPa)
0 Day	43.54	41.00	36.24	37.25
1 Day	37.15	38.90	35.17	30.97
3 Day	32.61	37.04	35.40	31.18
5 Day	34.45	33.45	32.95	31.52
7 Day	37.42	34.46	32.17	31.17
14 Day	37.61	37.08	33.34	28.00
14 Day Oven Drying	40.50	42.97	40.57	41.89

Table 4. Splitting tensile strength testing data (W/C=0.45)

Immersion Period	1 (MPa)	2 (Mpa)	3 (Mpa)	4 (Mpa)
0 Day	4.28	4.44	3.88	3.88
1 Day	4.11	3.95	4.01	3.05
3 Day	3.37	3.34	4.52	3.68
5 Day	3.66	2.99	3.37	3.71
7 Day	3.43	3.56	3.50	3.64
14 Day	3.25	4.55	3.10	2.76
14 Day Oven Drying	4.75	4.23	4.65	3.85

Table 5. Splitting tensile strength testing data (W/C=0.65)

Immersion Period	1 (MPa)	2 (Mpa)	3 (Mpa)	4 (Mpa)
0 Day	2.99	3.01	2.72	2.70
1 Day	2.68	2.53	2.44	2.39
3 Day	2.00	2.28	2.91	2.25
5 Day	3.03	2.56	1.83	2.60
7 Day	2.86	2.55	2.46	2.50
14 Day	2.68	2.72	2.46	2.52
14 Day Oven Drying	2.84	3.28	2.84	3.17

Table 6. Pressure tensile strength testing data (W/C=0.45)

Immersion Period	1 (MPa)	2 (Mpa)	3 (Mpa)	4 (Mpa)
0 Day	8.01	7.79	7.72	7.86
1 Day	7.14	7.24	7.95	7.14
3 Day	7.53	7.14	6.99	7.23
5 Day	6.25	6.60	6.81	6.42
7 Day	6.27	6.46	6.27	6.59
14 Day	6.48	6.35	6.39	5.39
14 Day Oven Drying	4.47	4.83	4.70	4.81

Table 5. Pressure tensile strength testing data (W/C=0.65)

Immersion Period	1 (MPa)	2 (Mpa)	3 (Mpa)	4 (Mpa)
0 Day	5.43	5.68	5.39	5.26
1 Day	5.38	5.44	4.88	4.85
3 Day	5.68	5.08	5.46	4.84
5 Day	4.01	5.46	5.36	4.63
7 Day	4.97	5.20	5.14	5.01
14 Day	4.85	5.15	4.71	5.25
14 Day Oven Drying	4.13	3.67	3.66	3.79

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