EFFECT OF CRUMB-RUBBER PARTICLE SIZE ON MECHANICAL RESPONSE OF POLYURETHANE FOAM COMPOSITES

By

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2012

Submitted to the Faculty of the
Graduate College of
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 2014

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ACKNOWLEDGMENTS

It has been a long journey for me to get to this point where I hold a Master's degree. It is the effort of various people put together that helped me to accomplish my dream. Firstly, I would like to thank my advisor Dr. Raman P. Singh for allowing me to work in one of the finest laboratories in America. His intellectuallity has been a major influence on my psychological evolution in the past two years.

I would also like to thank Dr. Ranji Vaidyanathan and Dr. Kaan A. Kalkan for their valuable advices through out my research.

I also want to thank my senior colleagues from lab Kunal, Vijay, Arif, Hamim and Leila who constantly acted as my mentors to refine my thinking abilities. I highly appreciate my peers and friends from lab Raghu, Nitesh, Sandeep, Surendra and Vidyullatha who never hesitated to help me with my experiments. I would like to acknowledge my friends from HRC Nikhil, Balaji and Sudheer for their suggestions and support.

I finally take this opportunity to thank my mother (Naznee S) and sister (Ayesha S) for their constant support through every single phase of my life which gave me the motivation to accomplish my Master's degree.

Name: OMER SHEIK SANJAY

Date of Degree: July, 2014

Title of Study: EFFECT OF CRUMB-RUBBER PARTICLE SIZE ON MECHANICAL RESPONSE OF POLYURETHANE FOAM COMPOSITES

Major Field: MECHANICAL AND AEROSPACE ENGINEERING

The compression properties of foam are governed by by three factors: i) cell edge bending ii) compression of cell fluid iii) membrane stresses in the cell faces. The effect of reinforcement, granular form of scrap tire rubber on contribution of each of these effects along with the physical properties of polyurethane foam is investigated. It is seen that the addition of crumb-rubber hinders the formation of cell membranes during the foaming process.

Four different sizes of particles were chosen to closely study the effect of particle size on the physical properties of the foam composite. There is a definite pattern seen in each of the physical property of the composite with change in the particle size. Addition of crumb-rubber decreases the compressive strength but in turn increases the elastic modulus of the composite.

The rubber particles act as the sites for stress concentration and hence the inclusion of rubber particles induces the capability to transfer the axial load laterally along the surface of the foam. Also, the filler material induces porosity into the foam, which is seen in the SEM images, and hence the addition of rubber particles induces brittleness, which makes the foam composites extensively applicable for structural application in sandwich components. The lightweight composite therefore is a potential substitute to the heavier metal foams and honeycombs as a protective layer.

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CHAPTER I

INTRODUCTION

I.1 Objective

Every year there are more than 700 million tires scrapped [1]. The unique cross-linked structure of rubber in tires make it very hard to decompose and not more than 1% of the raw materials can be reclaimed. The growing number of waste tires discarded every year is rapidly reducing the available sites for disposal, which is turning out to be a serious environmental issue. Most of these tires are burnt and used as fuel, but this method is unsophisticated as it emits harmful gasses into the atmosphere. This necessitates the concern for recycling and reclamation of rubber from scrap tires. The promising options to meet challenges of tire disposal are: (i) use of tire rubber in asphalt concrete mixture, (ii) incineration of reclaimed rubber for production of steam and (iii) reuse of ground tire rubber in number of composites as filler material [2].

One such method of recycling the scrap tires is using them in form of crumb-rubber crumb-rubber is granular foam of tire rubber obtained by shredding; grinding and magnetically separating the scarp tire rubber [3]. Amongst all the available options to recycle the scrap tire rubber, crumb-rubber is the most complicated subject that is least studied [4]. The use of powdered form of these scrap tires as filler in composite materials is one productive method to recycle the waste tires efficiently. Not only does this method overcome the hazards posed on the environment, but also inclusion of crumb-rubber particles as filler makes the material almost 30 % cheaper than its usual price [5].

During past 25 years, several studies have been carried out in an attempt to use crumb-rubber as filler in construction materials like asphalt and concrete [2, 6]. These studies indicate that, although the compressive and flexural strength of concrete material is lowered by addition of crumb-rubber particles due to the lack of bonding, the crumb-rubber particles in concrete are found to increase the toughness, crack resistance, shock wave absorption, noise level reduction and also the flexibility of concrete material [3].

One another material that has a huge potential to contain a large volume of scrap tire rubber in the form of filler material is polyurethane foam. The reason for polyurethane foam to be chosen as the core material in this study corresponds to its vast usage in almost every industrial field. It has wide range of applications in industries related to packaging, insulation, automotive and construction as a result of it its highly favorable properties such as abrasion resistance, thermal insulation, vibration dampening, high load bearing capacity and impact resistance [7].

Polyurethane foam is uniform dispersion of gaseous phase in a solid polymer material and is usually made by reaction of liquids along with a suitable blowing agent. The range of polyurethane end products is very vast starting from soft polyurethane foams to semi-rigid to highly rigid polyurethane foams and they have their particular applications in various fields. Previous studies on crumb-rubber modified polyurethane foam indicate that on addition of rubber particles to the foam, the bulk density is increased and the void volume fractions are significantly decreased. Along with this the compressive properties and the flexural strength are also enhanced greatly [15]. This approach will yield a good platform for recycling of rubber from used tires if the small rubber particles could be successfully incorporated inside polyurethane foam matrix with reinforcing the properties of the end products.

I.2 Background

I.2.1 Crumb-rubber

The unique cross-linked structure of rubber in tires makes it very hard to decompose and not more than 1% of the raw materials can be reclaimed. Reclamation of rubber from scrap tires corresponds to obtaining raw materials by selective breakage of the $-carbon-sulphur-carbon-$ cross-links in the vulcanized rubber [8].

A typical car tire gives out about 12 pounds of crumb-rubber on processing. Crumb-rubber particles are segregated into different types based on its corresponding mesh size. Particles of different mesh sizes are chosen for different applications with particularly desired properties. Few studies discuss the engineering economics and feasibility analysis of recycled rubber products and analyze methods to maximize the recovery value [2, 6]. These studies marked the significance in the usage of crumb-rubber, which yields economical and environmental benefits. The general demand for crumb-rubber products has been increasing and the submarkets are growing in size and variety. In 1994, only about 2% of scrap tires generated in the U.S. were reclaimed as crumb-rubber, which had jumped to 12% by 2001 [2].

Figure I.1: Processing of crumb-rubber

Fattuhi *et al.* suggested that crumb-rubber could possibly be used as a filler in materials required in following areas: (i) where vibration damping is needed, (ii) where resistance to impacts or blasts is required [6]. The elastic rubber particles are expected to absorb a large portion of impact energy through plastic deformation of particles. The resilience and crack pinning properties of rubber particles also account in the reinforcement of the matrix material. Khalid *et al.* described the recycling of dead vehicle tires as an aggregate into concrete gives rise to a new class of composite concrete in the field of construction which could be an opening to contain a large quantity of waste tires disposed in an efficient way [9]. There has been a wide research conducted on crumb-rubber reinforced materials to explore the increase in compatibility of crumb-rubber particles to use them as a replacement to conventionally used fillers like glass and sand particles.

I.2.2 Polyurethane

Polyurethane foams are polymers with long chains of carbamate links. The usage of polyurethane dates back to 1939 when it was first invented by Dr. Otto Bayer as a lighter replacement to rubber used in weapons during world war II. Polyurethanes are generally synthesized by the reaction between the isocyanate (R-N=C=O) and hydroxyl (R-OH) monomers in liquid form to give out urethane (-RNHCOOR) links [10]. The air bubbles that are trapped inside the closed cell structure during the formation of foam not only makes it more buoyant but also imparts additional insulating properties to make it a superior substitute to the heavier core materials used in packaging industries [11]. In account to the fact that changing the isocyanate-polyol system can easily alter the physical, mechanical, and thermal properties of polyurethane, polyurethanes are considered highly versatile materials [8]. Polyurethane foams are the kind of materials with highly favorable properties such as high impact strength, energy absorption capacity, and sound dampening, particularly useful in case of noise reduction. This becomes the driving motivation to choose polyurethane foam as the material to be reinforced.

Polyurethane foams are used as core materials to enhance the stiffness and impart good load bearing capacity to the composite material [12]. But when polyurethane foam is chosen as the protective layer in sandwich composites, it contributes to the reduction of damage and failure of structural components by inducing failure within the foam itself [13]. Finely ground inert organic fillers have been conventionally used as a filler material in polyurethane foam in order to increase its physical properties such as density, foam strength, thermal insulation and vibration dampening by sacrificing all other foam properties [14].

I.3 Literature survey

Crumb-rubber reinforced composites has been an interesting research topic for over the years. There is a vast research done on crumb-rubber modified concrete and there has been a significant advancement in its application in the construction field [15, 16]. Kontareva *et al.* described that the reinforcement in the form of rubber particles causes a slight deterioration in compressive strength of the rubberized concrete accounting to the low elastic modulus (E) and high Poisson ratio (v) of rubber particles. But there is a contrasting effect seen in matrix materials, which have lesser rigidity, compared to the rubber particles‘ [9], [17]. Rubber particles, due to high stress relaxation capability, delay the formation of micro cracks through the material and hence terminating the crack propagating by imparting crack-pinning effect [18].

Later on, owing to the favorable results accomplished in crumb-rubber modified concrete, many other materials were considered as a core material to be reinforced by crumb-rubber particles. Khalid *et al.* observed that inclusion of rubber particles usually has an adverse effect on the strength of composite but it induces improved strain capacity, which results in decrease of Crack Mouth Open Displacement (CMOD) of the composite material [9, 19].

There has also been a significant amount of research done on enhancement of mechanical properties of foam material by inclusion of particles in the form of reinforcement [20, 21]. The usually two-phase foam system is converted to three-phase system, the reinforcement being the third phase; the composite material displays a fusion of mechanical properties of all the three phases [22]. Katpay *et al.* determined that the stability of foam material could be improved by adjusting the viscosity of the liquid foam material by introducing particle reinforcement or alloying elements but it should be kept on mind that the liquid should be enough viscous to capture the gasses between the cells in order to expand. The positive or negative influence of the particle reinforcement largely depends on the foam matrix composition [23].

Although the mechanical properties of composite foam largely depend on the quantity or volume fraction of reinforcement added, the size of the particles used as reinforcement also plays a significant role in governing the properties of the composite foam. Esmaeelzadeh *et al.* stated that there is need to optimize the size of particles used as reinforcement along with its volume fraction and foaming temperature. It was observed in their work on reinforcement of AlSi7 foam with SiC particles that the size of SiC particles has a huge influence on the compressive behavior of the metal foam. Coarser SiC particles led to lower foam strength but whereas the densification strain increased significantly [24]. Also, the uniformity of cell structure is highly dependent on the size of particle reinforcement. The cells start to crumble with addition of coarser particles [25].

Kim *et al.* investigated various modes of failure of foams during compression. In his study on failure of syntactic foams on compression, it was observed that low density foams split longitudinally along the axis of load application. Whereas the high density foams split laterally across the cross section of foam material which is initiated at the weakest site and promoted by stress concentration sites along the layers [13]

Further, several studies also describe that an effective way of toughening foams is to add rubber particles as filler material since the rubber particles are capable of absorbing more impact energy through their elastic deformation. In addition to this, the lower stiffness of rubber particles serves as stress concentrators [9-11]. Azimi *et al.* investigated the fatigue crack propagation and fracture toughness of a crumb-rubber modified syntactic foam and noticed that the rubber particles impart rubber-pinning mechanism which enhance the crack propagation resistance and fracture toughness of the matrix system [12]. Rubber size has noticeable effects on the performance of the modified mixtures. Increasing rubber size results in a decrease in the resilient modulus values for modified mixtures regardless of rubber type [13].

I.4 Motivation

Despite of the extensive research done on reinforced metal foams and their applicability in various fields, there exists a driving need to over come the non-uniformity of physical properties along the foam structure caused by the inclusion of reinforcement [26]. Goods *et al.* stated that filler materials in foam may sometimes act as preexisting defect sites of stress concentration allowing crack initiation. The interaction of the filler material with the foam matrix plays a major role in determining the crush force associated with elastic collapse of closed-cell structure in the polyurethane foam [27].

Until today, there has been no comprehensive study done on the modes of failure in reinforced polyurethane foam during compression. In this work, a thorough investigation is done to observe the variation of physical properties by altering the size of crumb-rubber particles. It also important to examine the effect of crumb-rubber reinforcement on behavior of polyurethane foam compression in the plateau region. The present work focuses on the structural properties of reinforced polyurethane foam with a desire to modify the foam in such a way that it could turn out to be a potential replacement to the heavier honey combs and other metal foams as protective layer which can induce failure to itself.

This may increase the scope of its usage significantly which would in turn provide a huge volume of opening to recycle the scrap tire rubber.

CHAPTER II

EXPERIMENTAL DETAILS

II.1 Origin and Preparation of Samples

Crumb-rubber particles were obtained from Entech Inc. (White Pigeon, MI). A grade of 40-49 mm size particles were finely ground using a high-performance hand grinder. The crumb rubber particles are subjected to a sieve machine and particles of different sizes are separated using four different mesh sizes with corresponding sieve numbers (Dual Manufacturing Co. Inc., Chicago, IL; Figure II.1). The samples were accordingly labelled with the sieve numbers. The sizes of meshes chosen in this study are #8 (2.36-4.75 mm), #14 (1.40-2.36 mm), #16 (1.18-1.4 mm), and #20 (0.8-1.18 mm). These crumb rubber particles of different sizes are used to reinforce the Polyurethane foam. Resin in the form of liquid was purchased from U.S. Composites (West Palm Beach, FL). A rigid polyurethane foam of grade 4 lb density was chosen. The resin kit contains two parts; Part-A being polymethylene polyphenylisocyanate (PMDI) and Part-B being 1,1,1,3,3-pentafluoropropane. Equal proportions of Part-A and Part-B of the resin are mixed to react and form polyurethane foam.

A mold is set up with a 10” x 10” aluminum plate as the base and hard rubber of 1” thickness on four sides acting as walls.The composition of crumb rubber is kept constant to 35% by weight. Multiple batches of Polyurethane foam are made using crumb rubber particles of sieve numbers 8, 14, 16, 20 respectively in each batch along with few batches of virgin Polyurethane foam. The crumb-rubber particles are proportionately blended with part B of Polyurethane foam. This mixture is mechanically stirred for 1-2 minutes until the rubber particles are neatly coated with liquid part B. Now, equal proportion of part A as of part B of Polyurethane foam is added to this mixture and quickly hand stirred for 20-25 seconds and the thick slurry is poured into the mold within 20 seconds. This process is done promptly as the foaming process begins in 45 seconds after part A is mixed with part B. Once the foaming process starts, the mold is covered by another aluminum plate on the top closing the mold. The mixture is left for expansion and curing for 60-75 minutes at temperature of 70°F. The aluminum plates are covered with Polyethylene sheets, which act as releasing agents. The mold is placed horizontally during the foaming process to overcome the discrepancy in distribution of rubber particles in foam, as in the case of vertical molds.

The foam slab is released and cylindrical samples are cut out from the Polyurethane foam slab. The samples are machined to a thickness of 1 inch and diameter of 2 inches and labelled accordingly. Through out this work, samples labelled with the average sizes of a mesh range. For example average size of mesh # 8, which is 3.5 mm, indicates that the foam samples contain rubber particles of #8 mesh size (2.36-4.75 mm) and so forth. But, average size 0 mm indicates that the samples have no rubber reinforcement and are just cut out of virgin foam slab.

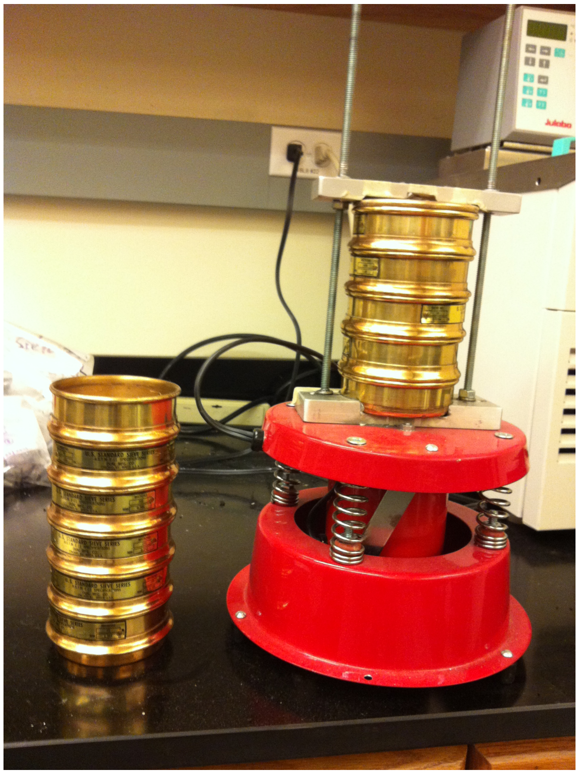

Figure II.1: Sieve machine used for seperation of particles of different sizes

II.2 Testing

II.2.1 Compressive Properties

Identical cylindrical samples with different sizes of crumb-rubber particles were subjected to compression using a compression platen of 30 KN cell in a screw-driven test frame (MTS INSTRON 5567, Norwood, MA) as seen in Figure II.2.1. Based on ASTM C-365/C-365M standard of measurement, the compressive moduli of the material are determined. The slopes of the stress-strain curve in the elastic region and plastic region are calculated to determine the compressive modulus of foam and the compressive modulus of solid material respectively.

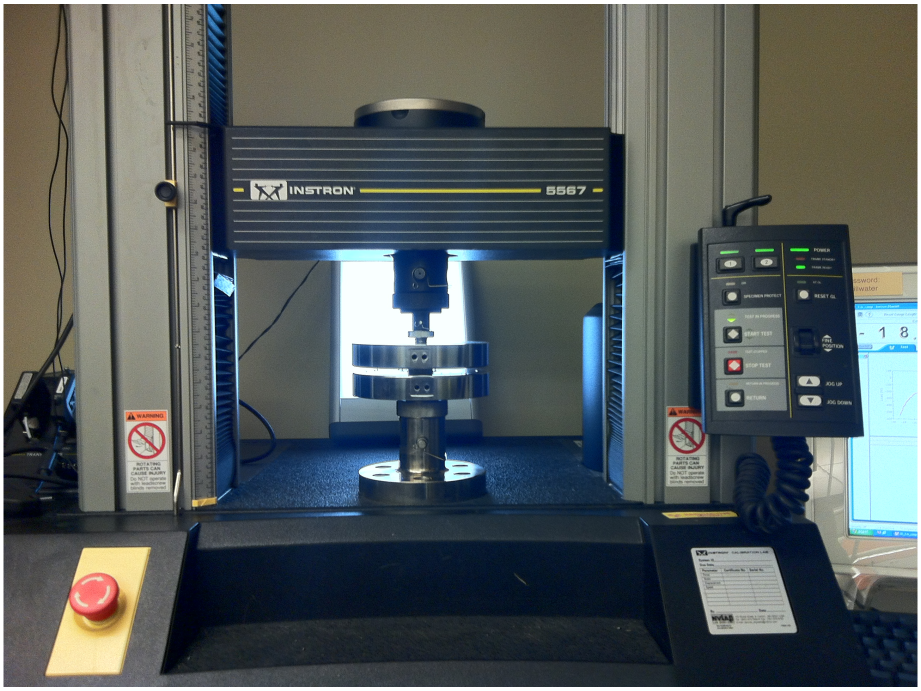

Figure II.2: Instron machine used for compression

Further, the compressive strength of foam material is determined by identifying the stress at the yielding point in the elastic region of compression.

Foams behave as a soft material which could further be compressed even after densification and exhibit all the properties as that of a simple solid material. The trend in the elastic modulus and compressive strength is compared both in initial elastic region and also in the solid region.

II.2.2 Plastic Indentation Hardness

Unlike dense solids which cannot be compressed further after deforming plastically, foams are materials which could further be compressed after densification and plastic deformation. The plastic indentation hardness is the peak stress on the foam material after complete collapse of the cell walls and compression of the foam material to a soft solid state with almost no porosity. This is a critical property to be evaluated to characterize the foams for cushioning properties.

II.2.3 Density & Prosity

In reference to the literature, the densities and porosities are highly influential properties in determining the ability of a foam material to be used as a protective coating on structural applications [28, 29]. The density and porosity of foam highly influence other physical properties of foam. Inclusion of rubber particles affects the density of foam significantly. The porosity of the sample is the ratio of the volume of pores to the total volume of the specimen. Densities of different foam samples are determined by the Archimedes setup using the principle of buoyancy as seen in figure II.2.3.

Solid density is simply the ratio of the mass of the sample and its solid volume. This is measured using an Ultrapycnometer (Quantachrome Instruments, Boynton Beach, FL; figure II.2.3). The samples whose solid densities are to be measured are crushed into powders to make sure there are no pores present in the material. By introducing this powder, which is simply the solid form of the foam composite into the pycnometer chamber, the solid volume is measured and therefore the solid density.

Figure II.3: Archimedes setup

Figure II.4: Ultrapycnometer used to measure solid density

Bulk density is the ratio of mass and total volume of the material. The bulk density of polyurethane foam composite is measured by using the principle of buoyancy on the Archimedes density determination set up. The dry mass, wet mass and mass in water of the sample are measured and the bulk densities of samples are calculated using corresponding equations. The bulk density, solid density and buoyancy together are used to evaluate the porosity of the specimen.

II.2.4 Material Characterization

Scanning electron microscopy (SEM) images were taken on the foam samples with crumb rubber and without crumb rubber to visualize the changes in morphology of foam on inclusion of rubber particles. Along with this, the rubber samples after undergoing compression test are subjected to SEM imaging to analyze the failure of cells in foam and crushing of foam associated with the rubber particles. In this research, Hitachi S-4800 Type II ultra-high emission scanning electron microscope (GCE Market Inc., Blackwood, NJ) was used. The composite foam samples are sputtered with gold to make them conductive and images were taken with an accelerating voltage of 5 KV. The pore sizes of foam material with different sizes of rubber particles are determined from these images. Also, the cell sizes of the closed cell structure of foam are measured subsequently to investigate the effect of reinforcement on the surface tension of cell walls during the foaming process.

II.2.5 Energy Absorption

The area under the stress-strain curve is evaluated to determine the energy absorbed by the foam composite in quasi-static loading conditions. The energies absorbed in linear elastic region and after the onset of densification are calculated. The energy absorption capacity of the foam composite for cushioning application depends on the amount of energy absorbed in the densification region [30].

CHAPTER III

RESULTS AND DISCUSSION

III.1 Elastic Modulus

With the inclusion of highly elastic rubber particles, the elasticity of foam is expected to increase by a fair amount. This effect is noticed with inclusion of crumb-rubber to into the polyurethane foam matrix. Although, on a relative scale, there is a slight decrease in modulus with inclusion of larger particles and the modulus slowly increases with decrease in size of particles. This effect is explained by the surface area of contact of the particles with the foam material. In the case of smaller particles, the elasticity of foam is transferred to the composite constructively along with the elasticity of the foam material. But as the particles get bigger the relative rigidity of the particles make them to pierce through the foam material along with crushing of foam material corresponding to the weak interface surrounding the larger crumb rubber particle. This is visualized in the SEM images where the crushing of foam is observed as seen in figure III.22.

In the solid region, since the foam is no longer porous as it is in the elastic region, there is no scope for the rubber particles to pierce through the foam and the larger particles resist deformation at higher loads and hence the compressive modulus of foam follows a reverse trend in the solid region.

Table III.1: Elastic Modulus and Solid Compressive Modulus

Average size of particles	**Elastic Modulus (MPa)**	**Solid Compressive Modulus (MPa)**
0 mm	3.5 ± 0.8	48 ± 19
0.9 mm	7 ± 1	95 ± 33
1.2 mm	4.6 ± 0.1	157 ± 7
1.9 mm	4.3 ± 0.3	131 ± 27
3.5 mm	2.8 ± 0.5	237 ± 42

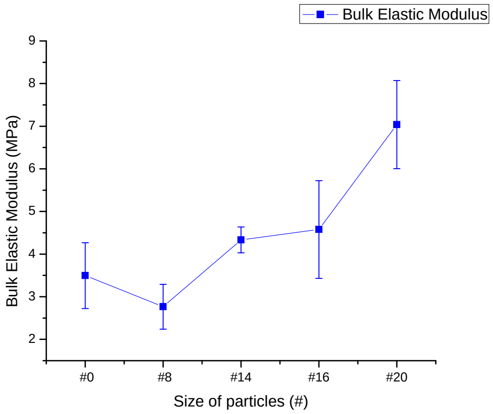

Figure III.1: Bulk elastic modulus

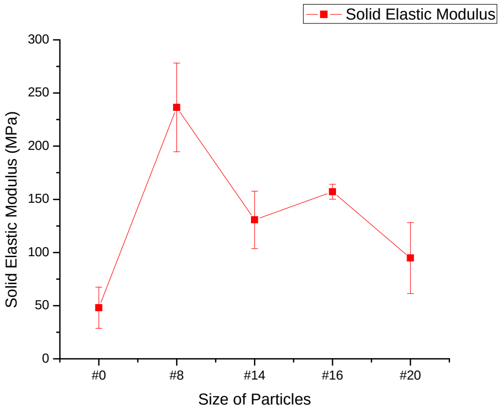

Figure III.2: Solid compresive modulus

III.2 Compressive Strength

The compressive strength also follows a similar trend as the compressive modulus. In the elastic region, since the bigger particles tend to rupture the foam material, the reinforced foam tend to yield at a lower load with bigger rubber particles in the elastic region. Whereas, in the solid region, the load is directly transferred on to the rubber particle with a stronger interface of foam and crumb-rubber particle.

Table III.2: Compresive Strengths

Average size of particles	Bulk Comp. Strength MPa	Solid Comp. Strength MPa
0 mm	0.36 ± 0.01	4.3 ± 0.5
0.9 mm	0.14 ± 0.01	5 ± 0.4
1.2 mm	0.27	6 ± 0.3
1.9 mm	0.20 ± 0.01	6.3
3.5 mm	0.18 ± 0.01	7.1 ± 0.2

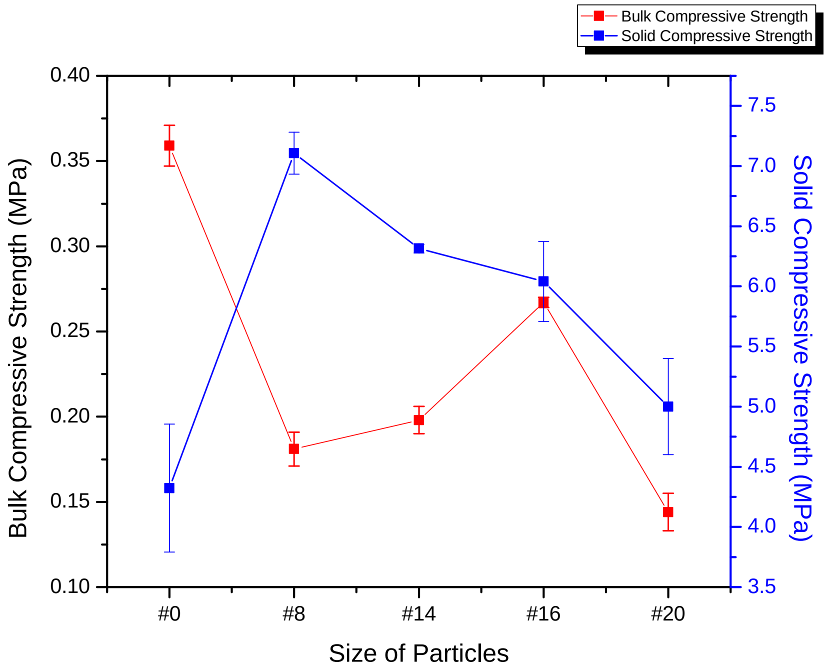

Figure III.3: Variation in compressive strengths with reinforcement

III.3 Plastic Indentation Hardness

The plastic indentation hardness, which is peak stress on the specimen at the end of densification when the total porosity is almost null, increases significantly with addition of crumb-rubber particles. This effect is obvious as the rubber particles are relatively harder when compared to the foam and the densification causes the distribution of rubber particles to accumulate and resist the load applied on the specimen. The plastic indentation hardness increases along with the size of rubber particles as the bigger sized particles get in contact with each other accumulating at a lower strain level when compared to the smaller sized particles as seen in figure III.4.

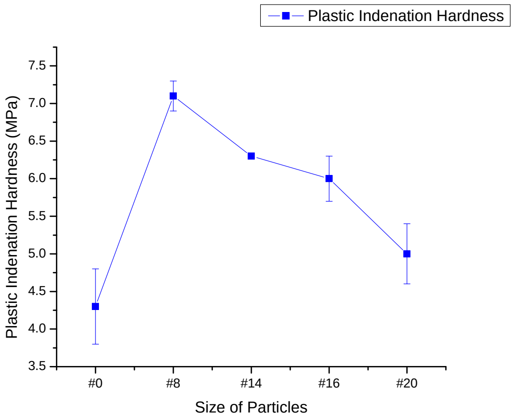

Figure III.4: Variation in plastic indentation hardness

This becomes one of the essential factors for cushioning applications of reinforced polyurethane foam.

III.4 Density

The density of foam increases with inclusion of denser crumb-rubber particles. This is also affected by the porosity induced in the foam by the crumb rubber particles. Inclusion of crumb-rubber affects the foaming process. It increases the viscosity of the foam resin and therefore decreasing the foamability of the resin by a noticeable level, which is seen in figure III.5.

The size of rubber particles also govern the density of the foam. It is number of particles per unit volume that changes with change in particle size. This affects the induced porosity and therefore the density. For structural application, the porosity, density and the pore sizes are to be optimized together to achieve desired strength of foam.

III.5 Porosity

The porosity is one other crucial property which governs the densification strain and compressive properties of foam. The viscosity of foam also effects the induced porosity in foams. Due to improper adhesion of rubber particles at the interface, the air is trapped around the crumb rubber particle and foaming occurs around the particle with the trapped gasses becoming voids in the form of pores. The integrity of new pore walls with the cell structure determines the compressibility of foam seen in figure III.6.

This effect is seen in increase of porosity with decrease in the size of crumb-rubber particles. As the number of particles per unit volume is increased with decrease in the size for a fixed quantity of reinforcement, the amount of air trapped around the rubber particles is increased.

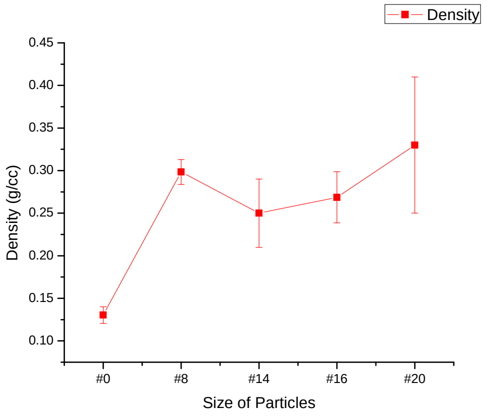

Figure III.5: Density

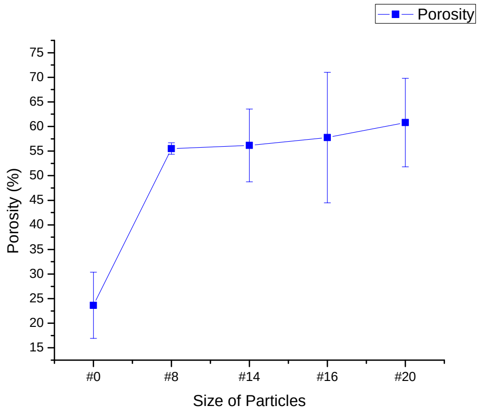

Figure III.6: Porosity

Table III.3: Density & Porosity

Average size of particles	**Density (g/cc)**	**Porosity (%)**
0 mm	0.13 ± 0.01	24 ± 7
0.9 mm	0.33 ± 0.08	61 ± 9
1.2 mm	0.27 ± 0.03	58 ± 13
1.9 mm	0.25 ± 0.04	53 ± 7
3.5 mm	0.30 ± 0.01	56 ± 1

III.6 Pore Size & Cell Size

The pore size along with the porosity alters the compressive properties of foam. The decrease in pore size increases the integrity of pores along with the cell walls in the order to increase resistance towards higher load before yielding. This phenomenon explains the increase of elastic modulus of foam with decrease in particle size of crumb rubber.

The smaller cell sizes also have a similar effect on compressibility of foam. As the cell size is small, the density of cell edges, which are thicker than the membranes of cell walls is higher. This indicates that the compressive property of foam depends majorly on bending of cell edges and the cell walls have a minor effect. The smaller size particles induce higher viscosity in to the foams and therefore the cell sizes are smaller with smaller crumb-rubber particles seen in figure III.7.

Table III.4: Average Pore Size & Cell Size

Average size of particles	**Pore Size (mm)**	**Cell Size (mm)**
0 mm	0.72 ± 0.07	0.7 ± 0.1
0.9 mm	0.24 ± 0.06	0.38 ± 0.04
1.2 mm	0.3 ± 0.08	0.34 ± 0.06
1.9 mm	0.35 ± 0.06	0.4 ± 0.07
3.5 mm	0.54 ± 0.16	0.52 ± 0.11

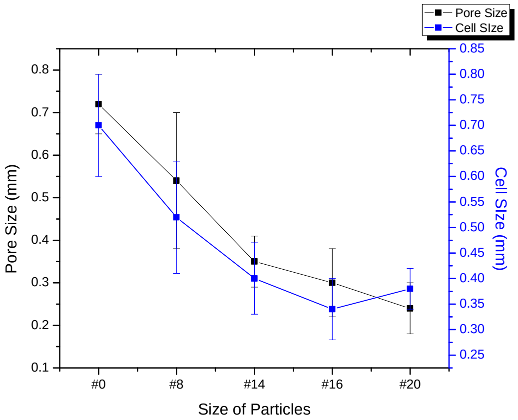

Figure III.7: Effect of reinforcement on pore size & cell size

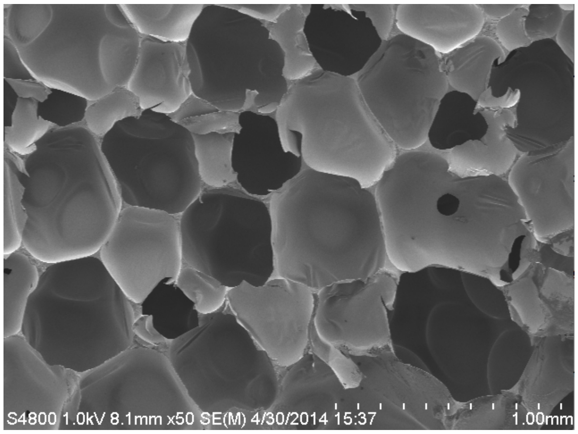

Figure III.8: SEM image used to determine the cell sizes & pore sizes

III.7 Energy Absorption

It is observed that the reinforcement of foam degrades the energy absorption capacity in the linear elastic region at lower load levels (figure III.9). But in reality, for the structural applications, it the higher load level at which the foams are operated. In the region of densification, the composite foam is seen to have enhanced energy absorption capacity (figure III.10). There is a subtle variation in energy absorbed with the change in size of particles but the rubber particles show a reinforcing effect on the foam composite. This effect assures the usage of crumb-rubber reinforced foams at high load operation levels.

Table III.5: Energy Absorption Capacity of Foam

Average size of particles	**Energy in Elastic Region (KJ)**	**Energy during Densification (KJ)**
0 mm	31 ± 4	333 ± 21
0.9 mm	12 ± 1	564 ± 19
1.2 mm	23 ± 2	627 ± 23
1.9 mm	14 ± 1	725 ± 31
3.5 mm	14 ± 3	432 ± 26

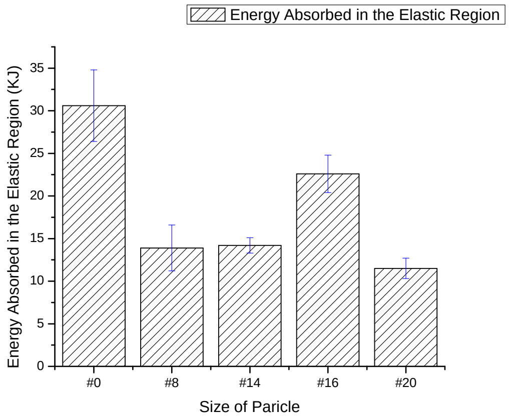

Figure III.9: Energy absorbed by foam in elastic region

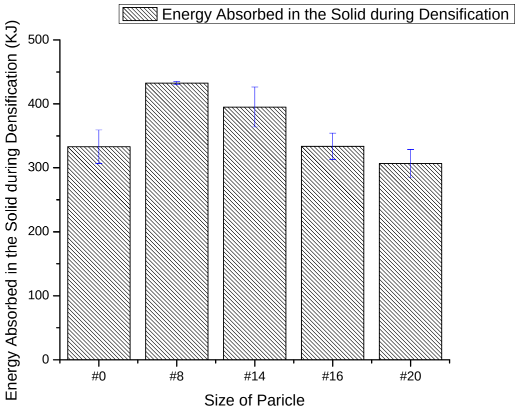

Figure III.10: Energy absorbed by foam during densification

III.8 Recovery of Foam

The recovery of foam at fixed strain level of 0.85 strain is investigated. It is seen that the elasticity of rubber particles is transferred to the foam on unloading curve in the form of recovery of foam. Specimen with different sizes of rubber particles were investigated for recovery and it is observed that the reinforcement enhances the recovery of foam at high strain levels as observed in figure III.11.

Table III.6: Recovery of Foam at 0.85 Strain

Average size of particles	**Recovery (%)**
0 mm	10 ± 1
0.9 mm	10 ± 1
1.2 mm	14 ± 2
1.9 mm	16 ± 2
3.5 mm	12 ± 1

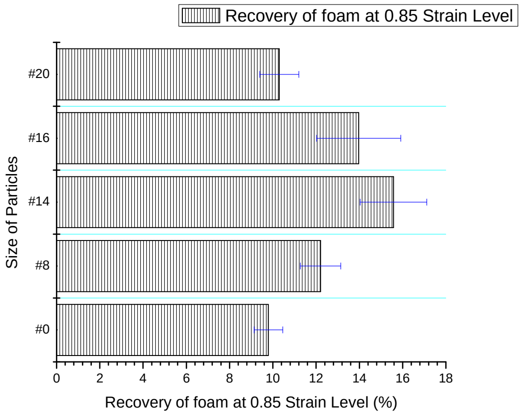

Figure III.11: Recovery of foam at 0.85 strain level

III.9 Overview of compression on crumb-rubber reinforced foam

The compressive properties of closed cell foams on axial loading has major contributions from the following: i) cell edge bending, ii) compression of cell fluid, iii) membrane stresses in the cell faces.

The reinforcement in the form of crumb-rubber particles do not have a noticeable effect on the cell edge bending but comes to play in the cases of compression of cell fluid and membrane stresses. The inclusion of rubber particles hinder the formation of membranes in the closed cell structure of foam. This further gives rise to partial open cell structure within the closed cell foam matrix as seen in SEM images, figure III.16.

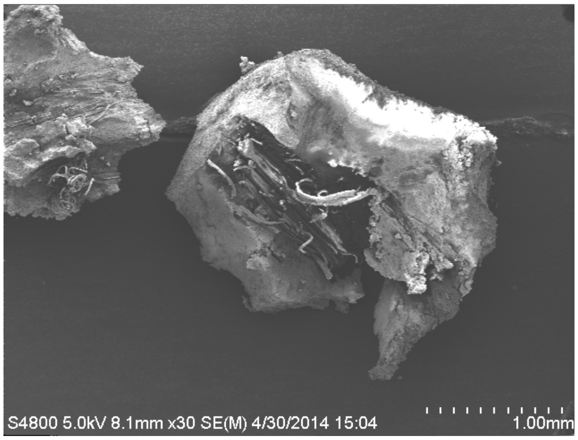

Figure III.12: SEM image of crumb rubber particle

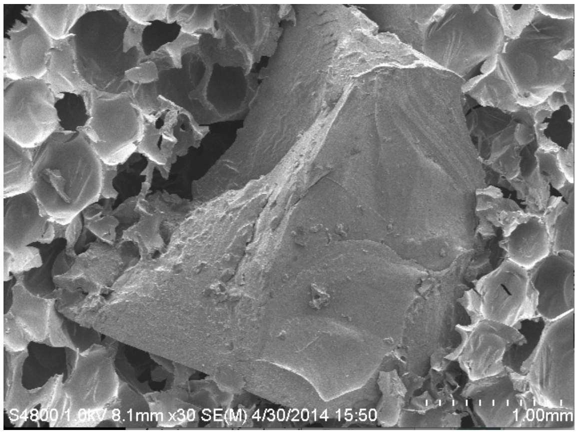

Figure III.13: Rupture of foam at the interface

The compression of foam is segregated into three stages. The initial linear elastic region, in which the load applied is directly transferred on to the cell walls and the curve has a constant slope until the cell walls start yielding. A typical stress-strain plot in loading and unloading conditions is shown in figure III.14. The description of higher elastic modulus before the elastic collapse of foam is observed in the figure III.15 from which it is clear that the stresses in plateau region mark the onset of foam deterioration. In this region, the load applied is also acting on the interface of crumb-rubber and polyurethane foam and at this low level of stresses, the elasticity of rubber is constructively transferred to the foam composite until the foam starts yielding and the rubber particles start to pierce through the porous structure (figure III.17).

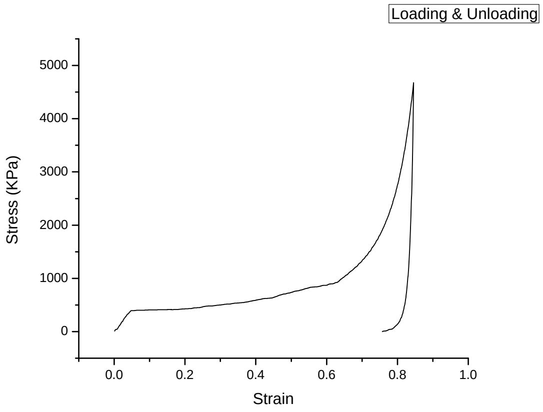

Figure III.14: Stress-strain path during loading and unloading conditions

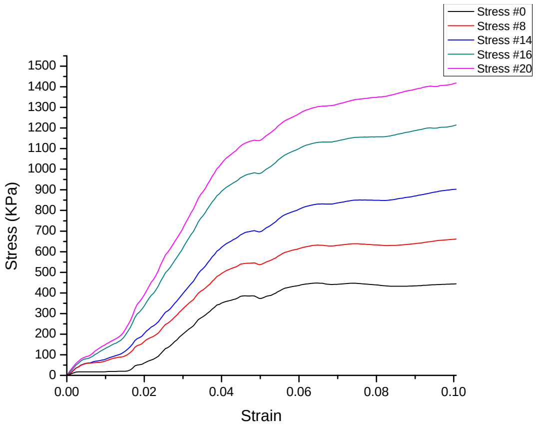

Figure III.15: Compression behavior in the elastic region

In the plateau region, the cell wall buckling takes place and there is an onset of plastic deformation of foam. This is the region of compression, which plays a major role in cushioning applications. The stress in this region falls from peak stress in the elastic region to the valley stress of plateau region. The crumb-rubber reinforcement shows a counter effect in this region due to its improper interfacial bonding with the foam. Since the cell walls start to buckle, the load is concentrated around the rigid rubber particle and it starts to rupture the cell membranes promoting the plastic deformation in foam. Here, the load bearing capacity is observed to be degraded and there is a fair chance to overcome this effect if suitable surfactants are used to enhance the surface adhesion of rubber particles with the foam matrix.

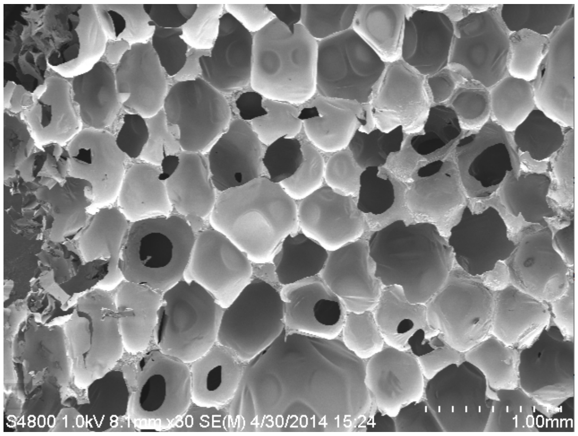

Figure III.16: Degradation of cell membrane formation

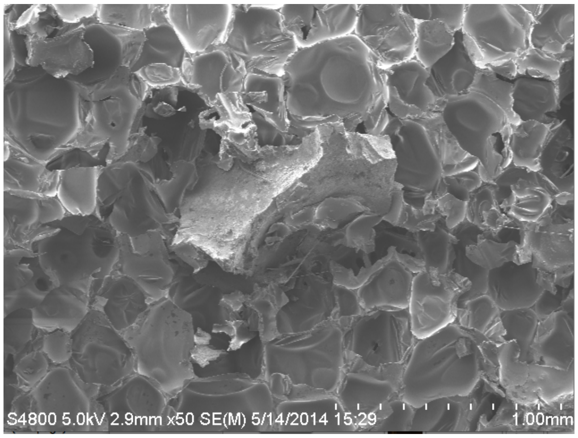

Figure III.17: Crumb rubber particle promoting layered crushing

At higher strain levels, when all the cell walls give out and the pores in the foam structure are compressed, there is an onset of densification. The stress rises with a steep with a small increase in the strain. The induced porosity due to inclusion of rubber particles lowers the densification strain. But in turn, during the densification, the counter effects of improper interfacial adhesion are nullified and the load is transferred directly on to the rubber particles. Also, the elasticity of crumb-rubber particles has a productive effect on the foam composite which is observed in the recovery of foam.

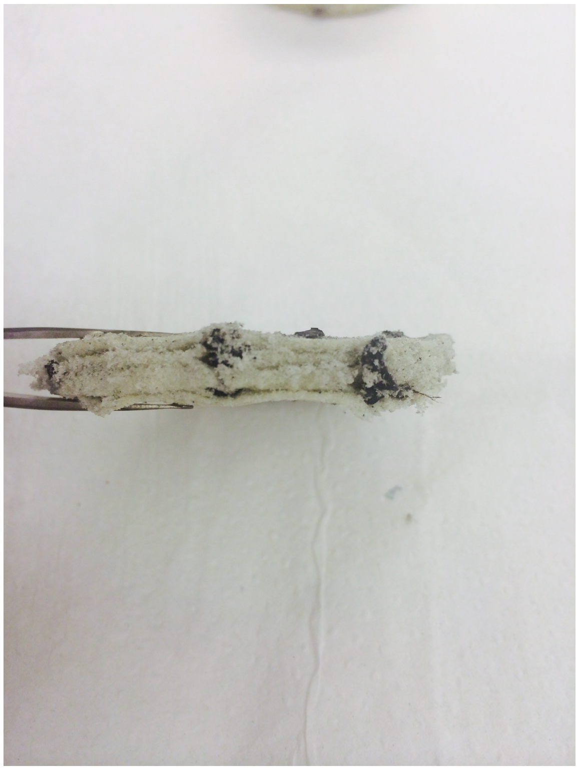

Figure III.18: Layered Crushing of Reinforced Foam

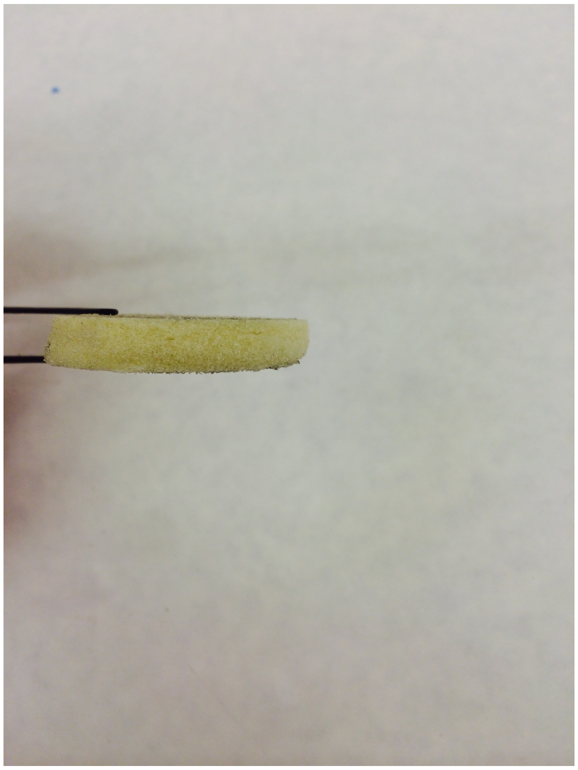

Figure III.19: Longitudinal Shearing of Virgin Foam

The deformation mechanism of foam is also altered by inclusion of crumb-rubber particles. In case of axial compression load, the inhomogeneity of the material causes the interface of the rubber-foam surface to be become the site of stress concentration. This builds up the stress around the rubber particle. There are several other rubber particles in the same layer of foam which undergo similar phenomenon. The axial stresses are deflected by the rubber particles along the layer and promote deformation in lateral direction. Hence, the rubber particles induce the tendency to localize the deformation and the energy absorbed during compression is utilized to break the bonds in the lateral direction. The lateral deformation is visually observed in the reinforced foam and not in the case of virgin foam (figures III.20, III.21). The virgin foam shears in the axial direction which shows that it undergoes longitudinal deformation. This induced tendency of lateral deformation by distribution of load across the specimen explains the enhancement in the energy absorption properties.

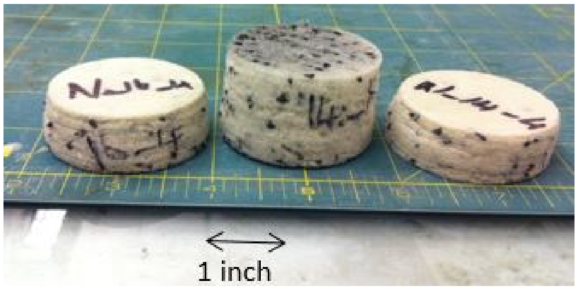

Figure III.20: Samples used for compression testing

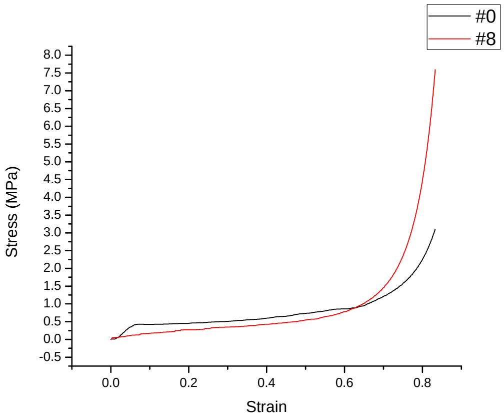

Figure III.21: Path of compression with reinforcement

III.10 Model to describe the deterioration of closed-cell structure

Despite the fact that the compressive modulus of foam is enhanced in both the initial elastic region and final dense region of foam, the onset of the plateau region with inclusion of crumb-rubber particles is at a lower stress level when compared to the virgin foam, which explains the degradation in compressive strength of foam. This occurs as the foam material yields at a lower stress with the inclusion of rubber. This phenomenon is explained by the effect of pressure exerted by the gasses present in the closed cell structure of foam.

Polyurethane foam, in general is made out of liquids by mixing them in proportionate quantities. The surface tension in the liquids draws the material during the foaming process to stimulate the formation of membranes, which enables the formation of closed cell structure. During the collapse of closed cell structure, the yielding of cellular foam occurs when the cells are buckled and deform plastically. This causes the gasses present inside the closed cells to exert pressure and press against the load-direction giving rise to higher compressive strength of the foam. This also brings a change to the collapse stress (σ) and the post behavior.

Although the contribution of the pressure exerted by the cell gasses on the compression property is small, this phenomenon cannot be neglected as it has a significant effect on the post behavior of foam after yielding and it alters the shape of elastic collapse plateau. This effect is not seen in the case of open cell foams with a certain reason that there is no gas trapped in the cells to exert pressure against loading. This also causes the open cell foams to collapse at constant load giving rise to flat plateau regions. Whereas, in the case of closed cell foams, the pressure exerted by the cell gasses along with the stretching of cell membranes gives rise to a plateau region with an increasing slope.

The inclusion of crumb rubber particles ruptures the cell walls (seen in SEM images), which hinders the formation of cell membranes inducing a partial open-cell nature into the closed cell polyurethane structure. The extent of openness introduced into the foam structure is quantified by modeling the foam with the following equation.

A variable 'λ' is introduced which is defined as the 'degree of openness introduced' due to the inclusion of crumb rubber particles. The rubber particles used as a reinforcement in the polyurethane foam shows an adverse effect on the pressure exerted by the cell

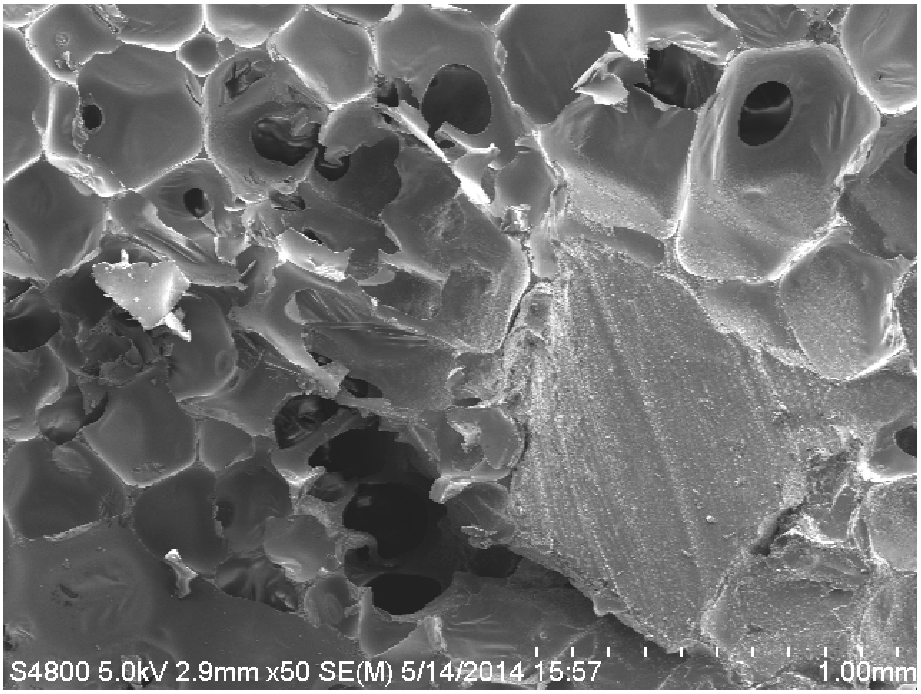

Figure III.22: Degradation of membrane formation by inclusion of crumb-rubber particles

gasses. Accounting to the decrease in foamability due to inclusion of rubber particles, the capability to form membranes as a part of closed cell structure is deteriorated. This phenomenon induces a partial open-cell nature into the foam structure in which the effect of the cell gas pressure is not seen. The extent to which the crumb-rubber paerticles induce the open-cell structure is quantified by the degree 'λ'.

Gibson *et al.* formulated an equation (III.1) to determine the elastic collapse stress of a foam material which includes the contribution of the cell-gas pressure.

$$\frac{\sigma_t}{E_f} = 0.05\frac{\rho_f}{\rho_s} + \frac{P_0\epsilon}{E_s(1-\epsilon-\frac{\rho_f}{\rho_s})} \tag{III.1}$$

where,

σ_t = Theoritical elastic collapse stress of polyurethane foam

E_f = Bulk elastic modulus of foam

E_s = Solid elastic modulus of foam

ρ_f = Bulk density of foam

ρ_s = Solid density of foam

P_0 = Cell-gas pressure = 1 atm

ϵ = Strain at the yield point

For a sample with #8 crumb-rubber particles, the polyurethane foam is modeled to determine the degree of openness 'λ' (equation III.2).

$$\frac{\sigma_t}{E_s} = 0.05\frac{\rho_f}{\rho_s} + \frac{P_0\epsilon}{E_s(1-\epsilon-\frac{\rho_f}{\rho_s})}$$

$$\frac{\sigma_t}{2.77} = 0.05\frac{0.3}{0.54} + \frac{0.1013 * 0.099}{2.77(1-0.099-\frac{0.3}{0.54})} \tag{III.2}$$

$$\sigma_t = 0.1057MPa$$

In reality, when the foam starts to yield at ϵ = 0.099, the elastic collapse stress is 0.083 MPa which is observed on the stress-train curve. The degradation in the elastic collapse stress is due to the partial openness of the closed-cell structure which is quantified by the degree 'λ'.

Here,

σ_a = Actual elastic collapse stress of polyurethane foam

$$\frac{\sigma_a}{E_s} = 0.05\frac{\rho_f}{\rho_s} + \lambda[\frac{P_0\epsilon}{E_s(1-\epsilon-\frac{\rho_f}{\rho_s})}]$$

$$\frac{0.083}{2.77} = 0.05\frac{0.3}{0.54} + \lambda[\frac{0.1013 * 0.099}{2.77(1-0.099-\frac{0.3}{0.54})}] \tag{III.3}$$

$$\lambda = 0.21$$

A drop in elastic collapse stress is observed on comparing the theoretical and actual values. This change is determined to quantify the effect of reinforcement on the plateau stresses by the equation III.4.

$$\%\Delta(\sigma) = 100[1-\frac{\sigma_a}{\sigma_t}] \tag{III.4}$$

The value of 'λ' attributes to the decrease in the elastic collapse stress of the foam composite. Although the decrease observed in the elastic collapse stress is not so high, the post behavior all along the plateau region depends on the degree of openness induced. The stress-strain curve does not see a rise in the plateau region which otherwise has a steep due

Table III.7: Degree of openness induced (λ)

Average size of particles	**Degree of openness (λ)**	**Percentage Decrease in σ (%)**
0.9 mm	0.52 ± 0.11	11 ± 3 %
1.2 mm	0.37 ± 0.14	9 ± 3 %
1.9 mm	0.45 ± 0.07	13 ± 1 %
3.5 mm	0.29 ± 0.09	18 ± 4 %

to the pressure exerted by the cell gasses.

The similar trend seen in the porosity induced due to inclusion of crumb-rubber particles corresponds to the value of 'λ'.

CHAPTER IV

CONCLUSIONS AND FUTURE WORK

IV.1 Conclusions

With a wide range of applications as a protective coating in structural applications, the crumb-rubber reinforced polyurethane foam provides a potential alternative to the heavier metal foams and honey combs. With the lightweight and insulating properties of polyurethane foam, there is a huge scope for this material to be used as layers protecting sensitive structures in aeronautical applications.

1. Rigid crumb-rubber particles in the form of reinforcement in foam enhances the elastic modulus both in elastic and solid regions of compression.
2. Induced porosity by addition of crumb rubber, makes the material brittle to increase the load bearing capacity.
3. Excellent cushioning properties are observed in the reinforced foam material which is also justified by the recovery of composite foam at high strain levels and desirable energy absorption
4. The crumb-rubber particles transfers the axial load along the lateral surface initiating the lateral failure which increases the load bearing capacity of composite to great extent which is essential for it structural applications in sandwich components

5. Smaller particles of rubber blend into the foam matrix without any hindrance giving out smaller cell sizes along with smaller pores compared to the foam with larger particles of crumb-rubber. The pores size and porosity together are to be optimized to give the desired results in for different applications.

6. The degradation of compressive properties in the plateau region is due to the rupture of cell membrane by inclusion of rubber. This effect is not only seen on the cell membranes but also the gasses, which are enclosed inside the closed cell structure, are let out which becomes another reason for the degradation of properties.

7. The degree of openness 'λ' in closed cell structure of foam illustrates the partial deterioration of the closed cell structure which is mainly caused by the poor surface interaction between the rubber particles and the foam matrix accounting to their hydrophobic and hydrophilic natures respectively.

Depending on the requirements of application, suitable size of crumb-rubber particles could be chosen as reinforcement to achieve desirable outputs in its physical properties. With such favorable enhancements in the physical properties of polyurethane foam, there is a huge market for the composite foam in regards to its structural applications, this method provides a large-volume application to recycle the scrap tire rubber and overcome the environmental issues faced by it to a considerable extent.

IV.2 Future Work

There are a few things that are recommended to be addressed further which would have to have a deeper understanding of behavior of reinforced polyurethane foam.

- A suitable surfactant could be used to coat the crumb-rubber particles to enhance interface adhesion. This can overcome the deterioration of plateau stresses, which would give out exceptional compressive properties of the foam.

- A similar behavior of crumb-rubber reinforced polyurethane foam is anticipated in dynamic loading conditions. It would be highly beneficial if one looks into the failure phenomenon at high strain rates and impact loading. Impact testing on a gas-gun setup is a suitable preliminary test to carry out to observe in dynamic impact environment.

- The compressive behavior of foam could be modeled using finite element analysis to see the effect of crumb-rubber reinforcement by varying the process parameters.

- A study could be carried out to determine a method in which the foaming process could be done with controlled uniform porosity and pore sizes. This method could be used to have a deeper understanding on effect of pore size and porosity on the dynamic and static loading conditions.

- Almost all the studies focus on mechanical properties of composite foams. It would be a very useful effort if there were a study conducted on the thermal properties of the reinforced polyurethane foam.

- There is also a scope to use crumb-rubber reinforced polyurethane foam in acoustics. The excellent sound dampening property of rubber may have a heavy influence on the capability of polyurethane foam to be used as sound barrier. Acoustic emission testing and pulse-echo method are two good approaches to look into the acoustic properties of foam material.

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