Water saturation effects on the tensile strength of rocks

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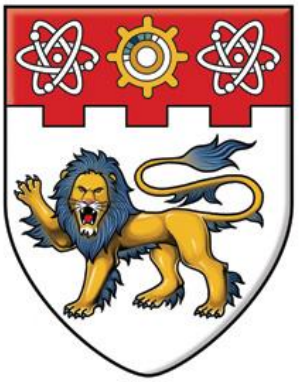
WATER SATURATION EFFECTS ON THE TENSILE STRENGTH OF ROCKS



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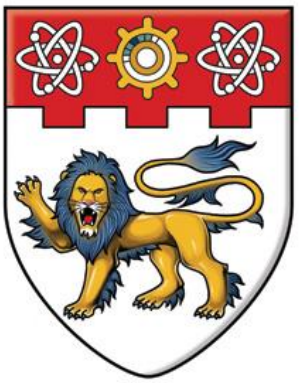
Water Saturation Effects on the Tensile Strength of Rocks



NANYANG TECHNOLOGICAL UNIVERSITY

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ABSTRACT

In the design and construction of underground structures, the tensile strength of rocks is an important parameter to consider. As underground structures are often built below the groundwater table where rocks can be subjected to various degree of water saturation, this study aims to determine the effect of water saturation on the tensile strength of rocks.

Specimens were prepared by molding using hydrocal gypsum cement and some of the finished specimens were kept in oven to obtain dry specimens while others were soaked in water for 1 week, 3 weeks and 10 weeks respectively to achieve different levels of water contents. Brazilian Tensile Tests were conducted on the specimens to determine their tensile strengths.

The test results showed that the tensile strength dropped to nearly half of its dry value after being soaked in water for only 1 week. The tensile strength reduced only slightly further after the specimens have been immersed in water for 3 weeks and 10 weeks. Analysis of the recorded high-speed footage showed that the primary crack initiated at the centre for majority of the tested specimens, hence validating the test results.

This study proved the weakening effect of water on the tensile strength of rocks and hence recommends that the saturated tensile strength should be used for a more conservative design of underground structures.

ACKNOWLEDGEMENTS

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Last but not least, the author would like to express his thankfulness to the staffs of Geotechnics Laboratory and Construction Technology Laboratory, especially to Mr. Koh Sun Weng, Andy and Mr. Cheng Weng Kong, for their great display of professionalism and assistance towards the project. Their dedication has helped ensured the timely availability of tools and equipments required for the experiments and led to the smooth and successful completion of this project.

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1. INTRODUCTION

The tensile strength of rocks has been the subject of research for many decades. Many engineering projects nowadays require extensive understanding of the behavior of rocks under tension. The construction of underground structures such as basements, tunnels and caverns will often result in certain regions of the surrounding rocks being subjected to tensile stresses. As the tensile strength of rocks is known to be much lower compared to their compressive strength, tensile failure is always a probable failure mechanism. Hence, the tensile strength of rocks is an important parameter to consider during the design and construction of all underground structures.

One of the important factors that can affect the tensile strength of rocks is their degree of water saturation. As the construction of underground structures usually goes beyond the depth of the groundwater table, rocks at different depths will be subjected to varying degree of water saturation. Hence, it is also important to understand the effects of water saturation on the tensile strength of the rocks.

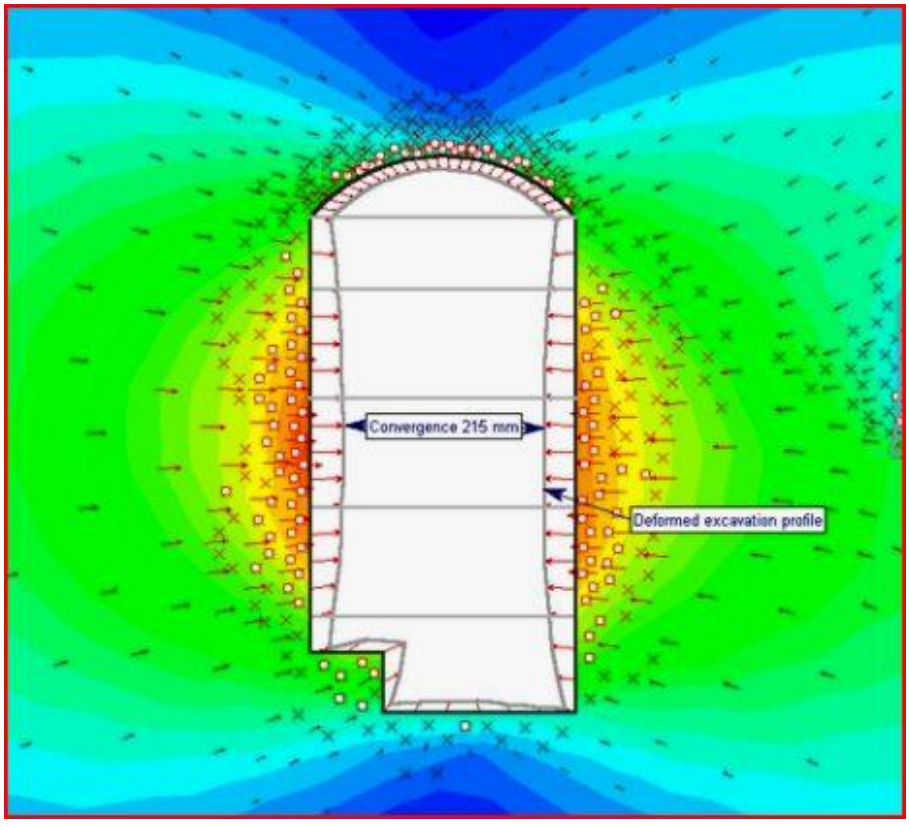

Figure 1 - The stress distribution around a large underground cavern. The red and orange areas indicate regions which experienced high tensile stresses (Hoek, 2006)

In Singapore, for instance, the Jurong Rock Cavern (JRC) Project involves the construction of underground rock caverns at depths of over 100 meters below the seabed of Banyan Basin (off Jurong Island). The first phase of the project alone will consist of 8 kilometers of tunnels and 5 caverns, each about 27 meters high. By the end of Phase 1 of the project, the storage capacity created will be about 1.47 million cubic meters which will be used primarily for the fuel storage (JTC, 2010).

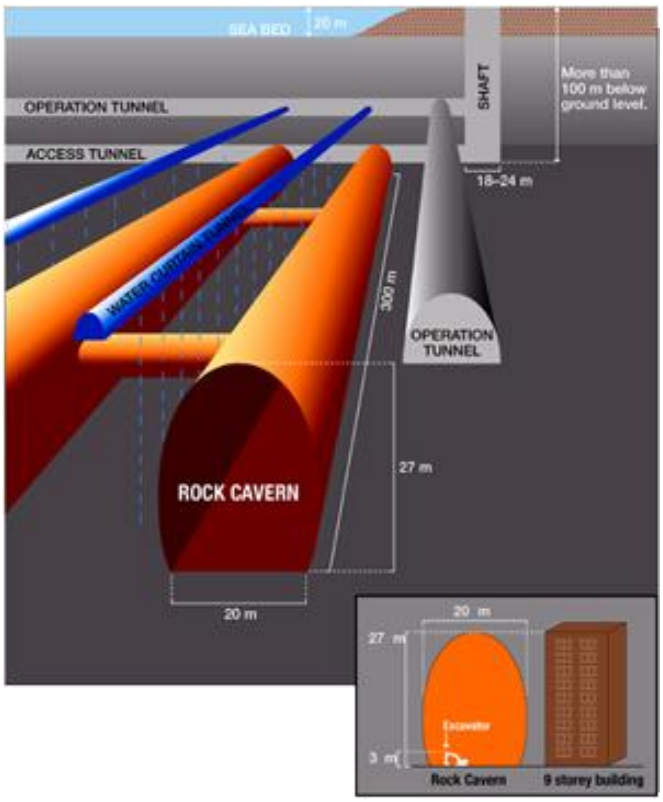

Figure 2 - Jurong Rock Cavern Project in Singapore (JTC, 2010)

Huge underground caverns such as the JRC will result in extensive regions of the surrounding rocks to be subjected to tensile stresses. Furthermore, the whole cavern is constructed at subterraneous depths below the seabed. Hence, a good understanding of the effect of water saturation on the tensile strength of rocks is vital for the structural stability of the entire underground structure.

2. OBJECTIVES AND SCOPE OF WORK

The primary objective of this study is to investigate the effects of water saturation on the tensile strength of rocks. Rock specimens will be immersed in water for different lengths of time to achieve different level of water saturation. Each of the rock specimens will then undergo a Brazilian Tensile Test to determine their tensile strength. The tensile strength values obtained will then be compared to determine the effects of water saturation on the tensile strength of rocks.

Apart from determining the effects of water saturation on the tensile strength of rocks, the experiment also aims to study the effects of water saturation on the Young's Modulus of rock. A high-speed camera will also be used to capture the moment of failure of the specimens. The recorded footage will be analyzed to determine the effect of water on the cracking pattern of the specimens.

In this study, molded gypsum specimens will be used instead of natural rocks due to the lack of rock outcrops and the only natural rocks available were excavated by blasting which have been known to create micro-fractures in the rocks samples. These micro-fractures could be unevenly distributed throughout the rock mass which could lead to inconsistency in the quality of the rock specimens produced. This subsequently can have great effects on the test results obtained during the experiment. Hence to achieve better quality control, specimens will be prepared by molding using hydrocal gypsum cement.

3. LITERATURE REVIEW

3.1. Tensile Strength Test for Rocks

3.1.1. Direct Tensile Test

Conducting direct tensile tests on rock specimens proved to be difficult as well as expensive. The conventional method used for determining the tensile strength of steel bars cannot be applied to rock specimens. This is because securing a rock specimen to the loading machine by gripping at its ends will damage the surface and result in stress concentration at the gripped ends. Hence, rock specimens are most likely to fail at the gripped ends rather than at the middle span of the specimen.

A commonly used method for securing a specimen to the loading machine is by applying bonding media between the specimen and a pair of metal caps or plates which can provide a platform for the loading machine to pull apart the specimen.

A method for conducting a direct tensile test was suggested by International Society for Rock Mechanics (ISRM, 1978). In this method, metal caps are first cemented to both the ends of a cylindrical specimen. These metal caps must have a suitable linkage system for load transfer from the loading machine to the specimen. The loading machine will then exert a tensile load on the specimen until it fails in the middle span of the specimen. The tensile strength of the rock will be calculated by dividing the maximum load at failure by the cross sectional area of the specimen.

One disadvantage of the method suggested by ISRM is it is virtually impossible to conduct such tests on rock specimens with have very high tensile strength. Ramana & Sarma (1987) argued that failure is most likely to occur at the bonding material rather than the specimen itself. Hence, a direct tensile test which secures the specimen to the loading machine by applying bonding media is not practical for rocks with high tensile strength.

Another commonly used method in conducting a direct tensile test is by using dog-bone shaped specimens. The enlarged ends of the specimens allow tensile force to be applied to the specimens without the use of any bonding media. However, the drawback of this method is it requires elaborate sample preparation which is costly and time consuming.

When properly conducted, direct tensile test can give the most reliable values for the tensile strength of rocks. However, due to its cumbersome nature, the direct tensile test is seldom used by researchers to determine the tensile strength of rocks.

3.1.2. Brazilian Tensile test

The Brazilian Tensile test is currently one of the most commonly used method for indirectly determining the tensile strength of rocks. The test involves a diametrical compression of a solid disk specimen which theoretically should induce tensile stresses along the loaded diameter and would ultimately lead to a tensile failure.

The tensile strength of the rock will then be calculated using the equation:

$$\sigma_t = \frac{2P}{\pi LD} \qquad (1)$$

where: σ_t = splitting tensile strength (MPa)

P = maximum applied load (N)

L = thickness of the disk specimen (mm)

D = diameter of the disk specimen (mm)

However, the validity of Brazilian Test has been criticized as specimens often fail due to compression rather than tension. As each specimen is compressed diametrically, compressive stresses are induced at the contact points between the specimen and the bearing blocks or platens. Hudson (1972) conducted Brazilian Test on granite and marble specimens and found that failure always initiated at the loading points when a flat-steel platen was used for loading. The fractures or cracks that are initiated at the loading points then propagate into the specimen along the loaded diameter until the specimen splits into two halves.

As contact stresses at the loading points are the biggest problems in Brazilian Test, attempts have been made over the decades to reduce the stress concentration. Several variations of Brazilian Test have been adopted in the determination of tensile strength of rocks. Two of the most commonly used standards for conducting a Brazilian Tensile Test are published by the International Society for Rock Mechanics (ISRM, 1978) and the American Society for Testing and Materials (ASTM, 2008).

ISRM (1978) suggested the use of curved-jaws as bearing blocks to reduce the contact stresses at the loading points. The recommended radius of the jaws is about 1.5 times the specimen radius.

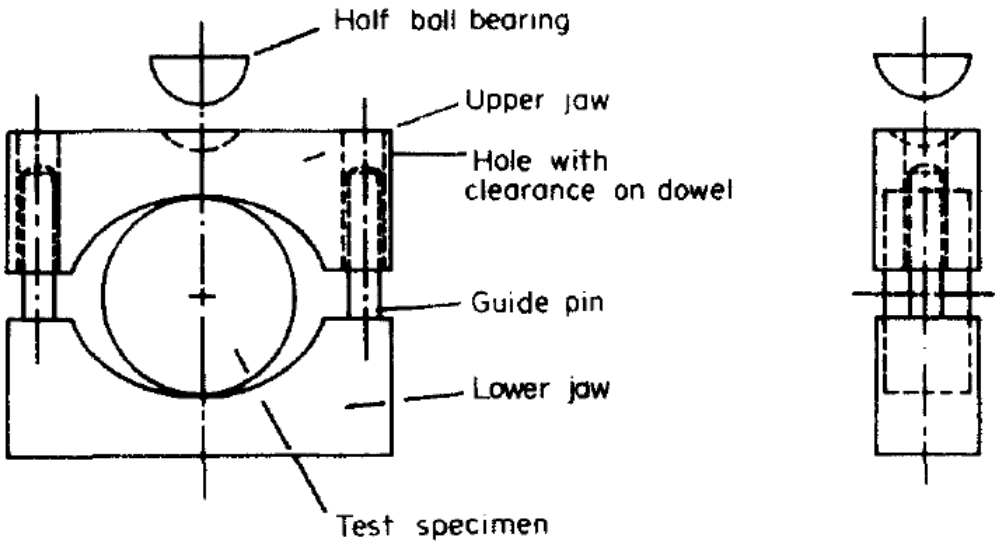

Figure 3 - The loading configuration for Brazilian Tensile Test as suggested by ISRM (1978)

ASTM (2008) allows the use of flat-bearing blocks as well as curved-bearing blocks. In case of the latter, the arc of contact shall not exceed 15^0. This is because the equation used in the determination of tensile strength is based on a line load, so the applied load should be confined to a very narrow strip. Bearing strips are recommended to be placed between the specimens and the bearing blocks in order to reduce the stress concentration at the loading points. The recommended bearing strips are cardboard cushion of thickness 0.01D, where D is the specimen diameter; or up to 0.25 inch thick plywood cushion.

Yu (2009) suggested a modified Brazilian Tensile Test which uses a pair of specially curved spacers that have the same radius as the specimen. The spacers created a perfect contact with the specimen over an arc angle of 20^0. In order to improve the contact condition between the spacers and the specimen, chipboards of 1mm thick were fastened to the steel spacers. As a result of this modification, none of the specimens fail at the loading points and the tensile strength values obtained has a relative error of less than 10% compared to those obtained from direct tensile tests.

3.1.3. Ring Test

The Ring Test is similar to the Brazilian Tensile Test except the specimen is annulus (disk with a central hole) rather than a solid disk. Hobbs (1965) suggested the Ring Test to overcome the shortcomings of the Brazilian Tensile Test. Compared to the Brazilian Tensile Test, the Ring Test has the merit of causing specimen failure due to tension rather than compression. Tension failure would occur at the internal surface of the vertically loaded diameter (the intersection between the internal circumference and the loaded diameter). Hence, compressive failure will not occur at the loading points of the specimen.

However, although the Ring test has the merit of causing actual tensile failure in the specimen, its validity has also been widely criticized. Experiments conducted by various researchers showed that the tensile strength values obtained from the Ring Test were mostly over-estimated.

Mellor (1971) argued that the Ring Test was an unacceptable test for rocks as it gave tensile strength values which were far higher than their uniaxial values. He concluded that this exaggerated estimates of tensile strengths were attributed to the quasi-plastic yielding of the test materials at the critical point. With a steep stress gradient, peak stress is relieved by stable crack growth, and structural failure of the ring, which is associated with unstable crack growth, does not immediately ensue.

Hudson (1969) observed that the tensile strength determined from the Ring Test was a function of the hole size of the specimens – the larger the hole size, the lower the value of tensile strength obtained. However, there exist a 'critical' hole size below which the hole has no effect on the failure load. He explained that the variation in tensile strength with hole size were due to the gradual breakdown of elasticity theory as the hole size is reduced.

Chen (2001) conducted Ring Test on anisotropic rock marble using samples of different hole sizes. His results were compared with those obtained from Brazilian Test and showed that the Ring Test gave tensile strength values which are about 3 to 5 times greater than that of the Brazilian Test. His results also showed the tensile strength values obtained from Ring Test decreases with increasing hole diameter. He concluded that the bi-axial stress state at the centre of the disk will have an influence on the tensile strength of rocks.

3.1.4. Comparison between Brazilian Test and Ring Test

Mellor (1971) made a detailed comparison between Brazilian Test and Ring Test and concluded that the Brazilian Test is still more preferable to the Ring Test. Although the Ring Test has the merit of causing actual tensile failure in specimens, the Brazilian Test has the following advantages over the Ring Test:

1. The Brazilian Test gives a closer approximation to the uniaxial tensile strength.
2. The Brazilian test uniformly stressed a relatively large volume of material to the critical level, whereas the ring test confines the peak stress to a small volume due to the steep stress gradients in the critical zones of the ring.

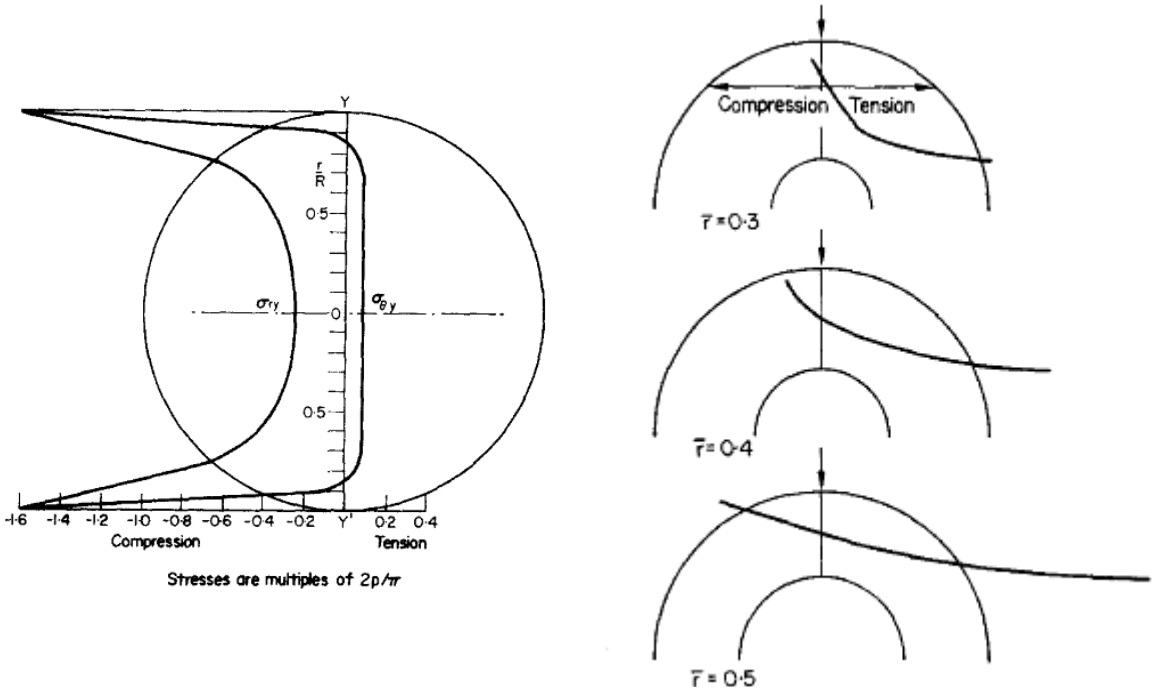

Figure 4 - A comparison of the tensile stress distribution along the loaded diameter between the Brazilian Test (Left) and the Ring Test (Right). The stress distribution is relatively uniform in the Brazilian Test while there is a steep stress gradient which varies with hole size in the Ring Test. (Mellor, 1971)

3. The Brazilian Test is relatively insensitive to inelastic behavior and non-linearity, but the Ring Test is highly sensitive.
4. The solid disk specimen for Brazilian Test is easier to prepare to acceptable tolerances whereas preparation of specimen for the Ring Test would require double the amount of work.

3.2. Effect of Water Saturation on Rock Strength

3.2.1. Compressive Strength

The Unconfined Compression Strength (UCS) is the standard in defining rock's compressive strength and is obtained through the uniaxial compression of a cylindrical specimen until failure in an unconfined state. The maximum applied compressive load at failure is divided by the cross-sectional area of the specimen to obtain the rock's UCS.

The effect of water saturation on the compressive strength of rocks has been widely studied by various researchers. Generally, the compressive strengths of rocks are known to decrease with increasing water content.

Hawkins & McConnell (1992) studied the loss in UCS between dry and saturated samples of 35 British sandstones. Their work demonstrated a large variation in sensitivity to moisture content throughout the different sandstones studied. The loss in UCS ranged from 8% in sandstones which have relatively high quartz contents to 78% in clay-rich sandstones. They also observed a sudden loss in strength at low moisture content with 80-90% of the strength reduction occurred before the moisture level reached about one-third of the moisture content at saturation. They concluded that the sensitivity of the sandstones to change in moisture content is primarily controlled by their mineralogy, particularly the relative proportion of quartz to clay minerals.

Some of the suggested mechanisms in strength reduction caused by the presence of water are (Waltham, 2009):

- Water interrupts the bonding between minerals, and allows the break-up of clay cements in some sedimentary rocks
- The presence of water increases pore water pressure which acts in opposition to confining stress. This as a result reduces the effective normal stress which consequently reduces the confined shear strength
- Water reduces the cohesion and friction in rocks

There is a strong correlation between the unconfined compressive strength and tensile strength of rocks (Zhang, 2005). The ratio of compressive strength to tensile strength of rocks (UCS/T_o) are normally around 10 but they can range from 8 to 20 depending on the rock types. This correlation is useful as it allows the tensile strength of rocks to be predicted from its unconfined compressive strength. Hence, understanding how water saturation affects the compressive strength of rocks can give insights on how it will affect their tensile strength.

3.2.2. Tensile Strength

Just like the compressive strength, the tensile strengths of rocks are also known to decrease with increasing water content.

Vutukuri (1974) studied the effect of different liquids on the tensile strength of limestone. Ring-shaped limestone specimens were soaked in different liquids including water, glycerine, ethanol, nitrobenzene, and several other types of organic solvent. After soaking for 20 hours, a ring test was immediately conducted on each specimen to determine its tensile strength. From his experiment results, limestone soaked in water showed the greatest decrease in tensile strength compared to the other liquids. He argued that this was due to water having the highest dielectric constant and surface tension compared to the other liquids and the greater the dielectric constant and surface tension of the liquid, the greater the decrease in the tensile strength of limestone.

Dube (1972) investigated the effect of environmental humidity on the tensile strength of sandstones. Several groups of specimens were kept in different desiccators with different degrees of relative humidity before Brazilian Tensile tests were conducted to determine the tensile strength of each of the specimens. It was found that humidity has a pronounced effect on the strength of sandstones and the strength reduction depends upon the porosity and the mineral composition of the sandstones. Sandstones with higher porosity and clay mineral content showed greater reduction in tensile strength when exposed to environmental humidity.

Ojo & Brook (1989) conducted UCS and Direct Tensile tests on sandstones saturated to various degrees. Although both the UCS and tensile strength of the rocks decreases with increasing water content, they observed that UCS/T_o ratio is higher at saturated conditions than at air-dried conditions. Hence, they argued that moisture has a greater reduction effect on the tensile strength of rocks than on their compressive strength.

You, Chen & Su (2011) investigated the effect of water saturation on the tensile strength of gneiss, marble and sandstone. Both the Brazilian Tensile Test and Ring Test were used in their experiment. Results from the Brazilian Test showed that all the rocks have lower tensile strength when saturated as compared to their dry state. However, results from the Ring Test showed little differences in tensile strength between the dry and wet specimens.

Although most of the previous studies in the literature showed the weakening effect of water on the tensile strength of rock, high-speed video technology was not used during testing in most of the studies. Apart from helping to verify that failure of the test specimens occur as expected in theory, the use of high-speed technology can also help to provide insights on the effect of water on the cracking behaviour of rocks.

3.3. Properties of Gypsum

Gypsum can be found in nature and are formed due to the evaporation of inland seas and lakes. Natural gypsum occurs mainly in two different forms – anhydrite ($CaSO_4$) and dihydrate ($CaSO_4 \cdot 2H_2O$).

Industrial gypsum is produced from partial dehydration of dihydrate to form hemihydrate ($CaSO_4 \cdot ½H_2O$). On mixing with water, hemihydrate is hydrated to form dihydrate, which will precipitate to become hardened gypsum.

The chemical reaction of the hydration of hemihydrate is:

$$CaSO_4 \cdot ½H_2O + 1½\ H_2O \rightarrow CaSO_4 \cdot 2H_2O$$

The strength of Gypsum is determined by several factors (Karni, 1995):

- Quality of cementitious material (gypsum & additives),
- Water/gypsum ratio during mixing,
- Age of the product, and
- Conditions of storage of the product.

Karni (1995) investigated the effect of different storage conditions on the compressive strength of gypsum after mixing. It was found that the strength of air-dried specimens reached maximum after about 14 days while the strength of specimens kept in water and humidity chamber decreased with time. He also found that if the specimens from the humidity chamber were air-dried for a few days, it showed higher strength than those which were kept in humidity chamber. This showed that wet gypsum is capable of regaining strength when dried.

Işık (2010) carried out a series of tests to determine the influence of water content on the UCS and elasticity modulus of natural gypsum. Samples of natural gypsum were obtained from the Hafik Formation in Sivas basin, Turkey, and the UCS and elasticity modulus of the samples were determined under air-dried condition as well as near saturated condition. His results showed that the strength of gypsum dropped by about 60% after being immersed in water for 1 week and dropped further to about 65% after 16 days. The best relationship between UCS and water content were found to be exponential. Similar trend was observed for its elastic modulus which decreased by about 55% when saturated.

Padevět, Tesárek, & Plachý (2011) studied the time dependent changes of the mechanical properties of gypsum after mixing and found that both the compressive and tensile strength increased rapidly between the 5^{th} and 14^{th} day after mixing. This period corresponded to the time where the specimens

were rapidly drying out as observed from the change in the specimens' weight with time. They concluded that as water leaves the specimen, the strength of the specimen increases to the expected value of the material.

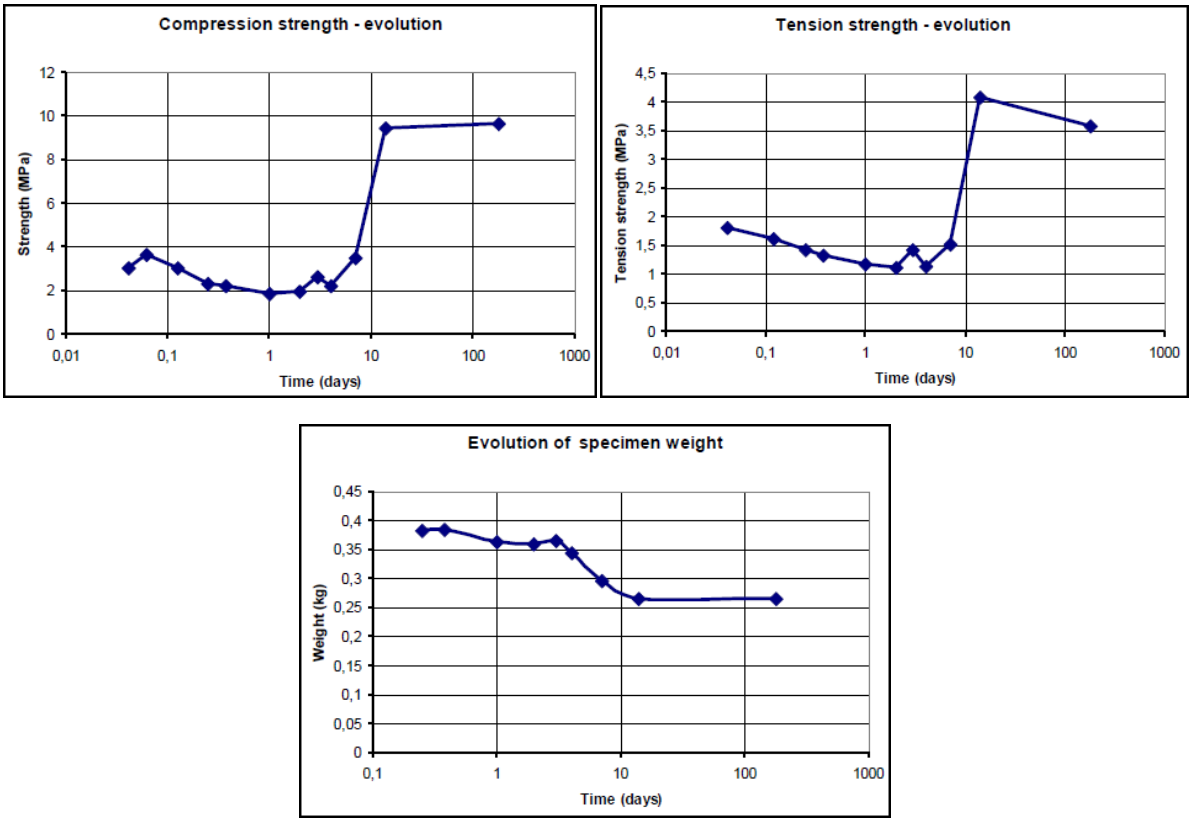

Figure 5 – Graphs showing the change in compressive strength, tensile strength and specimen weight with time after mixing. The period where the compressive strength and tensile strength increased rapidly corresponded to the period where the specimen is rapidly drying (Padevět, Tesárek, & Plachý, 2011).

4. METHODOLOGY

4.1. Specimen Preparation

Molded gypsum will be used as the specimen for this experiment. All the specimens are prepared in the Geotechnics Workshop of Nanyang Technological University.

Each cylindrical gypsum samples were prepared using 350g of Hydrocal Gypsum cement (Gypsum powder), 4g of Celite, and 140g of water (Weight ratio of 87.5:1:35). The water and celite powder are first poured into the mixer and mixed for 20 seconds. The gypsum powder is then poured into the mixer and mixed for 2 minutes.

Figure 6 - (Left) 140ml of water, 350g of Gypsum powder and 4g of celite;
(Right) Mixing the Gypsum paste in the mixer

With the cylindrical mold (50mm diameter; 120mm height) secured to a vibrating machine, the machine is switched on and the gypsum paste is poured into the mold through the opening in the cap of the vibrating machine. The gypsum paste in the mold is vibrated for about 5 minutes to remove as much trapped air from the paste as possible.

Figure 7 – (Left) The cylindrical mold secured to a vibrating machine where it is vibrated; (Right) The opening on the cap of the vibrating machine through which the gypsum paste was poured in the mold

After vibrating the gypsum paste, it is left to harden for 30 minutes before the hardened sample is removed from the mold. The sample is labeled and its weight is recorded before being placed in an oven set at 40^0C.

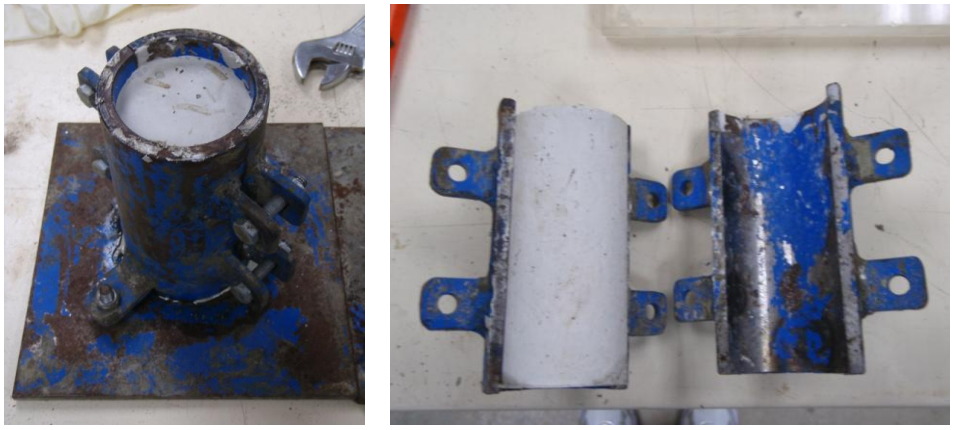

Figure 8 – (Left) The vibrated gypsum paste is left to harden for 30 mins; (Right) The hardened gypsum is removed from the mold

Figure 9 - The samples are labelled and kept in an oven at 40^0C

In order to determine the amount of time required for the sample to be sufficiently dry and hardened, the mass of the sample is recorded on a daily basis until it has dropped to a nearly constant value. From the trial experiments conducted, the mass of the samples dropped to a nearly constant value after about 10 days. Hence, all the samples prepared will be kept in the oven for at least 10 days.

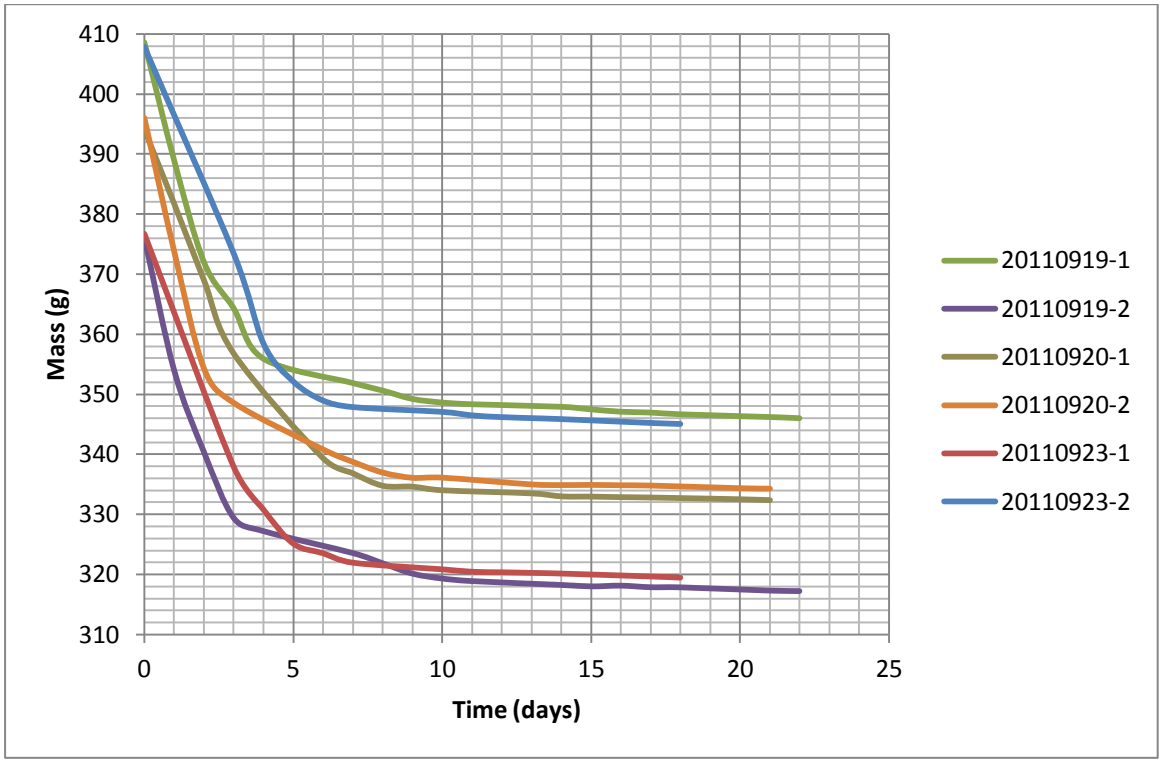

Figure 10 - The change in specimen weight with time

The cylindrical sample is then cut into disks of 30mm thickness and the specimens are stored in the oven until they're required for the experiment.

Figure 11 – The cylindrical sample is cut into disks of 30mm thickness

4.2. Saturation of Specimens

Dry specimens (obtained from the procedures described previously) are immersed in water for different lengths of time in order to achieve different level of water saturation.

In order to determine the immersion times required for the different levels of water saturation, several trial specimens were immersed in water and their change in mass with immersion time were recorded at regular intervals. Before the mass was recorded at a particular time, the trial specimens were first left to dry in the air for 30 minutes upon being taken out from the water.

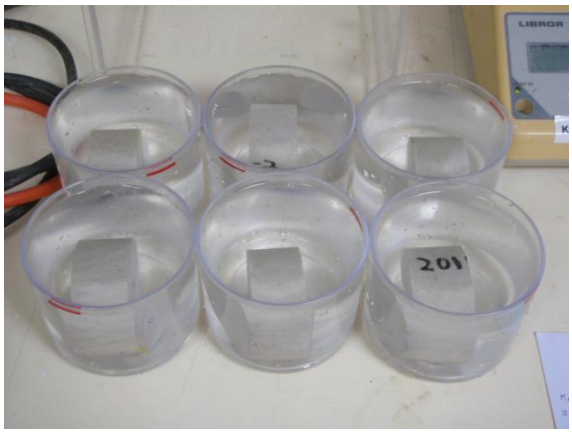

Figure 12 - Several trial specimens were soaked in water to determine their change in mass with immersion time

From the trial experiment conducted, the change in mass relative to the specimen with an immersion time of 1 day is shown in the graph below.

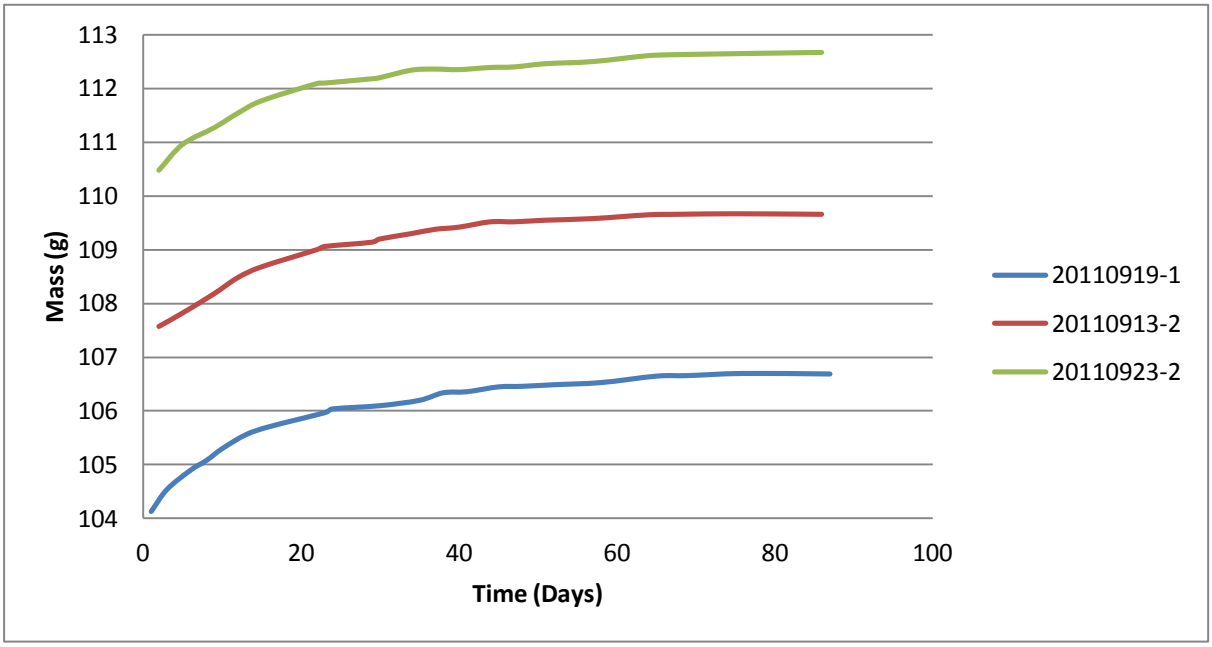

Figure 13 – The the change in mass relative to the specimen with an immersion time of 1 day

By dividing the change in mass into 3 equal segments, the immersion time required to reach about one-third and two-third of the increase in mass are approximately 1 week and 3 weeks respectively. The time required to fully saturate the specimens is approximately 12 weeks (or 3 months).

After the immersion time required has been determined from the trial experiments, the specimens for the subsequent actual experiments would be immersed in water for 1 week, 3 weeks, and 12 weeks to achieve their respective level of saturation. However, due to time constraint, the specimens can only be immersed for a maximum duration of 10 weeks. The Brazilian Tensile test will be conducted on the specimens once they're taken out from the water.

Figure 14 - Specimens for the subsequent actual experiments were immersed in water for 1 week, 3 weeks, and 10 weeks to achieve their respective level of saturation

4.3 Brazilian Tensile Test

The Brazilian Tensile Test will be used to determine the tensile strength of the specimens. The loading configuration will be based on the standards published by ASTM (2008).

Flat bearing blocks with cushion between the bearing blocks and specimen edges will be used in this experiment. The cushion was provided by several layers of masking tape with a thickness of 0.5mm at each edge. A hydraulic compression machine will apply a loading rate of 0.1kN/s to the specimen.

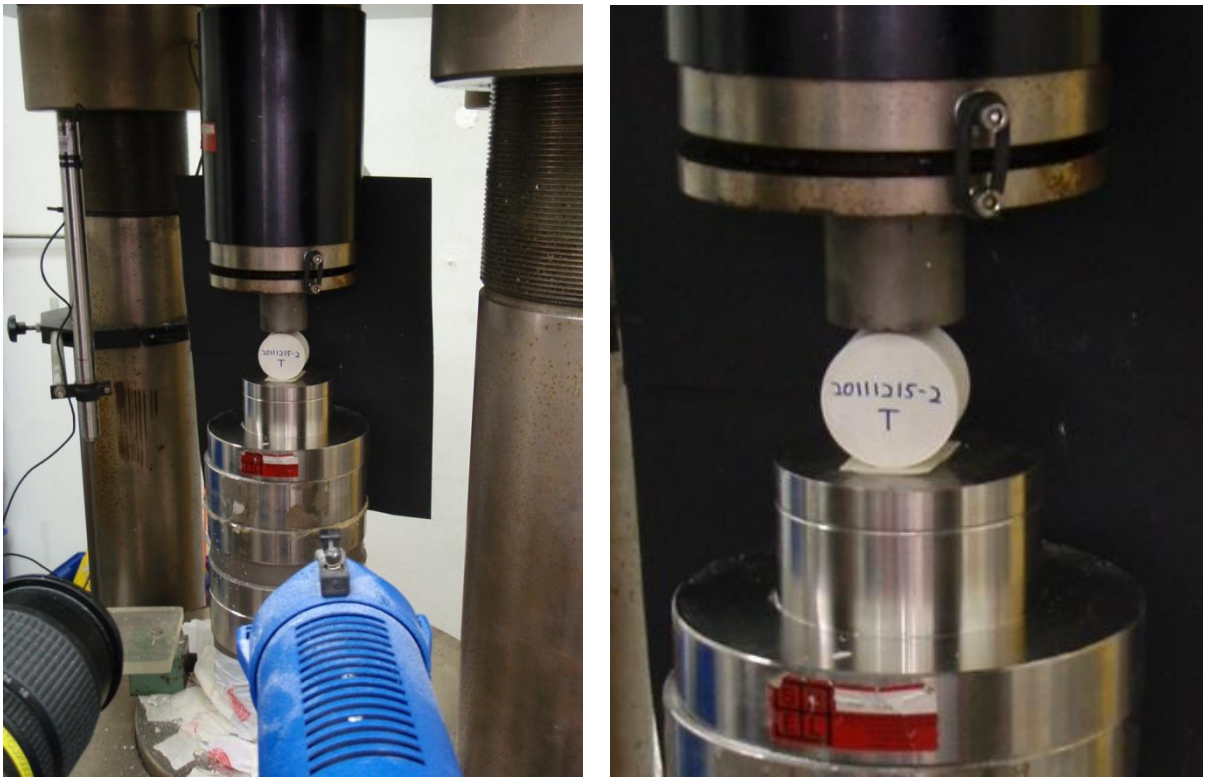

Figure 15 - (Left) A specimen placed in the hydraulic compression machine
(Right) A close-up view of the specimen placed in between two flat-bearing blocks

The deformation and load applied on the specimen were recorded every 0.01 second using a computer software. The recorded data was later analyzed and the highest load applied will correspond to the failure load of the specimen i.e. the load at which the specimen failed.

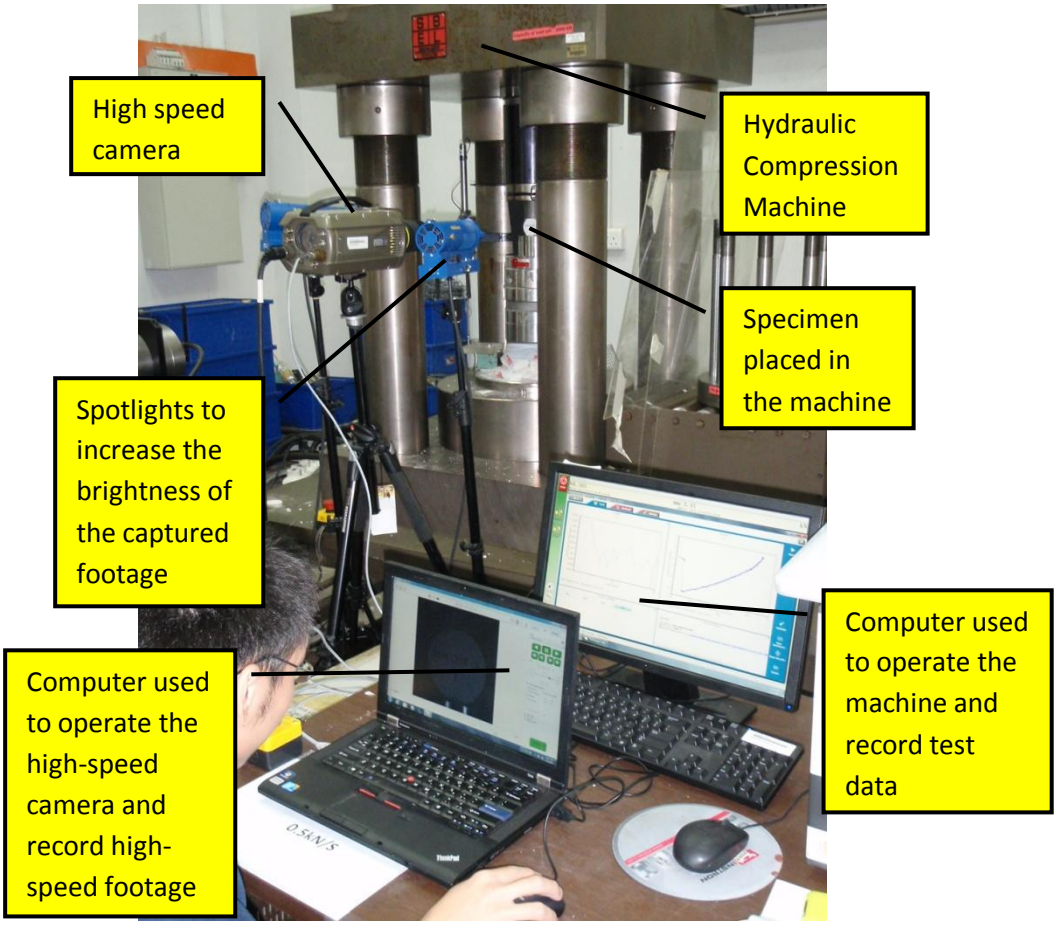

Figure 16 – The experiment setup for the Brazilian Tensile Test

The tensile stress of each specimen will then be calculated using the equation:

$$\sigma_t = \frac{2P}{\pi LD}$$

where: σ_t = splitting tensile strength (MPa)

P = maximum applied load (N)

L = thickness of the disk specimen (mm)

D = diameter of the disk specimen (mm)

A Phantom V310 high-speed camera will also be used to record the moment of failure of the specimen. The footage will then be analyzed to determine how each specimen fails; particularly where the failure crack is initiated in the specimen.

For the result of the Brazilian Tensile Test to be valid, the primary crack should occur along the vertically-loaded diameter of the specimen. Results from specimens which failed by surface spalling, sideway cracking, or failure initiated from a major preexisting flaw in the specimen will be discarded.

5. RESULTS

5.1. Change in Water Content with Immersion Time

Four sets of specimens with different immersions time were tested in this study:

1) Not immersed in water (Dry)
2) Immersed for 1 week
3) Immersed for 3 weeks
4) Immersed for 10 weeks

The water content for each specimen is calculated using the equation below:

$$w = \frac{m_w - m_d}{m_d} \times 100\%$$

where:

w = water content (%)

m_d = mass of specimen after being kept in oven (set at 40°C) until it has dropped to a constant mass (g)

m_w = mass of specimen after immersed in water for the required time (g)

The change in water content with immersion time appeared to follow an exponential relationship. After one week of soaking, the average water content of the specimens increased from 0% to 16.6%. The average water content increased slightly further to 17.6% and 18.2% after having been soaked for 3 weeks and 10 weeks respectively.

Imm. Times (Weeks)	Water Content (%)
Dry	0
1	16.6
3	17.6
10	18.2

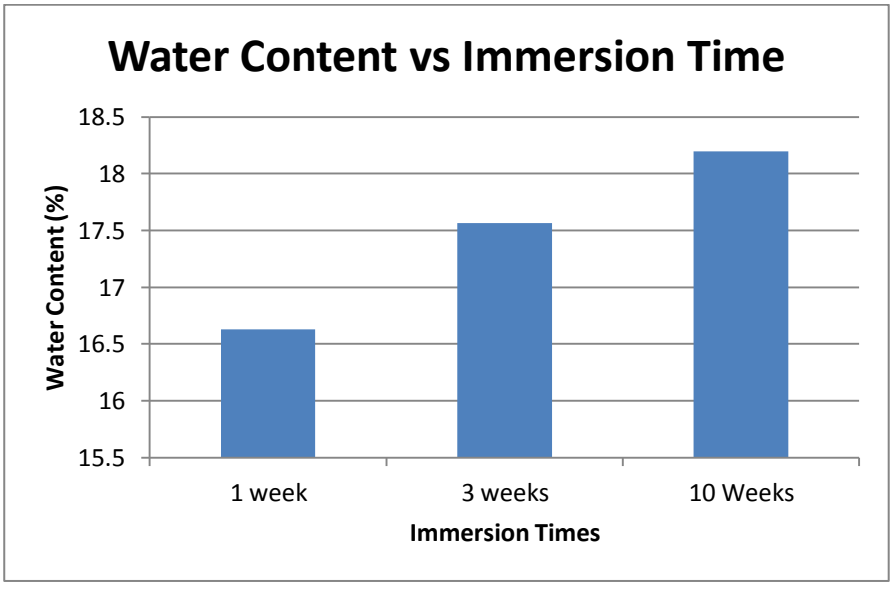

Figure 17 - Change in water content with immersion time

It is clear that most of the increase in water content occurred within the first week after the specimens were immersed in water. Specimens which were left immersed in water for another 9 weeks showed a further increase in water content of only less than 2%.

This phenomenon is probably due to the connectivity of the pores in the specimen. As many of the pores in the specimen were possibly interconnected, water can easily move in and occupy these pores when the specimens were initially soaked in water. Small continuous streams of bubbles were observed escaping from the specimens during the first week the specimens were immersed in water. This suggested that water was entering and displacing air from the interconnected pores inside the specimen, which contributed to most of the increase in water content during the first week. Then over time, water slowly seeps into the less accessible pores which are not connected with the other pores and this contributed to the smaller increase in water content between the 2^{nd} and 10^{th} week.

Another possible explanation to the huge increase in water content was the affiliation of water to unhydrated gypsum powder. It is assumed that all the gypsum powder has been hydrated during mixing. However in reality there could still be some unhydrated gypsum powder in the specimen. During the initial stage of mixing, the gypsum powder tends to form lumps when it first came into contact with water and this could have prevented the inner portions from fully reacting with water. When the finished specimens were later immersed in water, water could finally reach these unhydrated gypsum particles and react with them to form dihydrate.

5.2. Change in Tensile Strength with Immersion time

The change in tensile strength with immersion time also appeared to follow an exponential function. The average tensile strength of the dry specimen is 4.50MPa. After one week of soaking, the average tensile strength dropped significantly to 2.31MPa. The average tensile strengths dropped slightly further to 2.26MPa and 2.14MPa after 3 weeks and 10 weeks of soaking respectively.

The results obtained are summarized in the table below.

Immersion Time	Dry	1 Week	3 Weeks	10 Weeks
No. of specimens tested	15	15	15	18
No. of invalid test results discarded	5	1	1	0
Average Water Content*	0%	16.6%	17.6%	18.2%
Average Tensile Strength*	4.50MPa	2.31MPa	2.26MPa	2.14MPa
Standard Deviation*	0.41MPa	0.20MPa	0.23MPa	0.24MPa
Reduction in Tensile Strength	-	48.7%	49.8%	52.4%

***Results from discarded specimens were not included the computation of these values**

Table i - Summary of results for all the 4 sets of specimens

The results for each of the specimens tested are given in Appendix B.

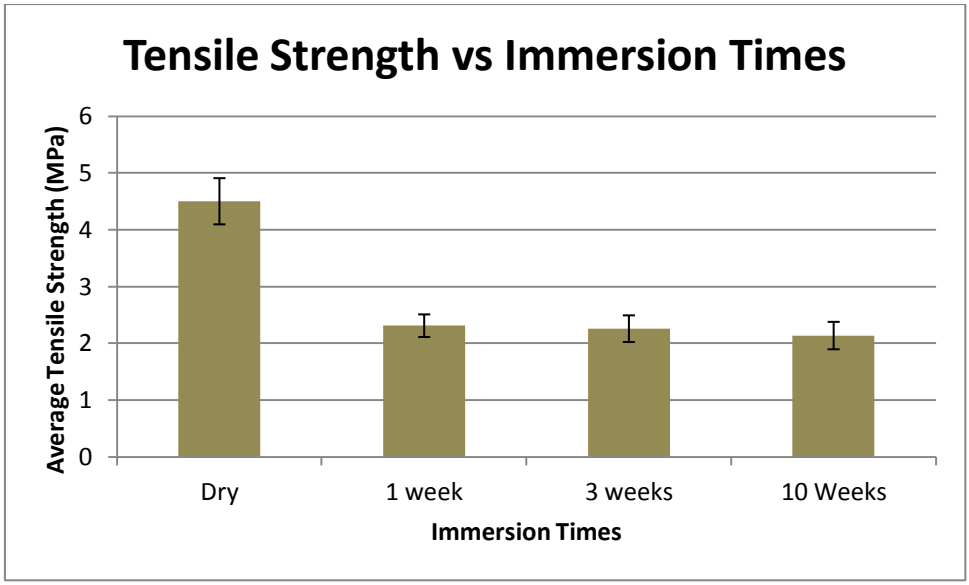

Figure 18 - Average tensile strength with error bars indicating 1 standard deviation for the 4 different immersion times

Apart from the obvious drop in average tensile strength, it was also observed that the standard deviation of the average tensile strength was lower when the specimens have been immersed in water. The average tensile strength for dry specimens has a standard deviation of 0.41MPa, whereas specimens immersed for 1 week, 3 weeks and 10 weeks have standard deviations of 0.20MPa, 0.23MPa and 0.24MPa respectively. This showed that the tensile strength values obtained were less scattered for wet specimens compared to dry specimens.

The presence of water possibly could have reduced the variation in tensile strength of the specimens. In dry specimens, the limits to their tensile strengths were largely controlled by the nature of their pre-existing flaws, such as the shape, orientation and distribution of the pre-existing cracks. Since the nature of these pre-existing flaws can vary greatly from one specimen to another, the tensile strength values obtained will be more scattered for dry specimens. In wet specimens, the presence of water could have greatly weakened the bonding between the mineral grains until this become the new limiting factor to the specimen's tensile strength. As the bond-weakening caused by water is less likely to vary much from one specimen to another, the resulting tensile strength of the wet specimens became less scattered compared to the dry specimens.

5.3. Crack Analysis

A high speed camera was used to capture the moment of failure for each specimen during the Brazilian Tensile Test. The recorded footage was later analysed to determine the validity of each test result. Due to the assumptions of the Brazilian Tensile Test, the result of each test will only be valid if the specimen fails along its vertically-loaded diameter.

The primary purpose of using a high speed camera is to determine where the crack initiated in each tested specimen and whether the primary crack occurred along its vertically-loaded diameter. A primary crack that was initiated at the centre of the specimen proved that the specimen failed due to tension. Secondary cracks often developed in the specimen shortly after the primary crack has occurred. Hence, the recorded high-speed footage was also used to identify the primary crack from among the several cracks in the specimen.

An example of a high-speed footage with selected frames showing the primary crack initiating at the centre of the specimen followed by secondary cracks is shown below.

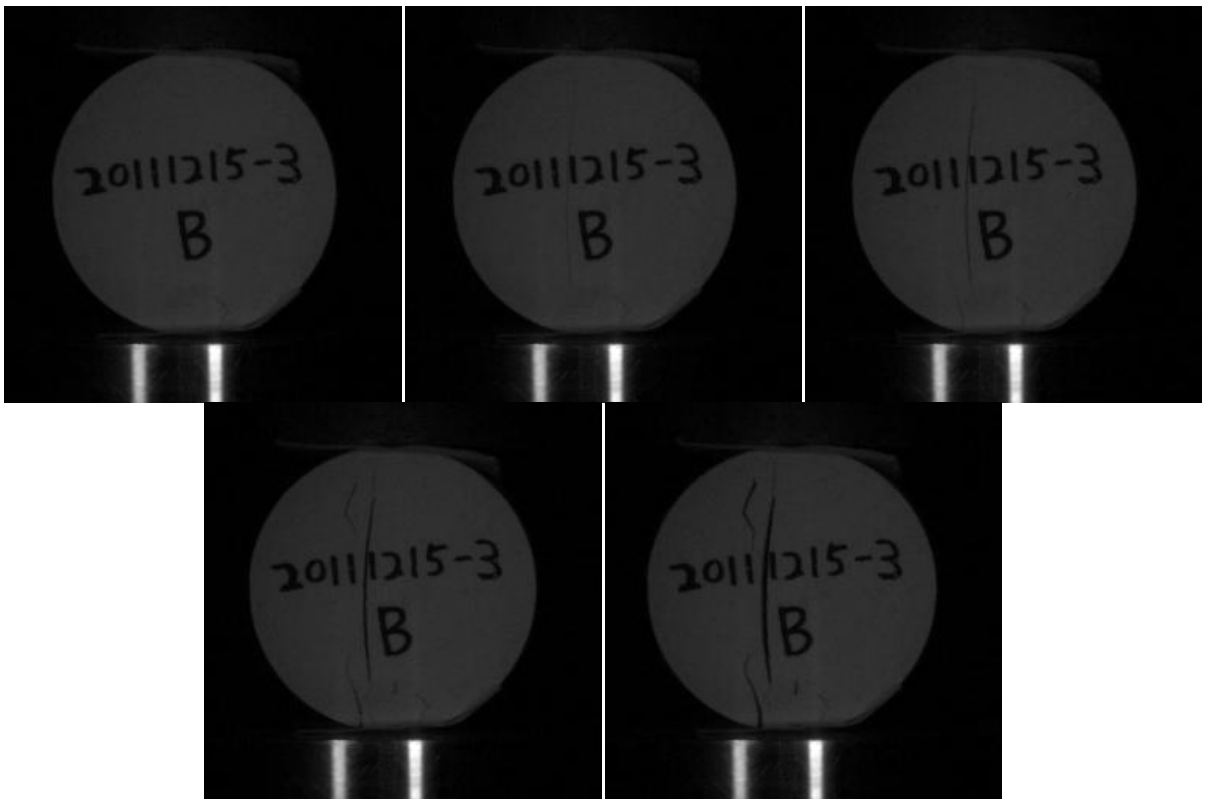

Figure 19 – Selected frames from a high-speed footage showing the primary crack initiating at the centre of the specimen followed by several secondary cracks

Apart from relying on the recorded high-speed footage, physical inspection of the failed specimen sometimes can also be useful in determining where the crack initiated in the specimen. This method is useful only if the crack initiated at the centre of the specimen but did not break through the top and bottom of the specimen. Through physical inspection, it can be immediately deduced that the crack initiated at the centre of the specimen if the failed specimen showed a diametrical crack which did not break through the top and bottom of the failed specimen.

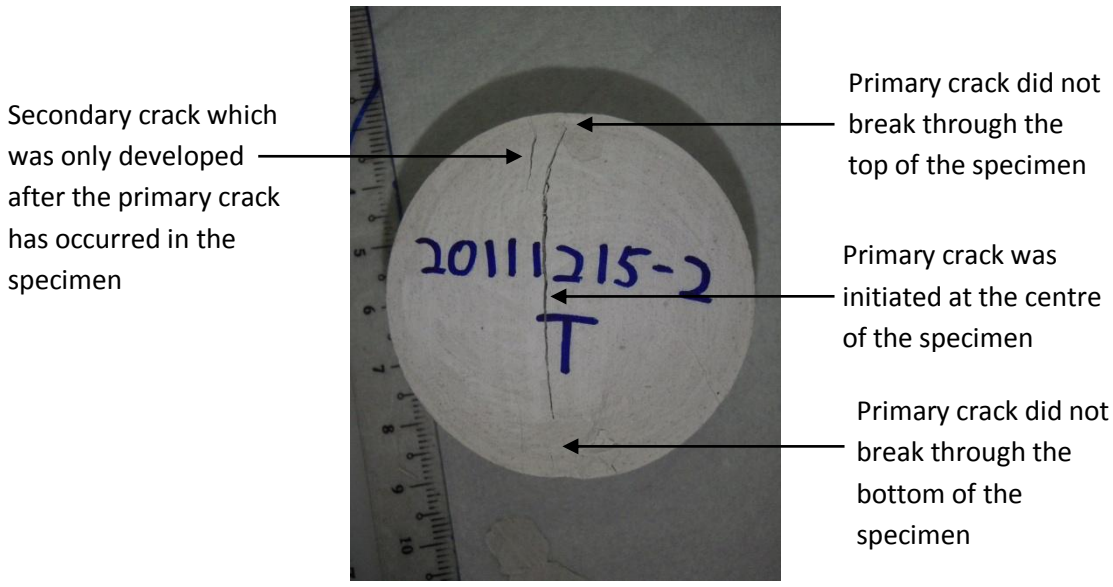

Figure 20 - Example of a specimen where the location of crack initiation can be determined by physical inspection

A test result will be discarded if failure did not occur along the specimen's vertically-loaded diameter, such as by surface spalling or along major pre-existing flaws in the specimen. Out of the total 63 specimens tested, there were 7 discarded test results – 5 were dry specimens, 1 was soaked for 1 week, and 1 was soaked for 3 weeks.

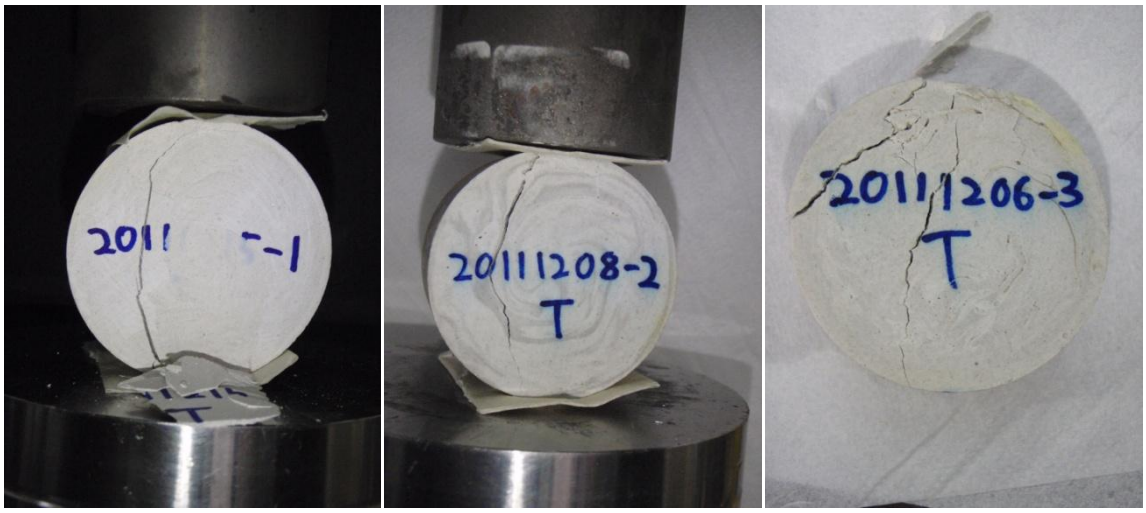

Figure 21 - Examples of discarded specimens (from left to right): Failure by surface spalling, failure along pre-existing cracks in the specimen, and failure through a sideway crack due to pre-existing flaw in the specimen.

A summary of the results of crack analysis is shown in the table below.

Immersion Time		0 (Dry)	1 week	3 weeks	10 weeks
No. of specimens tested		15	15	15	18
No. of discarded test results		5	1	1	0
No. of valid test results		10	14	14	18
Location of crack initiation	Centre	10	13	10	18
	Edge	0	0	3	0
	Unknown	0	1	1	0

Table ii - Summary of the results of crack analysis

The location of crack initiation for majority of the specimens tested was at the centre of the specimen. This validates the results of the Brazilian Tensile Test as it showed that the majority of the specimens failed due to tension.

It was also observed that surface spalling occurred in 5 out of the 15 dry specimens tested and this was the reason for their test results being discarded. There're another 2 specimens which showed minor spalling but were not discarded as the spalling were considered not severe enough to affect the test results. Hence overall, 7 out of the 15 dry specimens tested showed at least some form of surface spalling although only 5 of them were considered severe enough to be discarded.

One possible reason to why surface spalling occurred in many of the dry specimens was because of the brittleness of gypsum under dry condition. Even a slightly off-parallel misalignment of the upper and lower bearing block resulted in a much higher stress distribution on one side of the specimen. Hence, surface spalling occurred on the surface which was subjected to a much higher stress.

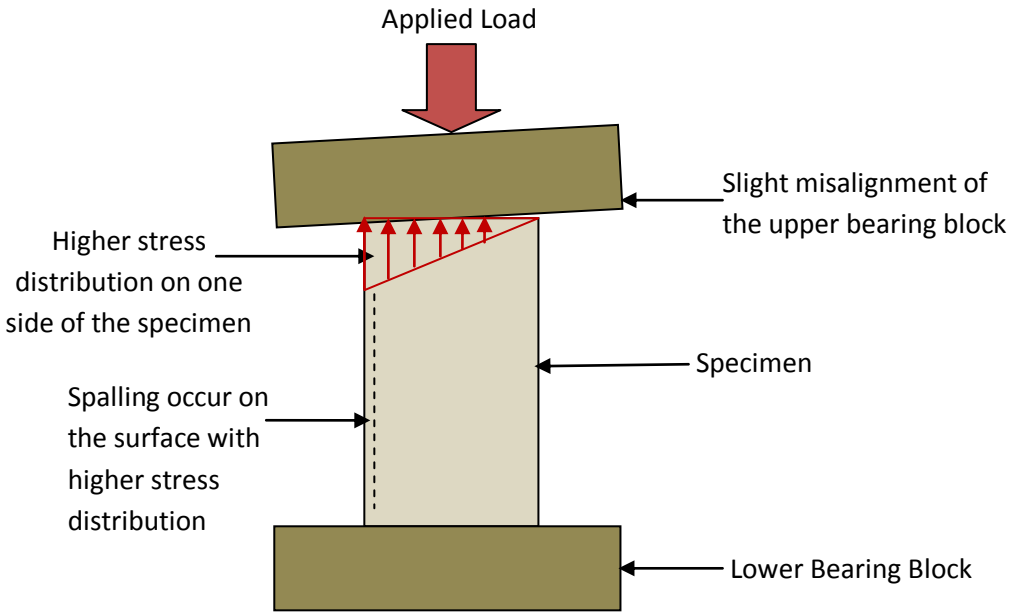

Figure 22 - Diagram showing the cause of surface spalling in dry specimens

On the other hand, the 2 wet specimens discarded (1 soaked for 1 week and 1 soaked for 3 weeks) were due to cracks occurring along pre-existing flaws in the specimens. Surface spalling did not occur in any of the wet specimens. This is probably because the gypsum specimens become less brittle and more elastic under wet condition and can easily deform to distribute the applied load evenly along the top and bottom of the specimen.

Another observation made during the review of the high-speed footage was the difference in the speed of crack propagation between the dry specimens and wet specimens. With the high-speed camera capturing at 40,000 fps, it was generally observed that upon crack initiation, it took 1 to 3 frames for the primary crack to propagate from the centre to the top and bottom of the specimen. For wet specimens, this took about 5 to 10 frames. Hence, this observation suggested that water reduces the speed of crack propagation in the gypsum specimens.

Closer examination of the high-speed footage showed that once a crack was initiated in a dry specimen, the crack will propagate through the specimen very quickly resulting in an abrupt failure of the specimen. For wet specimens, however, often more than one crack was initiated in a specimen before these cracks became connected to form the primary diametrical crack. As the diametrical crack in wet specimens were often the results of two or more cracks becoming connected together, these cracks appeared more crooked compared to those in dry specimens.

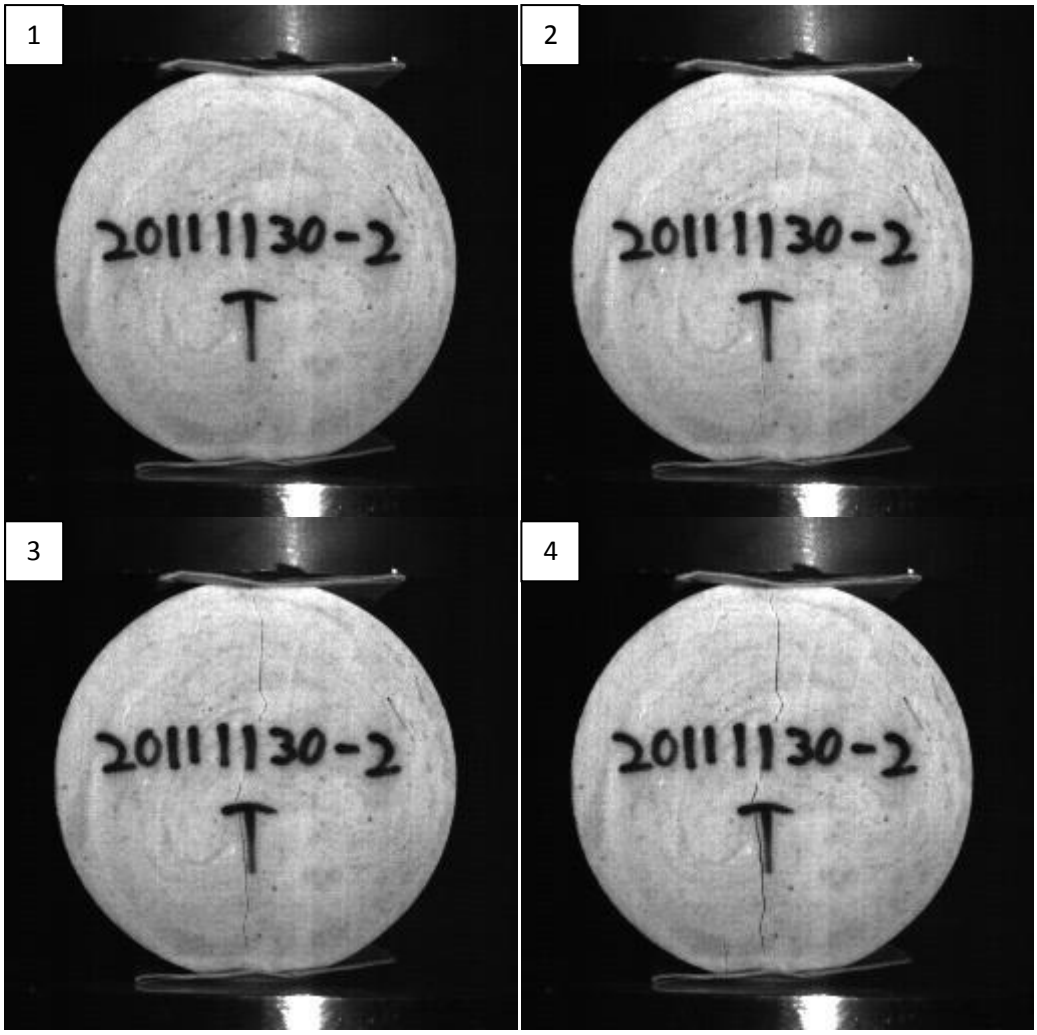

Figure 23 – High-speed footage showing the failure of a wet specimen. Two cracks were initiated before they become connected to form the primary diametrical crack.

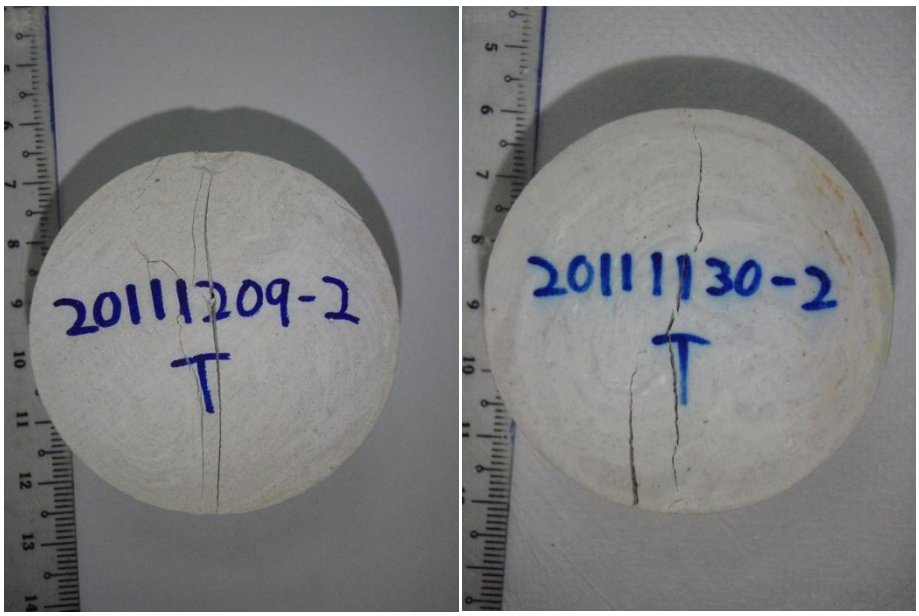

Figure 24 - A comparison between the diametrical crack of a dry specimen (left) and wet specimen (right). The diametrical crack of the wet specimen appeared more crooked compared to the dry specimen.

5.4. Young's Modulus

The Young's Modulus of the specimens in this experiment could not be accurately determined as strain gauges were not used to measure the strain at the centre of the specimen during the Brazilian Tensile test. Hence, the only readings obtained during the experiment were the load applied (P) by the loading machine and the displacement (δ) of the upper bearing block along the vertically-loaded diameter of the specimen.

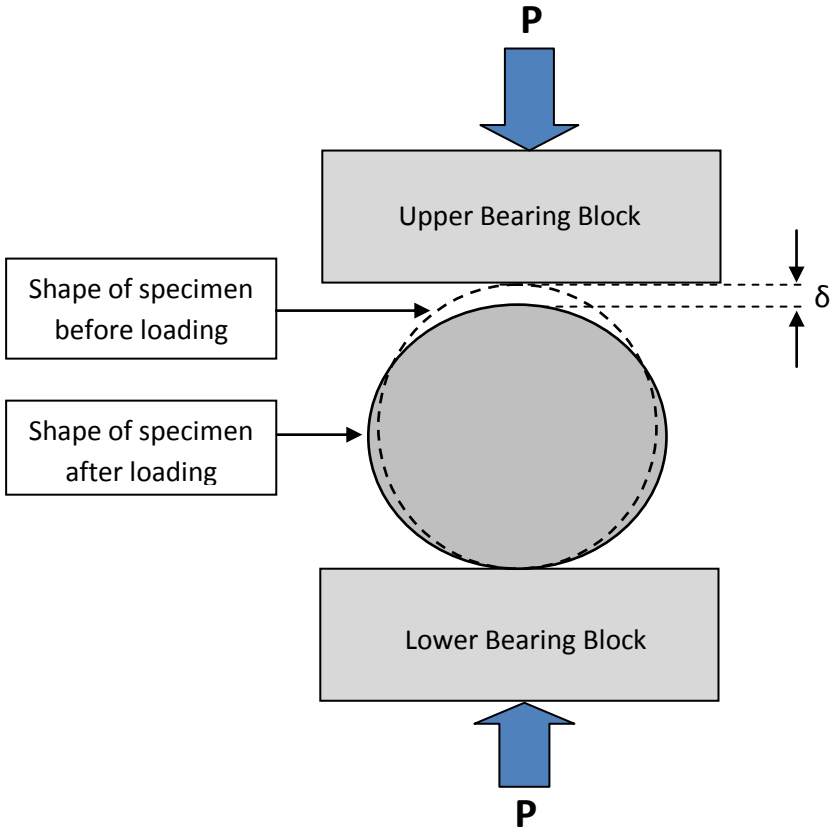

Figure 25 - Diagram illustrating the applied load (P) and vertical displacement (δ) of the upper bearing block during the Brazilian Tensile Test

A useful way of analysing the effect of water saturation on the Young's Modulus of the specimens is by comparing the load-displacement graphs between specimens of different water contents. When the applied load (P) was plotted against the displacement (δ) for each specimen, the gradient of the graph represents a form of 'stiffness' or 'resistance' of the specimen against the applied loading. As all the specimens used in this experiment were of similar dimensions (50mm diameter, 30mm thickness), a comparison of this 'stiffness' between specimens can give reliable insight to how water saturation has affected the Young's Modulus of the specimens.

The load-displacement graph for each of the tested specimens was plotted and the gradient was determined. The average gradients, which represent the average stiffness of the specimens for each immersion times, are shown in the table below.

Immersion Time	0 (Dry)	1 week	3 weeks	10 weeks
Average Gradient	24.53kN/mm	12.85kN/mm	13.10kN/mm	18.53kN/mm
Standard Deviation	11.85kN/mm	2.40kN/mm	1.14kN/mm	2.73kN/mm

Table iii - Average gradient of the load-displacement graphs for all the immersion times

A plot of the load-displacement graphs for a typical dry specimen and a typical specimen soaked for 1 week, 3 weeks, and 10 weeks is shown below.

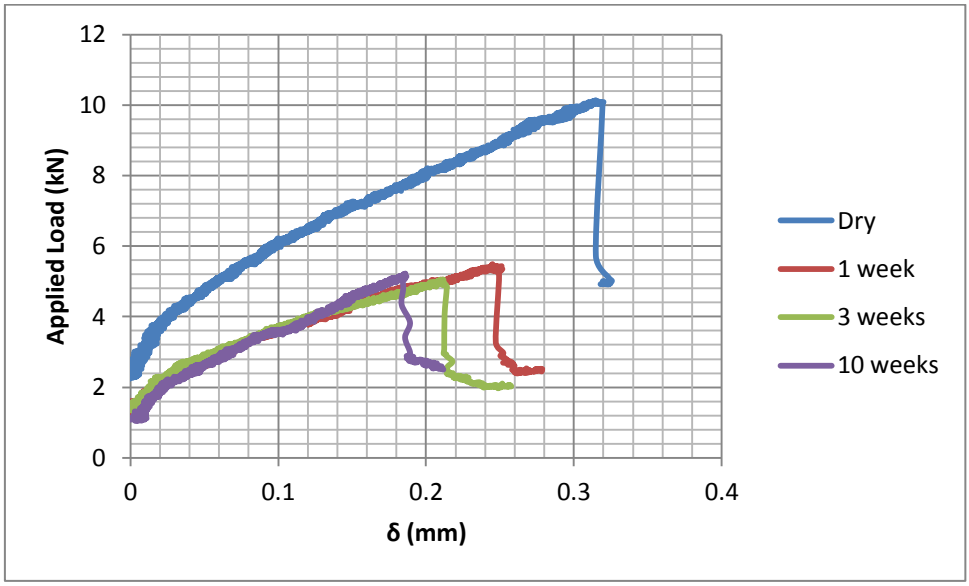

Figure 26 – Load-displacement graphs for a typical dry specimen and specimen soaked for 1 week, 3 weeks and 10 weeks

The average stiffness for a dry specimen was 24.53kN/mm. The average stiffness for specimens soaked for 1 week, 3 weeks and 10 weeks were 12.85kN/mm, 13.10kN/mm and 18.53kN/mm respectively. It can be seen that the average stiffness dropped to nearly half its dry value after being soaked for 1 week and 3 weeks. The average stiffness of specimens soaked for 10 weeks were significantly higher than those soaked for 1 week and 3 weeks. This is probably due to the use of a different cushioning material in the testing of the specimens. During the Brazilian Tensile Test of the specimens soaked for 10 weeks, a different type of musking tape which is slightly harder was used as the cushioning material between the bearing blocks and the specimen. This probably could have been the cause of the higher stiffness obtained for the specimens soaked for 10 weeks.

Overall, it was clear that dry specimens have a significantly higher average stiffness than wet specimens. As changes in stiffness of the specimen reflect a change in its Young's Modulus, the results suggest that water has a reduction effect on the Young's Modulus of gypsum.

6. CONCLUSIONS

Results from the experiment showed that the average tensile strength of the gypsum specimens decreased by 48.7%, 49.8% and 52.4% after being immersed in water for 1 week, 3 weeks and 10 weeks respectively. The tensile strength of gypsum dropped to almost half of its original value after being immersed in water for only 1 week. Immersing the gypsum specimens further to 3 weeks and 10 weeks resulted in slight further decreases in its tensile strength.

Analysis of the gradients of the load-displacement graphs, which represent the stiffness of each specimen, showed that the average stiffness also dropped to nearly half of its original value after being soaked in water for just 1 week. Although this reduction in stiffness may not accurately reflect the same extent of reduction in its Young's Modulus, it is evident that the presence of water does have reduction effect on the Young's Modulus of gypsum.

Through analysis of the recorded high-speed footage as well as through physical inspection of the failed specimens, it was observed that the location of crack initiation was at the centre of the specimen for majority of the specimens tested. Hence, this validated the test results of this experiment as it showed that the majority of the tested specimens failed due to tension.

Closer examination of the high-speed footage showed that upon crack initiation in dry specimens, the crack propagated through the specimen very quickly resulting in very abrupt failure of the specimen. For wet specimens, however, the failure occurred more gradually and often more than one crack was initiated before these cracks became connected to form the main primary crack.

It is evident from the results of this experiment that water does have a weakening effect on the tensile strength of gypsum. This result agrees with many previous studies in the literature conducted on other types of rocks. Hence, even though the dry tensile strength of rocks was used in the classification of rock strength, it is recommended that the saturated tensile strength should be used instead for a more conservative design of underground structures.

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http://www.knovel.com.ezlibproxy1.ntu.edu.sg/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=1848

APPENDIX A

Summary of Specimens Properties

Immersion Time: 0 weeks (Dry)

Specimen No	Diameter (mm)	Thickness (mm)	Dry Mass (g)	Wet Mass (g)	Water Content (%)	Max Load (kN)	Tensile Strength (MPa)	Stiffness (kN/mm)	Remarks
20111209-2T	50	30.5	93.09	-	0	8.5585	3.572797	19.735	
20111209-2M	50	29.9	91.22	-	0	11.9491	5.088321	26.891	Discarded
20111209-2B	50	30.2	92.72	-	0	11.5691	4.877566	43.737	
20111209-3T	50	30.1	92.28	-	0	10.7692	4.55541	12.425	
20111209-3M	50	30.0	92.05	-	0	11.4549	4.861615	14.447	
20111209-3B	50	30.1	93.14	-	0	10.7214	4.53519	33.959	Discarded
20111215-1T	50	30.5	93.33	-	0	8.5567	3.572045	20.753	Discarded
20111215-1M	50	29.8	91.39	-	0	10.2029	4.359311	18.858	Discarded
20111215-1B	50	29.9	91.82	-	0	10.1483	4.321481	22.843	
20111215-2T	50	30.4	92.58	-	0	10.2858	4.307993	19.536	
20111215-2M	50	29.8	90.98	-	0	10.0366	4.288257	21.816	
20111215-2B	50	30.6	93.66	-	0	11.8596	4.934681	48.32	
20111215-3T	50	30.2	92.74	-	0	8.9113	3.75703	19.221	Discarded
20111215-3M	50	30.0	92.03	-	0	11.0463	4.688199	20.496	
20111215-3B	50	30.8	94.71	-	0	11.1925	4.626865	21.934	
			Average water content* (%)		**0**	**Average Tensile Strength* (MPa) and Stiffness* (kN/mm)**	**4.503486**	**24.5289**	

**Results from discarded specimens were not included in the calculation of average water content, average tensile strength and average stiffness*

Immersion Time: 1 week

Specimen No	Diameter (mm)	Thickness (mm)	Dry Mass (g)	Wet Mass (g)	Water Content (%)	Max Load (kN)	Tensile Strength (MPa)	Stiffness (kN/mm)	Remarks
20111206-1T	50	30.0	91.46	107.09	17.08944	5.6498	2.397852	8.5415	
20111206-1M	50	30.0	91.94	106.87	16.23885	5.55498	2.357609	10.845	
20111206-1B	50	30.7	93.99	109.36	16.3528	4.22071	1.750482	11.54	
20111206-2T	50	30.1	91.38	106.98	17.07157	5.64776	2.389022	11.403	
20111206-2M	50	29.8	91.76	107.09	16.70663	5.49682	2.348582	14.214	
20111206-2B	50	30.4	93.63	109.27	16.70405	5.46108	2.28726	17.261	
20111206-3T	50	30.2	92.02	107.94	17.30059	4.94278	2.08389	4.1466	Discarded
20111206-3M	50	30.4	93.41	108.83	16.50787	5.83423	2.443546	14.184	
20111206-3B	50	30.0	91.96	107.03	16.38756	5.04264	2.140165	13.657	
20111207-1T	50	30.4	94.12	109.68	16.53209	5.02048	2.102723	9.011	
20111207-1M	50	30.4	93.35	109.26	17.04339	5.96626	2.498844	11.858	
20111207-1B	50	30.2	92.78	108.34	16.77086	5.56065	2.344386	14.585	
20111207-2T	50	29.9	90.03	105.25	16.90548	5.54287	2.360337	14.446	
20111207-2M	50	30.8	94.45	110	16.46374	6.10228	2.52262	14.322	
20111207-2B	50	29.5	91.15	105.75	16.01755	5.59595	2.415251	13.971	
			Average water content* (%)		**16.62799**	**Average Tensile Strength* (MPa) and Stiffness* (kN/mm)**	**2.311334**	**12.84561**	

**Results from discarded specimens were not included in the calculation of average water content, average tensile strength and average stiffness*

Immersion Time: 3 weeks

Specimen No	Diameter (mm)	Thickness (mm)	Dry Mass (g)	Wet Mass (g)	Water Content (%)	Max Load (kN)	Tensile Strength (MPa)	Stiffness (kN/mm)	Remarks
20111207-3T	50	30.4	93.43	110.3	18.0563	5.05152	2.115724	12.862	
20111207-3M	50	30.5	94.39	111	17.5972	5.85564	2.444472	12.483	
20111207-3B	50	29.8	92.06	108.26	17.59722	5.70838	2.438974	12.235	
20111208-1T	50	30.1	92.59	109.46	18.22011	4.36272	1.845446	13.618	
20111208-1M	50	30.1	92.87	108.95	17.31453	4.23591	1.791805	13.83	
20111208-1B	50	30.2	92.89	109.17	17.52611	5.64726	2.380901	13.447	
20111208-2T	50	29.6	90.81	106.68	17.47605	4.5006	1.935928	11.088	Discarded
20111208-2M	50	30.7	94.89	110.82	16.78786	5.19613	2.155024	15.748	
20111208-2B	50	29.8	91.82	107.46	17.03333	5.08094	2.170892	13.826	
20111208-3T	50	30.0	91.79	107.97	17.62719	5.09926	2.164195	12.098	
20111208-3M	50	30.9	94.85	111.24	17.27992	6.00698	2.475188	13.647	
20111208-3B	50	30.2	93.04	109.05	17.20765	5.90629	2.490109	13.454	
20111209-1T	50	30.4	92.74	109.47	18.03968	5.25527	2.20106	10.843	
20111209-1M	50	29.9	91.6	108.17	18.08952	5.73999	2.444277	12.254	
20111209-1B	50	30.2	93.04	109.35	17.53009	5.93872	2.503781	13.067	
			Average water content* (%)		**17.56476**	**Average Tensile Strength* (MPa) and Stiffness* (kN/mm)**	**2.258703**	**13.10086**	

**Results from discarded specimens were not included in the calculation of average water content, average tensile strength and average stiffness*

Immersion Time: 10 weeks

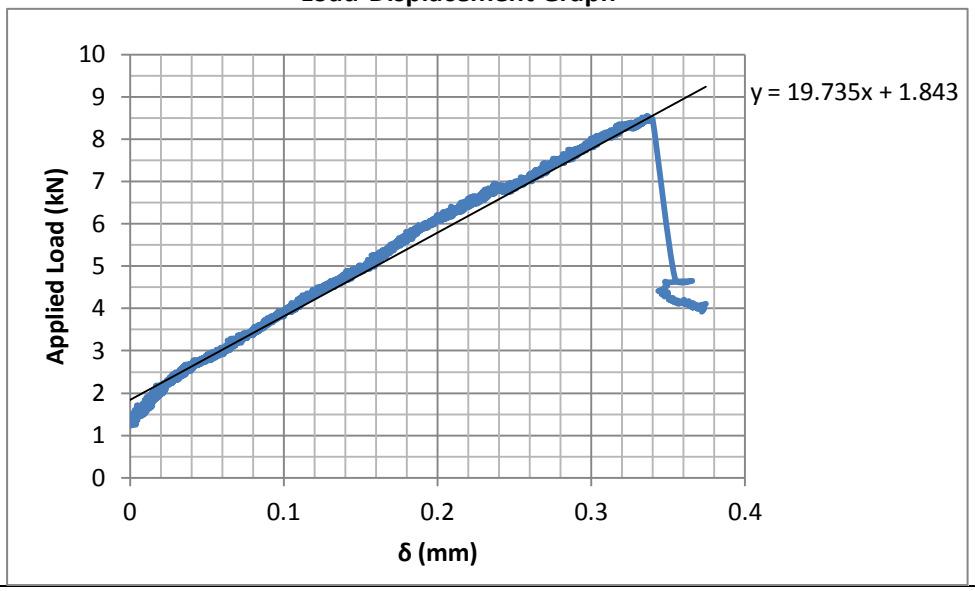
Specimen No	Diameter (mm)	Thickness (mm)	Dry Mass (g)	Wet Mass (g)	Water Content (%)	Max Load (kN)	Tensile Strength (MPa)	Stiffness (kN/mm)	Remarks
20111129-1T	50	31.5	95.85	113.46	18.37246	5.19503	2.099849	18.571	
20111129-1M	50	29.0	88.86	104.91	18.06212	5.03322	2.209828	14.197	
20111129-1B	50	31.4	96.97	113.73	17.2837	5.14311	2.085483	21.029	
20111129-2T	50	30.3	91.96	108.42	17.89909	4.11838	1.73059	22.698	
20111129-2M	50	30.4	92.96	109.41	17.69578	5.78066	2.421109	15.881	
20111129-2B	50	29.6	90.58	106.37	17.4321	5.31733	2.287243	20.582	
20111129-3T	50	30.7	93.47	110.36	18.06997	4.94345	2.050228	19.439	
20111129-3M	50	30.4	93.06	109.7	17.88094	5.61928	2.353518	21.147	
20111129-3B	50	28.5	86.65	101.97	17.68032	5.3396	2.385472	17.081	
20111130-1T	50	28.2	100.48	119.69	19.11823	5.15072	2.325569	19.19	
20111130-1M	50	29.0	88.17	104.3	18.2942	4.92666	2.163043	16.803	
20111130-1B	50	33.6	102.95	121.1	17.62992	5.28971	2.004486	20.962	
20111130-2T	50	31.4	95.17	113.43	19.18672	4.31745	1.750686	20.964	
20111130-2M	50	30.3	93.06	110.16	18.37524	4.76391	2.001849	20.604	
20111130-2B	50	33.2	102.1	120.54	18.06072	5.78099	2.217046	14.274	
20111130-3T	50	32.8	98.66	118.46	20.06892	4.42414	1.717376	13.471	
20111130-3M	50	30.1	91.74	108.62	18.39983	6.09773	2.579361	18.311	
20111130-3B	50	31.8	97.12	114.61	18.00865	5.21994	2.090012	18.398	
			Average water content (%)		**18.1955**	**Average Tensile Strength (MPa) and Stiffness (kN/mm)**	**2.137375**	**18.53344**	

APPENDIX B

Results of Brazilian Tensile Tests

Specimen No: 20111209-2T

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

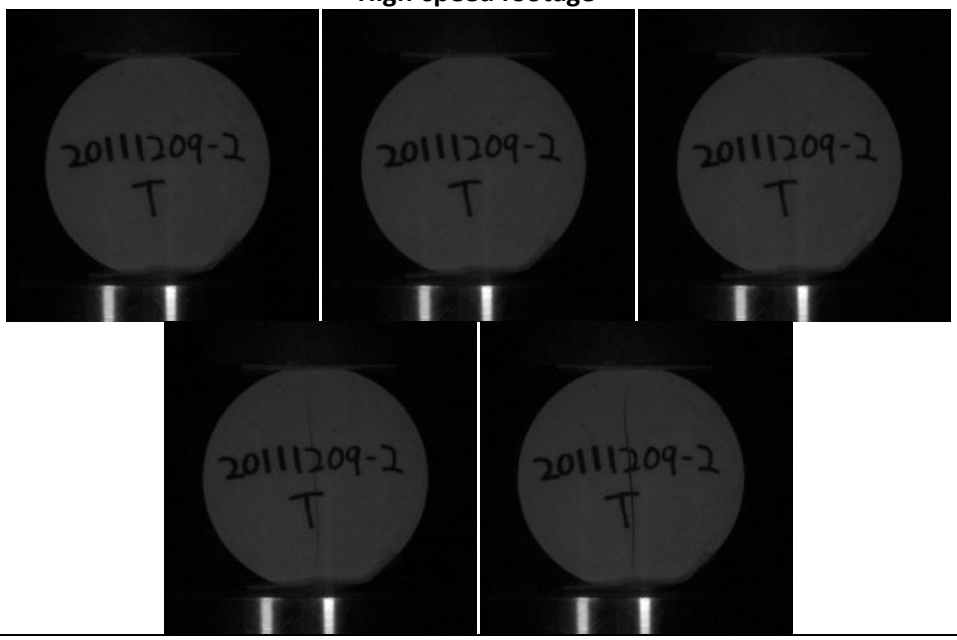
Thickness
30.5mm

Max Load
8.55851kN

Tensile Strength
3.573MPa

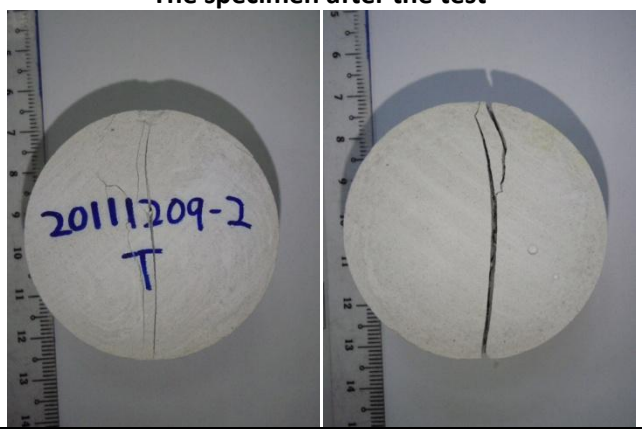
Stiffness
19.735kN/mm

High-speed footage



High speed footage shows the primary crack initiated at the centre of the specimen. The crack later lengthened to form a diametrical crack.

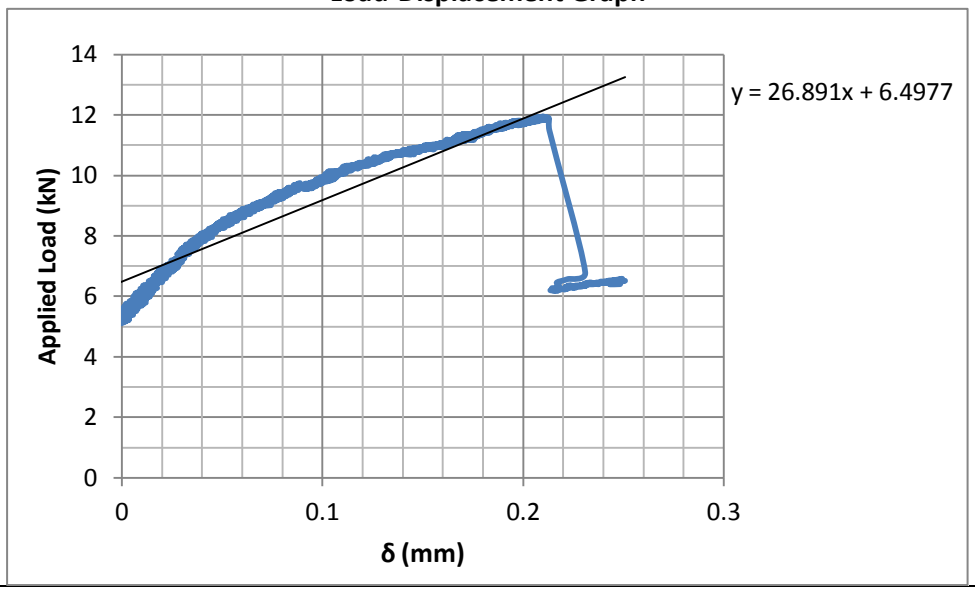
The specimen after the test



Some secondary cracks developed after the last captured frame from the high-speed camera.

Specimen No: 20111209-2M (Discarded)

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

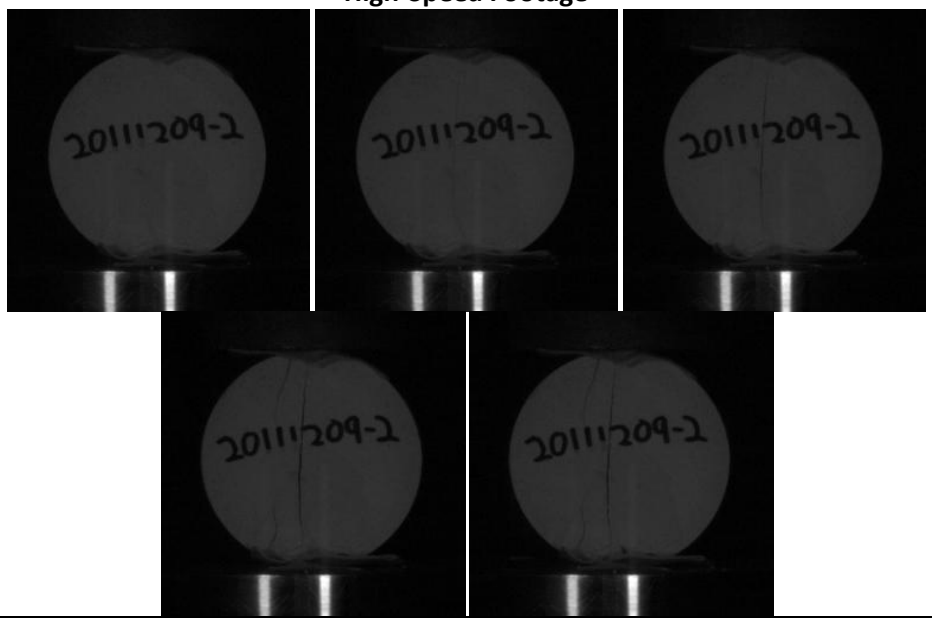
Thickness
29.9mm

Max Load
11.9491kN

Tensile Strength
5.0883MPa

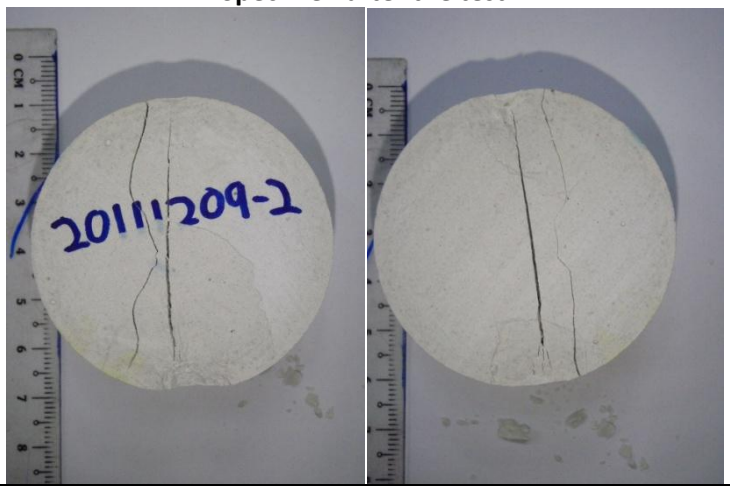
Stiffness
26.891kN/mm

High-Speed Footage



Surface spalling has occurred before the first diametrical crack was initiated. Secondary cracks occurred soon after the first diametrical crack.

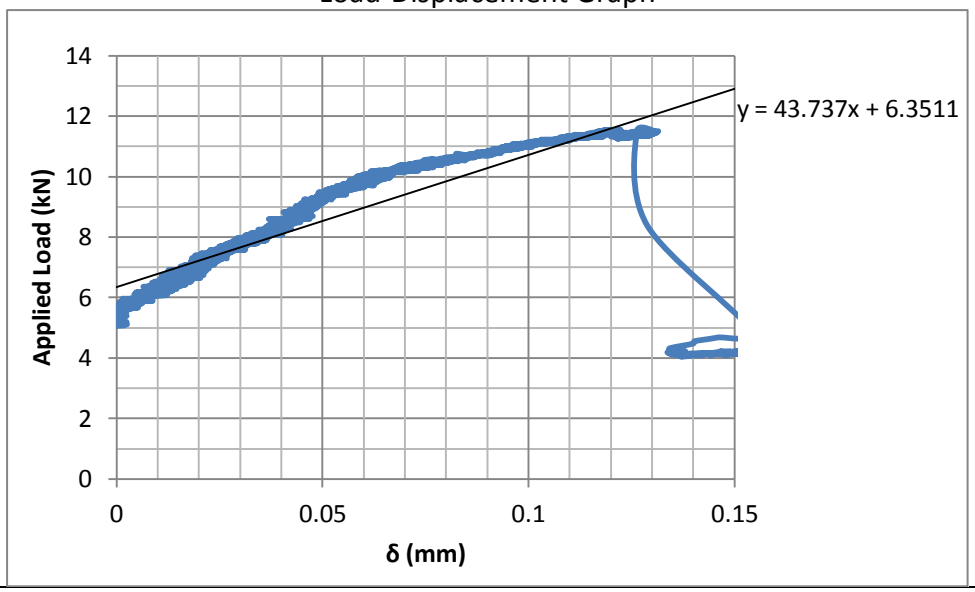
Specimen after the test



Note: Results from this specimen was discarded due to surface spalling before the first diametrical crack.

Specimen No: 20111209-2B

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

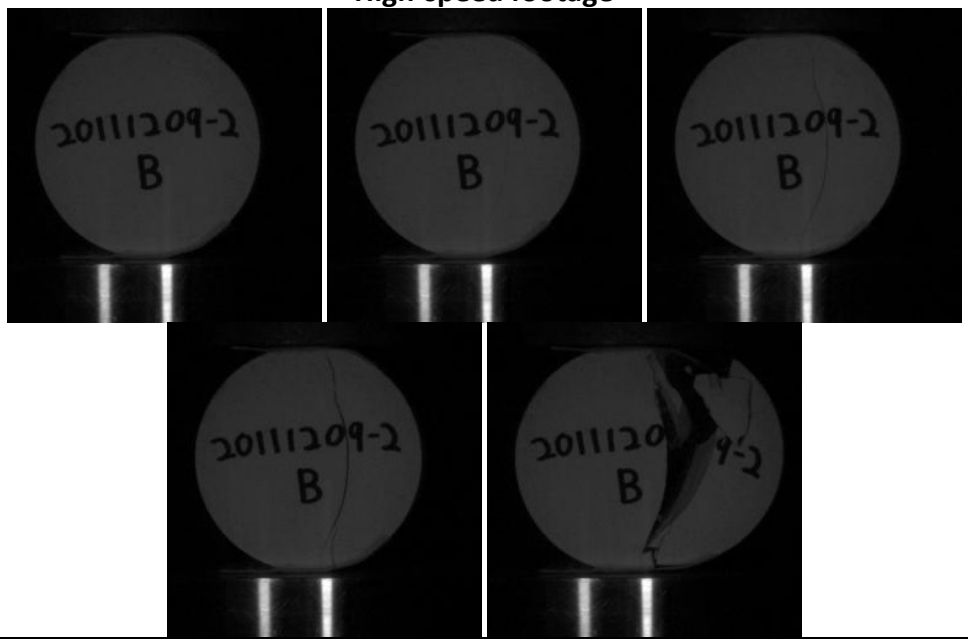
Thickness
30.2mm

Max Load
11.5691kN

Tensile Strength
4.878MPa

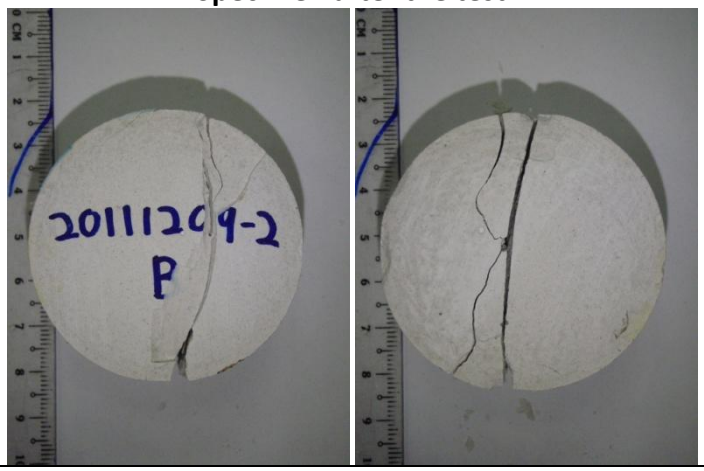
Stiffness
43.737kN/mm

High-speed footage



The crack initiated slightly off-centred in the specimen. The crack lengthened and broke through the top and bottom of the specimen causing the specimen to break apart.

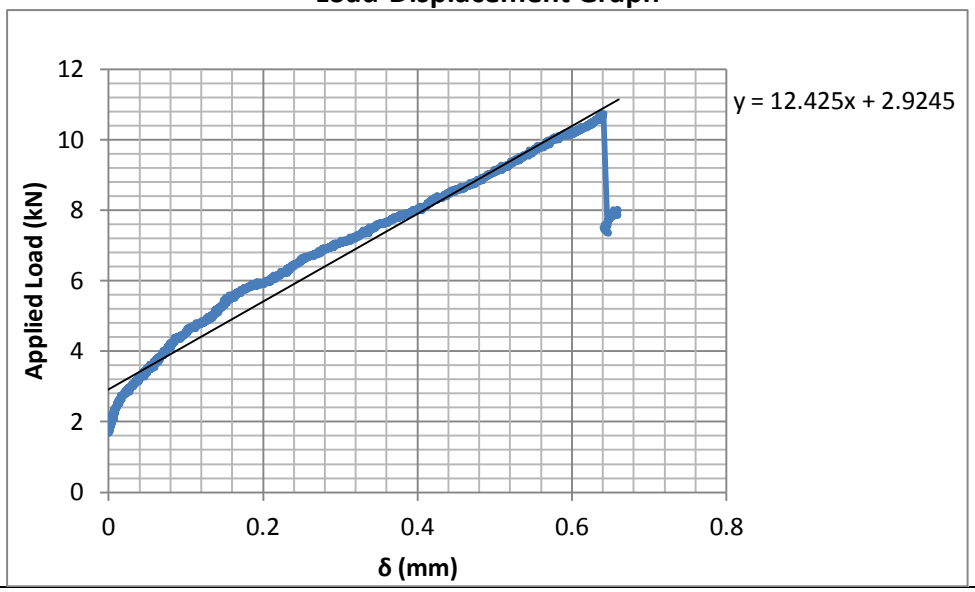
Specimen after the test



The front and back of the failed specimen showed secondary cracks developed after the primary failure of the specimen.

Specimen No: 20111209-3T

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

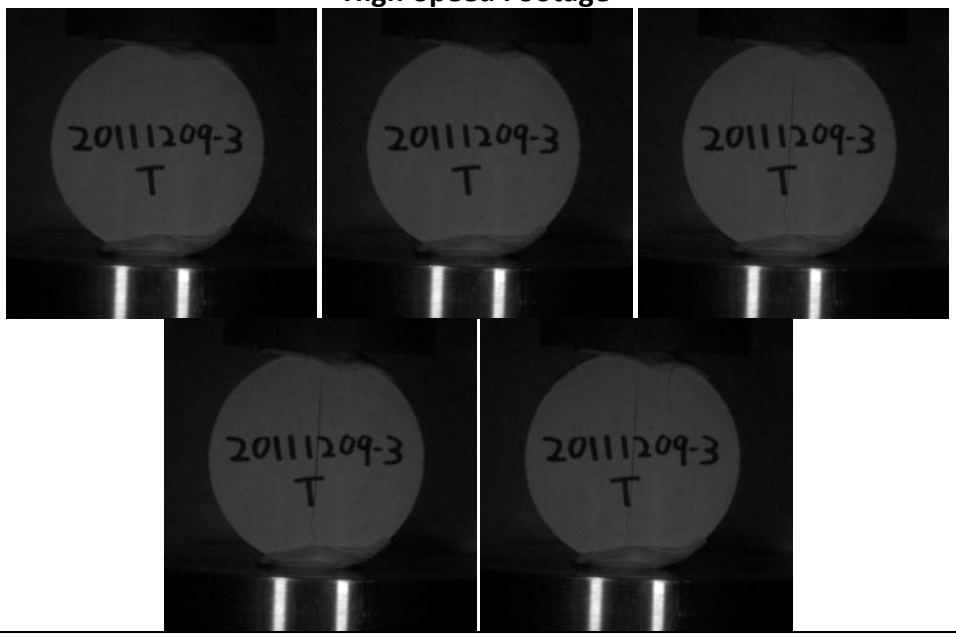
Thickness
30.1mm

Max Load
10.7692kN

Tensile Strength
4.555MPa

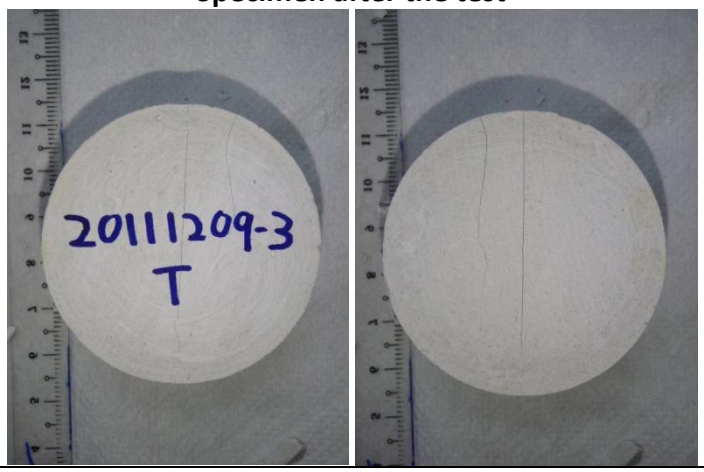
Stiffness
12.425kN/mm

High-Speed Footage



The primary crack initiated at the centre of the specimen before it lengthened and widened. Secondary cracks developed shortly after the primary diametrical crack.

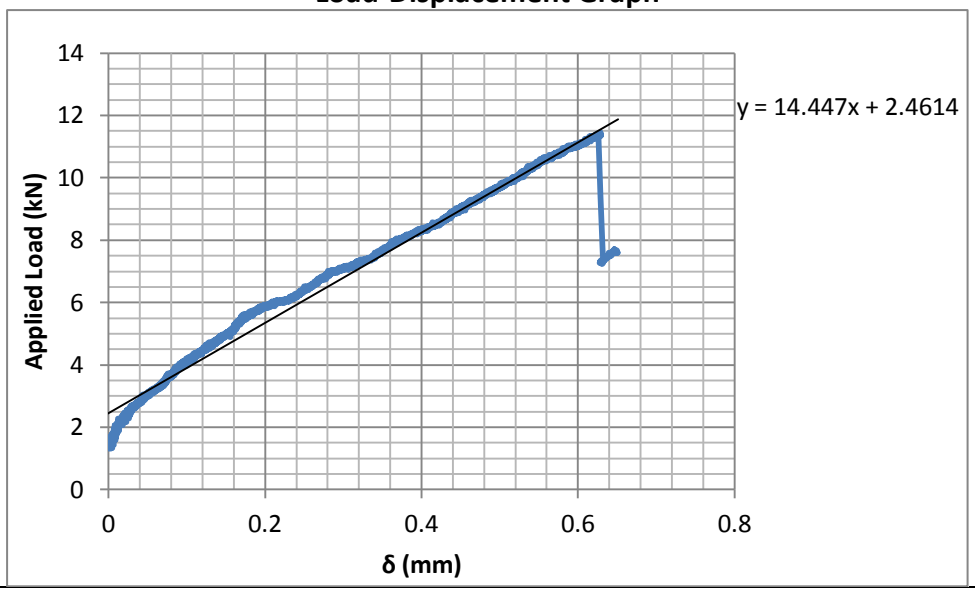
Specimen after the test



The primary crack did not extend through the top and bottom of the specimen. Through physical inspection of the specimen, it can be deduced that the primary crack initiated at its centre.

Specimen No: 20111209-3M

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

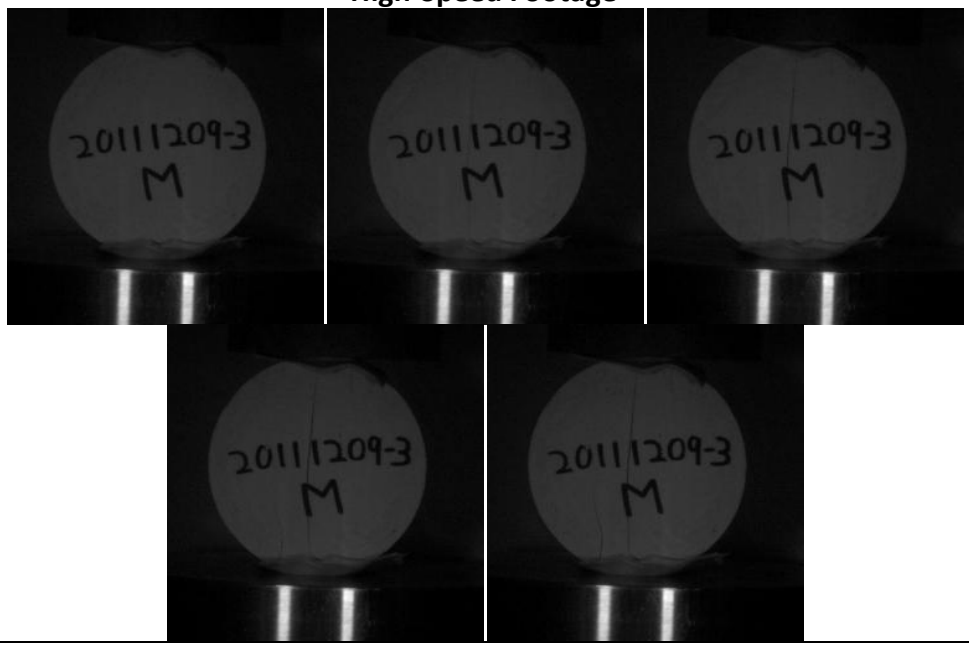
Thickness
30.0mm

Max Load
11.4549kN

Tensile Strength
4.862MPa

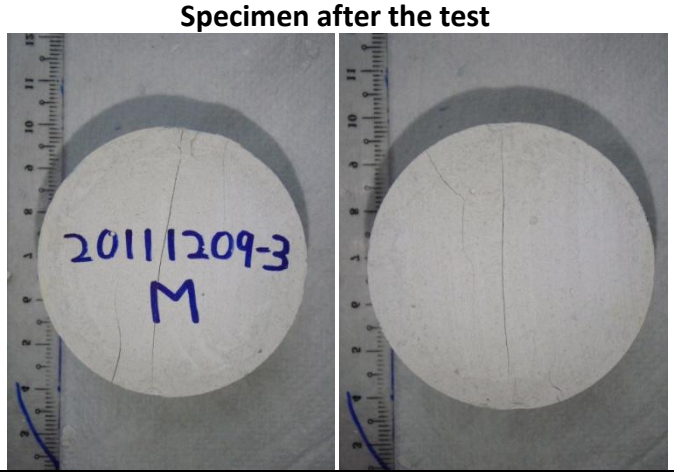
Stiffness
14.447kN/mm

High-Speed Footage



The primary crack initiated at the centre of the specimen before it lengthened and widened. Secondary cracks developed shortly after the primary diametrical crack.

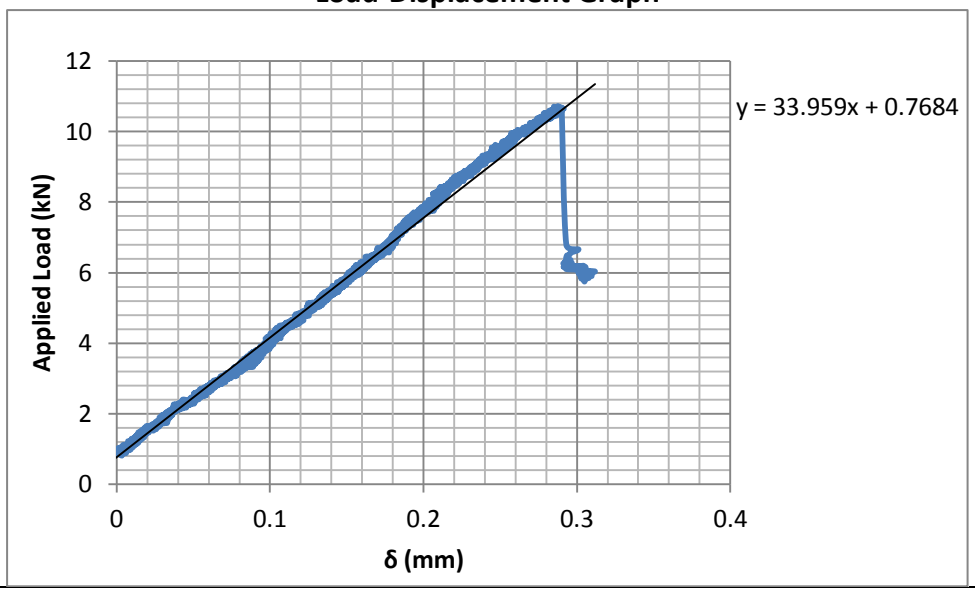
Specimen after the test



The primary crack did not extend through the top and bottom of the specimen. Through physical inspection of the specimen, it can be deduced that the primary crack initiated at its centre.

Specimen No: 20111209-3B (Discarded)

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

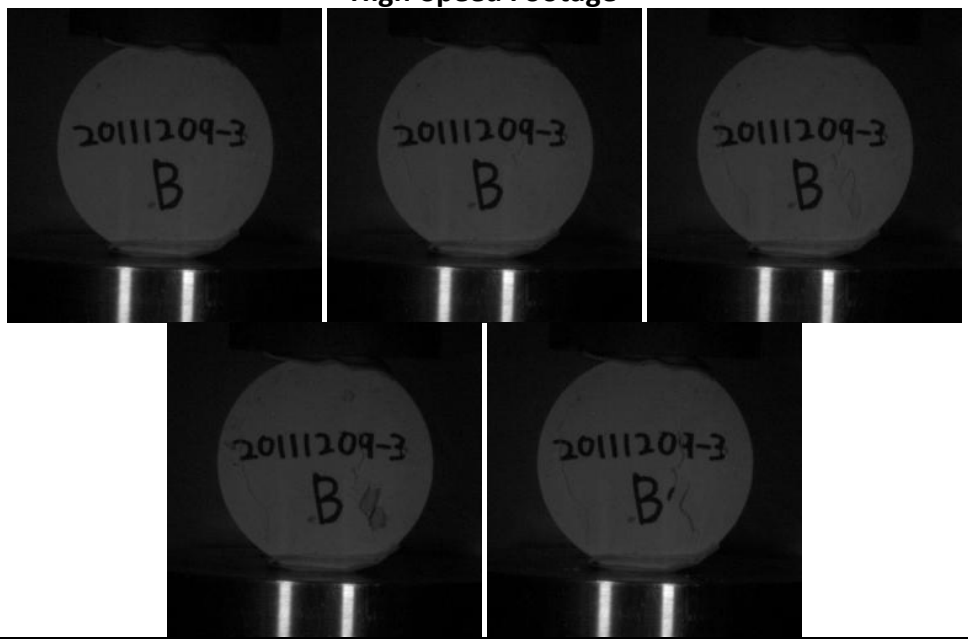
Thickness
30.1mm

Max Load
10.7214kN

Tensile Strength
4.535MPa

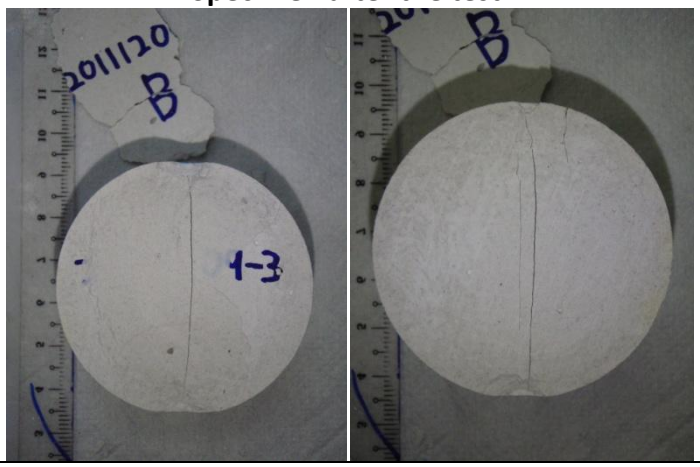
Stiffness
33.959kN/mm

High-Speed Footage



Surface spalling of the specimen occurred and prevented the high-speed camera from capturing the initiation of the primary crack.

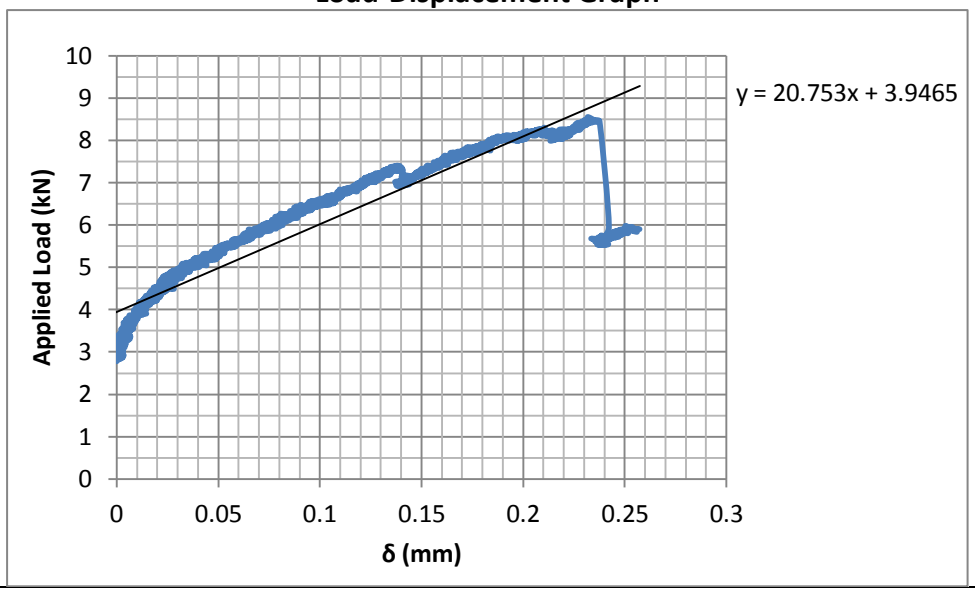
Specimen after the test



Note: Results from this specimen was discarded due to surface spalling occurring before the first diametrical crack.

Specimen No: 20111215-1T (Discarded)

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

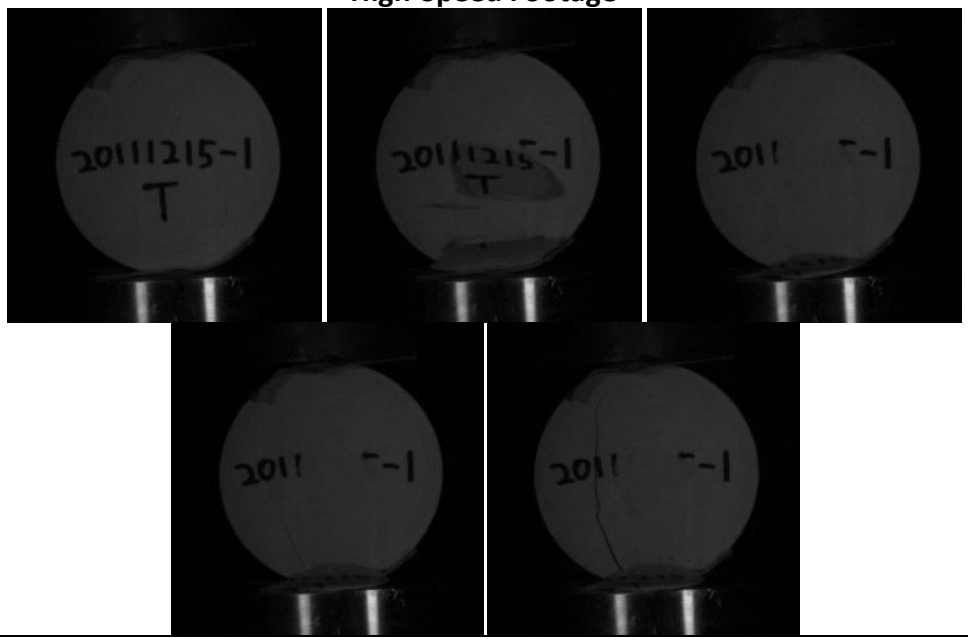
Thickness
30.5mm

Max Load
8.5567kN

Tensile Strength
3.572MPa

Stiffness
20.753kN/mm

High-Speed Footage



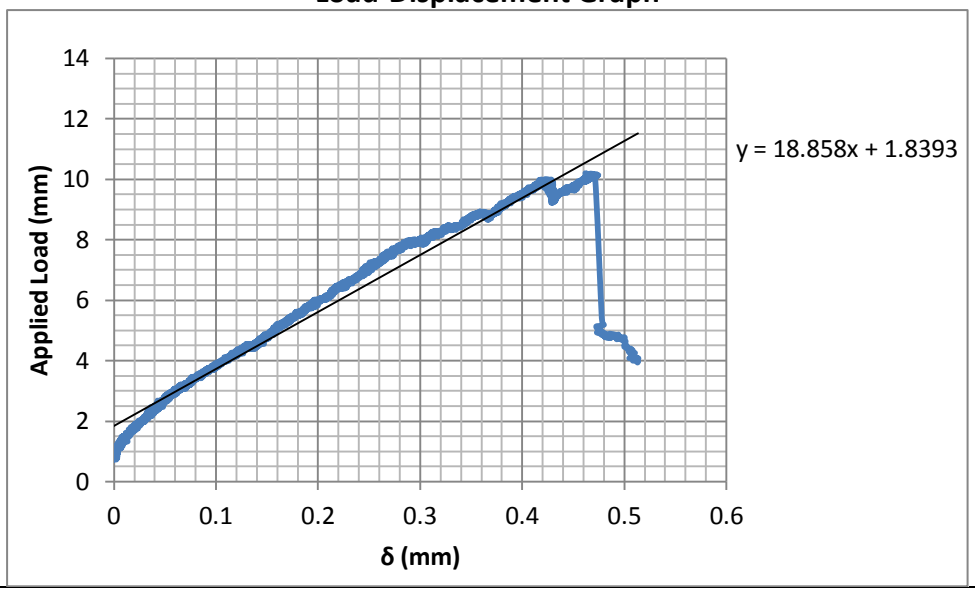
Surface spalling firstly occurred. The primary crack was then initiated at the bottom of the specimen and the crack propagated into the specimen along pre-existing weakness in the specimen.

Specimen after the test

Note: Results from this specimen was discarded due to surface spalling occurring before the actual failure of the specimen.

Specimen No: 20111215-1M (Discarded)

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

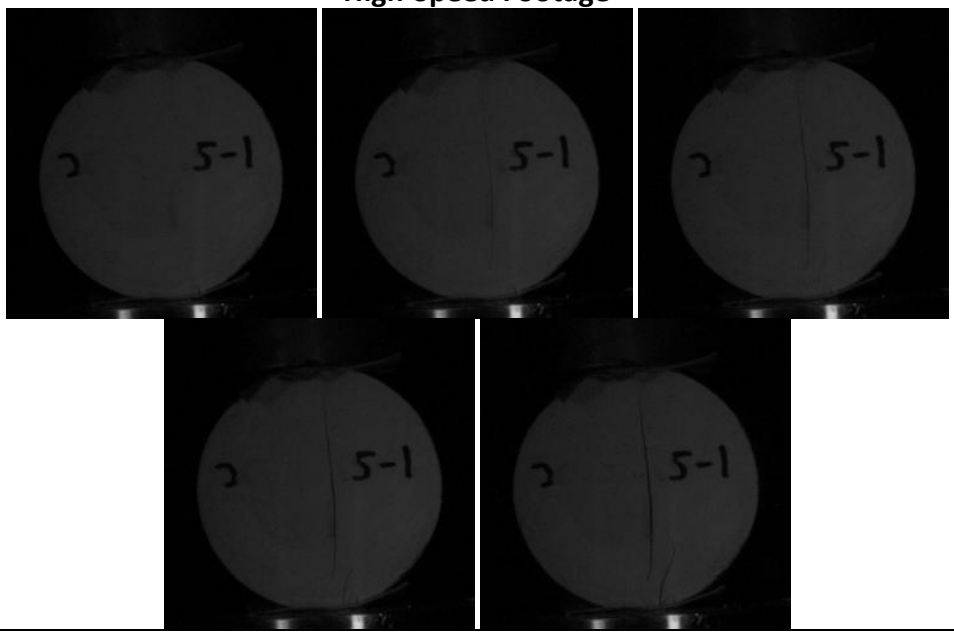
Thickness
29.8mm

Max Load
10.2029kN

Tensile Strength
4.359MPa

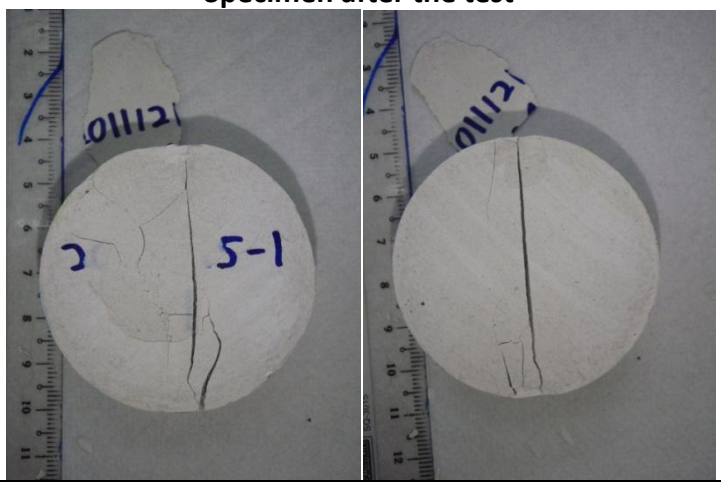
Stiffness
18.858kN/mm

High-Speed Footage



Surface spalling has occurred before the first diametrical crack was initiated at the centre of the specimen. Shortly afterwards, a secondary crack was formed near the bottom of the specimen.

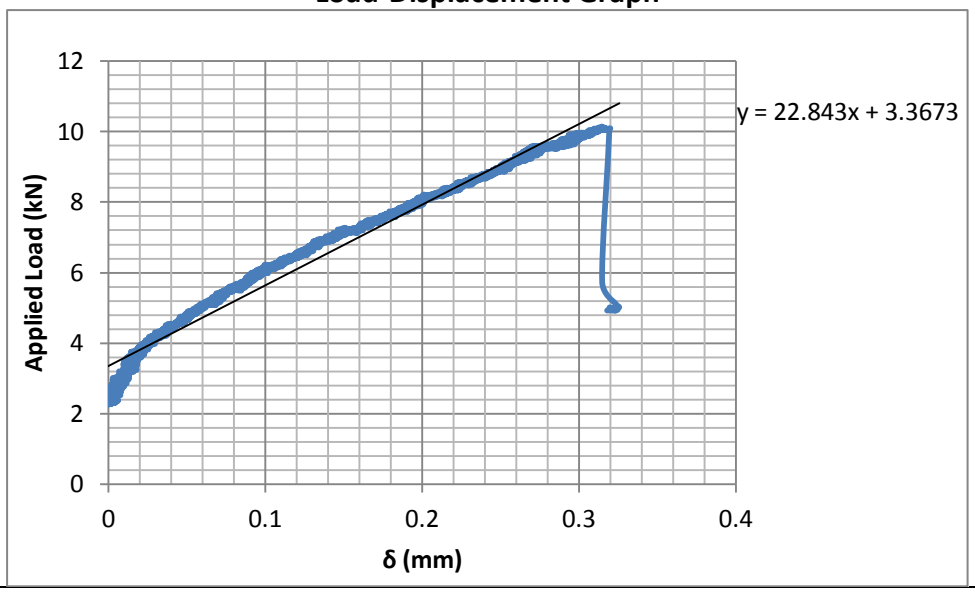
Specimen after the test



Note: Results from this specimen was discarded due to surface spalling occurring before the first diametrical crack.

Specimen No: 20111215-1B

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

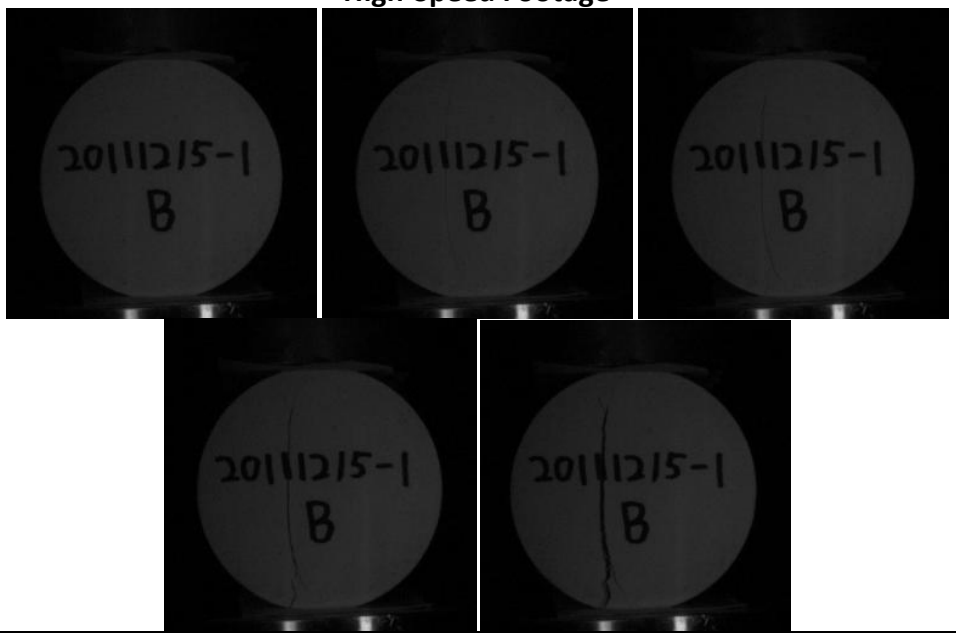
Thickness
29.9mm

Max Load
10.1483kN

Tensile Strength
4.321MPa

Stiffness
22.843kN/mm

High-Speed Footage

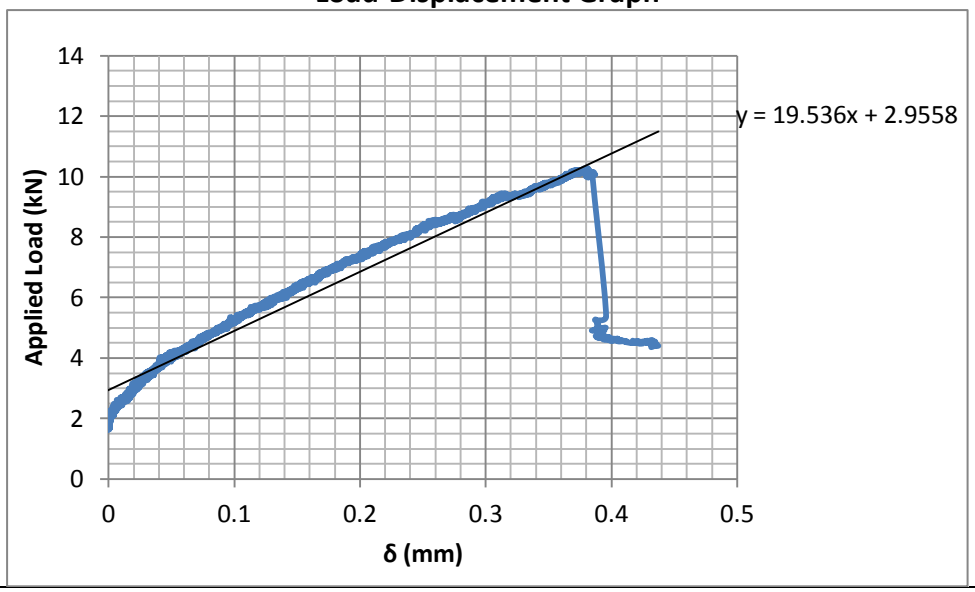


The primary crack was initiated at the centre of the specimen. Then, a secondary crack was formed from the bottom of the specimen and propagated into the primary crack causing the specimen to break apart.

Specimen after the test

Specimen No: 20111215-2T

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

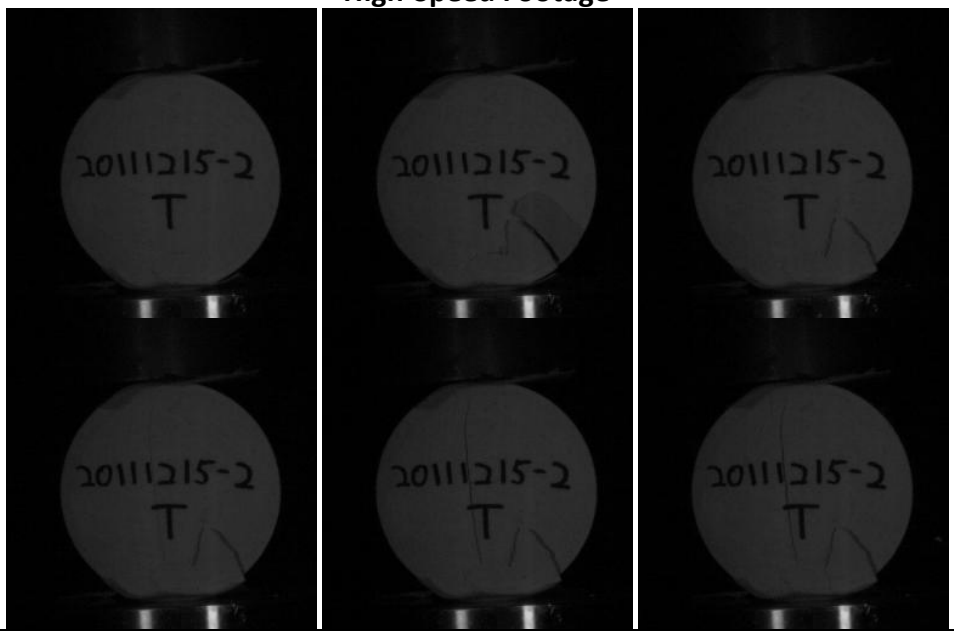
Thickness
30.4mm

Max Load
10.2858kN

Tensile Strength
4.308MPa

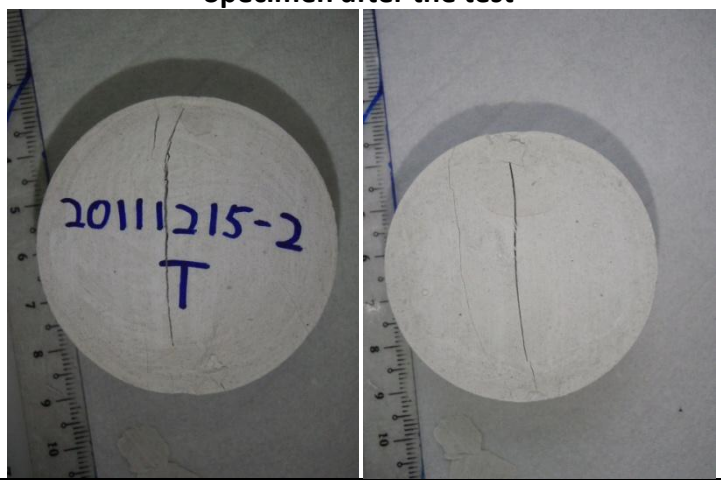
Stiffness
19.536kN/mm

High-Speed Footage



Minor surface spalling firstly occurred near the bottom-right of the specimen. Then, the diametrical crack was initiated at the centre of the specimen away from the spalled surface.

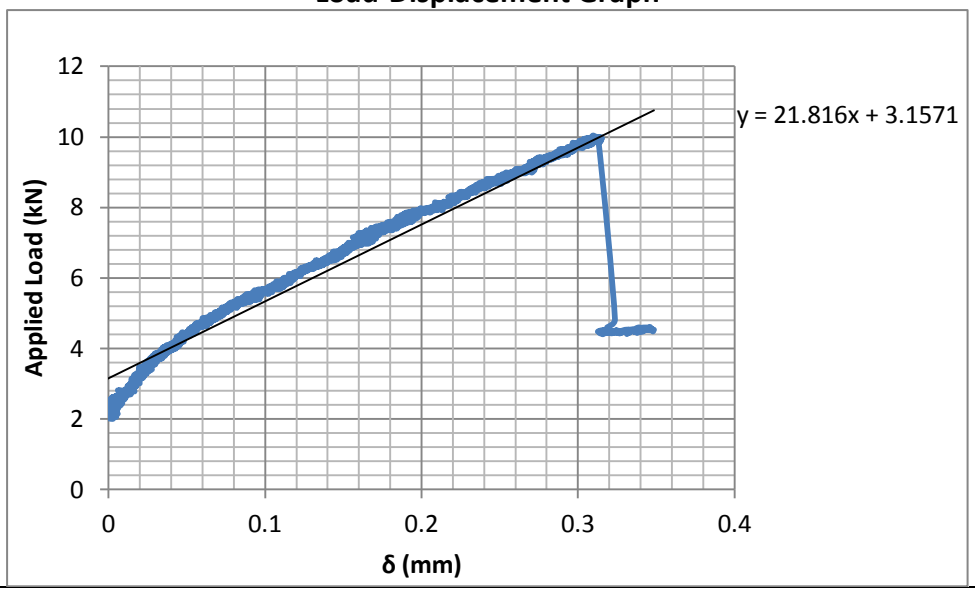
Specimen after the test



Although minor surface spalling occurred, the result of this specimen was not discarded as the primary crack was initiated at a location not affected by the surface spalling.

Specimen No: 20111215-2M

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

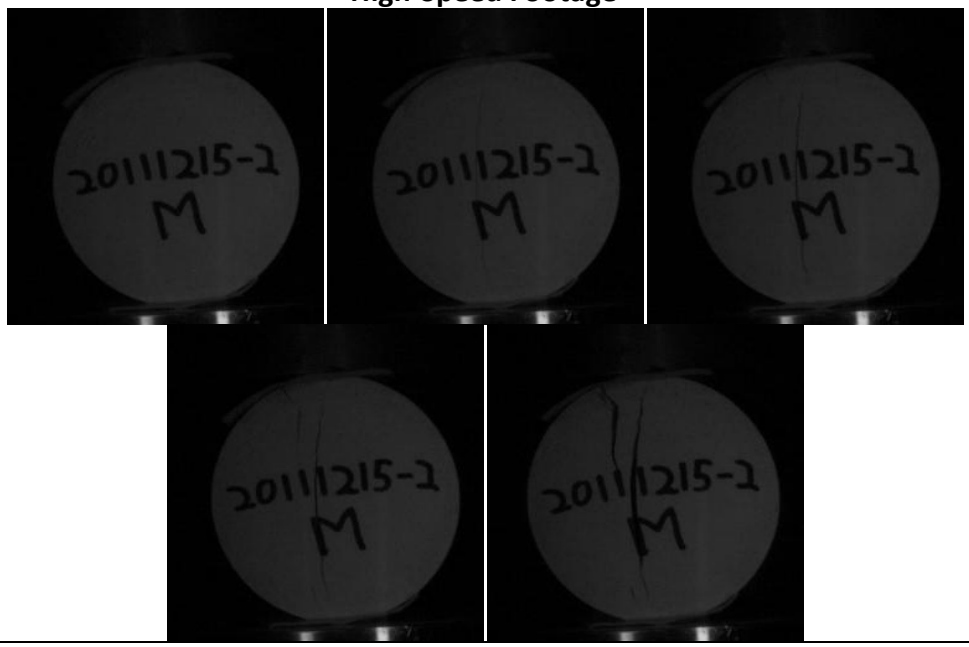
Thickness
29.8mm

Max Load
10.0366kN

Tensile Strength
4.288MPa

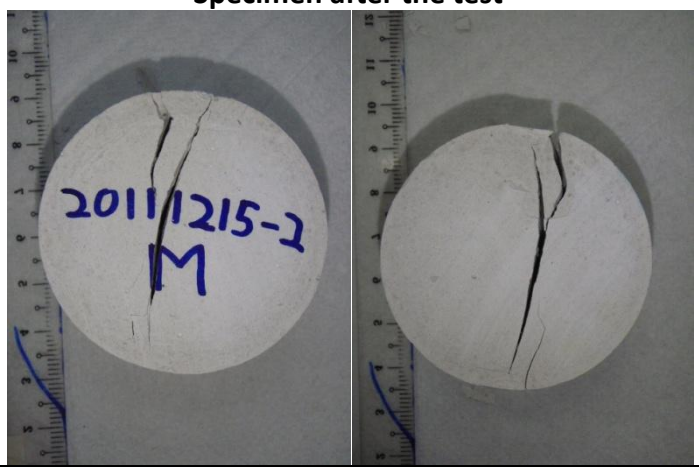
Stiffness
21.816kN/mm

High-Speed Footage



The primary crack was initiated at the centre of the specimen and lengthened to form a diametrical crack. Secondary cracks were formed shortly afterwards at the top of the specimen.

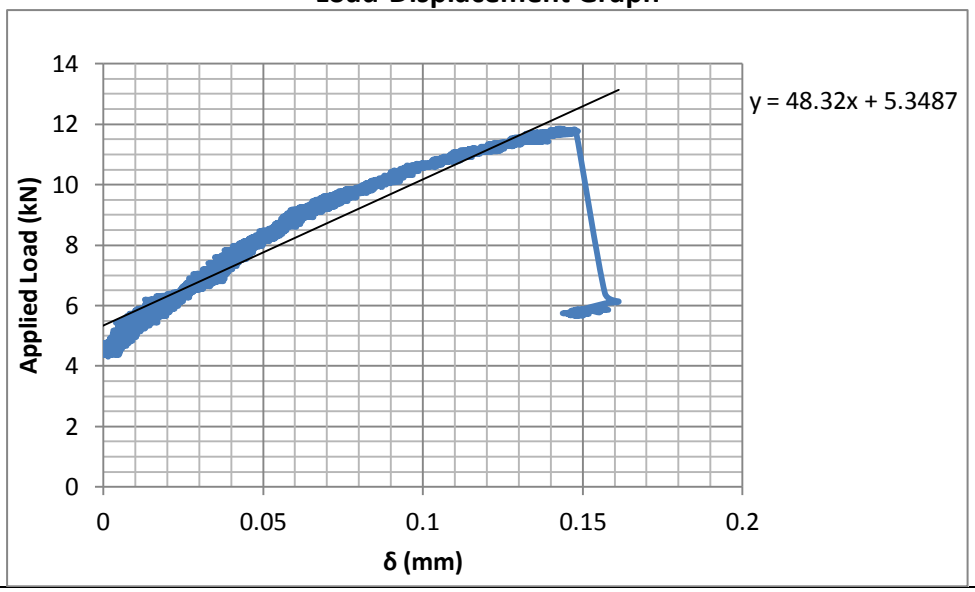
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen. Hence, tensile failure occurred in this specimen.

Specimen No: 20111215-2B

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

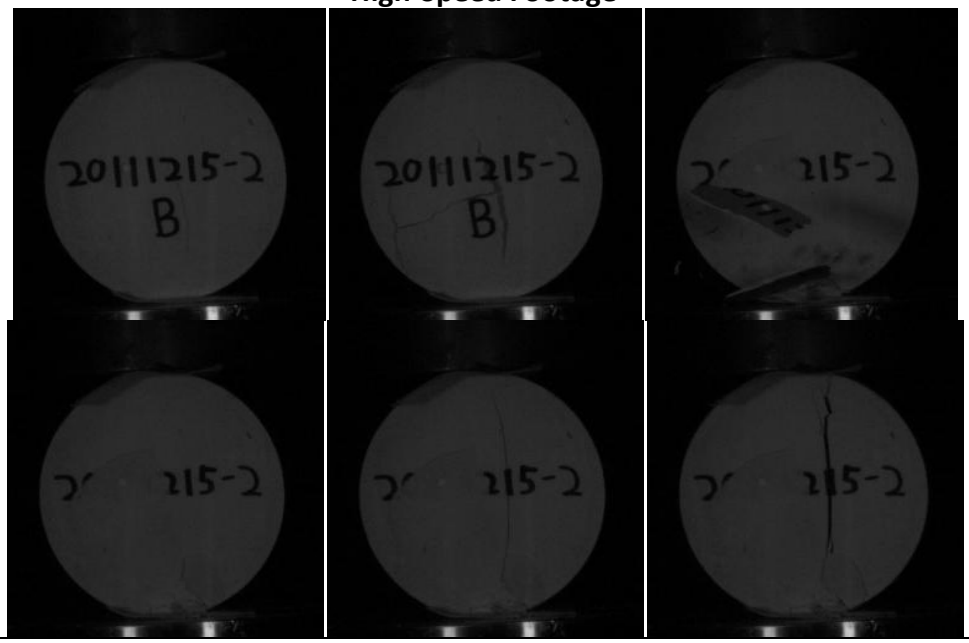
Thickness
30.6mm

Max Load
11.8596kN

Tensile Strength
4.935MPa

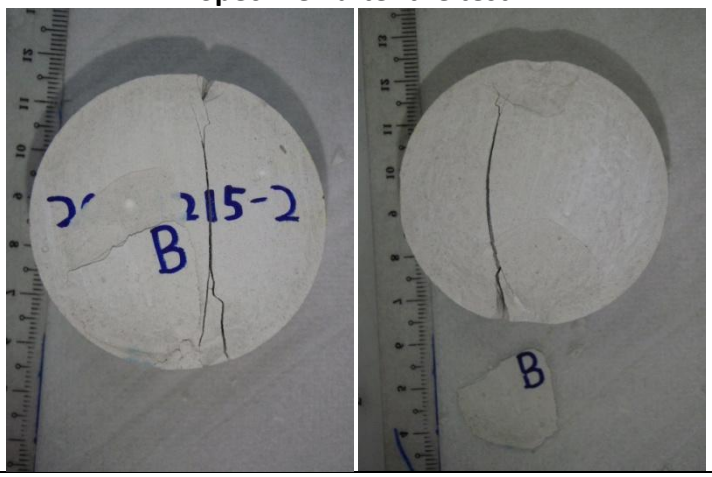
Stiffness
48.32kN/mm

High-Speed Footage



Surface spalling firstly occurred on the centre-left of the specimen. The primary crack was then initiated at the centre of the specimen away from the spalled surface.

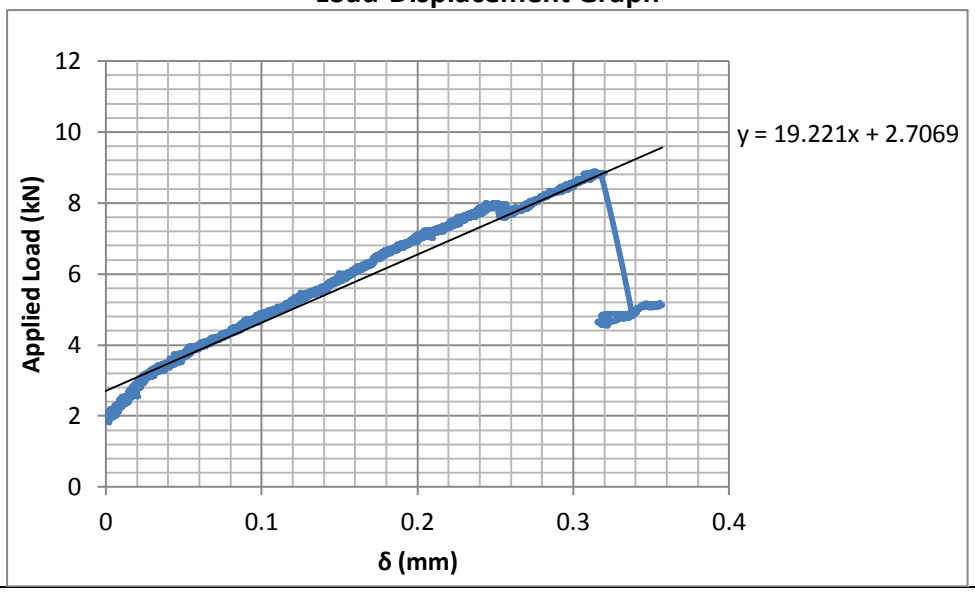
Specimen after the test



Although surface spalling occurred, the result of this specimen was not discarded as the primary crack was initiated and propagated through locations not affected by the surface spalling.

Specimen No: 20111215-3T (Discarded)

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

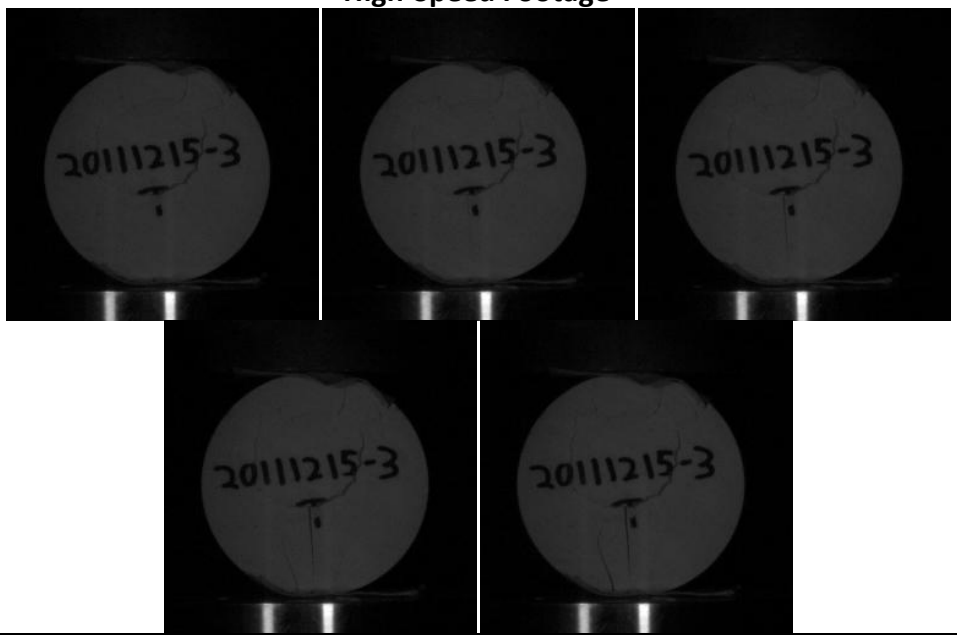
Thickness
30.2mm

Max Load
8.9113kN

Tensile Strength
3.757MPa

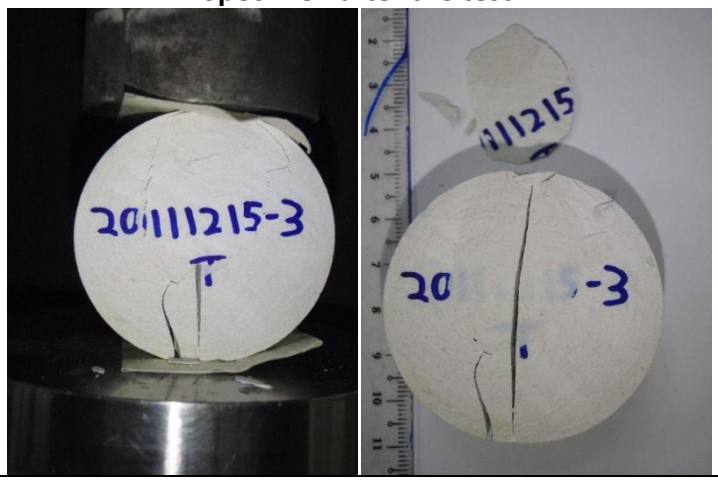
Stiffness
19.221kN/mm

High-Speed Footage



Surface spalling of the specimen occurred and prevented the high-speed camera from fully capturing the initiation of the primary crack.

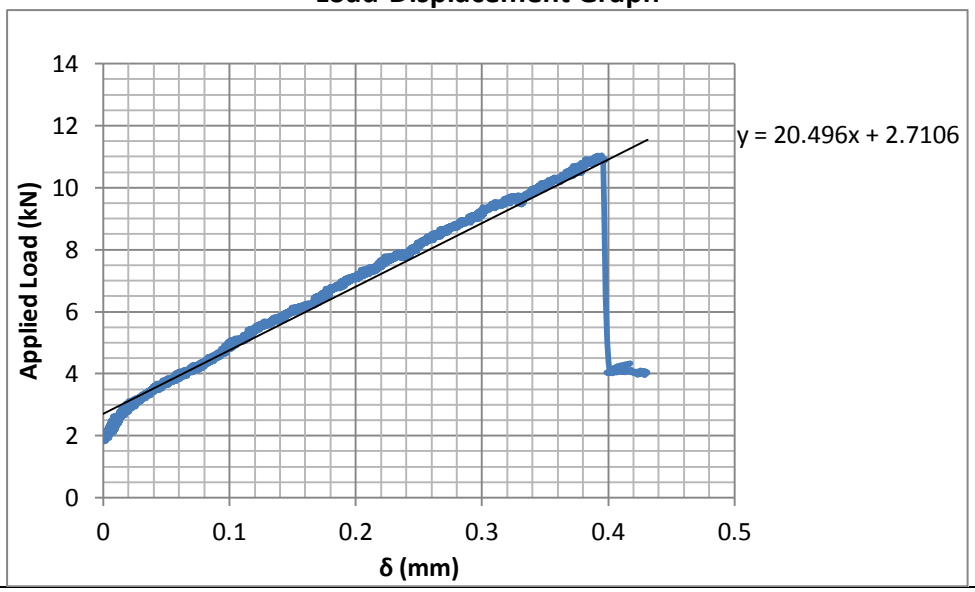
Specimen after the test



Note: Results from this specimen was discarded due to surface spalling occurring before the first diametrical crack.

Specimen No: 20111215-3M

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

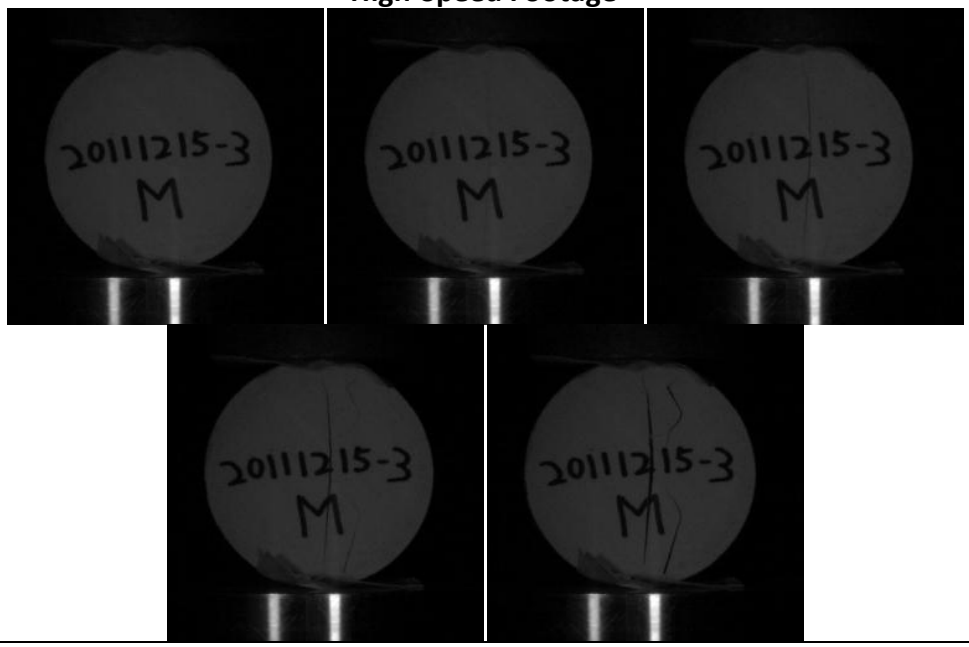
Thickness
30.0mm

Max Load
11.0463kN

Tensile Strength
4.688MPa

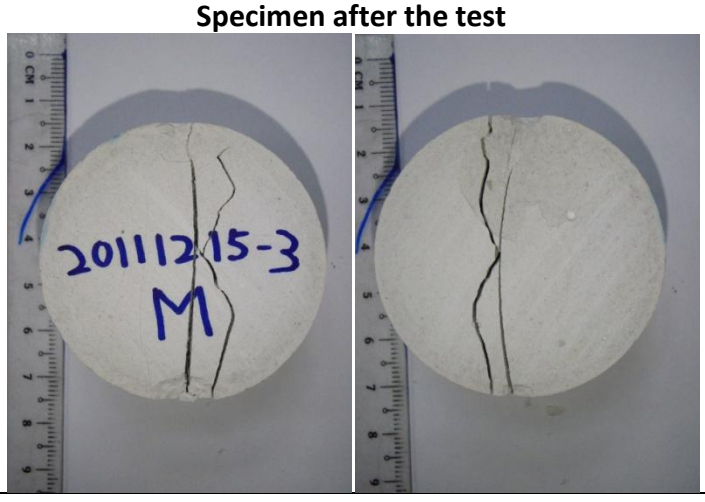
Stiffness
20.496kN/mm

High-Speed Footage



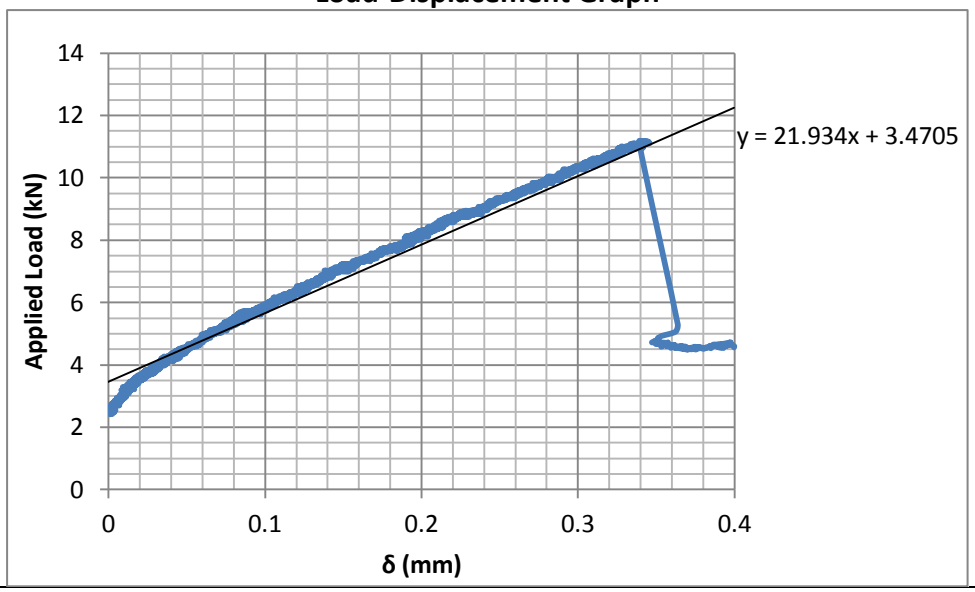
The primary crack was initiated at the centre of the specimen and lengthened to form a diametrical crack. Secondary cracks was formed shortly afterwards from the top and bottom of the specimen.

Specimen after the test



Specimen No: 20111215-3B

Load-Displacement Graph



Immersion Time
0 (Dry)

Diameter
50mm

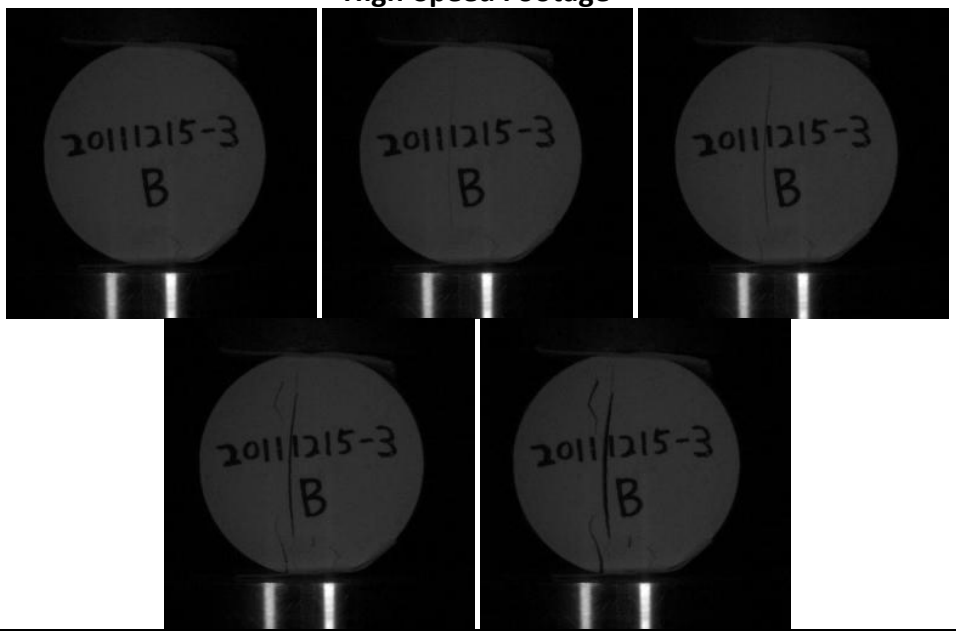
Thickness
30.8mm

Max Load
11.1925kN

Tensile Strength
4.627MPa

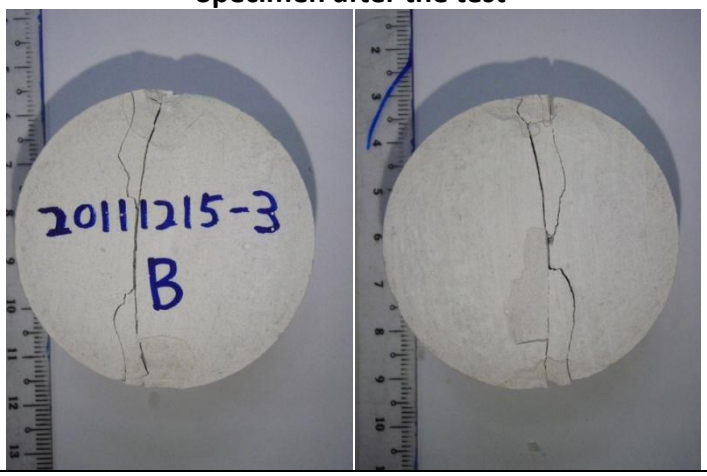
Stiffness
21.934kN/mm

High-Speed Footage



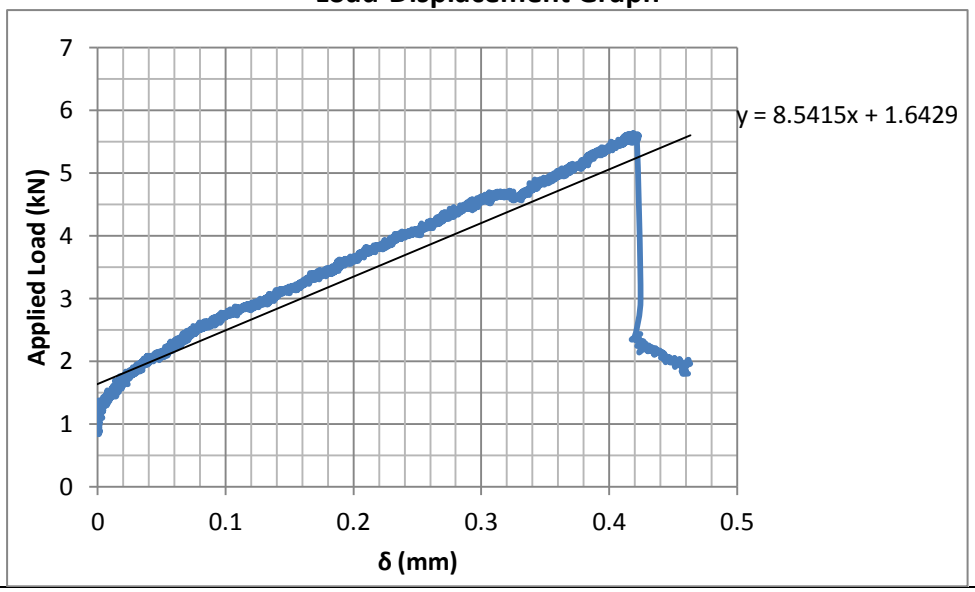
The primary crack was initiated at the centre of the specimen and lengthened to form a diametrical crack. Secondary cracks was formed shortly afterwards from the top and bottom of the specimen.

Specimen after the test



Specimen No: 20111206-1T

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

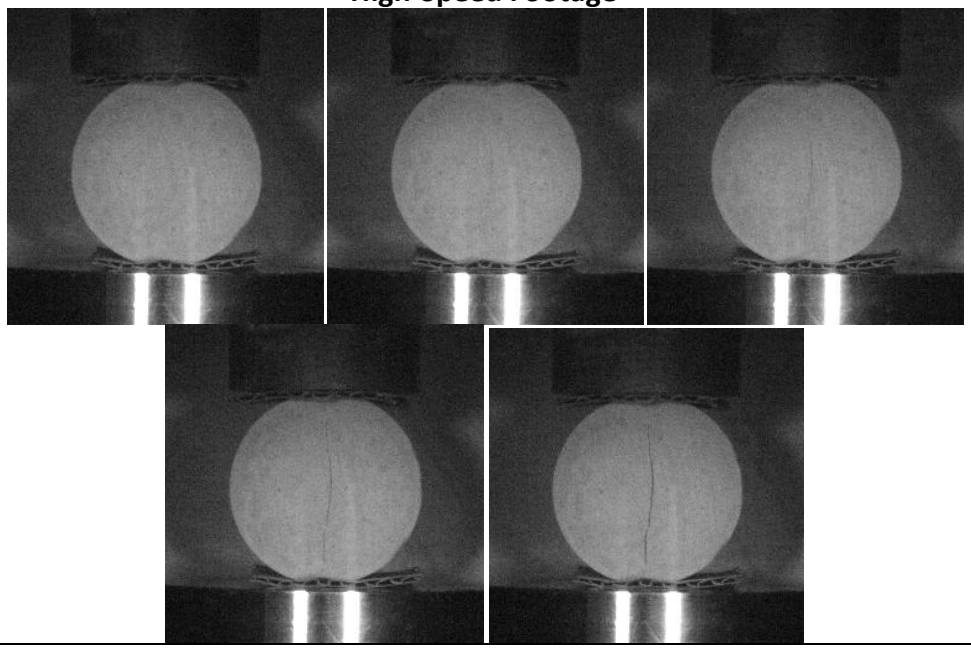
Thickness
30.0mm

Max Load
5.6498kN

Tensile Strength
2.398MPa

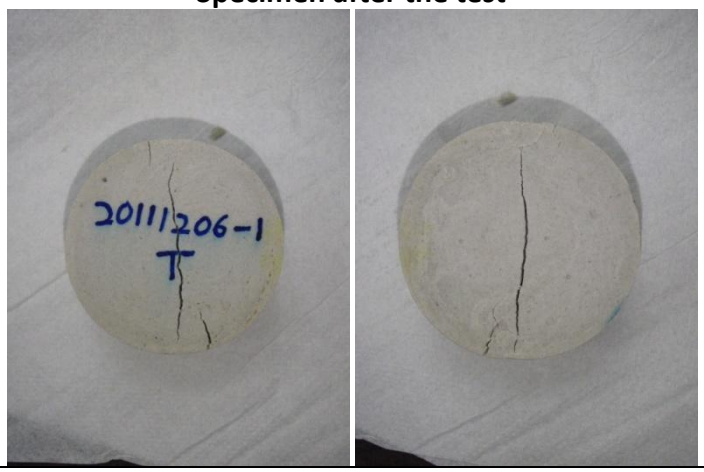
Stiffness
8.5415kN/mm

High-Speed Footage



High speed footage shows the primary crack initiated at the centre of the specimen. The crack later lengthened to form a diametrical crack.

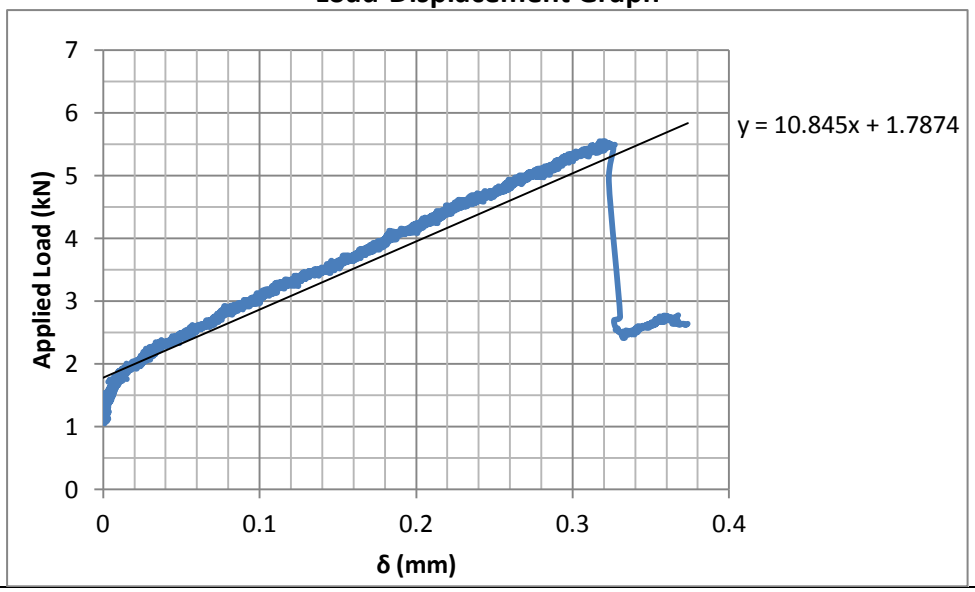
Specimen after the test



Secondary cracks are formed at the top and bottom of the specimen after the primary crack has occurred.

Specimen No: 20111206-1M

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

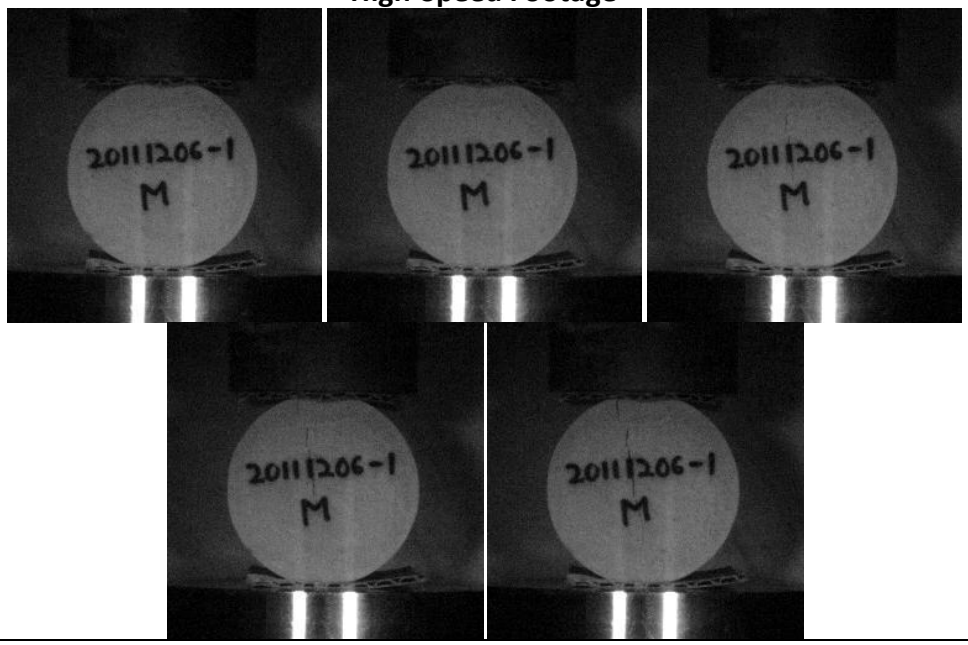
Thickness
30.0mm

Max Load
5.55498kN

Tensile Strength
2.358MPa

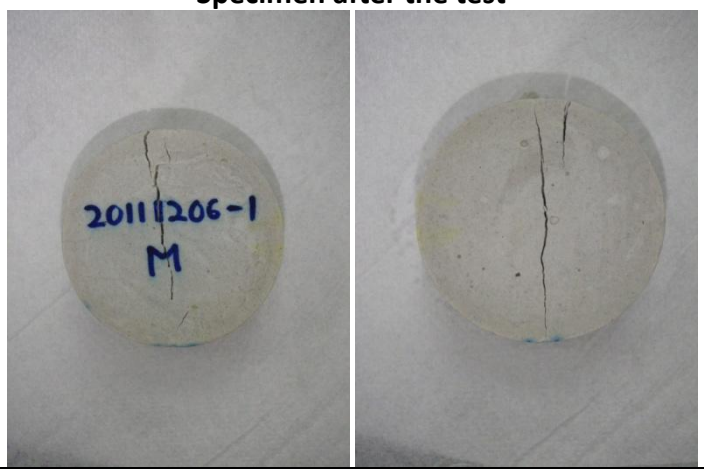
Stiffness
10.845kN/mm

High-Speed Footage



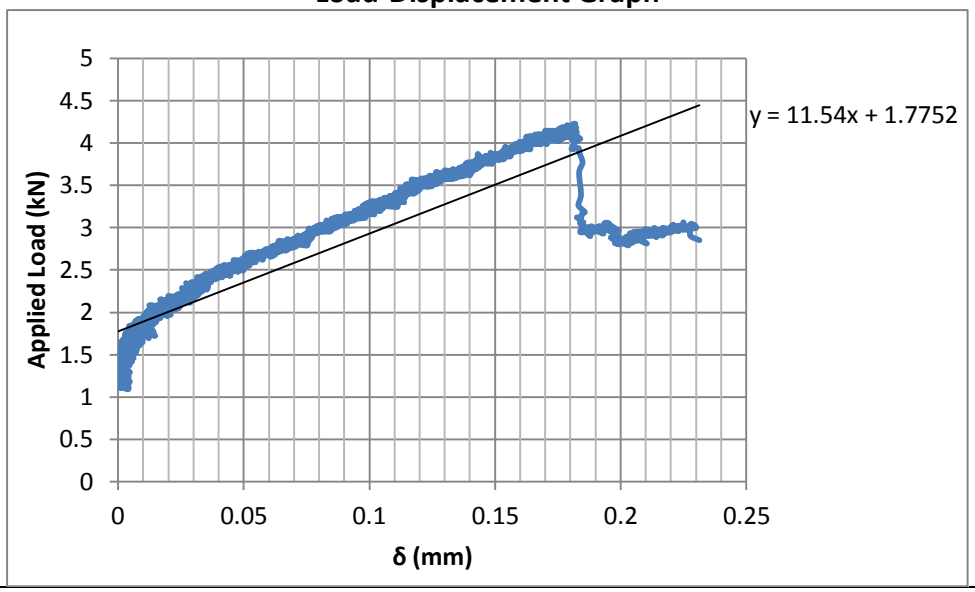
The primary crack initiated at the centre of the specimen and lengthened to the top and bottom of the specimen. The primary crack became connected to a secondary crack near the top of the specimen.

Specimen after the test



Specimen No: 20111206-1B

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

Thickness
30.7mm

Max Load
4.22071kN

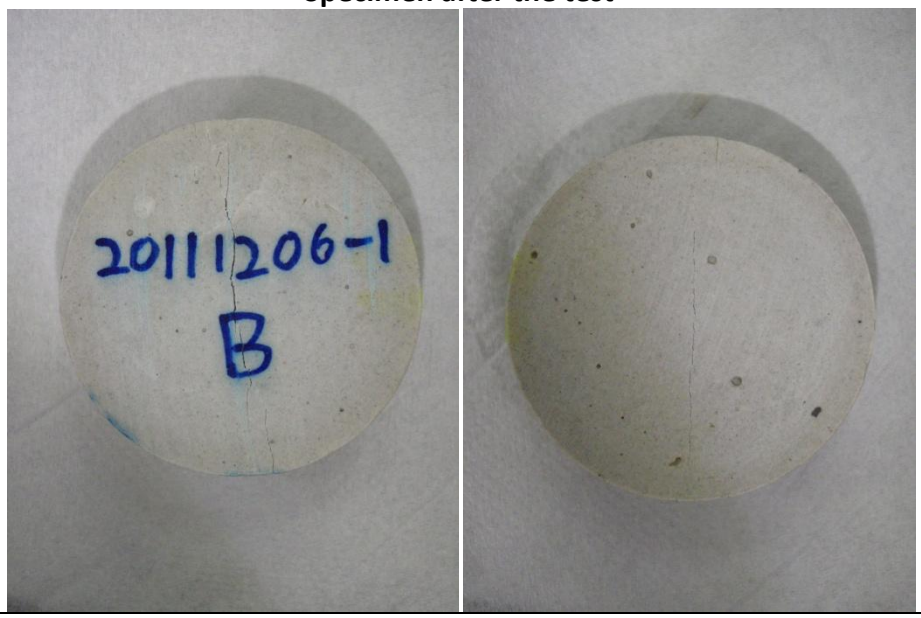
Tensile Strength
1.750MPa

Stiffness
11.54kN/mm

High-Speed Footage

Not Available

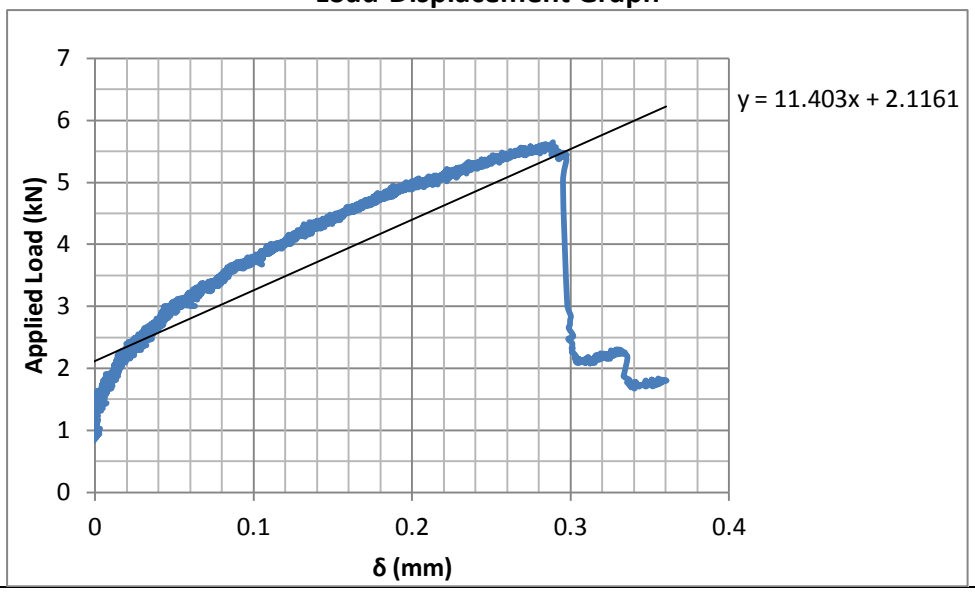
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen. Hence, it can be deduced that the crack initiated at the centre of the specimen and tensile failure has occurred.

Specimen No: 20111206-2T

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

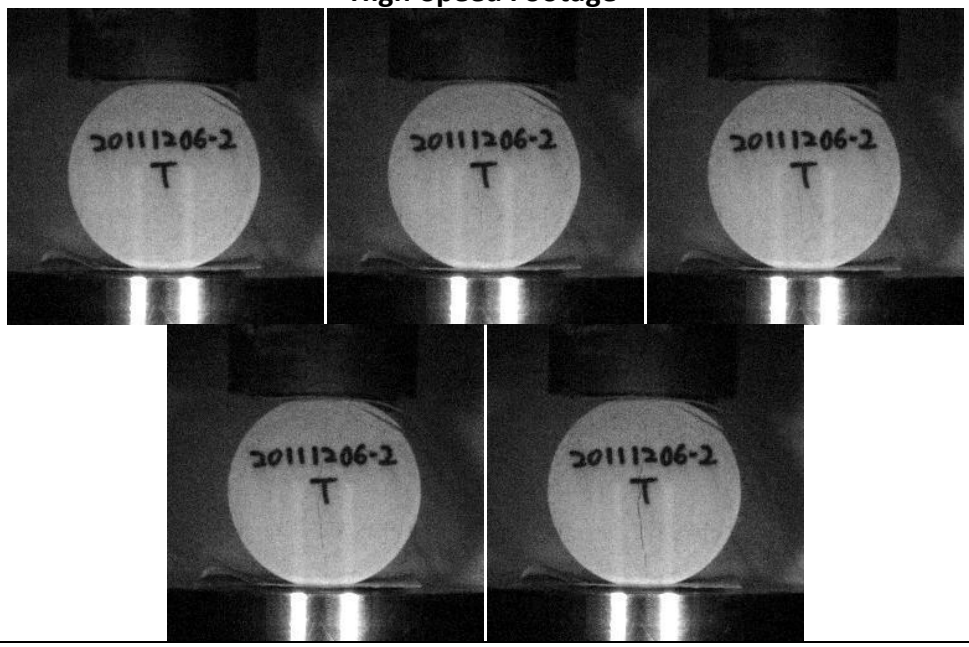
Thickness
30.1mm

Max Load
5.64776kN

Tensile Strength
2.389MPa

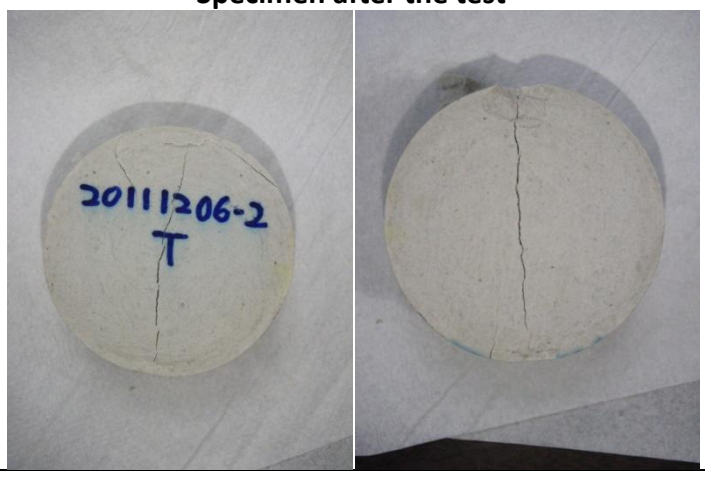
Stiffness
11.403kN/mm

High-Speed Footage



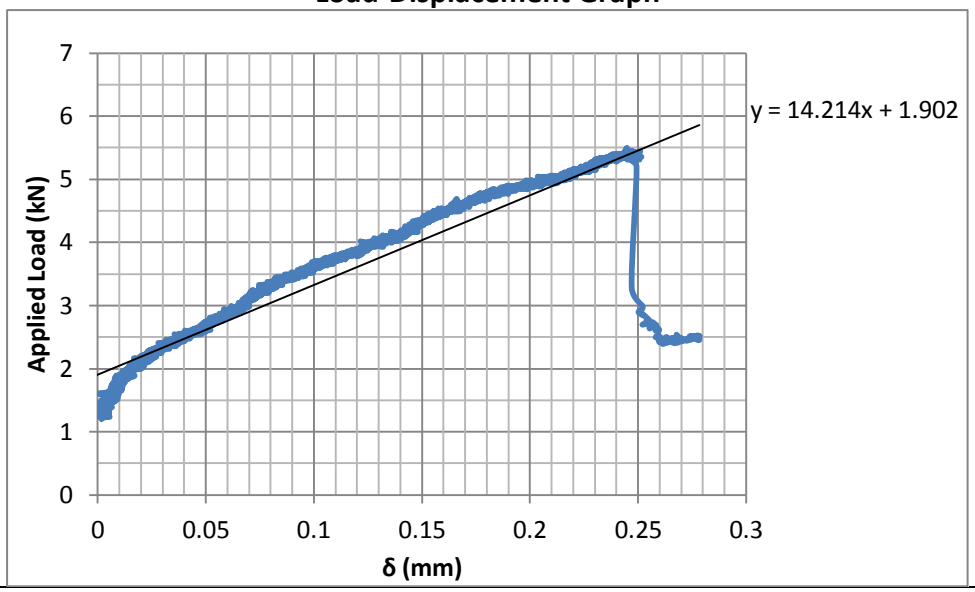
A minor pre-existing crack already existed near the top-right of the specimen but was considered to have little or no influence on the test. The primary crack was initiated at the centre of the specimen before it lengthened to form a diametrical crack.

Specimen after the test



Specimen No: 20111206-2M

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

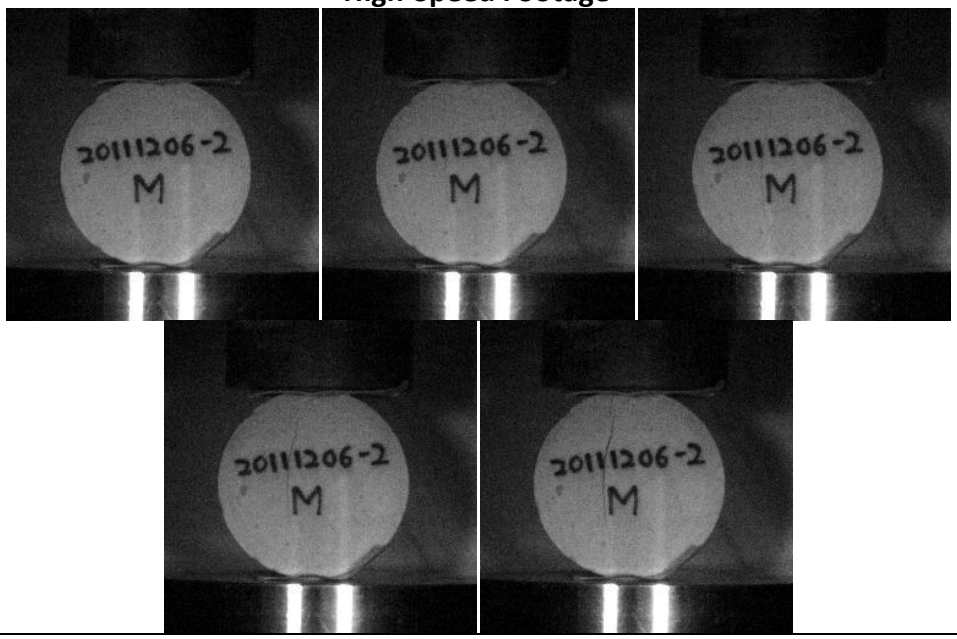
Thickness
29.8mm

Max Load
5.49682kN

Tensile Strength
2.349MPa

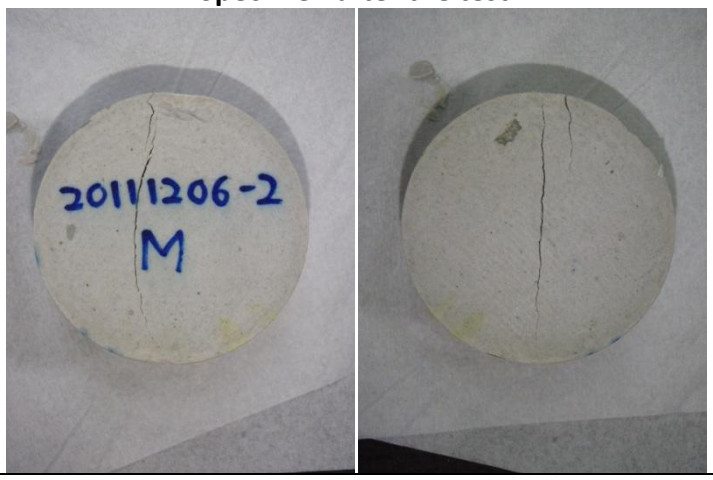
Stiffness
14.214kN/mm

High-Speed Footage



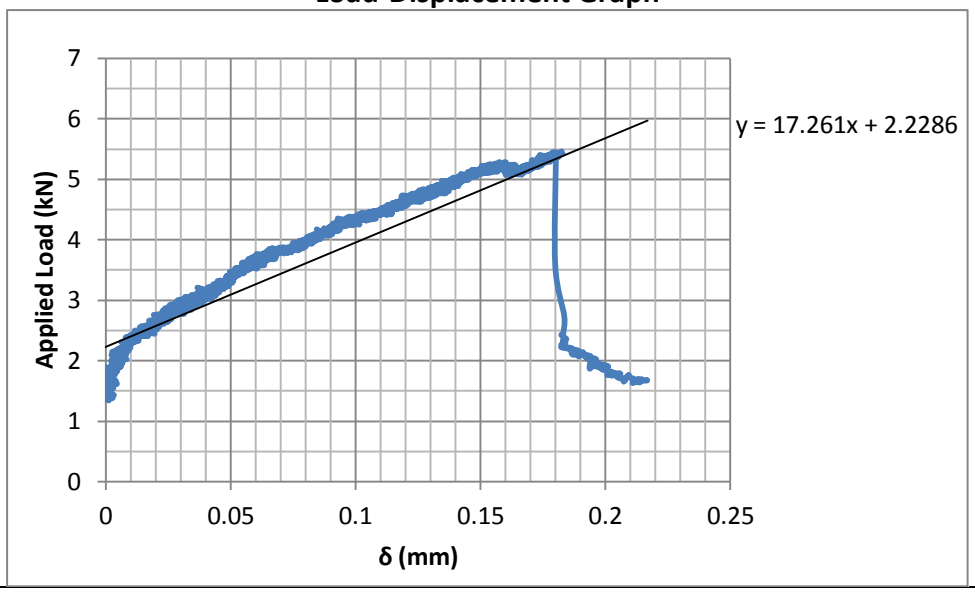
The primary crack initiated at the centre of the specimen and lengthened to the top and bottom of the specimen. The primary crack became connected to a secondary crack near the top of the specimen.

Specimen after the test



Specimen No: 20111206-2B

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

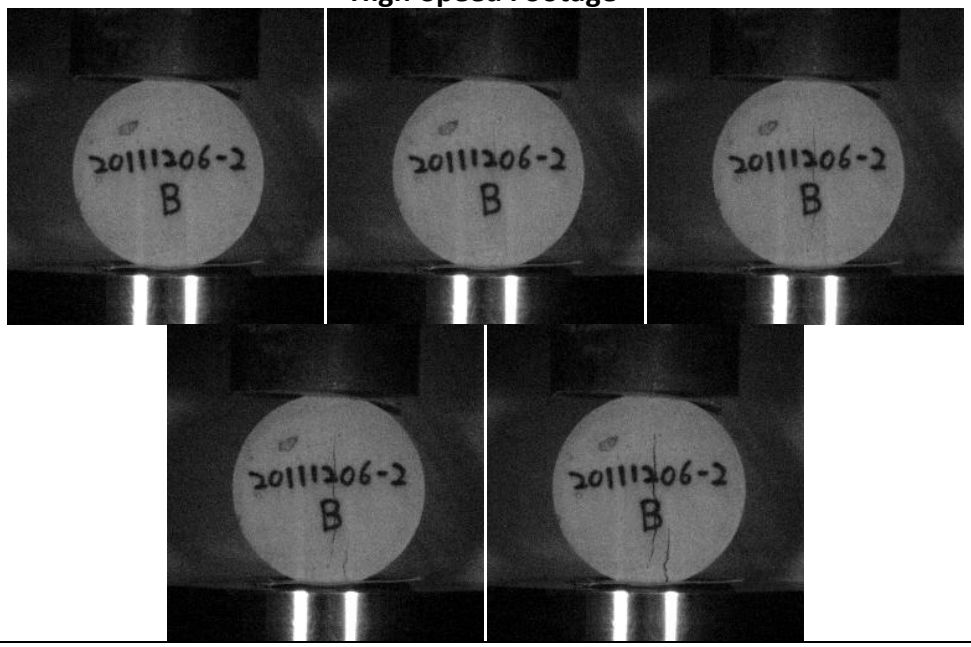
Thickness
30.4mm

Max Load
5.46108kN

Tensile Strength
2.287MPa

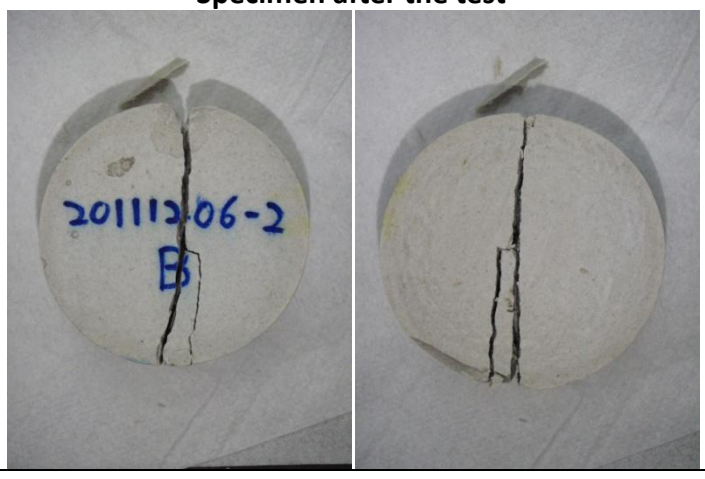
Stiffness
17.261kN/mm

High-Speed Footage



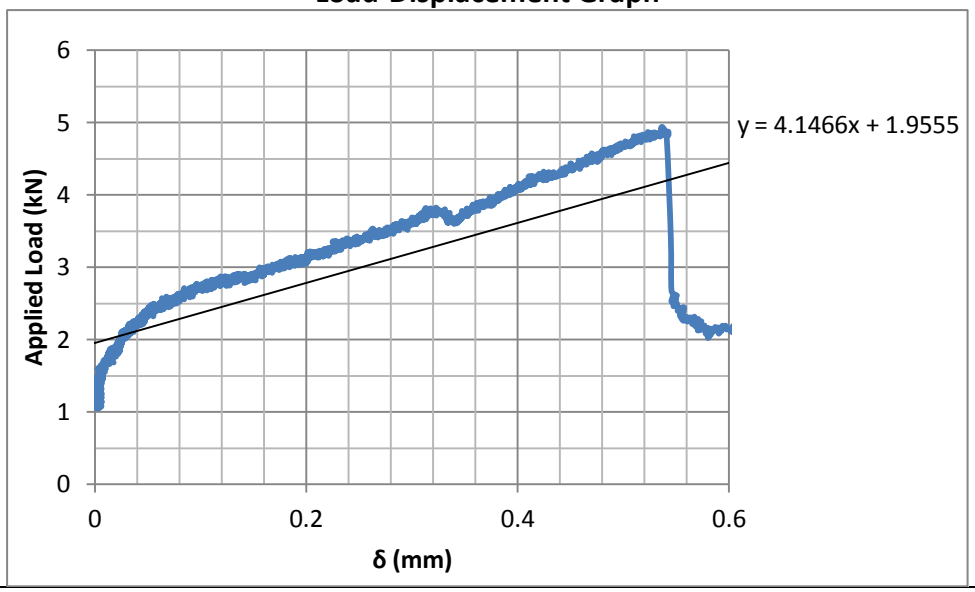
The primary crack initiated at the centre of the specimen and propagated towards the top and bottom of the specimen. A secondary crack was then formed at the bottom of the specimen.

Specimen after the test



Specimen No: 20111206-3T (Discarded)

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

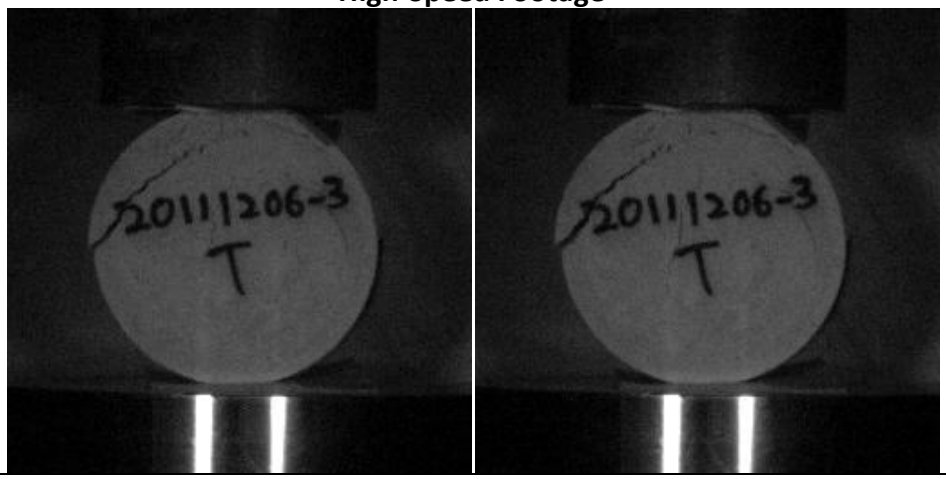
Thickness
30.2mm

Max Load
4.94278kN

Tensile Strength
2.084MPa

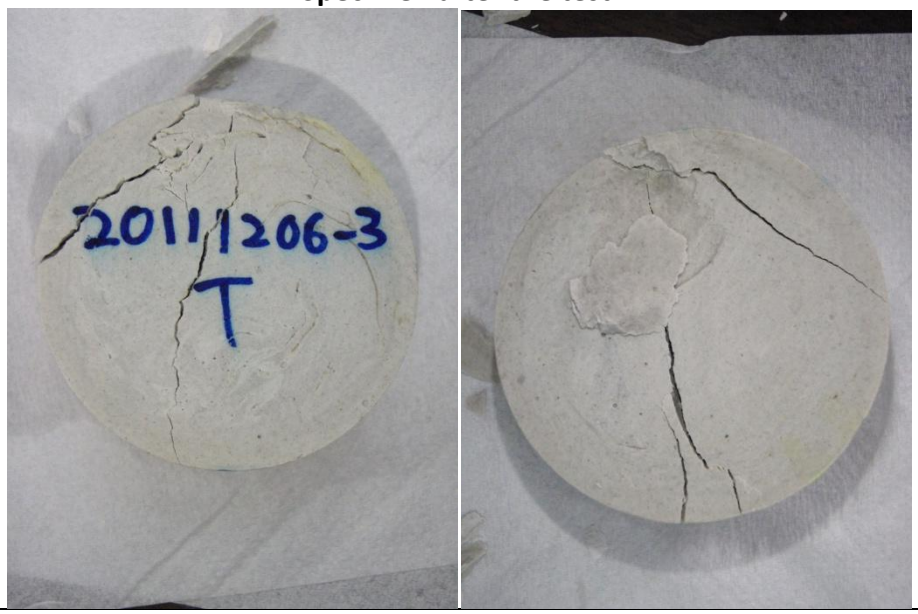
Stiffness
4.1466kN/mm

High-Speed Footage



A sideway crack was firstly initiated along pre-existing flaws near the top of the specimen.

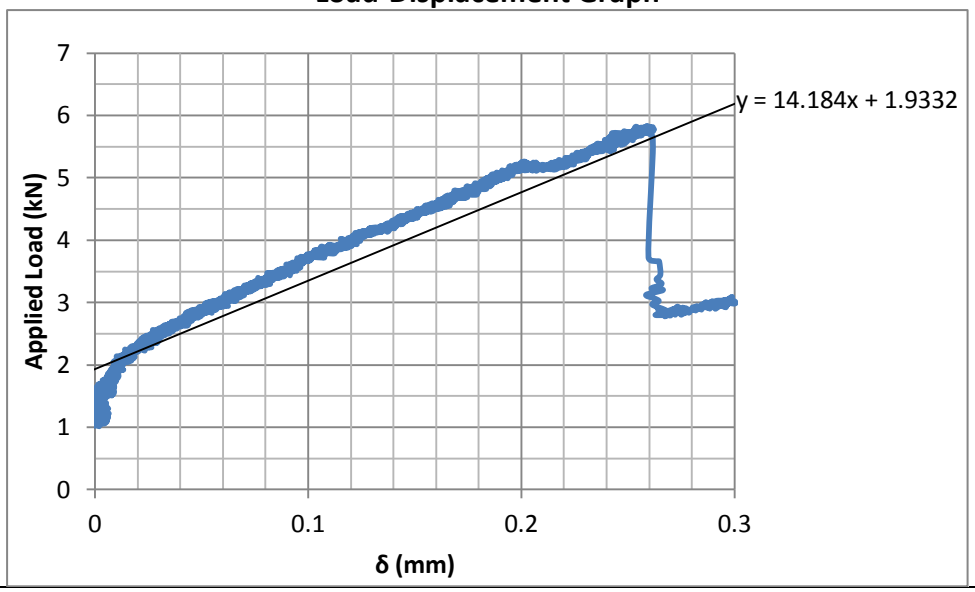
Specimen after the test



Many other cracks were also formed later along pre-existing flaws in the specimen. The test result of this specimen was discarded as the specimen did not fail as required for a Brazilian Tensile test.

Specimen No: 20111206-3M

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

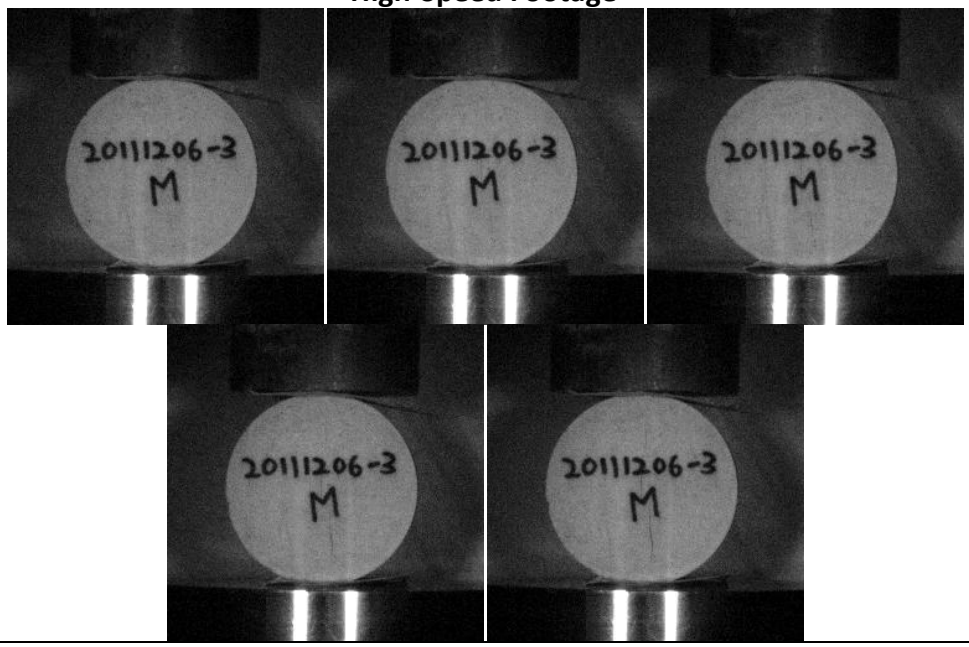
Thickness
30.4mm

Max Load
5.83423kN

Tensile Strength
2.444MPa

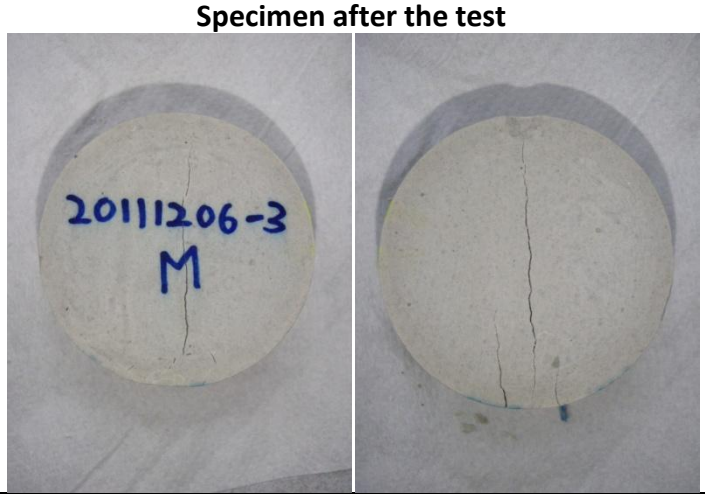
Stiffness
14.184kN/mm

High-Speed Footage



The primary crack initiated at the centre of the specimen and propagated towards the top and bottom of the specimen.

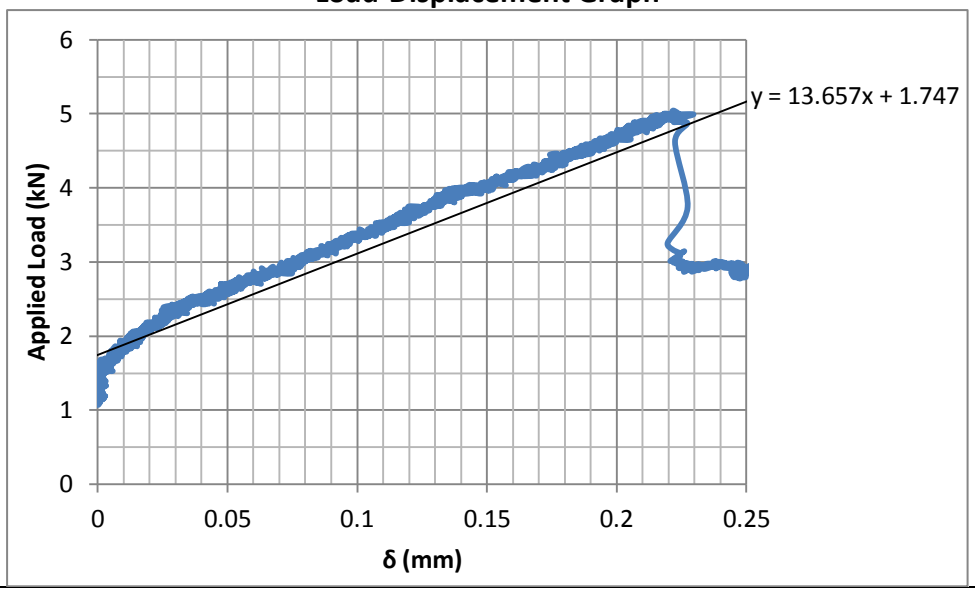
Specimen after the test



Some secondary cracks were formed at the bottom of the specimen.

Specimen No: 20111206-3B

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

Thickness
30.0mm

Max Load
5.04264kN

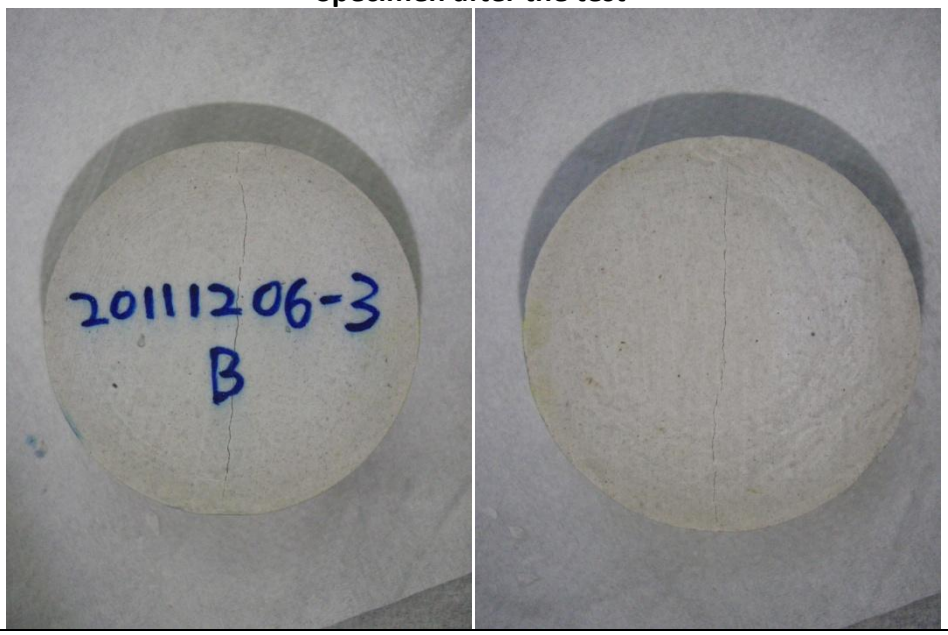
Tensile Strength
2.140MPa

Stiffness
13.657kN/mm

High-Speed Footage

Not Available

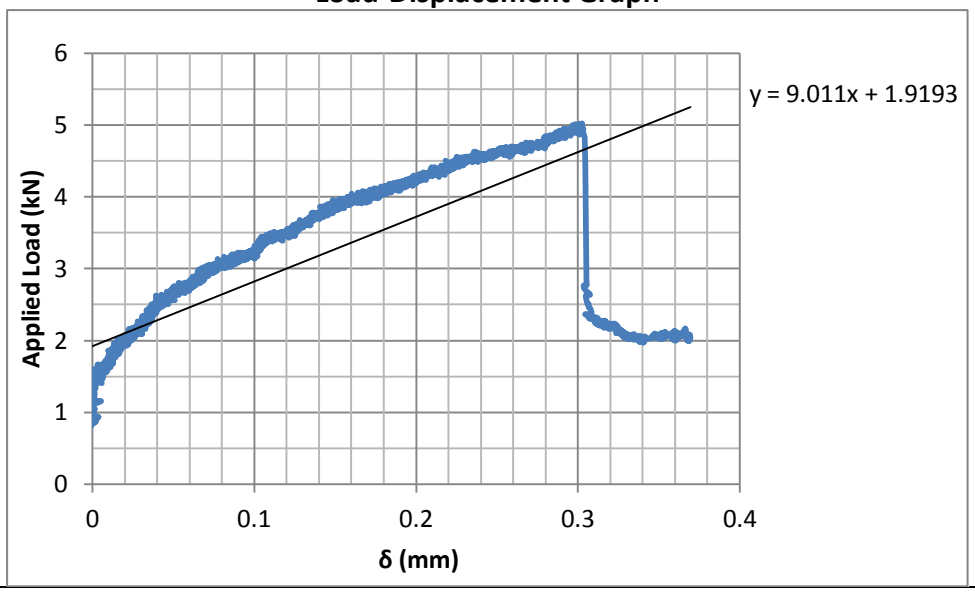
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen. Hence, it can be deduced that the crack initiated at the centre of the specimen and tensile failure has occurred.

Specimen No: 20111207-1T

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

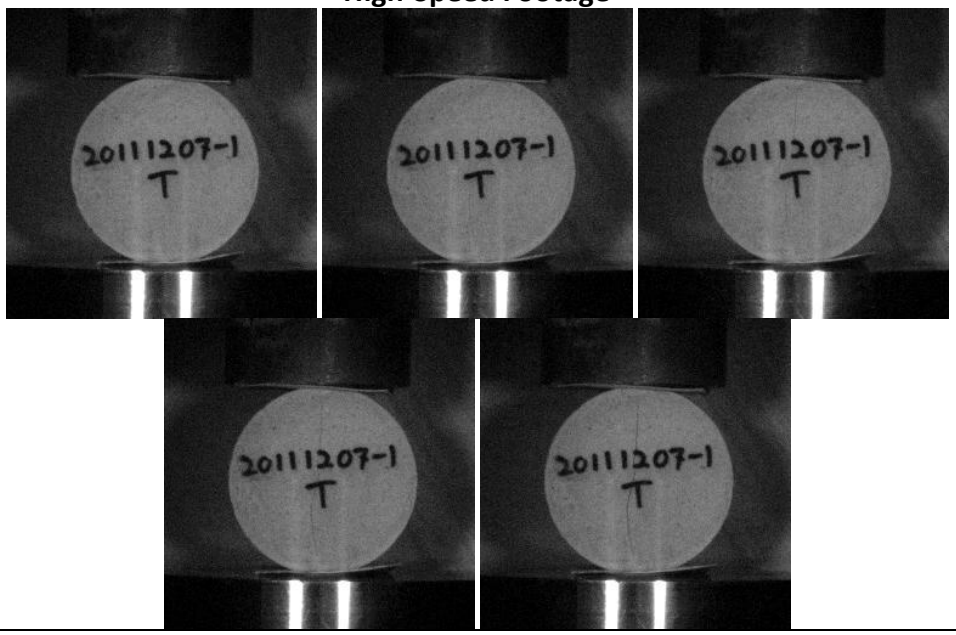
Thickness
30.4mm

Max Load
5.02048kN

Tensile Strength
2.103MPa

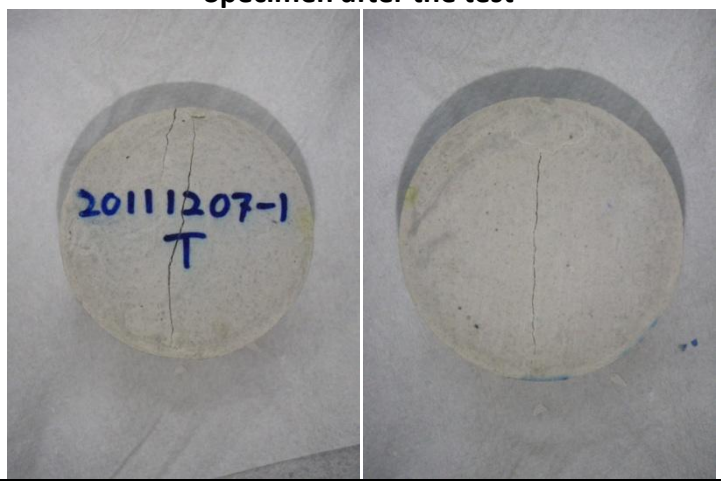
Stiffness
9.011kN/mm

High-Speed Footage



The primary crack initiated at the centre of the specimen and propagated towards the top and bottom of the specimen.

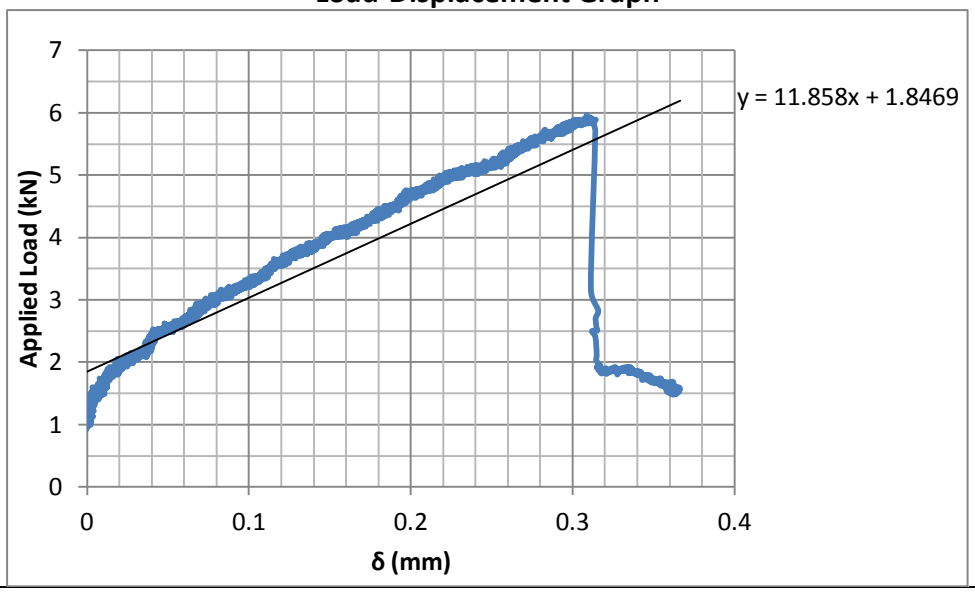
Specimen after the test



A secondary crack was formed at the top of the specimen after the primary crack has occurred.

Specimen No: 20111207-1M

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

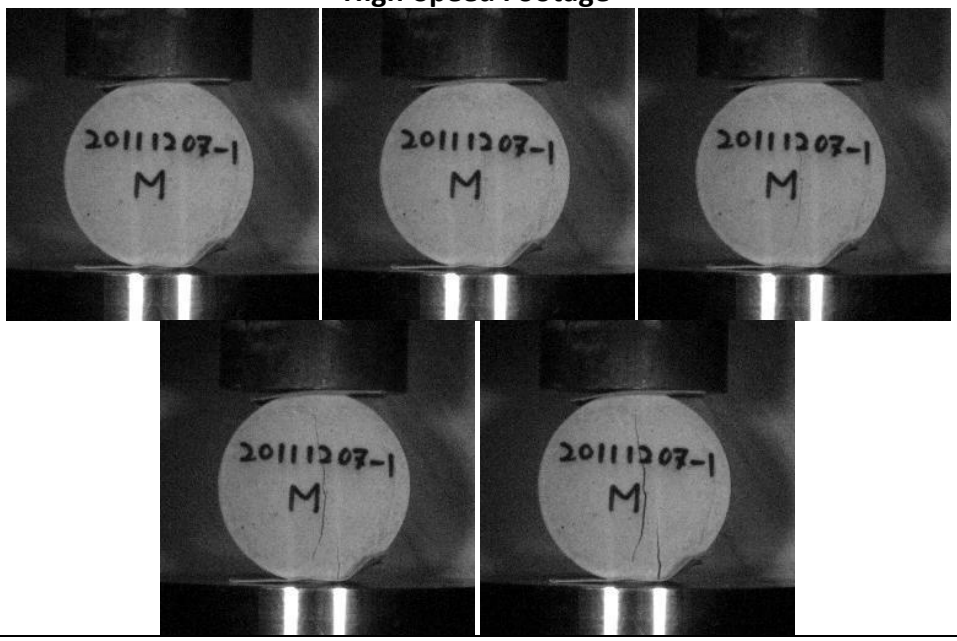
Thickness
30.4mm

Max Load
5.96626kN

Tensile Strength
2.499MPa

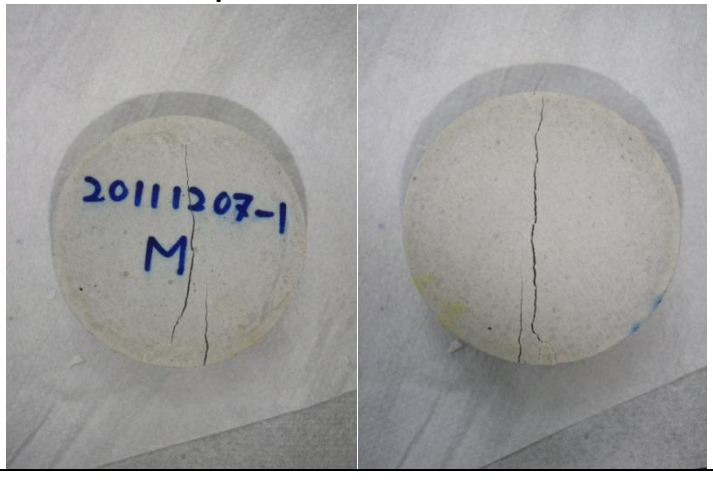
Stiffness
11.858kN/mm

High-Speed Footage



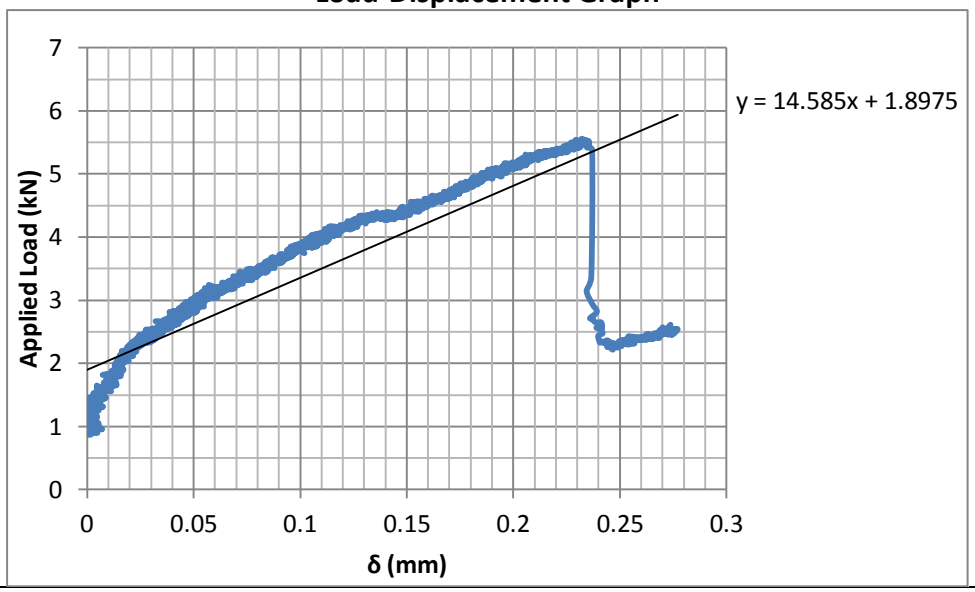
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111207-1B

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

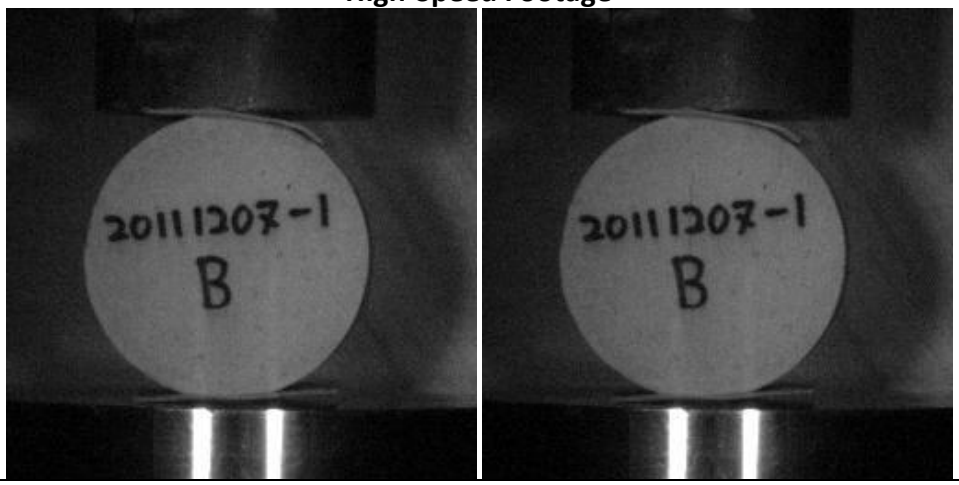
Thickness
30.2mm

Max Load
5.56065kN

Tensile Strength
2.344MPa

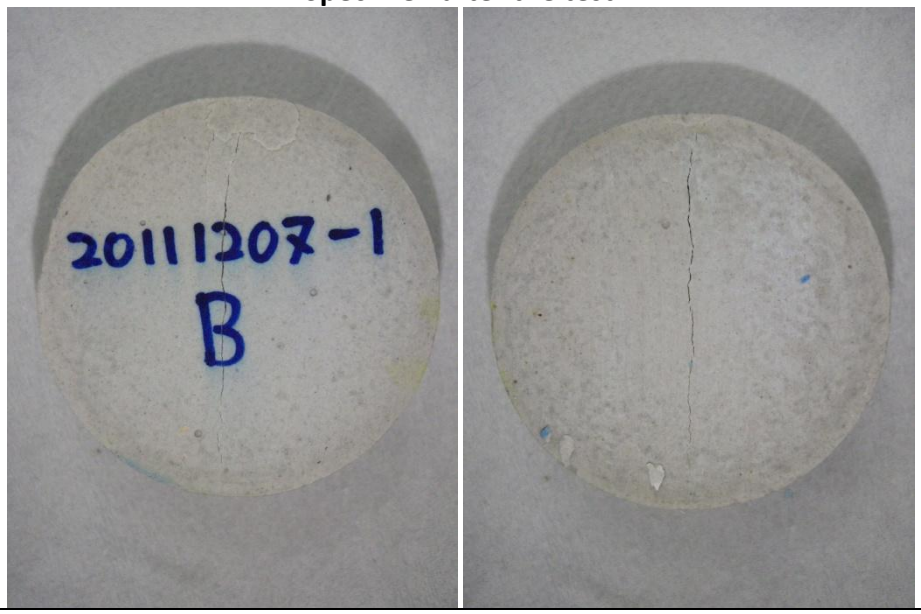
Stiffness
14.585kN/mm

High-Speed Footage



The primary crack initiated at the centre of the specimen.

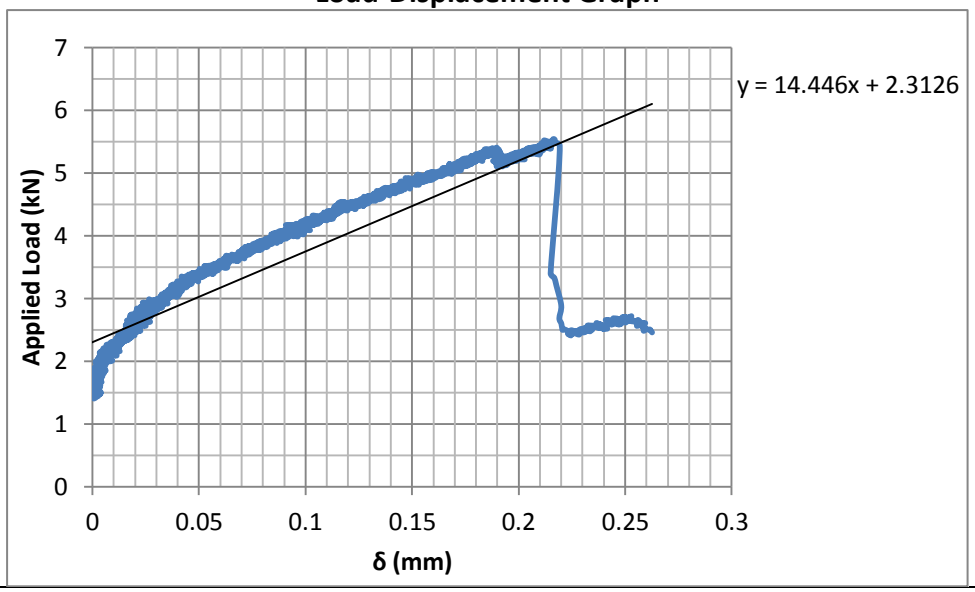
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen. Hence, it can be deduced that the crack initiated at the centre of the specimen and tensile failure has occurred.

Specimen No: 20111207-2T

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

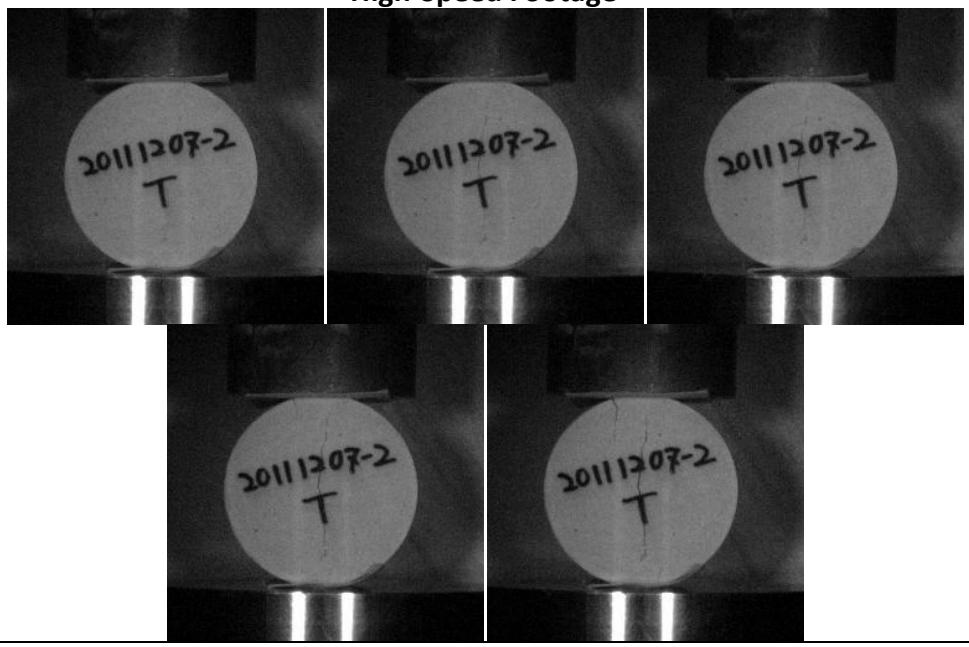
Thickness
29.9mm

Max Load
5.54287kN

Tensile Strength
2.360MPa

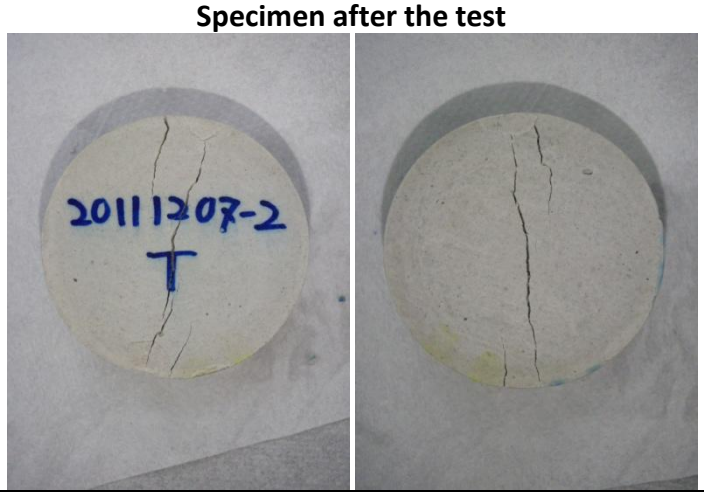
Stiffness
14.446kN/mm

High-Speed Footage



The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the top of the specimen after the primary crack has occurred.

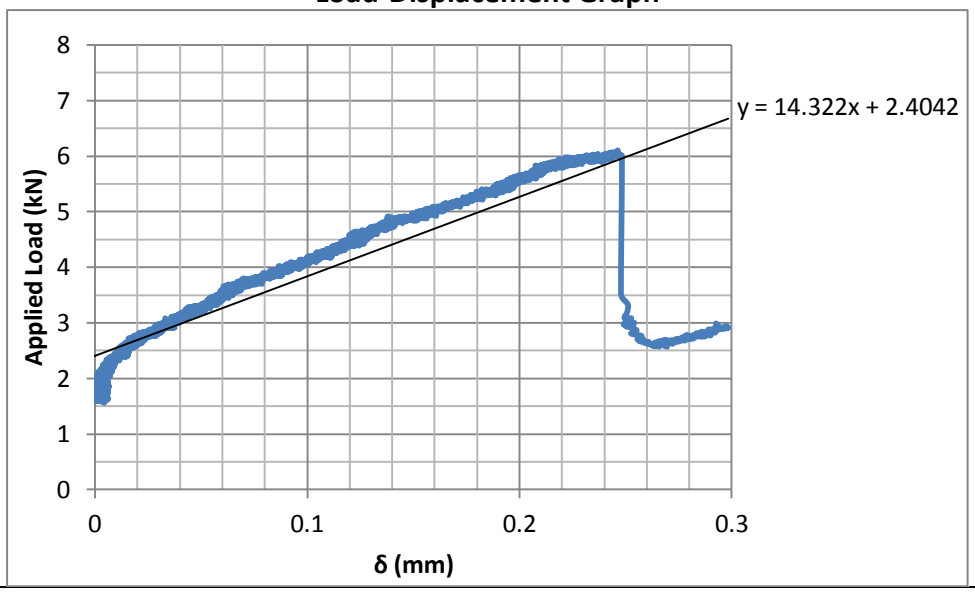
Specimen after the test



Secondary crack was also formed at the bottom of the specimen.

Specimen No: 20111207-2M

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

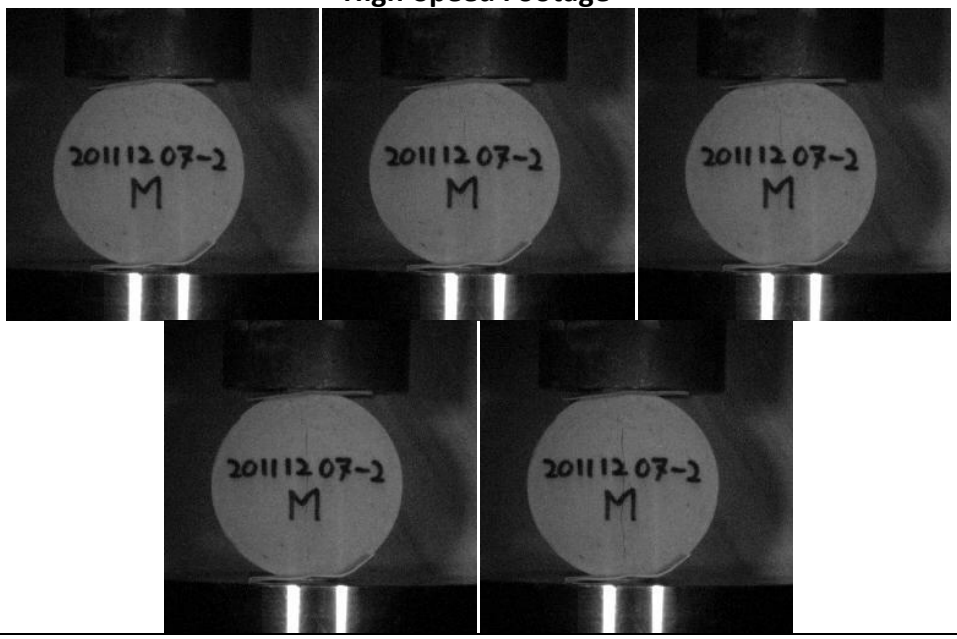
Thickness
30.8mm

Max Load
6.10228kN

Tensile Strength
2.523MPa

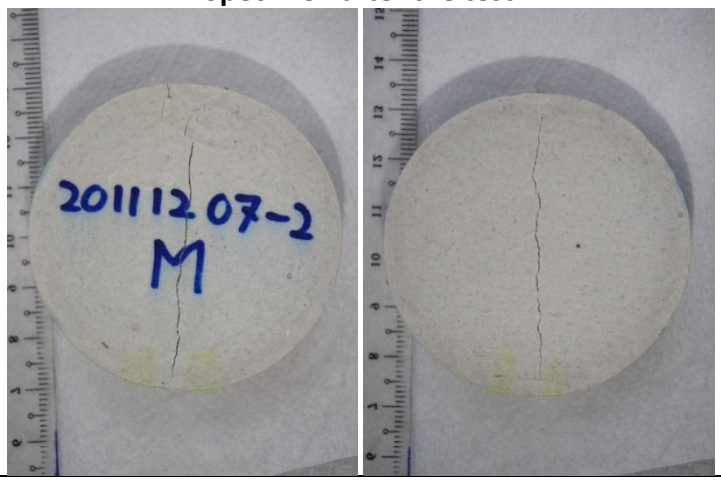
Stiffness
14.322kN/mm

High-Speed Footage



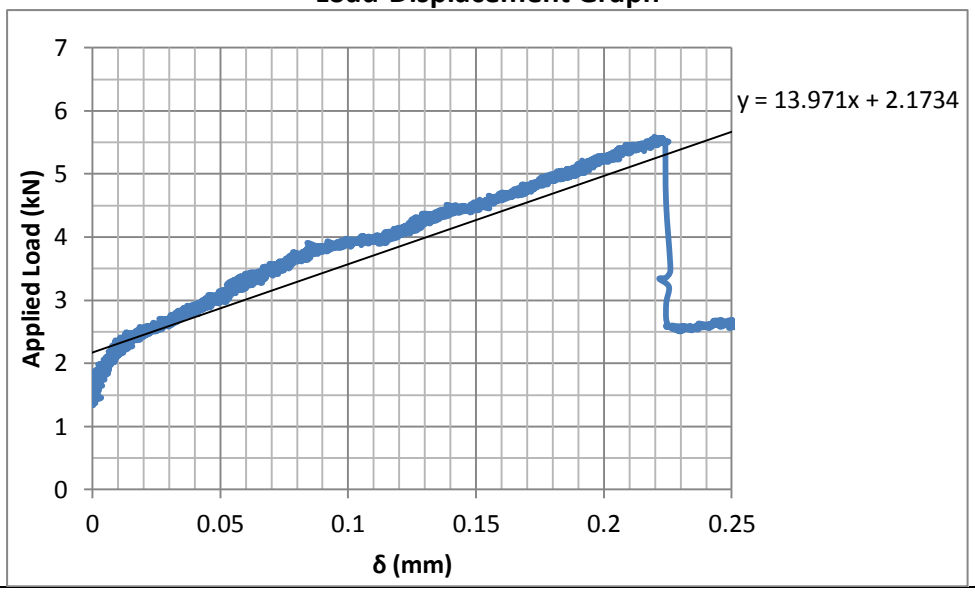
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen.

Specimen after the test



Specimen No: 20111207-2B

Load-Displacement Graph



Immersion Time
1 week

Diameter
50mm

Thickness
29.5mm

Max Load
5.59595kN

Tensile Strength
2.415MPa

Stiffness
13.971kN/mm

High-Speed Footage

Not Available

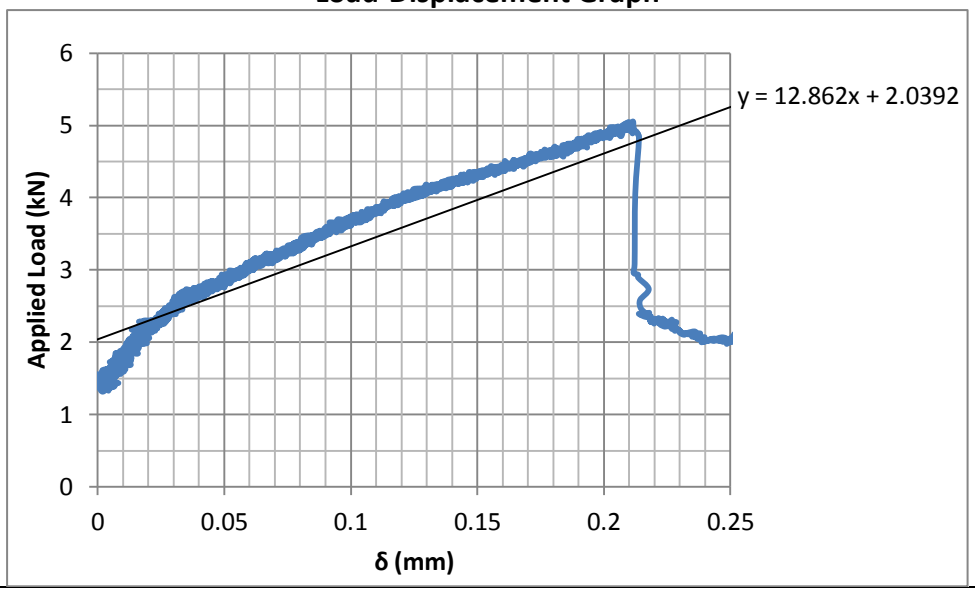
As the high-speed footage was not available and the primary crack broke through the top and bottom of the specimen, It is unknown where the crack initiated in the specimen.

Specimen after the test

As the primary crack occurred along the vertically-loaded diameter of the specimen, the test result was still considered valid although it is not known where the crack initiated in the specimen.

Specimen No: 20111207-3T

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

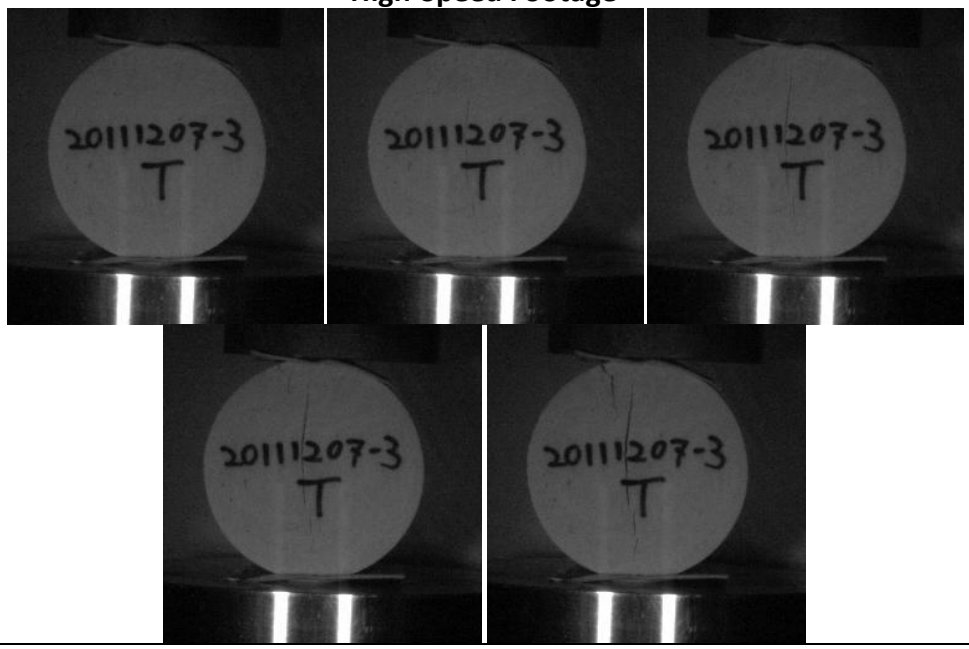
Thickness
30.4mm

Max Load
5.05152kN

Tensile Strength
2.116MPa

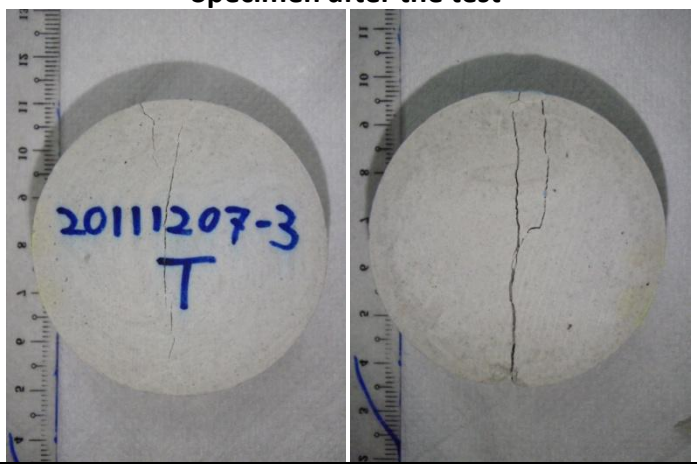
Stiffness
12.862kN/mm

High-Speed Footage



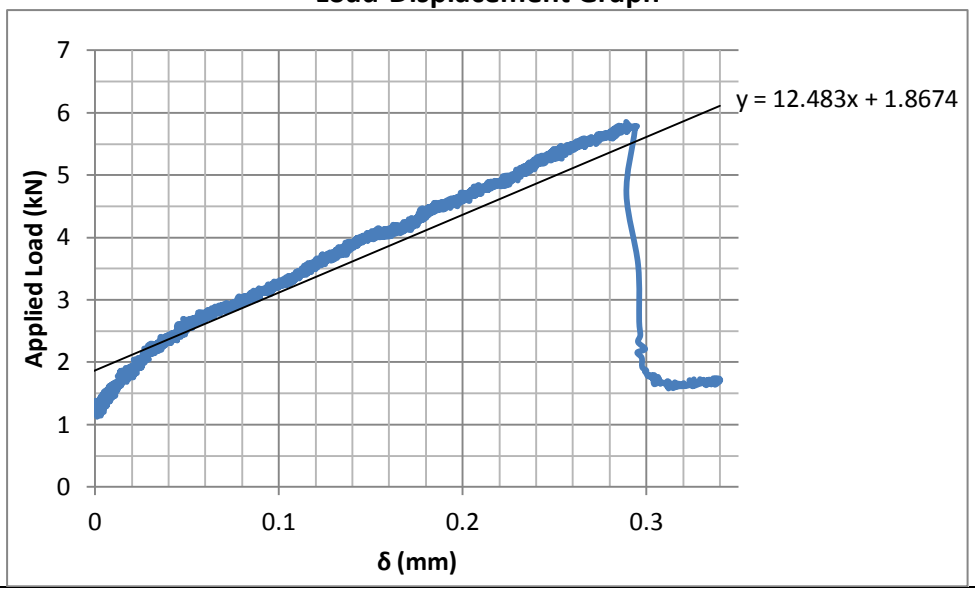
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the top of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111207-3M

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

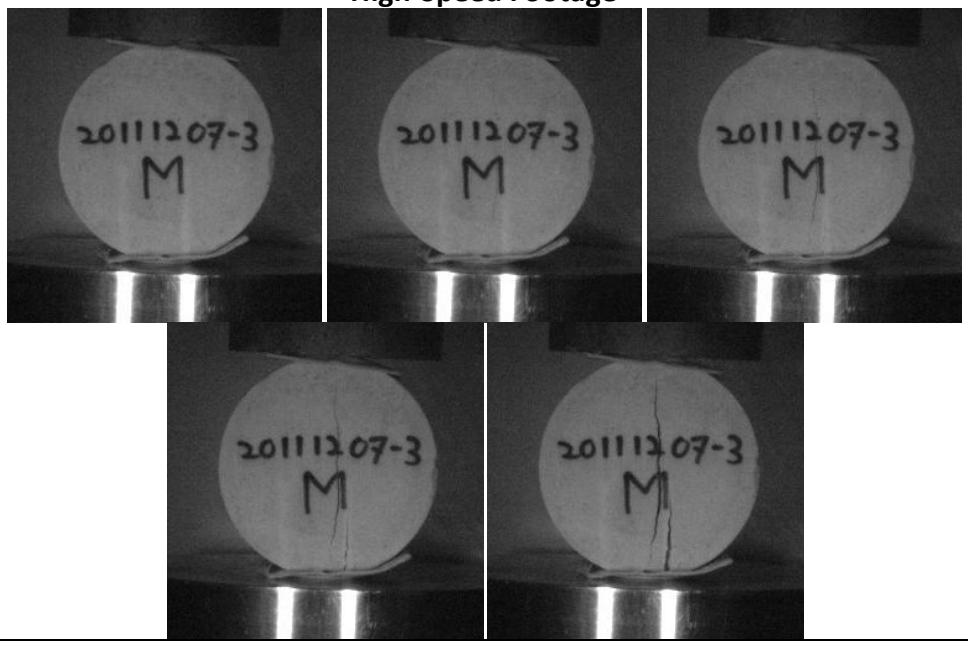
Thickness
30.5mm

Max Load
5.85564kN

Tensile Strength
2.444MPa

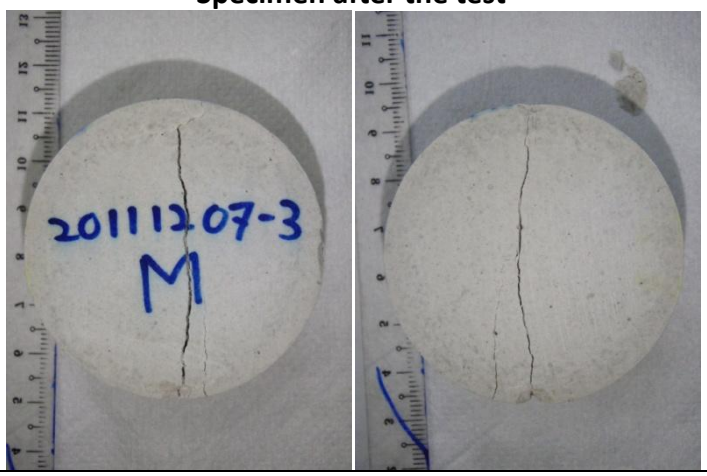
Stiffness
12.483kN/mm

High-Speed Footage



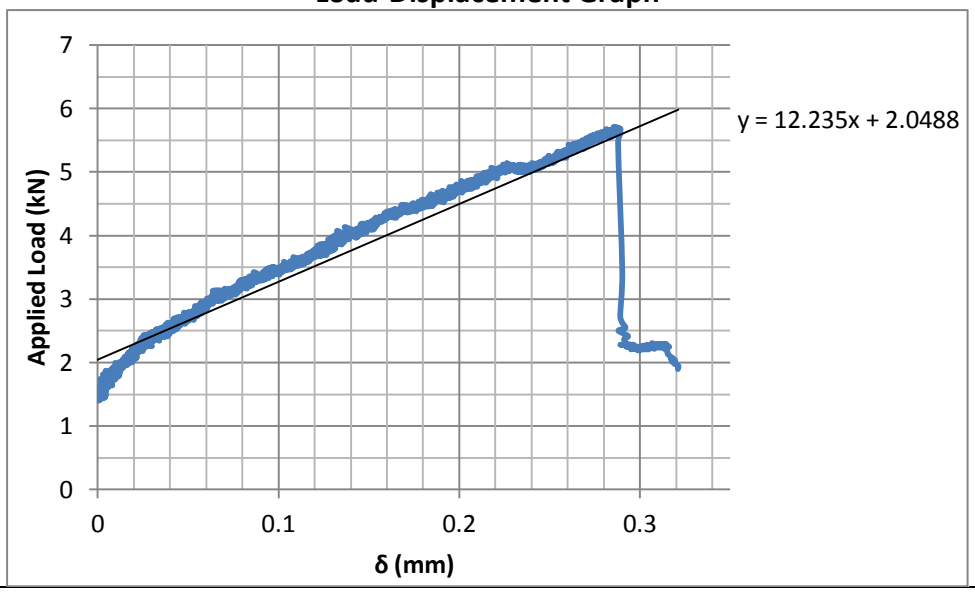
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111207-3B

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

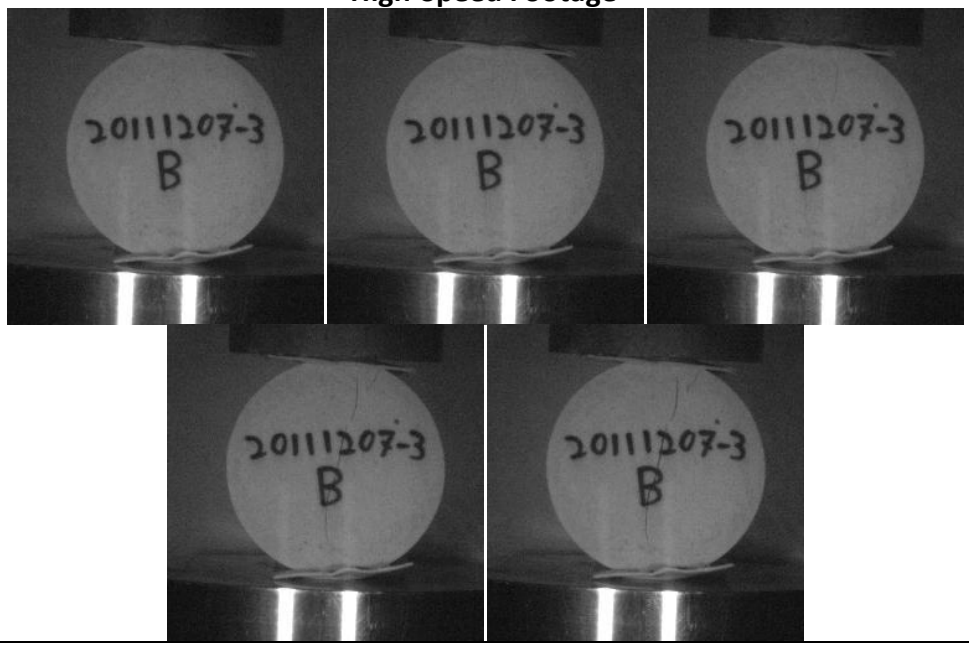
Thickness
29.8mm

Max Load
5.70838kN

Tensile Strength
2.439MPa

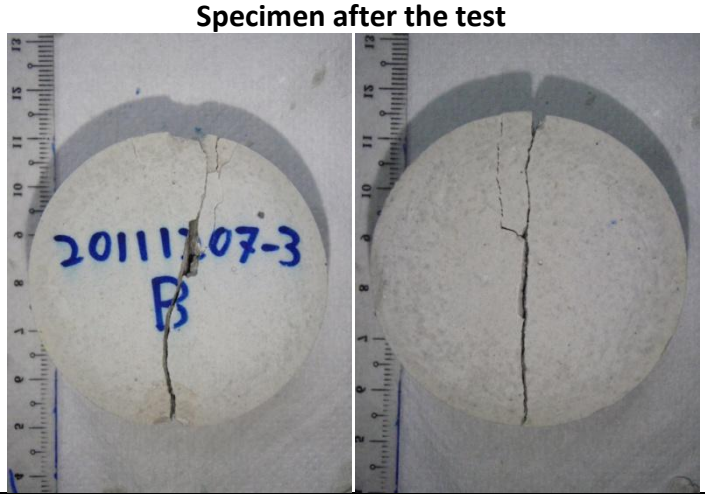
Stiffness
12.235kN/mm

High-Speed Footage



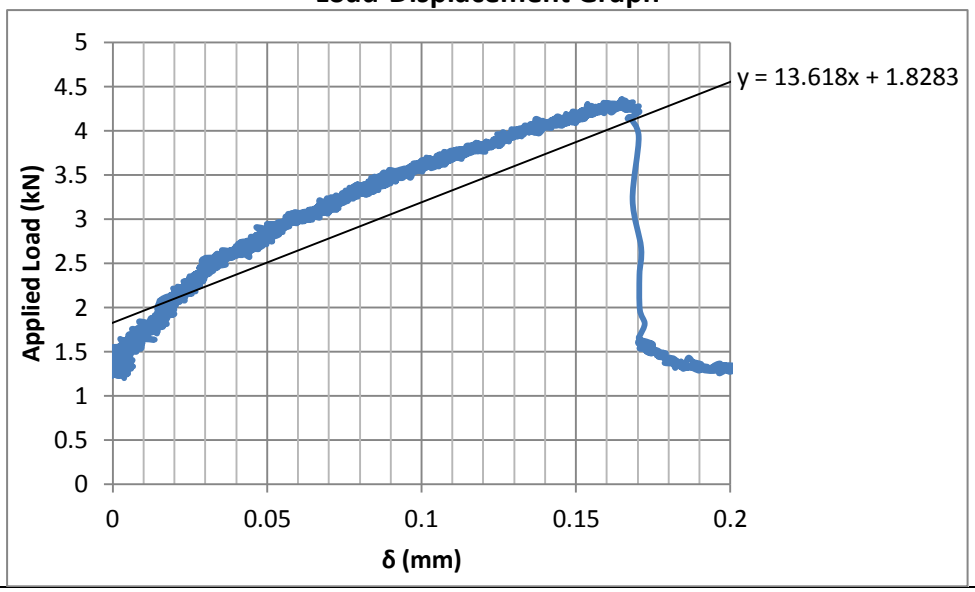
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the top of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111208-1T

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

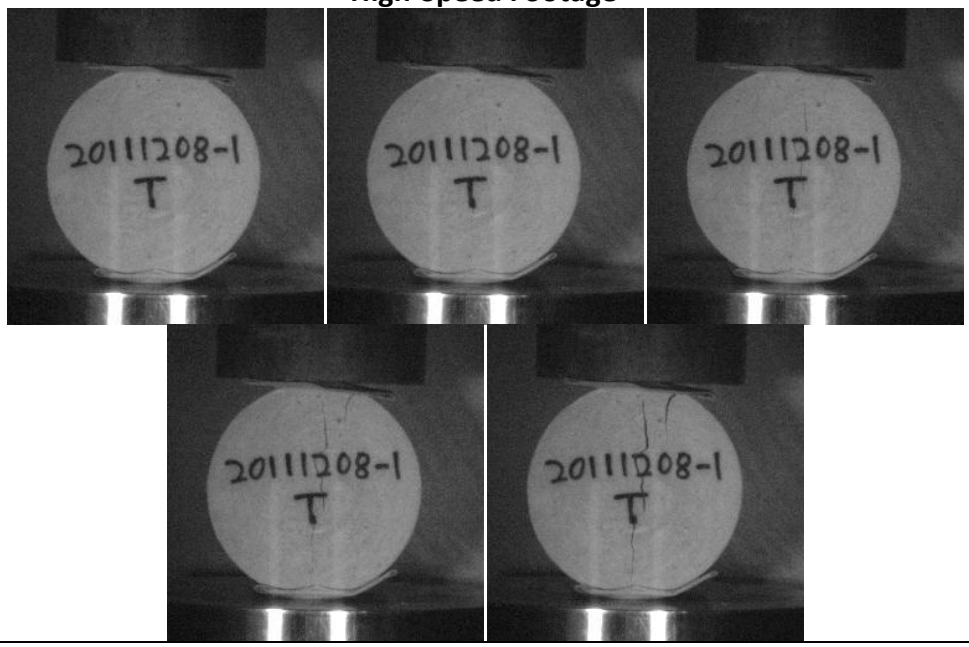
Thickness
30.1mm

Max Load
4.36272kN

Tensile Strength
1.845MPa

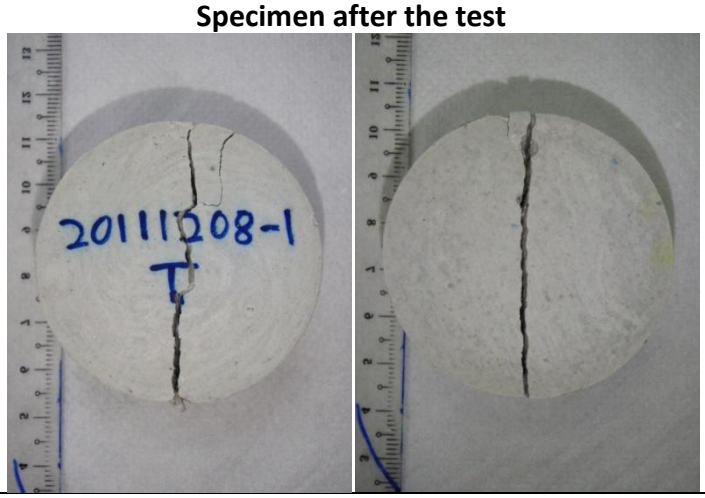
Stiffness
13.618kN/mm

High-Speed Footage



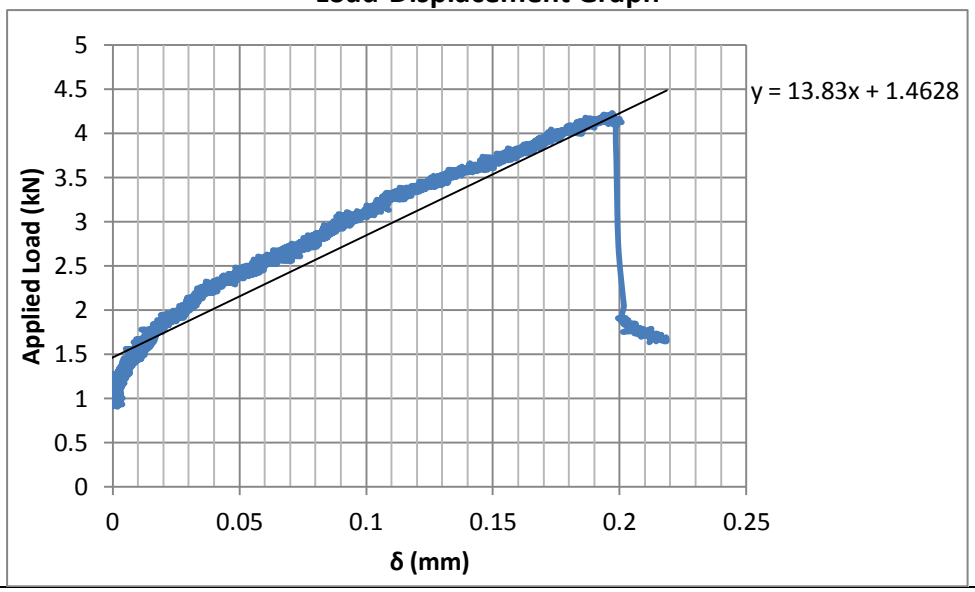
The primary crack initiated at the top and propagated into the centre until it reached the bottom of the specimen. A secondary crack was formed at the top of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111208-1M

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

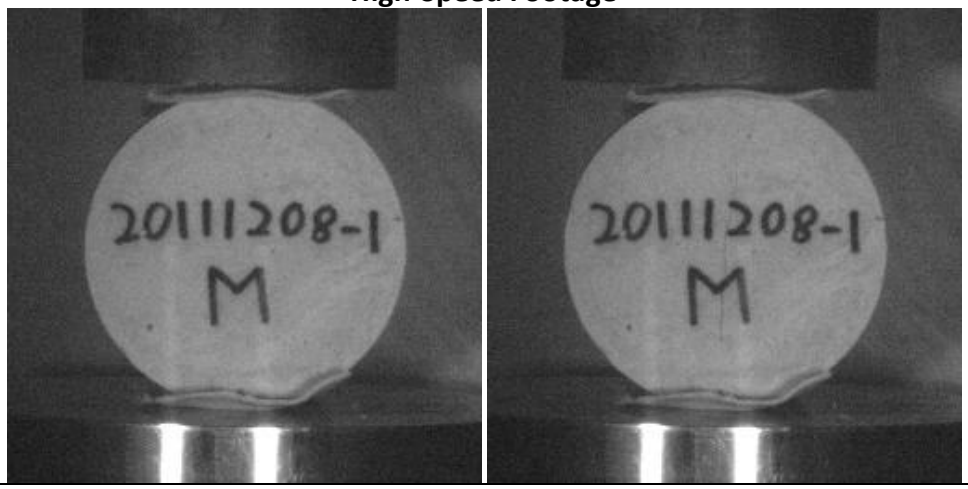
Thickness
30.1mm

Max Load
4.23591kN

Tensile Strength
1.792MPa

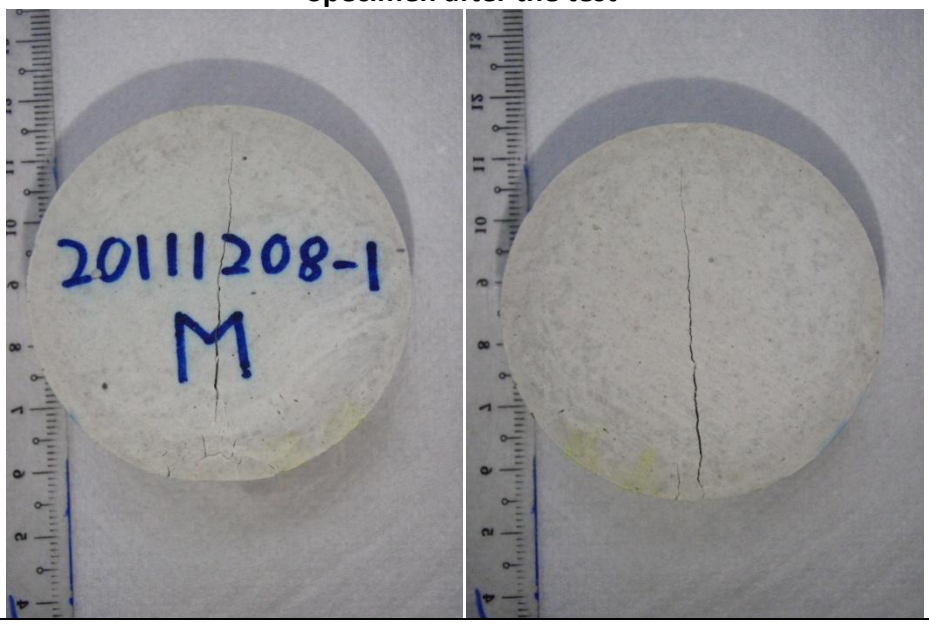
Stiffness
13.83kN/mm

High-Speed Footage



The crack initiated at the centre of the specimen.

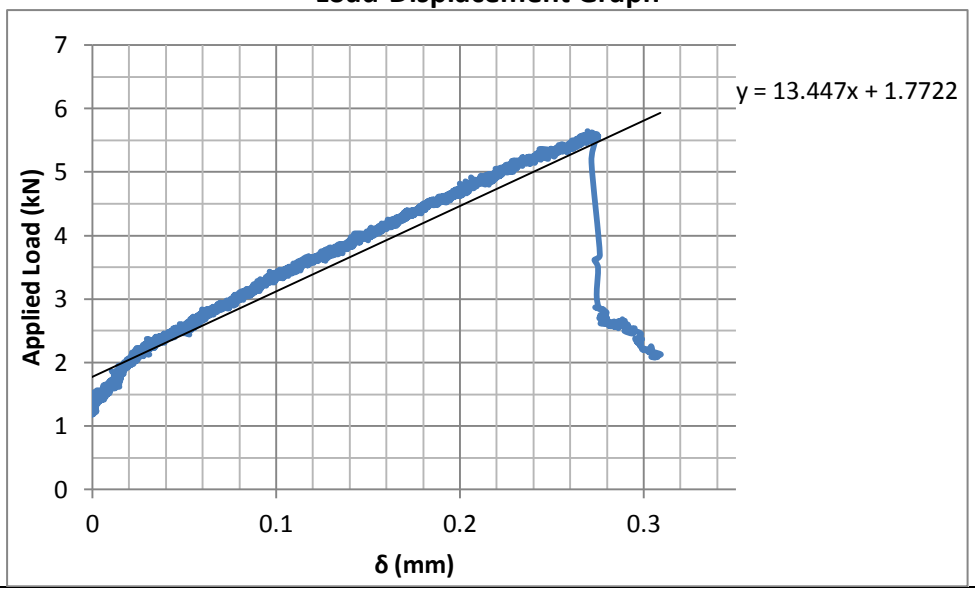
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen. Hence, it can be deduced that the crack initiated at the centre of the specimen and tensile failure has occurred.

Specimen No: 20111208-1B

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

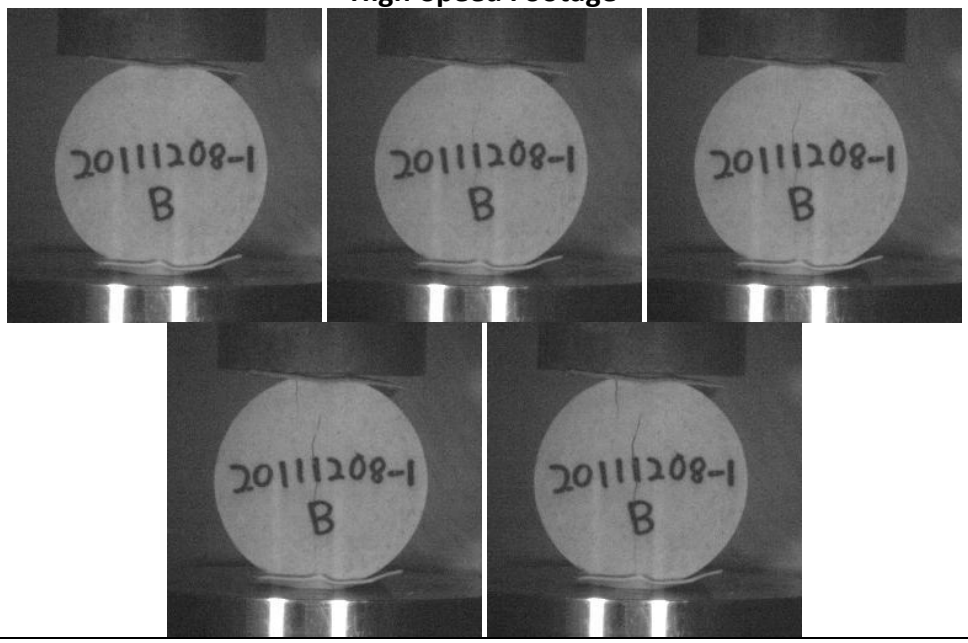
Thickness
30.2mm

Max Load
5.64726kN

Tensile Strength
2.381MPa

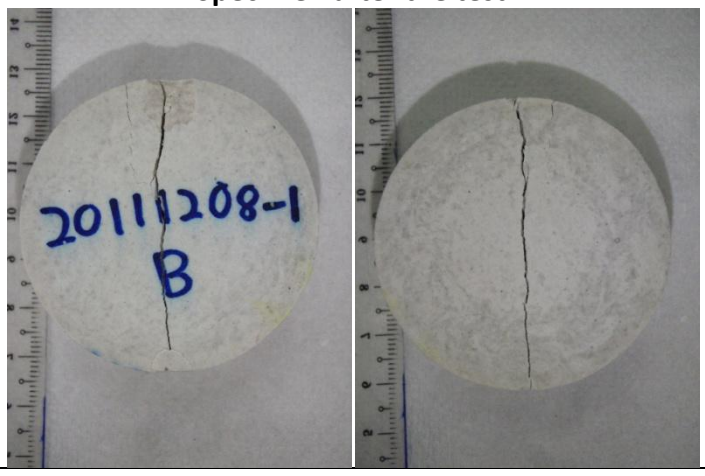
Stiffness
13.447kN/mm

High-Speed Footage



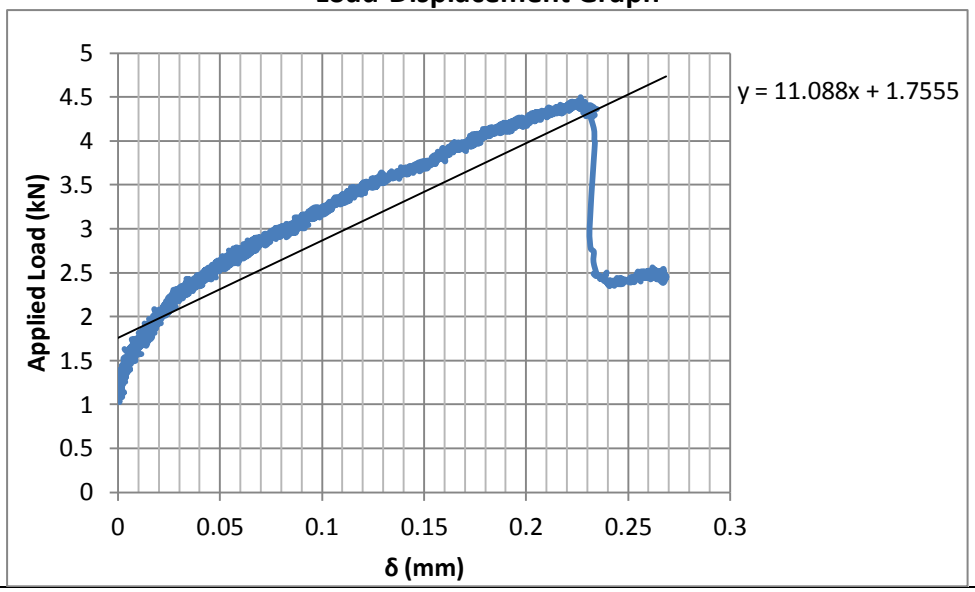
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the top of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111208-2T (Discarded)

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

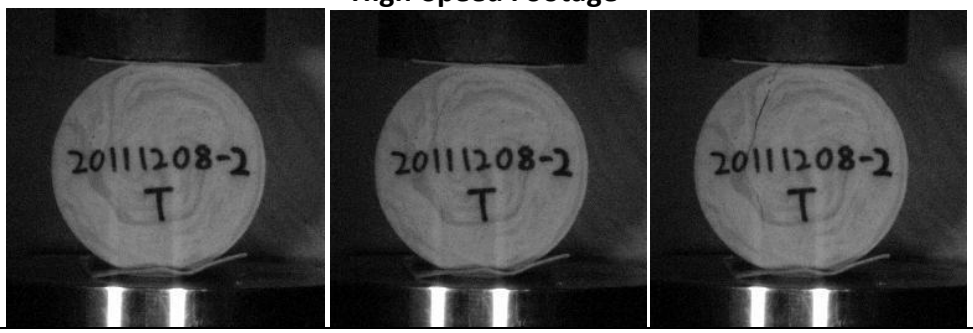
Thickness
29.6mm

Max Load
4.5006kN

Tensile Strength
1.936MPa

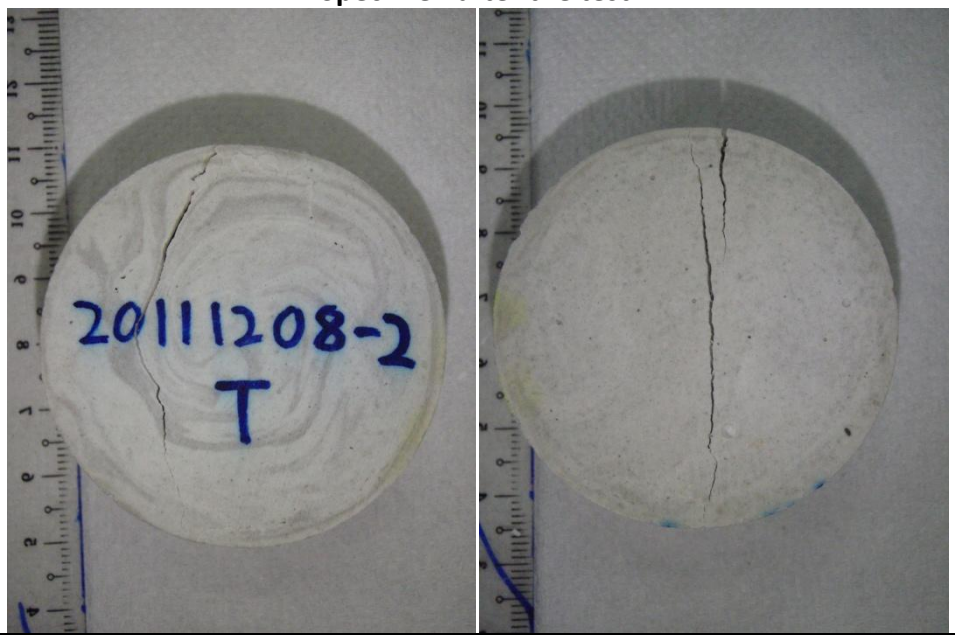
Stiffness
11.088kN/mm

High-Speed Footage



The crack initiated at a pre-existing flaw in the specimen which resulted in a non-diametrical crack.

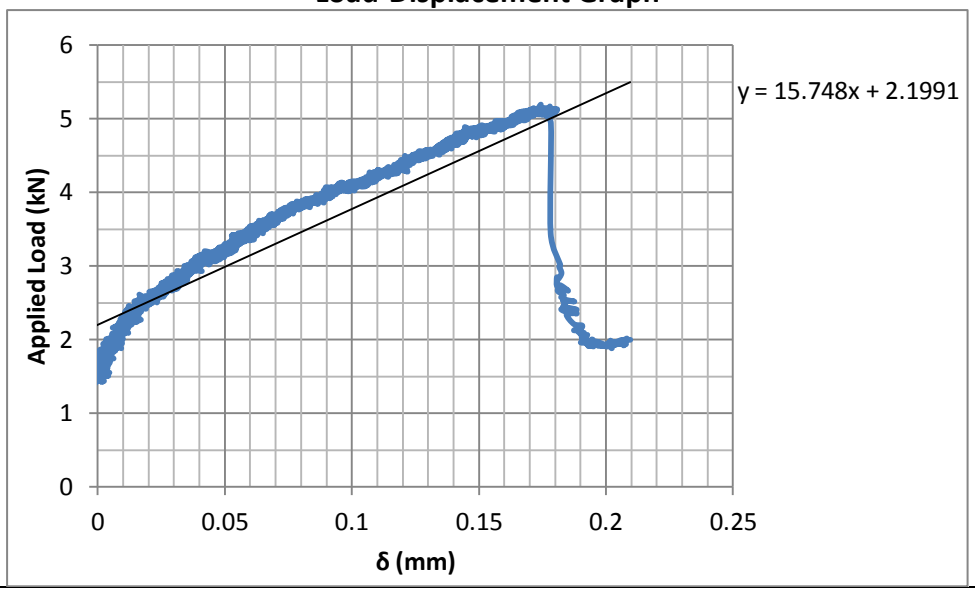
Specimen after the test



The test result of this specimen was discarded due to the initiation of the primary crack along pre-existing flaw in the specimen.

Specimen No: 20111208-2M

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

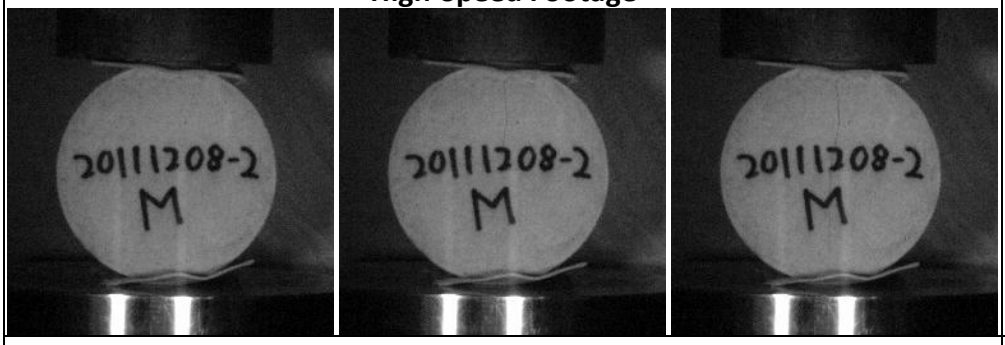
Thickness
30.7mm

Max Load
5.19613kN

Tensile Strength
2.155MPa

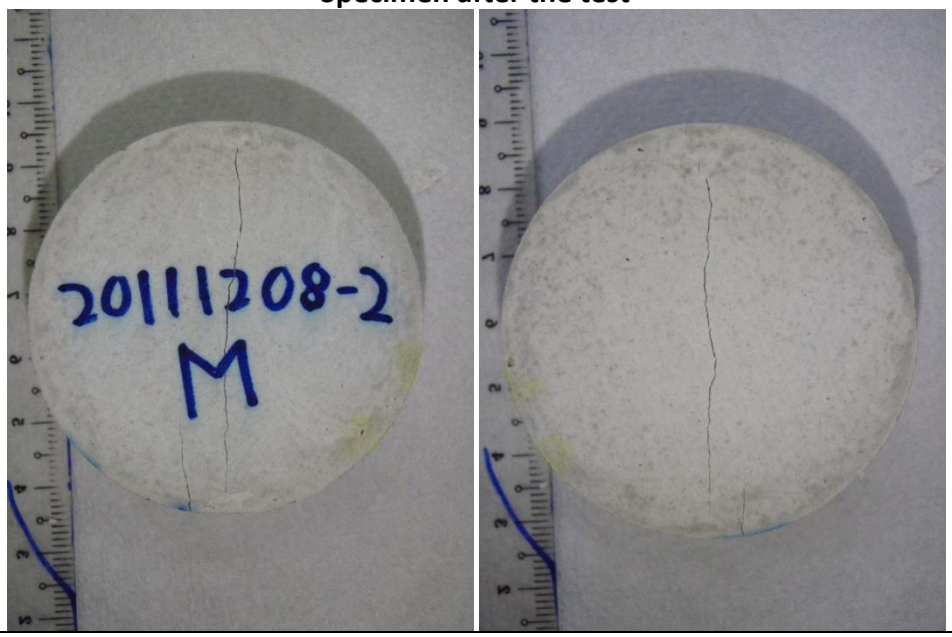
Stiffness
15.748kN/mm

High-Speed Footage



The primary crack initiated at the top and propagated into the centre until it reached the bottom of the specimen.

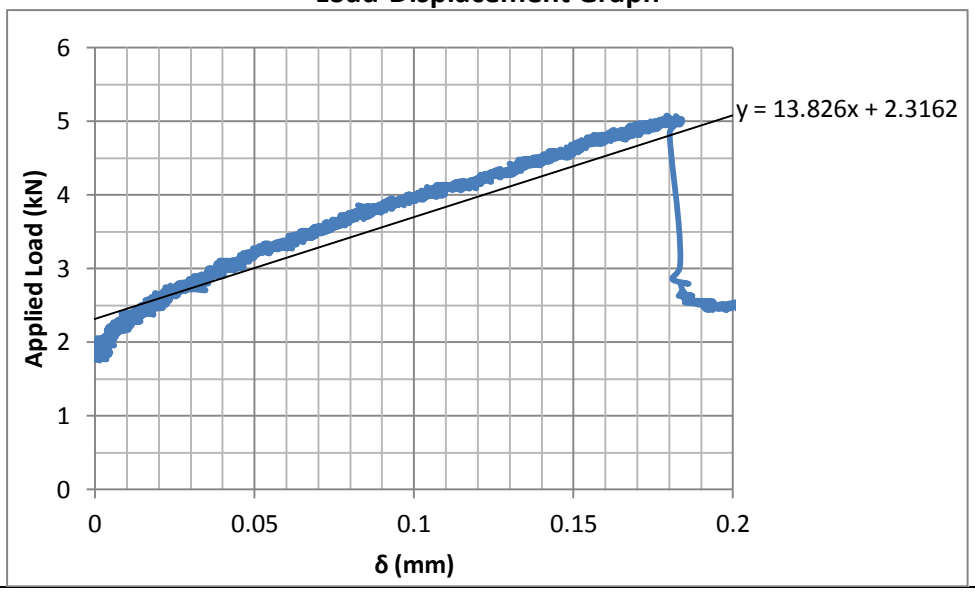
Specimen after the test



A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

Specimen No: 20111208-2B

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

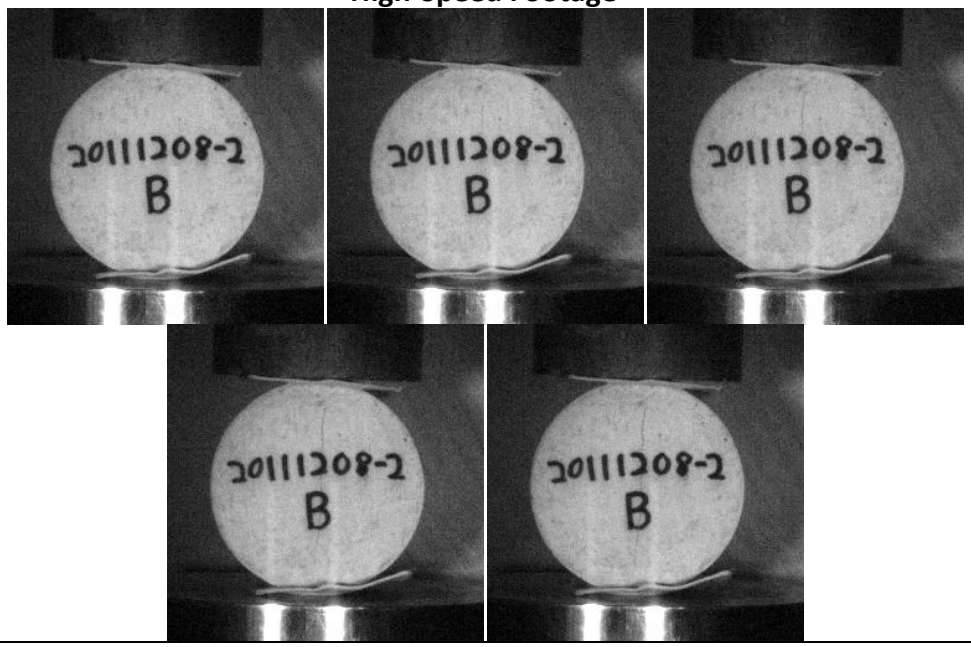
Thickness
29.8mm

Max Load
5.08094kN

Tensile Strength
2.1709MPa

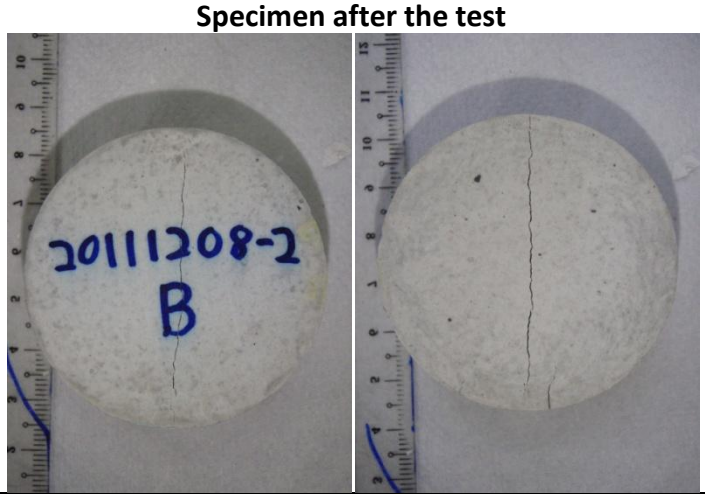
Stiffness
13.826kN/mm

High-Speed Footage



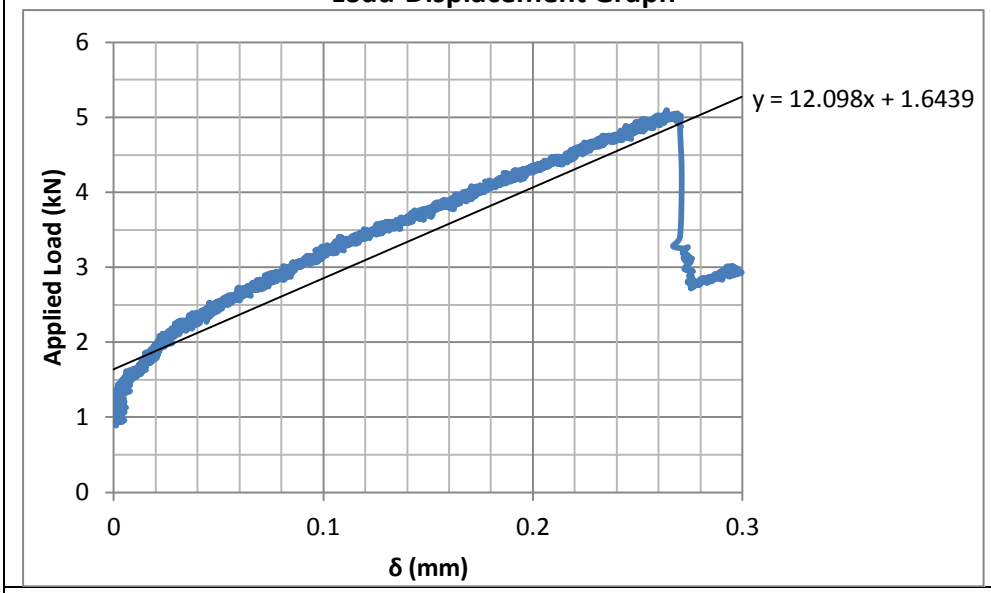
The primary crack initiated at the top and propagated into the centre until it reached the bottom of the specimen.

Specimen after the test



A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

Specimen No: 20111208-3T



Immersion Time
3 weeks

Diameter
50mm

Thickness
30.0mm

Max Load
5.09926kN

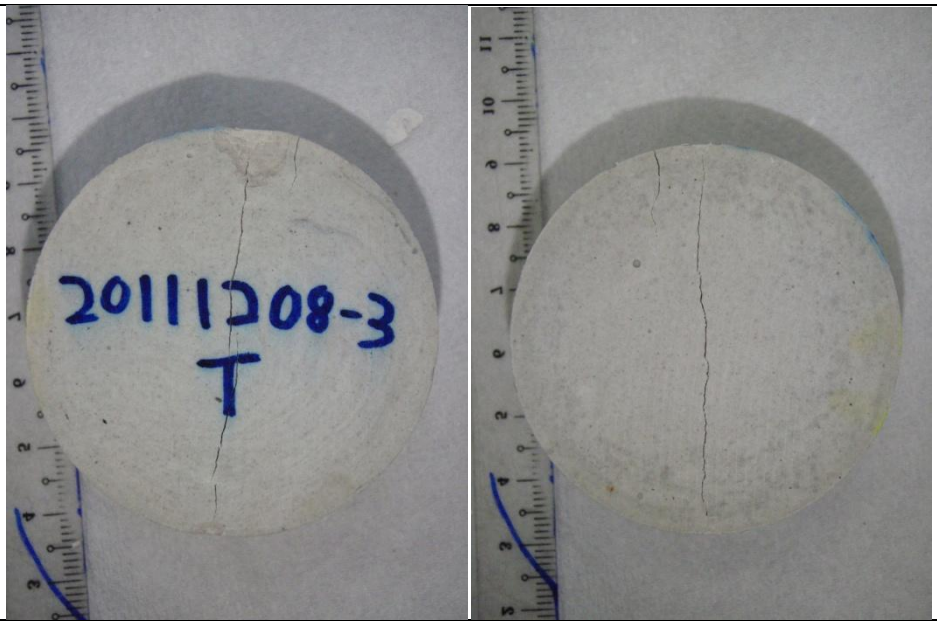
Tensile Strength
2.164MPa

Stiffness
12.098kN/mm

High-Speed Footage

Not Available

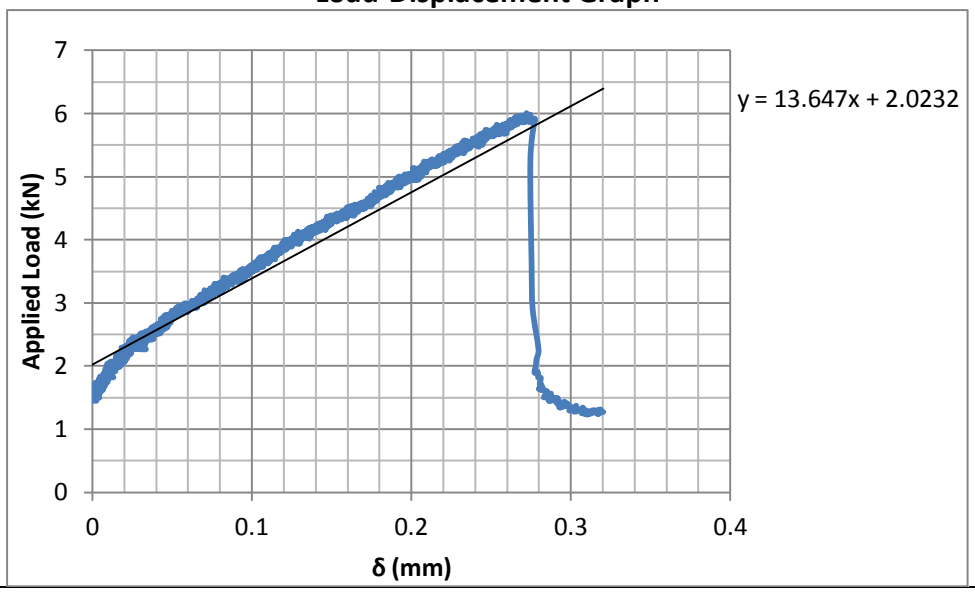
The captured footage was too dark and hence unable to determine the location of crack initiation.



As the primary crack occurred along the vertically-loaded diameter of the specimen, the test result was still considered valid although it is not known where the crack initiated in the specimen.

Specimen No: 20111208-3M

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

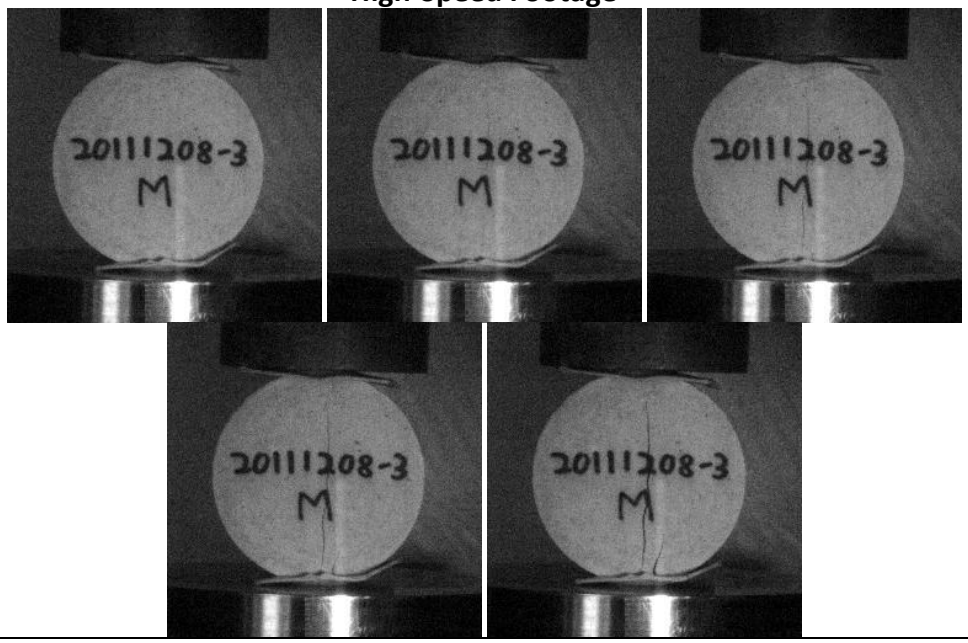
Thickness
30.9mm

Max Load
6.00698kN

Tensile Strength
2.475MPa

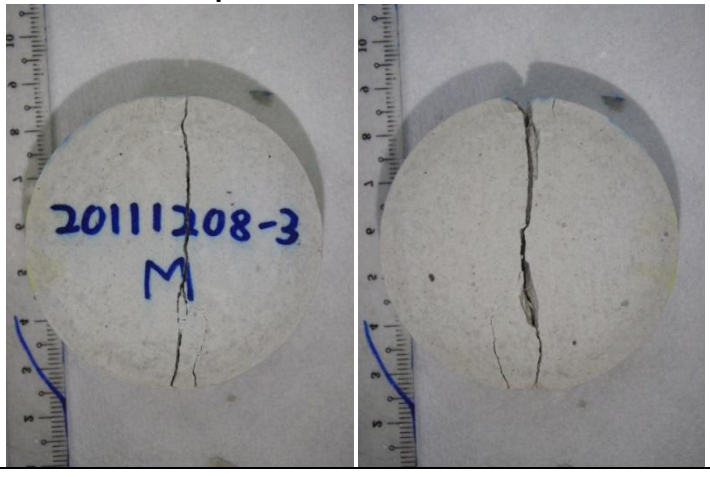
Stiffness
13.647kN/mm

High-Speed Footage



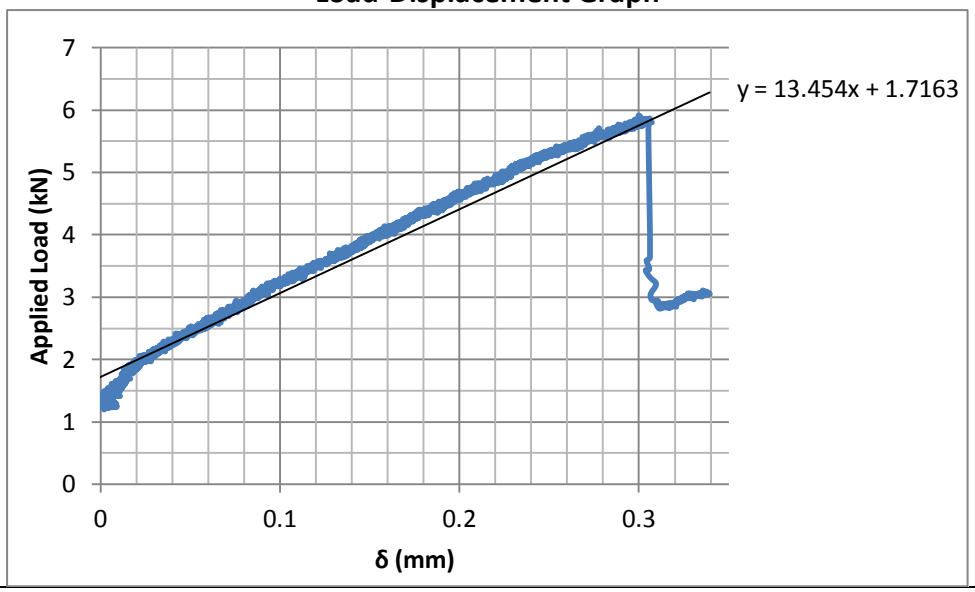
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111208-3B

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

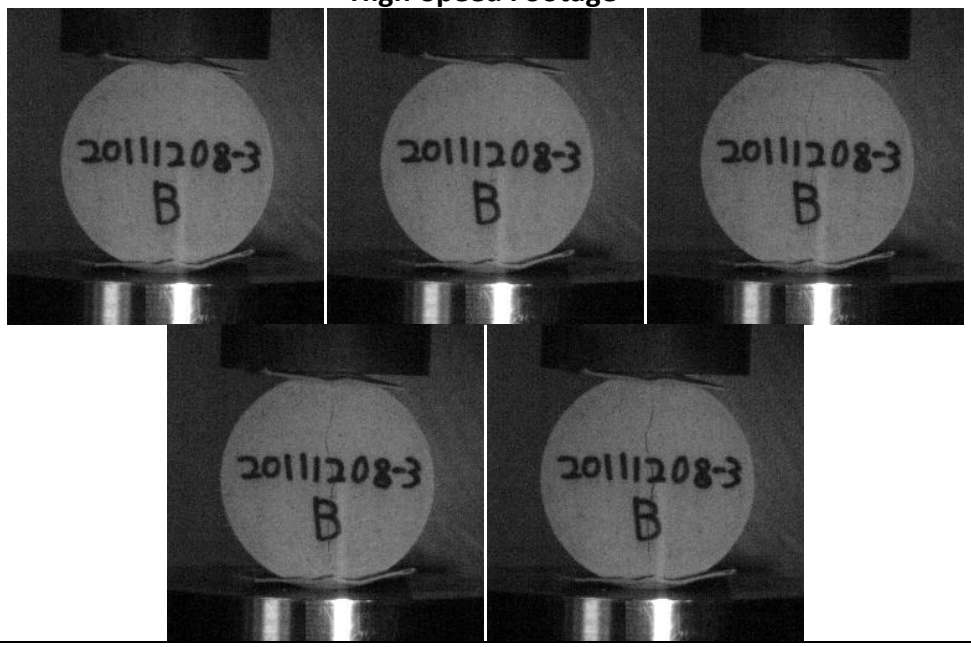
Thickness
30.2mm

Max Load
5.90629kN

Tensile Strength
2.490MPa

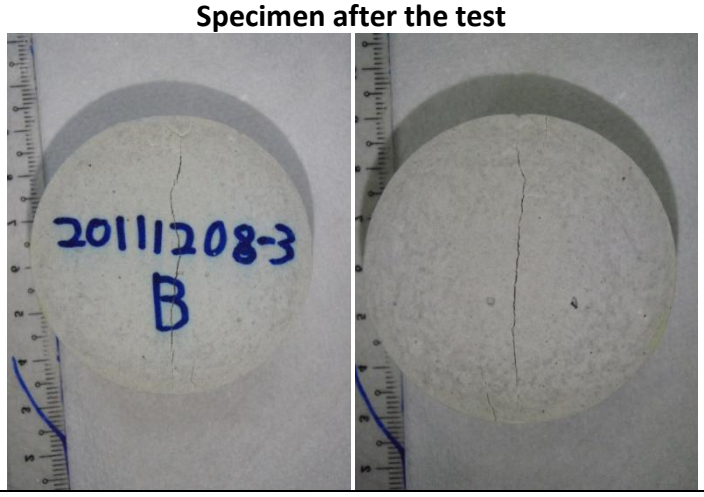
Stiffness
13.454kN/mm

High-Speed Footage



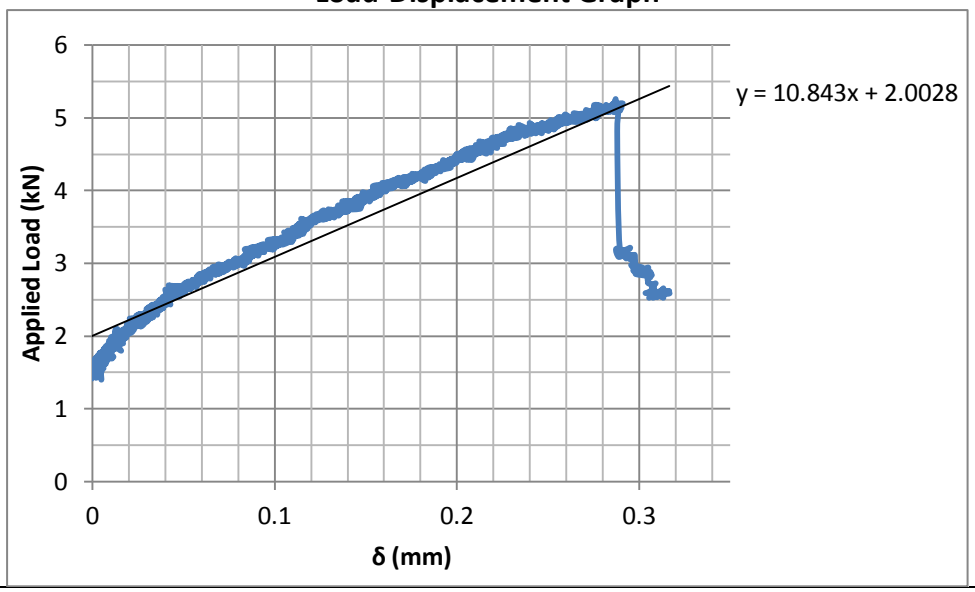
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen.

Specimen after the test



Specimen No: 20111209-1T

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

Thickness
30.4mm

Max Load
5.25527kN

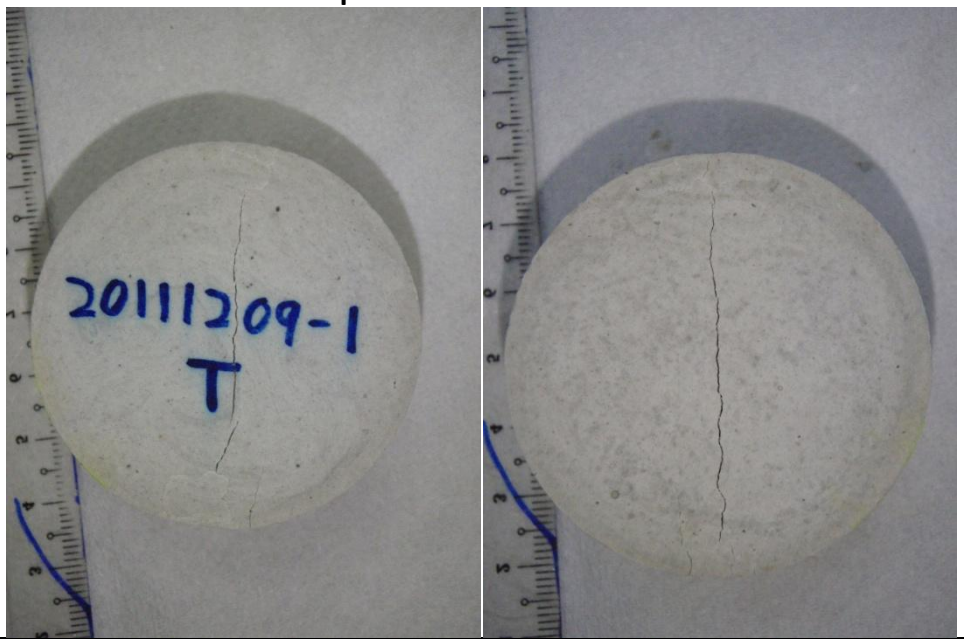
Tensile Strength
2.201MPa

Stiffness
10.843kN/mm

High-Speed Footage

Not Available

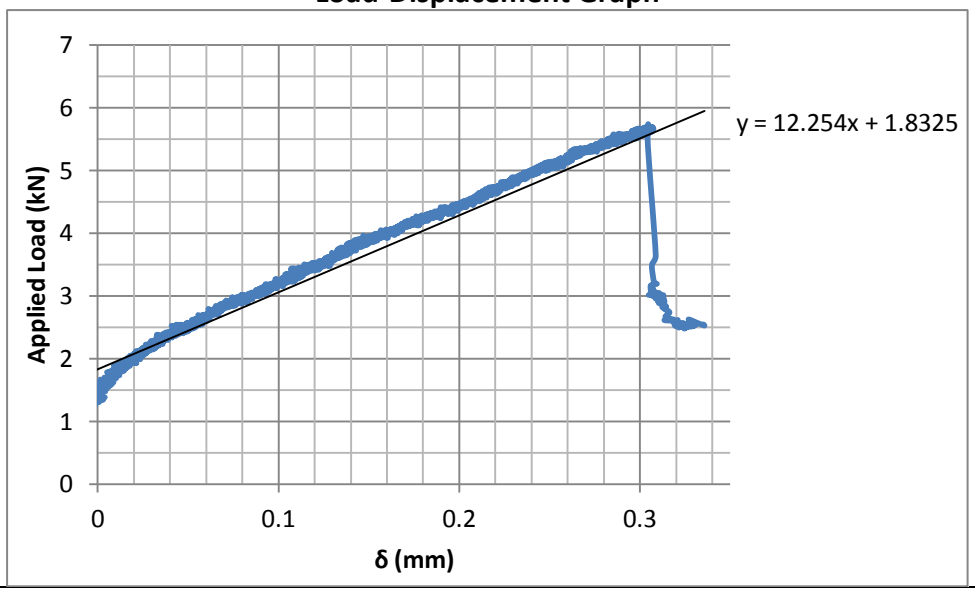
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen. Hence, it can be deduced that the crack initiated at the centre of the specimen and tensile failure has occurred.

Specimen No: 20111209-1M

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

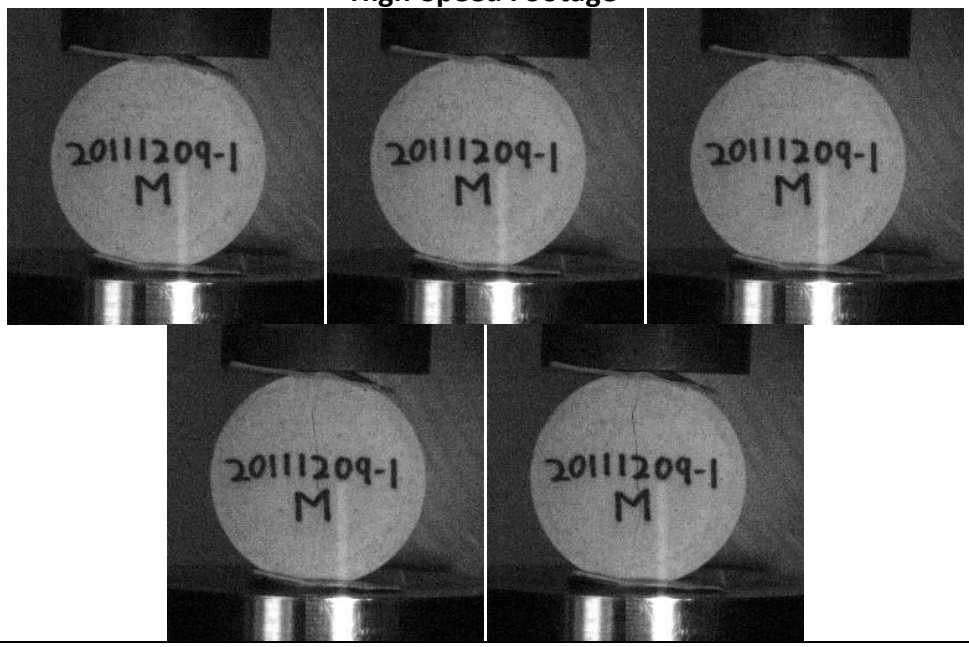
Thickness
29.9mm

Max Load
5.73999kN

Tensile Strength
2.444MPa

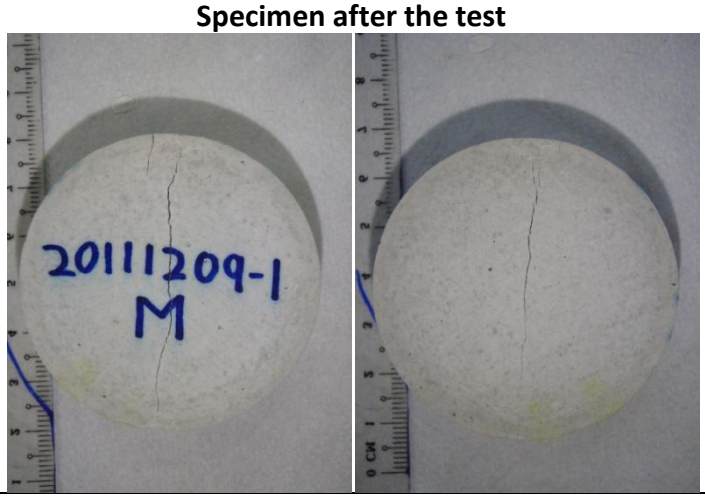
Stiffness
12.254kN/mm

High-Speed Footage



The primary crack initiated at the centre and propagated towards the top and bottom of the specimen.

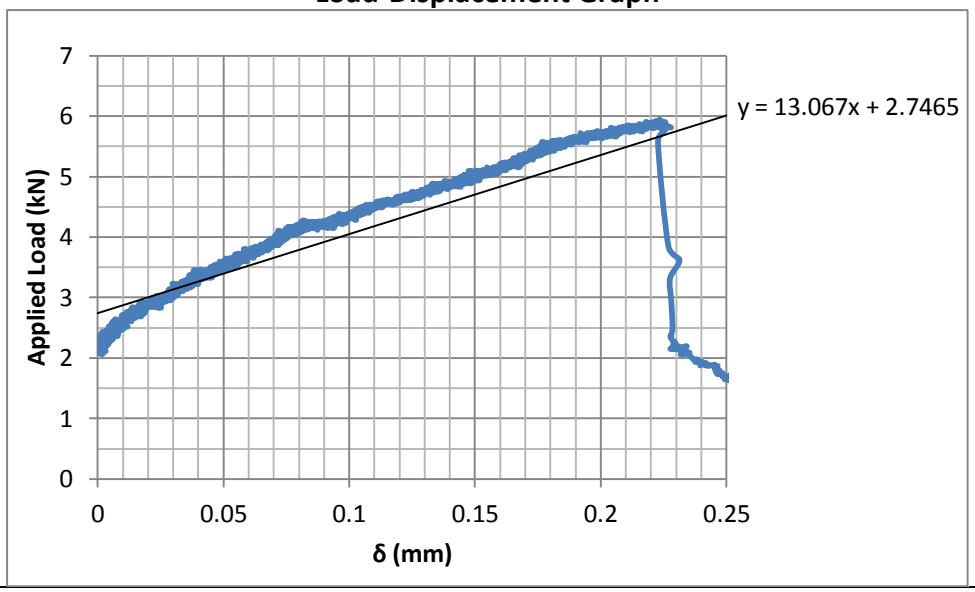
Specimen after the test



A secondary crack was formed at the top of the specimen after the primary crack has occurred.

Specimen No: 20111209-1B

Load-Displacement Graph



Immersion Time
3 weeks

Diameter
50mm

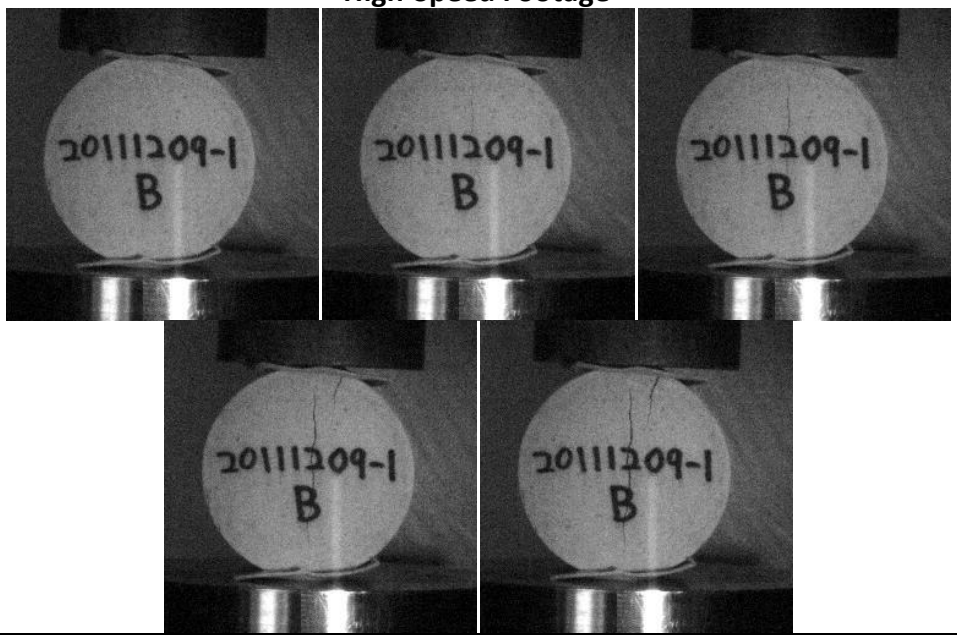
Thickness
30.2mm

Max Load
5.93872kN

Tensile Strength
2.504MPa

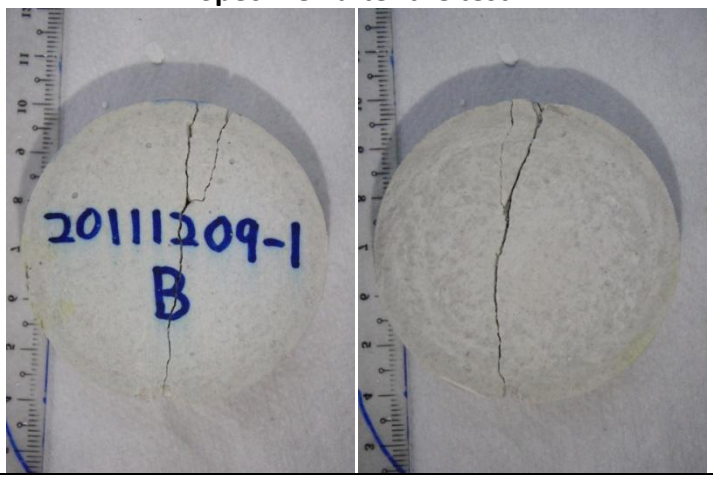
Stiffness
13.067kN/mm

High-Speed Footage



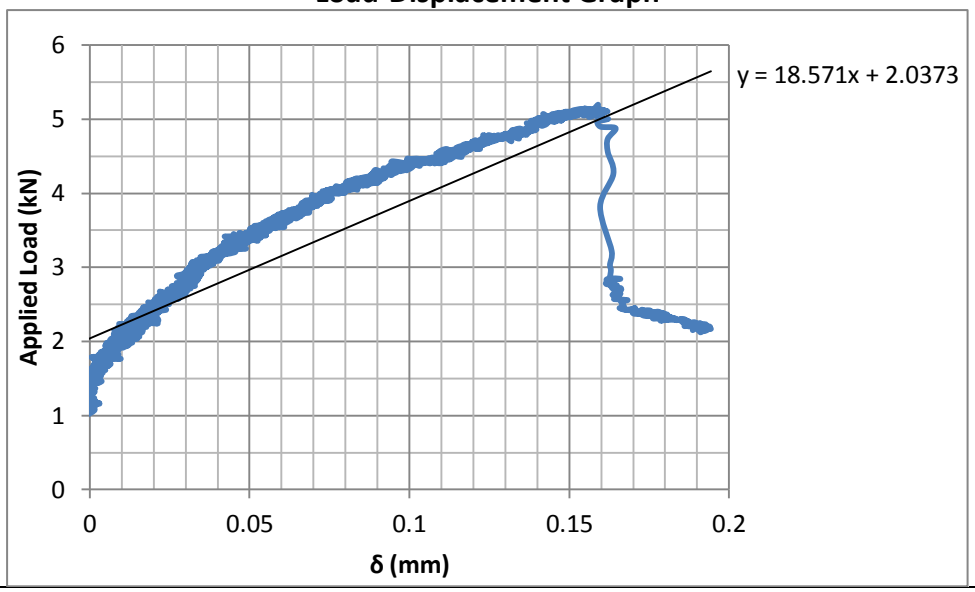
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the top of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111129-1T

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

Thickness
31.5mm

Max Load
5.19503kN

Tensile Strength
2.100MPa

Stiffness
18.571kN/mm

High-Speed Footage

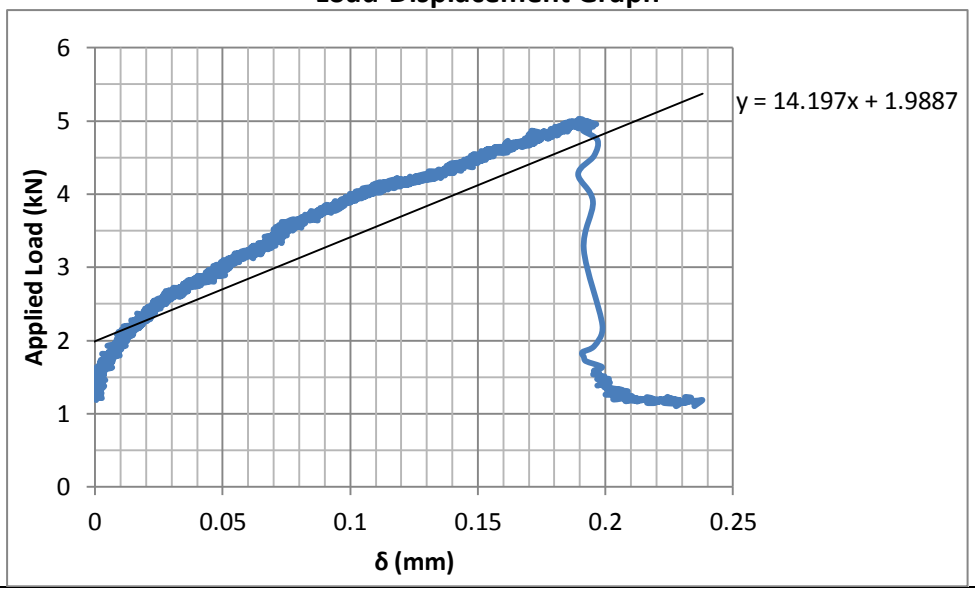
Not Available

Specimen after the test

Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen. Hence, it can be deduced that the crack initiated at the centre of the specimen and tensile failure has occurred.

Specimen No: 20111129-1M

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

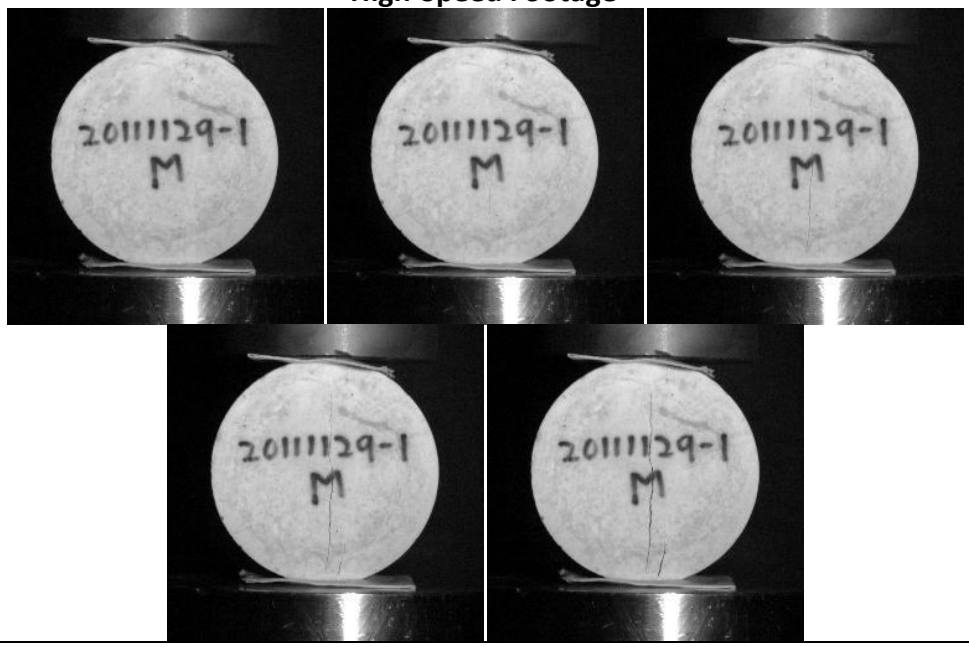
Thickness
29.0mm

Max Load
5.03322kN

Tensile Strength
2.210MPa

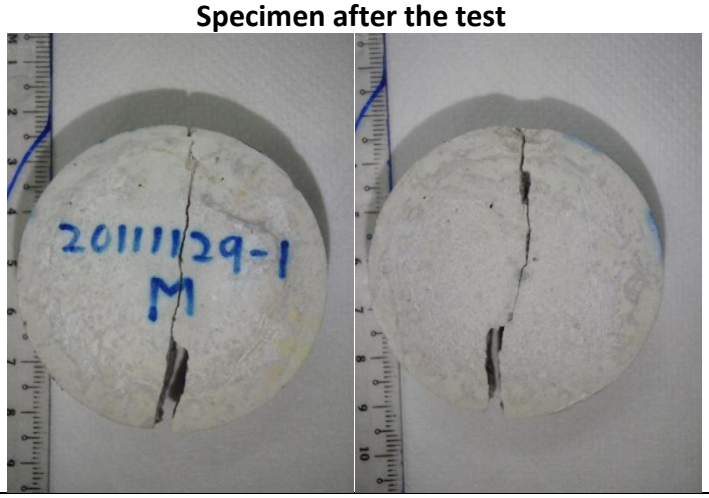
Stiffness
14.197kN/mm

High-Speed Footage



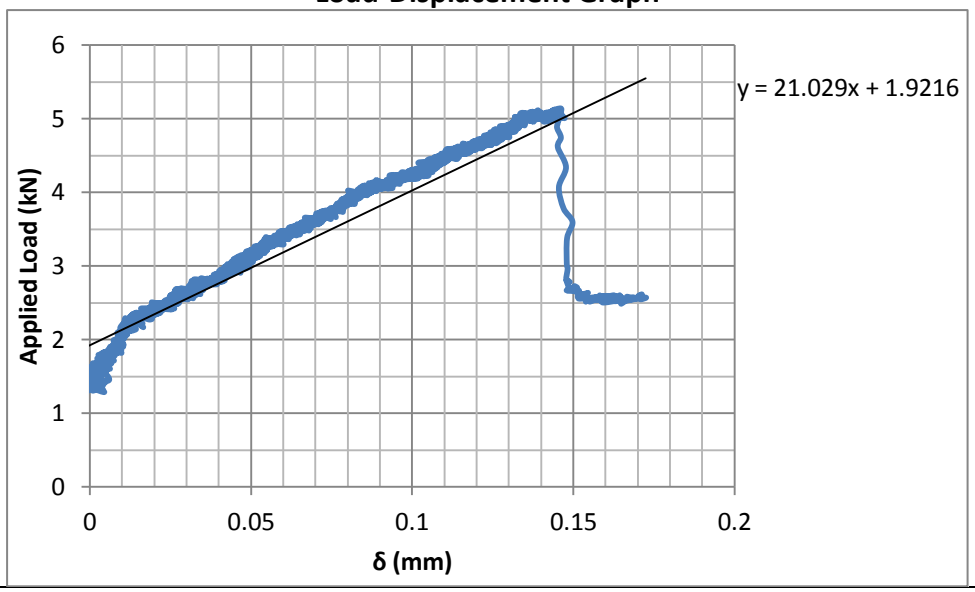
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111129-1B

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

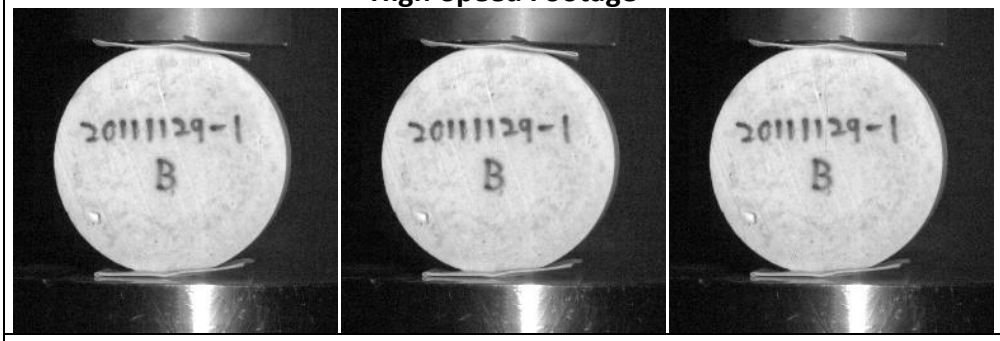
Thickness
31.4mm

Max Load
5.14311kN

Tensile Strength
2.085MPa

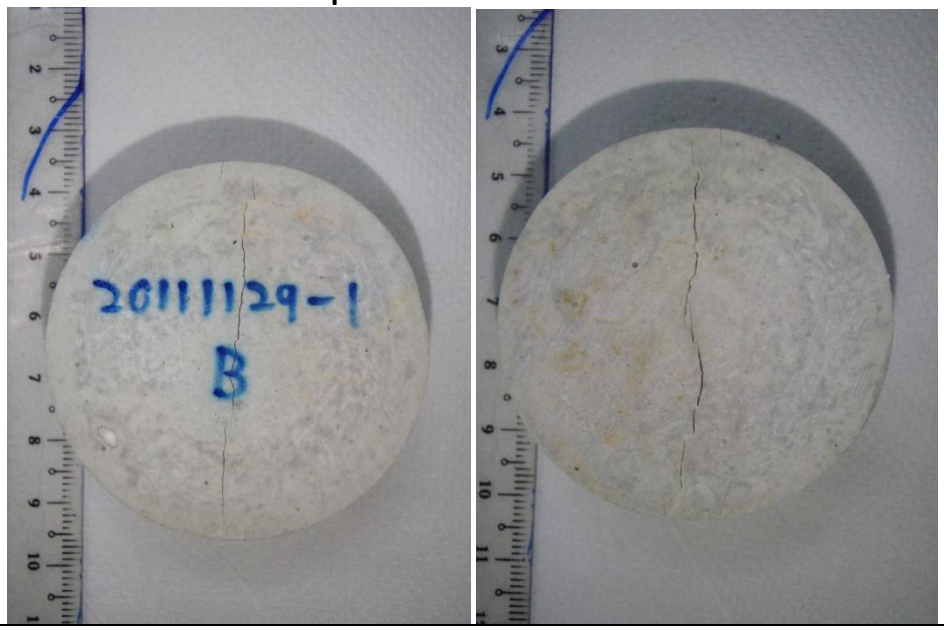
Stiffness
21.029kN/mm

High-Speed Footage



It is unclear from the high-speed footage where the crack initiated in the specimen.

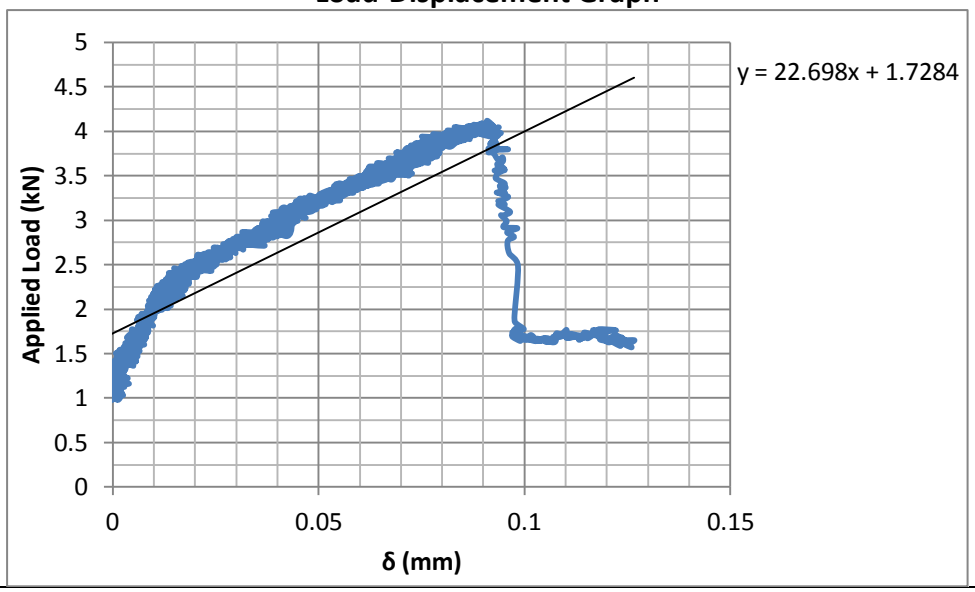
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen. Hence, it can be deduced that the crack initiated at the centre of the specimen and tensile failure has occurred.

Specimen No: 20111129-2T

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

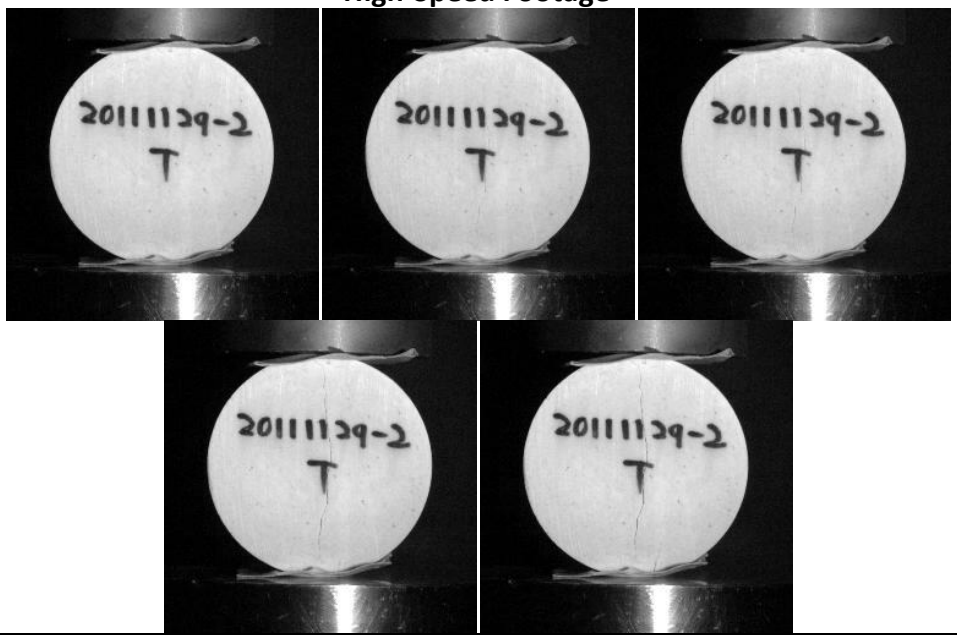
Thickness
30.3mm

Max Load
4.11838kN

Tensile Strength
1.731MPa

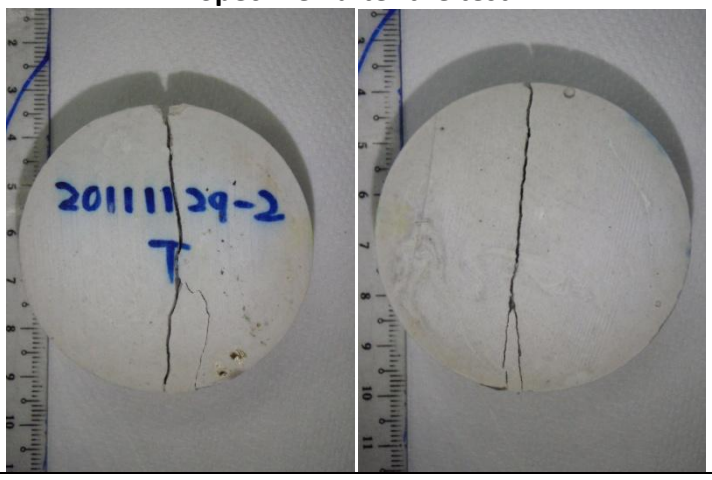
Stiffness
22.698kN/mm

High-Speed Footage



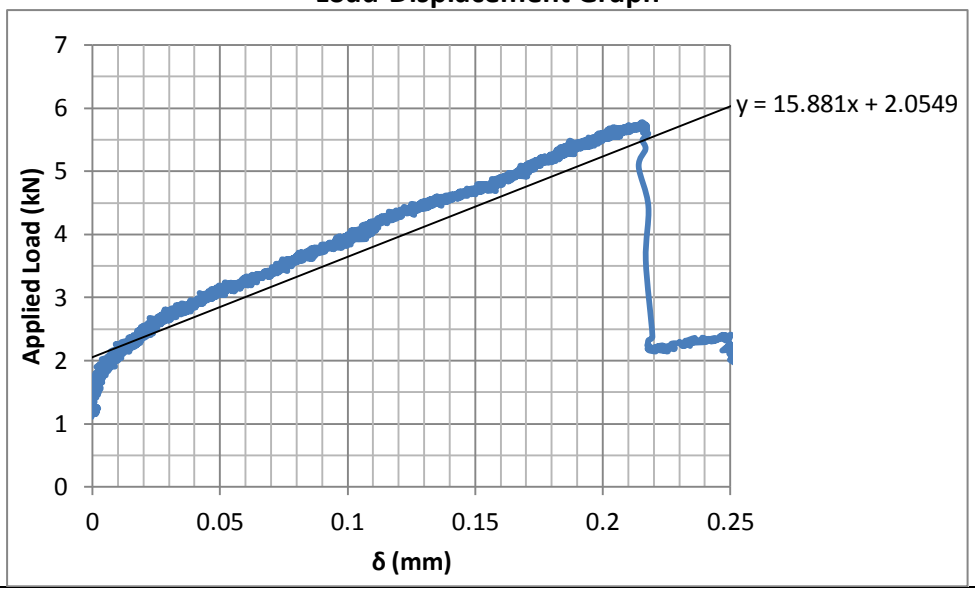
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111129-2M

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

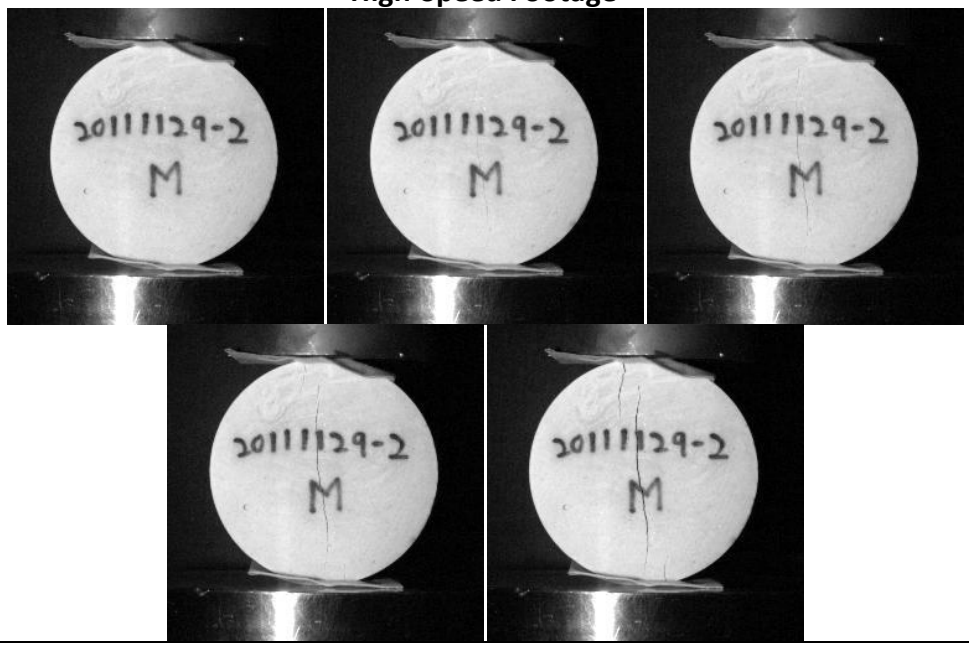
Thickness
30.4mm

Max Load
5.78066kN

Tensile Strength
2.421MPa

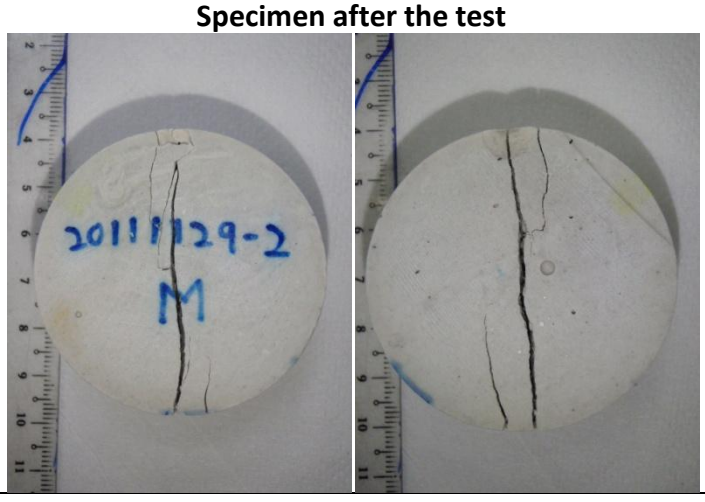
Stiffness
15.881kN/mm

High-Speed Footage



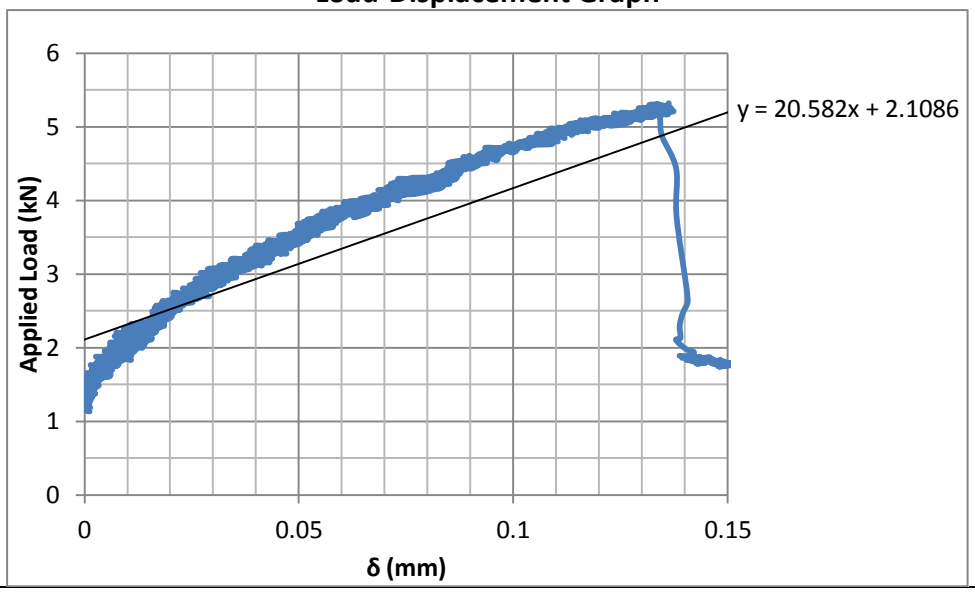
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the top and bottom of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111129-2B

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

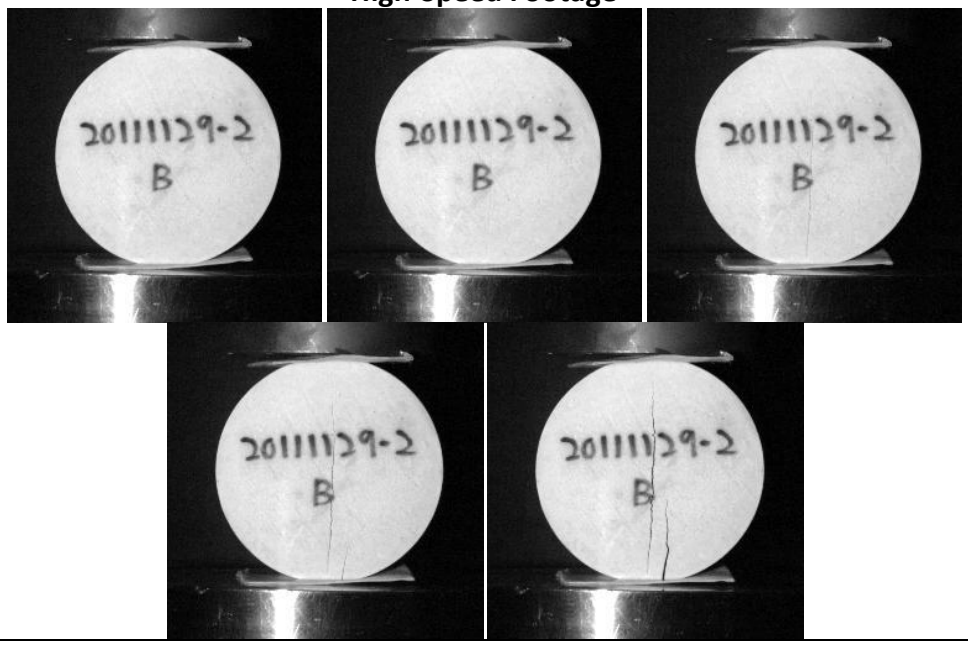
Thickness
29.6mm

Max Load
5.31733kN

Tensile Strength
2.287MPa

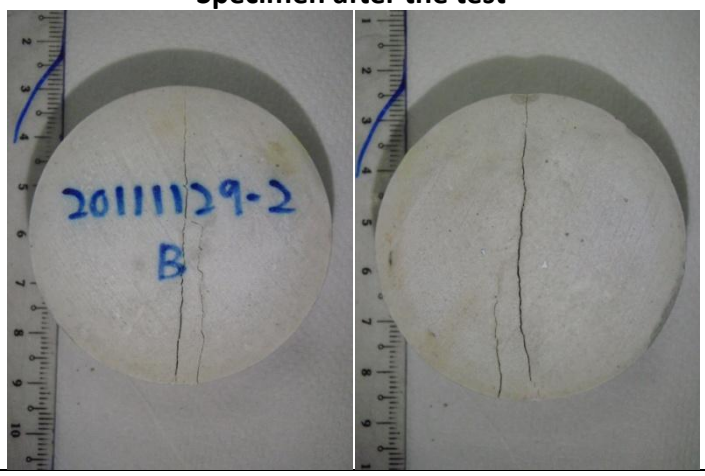
Stiffness
20.582kN/mm

High-Speed Footage



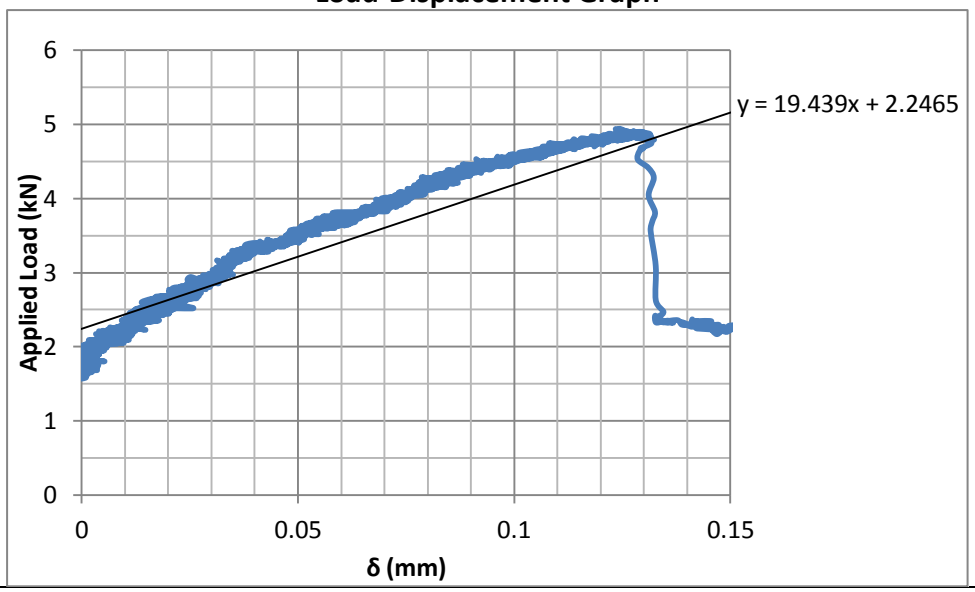
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111129-3T

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

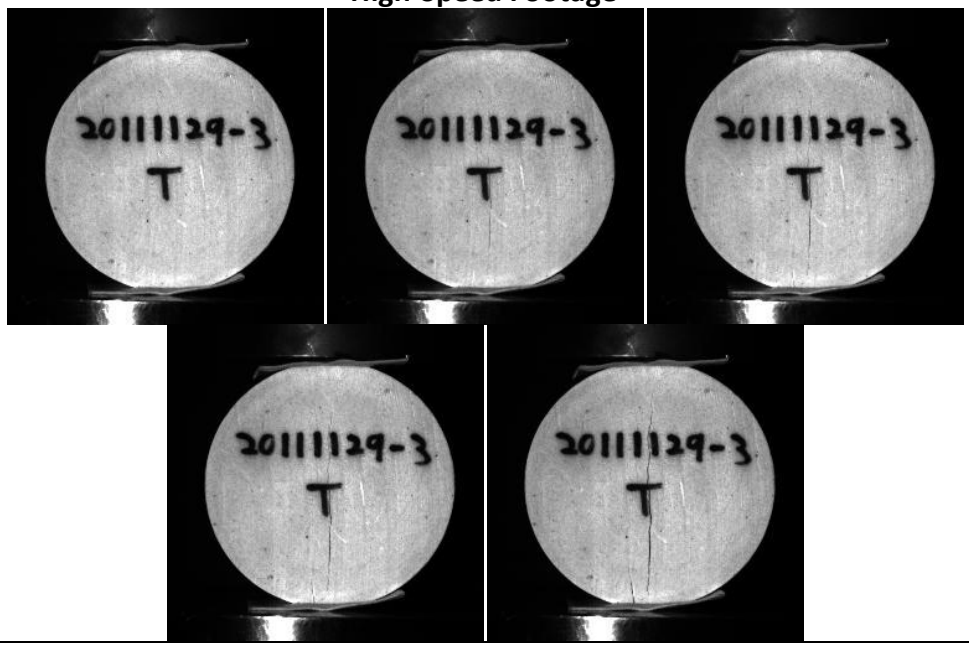
Thickness
30.7mm

Max Load
4.94345kN

Tensile Strength
2.050MPa

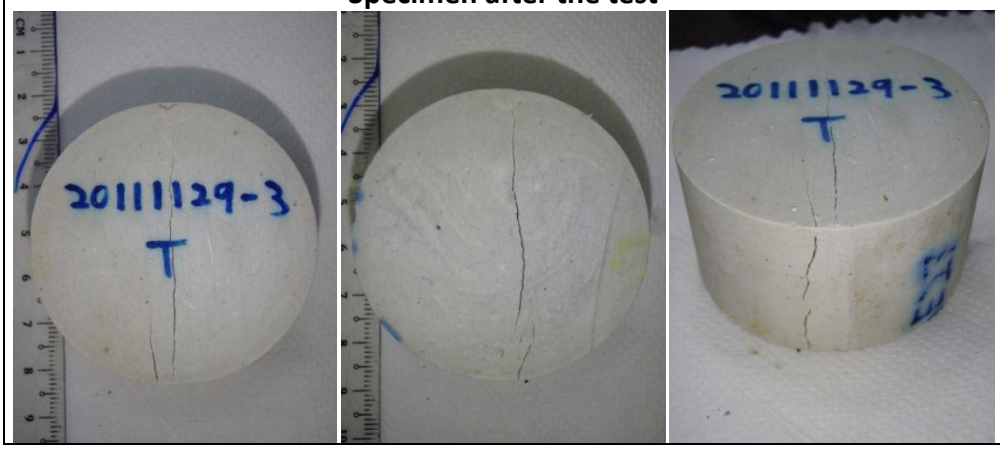
Stiffness
19.439kN/mm

High-Speed Footage



The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

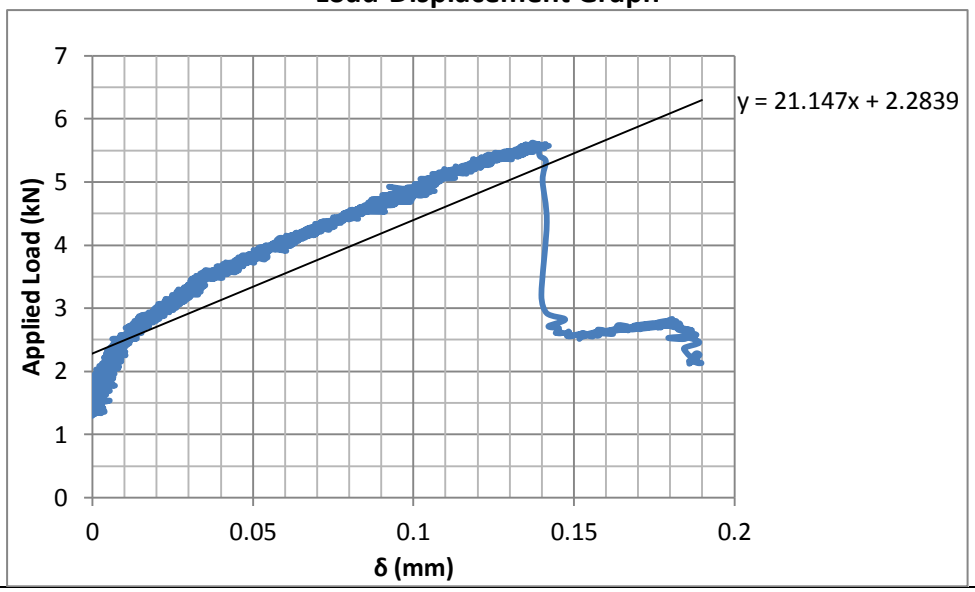
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen.

Specimen No: 20111129-3M

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

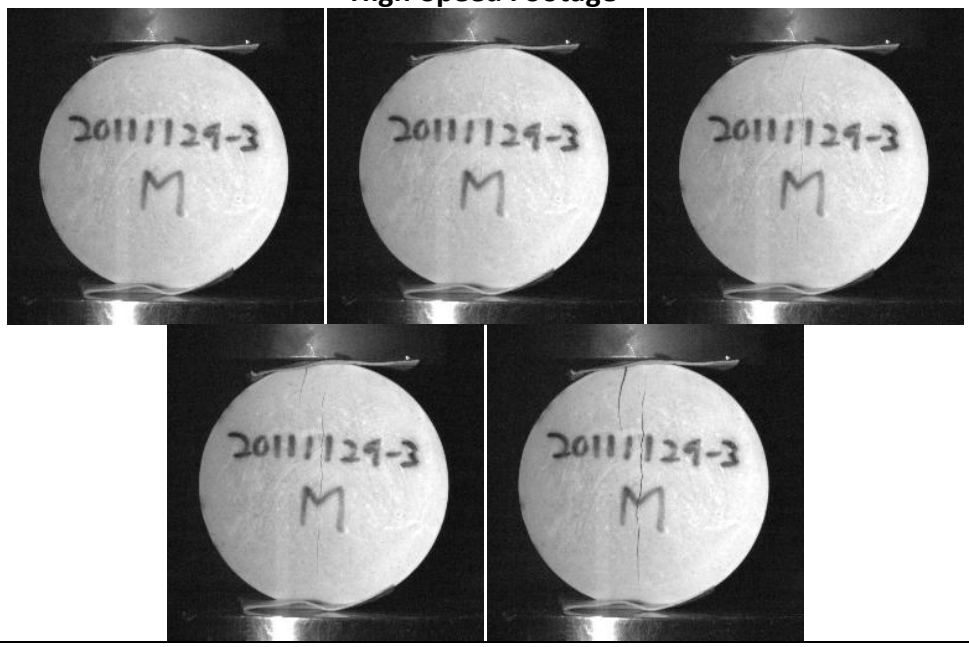
Thickness
30.4mm

Max Load
5.61928kN

Tensile Strength
2.354MPa

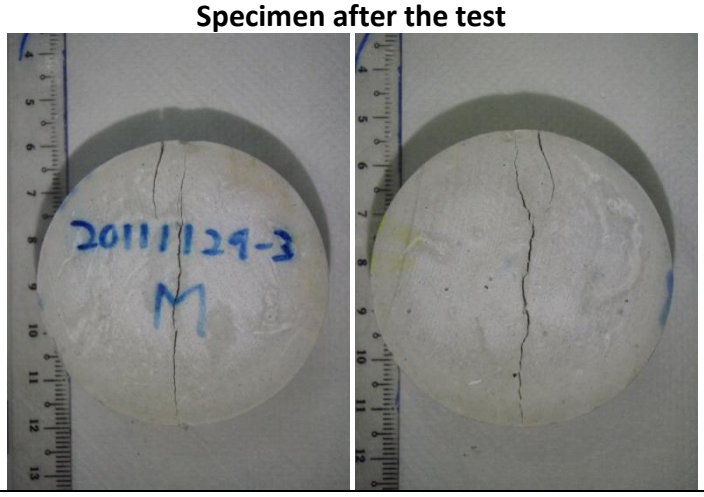
Stiffness
21.147kN/mm

High-Speed Footage



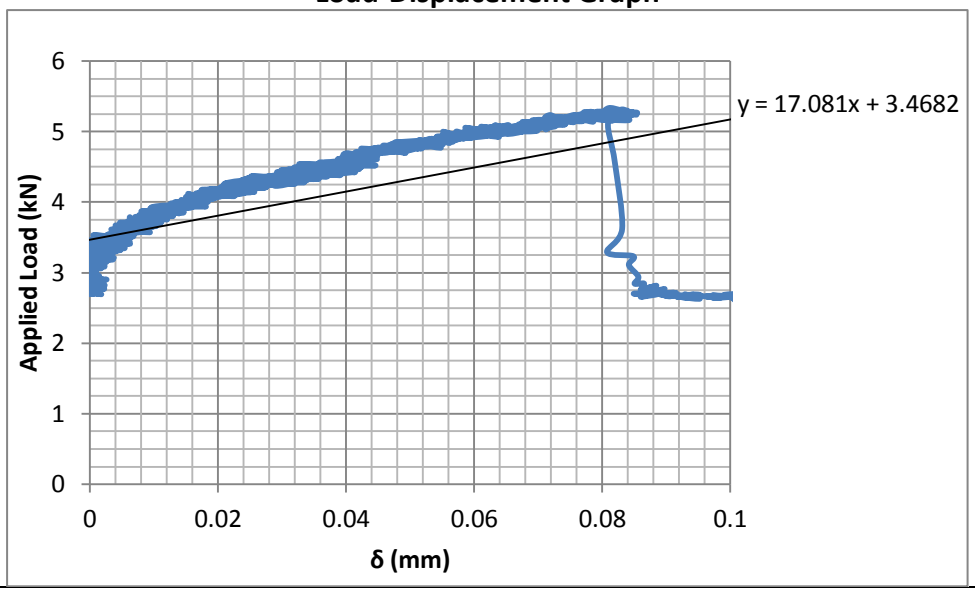
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the top of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111129-3B

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

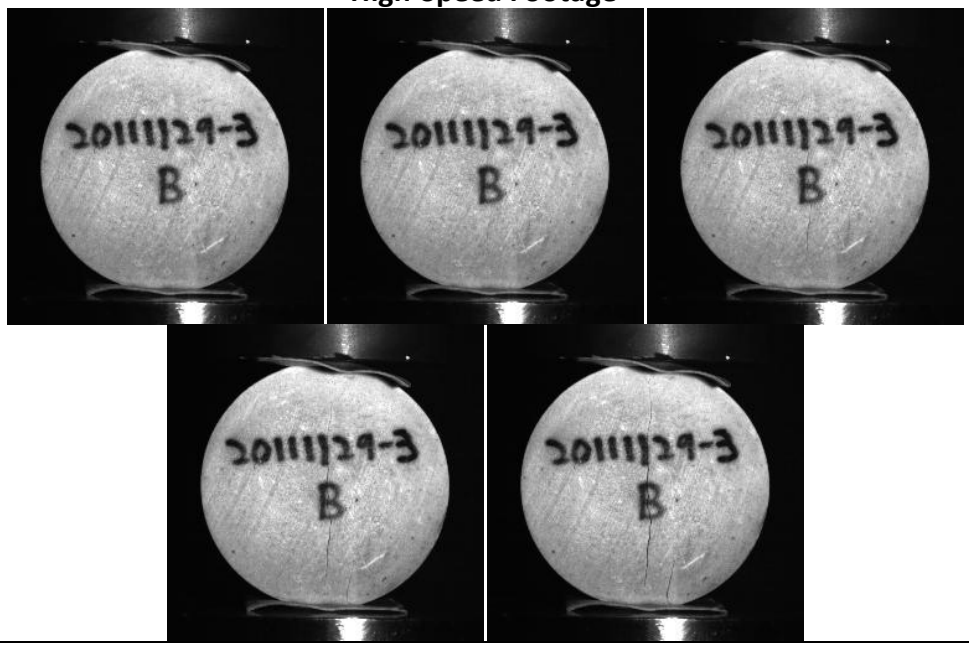
Thickness
28.5mm

Max Load
5.3396kN

Tensile Strength
2.385MPa

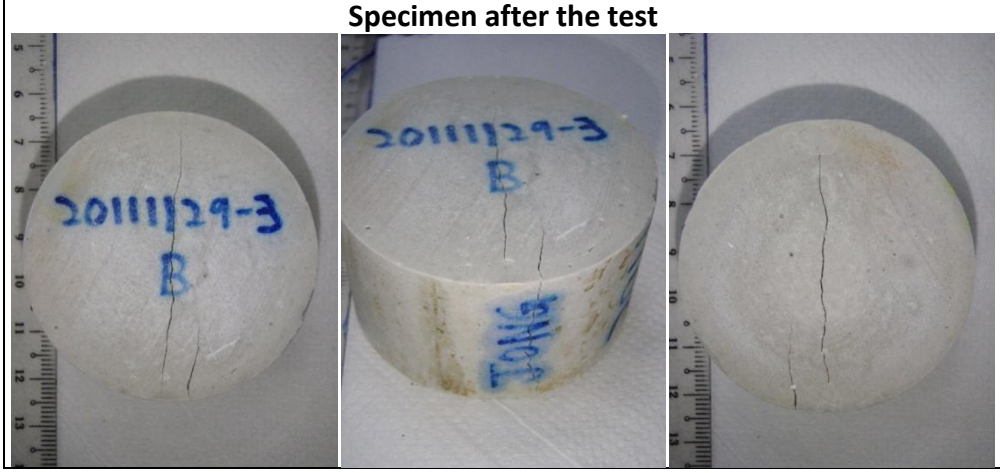
Stiffness
17.081kN/mm

High-Speed Footage



The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

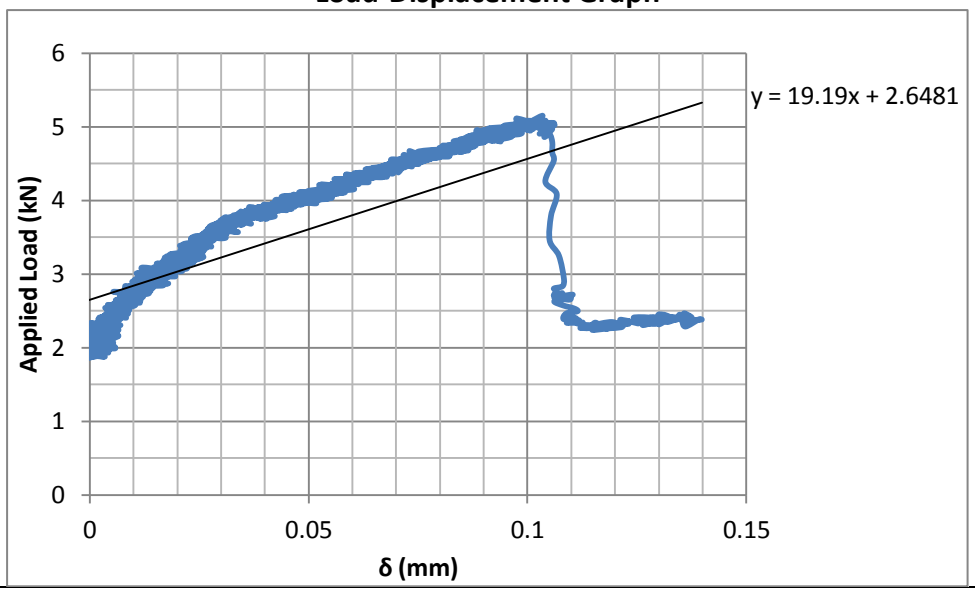
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen.

Specimen No: 20111130-1T

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

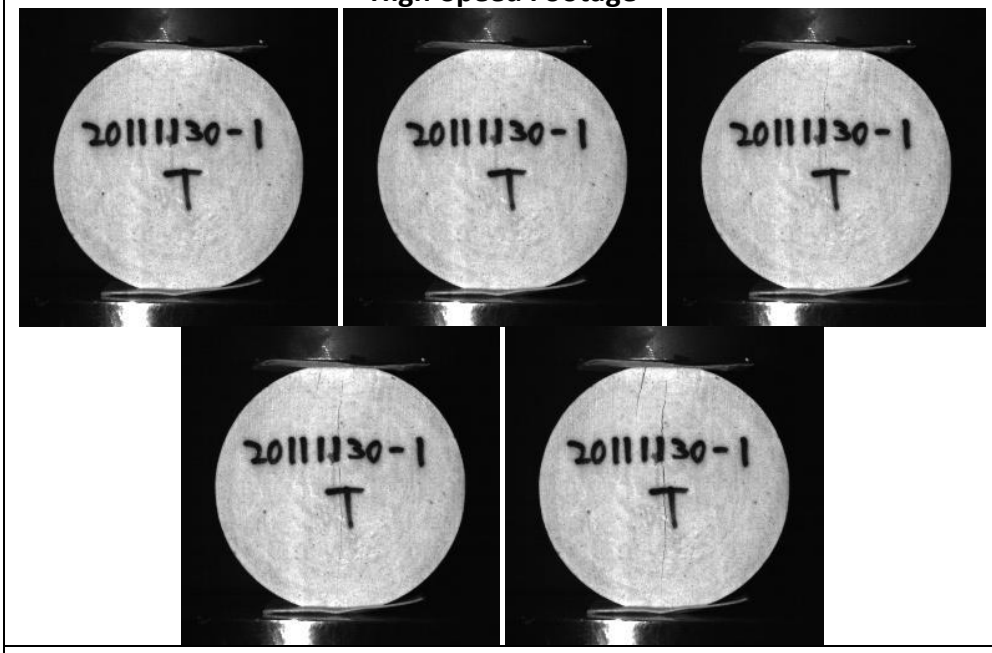
Thickness
28.2mm

Max Load
5.15072kN

Tensile Strength
2.326MPa

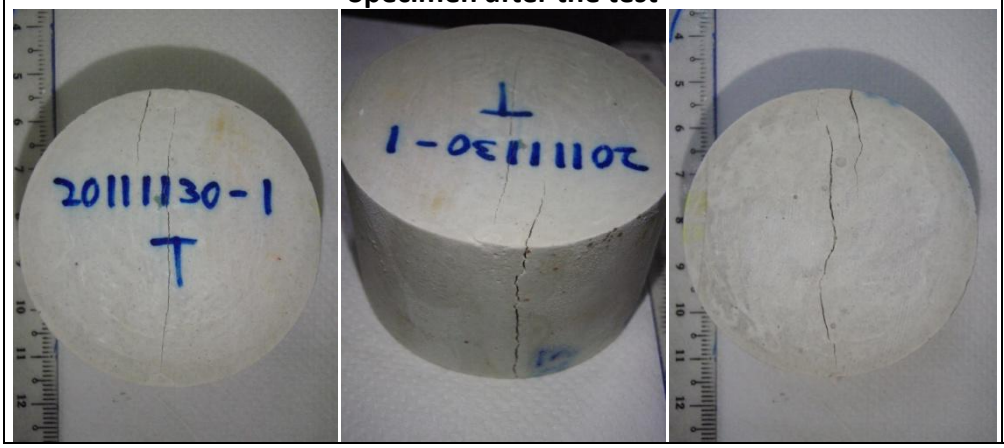
Stiffness
19.19kN/mm

High-Speed Footage



The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the top of the specimen after the primary crack has occurred.

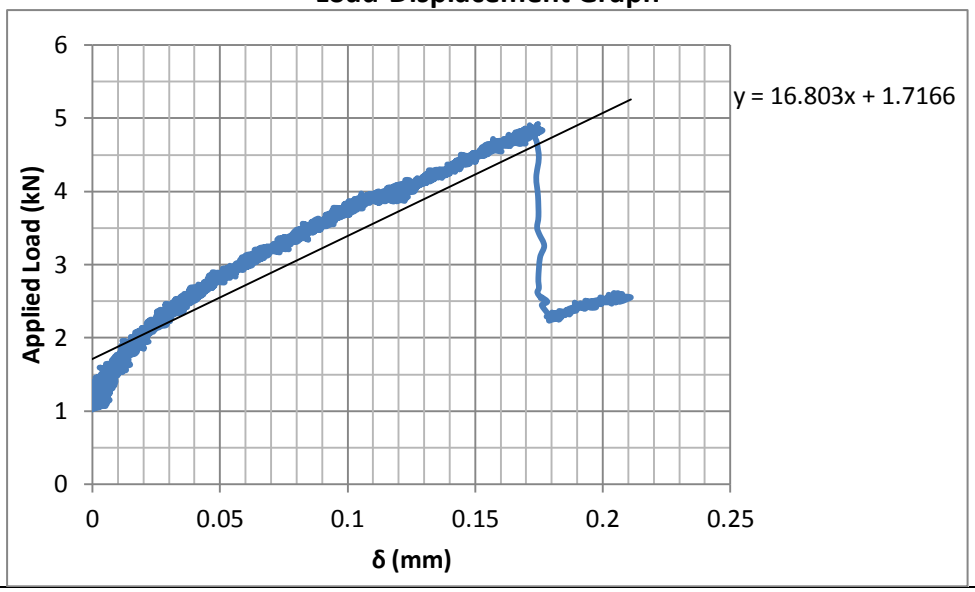
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen.

Specimen No: 20111130-1M

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

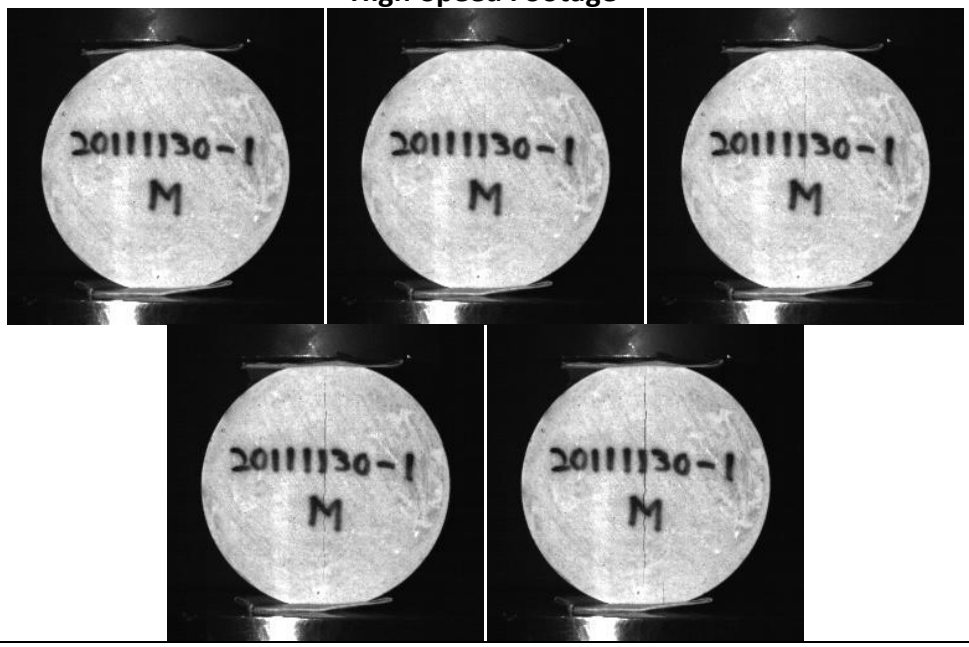
Thickness
29.0mm

Max Load
4.92666kN

Tensile Strength
2.163MPa

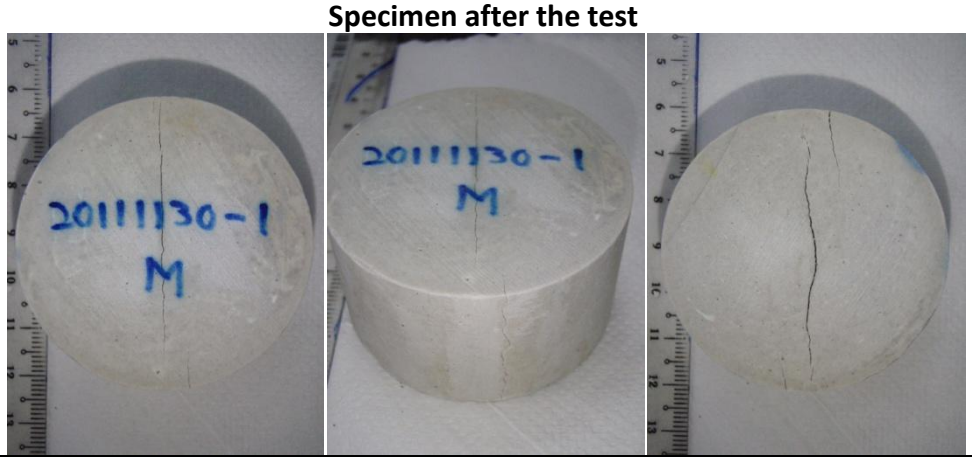
Stiffness
16.803kN/mm

High-Speed Footage



The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

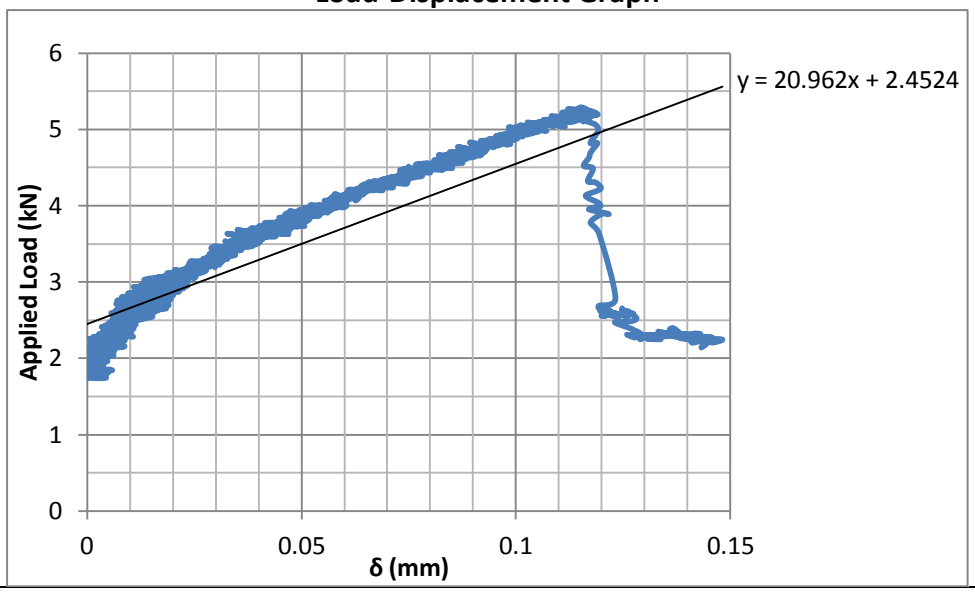
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen.

Specimen No: 20111130-1B

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

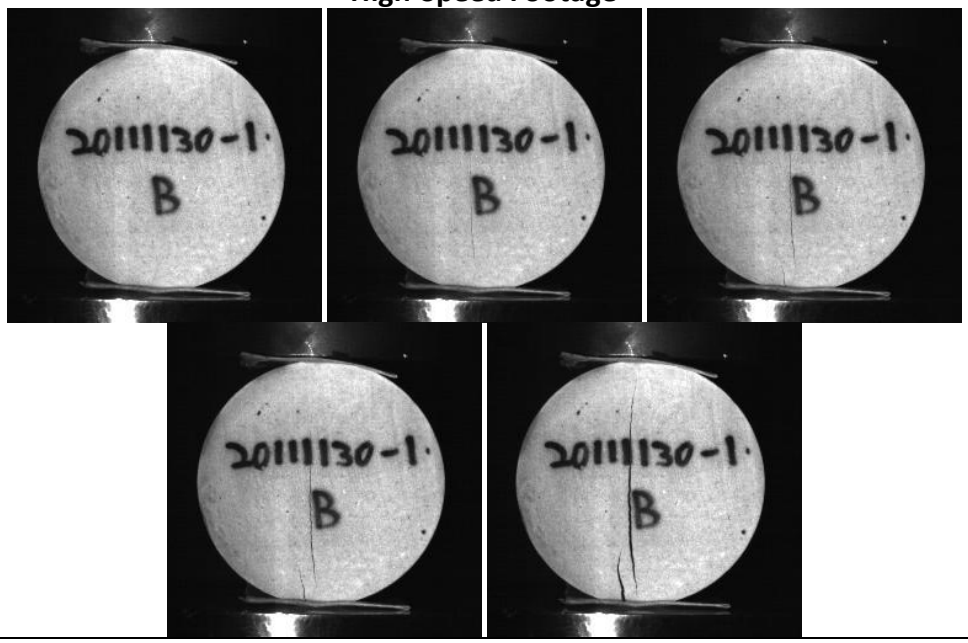
Thickness
33.6mm

Max Load
5.28971kN

Tensile Strength
2.004MPa

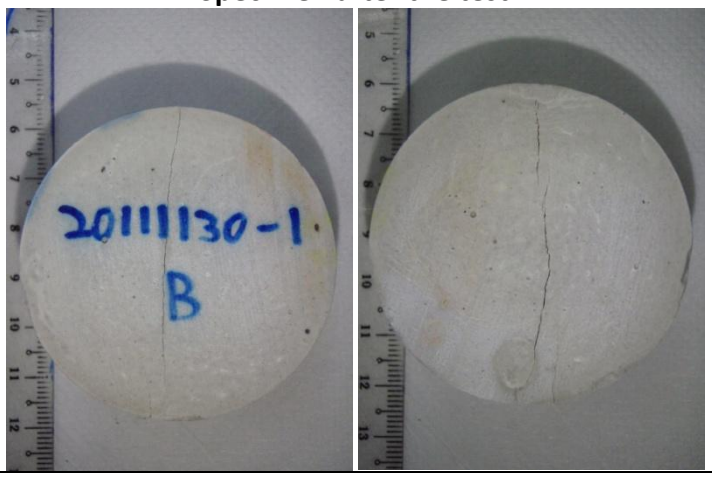
Stiffness
20.962kN/mm

High-Speed Footage



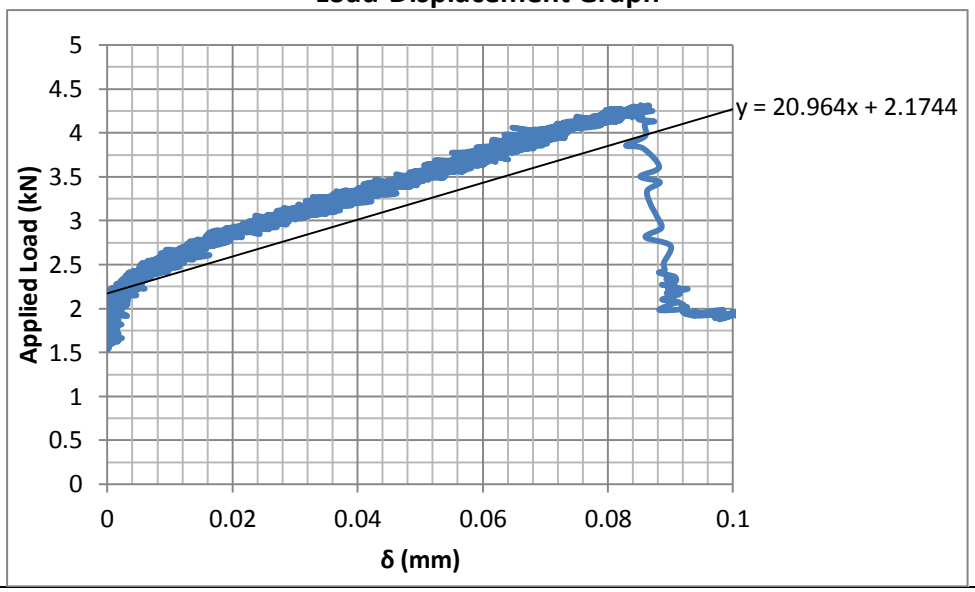
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111130-2T

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

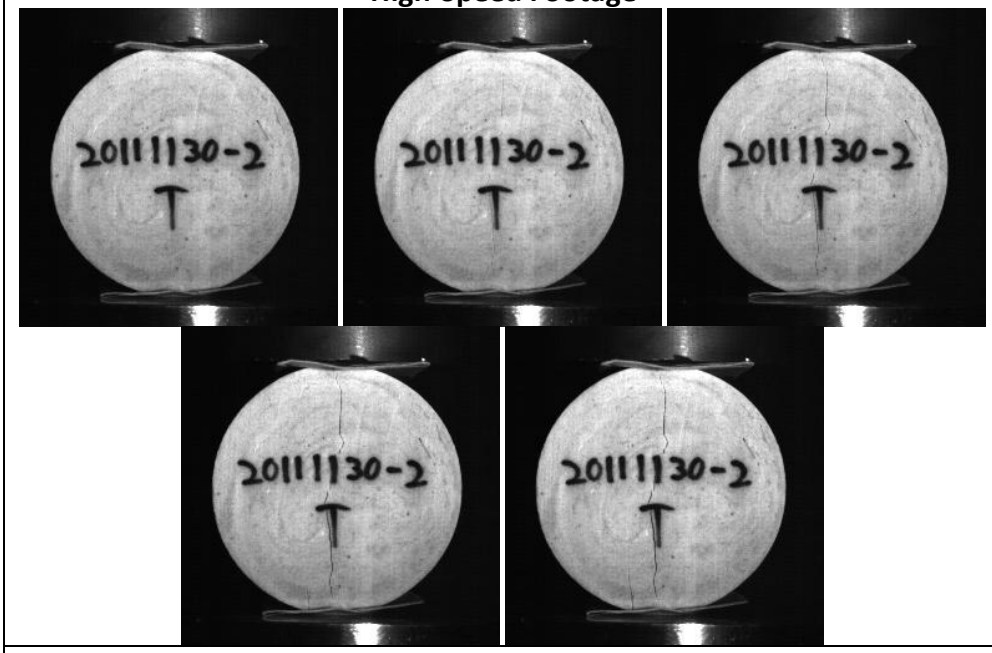
Thickness
31.4mm

Max Load
4.31745kN

Tensile Strength
1.751MPa

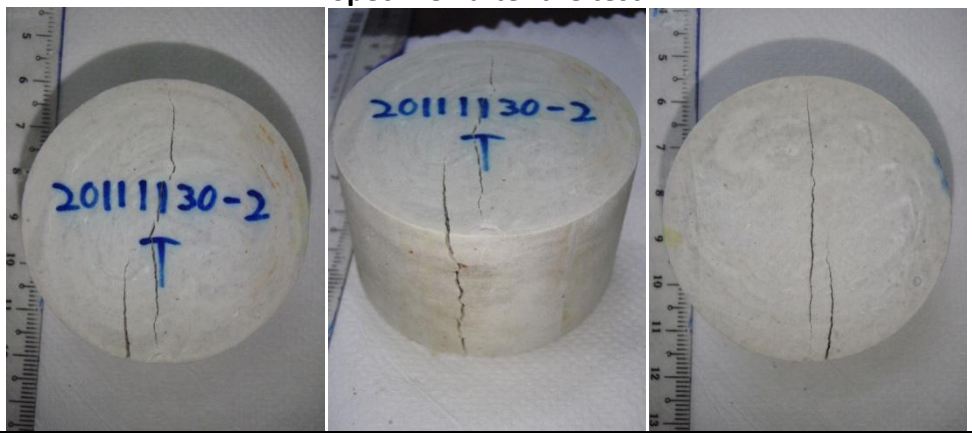
Stiffness
20.964kN/mm

High-Speed Footage



The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

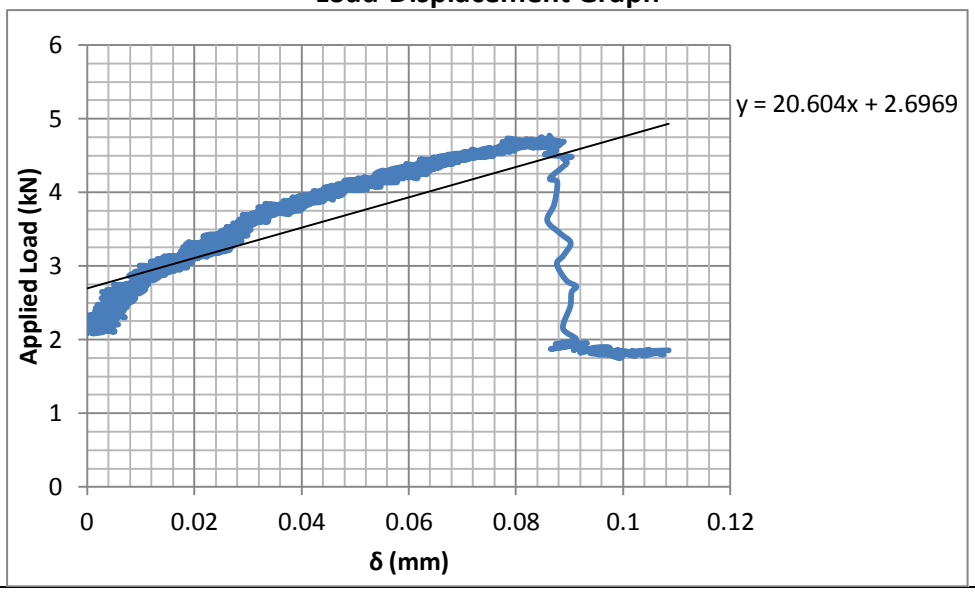
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen.

Specimen No: 20111130-2M

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

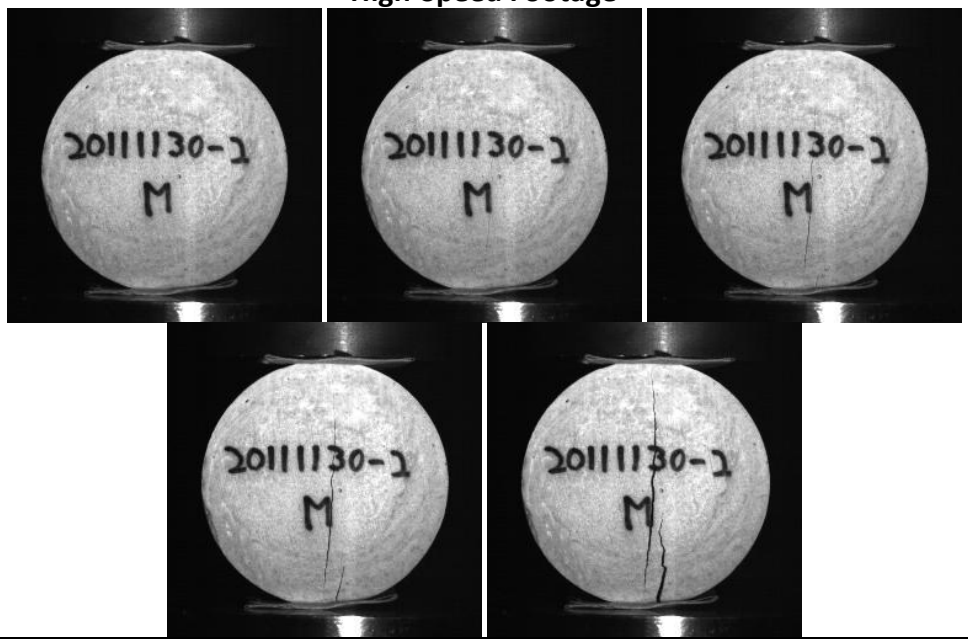
Thickness
30.3mm

Max Load
4.76391kN

Tensile Strength
2.002MPa

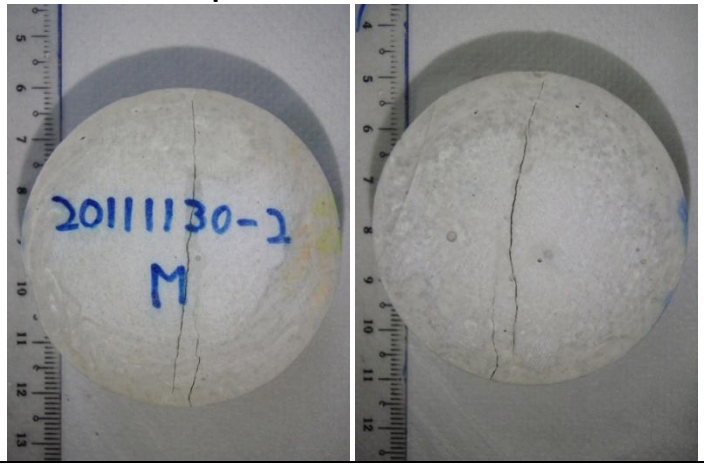
Stiffness
20.604kN/mm

High-Speed Footage



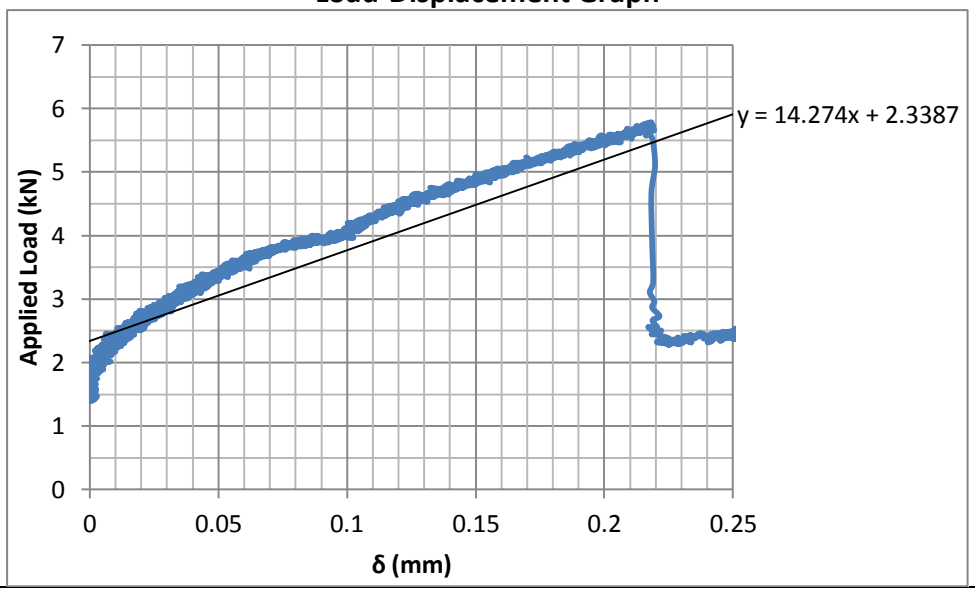
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

Specimen after the test



Specimen No: 20111130-2B

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

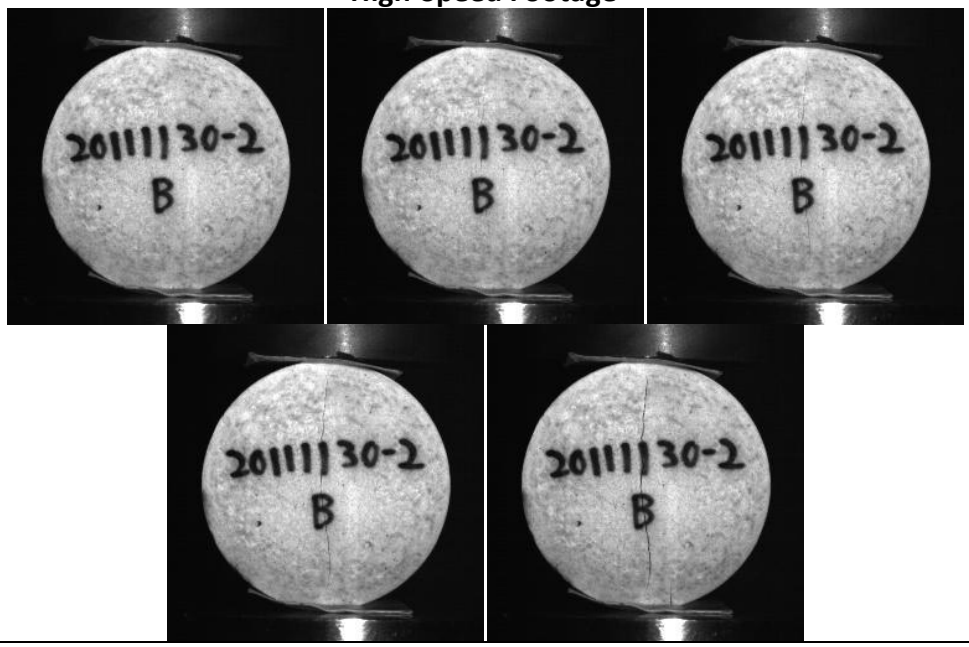
Thickness
33.2mm

Max Load
5.78099kN

Tensile Strength
2.217MPa

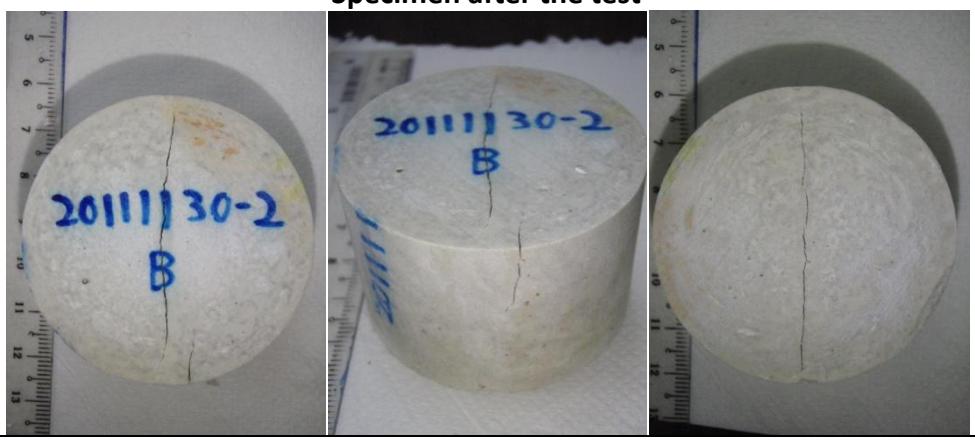
Stiffness
14.274kN/mm

High-Speed Footage



The primary crack initiated at the centre and propagated towards the top and bottom of the specimen. A secondary crack was formed at the bottom of the specimen after the primary crack has occurred.

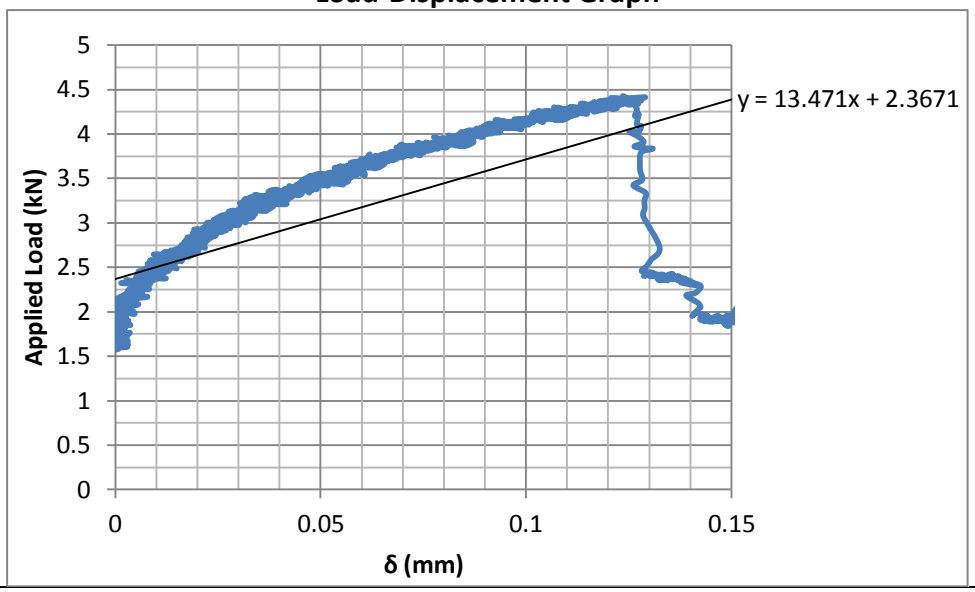
Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen.

Specimen No: 20111130-3T

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

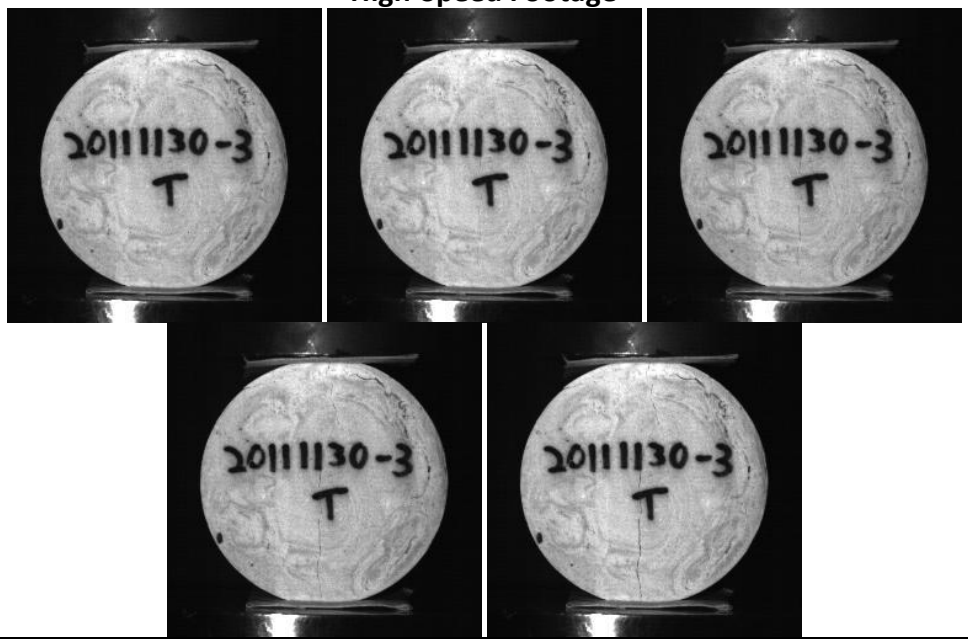
Thickness
32.8mm

Max Load
4.42414kN

Tensile Strength
1.717MPa

Stiffness
13.471kN/mm

High-Speed Footage



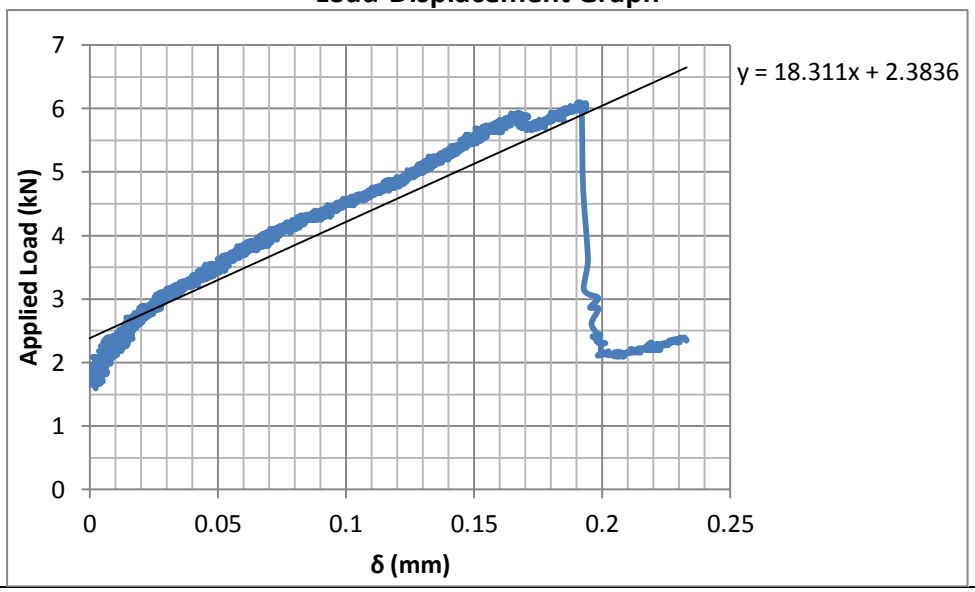
The primary crack initiated at the centre and propagated towards the top and bottom of the specimen.

Specimen after the test

A secondary crack was formed at the top of the specimen after the primary crack has occurred.

Specimen No: 20111130-3M

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

Thickness
30.1mm

Max Load
6.09773kN

Tensile Strength
2.579MPa

Stiffness
18.311kN/mm

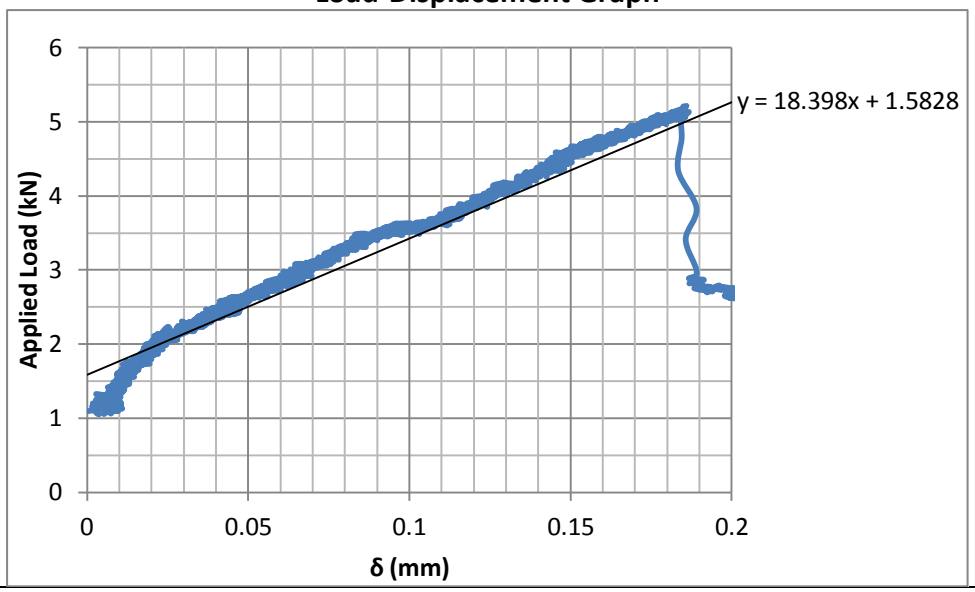
High-Speed Footage

The first crack appeared at the centre while a second crack was initiated at the top of the specimen. The two cracks propagated and became connected to form the main diametrical crack. Another secondary crack was formed at the top of the specimen after the primary crack has occurred.

Specimen after the test

Specimen No: 20111130-3B

Load-Displacement Graph



Immersion Time
10 weeks

Diameter
50mm

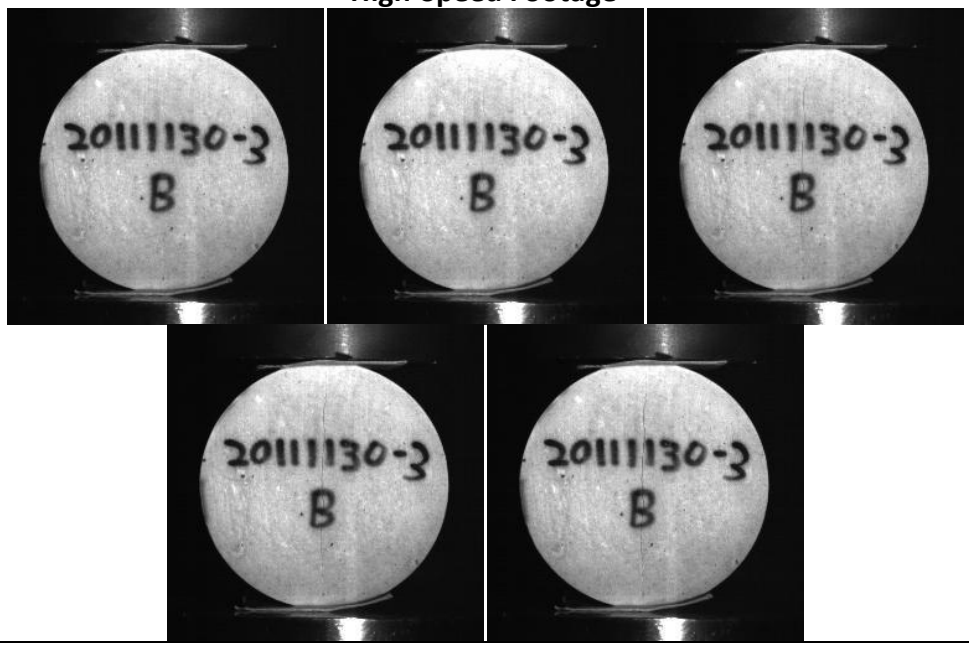
Thickness
31.8mm

Max Load
5.21994kN

Tensile Strength
2.090MPa

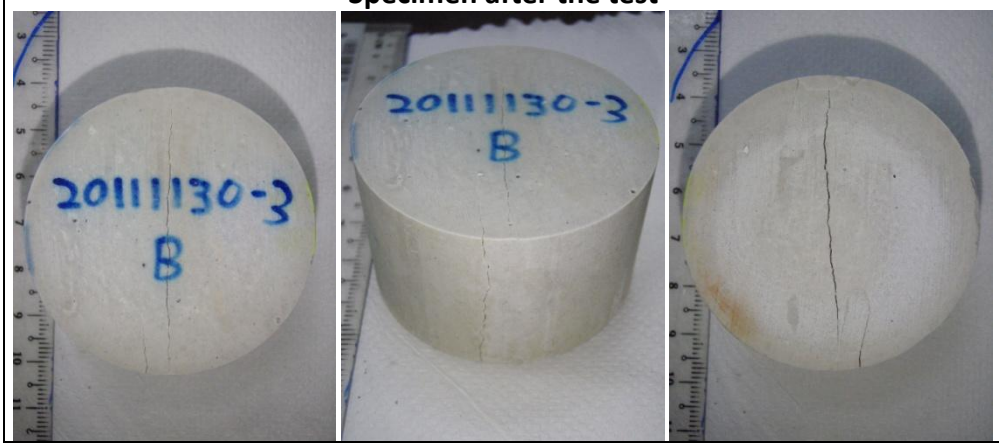
Stiffness
18.398kN/mm

High-Speed Footage



The primary crack initiated at the centre and propagated towards the top and bottom of the specimen.

Specimen after the test



Physical inspection of the specimen showed that the primary crack did not break through the top and bottom of the specimen.