Biaxial testing on the properties of pre-cracked partially saturated clay

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ABSTRACT

This paper presents the result of the biaxial testing on the properties of precrack partially saturated clay specimen. A modification of the conventional triaxial apparatus was used in this study. Cell pressure from the triaxial compression test and a rigid loading platen are used to apply the minor and major principle stresses to the specimen. A high air-entry disc (HAED) was used as the interface between the partially saturated soil and the pore water pressure measuring system. Experimental results proved that the existence of crack or fissure in soil influence the mechanical properties of the specimen tested.

KEY WORDS: Partially saturated; matric suction; pre-crack; biaxial; triaxial.

INTRODUCTION

The behavior of partially saturated soil is quite different from those of fully saturated soil because of the influence of suction. Partially saturated soils form the largest category of materials that cannot be classified by classical saturated soil mechanics concepts. Results obtained with the strength theory of saturated soil could not be directly applied to solve the partly saturated soil problems. Although soils are generally assumed fully saturated below the groundwater table, they may be semi saturated near the state of full saturation under certain conditions. The situation of partial saturation may be caused by several factors, such as variation of water table level due to natural or manmade processes.

Partially saturated soil is generally characterized by three phases, soil solids, water, and air. The presence of a fourth independent phase, a so called air–water interface or contractile skin was introduced (Fredlund and Morgenstern, 1977). Based on multiphase continuum mechanics, a theoretical stress analysis of an unsaturated soil has been presented (Fredlund and Morgenstern, 1977; Fredlund and Morgenstern, 1976). The analysis concluded that any two of three possible normal stress variables can be used to describe the stress state of an unsaturated soil. This is in contrast to saturated soil, where it is possible to relate the behaviour of the soil to the effective stress only. The presence of matric suction pressure is the main difference between saturated and unsaturated soil mechanics. It has been observed that several stability problems, involving soils used as construction materials, are due to water content changes and therefore to matric suction changes that occur periodically in nature.

For the purposes of evaluating constitutive behaviour and stability properties of soil, most laboratory experiments on soils in particular to the clayey soils are performed under axisymmetric or conventional triaxial conditions. However, most geotechnical field problems such as landslide problems, failure of soils beneath shallow foundations, and failure of retaining structures are truly or close to biaxial situations. Mochizuki-Min and Takahashi (1993) reported that when soil is tested under plane strain conditions, it, in general, exhibits a higher compressive strength and lower axial strain. Behaviour of fined grained sands tested under biaxial conditions has been reported (Alshibli-Godbold and Hoffman 2004; Alshibli and Sture, 2000; Bizzarri, 1995; Han and Vardoulakis, 1991; Hans and Drescher, 1993; Lee, 1970; Marach-Duncan-Chan and Seed, 1984; Mochizuki-Min and Takahashi, 1993). The plane strain testing of clay has only been initiated recently (Fauziah and Nikraz, 2008; Fauziah and Nikraz, 2007; Lo-Mita and Thangayah, 2000; Drescher et.al (1990)) and published data of such tests especially for hard clay material is very limited.

The present modeling of brittle soil and weak rock is based on principles of continuum mechanics in spite of the fact that discontinuities are known to develop when such geological materials are subject to loading. In the case of strong rock, on the other hand, there has been considerable interest in the application of fracture mechanics to account for such discontinuities (Ingraffea, 1987). Many studies have been conducted on detailed aspect of such discontinuities, but these are of limited practical application in an actual situation. The existence of cracks and fissures, which are the result of mechanical, thermal and volume-change-induced stresses, such soils are non uniform and therefore not amendable to analysis by continuum mechanics. On the other hand, fracture mechanical theory may be used to advantage to replicate their behavior.

The conventional failure criteria for soils (Atkinson and Bransby, 1982) may be partly appropriate to yield-dominant behaviour, but not this category of brittle fracture. In practice, there is the possibility that soil behaves more like a brittle material. The soil ruptures suddenly under compressive loading like soft rock, starting from the weakest crack in it. A basic premise of fracture theory is that crack like imperfections are inherent in engineering materials. These defects have the tendency to make stresses higher, which eventually trigger off fractures when a material body is subjected to a critical load or undergoes damage under cyclic loading. This present state of fracture mechanical theory has been summarized (Anderson, 2004). Lo-Nikraz-Thangayah and Zhao (2005) modeled brittle overconsolidated clay accordingly and thereby provided a rational basis for the prediction of such soil behaviour.

The behaviour of pre-crack partially saturated clay specimens by the use of biaxial compression apparatus will be presented in this paper, although the behaviour of overconsolidated clay (Fauziah and Nikraz, 2007) and fracture characteristics of brittle clay may also be determined by this test apparatus. Details of the apparatus, specimen preparation and data evaluation will be presented in the following discussion. Some results of the testing will be compared with the known soil mechanical concept.

BIAXIAL TEST EQUIPMENT

The biaxial apparatus used in this experimental study was a modification of the conventional triaxial apparatus. The biaxial arrangement is placed in a cell, with the height of 300 mm, 200 mm internal diameter and 3 mm wall thickness. A prismatic specimen of initial width of 36 mm, height of 72 mm, and thickness of 72 mm, so that the aspect ratio is 2, is placed on the base pedestal where it is restrained laterally by two rigid perspex plates to restrain its out-of plane movement which make ε_2=0. Therefore, only major (σ_1) and minor (σ_3) principal stresses acting on the soil specimen (Figure. 1 and Figure. 2). Previous researchers (Taylor, 1941; Rowe and Barden, 1964; Lee and Seed, 1964; Bishop and Green, 1965) found that if the specimen aspect ratio (height to width) was bigger than 2, the effect of loading platen friction and the restraint of loading frame would be negligible and the specimen would maintain constant strength.

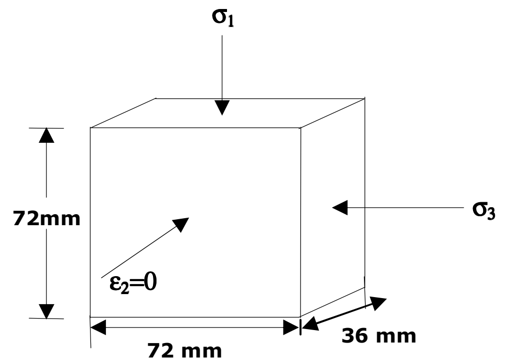

Figure. 1 A schematic diagram of biaxial condition

A high air-entry disc (HAED) was used as the interface between the unsaturated soil and the pore water pressure measuring system. This was to prevent any air from passing through the disc into the measuring system, provided that the matric suction did not exceed the air-entry value of the disc. To avoid the likelihood of scratching and reduced friction, all surfaces which are in contact with the specimen were lubricated. The cell was filled with water to enable the specimen to be pressurized laterally using the pressure generator for applying confining pressure, which was supplied by a compressed air cylinder, connected to gas-water pressure accumulator equipped with pressure gauges and regulators. A 50 kN capacity of Wykeham Farrance displacement-controlled compression machine was used for the application of axial load of the biaxial testing.

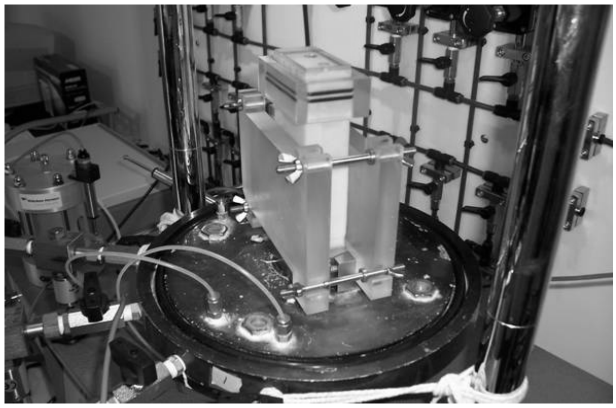

Figure. 2 Side view of biaxial test set up (Fauziah and Nikraz, 2008)

A submersible load cell of 5 kN capacity was used to measure the axial load of the specimen. A 35-mm range LVDT (Linear Vertical Displacement Transducer) which was attached on top of the top cover of the cell was used to measure the axial displacements of the test specimen. To measure the applied cell pressure, back pressure pore pressure and flush pressure of the specimen four pore pressure transducers were used and mounted to the base plate of the cell. An automatic volume change unit which is connected to the back-pressure line was used to monitor the global volume change of the water-saturated soil specimens.

A data acquisition system consisting of an MPX 300 data logger and a set of microcomputer were used to record the displacement, loads, pressure and volume change reading of the specimen. WINHOST 2.0 package software was used to convert digital bit data from the ADU (Analogue digital Unit) to engineering units based on the calibration of the relevant measuring unit, which was done before running the plane strain test.

SPECIMEN PREPARATION

Biaxial experimental testing has been performed on remoulded kaolin clay specimens. The material used in this study was commercial Kaolin clay, with a specific gravity G_s =2.6, Liquid Limit LL = 53.5 % and plastic limit PL = 30.76 %. It took few weeks to complete the preparation of soil specimen.

Firstly, slurry of kaolin clay was mixed to a uniform consistency of 1 ½ times its liquid limit using an electrical soil mixer. This slurry was obtained by mixing 8 kg of kaolin powder with 6 kg of water using the electric mixer for about 2 to 3 hours. A steel cylindrical mould with the height of 600 mm and 150 mm in diameter was used to consolidate the slurry using a hydraulic tester. To ease the extrusion of the sample from the mould at the the end of consolidation, the inner wall of the cylinder mould was greased before pouring the kaolin slurry to the consolidation unit. A layer of sand and geosyntethic were placed on the top and the bottom of the slurry to accelerate the consolidation process. To apply the pressure evenly to the slurry, two circular perspexes were placed at both ends of the slurry in the mould.

A vertical pressure of 300 kPa was applied on the top of the slurry to allow the consolidation process.in over a period of one to two weeks which the maximum pressure of 300 kPa was applied in three stages. The slurry was allowed to consolidate by its own weight to prevent the slurry being squeezed out between the circular perspexes and the mould. A higher vertical pressure was applied when there was no further settlement change. Once the consolidation process completed the soil was extruded from the mould into lubricated formers. Following this, the specimen and the former were wrapped in plastic film sheeting after sealing both their faces with liquid wax. To obtain even pore water pressure, the specimens were placed in the dehumidifier for at least 2 days until it is tested.

The specimen in the former was then extruded using a hidrolic perspex rectangular block. The specimen was allowed to be intact initially, while for the pre-crack specimen it was given a 30 mm pre-crack in the center of the specimen. In the plane strain test set-up, the rubber membrane was first placed over the test specimen with the aid of a sleeve stretcher. The rectangular porous plate was then placed on top of the specimen followed by the top assembly and the high air-entry disc (HAED). The rubber membrane was next slipped over the porous plate, the top assembly and the HAED and secured by the use of a set of O-rings and rectangular Perspex clamp. The specimen, together with the porous plate and the top assembly were then placed over the pedestal of the plane strain compression apparatus. The rubber membrane was next slipped over the pedestal and secured by the use of a set of O-rings and clamp set. Two rigid perspex plates were then placed and secured by the use of clamp set. The pressure cell, top assembly and laser sensor set-up were then installed. The cell was then filled with water to enable the specimen to be pressurized laterally by the use of the pressure generator for applying confining pressure. Figure. 3 shows the biaxial testing arrangement.

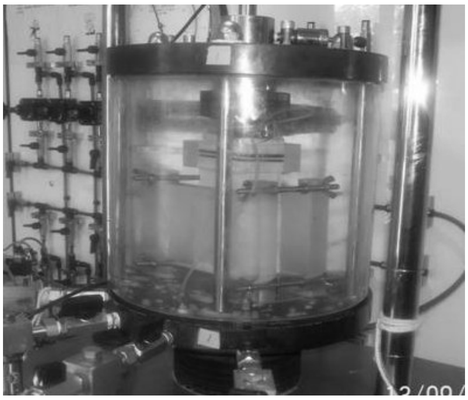

Figure. 3 Biaxial testing arrangement (Fauziah and Nikraz, 2007)

TEST PROCEDURES

Three types of specimens of IB (intact specimen, biaxial), PCB (Pre-crack specimen, biaxial) and IT (intact specimen, triaxial) were tested under net normal stress of 0 and maximum matric suction of 500 kPa and matric suction of 0 and maximum net normal stress of 800 kPa. Firstly, the specimen was saturated until the B-value of the specimen reached the value of 0.95-0.98, followed by matric suction applied and loading compression processed.

A cell pressure of 600 kPa, back pressure of 590 kPa and pore pressure of 600 kPa were applied to the specimen to provide an initial net normal stress of 0 and matric suction of 10. The volume change of the soil skeleton ΔVs was monitored continuously by the laser sensors. The change in volume of water in the specimen ΔVw was also monitored continuously by the volume change gauge which was connected to the back-pressure line. Once the changes in the soil and water volumes had ceased, the test specimen was presumed to have fully consolidated under a matric suction of 10 kPa. The matric suction was next increased to 20 kPa by reducing the back pressure to 580 kPa. The corresponding changes in the soil skeleton and water volumes were monitored continuously until they had ceased, at which stage the corresponding void ratio e and the water content of the test specimen were computed from the cumulative changes in soil skeleton and water volumes. The entire procedure, that is from increasing the matric suction to the desired value up to flushing out the air bubbles, was repeated for matric suctions of 50, 100, 200, 300, and 500 kPa respectively, which were applied by reducing the back pressure accordingly.

Another test apparatus set up similarly as before, except that the head was replaced with a porous disc. A cell pressure of 110 kPa, back-pressure of 100 kPa and pore-air pressure of 100 kPa were then applied to the specimen to provide an initial net normal stress of 10 kPa and matric suction of 0. The changes in soil skeleton and water volumes were then monitored continuously and when these changes had ceased, the total changes in soil and water volumes were noted. The net normal stress was first increased to 20 kPa by increasing the cell pressure to 120 kPa. Thereafter, the entire above procedure, starting from applying the net normal stress up to when the changes in soil and water volumes ceased, was repeated for net normal stresses of 50, 100, 200, 300, 500 and 800 kPa.

The specimen was then compressed by elevating the base of the confining pressure cell at a constant velocity of 0.08 mm/m with the drainage line closed at matric suction of 0 and net normal stress of 800 kPa. This loading rate was deduced based on the permeability of adopted kaolin clay suggested by Bishop and Henkel (1962). The data were recorded at 3 minute interval test and it was terminated at the axial strain of about 20 % or sooner. Following this, the specimen was taken out immediately for the purpose of moisture content test. In the analysis of the behaviour of the brittle unsaturated clay, the pore pressure parameter would be required in order to the determined the pore pressure increments and the matric suction. The pore pressure parameters were deduced from the volumetric deformation coefficient, which was obtained by laboratory testing. This procedure was proposed by Fredlund and Rahardjo (1993), although adapted to biaxial conditions.

RESULTS AND DISCUSSION

Figure. 4 shows the strain softening response of the IB, PCB, and IT specimen tested at matric suction of 0 and net normal stress of 800 kPa. In general, the shear stress curves increase monotonically with the increasing vertical strain until they reach peak stresses followed by strain softening behaviour. According to Lo-Nikraz-Tamiselvan and Zhao (2005) this is the typical phenomenon of specimen of brittle, hard partly saturated soil specimen and exhibit elastic only. The highest failure stress of 159.178 kPa was reached by the intact specimen of IB, and the lowest failure stress of 125.336 kPa was derived by the pre-crack specimen of PCB.

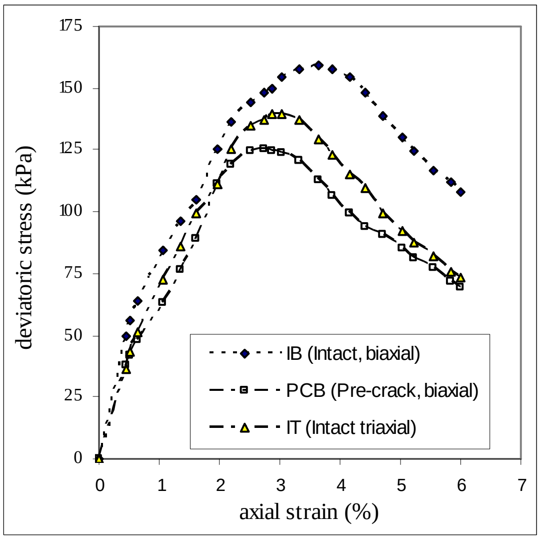

Figure. 4 Stress-strain behavior of the specimen

The presence of a crack or discontinuity makes the soil weaker as the effective area offering resistance to shear is reduced. The shear strength along a surface of discontinuity is thereby less than that of the intact material. The pre-crack specimen of test PCB reached earlier peak strength before falling toward whereas the peak strength of the pre-crack specimen of PCB was correspondingly lower. Compared to the intact specimen tested under triaxial condition of test IT, not only had higher peak stress, but the specimen of test IB also had higher shear strength along the vertical strain. Similar observation had been reported elsewhere (Lo-Mita and Thangayah, 2000 and Mochizuki-Min and Takashi, 1993).

The volume change relationships of the kaolin clay specimens is summarised in Table 1. The constitutive surface of void ratio is defined by the volume change index C_m and C_t corresponding to the matric suction and net normal stress respectively. C_t is the slope of the consolidation curve and is equal to the compressive index of a saturated soil, while C_m is the slope of the shrinkage curve. The value of compressive index obtained by determining the gradient of the linear portion of the curve of the water content against the log of matric suction for D_m and the log of net normal stress for D_t. The constitutive surface of water content is defined by the water content index D_m and D_t corresponding to the matric suction and net normal stress respectively. It clearly shown from the table that the specimens containing pre-crack of PCB had higher compressive index than that the intact specimen of IB. The reducing in effective area offering resistance to shear of pre-crack specimen makes it had lower compressive strength than that the intact specimen.

Table 1. Volume change index of the specimen

Specimen Type	Void ratio (e)		Water content (%)	
	Cm	Ct	Dm	Dt
IB	0.0115	0.2186	0.0548	0.0560
PCB	0.0160	0.2573	0.0708	0.0677
IT	0.0173	0.2318	0.0899	0.0623

Constitutive surface of void ratio versus log net normal stress and log matric suction of the specimen were plotted in Figures. 6-8. The slope of the intersection curves are the volume change index C_m and water content index D_m respectively for the case that net normal stress set to zero, whereas the slope of the intersection curves are the volume change index C_m and water content index D_m when the matric suction set to zero. It can be shown from the graphs that the curves went down with the increasing of either matric suction or net normal stress for all of the specimens.

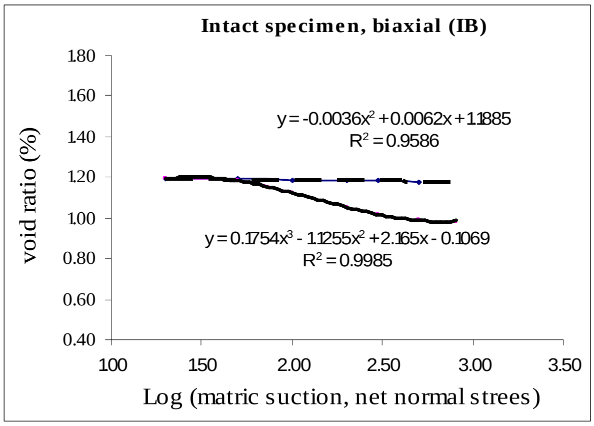

Figure. 5 Constitutive surface of void ratio versus net normal stress and matric suction of IB specimen (Intact, biaxial test)

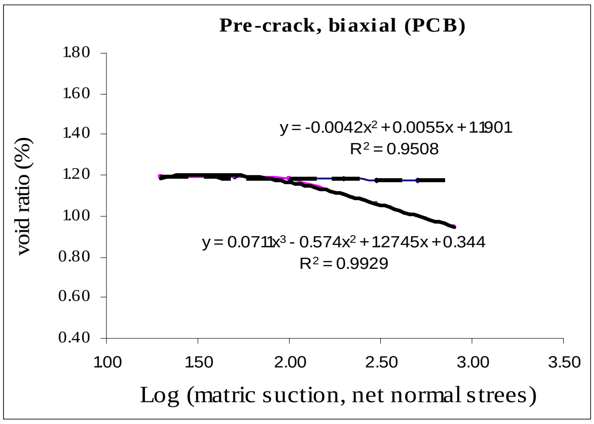

Figure. 6 Constitutive surface of void ratio versus net normal stress and matric suction of PCB specimen (Pre-crack specimen, biaxial test)

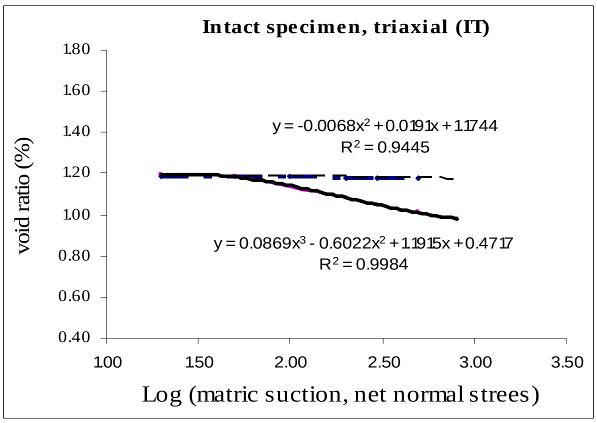

Figure. 7 Constitutive surface of void ratio versus net normal stress and matric suction of IT specimen (Intact specimen, triaxial test)

Constitutive surface of water content versus net normal stress and matric suction of the specimen were depicted in Figures. 9-11. Similar to the curve of the volume change result in Figures. (9-11), and consistent with the stress-strain behaviour of the specimens shown in Figure 4, the existence of discontinuities cause by crack or fissure on the specimen makes the specimen weaker than that the intact specimen. The slope of the compressive index of the specimen indicated that the specimen containing pre-crack had lower strength than that the intact specimen.

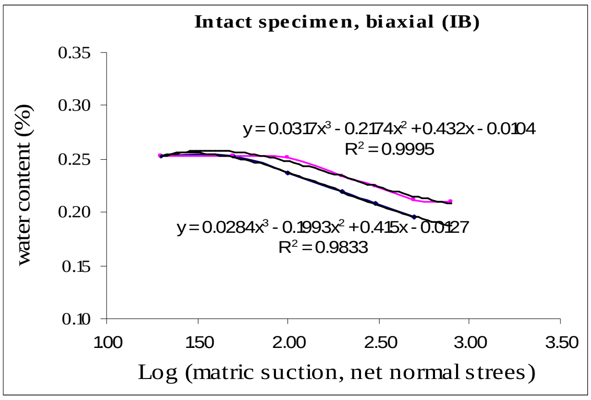

Figure. 9 Constitutive surface of water content versus net normal stress and matric suction of IB specimen (Intact specimen, biaxial test)

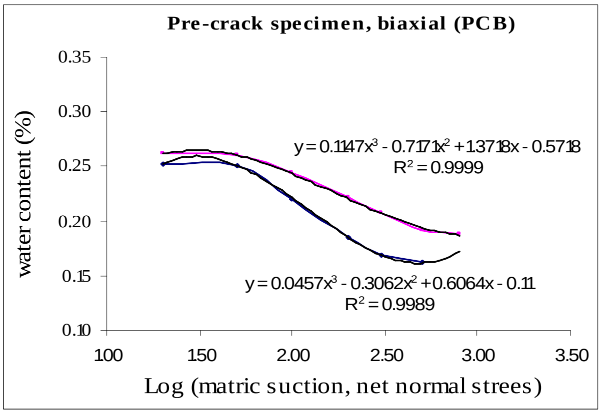

Figure. 10 Constitutive surface of water content versus net normal stress and matric suction of PCB specimen (Pre-crack, biaxial test)

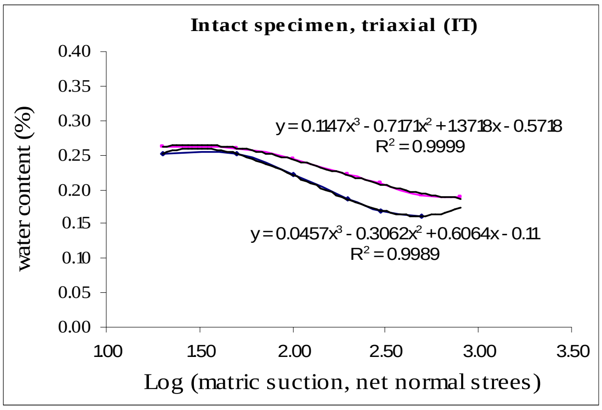

Figure. 11 Constitutive surface of water content versus net normal stress and matric suction of IT specimen (Intact specimen, triaxial test)

CONCLUSIONS

Experimental results proved that the existence of crack or fissure in soil influence the mechanical properties of the specimen tested. The result of shear strength curves indicated that the specimens were the typical of brittle and exhibit elastic only failure. A pronounced failure and lower shear strength as well as compressive strength were reached by pre-crack specimen than the intact specimen. It is also noted that shear strength and compressive strength of the intact specimen under triaxial testing was lower than specimen tested under biaxial condition.

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