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CHARACTERIZATION OF PHYSICAL AND MECHANICAL PROPERTIES OF RIGID POLYURETHANE FOAM

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ABSTRACT

In home construction, rigid polyurethane foams have been widely used as nonstructural component such as thermal insulation or sound absorbser material, and as structural component such as core of sandwich panel. For structural component, it is necessary to study the behavior of the material first, how the cells are constructed, also to get the physical and mechanical properties. Those two properties are the main items to be able to design the sandwich panel or to make a further analysis. This investigation was made to reveal several things such as density, microscopic foam structure, material strength, modulus, poison's ratio, and failure mode in tension, compression and shear, based on American Standard Testing Method (ASTM). This research, by microscopic observation, states that this foam is categorized as an anisotropic material, where strength in longitudinal (L) direction (foam rise direction) is stronger than that in transverse (T) direction, with geometric anisotropic ratio of 2.2. For the foam density of 48.5 kg/m^3, the test yielded compressive strength and modulus of, respectively, 358.221 kPa, and 11602.8 kPa. Consistent with the results from other researchers, higher density gives higher compressive strength and modulus. For tensile mode, it is also obtained values of tensile strength 229 kPa in L direction and 393 kPa in T direction, tensile modulus in L and T direction, respectively, are 929 kPa and 3256 kPa, strains to failure are respectively 0.276 and 0.334 and poisson's ratio is 0.184 on longitudinal – based specimen. For shear mode, we get 228 kPa for shear strength and 3240 kPa for shear modulus. The patterns of stress – stress curve from compression and tension test, give us an indication that this foam is classified as elastic plastic foam.

Keywords: microscopic observation, anisotropic material, tension, compression, shear.

1. INTRODUCTION

Rigid polyurethane foams are made with a remarkably strong, yet lightweight, low density structure, that make them widely used as a core material in sandwich structure. The density varies from 20 **Error! Reference source not found.**] to 96 kg/m3 **Error! Reference source not found.**] or not greater than 4 % of concrete density. That is why people nowadays propose this material as a replacement to the existing home construction material (Figure-1.). If this material play huge amount in structure, the whole weight will significantly decreased. Lower weight will completely reduce earthquake force, making the building safer for the people inside.

To involve rigid polyurethane foam in the structure, physical and mechanical properties should be figure out first, then it can be followed by analysis in order to get structural design. Product data sheet sometimes attach several data such as density, compressive strength, dimensional stability and thermal conductivity, but they are not adequate to lead us to deep analysis. Foam analysis and failure criterion in finite element program require to provide more data such as material strength, modulus, poison's ratio, and failure mode in tension, compression and shear. Since each foam has its own distinctive characteristics, those data should be independently figured out. Therefore, these investigations are made.

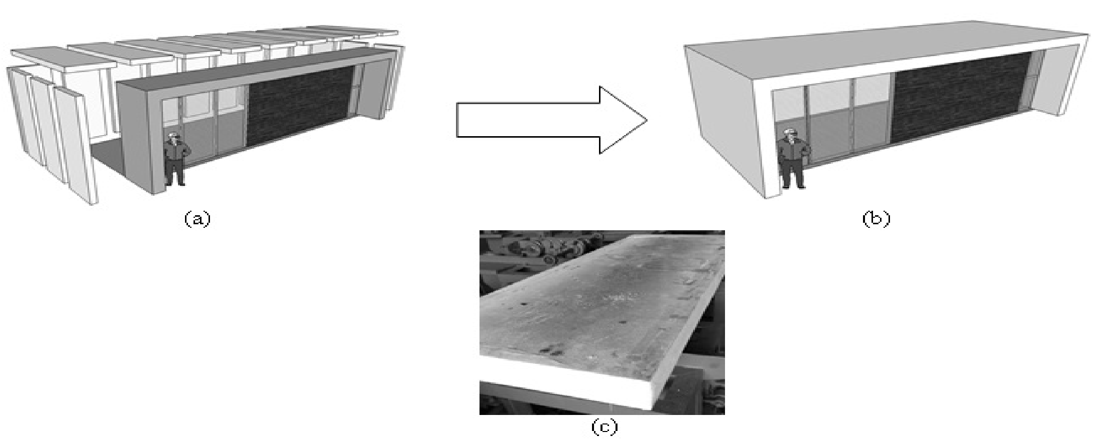

Figure-1. Knock down residential building using panel sandwich with polyurethane core (a) panel position in the building (b) assembled prefab home (c) panel sandwich with polyurethane core.

2. LITERATURE REVIEW

a) Compression

Gibson *et al.* **Error! Reference source not found.**] revealed that there are three different kinds of stress-strain curve of solid foam under compressive loading (Figure-1) – elastomeric foam (e.g. flexible foam), elastic-plastic foam (e.g. rigid PU foam) and elastic-brittle foam (e.g. ceramic foam). Foams have extended stress-strain plateau after yield, making them different from common solid materials such as metals, which normally do not.

b) Tension

Although Gibson *et al.* **Error! Reference source not found.**] stated that there are also three different kinds of stress-strain curve of solid foam under tension loading– elastomeric foam, elastic-plastic foam and elastic-brittle foam – but Ridho **Error! Reference source not found.**] asserted that the linear portion is not really elastic, it is curved downward. Motz and Pippan **Error! Reference source not found.**] also clarified Gibson *et al.* **Error! Reference source not found.**] that in Figure-2 b, there should be no rapid increase of stress after plastic collapse.

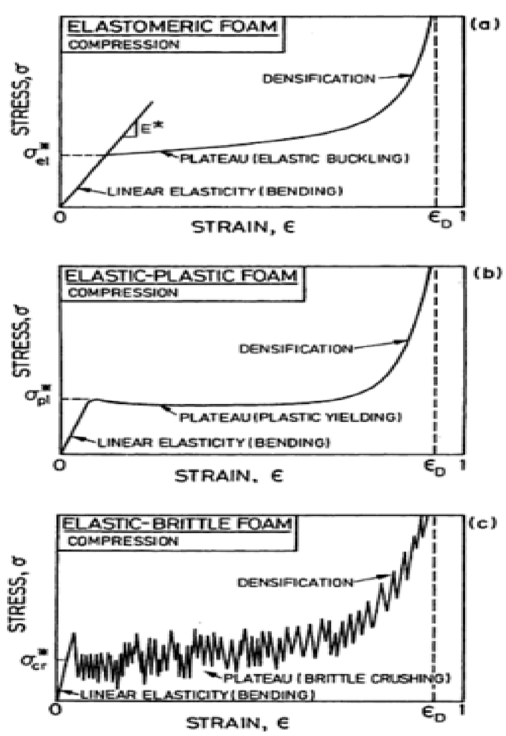

Figure-1. Stress-strain curve of foams under compression loading (Gibson *et al.* **Error! Reference source not found.**]).

3. MATERIAL AND METHODS

Various tests such as compressive test, shear test and tensile test, were conducted to commercial rigid polyurethane foam to obtain mechanical properties, where the size of the specimens, the required apparatus, the test method, and how to present the report basically referred to American Standard Testing Method (ASTM) with several modifications on the testing media and specimen, adapting to the existing testing machine model and mechanism. The results then will be compared to those by other researchers to verify that they are in right range.

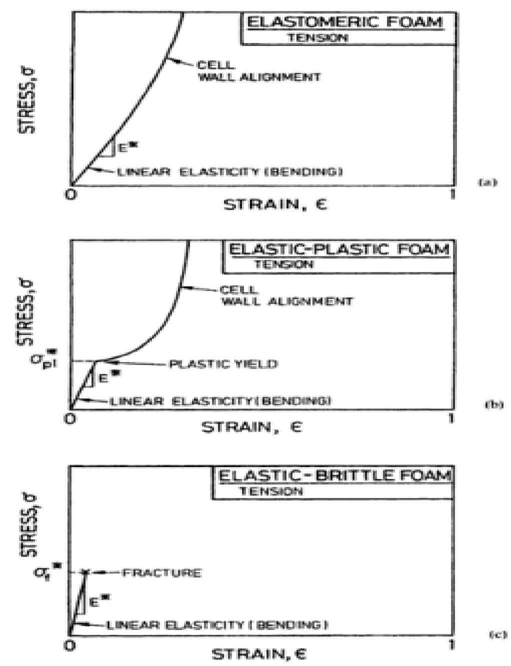

Figure-2. Stress-strain curve of foams under tension loading (Gibson *et al.* **Error! Reference source not found.**]).

4. RESULT AND DISCUSSION

a) Fabrication of rigid polyurethane foam and density investigation

Rigid polyurethane foam specimens were made by mixing two components, polyol, (resin, RF50593 / 7-25A, light brown liquid) and diisocyanate (hardener, RF50593 / 7-25B, dark brown liquid), a product by Asia Polyurethane Pte Ltd **Error! Reference source not found.**], with mixing ratio 1:1 (volume based). Afterward, they were poured into a cylinder mold – concrete mold with a diameter of 100 mm and a height of 200 mm – reacting in free rise mode and let them harden for at least 12 hours before they can be released. After cutting the excessive part (the denser part at the upper region,

Figure-4), the product created a density of 48.5 kg/m^3 (ASTM D1622 – 03).

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Figure-4. Fabrication of rigid PU foam specimens for density and compression test.

Figure-3. Fabrication of rigid PU media (a) cube concrete mold for tensile specimen (b) wooden formwork for shear specimen.

b) Micro CT– imaging of rigid polyurethane foam cells

This observation was conducted to study the cell structure, the item that play important role in determining its mechanical properties. The images were taken using Dino-Lite® digital microscope. **Error! Reference source not found.** show that the cells are primarily closed cells consisting of struts and thin membrane, where struts define the cell edge, while thin membrane cover the cell wall. The thickness of the cell and the strut – the spacing between cells – in longitudinal section are wider but thinner and less stiff than those in cross section, indicated by the color that they in longitudinal section look yellower, the color of the region where the main components constructing polyurethane foam are highly accumulated. Those two figures also tell us that the cells are elongated in foam rise direction, generating an anisotropic material with geometric anisotropic ratio (cell length in longitudinal: cell length in transverse) of 1.223 : 0.564 = 2.2.

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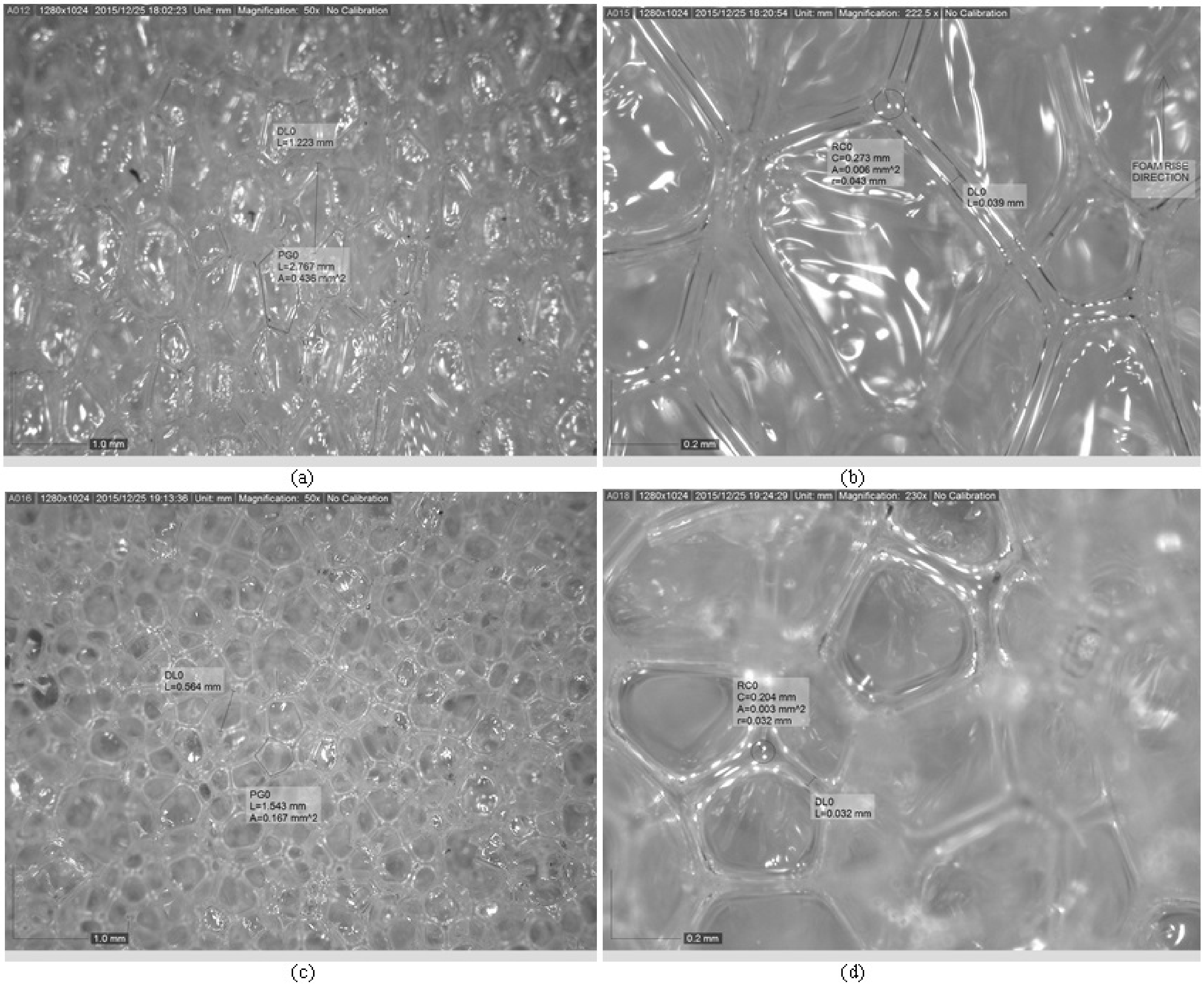

Figure-6. 2D image of the cell (a) longitudinal section (foam rise direction) with magnification level of 50X (b) longitudinal section with magnification level of 222.5X (c) cross section with magnification level of 50X (d) cross section with magnification level of 222.5X.

c) Mechanical properties investigation

i. Compression test

Test was performed according to ASTM D1621-00 on three cylindrical specimens having a diameter of 100 mm and a height of 80 mm at a constant rate of 7.87 mm/min and loaded to foam rise direction. The behavior was that deformation began at the area affected by the load (Figure-7) or at the base, then developed and spread to the loading direction, until the cells of the foam reached yield point, forming plateau regions before going on densification (hardening) when the load continued to increase (see Figure-8). The result was consistent to Gibson *et al* as Figure-2 b and categorized as elastic plastic foam.

Figure 4. Rigid PU foam behavior when exposed to compressive load, stopped before hardening.

To generate the value of compressive strength and compressive modulus, the test was stopped when the specimen reached yield point, or when the deformation reached about 5 mm. From the data, it is known that the compressive strength and modulus, respectively, are 358.221 kPa, and 11602.8 kPa.

Verifications for the results were performed by comparing them to those by other researchers such as Lim *et al.* **Error! Reference source not found.**], Chen *et al.* **Error! Reference source not found.**], and Witkiewicz and Zieliński **Error! Reference source not found.**]. Data in Figure-11 lead to a conclusion that higher density gives higher compressive strength in a linear equation of with R squared value more than 98%. Similar conclusion was also obtained by modulus comparison, giving strong dependency with R squared value of 95%. Thus, the results here are correct.

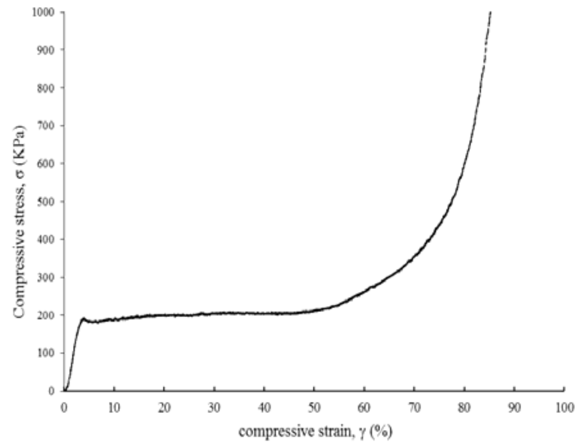

Figure-5. Typical elastic – plastic curve of rigid PU foam in compression, continued to hardening.

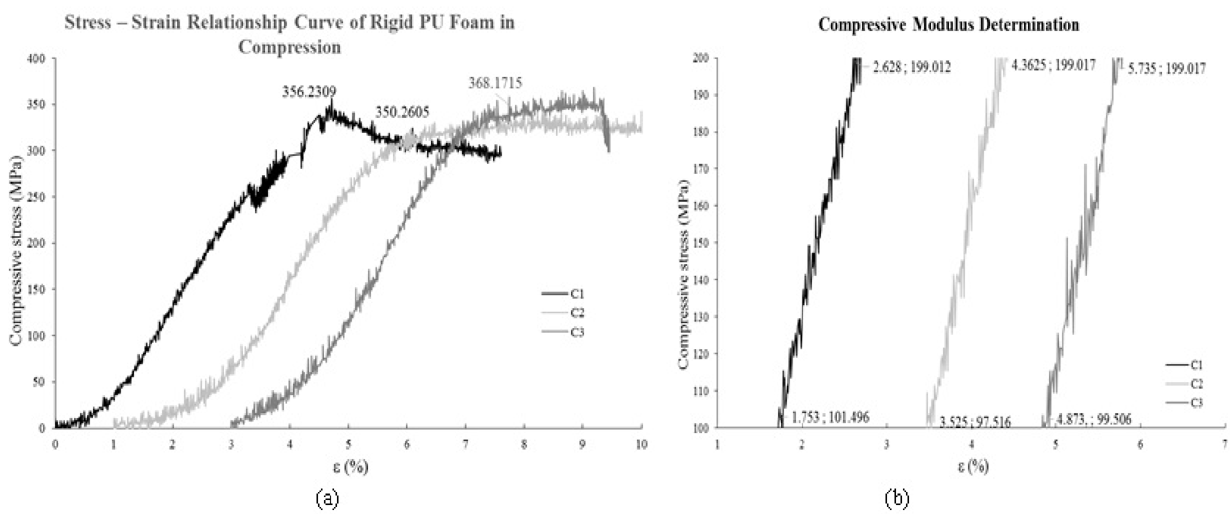

Figure-9. Compressive test result (a) Stress – strain relationship curve of rigid PU foam in compression (b) Compressive modulus determination.

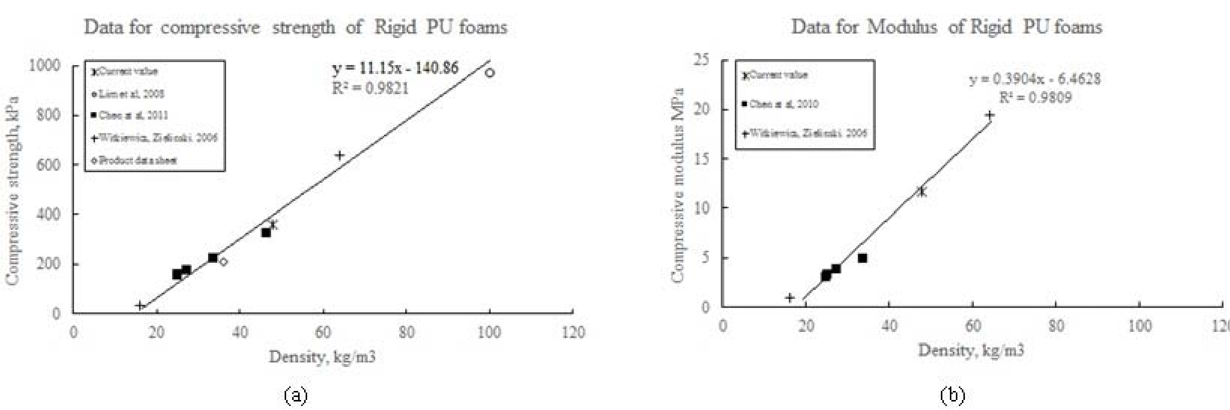

Figure-10. Data of Rigid PU foams (a) Compressive strength comparison (b) Compressive modulus comparison.

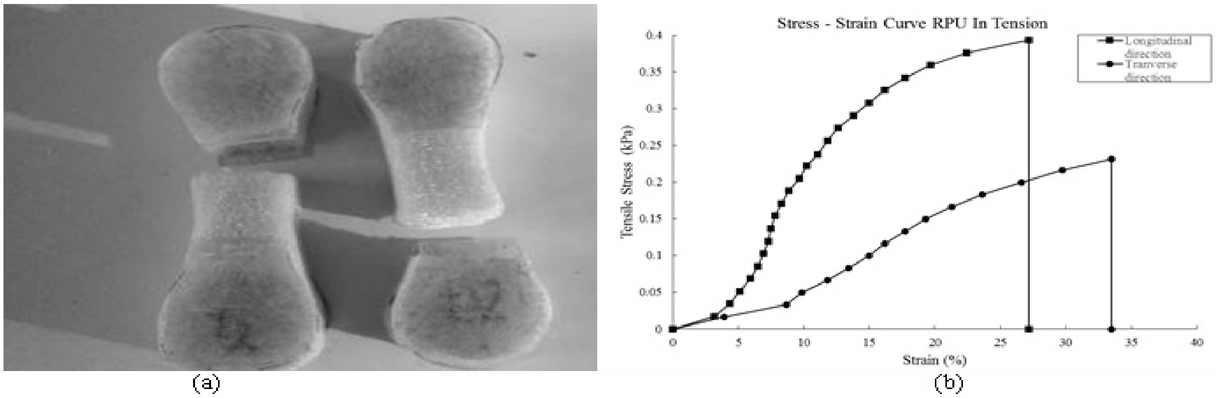

Figure-11. (a) Failure of the PU foam after static tensile test (b) Stress – strain relationship of RPU foam in tension.

ii. Tensile test

The tests were performed according to ASTM D1623 – 03 to determine the strength of the polyurethane foam to static tensile. Specimens for each direction, foam rise (L) and transverse direction (T) were prepared in dog bone form with cross sectional area of 600 mm2 and measured length between the grips of 25.4 mm. From the test, we get the values of the tensile strength for L and T were, respectively, 229 kPa and 393 kPa, the tensile modulus for L and T were respectively, 929 kPa and 3256 kPa, and strain to failure were respectively 0.276 and 0.334. Poisson's ratio of the Rigid Polyurethane foam was also determined through this tensile test, with the value of = - 0.184. Referring to Figure-2 by Gibson et.al **Error! Reference source not found.**], the pattern of stress – stress curve here tells us that this kind of rigid polyurethane foam can be also classified as elastic plastic foam.

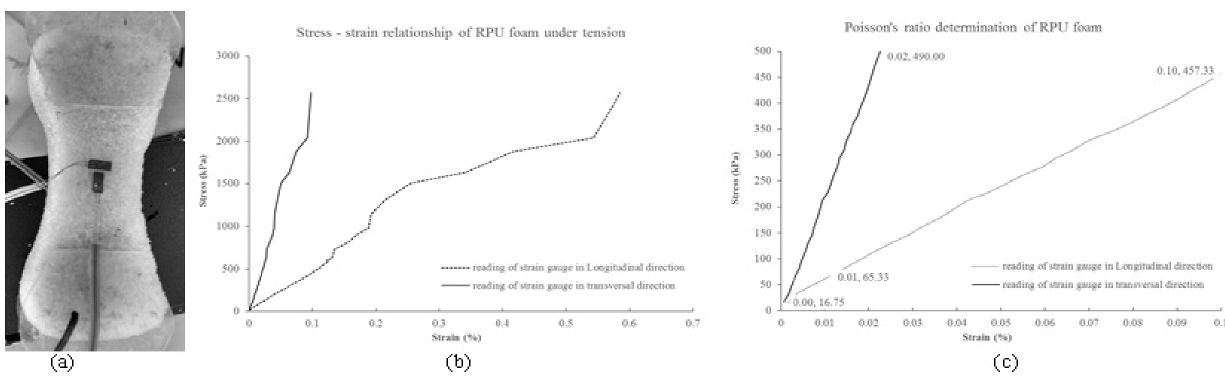

Figure-12. (a) Position of the strain gauges on the longitudinal-based specimen (b) Stress – strain relationship of RPU foam under tension (c) Poisson's ratio determination.

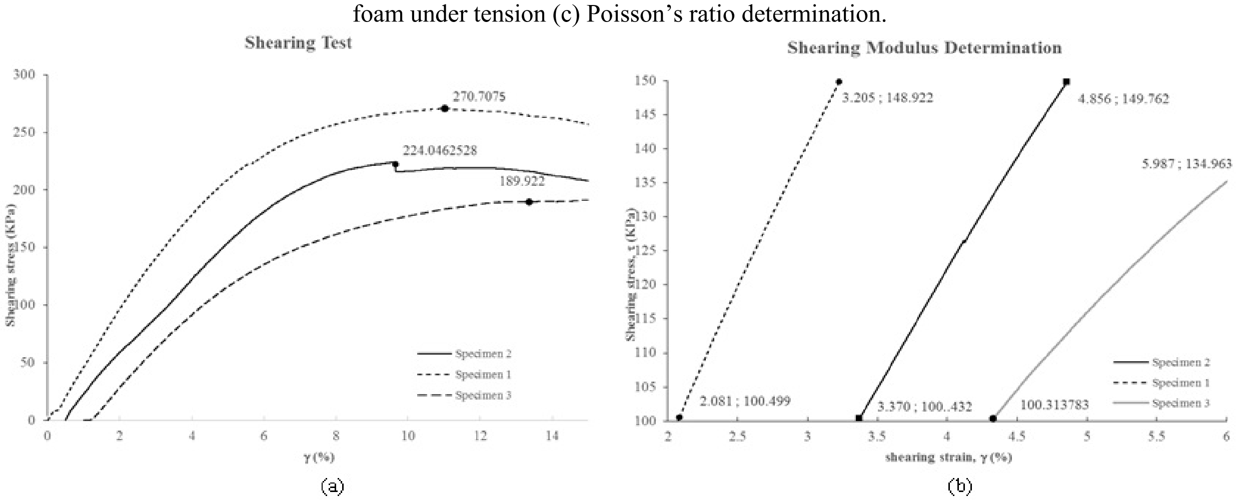

Figure-13. (a) Stress – strain graph of PU foam shear test (b) Shear modulus determination of PU foam.

iii. Shear test

This shear test was conducted through tensile mechanism according to ASTM C273 – 00 on Shimadzu AG-X using cuboid polyurethane foam specimen by constant rate of 0.5 mm/min. The specimen was rigidly supported at the faces by steel plate having a thickness of 8 mm or a bending stiffness per unit width, $D = EI/b =$ 8.533 MN-mm^2/mm. To ensure a core shear failure on some foam cores, two step gluing process using polyester resin were applied to bond the foam to the steel plates after some slices were made on the faces of the foam, to enlarge the bonded area. Figure-6 shows both steel plate and resin have performed satisfactorily as the failure occurred on the foam core without creating any peel force at the bonded area. From the test, it is known that the shear strength and modulus, respectively, are 228 kPa, and 3240 kPa

5. CONCLUSIONS

The main objective of these investigations was to find out the mechanical properties of the rigid PU foam i.e strength, modulus, poisson ratio, and failure data in compression, tensile, and shear mode. Those data are very important as input data in the design or evaluation involving rigid polyurethane foam as structural component. Reverse analysis is often used in determining the reason why materials behave like they do and microscopic analysis often give the answer. That is why micro CT imaging analysis gets involved here. Some tests may differ from American Standard Testing Method (ASTM) as some changes to the specimen forms were made, adjusting to the existing test aparatus and mechanism.

Figure-6. Shear test specimen and the equipment.

Microscopic observation states that this foam is categorized as an anisotropic material, where strength in longitudinal (L) direction (foam rise direction) is stronger than that in transverse (T) direction, with geometric anisotropic ratio of 2.2. For the foam density of 48.5 kg/m^3, the test yielded compressive strength and modulus of, respectively, 358.221 kPa and 11602.8 kPa. Consistent with the results from other researchers, higher density gives higher compressive strength and modulus. For tensile mode, it is also obtained values of tensile strength 229 kPa in L direction and 393 kPa in T direction, tensile modulus in L and T direction, respectively, are 929 kPa and 3256 kPa, strains to failure are respectively 0.276 and 0.334 and poisson's ratio is 0.184 on longitudinal – based specimen. While for shear mode, we get 228 kPa for shear strength and 3240 kPa for shear modulus. The patterns of stress – stress relationship curve from two of three tests conducted, compression and tension test, give us an indication that this foam is classified as elastic plastic foam.

To accommodate polyurethane foam as a fully anisotropic material, future investigation in compression and tension (in order to get poison' ratio, ν_{23}) should be made by considering two directions, foam rise and transverse direction. To control the product quality as well as to reduce the variance, the future fabrication should be improved using sealed mold and by high pressure foaming machine.

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