Evaluating compressive properties of expandable polyurethane foam for use in a synthetic spine

Nor Amalina Muhayudin
School of Manufacturing Engineering
University Malaysia Perlis
Perlis, Malaysia
noramalina@unimap.edu.my

Nor Amalina Muhayudin, Fiona McEvoy, Anthony Tansey, Yanyi Blake
Mechanical Engineering Department
Institute of Technology Tallaght
Dublin, Ireland.

Abstract- This study aimed to determine whether expandable rigid polyurethane foam was an appropriate substitute for rigid block polyurethane foam to model the trabecular bone in biomechanical testing. Static compression tests were performed to determine compressive moduli and yield stresses on three polyurethane foam densities namely 0.16 g/cm^3, 0.24 g/cm^3 and 0.42 g/cm3. The compressive modulus for 0.16 g/cm^3 and 0.24 g/cm^3 varied from 40 to 43 MPa and 83 to 92 MPa while yield stress ranged from 2.1 to 2.3 MPa and 3.4 to 4.8 MPa respectively. As for 0.42 g/cm^3, the compressive modulus and yield stress varied from 240 to 256 MPa and 38-40 MPa. Based on these results, the compressive modulus and yield stress of 0.24 g/cm^3 compared favourably with rigid block PU foam and human cadavers presented in relevant literatures and therefore may have potential as a substitute for trabecular bone.

Keywords— polyurethane foam, synthetic spine, trabecular bone.

I. Introduction

This study forms a subset of the author's work on developing a synthetic spine for replicating scoliosis cases using synthetic materials. In general, scoliosis is a medical condition where the spine is deformed from the normal frontal axis of the body. Scoliosis generally is associated with children and therefore conducting experiments on cadavers of children was not feasible.

Mosekilde et al. [1] demonstrated the relationship between age with ash density (bone mass) and modulus of elasticity of human cadavers. However it only holds valid for samples between 20 to 80 years. Younger bone has a higher modulus when compared to adults as based on Mosekilde's Equation (1). Ash density decreases from young to adult based on Equation (2). This was demonstrated by varying the apparent bone density from 0.05 g/cm^3 to 0.30 g/cm^3 between range of individuals, levels and age.

$$E = -1.7 \times \alpha + 160 \text{ [MPa]} \qquad (1)$$

Equation 1: Relationship between modulus of elasticity (E) and age (α).

$$AD = -0.0017 \times \alpha + 0.23 \text{ [g/cm}^3\text{]} \qquad (2)$$

Equation 2: Relationship between age (α) and ash density (AD).

As the synthetic model will be used to model paediatric scoliosis cases, the bone density need to be considered between scoliosis and normal bone. Sadat Ali et al. [2] conducted a study on Arabian girls, ages ranging from 12 to 26 years contrasting bone mass between scoliosis and normal bone. The study indicated that scoliosis causes osteoporosis while the normal bone retained normal mass. Li and Aspden [3] compared the mechanical properties of human trabecular bone specimens from osteoporotic femoral heads between osteoporosis and normal bone. The study showed that osteoporosis bone had a slightly lower modulus when compared to normal bone.

Currently rigid polyurethane (PU) foams are widely used to replicate bone in favour of cadaveric specimens as they have similar mechanical properties to human bone. Research studies have been carried out on both open and closed cells of PU foam by varying the densities for different applications.

Palissery et al. [4] presented that the static mechanical properties of the closed cell similar to a human trabecular bone. Johnson and Keller [5] stated that the appropriate model for a synthetic thoracic vertebra was the open cell rigid PU foam with the density of 0.09 g/cm^3 and 0.12 g/cm^3. They also suggested the open cell foam as an alternative for static or fatigue studies of human vertebrae. Patel et al. [6] suggested that rigid block PU foam with density of 0.16 g/cm^3 was the most suitable model for osteoporotic bone in compression.

However, commercial rigid PU foams are only available in blocks or pre-machined into long bone shapes like femur and tibia. The main challenges in developing a synthetic spine are matching the biological spine in terms of kinematic, physical and mechanical behaviours. The first synthetic spine developed was too rigid and did not mimic the motion range of a natural spine [7]. An alternate solution was to use expandable rigid PU to replace the rigid block PU. As the foam expands, it can form into complex shapes, with a shell like structure on the outside and honeycomb structure on the inside.

There have been no apparent studies focused on using expandable foams as a substitute for trabecular bone. This study aimed to determine whether the expandable rigid PU foam was an appropriate material to replace trabecular bone for biomechanical testing. The objective was to compare the compressive moduli and yield stresses of the expandable rigid PU foam with block rigid PU foam and human data.

II. Materials and Methods

Commercial expanding rigid PU foams are available in a range of densities from 0.048 g/cm^3 to 0.42 g/cm^3. For this study, three different densities of expandable rigid PU foams were tested, which were supplied by Smooth On, Inc [8]. The densities selected were 0.16 g/cm^3, 0.24 g/cm^3 and 0.42 g/cm^3. The first two densities fall under ASTM F 1839 (Standard Specification for Rigid Polyurethane Foam for Use as a Standard Material for Testing Orthopaedic Devices and Instruments) grade 10 and 15 [9].

A. Apparent Density

The expandable rigid PU foams were supplied in the form of two-component water blown rigid foams. The mixing ratio for all the foams was 1:1 in volume with 4 to 5 minutes of tacking time. Apparent density was important in this study to justify the technique used to ensure that the density for the end product matched to the density provided by the supplier.

B. Microstructure

The expandable rigid PU foams morphology for all three densities (0.16 g/cm^3, 0.24 g/cm^3 and 0.42 g/cm^3) was observed using a JEOL (JSM-6390LV) Scanning Electron Microscope (SEM) on small rectangular sections. A standard stereological method was performed on the SEM images with 500 µm scale bar to measure the average cell size and the mean intercept length. The mean intercept length was calculated by dividing the L_L (total length of cells intercepted by the lines divided with total length of the lines) over N_L (number of cells intercepted in length of the lines). Average cell size was calculated by the total length intercepted by the lines divided by the number of cells intercepted by the lines. [10]

C. Specimen Preparation

Five specimens for each three densities were core drilled to form 9 mm cylindrical cores. The average diameters were then measured for all specimens using the digital vernier calliper. The specimens were filed to obtain approximately 7.7 mm in height, to enable direct comparison with a published study of rigid block PU foam [6].

D. Static Compression Tests

The static compression tests were conducted using an Instron 3343 materials testing machine (Norwood, MA, USA). Due to the size and structure of the specimens, no preload was applied and the upper plates were aligned closed to make contact directly with the specimens instantly thus reducing the chance of the 'toe' region in the results. These specimens were compressed under the displacement control at 0.026 mm/s equivalent to a strain rate of 0.0033 per second from literature until failure [6]. Each specimen was placed such that the axis of the compressive load applied was parallel to the expandable foam rise direction.

E. Statistical Analysis

Statistical analysis was conducted using MINITAB Release 16.0 Statistical Software (Minitab Inc., Pennsylvania, USA). Data was analysed using one sample T-test with the significance level at 0.05 to compare the results with literature. Normality distribution was evaluated using the Anderson-Darling test. Comparison between literature and the current study was made at the approximate ranges of 95% confidence intervals for all values.

III. Results

A. Apparent Density

The results of apparent density according to ASTM D1622 for the five specimens were found to be similar to the density presented in the manufacturing MDS (Materials Data Sheet). Table I presented a comparison between average apparent densities of foams to the data given by the manufacturer, Smooth On, Inc., [8].

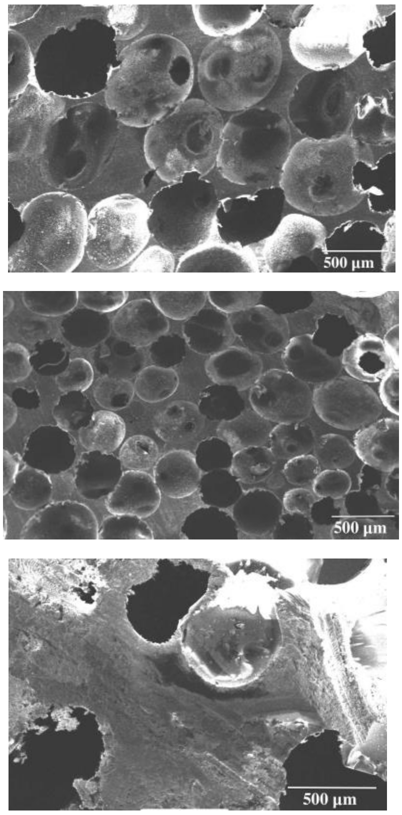
TABLE I. Comparison of average apparent density from current study and supplier data-Smooth On, Inc. MDS [8]

Foam Type	**Apparent density from Smooth On (g/cm^3)**	***Average apparent density from current study [Stddev] (g/cm^3)***
Foam it 16	0.16	0.158 [0.002]
Foam it 24	0.24	0.240 [0.003]
Foam it 42	0.42	0.418 [0.003]

B. Microstructure

SEM microstructure images were taken which displayed the closed cell PU foam for three different densities. The image showed in Fig 1 displayed a uniform distribution of cells (pores) across the surface image when the foam expanded. It was expected that the higher density foam would have a larger value of cell size since there was an inverse relationship between density and cell size of the foam. Table II summarised the density and cell size measurements for each density.

From Table II, with 500 µm scale bar as reference, 0.24 g/cm^3 foam has smaller average cell size than 0.16 g/cm^3 foam, showing that there was an inverse relationship between density and cell size. However, for the highest density foam, 0.42 g/cm^3, this relationship did not hold true, as the distributed cells were more distinct and larger.



(a)

(b)

(c)

Fig 1 SEM images of expandable rigid PU foam of three different densities at 500 µm scale bar : (a) 0.16 g/cm^3 (b) 0.24 g/cm^3 and (c) 0.42 g/cm^3.

TABLE II. SUMMARY OF APPARENT DENSITY; AVERAGE CELL SIZE AND MEAN INTERCEPT LENGTH OF THREE DIFFERENT DENSITIES (0.16 G/CM^3, 0.24 G/CM^3 AND 0.42 G/CM^3).

Foam Type	**Apparent Density (g/cm^3)**	**Average cell size (µm)**	**Cell size range (µm)**	**Mean Intercept Length (µm)**
Foam it 16	0.16	408.51	295 - 692	388.54
Foam it 24	0.24	261.57	116 - 428	258.52
Foam it 42	0.42	422.56	344 - 527	387.13

C. Static Compression Tests

This study focused on compressive modulus, yield stress and ultimate stress. The results were presented as force-displacement curves and engineering stress-strain curves. The engineering stress was calculated by dividing the force at every data point with the cross sectional area of the PU foams while the engineering strain was determined by dividing the displacement at each point with the original height of the PU foams.

Fig 2 shows typical engineering stress-strain curves obtained for all three densities before reaching the collapse region. Fig 3 comprises of the lower two densities: 0.16 and 0.24 g/cm^3 in a smaller axis scale. The compressive modulus was calculated from the maximum linear slope at the linear elasticity region of the engineering stress-strain curves. The ultimate stress was measured from the maximum value of the first curve before collapse and yield stress was measured using 0.2% offset technique (Refer Fig 4).

Table III summarises the average, range and standard deviation of compressive modulus, yield stress and ultimate stress for 0.16, 0.24 and 0.42 g/cm^3 PU foam. Based from table III, the average results for yield stress and ultimate stress of 0.16 and 0.24 g/cm^3 were within 2 to 5 MPa while the compressive moduli for both densities ranged from 40 to 90 MPa. Significance differences were observed between the highest density PU foam (0.42 g/cm^3) and the two lower densities foam (0.16 and 0.24 g/cm^3) for all mechanical properties.

The results obtained for 0.42 g/cm^3 PU foam were significantly higher than the other foams due to the morphological structure of the foam itself. From Figure 1, the microstructure of the 0.42 g/cm^3 PU foam showed that it contained 50% more solid than voids in comparison with the other two foams. The 0.24 g/cm^3 PU foam cells size were smaller than 0.16 g/cm^3 PU foam that showed that it was more compacted and stronger and this was evident in the results obtained.

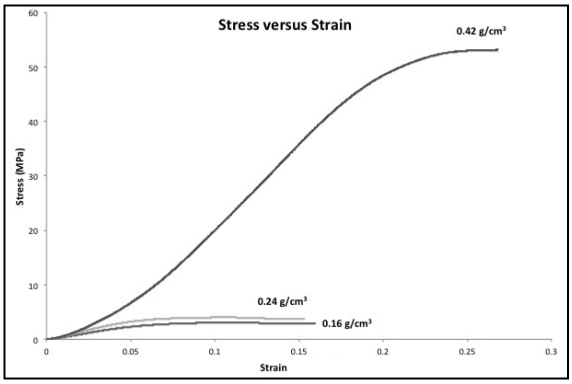


Fig 2: Typical Engineering Stress-Strain graphs for expandable polyurethane foams tested using 9 mm diameter and 7.7 $\pm$ 0.2 mm specimens for 0.16, 0.24, and 0.42 g/cm^3.

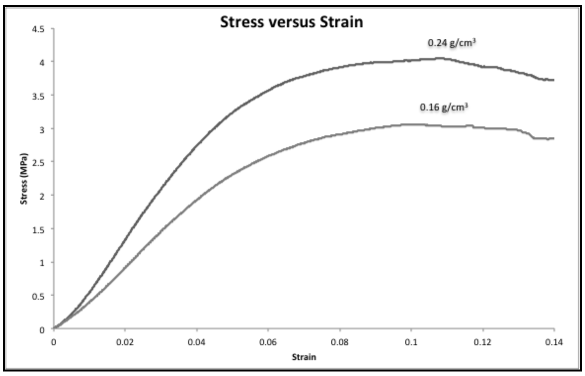


Fig 3: Typical Engineering Stress-Strain graphs for expandable PU foams tested using 9 mm diameter and 7.7 $\pm$ 0.2 mm specimens for 0.16 and 0.24 g/cm^3 in smaller axis scale.

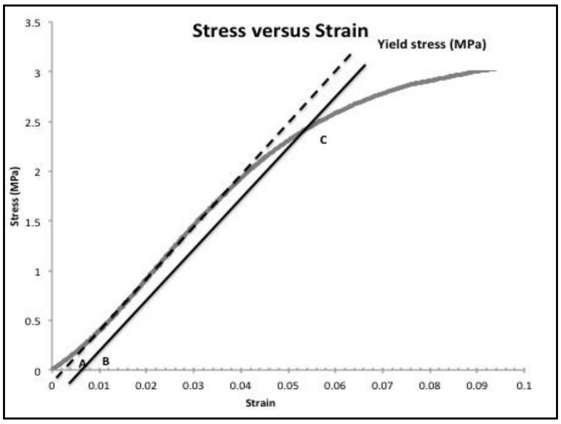


Fig 4: Yield stress was measured using 0.2 % offset technique. The two lines in the Stress-Strain graph demonstrating calculation of yield properties with the 0.2% offset technique (B – A = 0.002).

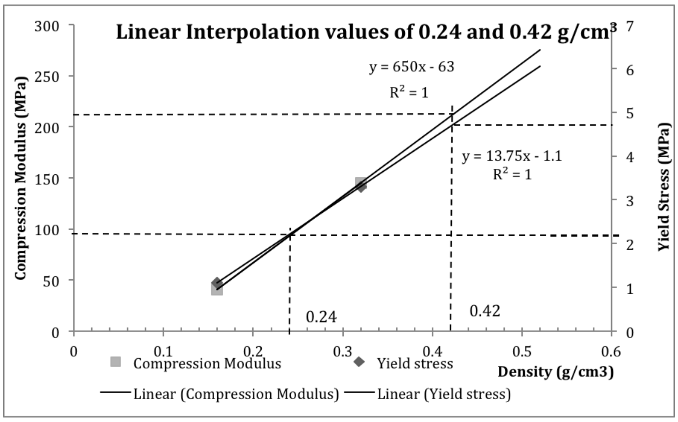


Fig 5: Linear interpolation of average values extracted from Patel et al. [3] for 0.24 and 0.42 g/cm^3 for Compression Modulus and Yield Stress.

TABLE III. COMPRESSION MODULUS, ULTIMATE STRESS AND YIELD STRESS FOR SUMMARY FOR 0.16 G/CM^3, 0.24 G/CM^3 AND 0.42 G/CM^3.

Mechanical Properties	Density (g/cm^3)	Average [Stddev] (MPa)	Range (MPa)
Compression Modulus, E	0.16	42.19 [1.04]	40.67 - 43.5
	0.24	89.89 [4.31]	83.4 - 93.4
	0.42	247.58 [6.15]	240.3 - 255.7
Ultimate Stress, σ_{ult}	0.16	3.2 [0.09]	3.1 - 3.26
	0.24	5.12 [0.58]	4.08 - 5.52
	0.42	59.68 [2.98]	56.3 - 63.2
Yield Stress, σ_{yield}	0.16	2.21 [0.09]	2.1 - 2.3
	0.24	4.27 [0.52]	3.44 - 4.84
	0.42	39.44 [0.76]	38.4 - 40.3

D. Statistical Analysis

Table IV summarised the values for compressive moduli and yield stresses between this study and Patel et al. [6] for 0.16, 0.24, 0.32 and 0.42 g/cm^3. No direct comparison could be made for 0.24 and 0.42 g/cm^3, therefore a linear interpolation and extrapolation graph was plotted to show the expected value for 0.24 and 0.42 g/cm^3 PU foam by adapting Patel et al. [6] 0.16 and 0.32 g/cm^3 average value as a reference. The equations of the linear slope between the reference points were measured for both compressive modulus and yield stress as presented in Fig 5. As the density was known, the ‘y’ value could be calculated using the equation. The value for 0.24 and 0.42 g/cm^3 was approximated to 93 and 201 MPa for compressive modulus and 2.2 and 4.7 MPa for yield stress.

Assuming the true statement was when the null hypothesis (H_0) was equal to the average values from literature. The tests were carried out to observe whether the statement was likely true or not. According to the T-test, for 0.16 and 0.24 g/cm^3 PU foam, no significant differences were detected for the compressive modulus ($p > 0.05$) but there were significant differences for the yield stress ($p < 0.05$) with a α-level at 0.05. The compressive modulus data failed to reject H_0 but the yield stress data clearly rejected the $H_{0.}$ As for 0.42 g/cm^3, both compressive modulus and yield stress rejected H_0 with α-level at 0.05. The normality test and the time series plot indicated that the data met the T-test’s assumptions of normality and randomness. By using α-level at 0.05, all the p values were greater than α value on Anderson-Darling test for normality distribution, suggesting that all the data was normally distributed.

The 95% confidence interval indicated the true value of the current study for 0.16 g/cm^3 was between 40.90 to 43.48 MPa for compressive modulus and 2.09 to 2.32 MPa for yield stress. As for 0.24 and 0.42 g/cm^3, the true value was within the range of 84.53 to 95.24 and 240.3 - 255.7 MPa for compressive modulus and for yield stress, the values range from 3.63 to 4.92 and 38.4 - 40.3 MPa respectively. All values were summarised in Table IV and V.

TABLE IV. CURRENT STUDY VERSUS PATEL ET AL. [3] FOR 0.16, 0.24, 0.32 AND 0.42 G/CM3 PU FOAMS.

Mechanical Properties	Reference	Density (g/cm^3)	Average [Stddev] (MPa)	Range[b] (MPa)
Compression Modulus, E	Current Study	0.16	42.19 [1.04]	40.67 - 43.5
		0.24	89.89 [4.31]	83.4 - 93.4
		0.42	247.58 [6.15]	240.3 - 255.7
	Patel et al [6]	0.16	41 [3]	31.85 - 44.15
		0.32	145 [6]	138.70 - 151.30
		0.24[a]	93	-
		0.42[a]	201	-
Yield Stress, σ_{yield}	Current Study	0.16	2.21 [0.09]	2.1 - 2.3
		0.24	4.27 [0.52]	3.44 - 4.84
		0.42	39.44 [0.76]	38.4 - 40.3
	Patel et al [6]	0.16	1.1 [0.1]	1.0 – 1.21
		0.32	3.3 [0.9]	2.54 – 4.24
		0.24[a]	2.2	-
		0.42[a]	4.7	-

[a] 0.24 g/cm^3 values based on linear interpolation value from 0.16 and 0.32 g/cm^3
[b] The ranges are approximate ranges of the 95% confidence interval

TABLE V. CURRENT STUDY VERSUS HUMAN TRABECULAR BONE AS PRESENTED IN LITERATURE.

Mechanical Properties	**Reference**	**Type**	**Average [Stddev] (MPa)**	**Range[a] (MPa)**
Compression Modulus, E	Current Study	PU F 0.16 g/cm^3	42.19 [1.04]	40.67 - 43.5
		0.24 g/cm^3	89.89 [4.31]	83.4 - 93.4
		0.42 g/cm^3	247.58 [6.15]	240.3 - 255.7
	Morgan/ Keaveny [11]	HV	344 [148]	90 – 875
	Kopperdahl/ Keaveny [12]	HV	291[113]	90 – 536
	Banse [13]	HV	352	127 – 725
	Li and Aspden [3]	FH - O	247	50-410
		FH- N	310	40-460
Yield Stress, σ_{yield}	Current Study	PU F 0.16 g/cm^3	2.21 [0.09]	2.1 - 2.3
		0.24 g/cm^3	4.27 [0.52]	3.44 - 4.84
		0.42 g/cm^3	39.44 [0.76]	38.4 - 40.3
	Morgan / Keaveny [11]	HV	2.02 [0.92]	0.50 – 4.60
	Kopperdahl / Keaveny [12]	HV	1.92 [0.84]	0.56 – 3.71
	Li and Aspden [2]	FH - O	2.5	0.6-5.8
		FH-N	3.3	0.4-9.0

PU F- Polyurethane foams, HV-Human Vertebrae,FH-Human Femur, O-Osteoprotic, N-Normal
[a] The ranges are approximate ranges of the 95% confidence interval

IV. DISCUSSION

The purpose of the synthetic spine was to represent paediatric with scoliosis cases, so it was important to select expandable rigid PU foam that behaved similar to human trabecular bone. Based on Equation 1 and 2, for 20 years old trabecular bone, the expected modulus was 126 MPa and the approximate density was 0.196 MPa. Although the age selected may not be valid for an adolescent but the trend should hold true for normal bone. As discussed earlier, a series of studies have suggested that scoliosis condition is a precursor to osteoporosis. Based on this, it was essential to consider osteoporotic behaviour before selecting the suitable expandable rigid PU foam.

Patel et al. [6] suggested that 0.16 g/cm^3 density rigid PU foams was possibly the best material to represent an osteoporotic condition. To enable a direct comparison, the main test procedures used in this work were setup according to Patel et al. [6]. In Table IV, the mean compressive Moduli for 0.16 g/cm^3 and 0.24 g/cm^3 were 42 MPa and 90 MPa respectively. This data was close to the mean compressive modulus found by Patel et al. [6]. These were shown using T-test as the P-values for both PU foams were statistically greater than 0.05. The values provided sufficient evidence to accept the null hypothesis that the mean values for both foams were equal to the mean value from Patel et al. [6].

The yield stress of all PU foams were neither equal to the mean figure found by Patel et al. according to the T-test ($p > 0.05$) nor within the approximate ranges when compared with the 95% confidence interval. However, Patel et al. [6] stated that for 0.16 g/cm^3 and 0.32 g/cm^3, the results were within the range from 0.9 to 4.5 MPa. If taking the latter factor into consideration, the yield stress values obtained in this study were still within the ranges presented in the literature in Table IV. The denser PU foam used in this study demonstrated higher strength and stiffness as compared to Patel et al.

In Table V, the Young's modulus of human trabecular bone varied from 90 to 700 MPa. This variation was due to several diverse factors such as the age, cause of death, bone density and the methods used to calculate the compressive modulus. Keaveny et al. [12] and Banse et al. [13] calculated the compressive modulus using the slope of the best-fit straight line within different ranges of strain, while others calculated within the maximum slope of the stress-strain curve. In this study, the compressive modulus was calculated as the maximum slope within the elastic region of the stress-strain curves (Refer Fig 4).

As for the yield stress, it varied from 0.4 to 9.0 MPa, using 0.2% offset. Keaveny et al. [12] suggested that yield stress depended on the direction of testing and tended to overestimate if the platens used were not fixed at the end. In the current study, the specimens were positioned as recommended on ASTM, which required that the axis of the compressive load applied was parallel to the foam rise direction.

Although the compressive modulus of 0.42 g/cm^3 (247.58 MPa) expandable rigid PU foam was closer to the human trabecular bone, the yield stress (39.44 MPa) was 20% higher than human trabecular bone. As in most cases for rigid materials, the stronger materials are too brittle and fracture easily and therefore do not replicate human trabecular bone. The structure of this foam was displayed in Figure 1. In comparison with the other two foams, the 0.42 g/cm^3 foam showed that it was less porous, which could explain why the yield stress was higher than human trabecular bone. Therefore, 0.42 g/cm^3 PU foam was eliminated from this study.

The results were also compared with Li and Aspden [3] for osteoporotic bone and normal bone. Although, studies suggested that the trabecular bone of femoral heads was higher when compared to human vertebra. In Table V the range of values range for both strength and stiffness fell within the range of human vertebra. Direct comparisons were made between this study and Li and Aspden [3] because the specimen's sizes were similar. The average compressive modulus and yield stress values for 0.16 and 0.24 g/cm^3 were not similar to the human osteoporotic trabecular bone. On the other hand, the range values for compressive modulus and yield stress for 0.24 g/cm^3 were shown within the 95% confidence interval, while those for 0.16 g/cm^3 were only within the targeted range for yield stress. It was expected that the average values for compressive modulus and yield stress of the synthetic bone would be lower than the human bone because the density was reduced by 40%.

The results obtained for PU foams were limited to uniaxial compression test and did not necessarily exhibit the human trabecular bone behaviour. Recent studies by Kelly et al. [15] showed that the pressure dependent yielding is an essential feature in identifying the suitability of synthetic materials for spinal applications. A beneficial future study would be to perform confined compression tests to demonstrate post yield behaviour of each PU foams and hence strengthen the case of using the selected PU foam as the synthetic bone.

V. CONCLUSION

The results achieved in this study highlighted the difficulties in determining which expandable rigid PU foams could replicate the osteoporotic bone behaviour. This was due to the very wide range of data for human bone from literature. In this study, expandable rigid polyurethane foams with densities of 0.16 g/cm^3, 0.24 g/cm^3 and 0.42 g/cm^3 were tested in uniaxial compression and the results showed that the 0.16 g/cm^3 foam was too low to be used for trabecular bone testing. Although the compressive modulus value of 0.42 g/cm^3 was close to the literature, the yield stress for 0.42 g/cm^3 foam was 20% higher than the ranges given in literature. Additionally, the structure of this foam was less porous and did not exhibit the structure expected for human trabecular bone therefore this foam was eliminated. On the other hand, the compressive modulus and the yield stress for the 0.24 g/cm^3 PU foam fell within the range given for human osteoporotic trabecular bone presented in literature. Hence, in adolescents the compressive modulus was expected to be lower (126 MPa from Equation 1) than for adult data used in literature. Therefore the expendable rigid PU foam 0.24 g/cm^3 is believed to have the potential to replace the trabecular bone to model the adolescent scoliosis synthetic spine. Future work will consider different specimen size with cylinders shape and 2:1 (diameter to length) aspect ratio. These specimen sizes have been used previously to test human trabecular bone and according to Keaveny et al. [16] by using this specimen aspect ratio, the variance of compressive modulus and yield stress will relate better with the density of human bone.

References

[1] L. Mosekilde, L. Mosekilde, C.C. Danielsen. "Biomechanical competence of vertebral trabecular bone in relation to ash density and age in normal individuals". Bone vol 8, 1987, pp. 79-85.

[2] M. Sadat-Ali, A. Al-Othman, D. Bubshait and D. Al-Dakheel. "Does scoliosis causes low bone mass? A comparative study between siblings." Eur Spine J vol 17, 2008, pp 944–947.

[3] B. Li, RM. Aspden. "Composition and mechanical properties of cancellous bone from the femoral head of patients with osteoporosis or osteoarthritis". J Bone Miner Res 1997,vol 12,pp 641-651.

[4] V. Palissery, M. Taylor, M. Browne. "Fatigue characterization of a polymer foam to use as a cancellous bone analog material in the assessment of orthopaedic devices." J. Mat. Sci. Mat. Med. Vol 15 (1), 2004, pp 61-67.

[5] A.E. Johnson A.E. and T.S. Keller. "Mechanical properties of open-cell foam synthetic thoracic vertebrae." J. Mat. Sci. Mat. Med. Vol 19, 2008, pp. 1317-1323.

[6] SD. Patel, ET. Shepherd, WL. Hukins: "Compressive properties of commercially available polyurethane foams as mechanical models for osteoporotic human cancelleous bone." BMC Musc Disorders vol 9, 2008, pp 137.

[7] M. Nor Amalina, T. Anthony, M. Fiona, K. Pat: "Characterisation of correction forces in spinal fusion surgery." In proceedings of 6th World Congress of Biomechanics (IFMBE Proceedings) vol 31(2) , 2010, pp 573-576.

[8] Smooth On, Inc. [http://www.smooth-on.com/].

[9] ASTM F1839-01 Standard Specification for Rigid Polyurethane Foam for Use as a Standard Material for Testing Orthopaedic Devices and Instruments. Pennsylvania: American Society for Testing and Materials 2001.

[10] L.J. Gibson, and M.F. Ashby: "Cellular Solids: Structure and Properties (1st Edition)", New York: Pergamon Press. 1998, pp. 357.

[11] E. Morgan and T. Keaveny. "Dependence of yield strain of human trabecular bone on anatomic site." J Biomech vol 34(5), 2001,pp 569-577.

[12] DL. Kopperdahl, TM. Keaveny. "Yield strain behaviour of trabecular bone." J Biomech vol 31, 1998, pp 601-608.

[13] X. Banse, T.J. Sims, and A.J. Bailey. "Mechanical properties of adult vertebral cancellous bone: correlation with collagen intermolecular cross-links." J. Bone Miner. Res vol 17(9), 2002, pp 1621-1628

[14] N. Kelly, J.P. McGarry. "Experimental and Numerical Characterisation of the Elasto-Plastic Properties of Bovine Trabecular Bone and a Trabecular Bone Analogue," J. Mech. Behav. Biomed vol 9,.2012, pp184-197.

[15] E. Morgan and T. Keaveny. "Dependence of yield strain of human trabecular bone on anatomic site." J Biomech vol 34(5) 2001, pp 569-577.