Waste rubber based composite foams

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Abstract

The common strategies for recycling of waste rubbers have been the conversion of rubbers into thermoplastic elastomers and use in composite foams. The advantages of waste rubber composite foams are that they are lightweight, low cost and provide an ecological and economic solution for the disposal of waste rubbers. Rubber foams possess interesting properties such as thermal and acoustic insulation as well as impact damping. This has led to their use in thermal insulation, energy absorption and non-structural applications. This book chapter aims to document the findings relating to the use of waste rubber eg. waste ground tyre rubber (GTR), waste latex glove and waste ethylene propylene diene monomer (EPDM) in composite foams. The chapter will describe common processing techniques used to manufacture such composite foams and studies dealing with the preparation and characterization of waste rubber composite foams and their properties have also been enumerated. Finally, the applications of the rubber foams in different industrial sectors are also discussed.

1.   Introduction

An estimated 22 million tonnes of rubber are processed per year throughout the world, majority of which goes into production of tyres.[1] At the end of their useful life, massive amounts of the waste rubber are created. Waste rubber maybe be in the form of waste tyre rubber, waste latex gloves, and waste conveyor belts. The increase in stockpiles of waste tyres is a serious problem to the environment and the economy, hence most industrialised countries are in need of innovative solutions to address the issue.[2,3] Tyres being highly engineered materials, can withstand most

chemical and biological attack, making their disposal into landfills highly impractical and in some countries illegal.[4,5] In addition, the accumulation of waste tyres in massive stockpiles is a fire hazard that can result in toxic gases released into the environment.[6] The well-known and adopted waste management strategy for waste materials advocates for prevention and re-use of the waste to precede recycling, energy recovery and disposal.[7] For tyres, re-use is mainly limited to re-treading, which can only be done once, or at most twice for all pneumatic car tyres depending on the strength of the carcass. This means re-using waste tyres is not adequate nor capable of eliminating the waste tyre problem. Alternative approaches often adopted for the valorisation of waste tyres include material recovery (e.g. rubber, carbon and metals) from tyres, through processes such as crumbing and devulcanization, and energy recovery through processes such as pyrolysis.

The use of waste ground tyre rubber (GTR) in composites is well established in the literature and has been used for decades.[8-11] In most of these applications, GTR served mainly as a damping additive and for improved impact in both concrete and in polymer based composites.[12-14] Studies have also reported that incorporation of upto 20% of fine crumb rubber aggregate and upto 15% of coarse GTR or 15% a mixture of fine and coarse GTR particles are suitable for structural applications. Upto to 30% GTR modified concrete was most suitable for non-structural applications.[14, 15] However; other techniques such as foaming have also been widely used to attain similar properties such as sound damping.

Composite foams are lightweight materials formed when blowing agents/air-entrapping agents (AEA) are used to disperse air pockets throughout the composite structure. Blowing agents used in the past were mainly halogenated hydrocarbons based which are harmful to the environment.[16,17] However, greener options have since been adopted to align the process with environmental legislation.[18-21] Foaming has been used in cement applications since ancient history, mainly to impart thermal insulation, shock and sound absorption properties.[22-28] Other advantages of foaming include low production costs which has attracted attention of a number of industries such as construction[26] and light metal application industries.[27] This technique has also been used for polymers such as polystyrene[29,30], polycarbonate[31], nylon 6[32] polyolefins[33,34], polymethylmethacrylate[35,36], polyurethanes[20] and rubber.[37-39]

A well-known disadvantage of foamed composites is reduced mechanical properties as opposed to unfoamed version especially for concrete.[20] As a result, research trends in this field have inclined towards combining both foaming and addition of waste rubber in one composite material to take advantage of the properties each technique offers. Such composites were reported to possess superior thermal and acoustic damping properties as compared to composites where each technique was used independently.[10,40,41]

2.   Processing of rubber foam composites

Foamed rubber products can be produced by using a chemical or physical blowing agent that form bubbles in the sample during the compounding process. Common processing technologies of rubber foams include foam extrusion, foam injection molding, compression molding and microfoaming. Of all these processing technologies, injection molding is highly preferred due to associated reduced weight, improved aesthetics, faster production cycle time, high stiffness to weight ratio and the possibility of manufacturing large complex shaped products with high accuracy. In the physical blowing process, an inert gas is injected into the polymer melt where it dissolves under high pressure. Physical blowing agents are advantageous to chemical blowing agents in terms of economy, ecology, and efficient processing and they include the use of nitrogen, carbon dioxide and water.[42] Another physical process is mechanical foaming which is exclusively used for latex emulsions. In this case, the degree of foaming depends on the design and engineering of suitable mixing equipment.[43] In all processes, varying the amount of blowing agent and additives results in changes in the formation of bubbles and bubble sizes during foaming. This in turn affects the foam density, cell size and cell shape which eventually influences the structural behavior and various properties of the polymer foam product.

In the case of solid rubbers, azodicarbonamide and modified azodicarbonamide compounds[44] are the commonly used chemical blowing agents along with the use of additives such as zinc oxide (ZnO) and stearic acid which are used as cell stabilizers or cell nucleating agents.[45] At high temperatures and presence of water, azodicarbonamide compounds decompose in an exothermic reaction releasing gases such as nitrogen, carbon monoxide and ammonia.[21] In this process, uniform cell structures and surfaces are obtained through even distribution of the blowing agents. Table 1 presents the most common exothermic blowing agents.

Table 1 should be placed here

2.2   Processing of foamed composites with GTR

Compounding of foamed composites containing GTR is achieved through two main techniques, namely mechanical stirring and through mechanical milling methods, where the latter includes pan-milling and two-roll mill mixing processes. Mechanical stirring processes are usually used for compounding of foamed polyurethane (PU)/GTR and foamed concrete/GTR composites. These processes entail either mixing the dehydrated polyol, with GTR for few minutes at speed ranges around 1200-2000 rpm. Subsequently, other ingredients like the blowing agent (water or pentane), the catalyst or mixture of, and surfactant are added with further stirring for an additional minute using an overhead stirrer fitted with special dispersion discs for a specified amount of time. This solution mixture, referred to as A, is then mixed with polyisocyanide (B) and placed in the mould where foaming is allowed to take place. The foam is finally cured at high temperature for prescribed amount of time.[46,47] In other cases, the foam is prepared separately and then mixed with the wet concrete mixture containing GTR, placed in the moulds and then cured.[25, 27] Alternatively, GTR is mixed with the foam prior to moulding and curing [48] or mixed with B instead of A as previously highlighted.[49]

Mechanical milling methods are employed for solid state mixing of rubber or thermoplastic matrices with GTR followed by foaming. These methods entail milling the matrix with GTR in a pan milling setup then the powder from the pan-milling process is melt mixed with the blowing agent, crosslinking agent, and blowing co-agent. This melt is then placed in a mould and press cured at a high temperature.[50, 51] A typical formulation for a foamed linear low density polyethylene (LDPE)/GTR composite is shown in Table 2.

Table 2 should be placed here

Zhu *et al* prepared foamed linear low density polyethylene (LDPE)/GTR composites by co-milling GTR powder with LDPE pellets in the pan-mill at 30 rpms for 20 cycles at ambient temperature. The pan-mill was equipped with a jack of circulating water to remove excess heat generated by the milling process. The product was then melt mixed for 4 min in a Brabender Plasti-Corder at 130 °C, at the same rotation speed while adding the blowing agent, crosslinking agent and blowing

co-agent for an additional 6 minutes. The mixture was then placed in a mould and pressed at 180 °C in a hydraulic press at 9 MPa for 15 min. Foaming occurred during rapid depressurization, and the obtained foams were allowed to cool down at room temperature.[51] In another study, the mechanochemically pan-milled GTR was blended with ethylene propylene diene monomer (EPDM) on a two-roll mixing mill (diameter, 150 mm; working distance, 320 mm; speed of the slow roll, 15 rpm; friction ratio, 1:1.4) at about 50°C. Initially, the mixture of powdered GTR and virgin EPDM were masticated and then mixed with other compounding ingredients for 10 minutes. The blends were then placed in a mould followed by pressing in a hydraulic press at 160°C and 8 MPa for 15 min. Post pressurization, the foam expanded almost immediately and the foam was allowed some time to cool down to room temperature.[41]

3.   Properties of foamed/GTR composites

3.1 Morphological properties

The microcellular and cellular structure of the foamed/GTR composites are usually studied via robust surface techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM) and atomic force microscopy (AFM). Studies have found that the microstructure and morphology of foamed composites with GTR is controlled by a number of factors such as the type and concentration of AEA agent used[10, 21] concentration[52] and particle size of the GTR in the composite and finally by the processing conditions.[21, 31, 53]

It is well known that the three-dimensional cross-linked structure of GTR results in poor interaction when added to polymer matrices.[31,47,54] As such, studies have been conducted to modifying the structure of GTR by thermo-mechanical[55,56], and mechano-chemical[46,48,57] devulcanization methods. Solid-state thermo-mechanical milling with a pan-mill reactor is widely used to break the cross-linked structure of GTR and achieve partial devulcanization because of its high capacity, relatively low cost, energy efficiency, and the fact that chemicals need not be used.[48] Pan-mill has a pair of three-dimensional scissors that applies strong shear forces to the material during milling. In addition, the technique also has multi-functions such as pulverization, dispersion, mixing as well as activation.[58] Generally, for polymer composites, the particle size of filler plays a significant role in the final properties of the material. During pan-milling process, the particle size of GTR is controlled by varying the number of milling cycles. Zhang et al investigated

the particle size of GTR before pan milling, after 5 cycles and after 20 cycles of milling. Before milling, large particle sizes with the average size of 300 µm and smooth surface were observed, while; after milling, particle sizes decreased with the increase in the number of milling cycles. In addition, SEM images reported after 5 cycles of milling, showed irregular particles with rough surface, while fluffy and ultrafine powder with particle size of~about 35 µm were observed after 20 cycles of milling.[57]

The foamability of polymer/filler composites and their resultant properties depend on factors such as foaming pressure, foaming elasticity and adhesion between the polymer and the filler.[57,59] For example, in the case of foamed ethylene-propylene diene monomer (EPDM)/GTR composites, the presence of untreated GTR decreased the foaming pressure due to poor adhesion between the two components. This was attributed to the lack of compatibility that enhanced the formation of defects during foaming, thus allowing the gas to escape and inhibit bubbles from growing. On the other hand, increased foaming pressure was observed with devulcanized GTR and this was ascribed to the improved interfacial adhesion between the polymer and GTR.[41,57]

Polyurethane (PU) foams can form either open-cell or closed-cell structures with different properties such as density. SEM images of open and closed-cell structures are shown in Figures 1 and 2 respectively. Normally a closed-cell structure is formed by using low amounts of physical blowing agent while an open-cell structure requires high amount of blowing agent, especially water.[60, 61] The disruption of cell structures was observed in the presence of untreated GTR particles in both closed and open cells. This resulted in less regular structures with various cell sizes as can be seen in Figures 1 (b) and 2(b). This behavior was ascribed to poor interfacial interaction between the PU and the large GTR particle sizes, which readily formed agglomerates and disrupted foamability. Nonetheless, foamed PU/GTR composites prepared with devulcanized GTR [shown in Figure 1 (c) and 2(c)] showed more well-defined cells.[46] Similar observations were reported in the case of foamed low density polyethylene (LDPE)/GTR composites.[50,52] The influence of GTR particle size on the cell morphology of foamed PU/GTR composites was also investigated and found to be more uniform with the smallest GTR particle size.[46]

Figure 1 should be placed here

Figure 2 should be placed here

In the case of polypropylene (PP)/WGTR foamed composites, the average cell size decreases with the increase in WGTR loading compared to the pristine PP foam[62-64] while the cell density and relative density increases. The decreases in cell size was mainly attributed to the high viscosity of the composite which inhibited cell nucleation and growth. Uniform cell distribution was observed at 20 - 25 wt.% WGTR loading, however, at 40 and 50 wt.% WGTR loading, the cell distribution was non-uniform.[63, 64] This was brought by the weak surface adhesion between the PP and WGTR, aiding channel formation through which CO_2 escaped from the composite. Compatibilizers such as PP-g-MA[65] and SEBS-g-MA[66] have been introduced in PP/WGTR foamed composites. The addition of SEBS-g-MA at 5 and 20 wt. % loading further decreased the cell size of PP/WGTR foamed composites compared to the composites without the compatibilizer. Thus, SEBS-g-MA improved the interfacial interaction between PP and WGTR and hence preventing channel formation.

In cement, the morphological changes in the rubberised composites showed two types of porous structures. Firstly, the porosity typical of the cement matrix and secondly, the porosity induced by the presence of GTR in the matrix.[67] In a similar notion, it was shown that in foamed GTR cement composites, the higher GTR content promoted air entrapment in the composites even at higher AEA concentration. Thus, GTR helped stabilize air bubbles in the composites regardless of the aeration level.[10] In addition, the SEM images revealed that around the GTR aggregates, hydration products were of different nature from the ones distributed elsewhere in the composite matrix. It was therefore suggested that calcium aluminium sulfate hydration product tended to migrate to the places of low pressure, which are located near cavities and large pores.[10]

3.2 Physical properties

The physical properties such as rebound resilience of polymer foams are important for applications such as sealing and packaging. The increase in rebound resilience for foamed composites of EPDM/ GTR[41] and foamed LDPE/GTR[50] were reported upon the addition of devulcanized GTR,

this was attributed to the stress transfer from the EDPM to GTR. As GTR is elastic, it enhanced rebound resilience. Similar observations were reported in the case of foamed LDPE/GTR composites. In the case of foamed EPDM/GTR composites with untreated GTR, a decrease in rebound resilience was observed and ascribed to the lack of stress transfer due to poor interfacial adhesion between untreated GTR and EPDM foam. Furthermore, the presence GTR aggregates served as defect points that diminish rebound resilience properties of the composites.

The incorporation of GTR into polymer foams influenced the density of the foamed polymer composites.[48] Generally, the increase in density of foamed PU/GTR composites was observed with the addition of both untreated[68,69] and devulcanized GTR.[58,55] This was ascribed to high density of GTR compared to that of PU foam. However, foamed PU/GTR composites containing devulcanized GTR particles showed even higher density increase, due to the improved interfacial interaction between the components, which improved foamability and formed a well-defined cell structure.

The process of foaming and partially replacing sand with GTR in cement and concrete applications has been found to result in reduced density of composites. This has been ascribed to the low density of GTR (1.1 g/cm^3) as opposed to that of sand (2.7 g/cm^3).[9] On the other hand, air pockets in the matrix of the composite also contributed to the lightweight property of the said composites. These composites were also reported to have decreased viscosities and as such were easily workable as compared to the neat composites. Furthermore, the reduced workability of the concrete/GTR foams was observed by a reduction in the compaction factor[10,70] or slump height of the mortars.[71,72] However, these composites had significantly higher water absorption due to high porosity.[10,73]

3.3   Mechanical properties

The weak interfacial linkage between the GTR and concrete has been reported to result in up to 90% reduction in the mechanical properties of the foamed cement composites such as mechanical, flexural, and compression strength. Compressibility tests are usually studied according to ASTM C39(74) standards where the maximum load carried and compressive strength by the specimen is recorded and calculated using the formula similar to the one shown in Equation 1.

$$f'c = \frac{P}{A} \qquad\qquad (1)$$

where $f'c$ is the compressive strength in MPa, P is the maximum load carried by the specimen, N, A (width × thickness) is surface area of specimen carrying the load in mm². Compressibility of foamed cement composites was found to decrease as a function of increasing GTR content in the composites. However, it increased with aging the composite for 7, 21 and 28 days.[10,70] Similar results were previously reported for cement/GTR composites where the detrimental decline of mechanical properties was assigned to the air void formation which was promoted by incorporation of GTR.[15] Thus, the air pockets in composites exacerbate the weakened interfacial bond between the two matrices. The same reasoning was acknowledged for the decline in flexural and tensile strength.

It has been established that the shape of cells and density of the foam have a significant influence on the mechanical properties. In several studies, it was found that the compression strength of foamed PU increases with the addition of both untreated[68, 69, 75] and devulcanized GTR.[48,55] However, the addition of untreated GTR decreased the compression strength of foamed PU/GTR composite at higher loading, and the maximum strength was observed at 6 %[75] and 1.4 %[70] loadings. The decrease in composites strength was associated with the presence of agglomerates and their tendency to tear the walls of the cell structure. In the case of devulcanized GTR, an increase in compression strength of foamed PU/GTR composites was reported with the increase in GTR loading. This behavior was related to the improved interaction between PU foam and GRT.[48,55]

The particle size of a filler has a significant influence on the mechanical properties of polymer composites; as such, the influence of GTR particle size on the mechanical properties of polymer foams had been reported.[46,52,57] Without milling, the tensile strength and elongation at break of foamed EPDM/GTR composites were reported as 0.27 MPa and 290.7 % respectively, and after 20 cycles of milling, tensile strength increased to 0.72 MPa and elongation at break increased to 748.2 %. The enhanced compatibility between the devulcanized GTR and EPDM foam was attributed to large surface area and activated GTR surface enhanced stress transfer.[57] In another study, it was reported that the addition of untreated GTR also increased the tensile strength of foamed PU/GTR composites; however, the elongation at break only increased at low GTR loading

and decreased significantly as the loading increased.[68] It was observed that the addition of GTR increased the thickness of the cell wall from 91.95 to 102.15 µm, which ultimately increased the stiffness of the foamed composites and decreased the ability of the foamed composites to elongate.[68]

3.4   Damping properties

Damping is described as a measure of energy loss in the form of friction as the material is perturbed by vibration. This property is measured via ultrasonic pulse velocity measurements based on the model proposed by Albano *et al.*[71] or through vibration measurements. In cement, the ultrasonic pulse velocity and resistance indicated an increase in damping as a function of increase in AEA content and the increase in % GTR in the composites. The vibration damping properties on the other hand were found to increase linearly with increasing GTR and AEA contents in the composites.[10] The increase in damping was attributed to the increase in the number of discontinuities in the materials. Thus, vibration damping were found to be higher in foamed GTR composites when compared to standard cement mortar. Additionally, an increase of between 2-4 times the damping coefficient of the reference mortar were observed for rubberised foamed composites. These can be observed on the time histories obtained from the fundamental transverse frequency test for mortars containing 40% GTR as a function of increasing AEA content (Figure 3).[10] These results corroborated the findings of Najim and Hall[76] on rubberized concrete; however, in foamed GTR composites the damping was found to be much more pronounced.

Foams have been used in thermal insulation and acoustic absorption applications; however, the ability of the material to be used as an absorbent depends on its sound absorption efficiency.[77,78] As such, materials that are able to absorb sound waves in wide frequency regions are desired. Gayathri *et al.*[49] studied the sound absorption efficiency of foamed composites over the frequency range of 100 to 200 Hz while Zhang *et al.*[46] focused on the middle frequency range of 500-1500 Hz. In both studies it was found that sound absorption efficiency of PU foam increased upon the addition of GTR. Nonetheless, foamed PU/GTR composites prepared with devulcanized GTR showed higher sound absorption properties compared to the case of untreated GTR. In the presence of devulcanized GRT, sound absorption coefficient increased from 0.15 to 0.35 at 30 wt.% loading and this phenomenon was attributed to the increase in viscoelastic properties of GTR, as the

devulcanization of GTR facilitated the movement of rubber chains. Viscoelastic polymer foams are reported to have good performance in the acoustic absorption due to their ability to weaken certain vibrations and absorb sound energy.[79]

Figure 3 should be placed here

3.5   Thermal properties

Thermal properties of composites are usually studied by employing differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), dynamic mechanical analysis (DMA) and thermal conductivity measurements. However the thermal behaviour of foamed polymer composites has been limited.[55,68] For instance, thermal stability of foamed PU/GTR composites prepared with untreated (R) and devulcanized (D) GTR slightly increased when compared to pristine PU foam (Figure 4), and this was ascribed to the presence of carbon black in GTR.[55,68] Also, the addition of pan-milled or untreated GTR was found to increase the glass transition temperature of PU foams as can be seen in Figure 5. This increase in glass transition temperature was attributed to the decreased mobility of the polymer chains which resulted in the stiffening of the PU foams.[55]

Figure 4 should be placed here

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Thermal conductivity studies of foamed concrete showed a significant decrease in thermal conductivity with the incorporation of GTR (Figure 6). These observations were ascribed to the lower thermal conductivity of GTR relative to that of sand particles as well as the facilitation of air absorption by the GTR.[80]

Figure 6 should be placed here

4. Studies of waste rubber foams

The microstructure of foamed reclaimed natural rubber from waste latex gloves (r-NRG) was studied and the effect of varying the sodium bicarbonate (SBC) concentration on the compressive and water contact behaviour of foams was studied. The blowing agent concentration was varied from 4, 6, 8, 10 and 12 phr and then melt mixed at 60 °C with r-NRG in an internal mixer. Higher concentrations of blowing agent subsequently generated more gaseous media and hence reduced relative foam density and cell structures with large pore sizes were formed. This phenomenon was described by Zakaria[81] that high blowing agent concentrations shortens the growth time of the foam. Thus, minimum gas bubbles are escaping through the foam surface allowing more foam expansion and consequently resulting in reduction of the foam relative density. Additionally, due to open cell structure, more water absorption was realised while reduction in compressive strength was observed upon increasing the blowing agent concentration in the foams. In this study, a blowing agent at concentration of 4 phr was found to have the highest compressive strength, highest relative density and lowest water absorption.[82] Chin *et al* studied the foamed blends of reclaimed NR from latex gloves (r-NRG) with Malaysian Natural Rubber (SMR 20). The blends were prepared by varying the r-NRG content from 20%-95% using two roll mill compounding with ADC as a blowing agent. The cure characteristics and scotch time of the blends decreased with increase of r-NRG in the blends due to the semi cross-linked nature of r-NRG. In addition, a detrimental decline in the tensile properties and elongation at break was observed with increase of r-NRG in the blends. This indicated poor compatibility between the SMR 20 and r-NRG phases.[83] Blends of epoxidised natural rubber (*ENR)* and reclaimed rubber glove blends were also prepared

using SBC as a blowing agent through melt compounding. It was shown in this study that the ENR/RR with the blend ratio of 90/10 yielded the rubber foam with the highest relative density of 0.85, the lowest water absorption rate of 0.1 g/hrs and an improved energy absorption behaviour amongst other properties.[84]

Composites of foamed LDPE/waste EPDM (w-EPDM) were prepared by mixing LDPE pellets and waste EPDM powder (0, 30 and 40 %) by twin-screw extruder.[85] The influence of foaming conditions such as pressure, temperature and the amount of w-EPDM on the foamed microcellular structure and mechanical properties were reported. The addition of w-EPDM decreased the microcellular size of foam LDPE, and at 30 % w-EPDM loading the cell pattern and distribution was mostly uniform. However, at 40 % the microcellular structure was uneven due to presence of w-EPDM agglomerates. The same behaviour was reported in the case of foamed LDPE/waste GTR composites (50). The most uniform microcell patterns with smaller dimensions were observed at optimum conditions of 30 % w-EPDM, 100 °C and 200 bar. The density and the compression strength of the composites increased with an increase in w-EDPM loading. On the other hand, the tensile strength and elongation at break of foamed LDPE composites decreased with the increase in w-EPDM loading. This was attributed to the lack of compatibility of highly cross-linked w-EPDM and LDPE which resulted in inferior mechanical properties. However, the tensile strength of the foamed composites was improved by incorporating dicumyl peroxide (DCP) at 1.50 phr loading. The presence of DCP induced crosslinking resulted in finer and more uniformly arranged microcells, ultimately, increasing tensile strength and compression strength even more. Furthermore, the increase in crystallinity, and number of crosslinking sites between w-EPDM and LDPE decreased the elongation at break.[85]

Various amounts of recycled EPDM (r-EDPM) (0, 35, 50 and 65 wt.%) was blended with virgin PP by twin-screw extrusion.[86] The samples were pelletized and foamed by injection moulding, using ACD as a blowing agent. The tensile strength, tensile modulus, flexural modulus and hardness of foamed PP decreased with the increase in r-EPDM loading. This was due to the elastic nature of r-EPDM which lowered the stiffness of the composites, as a result, elongation at break increased. The toughness of the composites also increased with r-EPDM loading; hence, the soft EDPM absorbed energy through elastic deformation.

5. Applications of waste rubber foam composites

5.1 Non-structural applications

Foamed concrete/GTR composites lack mechanical strength and as such have limited use in structural applications. Eiras *et al* found that the mechanical strength of these composites ranged between 1MPa and 10MPa making them suitable for non-structural applications. The authors also found that composites containing 40-60% GTR at AEA concentrations ranging between (0.125-0.500%) met the requirements [10] for application in masonry units. Another application which has been patented is in the production of composite boards for re-roofing a roof deck using foamed polyurethane filled with GTR.[87]

5.2 Lightweight applications

Flexible foamed polyurethane/GTR composites have been investigated for use as floating trays and compression-absorbing buoys application. For these applications, it is required that the apparent density of the composite be lower than that of water to achieve the floatability in water as well as good compressive stress absorption.[47] For the floating trays, the foam with bulk apparent density of 89 kg m^3 was reported to be ideal and was composed of 150% of rubber, 4% of water, 0.6% of Tegostab B8225, 0.086% of DABCO (1,4-diazabicyclo[2,2,2] octane, 33LV, Air products) catalyst, 0.25% of DBTL (dibutyltin dilaurate, T12, Air Products) catalyst, and an isocyanate index of 105%. From the compression tests, the foam capable of absorbing the highest compressive stress was composed of 200% of rubber, 3% of water, 0.6% of Tegostab B8225, 0.086% of DABCO catalyst, 0.25% of DBTL catalyst, an isocyanate index of 105%, with an apparent density of 121 kg m^3. This foam absorbed a compressive stress of 0.07 MPa when subjected to deformation of up to 60%.[47]

5.3 Sound and vibration absorption

Foamed concrete/GTR and foamed polyurethane/GTR composites have been shown to display excellent acoustic absorption and as such they find applications in sound proofing rooms.[37] Mechano-chemical treated foamed PU/GTR composites were also reported to have better sound absorption especially in the frequency region near 1000Hz.[46)]

5.4   Insulation and impact isolation

The low thermal conductivity of the foamed concrete/GTR composites presents them as ideal for thermal energy saving in buildings. Thus, these materials can be used as a base for roofing to lower the heat transfer in and out of the building.[37] These materials also possess high damping properties suitable for use in impact isolation.

5.5   Drainage systems

As foamed composites have high porosity it has been suggested as ideal for use in drainage systems to capture storm water and in pavements to replenish underground water.[37,88]

6.   Concluding remarks

This chapter gives an overview of waste rubber composite foams, its processing techniques and applications in various sectors. The use of waste rubber from different sources - waste ground tyre rubber (GTR), waste latex glove and waste ethylene propylene diene monomer (EPDM) - in composite foams have been discussed. As waste rubber foams are lightweight and have insulating properties, they are commonly used for thermal insulation, energy absorption and non-structural applications. Future applications will involve in improving the strength properties of the rubber based foams.

Table 1: Common exothermic blowing agents [Adapted from[43]]

Blowing agent	Decomposition temperature [°C]	Gas yield in ml/g, air, blowing agents	Comments
Azodicarbonamide (AZO ADCA)	205-215	270 N_2, CO, NH_3, CO_2	Used for elastomers and plastics
OXYbis (benzenesulphonyl hydrzide)	155-165	160 N_2, H_2O	Used for elastomers and plastics
p-Toluenesulphonyl hydrazide	120-130	120 N_2, H_2O	
Toluenesulphonyl semicarbazide	230-250	140 N_2, H_2O	Used for high temperature thermoplastics
5-Phenyltetrazole	215-225	220 N_2	Used for high temperature thermoplastics

Table 2: Compound recipe used for foaming LDPE/GTR composites.ᶻ Redrawn with permission from the Journal of Vinyl & Additive technology[50]

Ingredients (phr)	Formulation code										
	1	2	3	4	5	6	7	8	9	10	11
LDPE	100	100	100	100	100	100	100	100	100	100	100
Milled GTR	-	10	20	30	40	50	-	-	-	-	-
Raw GTR	-	-	-	-	-	-	10	20	30	40	50
AC	5	5	5	5	5	5	5	5	5	5	5
DCP	2	2	2	2	2	2	2	2	2	2	2
Zinc oxide	4	4	4	4	4	4	4	4	4	4	4
Stearic acid	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

[z] The tabulated amounts are parts by weight
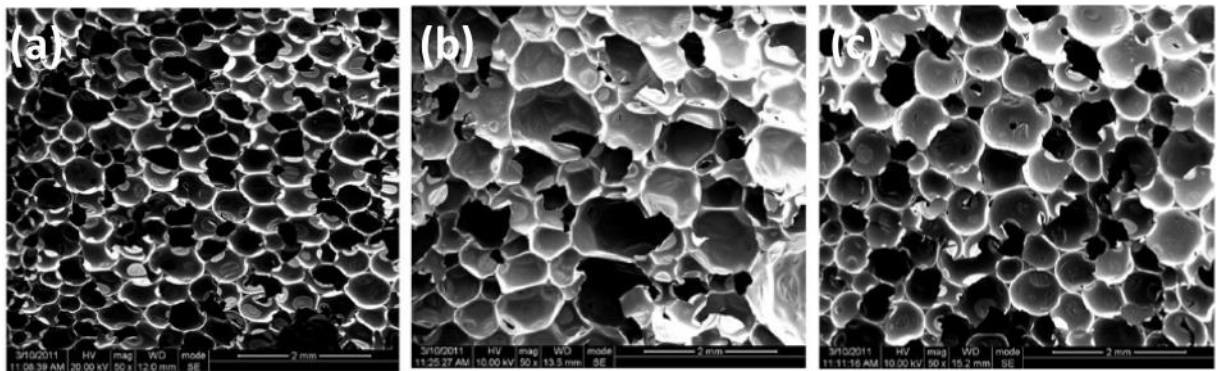
Figure 1: SEM images showing open cell of pristine PU form (a) and PU/GTR foamed composites (b) 10% untreated; (c) 10% devulcanized GTR. Reproduced with permission from Journal of Applied Polymer Science[46]
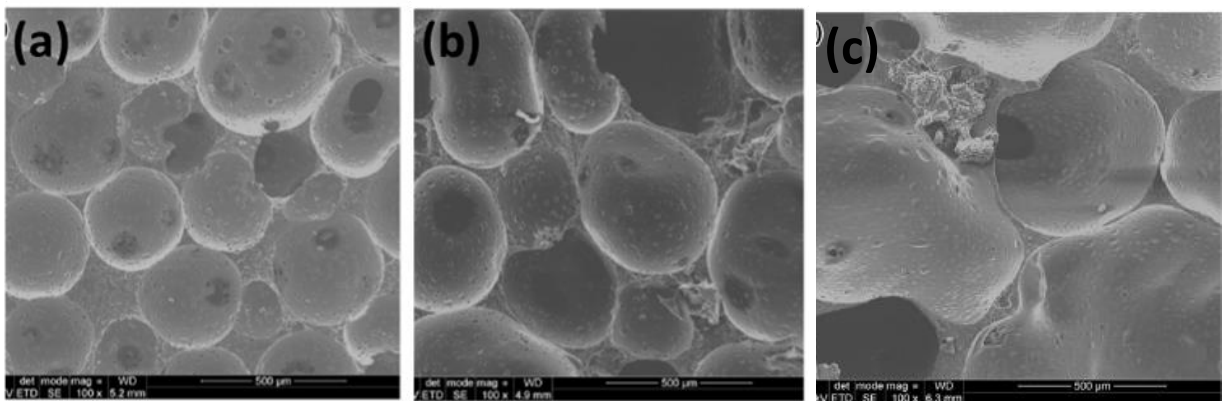
Figure 2: SEM images showing closed cell of pristine PU foam (a) and PU/GTR foamed composites with (b) 10% untreated; (c) 10% devulcanized GTR. Reproduced with permission from Iranian Polymer Journal[55]
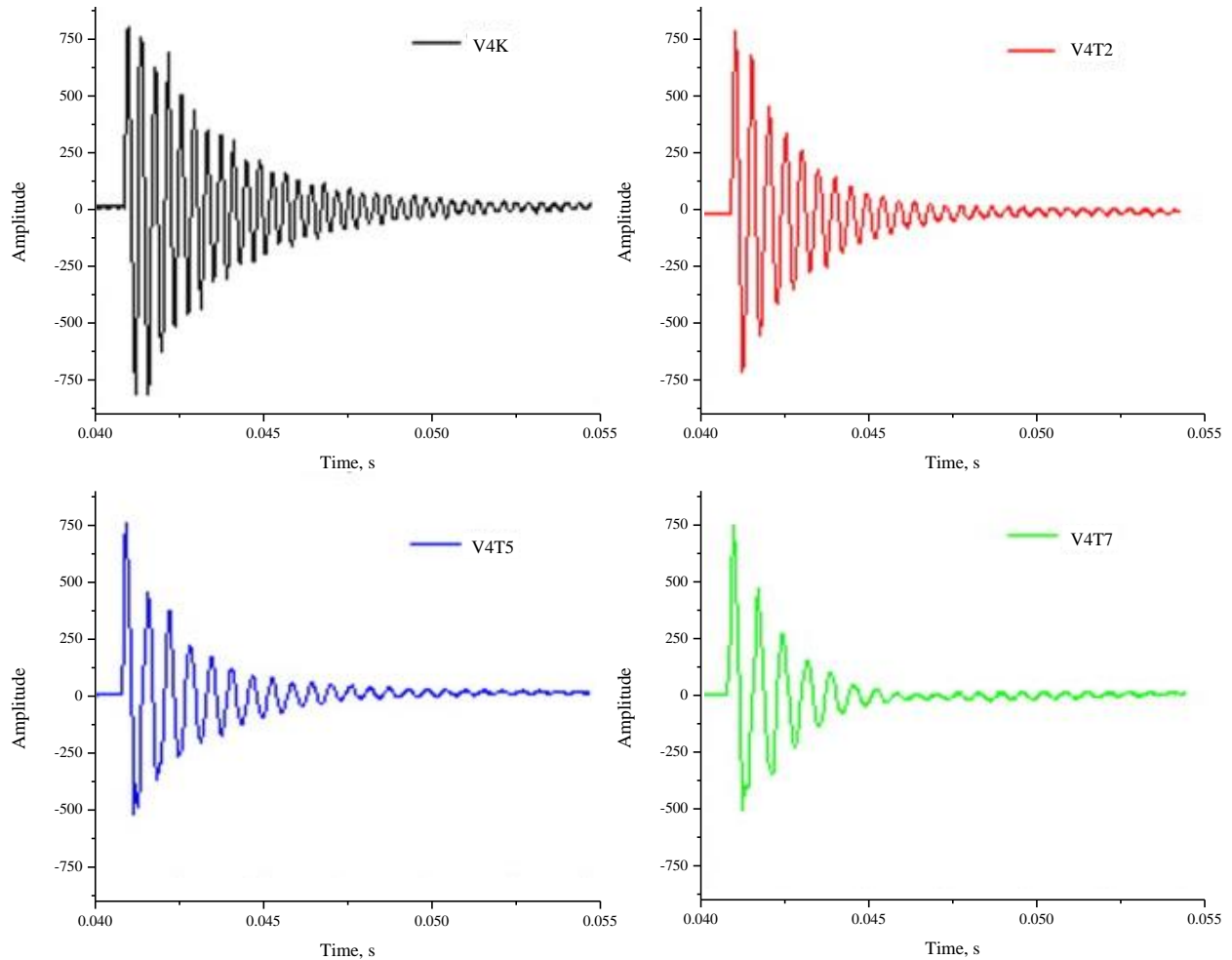
Figure 3: Typical signal responses in time domain for mortars V4K (40% GTR and 0% AEA), V4T2 (40 % GTR and 0.250 % AEA), V4T5 (40 % GTR and 0.0500 % AEA) and V4T7(40 % GTR and 0.0750% AEA) at 25 kHz. Redrawn with permission from Materials and Design.[10]
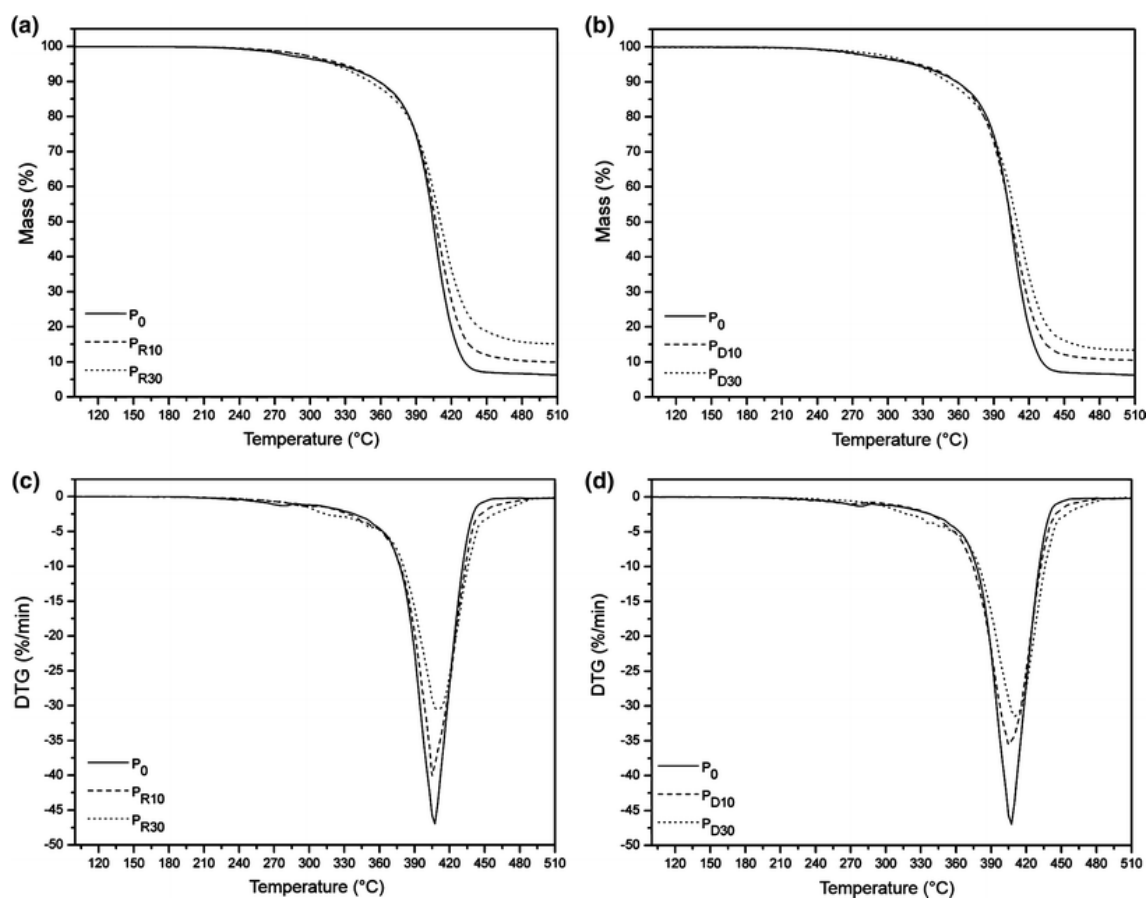
Figure 4: Mass loss and differential thermogravimetric curves as a function of temperature for polyurethane foams filled with ground tire rubber. Reproduced with permission from Iranian Polymer Journal.[55]
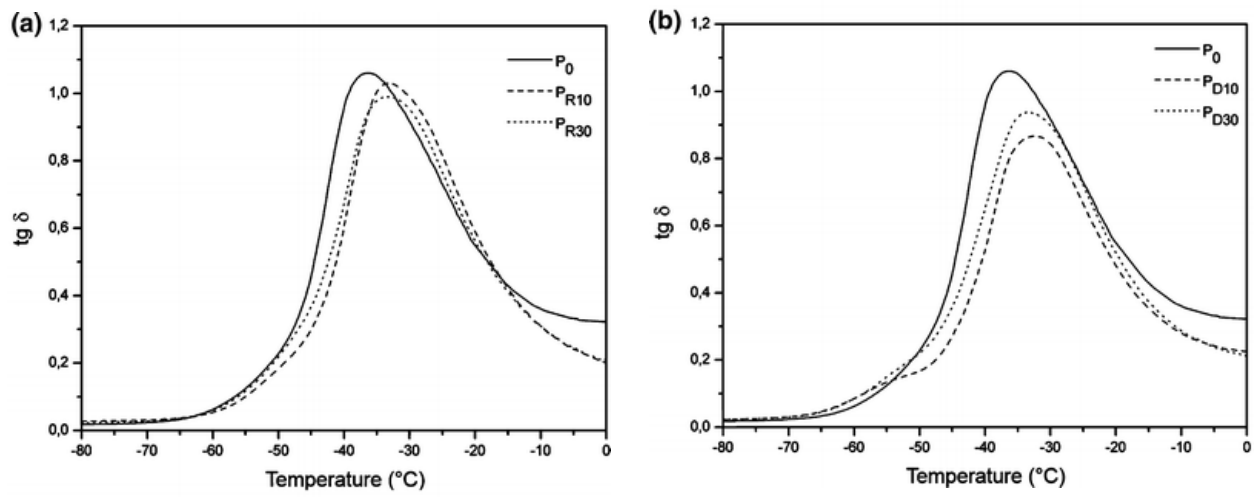
Figure 5: Loss tangent curves of flexible PU/GTR with (a) untreated (R) and (b) treated (D) GTR. Reproduced with permission from Iranian Polymer Journal.[55]
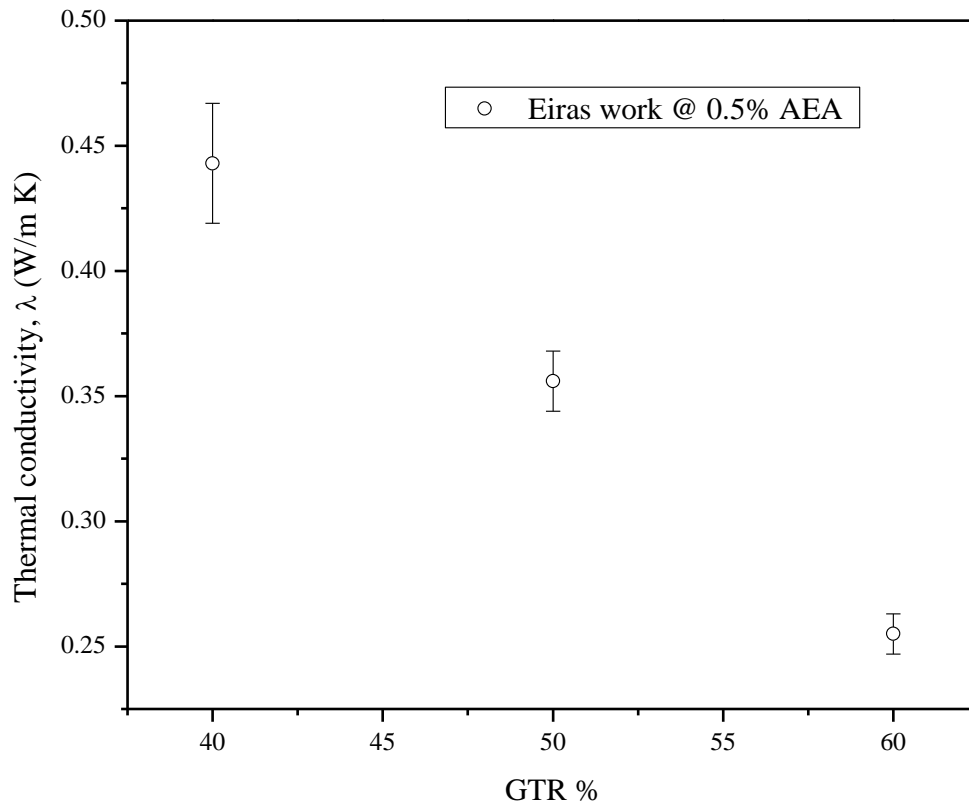
Figure 6: Thermal conductivity with GTR content. Redrawn with permission from Materials and Design.[10]

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