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Effect of moisture content on compressive and split tensile strength of concrete

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The aim of this study is to evaluate the moisture effect on the strength of concrete specimens that has completely cured. This study is also aimed to develop relations that can be used to determine the properties of concrete with different moisture contents that are normally experienced in outside conditions. Numerous compressions and split tensile tests are performed. In order to better understand the results obtained from mechanical tests, a simple empirical formula is suggested that accurately fits experimentally measured sorption data for concrete specimens. Analysis of the collected test results suggests that the moisture content in concrete does have a significant effect on the compressive strength of concrete, but has a much lesser effect on the split tensile strength. As the specimen degrees of saturation increased, the compressive strength fell. However, at nearly saturated condition, an increase in compressive strength can be found.

Keywords: Concrete, Moisture content, Compressive strength, Split tensile strength

Concrete is a construction material that is widely used in many different structures including houses, commercial buildings, roadways, underground structures, and waterfront structures. These structures are dynamic systems subjected to continuous changes in moisture content. More importantly, parts of these structures are exposed to extreme environmental conditions such as with bridge piers, dams, and waterfront structures. They experience variations in the tidal zone, hence continuous changes in the moisture content[1].

Concrete contains a great number of voids comprising gel pores, capillary pores and flaws. At the two extremes, these voids may either be full (filled with water when the concrete saturated) or empty (filled with air) when the concrete is fully dry[2,3]. Under intermediate conditions, a mixture of water, water vapor and air may be present. The change in moisture content caused by wetting and drying has a considerable effect on the mechanical properties of concrete[4]. This is important for the design of concrete structure. The strength of concrete is one of the basic engineering indicators in the design of concrete structures, but in practice the influence of moisture on the strength of concrete is not usually taken into account[5].

Mechanical tests have been used to evaluate the variations due to moisture difference. From literature, it can be found that there exists uncertainty on the moisture effects on strength and elastic modulus. Results on compressive strength variations, which are reported in the literature, are ambiguous. It is well known that the compressive strength of concrete in water is 10-20% smaller than in air[6]. Studies have shown progressive increase[2,7,8] or decrease[1,9] in axial strength as moisture content decreased. However, two phases are sometime present: a decrease in strength in the range 100% to 50% of moisture content followed by an increase for lower content[10]. The variation of elastic modulus with relation to moisture content has been observed with axial compressive tests[11-13]. Haque and Cook[14] found that there was no variation down to 50% relative humidity. On the other hand, Brooks and Neville[2] observed a 7% decrease was measured for a concrete under 60% relative humidity compared with the same concrete wet cured for 56 days. A 25% decrease was also observed by Burlion ***et al.***[15] for a concrete stored at 60% relative humidity.

Although most researchers have found a compressive strength increase on drying, data have been reported that support either strength gain or loss upon drying for the cases of tensile and flexural strength. Abrams[16] reported a general loss of flexural strength upon drying, while Fitzpatrick[17] and Pihlajavaara[7] have both reported flexural strength increases upon drying. Cook and Haque[18] reported that wetting reduced the tensile strength.

There have been various discussions about the reason for the moisture dependency of mechanical behavior of concrete. Representative examples of the

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mechanism are as follows: (i) pore water pressure helps separation at the tip of micro-cracks decreases because incompressible water gets wedged into the cracks[4], (ii) when concrete loses water it shrinks, and when it gains water it swells. Whenever these volume changes are not uniformly distributed across a section, differential volume change strains and/or stresses are generated, exactly as in the case of thermal stresses[1], (iii) water-filled capillaries form menisci upon drying, and the water pressure in the capillaries falls to less than atmospheric, thus creating an internal "suction", this pressure acts in the material like an isotropic pre-stressing and leads to a stiffening effect[10], and (iv) the surface energy that forms new micro-cracks decreases because moisture adheres to the surface of micro-cracks[6]. However, no consensus has been reached. To account properly for the influence of moisture content on the mechanical properties of concrete, the mechanism that is involved has to be clarified.

The objective of present study is to evaluate the moisture effect on the mechanical behavior of concrete and to develop relations that can be used to determine the properties of concrete with different moisture contents. A number of compressions and split tensile tests were carried out.

Concrete environments and pore structure

The main components of concrete are water, cement, fine and coarse aggregate, which when hardened are represented as mortar, coarse aggregate and pore matrix. The mechanical properties of hardened concrete depend on the characteristics and the volume fractions of these components[19,20]. Typical phases of hardened concrete are represented by mortar, aggregate, and void (Fig. 1). The capillary pores can be described as space originally occupied by mixed water that hydration of cement grains can continue in such pores, while the gel pores, sometimes called as "micro-pores", exist in the interlayer spaces within the clusters of the calcium silicate hydrate (C-S-H) sheets. In addition to capillary and gel pores, voids caused by entrapping or entrained air will be found in hardened cement paste.

In concrete, the water is globally present in three different forms, namely chemically bonded water, physically bonded water and capillary (free) water[21]. Figure 2 shows the diagrammatic model of the type of water associated with the calcium silicate hydrate. The chemically bonded water is used in the hydration process and consists of about 25 wt.% of the cement at complete hydration. It is an integral part of the structure of the various hydration products. The physically bonded water (about 15 wt.% of the cement) is water bonded to the solid material by adhesive forces. Free water is water which is beyond the range of solid surface forces and is considered to behave like in bulk water[22].

The chemically bonded water is not lost in drying, and it can only be released when the hydrates decomposed on heating (>1,000°C). It also does not contribute to any transport phenomena[23]. The distribution of the physically bonded water and the free water in porous materials strongly depends on the moisture content. The moisture content of the concrete is defined as the volume of (free and physically bonded) water over the effective pore

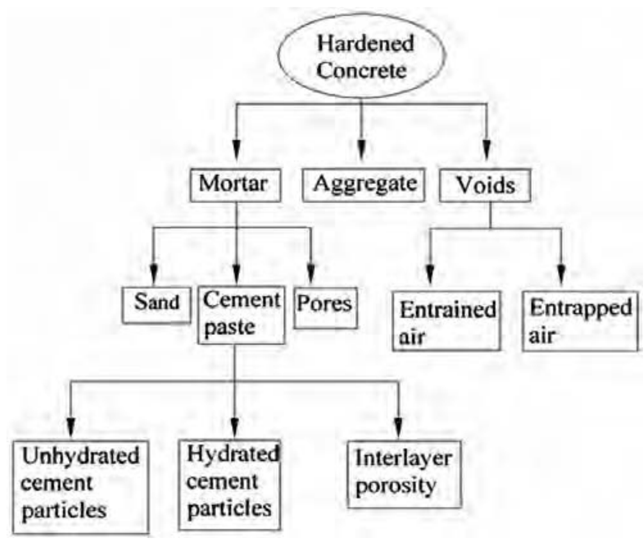

Fig. 1—Typical phases of hardened concrete

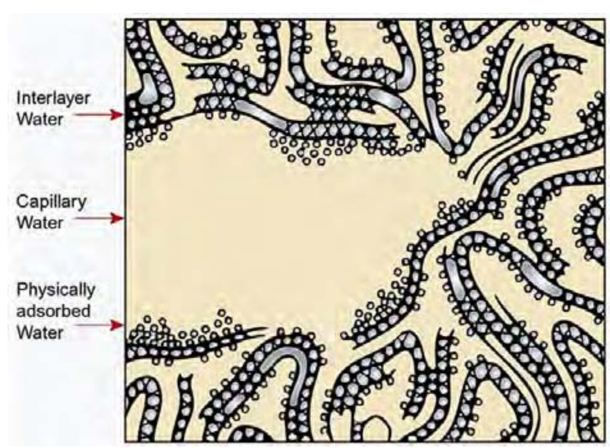

Fig. 2—Diagrammatic model of the water type in concrete (adapted from Metha and Monteiro[22])

volume[21]. At low moisture content (0-45%), the water in the concrete is present only as physically bonded water. The distribution of this physically bonded water is unknown[6]. It depends on the microstructure of concrete and especially on the structure of the calcium silicate hydrate particles. For moisture content greater than 45%, the fluid film in the capillary pore thickness so that the water in capillary pore systems becomes continuous. Stable water-air interfaces are established in the capillary pores and the water becomes capillary bond. With an increase in water film thickness, the outer water molecules of the fluid are no longer under the influence of adhesive forces exerted by the solid surfaces[24]. The water is free water. Based on Huang and Aboutaha[23]'s results, approximate values of the total content of pore water and the content of capillary and absorbed water in concrete with regard to the change of relative humidity (RH) are given in Table 1.

Moisture induced stresses

The distribution of moisture in cement-based materials depend on the moisture content (degree of saturation). To understand how the moisture does influence the mechanical behavior of concrete, first the stresses induced by moisture are discussed.

When the vapor pressure over the liquid is equal to the saturation vapor pressure, equilibrium between liquid and vapor exists, equal to the number of molecules returning to the liquid of any given time. This state corresponds to the relative humidity of 100%, or, in other words, vapor pressure is under saturated pressure, evaporation takes place[21]. Capillary tension is linked to the development of curved menisci in the partially saturated pore system. The formation of curved menisci disrupts the static pressure within the pore fluid. As a reaction to the negative pressure (tension) in the pore fluid, compressive develops in the solid microstructure[22].

Table 1—Moisture content in pores with change of relative humidity (RH)

RH (%)	Moisture content (%)	Content of capillary and adsorbed water (%)	Ratio of capillary and adsorbed water
100	100	76	1
90	68	44	0.578
80	55	31	0.408
70	45	21	0.276
60	38	14	0.184
50	34	10	0.131
40	29	5	0.065
30	24	0	0
20	20	0	0
10	14	0	0
0	0	0	0

At an internal relative humidity (RH) below, capillary menisci are not stable[25]. At lower moisture content, disjoining pressure and solid surface tension (Gibbs-Bingham) are believed to active, with solid surface tension becoming predominant as moisture content is continually reduced. The solid surface tension at the interface between the adsorbed water layer and the solid hydration products is a function of the adsorbed layer thickness (as thickness goes down, the tension goes up), which is in turn relative to the moisture content[26].

The surface tension due to absorption of the moisture, disjoining pressures and the capillary tension are difficult to predict quantitatively, since they may occur at similar degree of saturation and their micro-mechanical effects are not yet fully understood. Moreover, the stresses are known to depend only on the degree of saturation but also on the saturation history.

Based on the above review, it can be found that moisture induced mechanical behavior changes are described by more than one mechanism. The appearance of one or another is strongly dependent on the degree of saturation of the concrete. Capillary pressure, for example, becomes important when pore water becomes continuous, whereas disjoining pressure is important at low degree of saturation[27]. Another concern is the activation of the mechanisms are the RH of the concrete, which however is obviously connected with the degree of saturation since the equilibrium between adsorbed water and vapor pressure must exist. Indeed, any change in relative humidity disturbs the equilibrium. Most researchers attribute behavior changes at RH above 40% to the capillary tension. It is assumed that variations in surface energy are the cause of behavior changes at RH below 40%[26], while contrary it some researchers believe this mechanism is active above 40%. Disjoining pressure is also the object of controversy. Some researchers suppose that disjoining pressure is responsible for the changes at high RH, some consider it is operating at low RH, and some completely reject this mechanism.

Experimental Procedure

Materials and specimens

Ordinary Portland cement was used in the production of concrete. The water-cement ratio (*w/c*) was 0.64.

Water was obtained directly from the City of Nanjing drinking water supply. The coarse aggregate with a nominal maximum size of 12 mm was crushed granite with the density of 2700 kg/m^3. Quartz sand with a maximum size of 0.5 mm was used. The *w/c* was higher than 0.42 was chosen in order to minimize the early stages of drying, the possible effects of hydration and endigenous shrinkage on strength and elastic properties measurements[28]. Detailed mix proportions of concrete specimens are given in Table 2.

The concrete was cast in steel molds 1.5 m in length and with a cross-section of 500×500 mm^2. Following casting, the specimens were covered with a plastic membrane to prevent the moisture from evaporation. The specimens were de-molded after 24 h, and then moist-cured in a water tank at temperature of 20°C. At the end of six month period, the specimens were produced by coring of large blocks in order to avoid the side effects as well as aggregate segregation, and generally, to avoid the non-homogeneity. Concrete cores were cut and grinded smooth to produce 58-mm-diameter cylindrical specimens of 25 mm in thickness for the tests. Over 40 specimens were prepared for compressive and split tensile tests.

Compression tests

Each group of specimens were underwent compressive tests, which were performed in a closed loop, servo-controlled MTS test machine as shown in Fig. 3. Before testing, the ends of each specimen were made parallel by grinding. A personal computer, serving as a data acquisition system, was used to read the data. In the test process, displacement control was adopted and the loading rate was 10 kN/min. The equation used for the computation of compressive strength was

$$_{c} = \frac{P}{A} \qquad \ldots (1)$$

Where P is the load at failure (kN), A is the cross-sectional area of the concrete cylinder (mm^2) and   is the stress at failure (compressive strength).

Splitting tension tests

In the splitting test, a specimen was compressed along the two diametrically opposed generators. To prevent multiple cracking and crushing at the points of loading, the load is distributed through two bearing strips as shown in Fig. 4. Assuming the material behavior is linear-elastic, the geometry leads to a nearly uniform tensile stress along the plane of loading, and the expected rupture mode is the splitting of the specimen in two halves across that plane[29]. In the case of concentrated loads, the maximum tensile stress on this plane can be calculated by:

$$_{t} = \frac{2P}{DL} \qquad \ldots (2)$$

Table 2—Mix proportions of concrete (kg/m^3)

Water	Cement	Fly ash	Quartz sand	Aggregate	Super-plasticizer	Air entraining agent
12	18.8	8	76.9	45	0.2	0.00147

Fig. 3—MTS material system layout

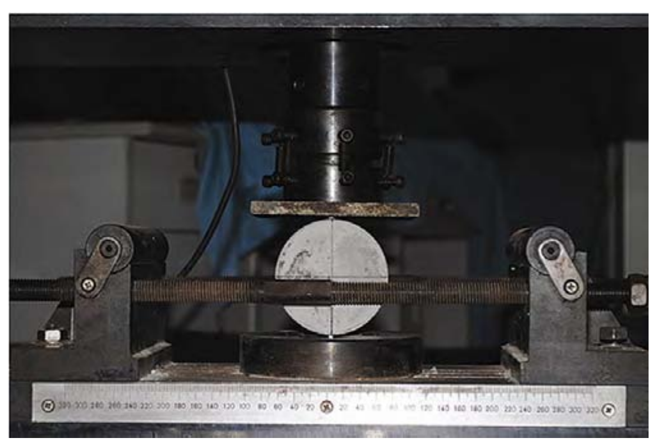

Fig. 4—Split tensile testing system layout

where D is the diameter of the concrete cylinder (mm), L is the length of the concrete cylinder (mm) and $_{t}$ is the splitting tensile strength of concrete.

Specimen preparing for moisture test

During the phase of this investigation, the distribution and concentration of moisture in concrete specimens were manipulated by exposing the specimens to drying and wetting environments for various periods of time. The data collected during this moisture-conditioning period formed and empirical basis for predicting the time required to cause given moisture change under various conditions. As a result of this work, much was learned about the movement of moisture through concrete.

Moisture testing presented a few challenges. It was difficult and cost prohibitive to use moisture sensors for cured concrete specimens, but an accurate way to measure the moisture level in the specimens was needed. The specimens instead were weighed on a scale accurate to the hundredths place. Caution had to be used to prevent errors. All dust had to be removed from the specimen and the scale before each test. The compression and split tension tests were done in conjunction with variable moisture contents.

All concrete specimens were kept in an oven at 105±1°C for 3 days after 180 days of water curing. For oven-drying tests, drying operations (approximately 7 days in duration) were achieved in extremely well-controlled conditions. No heating rates were used for these drying procedures. After drying, samples were stored in sealed containers with silica gel to prevent rehydration.

After drying, seven specimens under test were placed on water reservoir again. Water, at room temperature, was then added to the reservoir. The specimens were then subsequently removed and dried until the moisture content of interest. The test at moisture content just involved drying the surface and immediately testing the specimen while its temperature remained 20°C. This is important because the evaporative effect of water will cool the specimen. The mass of the specimen was measured at regular intervals using a balance accurate to one hundredth of a gram. The amount of water taken in from the specimen was calculated and normalized by the cross-sectional area exposed to water. The percentage of moisture content was found through interpolation by finding the mass of the specimen oven dried. The moisture content is 0% in an oven dried specimen and 100% in a saturated specimen.

The moisture content of concrete specimens can be reflected by the degree of saturation. Degree of saturation was calculated as[8]:

$$S_{\mathrm{r}} = \frac{W - W_{\mathrm{d}}}{W_{\mathrm{w}} - W_{\mathrm{d}}} \times 100\% \qquad \ldots (3)$$

where S_{r} is the saturation of the specimen (%), W is a mass of the specimen (g), W_{W} is the specimen water saturated mass (g), and W_d is the dried mass of a specimen (g).

Test procedures

After the various soaking periods were complete (0 min, 30 min, 90 min, 200 min and 5 days), the concrete cylinders were tested using two different strength testing procedures: the compression tests and the split tension tests. For each set of moisture content specimens, all three testing procedures were done in essentially the same time, before a moisture content could change significantly between tests.

Results and Discussion

Water transport in concrete

In order to better understand the results obtained from mechanical tests, it was necessary to relate the experimental observations to the body of knowledge concerning water transfer in concrete materials. Although this is an interesting and valuable field of study, which is closely related to the primary focus of this present work, it is extremely complex. Within the scope of this paper it is possible to present only a basic description of the phenomena involved, to discuss some of the applicable theories, and to present some examples of experimental findings.

Moisture transport through concrete is more complex than many other porous media because of the wide range of pore sizes present in the material and the strong interaction between water, water vapor, and the pore system, as well as changes occurring in the pore structure with maturity[30,31]. In field concrete, this problem is compounded by the varying moisture status of the material. In the dry state, pores are empty and water vapor diffusion dominates, while some pores are filled in higher humidity region[32]. These mechanisms make it difficult to predict the water content and moisture migration.

There are three primary mechanisms that control the transport of fluids through concrete. They are permeation (saturated fluid flow under a pressure head), diffusion (fluid flow under a concentration gradient), and capillary suction[33] (fluid flow due to capillary pressures in an unsaturated element). The dominant mechanisms of ingress a short period of exposure (a few hours), especially near partially saturated or unsaturated surfaces, is sorption, defined as the absorption of water by capillary pores and transport by capillary action. Long-term moisture movement is controlled by transport through the gel pores and moisture diffusion, which is driven by a concentration gradient[34-36]. All of these mechanisms are nonlinear functions of moisture content in the material.

Sorption of water in concrete is typically described by Eq. (4)[34],

$$\frac{W}{A} = m\sqrt{t} + m_0 \quad \ldots (4)$$

where W is the volume of water absorbed, t is the immersed time (h), A is the sample surface area exposed to water, m is the sorption factor and S_o is a correction term added to account for surface effects at the time the specimen is placed in contact with the water. Eq. (4) is based on the assumption that the pore structure has a tube-like topology and that the meniscus, formed at the air water interface, is spherical cap. Of course, a random porous material like concrete cannot be accurately modeled as a collection of tubes. The pore surface topology is far more complex so that, as the air/water interface moves through the porous medium, there are many orientations of the local interface which may be stable despite the smallness of the pore size. However, it has not been quantitatively demonstrated how such alternations of the pore structure affect a material's sorption.

It has been suggested that as water is absorbed in concrete, calcium hydroxide is dissolved into the pore solution producing a concentration gradient which diminishes the absorption rate. However, previous results obtained by Martys and Ferraris[32] did not show a significant difference between the sorption of water or the sorption of calcium hydroxide saturated water.

Details of the specimens in sorption tests are shown in Fig. 5. Let us first consider sorption during initial exposure to water. In nearly all cases, we found that total water absorbed increased quickly for a period of a few hours. Not then this high porosity mix is subject to very strong surface effects as the sorption data offsets from zero when t = 0. After a period of about 6 h, the rate of sorption began to noticeably decrease, and the near-zero of moisture change after only a few days.

Figure 6 shows the saturation ratio as a function of exposure time for specimens that were oven-dried to zero moisture content and then immersed. Each data point is the average of seven specimens. The results showed that saturation of concrete specimens during the soaking process could be described by the exponential functions, which are plotted in Fig. 6. From the fitted curve, the formula for the saturation ratio of the concrete during the soaking process can be obtained by Eq. (5),

$$S = S_0 + A_1 e^{-t/m} + A_2 e^{-t/n} \quad \ldots (5)$$

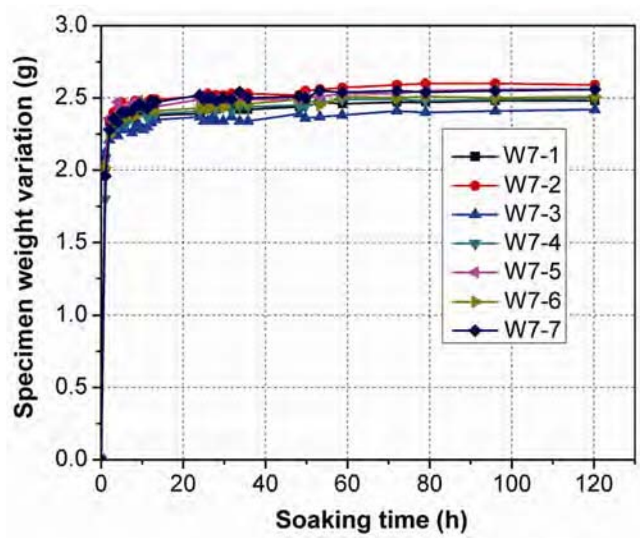

Fig. 5—Variation of specimen weight during soaking process

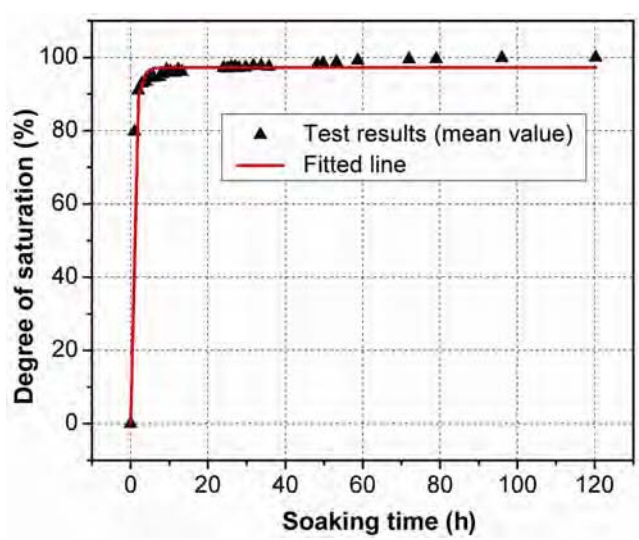

Fig. 6—Variation of degree of saturation ratio during soaking process

where S_0, A_1, A_2, m and n are fitted parameters, which are given in Table 3.

This simple empirical fitting form (Eq. 5) was suggested accurately fits experimentally measured from sorption data for concrete specimens that assume that pores at two different length scales control the sorption. Such correlations proved helpful throughout the work in estimating the length of time required to condition a specimen to selected moisture contents. It is emphasized, however, that this empirically-determined relationship is valid only over the range of times considered in these experiments. Then the saturation ratio of the specimens after immersing in water for different time could be obtained as shown in Table 4.

Effect of moisture content on concrete strength

Compressive strength

Table 5 shows the compressive test results for 15 specimens. The mean values of compressive strength is shown in Fig. 7. The concrete specimens are stronger at lower degrees of saturation and weaker at higher degrees of saturation.

In the range of low degree of saturation, the physical adsorption is the result of the forces of attraction and the molecules or ions in the solid[13]. It can be seen from the test results that, with decreasing degree of saturation, increase surface tension and compressive stress. It should be noted that as only physically absorbed water affects surface tension. At higher moisture content, water starts to fill capillary pores in the concrete, which is outside the range of surface tension. Another hypothetical explanation has been suggested by Wittman[6] that the water absorbed into gel pores lead to a transverse bursting effect in the solid matrix of the concrete and this effect increases with an increase in the external compressive load.

The increase in concrete strength with decreasing saturation in the range of higher saturation ratio (52-92%) is assumed to come from the capillary suction effect leading to an almost isotropic compression of solid skeleton. As a result, the material behaves like a pre-stressed concrete of higher strength. This phenomenon, commonly observed by rocks and glass, is combined with an increase in compressive strength. However, as discussed by Visser[21], the capillary pressure mechanisms bad fit at a low degree of saturation is likely a consequence of the absence of capillary pressure in this low range.

However, at nearly saturated condition (92-100%), an increase in compressive strength can be found. This could probably due to the pore pressure developed in the concrete. The pore pressure is defined as the pressure in the free water in the center

Table 3—The curve fitting parameters

S_0	A_1	A_2	m	n
97.273	-46.963	1.134	-50.285	0.013

Table 4—Saturation ratio of specimens prepared for mechanical tests

Soaking time	0 min	30 min	90 min	200 min	5 days
Saturation ratio	0	52%	87%	92%	100%

Table 5—Effect of degree of saturation on compressive strength

Specimens No.	Degree of saturation (%)	Compressive strength (MPa)	Average strength (MPa)
C1-1		38.7	
C1-2	0	40.9	39.8
C1-3		39.8	
C2-1		33.3	
C2-2	52	32.3	33.4
C2-3		34.6	
C3-1		30.8	
C3-2	87	32.1	32.16
C3-3		33.6	
C4-1		24.6	
C4-2	92	25.4	24.5
C4-3		23.5	
C5-1		27.7	
C5-2	100	29.0	28.4
C5-3		28.5	

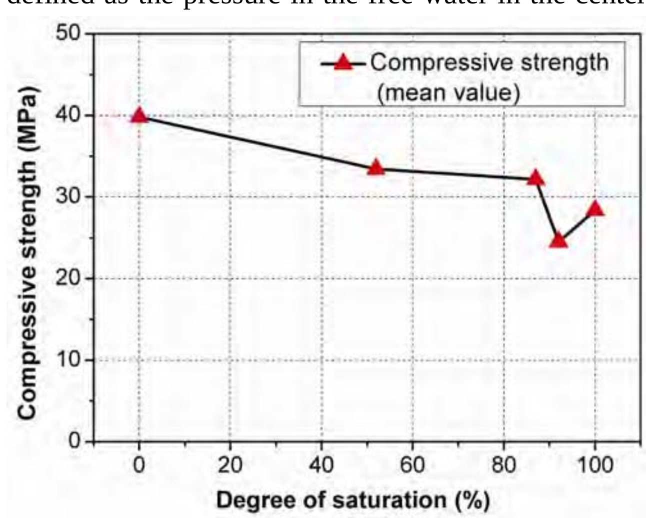

Fig. 7—Effect of degree of saturation on compressive strength (mean values)

of the capillary pores and air bubbles. The increasing compressive load on the concrete specimen during testing develops an increasing internal pressure, not only on solid components of the concrete, but also on the liquid in the pores, trying to squeeze the liquid out of the specimen. Since, however, the migration of the water is not free due to the smallness of the capillary sizes; the hindrance produces a pressure on the contacting pore walls which increases as the external load on the specimen increases. When the concrete specimen is near fully saturated, a small percentage of air in the pores cannot diminish the changes in pore pressure caused by loading. The higher the degree of saturation, the sooner the full saturation will be obtained, therefore the measured compressive strength will be higher.

Split-tensile strength

Table 6 shows the split-tensile test results for 15 specimens. The mean values of compressive strength is shown in Fig. 8. The effect of moisture content on the splitting tensile strength of concrete is not significant. Comparing the strength of totally dry and saturated specimens, split tensile strength increased 4.8%. According to statistical data analysis, the moisture content does not affect significantly split tensile strength. 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.

However, the experimental evidence is somewhat contradictory with reported results for split tensile strengths[7,16]. Since concrete has fairly low diffusion rate, and dried only from the outside, drying too quickly may also induce tensile cracks due to non-uniform drying of the specimen. These cracks do not have much effect on the compressive strength, but will lower tensile strengths[37]. The pore structure of the concrete specimens has been altered after being oven dried. As previously reported by Galle[38], the cumulative pore volume and average pore diameter are larger. Under compressive stress, the cement gel is the main source of strength in concrete; the pore structure does not have much effect. Also under compressive stress, most of the micro-cracks will close and not affect the resulting strength. But, the concrete's brittle will increase after being oven dried[37]. 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 pore of the aggregate particles are usually broken along the surface of failure. This may be due to the fact that the tensile stresses reach the maximum in the split specimens within a narrow strip along the central vertical plane[29,39]. This is why the moisture content does not affect the testing strength too much.

Table 6—Effect of degree of saturation on split tensile strength

Specimens No.	Degree of saturation (%)	Split-tensile strength (MPa)	Average strength (MPa)
W101007		4.14	
W101001	0	3.85	3.98
W101102		3.95	
W101402		3.40	
W101507	52	3.56	3.41
W101002		3.27	
W101202		3.41	
W101204	87	3.68	3.56
W101205		3.59	
W101306		3.74	
W100901	92	3.91	3.83
W101209		3.84	
W101107		4.01	
W101802	100	4.19	4.17
W101206		4.15	

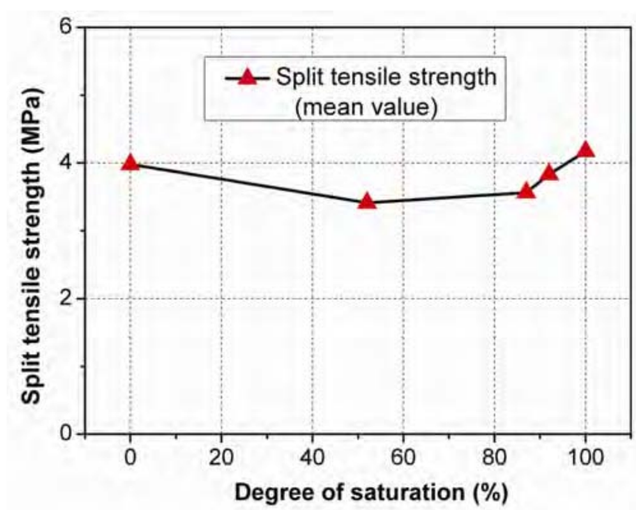

Fig. 8—Effect of degree of saturation on split tensile strength (mean values)

Conclusions

The following conclusions can be drawn from this study:

(i) A simple empirical fitting form (Eq. 5) was suggested that accurately fits experimentally measured sorption data for concrete specimens that assume the pores at two different length scales control the sorption.

(ii) Moisture content in concrete does have a significant effect on the compressive strength of concrete, but have a much lesser effect on the split tensile strength. As the specimen degrees of saturation increased, the compressive strength fell. However, at nearly saturated condition, an increase in compressive strength can be found.

(iii) The exact effects of moisture content in concrete needs to be examined and quantified. The research presented herein only analyzed the trend of the effects and did not investigate the exact relationship between moisture content and strength of concrete.

(iv) Due to the moisture induced stress, the compressive behavior of concrete does influenced significantly by moisture content. Nevertheless, new investigations have to be performed to better understand the role of their porous network linked to the compressive behavior.

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