

THERMOPLASTIC ELASTOMERIC (TPE) MATERIALS AND THEIR USE IN OUTDOOR ELECTRICAL INSULATION

Salman Amin¹ and Muhammad Amin²

¹University of Engineering & Technology, Taxila, Pakistan

²CIIT, Wah, Taxila, Pakistan

Received: March 03, 2011

Abstract. The use of polymeric materials has become very popular since last thirty years in many applications. The materials in this category can be broadly divided into two categories i.e. thermo set and thermoplastics. With increasing the world's concern about recyclability and environment protection issues thermoplastics have gained more attraction over the thermo set. Thermoplastic elastomers are novel constructional polymers, which are physically cross linked materials made up of a thermoplastic and an elastomer. TPE have been the interest of numerous researchers world wide since last three decades. Thermoplastic elastomers have a very wide-spread application domain. This paper reviews the history, physical, chemical, mechanical, electrical characteristics, advantages and uses of these materials along with a particular focus on their use as outdoor electrical insulation. Results of using different kinds of thermoplastic materials as outdoor insulation in different environments of world are also reviewed. This review expected to be useful for researchers working on thermoplastic elastomers in general and particularly for those working in filed of electrical insulation.

1. INTRODUCTION

Polymeric materials can be classified as Thermosets and Thermoplastics. Before looking onto thermoplastic elastomeric materials it is necessary to understand the thermosets and thermoplastics first.

1.1. Thermoset

Thermoset is a polymer that is cured by heat or chemical reaction and becomes infusible and insoluble material. Thermoset polymers have a permanent irreversible polymerization. Thermoset polymers possess a cross linked molecular structure and are formed in two stage polymerization. The first stage is formation of a polymer with linear chains. The second stage of polymerization results in final cross linked structure. The end product can be made rigid or flexible. The Polymerization is controlled to result in heavily cross linked short chains for hard product and lightly cross linked long chains for soft and flexible products [1].

1.2. Thermoplastic

Thermoplastic is a plastic that softens upon heating and hardens when cooled. Thermoplastics are made up of linear molecular chains and can be shaped by flow into articles by molding or extrusion without need of any chemical processing before molding. The most useful physical property of a thermoplastic is its glass transition temperature at which it begins to soften. Glass transition temperatures of different thermoplastics can be seen in [1]. There are three types of thermoplastics crystalline, amorphous and semi-crystalline [2,3].

1.2.1. Crystalline thermoplastics

They are usually translucent and their molecular chains have a regular arrangement. They have high and sharp melting temperatures. Compared to amorphous thermoplastics they have more mechanical impact resistance. Their load bearing capacity can be enhanced considerable with addition of fibers.

Corresponding author: Salman Amin, e-mail: mani_6pk@yahoo.com

Upon curing they shrink more as compared to amorphous thermoplastics. Examples are polypropylene (PP), polyethylene (PE) [1].

1.2.2. Amorphous thermoplastics

They are usually transparent and have diffused melting point. The molecules are arranged randomly and that's why do not flow as easily into mold compared to crystalline polymers. Upon curing they shrink less as compared to crystalline thermoplastics [3,4]. Examples are polycarbonate (PC), polymethylmethacrylate (PMMA), polystyrene (PS), polyphenylene oxide (PPO), acrylonitrile butadiene styrene (ABS) [1].

1.2.3. Semi-crystalline thermoplastics

Semi-crystalline polymers plastics have combined properties of crystalline polymers and amorphous polymers. Examples are polyester Polybutylene terephthalate (PBT) and Polyamide (Nylon 6, Nylon 66).

1.3. Thermoplastic elastomers

Thermoplastic elastomers are one of the most versatile plastics in today's market. Thermoplastic elastomeric materials are a physical mixture of polymers (a plastic and a rubber). They exhibit the properties of both plastics and rubbers. The unique properties of both materials exist because TPE materials are created only by physical mixing of a thermoplastic and elastomer and no chemical or covalent bonding exists between the two. This behavior has opened a new field of polymer science. Thermoplastic elastomers have become a significant part of the polymer industry. They are used in many applications like adhesives, footwear, medical devices, automobile parts house hold goods, etc.

TPE were introduced commercially in 1960. Since then they have grown very rapidly and world's annual consumption of TPE materials is growing at a rate of 11% per year.

The first generation TPE were made using Ethylene Propylene Diene Monomer (EPDM) and polypropylene (PP) [5-7]. Later on Ethylene Propylene Rubber (EPR) replaced EPDM due to its low cost. Since these materials were mixed only physically and no cross linking existed there so hard thermoplastic cannot be produced using them. Another draw back is that both EPR and EPDM have low tensile strength and less resistance to organic solvents especially oil or grease.

In order to resolve the problem of low thermal and chemical stability of thermoplastic elastomers, dynamic vulcanization techniques were used in late 1970's to mix the soft elastomer into hard thermoplastic. In dynamic vulcanization the thermoplastic and elastomers are both cross-linked and physically mixed together. This gave rise to a second generation of thermoplastic elastomers which had better tensile strength and oil resistance as compared to those formed by physical mixing only [8].

In 90's third generation thermoplastic elastomers were introduced which were made by same dynamic vulcanization process but using natural and butyl rubbers in place of EPR and EPDM. Natural and butyl rubbers have the advantages like low cost, very good over molding properties, reusable and very easily recyclable scrap [9,10]. Butyl rubber based thermoplastic elastomers have excellent adhesion with other thermoplastics hence it is still used to date for many over molding applications [11]. A list of common thermoplastic elastomers used in modern world is given in Table 1.

1.4. Uses of thermoplastic elastomeric materials

There are countless applications where thermoplastic elastomeric materials are used. Major applications include replacements for artificial and natural rubber, foam making, soft and hard thermal insulation sheets, door and window handles for household and automobiles, car dash boards, car dash boards knobs, bumpers, CV joint boots, suspension bushings, window & door trim, seals, floor Mats, gear Knobs, flexible grip, mirror case, automotive gaskets, colored interior components and many other body parts, house hold plastic furniture, coat hangers, lacquer, varnishes, paints, latex, adhesives, weather stripping applications, shoe soles, sports equipment, electrical accessories, expansion joints, water sealing rubbers, pipes, belts, ring gaskets, electronics appliance casings, handles for knives, scissors, and other non slip grip equipment, food packaging cling films, syringes, nebulizers, catheters, components for gas masks, flexible tubing for various applications, toys, plastic eye wear, asphalt modification, personnel hygiene equipment like razors, shavers, safety equipment, casings for lead acid batteries, document lamination films, packing foam, blister packs of medicines, workshop helmets, lenses for cameras, projectors and copiers, soft contact lenses for eyesight, vials, monitors, medical devices like IV sets, blood bags seal, urine bags seal, and latest in replacement of metals in many

Table 1. Common thermoplastic elastomeric materials.

	Amorphous		Crystalline	
Low cost	PVC	Poly Vinyl Chloride	HDPE	Poly Ethylene High Density
	SAN	Styrene Acrylo Nitrile	LDPE	Poly Ethylene Low Density
	PS	Poly Styrene	PP	Poly Propylene
	PMMA	Poly Methyl Metha Crylate		
	ABS	Acrylonitrile Butadiene Styrene		
	SMA	Styrene Maleic Anhydride		
Medium Cost	PPO	Poly Phenlene Oxide	UHMWPE	Ultra High Molecular Weight Poly Ethylene
	PC	Poly Carbonate		
	PPC	Poly Phthalate Carbonate	POM	Poly Oxy Methylene
			PA	Poly Amide
	PTFE	Poly Tetra Fluoro Ethylene(Teflon)	PBT PET	Poly Butylene Terephthalate Poly Ethylene Terephthalate
High Cost	PAR	Poly Arylate	PA-4,6	Poly Amide-4,6
	PES	Poly Ether Sulfone	PPA	Poly Phthal Amide
	PEI	Poly Ether Imide	PPS	Poly Phenylene Sulfide
	PPSU	Poly Phenyl Sulfone	LCP	Liquid Crystal Polymers
	TPI	Thermoplastic Polyimide	PVDF	Poly Vinyl Diene Fluoride
			FP	Fluoro Polymers
	PAI	Poly Amide Imide	PEEK	Poly Ether Ether Ketone

applications like aircraft, space ships where they provide strength like metals but in less weight, indoor/outdoor electrical cable insulation, optical fiber sheaths, welding cable insulation, high voltage automobile cables insulation, coil forms and bobbins for transformers, parts for motors, aerospace electrical parts, flame retardant insulations for cables and housing for composite high voltage outdoor insulators, substation and transformer bushings, over molded products and encapsulation of coils and microelectronic chips etc.[1,2,4-6,12-14].

1.4.1. Over molding [15]

Over molding means outside covering of any material with any other material to change its appearance and aesthetic properties. Nowadays thermoplastic elastomeric materials are very widely used for over molding the rigid products like knives, hand held electronics, house wares and computers, hand tools, personnel hygiene tools and a lot of consumer market products requiring improved soft feel and touch, good impact absorption, aesthetics and damping of vibration along with excellent perfor-

mance. Polypropylene and polyethylene are the best suitable among the TPE materials for over molding purposes.

The major factors responsible for strong bonding and adhesion between a TPE and a hard inner material or substrate are [6,7]

- Chemistry of TPE
- Chemistry of substrate
- Matching the surface energy on both materials (selection of proper TPE in combination with substrate)
- Hydrophobicity of TPE on substrate surface
- Over molding process, machine type and material preparation,
- Substrate design and mold.

1.4.2. Encapsulation of coils and electronic chips

The encapsulation is covering of an object with some material to protect and/ or insulate it. Polymeric materials are used extensively as encapsulants for coils, motor windings and micro electronics packaging industry. Since late 1980s the thermoset rub-

bers were mainly used for encapsulating coils, electronics chips etc. Use of thermoplastic elastomers speed manufacturing with low cost compared with any other material and technology [16].

Thermoplastic encapsulation has almost 40% less cost than using thermoset rubbers because of rapid mold cycles and possibility of injection molding which enables to efficiently integrate separate parts into the encapsulating component. Polyester and polyamides are best suitable options among the TPE materials for encapsulation [17].

Lianhua Fan and C. P. Wong investigated the performance of thermoplastic materials along with thermosetting materials as encapsulation materials for some special microelectronic products. Both thermosetting bisphenol epoxy and thermoplastic phenoxy resins were investigated in terms of their adhesion capacity durability. The results indicate that thermoplastic resins having high molecular weight chains show more adhesion capabilities than thermosetting ones [18]. There results of this work are particularly useful towards the development of materials for future generation of low cost solenoid and microelectronic packaging, etc.

1.5. Advantages.

TPE materials have performance properties like that of thermoset rubbers but with the process and design flexibility like plastics, thereby providing wide design options and enhanced cost reduction opportunities [1]

They can be processed speedily, efficiently and economically. Thermoplastics and can be insert molded with other olefin based materials, such as polypropylene, without the use of adhesives. The other advantages include lightweight, elastic recovery properties with in a specific temperature range, metal replacement, noise reduction by self lubrication, very good electrical insulation properties, heat resistance with in a specific temperature range, oil resistance, improved adhesion, tear resistant surface, low permeability and colorable and can be made in a variety of hardness grades[2,6,12,13]. Worldwide consumption of TPE rubbers of all types was estimated about 3.2 million metric tons for the year 2009 and the % share of different types among them is shown on a pie chart in Fig. 1 [19,20].

1.6. Disadvantages

In comparison to thermoset rubbers TPE materials have decreased chemical & environmental resistance and thermal resistances as they melt or be-

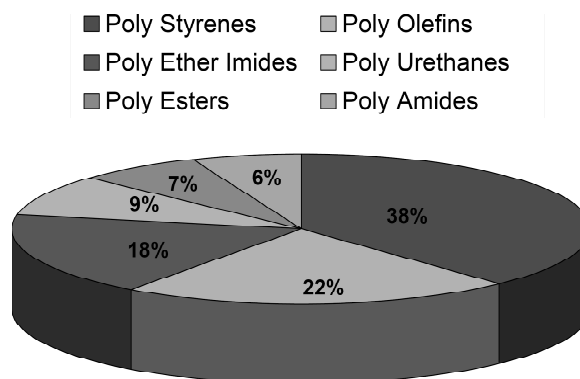


Fig. 1. Percentage share of different TPE materials in global consumer market.

come soft at high temperatures and lose their rubbery behavior.

The cost of TPE materials are higher than the thermoset materials, in addition to this they cannot be used with fillers in order to make products requiring large amounts of material at low cost. TPE materials also lose their surface hydrophobicity in short time when use din outdoor environment especially in high voltage insulation applications.

2. CLASSIFICATION AND CHEMISTRY OF THERMOPLASTIC ELASTOMERIC MATERIALS

Thermoplastic elastomers are classified by their chemistry into following six categories [2,5,7,21].

1. Poly Styrenes
2. Poly Olefins
3. Poly Ether Imides
4. Poly Urethanes
5. Poly Esters
6. Poly Amides

Each category has a slight difference in its chemistry and therefore offers different properties. Thermo set rubbers have chemical cross linking which is achieved by the process of vulcanization. Vulcanization is an irreversible and slow process which takes place upon heating. The thermoplastic elastomers are formed by a physical mixing and/or cross linking of two components, which is a reversible process and occurs upon cooling the reactants. TPE materials can be polar (copolyesters, copolyamides, polyurethanes) or non-polar (PP, PE EPM, EPDM, NR, BD).

2.1. Chemical structure

In simplest form TPE materials are like an X-Y-X block copolymers. Where X is a hard thermoplastic

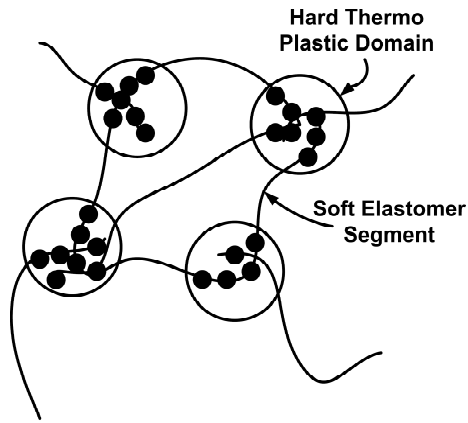


Fig. 2. Structure of Poly Styrene.

at room temperature but soften at elevated temperatures, and Y is a soft elastomer. Examples for X are polystyrene, polyethylene, or polypropylene, whereas examples for Y are polydimethylsiloxane, polybutadiene, polyisoprene or poly (ethylene-propylene) [2]. Most polymer pairs are incompatible thermodynamically due to different surface energies and so in hot state their mixture separates into two phases [5,22]. This is the reason thermoplastic elastomers are not heat resistant beyond a certain temperature range.

In order to understand the chemistry of TPE materials consider polystyrene which is an example of styrenic block copolymers. Polystyrene has hard spherical styrene domains connected with soft elastomer segments as shown in Fig. 2. The ends of elastomer segments are dispersed in hard styrene domains [23]. Polystyrene is hard at normal temperature and melts on high temperatures.

This structure resembles the one present in vulcanizing rubbers having sulphur cross linking. The main difference is that thermoplastic domains lose elastomer segments in TPE materials upon heating or dissolving in solvents. This causes the molten material to flow. Again upon cooling the material or on the evaporation of solvent the physical links between thermoplastic domains and elastomers are formed and material hardens itself [24]. The above explanation applies to all kinds of thermoplastic elastomers which have structure like X–Y–X–Y–X....

The block copolymers having structures like X–Y or Y–X–Y (where X is any hard thermoplastic and Y is any soft elastomer) are not called thermoplastic elastomers. The reason is that for a thermoplastic elastomer to be stable at any given temperature, both end points of elastomer segment should be trapped in hard thermoplastic domains. The materials formed by structure Y–X–Y are much weaker like

un-vulcanized synthetic rubbers [25]. The chemistry described until now applies particularly to styrenic block copolymers but in general to all six categories of thermoplastic elastomers. Each category has its own specific properties which will be discussed now.

2.1.1. Poly Styrenes

Poly Styrenes are the largest group among TPE materials and probably the most versatile, they can be produced over a variety of hardness values. Styrenic block copolymers are amorphous and opaque polymers. Styrenic block copolymers have elastomer segments with relatively short lengths so each elastomer may pass through a few hard domains before it ends. These are most cheap and widely used category of thermoplastic elastomers for making different kinds of foam and packaging materials. The typical value of glass transition temperature for these polymers can be exceeding 95 °C. They are resistant to polar solvents whereas they dissolve in non-polar solvents [5,25,26]. A styrene block is shown in Fig. 3a. This block acting as hard thermoplastic can be attached with many different elastomers to make different styrenic block thermoplastic elastomers. The most commonly used elastomers with styrene are butadiene, isoprene and ethylene-butylene. The structures formed using these elastomers are shown in Figs. 3b - 3d [26, 27,28].

2.1.2. Poly olefins

This is a new class among thermoplastic elastomeric materials as compared to styrenic block copolymers and they are also called Poly Alkenes. Polyolefins are simple long chain hydrocarbons, polyolefins are produced by reaction of an alkene as a monomer with general formula C_nH_{2n} . Low and high density polyethylene copolymer, polypropylene copolymer and poly methyl pentene are most prominent polyolefins in use [29]. Polyethylene and polypropylene are produced by long chain polymerization of olefins ethylene and propylene respectively as shown in Fig. 4.

Polyolefin block copolymers are amorphous and transparent polymers. Polyolefins are chemically inert, extremely flexible, nontoxic, very light weight and sterile. They are resistant to all kinds of solvents. The typical value of glass transition temperature for these polymers can be exceeding 140 °C. Polyolefin block copolymers are mostly injection moulded and can be produced in any shape like cast, wire or film. The films are most commonly used in food and blister packaging of medicines. They are also used

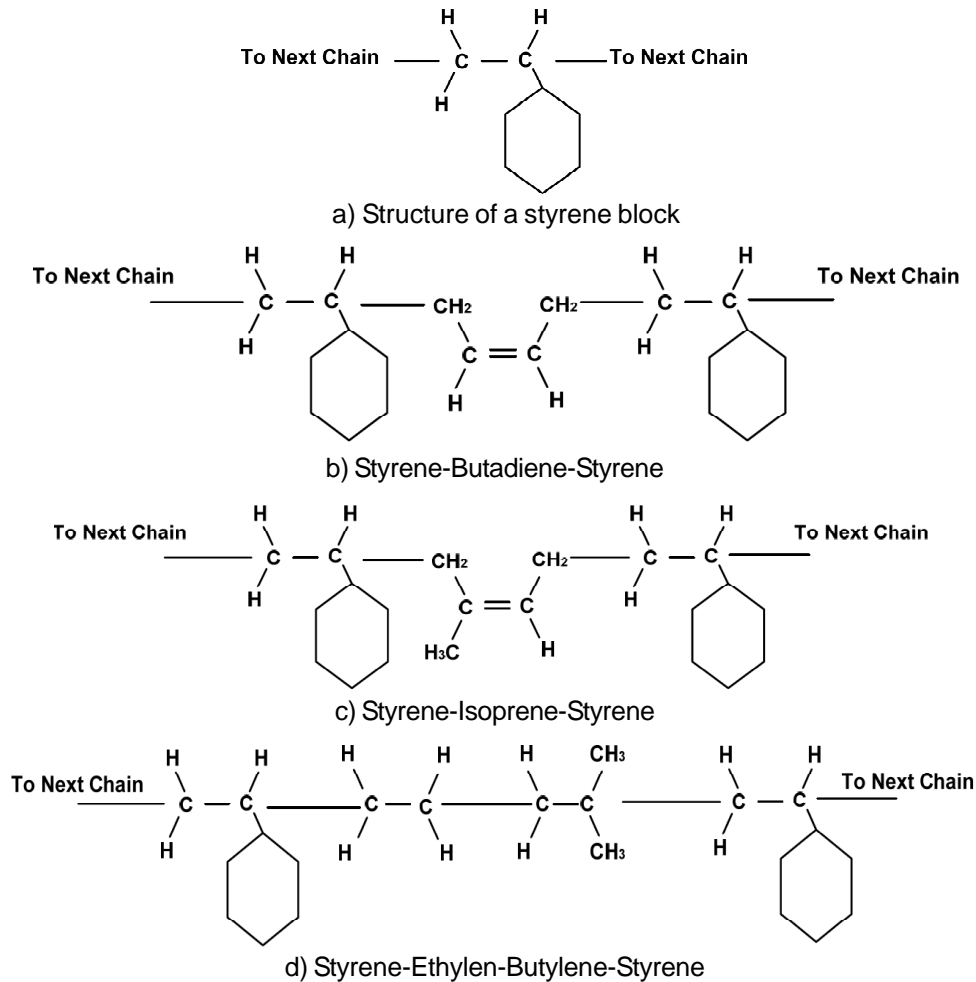


Fig. 3. Chemical structure of different kinds of poly styrenes.

to make lenses for cameras, projectors and copiers, LCD monitors, contact lenses for eye and reinforced tubes or pipes for medical use [30]. Wires made up of Polyolefin block copolymers are used as fiber optical media because of their excellent glass like transparency, low dielectric loss over time and high resistance to dielectric breakdown. Long term exposure to sunlight and strong oxidizing agents causes brittleness in them which may lead to shattering [31].

2.1.3. Poly ether imides

Polyetherimides are also called thermo plastic vulcanizates. Thermoplastic vulcanizates are compounds with fully cross linked rubber. They are made up of long elastomers bonded with thermoplastics. Structure of a typical polyetherimide is shown in Fig. 5. They are crystalline, highly elastic and have excellent impact resistance due to long elastomer segments present in them. Their natural color is amber or either black but can be dyed in any color

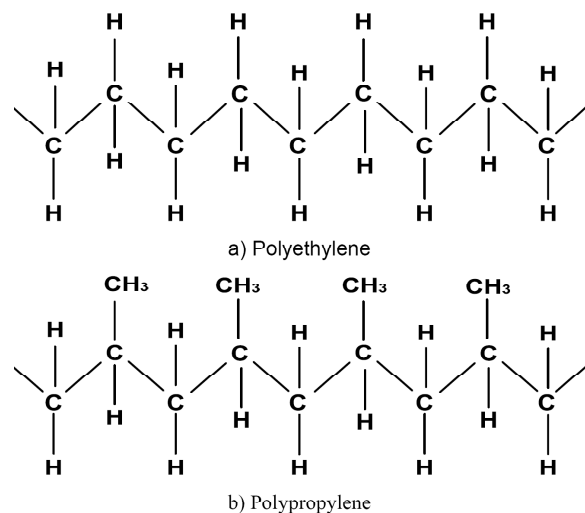


Fig. 4. Chemical structure of different polyolefins.

[29]. They are light weight and have very good weather and chemical resistance as compared to other TPE materials. They are highly resistant to flame and fire. They have high resistance to surface chalking.

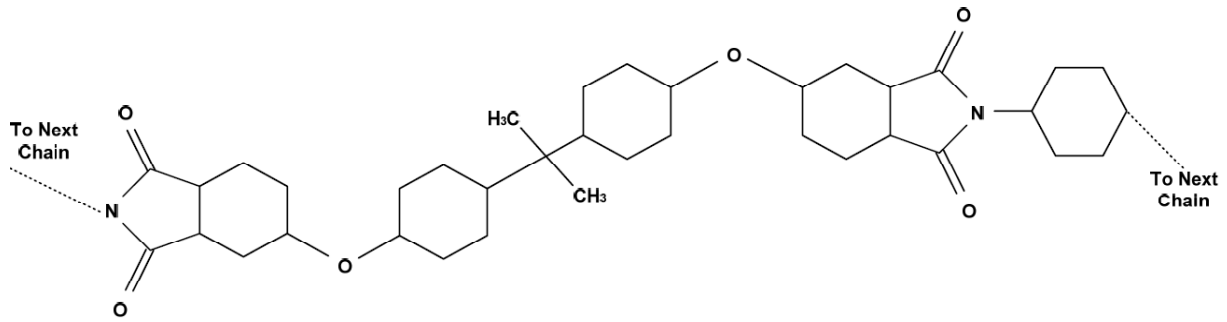


Fig. 5. Chemical structure of a typical polyetherimide.

The typical value of glass transition temperature for these polymers can be exceeding 225 °C. They are resistant to majority of solvents. Their uses include electrical & electronics cable insulations, flame retardant insulations, industrial tubing, hoses, pipes and seals for industry and medical applications [30].

2.1.4. Poly urethanes

Polyurethanes are amorphous polymers which are class of polyurethane plastics. These are elastic and transparent polymers with outstanding high and low temperature performance [29]. The typical value of glass transition temperature for these polymers can be exceeding 190 °C. Thermoplastic polyurethanes are composed of both long chain elastomers (Polyols) and short chain elastomers (Diols) with short and hard segments of urethane thermoplastic in alternating positions, the segments are linked together by covalent bonds [32]. Chemical structure of a polyurethane elastomer is shown in Fig. 6.

Therefore we can make unlimited combinations of thermoplastic polyurethanes with characteristics as desired, by varying the structure and/or molecular weight of the polyols, diols and thermoplastic [33]. That's why a large variety of thermoplastic polyurethanes is now available in market. Thermoplastic polyurethanes have very good resistance to mechanical impact, oil, grease, and abrasion.

2.1.5. Poly esters

Polyesters get their name due to presence of ester group in them which has hydro carbon chains attached with them. Copolyesters are crystalline and transparent polymers. The typical value of glass transition temperature for these polymers can be exceeding 185-220 °C. they have very high mechanical and tensile strength. They are resistant to almost all kinds of solvents and chemicals. The two very common copolyesters are Poly Ethylene Terephthalate (PET) and Poly Ethylene

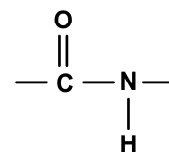
Naphthalate (PEN). The structure of PET is shown in Fig. 7. PET is most commonly used for making shatter free bottles for beverages.

The ester is polar group, with the negatively ionized oxygen atom and positively ionized carbon atom. The positive and negative poles of different ester groups are attracted together. This causes a linear alignment of ester groups to result in a crystalline form. Due to this crystalline structure copolyesters can form strong fibers [6].

Poly Ethylene Naphthalate (PEN) is a new kind of polyester as compared to PET. PEN has a higher glass transition temperature than PET. The chemical structure of PEN is just like PET except in place of one there are two benzene rings attached together [27]. Presence of one extra benzene ring makes the PEN more resistant to heat than PET. To make a bottle heat resistant a small amount of PEN is mixed with PET which gives a bottle that can take the heat a lot better than only PET. Copolyesters are cheap and widely used in making high volume, low cost plastic items, packaging of many kinds of industrial, commercial, medical and domestic fluids, drinks, etc. [29].

2.1.6. Poly amides

Polyamides contain amide as their repeated unit which is linked by different elastomers. An amide group has the formula CONH_2 and the structure as shown below.



Polyamides are amorphous and opaque polymers which very high resistances to temperature and electrical stress, mechanical stress, flame and chemicals [29]. The typical value of glass transition temperature for these polymers can be exceeding

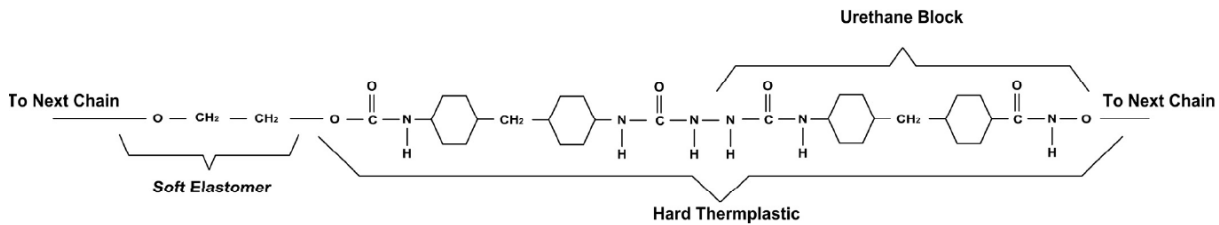


Fig. 6. Chemical structure of a typical polyurethane.

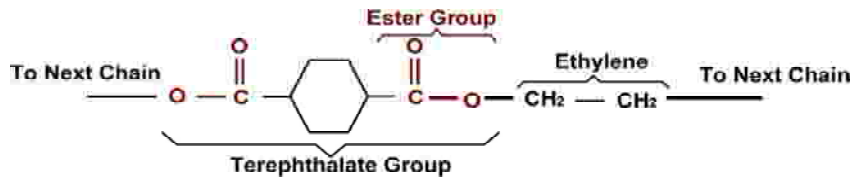


Fig. 7. Chemical structure of PET (a very commonly used polyester).

220-275 °C. Polyamides can be made in a large variety, each type is useful for specific applications, and the most widely used polyamides are PA6, PA 6.6 (also known as Nylon), kevlar and PA 4.6. The kevlar and PA 4.6 reinforced with glass fibers are used for metal replacement [34]. Polyamides show low viscosity and high fluidity at elevated temperatures, therefore they are very to mold in thin parts using injection molding.

Nylon and nylon 6.6 are formed by combining the amide groups with chains of five and six carbon atoms which is shown in Figs. 8a and 8b respectively. The structure of kevlar is shown in Fig. 8c.

Kevlar

Kevlar is a very strong material, about five times as strong as steel in equivalent weight. Kevlar is made when amide groups are linked by a benzene ring instead of long carbon chains. The presence of benzene ring imparts extreme strength to kevlar and hence it is used for metal replacement. Besides all the advantages a major issue with polyamides is their affinity to absorb moisture. Moisture uptake causes variation in the dimensions. Amides are also easily attacked by acids or alkalis even in dilute concentrations in case of acids. The reaction is catalyzed by high temperatures. The reason is that amide linkage is readily broken down by dilute acid, and the elastomer fibers in the material are detached and destroyed. The net result is a hole in the material. Kevlar is more resistant to acid or alkali attack as compared to nylon [36].

Nylon is used in textiles for clothing and carpets, tire cords, ropes. Kevlar is used in bulletproof vests, lightweight skis, in replacement of metals in

many applications like space and aircraft bodies, light weight automobiles etc.

2.2. Environmental Issues

Thermoplastic elastomers are stable materials. They decompose slowly under normal circumstances. When decomposed they usually convert into the products which are not hazardous and do not pose any problems [2,3]. However the products containing polyolefins and PVC should be handled with care so as to avoid their overheating. Also they should be disposed off properly to avoid their burning because they emit isocyanates and caprolactam, which are potential pollutants and cancer producing carcinogenic agents [6,25].

3. MECHANICAL PROPERTIES OF THERMOPLASTIC ELASTOMERIC MATERIALS

With a huge variety of TPE materials, the future expectations from TPE materials are very wide. Most thermoplastic elastomers are phase separated so they show many characteristics of the individual polymers constituents [2]. For example, each polymer has its own glass-transition temperature (T_g or crystal melting point T_m if it is crystalline). This in turn determines the temperatures at which a particular thermoplastic elastomer will melt. So broadly speaking, elasticity modulus curve of any certain thermoplastic elastomer shows three distinct regions as shown in Fig. 9.

At very low temperatures, both the thermoplastic and elastomer are in hard and brittle state. At T_g or T_m they start melting. At temperature mentioned in useful state both of them are in rubber state. In-

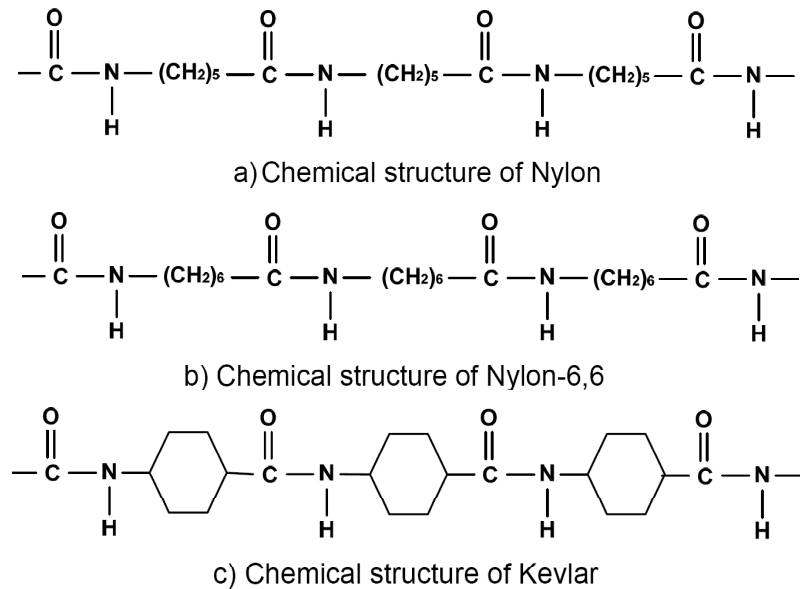


Fig. 8. Chemical structure of different poly amides, replotted from [29,36].

creasing the temperature finally results in molten state where both thermoplastic and elastomer are in a weak liquid and moldable state. The thermoplastic elastomer has the properties which are intermediate between its two ingredients and shown by a grey line in Fig. 9. So a thermoplastic elastomer will have two service temperatures. The lower service temperature which is dependant on the T_g of the elastomer and the upper service temperature is dependant on the T_g or T_m of the hard thermoplastic phase [5].

There are some other factors which govern the mechanical properties of thermoplastic elastomers, which include effect of individual molecular weight of soft elastomers and hard thermoplastic used and the proportion of hard and soft phases.

Thermoplastic elastomers have high melting points and tensile strength when compared with homo polymers of same molecular weight [6,11,23]. The reason for this is the two phase separated structure as discussed earlier. One phase is hard thermoplastic other is soft elastomer, whereas both of them are retaining their properties in the mixture and hence called two phase structure. If the thermoplastic content is held constant while varying content of elastomer, no change in tensile strength of thermoplastic occurs. This shows that tensile strength has no relation with the amount of elastomer used. In fact the tensile strength is related with composition of elastomer used and the type of bonding that exists within elastomer or between elastomer and thermoplastic. In addition to that tensile strength of a thermoplastic elastomer depends

a lot on the amount of hard phase thermoplastic. When the amount of hard thermoplastic is increased as compared to soft elastomer, the product first becomes strong rubber then leather like and finally hard flexible plastic [25,33].

The amount of hard thermoplastic also influences the melting point and thermal stability of resulting thermoplastic elastomer. The very popular low cost and yet having good solvent/oil resistance thermoplastic is propylene. It is crystalline and results in a thermoplastic elastomer having high upper service temperatures [29].

The amount and type of elastomer used in thermoplastic elastomeric materials controls the chemical resistance of resulting material. The elastomers with double or triple carbon bond show more solvent and chemical resistance. The use of polar elas-

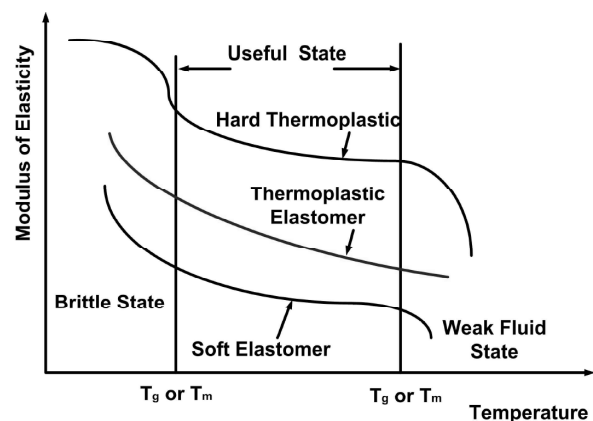


Fig. 9. Temperature Vs elasticity of TPE materials.

tomers like ethylene also increases oil resistance many fold [36].

3.1. Ultra sonic welding

A very useful and advantageous property of thermoplastic elastomers is the possibility of welding together using ultra sound waves. Ultrasonic waves cause local melting of thermoplastic elastomeric materials due resonant energy absorption [37]. Ultrasonic welding is a very fast method of joining the plastics together than using any solvent or adhesive. The process can be automated and welded joint has excellently clean look. The application of ultrasonic welding for thermoplastic elastomers was first introduced in 1965 by Soloff and Seymour Linsley [38,39]

Crystalline and semi crystalline thermoplastic elastomers are most suitable candidate for ultrasonic welding, however amorphous thermoplastic elastomers can also be welded together by this method but with less tensile strength. Details of ultrasonic welding systems can be seen in [40,41]

Ultrasonic welding is most widely used in packaging, sealing containers of explosive materials butane cigarette lighters, and lead acid batteries which cannot be sealed using heat or flame, sealing tubes and blister packs of medicines are among other important to mention [42].

3.2. Recycling

Easy recycling and repairing is the factor that emphasizes the use of thermoplastic elastomers over conventional thermoset rubbers. For recycling the scrap, the first step is to grind it. To grind it easily material should be absolutely dry. Grinding involves cutting material with sharp and narrow gap blade shredders and/or grinders. Often some amount of new and virgin hard thermoplastic is mixed with ground material to increase its tensile strength and reduce brittleness. This mixture is then melted and remolded [25].

There are many requirements where a part made up of rubber or plastic needs repair for example in case of automobile exterior parts, and in application where replacement is difficult due to financial or availability constraints. The broken or cracked portion of any part made up of thermoplastic elastomer can be easily repaired by just melting and joining it to settle again. However the molten joint after settlement some times may not have same tensile strength as before, to counter this metal strips or fibers can be easily be incorporated in the

joint while maintaining the aesthesis of part same as before.

4. ELECTRICAL PROPERTIES OF THERMOPLASTIC ELASTOMERIC MATERIALS

With growing transmission voltages high reliability insulating materials are required. The performance of a material as electrical insulation is determined by its dielectric breakdown strength [43]. This breakdown strength depends on the factors like frequency and waveform of voltage applied, moisture level, temperature, partial discharges, impurities in that material, thickness and layers of insulation, dielectric constant and volume resistivity [44,45].

For a material to qualify for the use in electrical insulation there are some particular requirements on its properties. These properties include low specific weight, good mechanical, chemical and thermal strength, good surface leakage resistance, ability to maintain good surface hydrophobicity, easy processing and production [46]. A good combination of these properties is found in modern thermoplastic elastomers (TPE). Before the introduction of TPE materials blends of ethylene-propylene-diene monomer (EPDM) were introduced for electrical insulation for the first time in 1960's. But they proved to be a failure shortly [44]. Ethylene-propylene copolymer (EPR) and silicon rubber (SiR) were then introduced till 1980's. In late 90's TPE materials were first time introduced in the field of electrical insulation. In recent years the importance of thermoplastic elastomeric materials has increased exponentially for indoor, outdoor, machine and cable insulations.

Olefinic block copolymers are well known in the electro technical field. Among them polyethylene is used for insulation in high and medium voltage underground cables.

Polyesters and polyamides are particularly useful in encapsulation of coils and electronic devices. For manufacturing motors glass reinforced polyamides and polyesters are very suitable. Polyesters have very good dimensional stability and high resistance to thermal deformation. Among polyesters PET has been most widely used today to encapsulate many electronics devices in order to protect them from environmental effect in addition to electrical insulation. When compared with the metals, PET polyester and polyamides reinforced with 30 to 45% glass fibers, show sufficient strength to be used for making all parts of a motor provided that the designed enhances the beam strength [47].

Encapsulation of coils in polyester or polyamides replaces the need of tape wrapping.

In modern electrical manufacturing the coil bobbins for transformers are made with 6,6 nylon. Stator, end bracket and housings for motors are made with PET polyester. PET does not corrode and hence parts made up of it require no painting or machining. The bearings are generally made with polyamides which have natural lubrication and can be used without any other lubricant. Since loss of lubricant cannot occur so chance of failure is completely eliminated, and startup becomes fast in cold weather conditions [47]. A more detailed study on electrical properties of polyamides is presented in [48] where the authors rate polyamide among the very successful for making indoor insulation, however authors report that polyamides due to their extreme affinity for moisture, may not be suitable for making outdoor insulation. Polyimides such as Kapton is used largely for making the electrical insulation in protected environments, but it is only available as a film [49].

PET is also used in gas insulated substation. Yannick Kieffel and his co workers [49] performed an investigation to see suitability of PET for making gas insulated substation (GIS) post insulators. All the results obtained on virgin material as well as on aged material fully indicate that the selected PET is suitable for thick insulation in high voltage applications. The thermal as well as electrical and mechanical characteristics satisfy the specification of the GIS. In conclusion, the recyclability and reliability of GIS can be improved by using TPE materials [49]. However for application as outdoor insulator, it does not have sufficient chemical resistance [50].

Sam J. Ferrito and his coworkers in their study [51] investigated the change in electrical properties of the three polyester materials, i.e., PBT, PET, and PCT, along with two polyphthalamide materials (PPA) at 60 °C and a relative humidity level of 100%. The results show that the PBT and PET materials are the most prone to hydrolytic degradation when compared to PCT and PPA. The obvious reason behind it seems to be lack of symmetry in the molecular weight distribution among PBT and PET. S. Grzybowski and his co workers in [52] performed a detailed study on break down voltage of samples of polyester cups of different thickness used for encapsulating high voltage coils and electronics components. Results of this study show that in dry state DC breakdown voltage of samples was much higher than that of the AC breakdown voltage. Both AC and DC breakdown voltages reduce upon wet-

ting but DC breakdown voltage degraded more significantly as compared to AC breakdown voltage. DC breakdown voltages are widely scattered as compared to AC breakdown voltages.

As already discussed in Section 2.1.5 polyester and polyamides are very prone to undergo hydrolysis. Even they can hydrolyze processing so extreme care should be taken in drying them prior to molding. Another source of hydrolytic degradation is environmental aging. Hydrolytic degradation of the polymer causes random chain scissions to occur, normally at the ester and amide linkages, which causes a reduction in molecular weight and hence a reduction in mechanical integrity [53-55]. Also, ester hydrolysis produces hydrophilic acid (carboxyl) end groups in the polymer which increase the ability for the polymer to absorb water decrease its surface resistance and hydrophobicity [54,56,57]. This degradation process also occurs in case of polyetherimides and polyurethanes particularly at high temperature and humidity [58]. So each thermoplastic polymer category demands a comprehensive evaluation before its use in any environment and/or application [59].

Polyetherimides (PEI) are used for high voltage switchgear applications. For semi-crystalline thermoplastic, mechanical and electrical properties depend on the morphology of the material especially the ratio between crystalline and amorphous parts [49]. A change of components share in copolymers is an effective way to obtain materials with required parameters. This is the reason many researchers are focusing their work to see the effect of nanofillers addition to polymeric materials in order to enhance their mechanical and electrical properties.

5. PERFORMANCE OF TPE MATERIALS AS OUTDOOR ELECTRICAL INSULATION

Since biological effects are different in each region of earth, so it requires aging of polymeric insulators in each region of world prior to use its use. Aging is the application of stresses to an insulator, that it is expected to encounter in real life service environment, in order to see what would be its status and/or performance after a certain time.

5.1. Natural aging

Installation of an insulator in actual outdoor environment for the period of time its performance is to be measured/estimated. The Natural aging has the drawback it takes a long time to age a sample. For ex-

ample if we want to see the effect of aging on an insulator after 30 years, no one can wait 30 years. To resolve this problem, H.M. Schneider and his associates first ever put the concept of accelerated multi stress lab aging in 1991.

5.2. Accelerated multi stress lab aging

In the accelerated multi stress lab aging, all the stresses are applied on insulators like they appear in real life, but in a calculated accelerated manner, e.g. day and night cycles are simulated faster than actual. The other factors such as temperature, UV radiation simulating sunlight, rain, etc. are also increased. The increase is not straight. Some stresses cancel each other, whereas others enhance each other, e.g. effect of UV is nullified by rain, but the heat multiplies the effect of UV. So while applying acceleration one has to take into account these factors [59].

Accelerated multi stress aging of polymeric insulators simulates real field conditions and produces result just like natural aging. It also has advantage of causing these changes to occur in less time. Hence effect of long term natural aging can be achieved in short time. The accelerated multi stress lab aging has now become very popular to test any material and especially polymeric insulators.

5.3. Accelerated multi stress aging of TPE insulators in different environments

S.M. Oliveria and C.H. Tourreil [60] studied the composite EPR (Ethylene Propylene Rubber) under IEEE/IEC 1000 h test procedures. The authors state that EPR formulations perform better than the first generation of epoxy resin insulators. The authors claim that aging test methods and the acceptance criteria proposed by IEC and the IEE are not suitable to describe the performance of several polymeric insulator materials under different environments of the world. So test procedures for every environment should be developed individually.

H. M. Schneider et al. [61] presented the behavior of 138 kV non-ceramic (polymeric) line post insulators investigated by means of clean fog tests conducted before and after aging in a specially designed accelerated aging chamber simulating the environment of coastal regions of Florida. The results of this study show that clean fog flashover voltage of polymeric insulators exceeded that of the high strength porcelain line post insulators. Authors state that ESDD is not an adequate index of con-

tamination severity for polymeric insulators which have high hydrophobicity. Polymeric insulators produce increased audible noise but decreased radio interference as a result of aging.

J. L Fierro Chavez, et al. [62] developed a system for measurement of leakage current and surface resistance of TPE insulators in Monterrey, Mexico. This system was installed on several towers along the 400 kV line as a diagnostic tool to monitor the surface condition of polluted insulators. The results showed values from 50-150 mA in first two months of installation. But such high values never appear again when some of faulty insulators were replaced once. The authors suggest that cleaning or replacement of insulators is necessary when peaks of 250 mA or more are observed in rainy season.

R. Matsuoka et al. [63] presented an overview of different techniques use to study the aging of TPE insulator. Authors suggest a most suitable set of following five techniques namely Visual inspection, FTIR, SEM, hydrophobicity, and leakage current measurements.

R. Sundararajan et al. [64] presented a one year field and lab aging study of 28 kV distribution dead end type insulators in two different US environments. Weather cycles simulating summer and winter of Phoenix and Boston were developed. Good correlation between field and lab aging was observed. Authors conclude that meaning full studies can be carried out to observe the long term performance of a number of insulators at a given environment using accelerated multi stress lab aging. Based on results authors have guaranteed a 15 year life of these insulators. However the actual life may be more longer than this.

P. Cygan and J.R. Laghari [65] presented an overview of multi stress aging techniques. The authors have presented the several methods used by researchers all over the world to accelerate the aging process, but suggest that most popular are the experiments performed at voltages and temperatures. The authors classify all methods in two categories. In first category stresses are kept constant time to failure or satisfactory period is noted. In the second category stresses are increased in steps until the failure occurs. The results from both of them are then correlated to get an empirical formula or model of aging. The authors have also discussed feasibility of setting many mathematical models, to get equation of aging from experimental data. At the end authors predict that multi stress aging will be the most suitable option in a few years to demonstrate the performance of insulating materials.

Ali Naderian, Majid Sanaye, Hosein Mohseni [66] presented a review of artificial contamination with stand test methods used for polymeric materials. The authors give details of equivalent fog test, pollution rain test, variable voltage test, rapid flashover test, dust Cycle test, salt fog test, clean fog, accelerated multi stress tests, etc. Authors state that although several standards and recommendations have been published by many recognized organizations in order to carry the aging of composite insulators, but still there remains some uncertainty about the contamination behavior of these insulators. Because of this there are several non-standard test recommendations formulated to evaluate the behavior of insulators under different conditions which are proving to be better than standard methods. At the end authors stress that it is necessary to determine age polymeric insulators for field application of different environments so that users and customers can select proper composite insulators according to the each environment.

C. Olave et al. [67] conducted 5000 h multi stress aging of 28 kV TPE insulators under slightly modified IEC conditions. There was no major degradation, such as flashovers, heavy arcing, erosion, cracking or tracking. In general the insulators performed well showing only superficial changes like corrosion of the HV end fittings, light arcing, and shallow cracking. Authors conclude that TPE insulators can perform well in many service environments in excess of 20 years at least. Further more accelerated multi stress aging is very beneficial to see performance of any insulator in nay service environment.

J.L. Bessede and his coworkers [68] analyzed the suitability of thermoplastic polymer used as support insulator in high voltage gas insulated substation using a semi crystalline thermoplastic polyethylene-terephthalate (PET) using accelerated multi stress aging. A plate shape insulator for 72.5 kV gas insulated substation was made and tested. Results show that main electrical properties of the material were not affected by aging under used SF₆. Authors have estimated a 24 year satisfactory life of these insulators.

Raji Sundararajan et al. [69] performed multi stress accelerated aging of polymer housed ethylene propylene silicone blend (EPSB) and Silicon Rubber (SiR) surge arrestors under coastal Florida conditions. The authors simulated 15 lab years. SiR showed less physical changes as compared to EPSB. But leakage current was higher for SiR as compared to EPSB. However on the overall both the materials preserved excellent surface resistance

at the end of 15 years of lab aging Authors state that is very beneficial to use multi stress aging to evaluate the long term performance of polymeric arresters and insulators in the field.

R. Sundararajan [70] presented the results of a 2544 hours multi stress aging of TPE and SiR polymeric insulators under simulated conditions of Mexico City. The results indicate that the silicone rubber insulators perform better than TPE and there is discoloration, light arcing loss of hydrophobicity and bond breaking in both type of insulators, but still they have preserved good electrical and mechanical x-tics and are estimated to serve several years in the field.

Salman Amin et al. performed a 10000 hours comparative multi stress accelerated aging of TPE and SiR insulators in the environment of HATTAR, Pakistan under the effect of UVA, heat, salt fog, acid rain and electric stress. The analyses were made using electrical (leakage current), physical (discoloration, hydrophobicity classification) variables, and sophisticated material analysis techniques, such as Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM). It was seen that all insulators showed excellent performance till 13th year. But in 14th and 15th year all of them showed a drastic change, however still preserving good electrical properties. There was a drastic change in results of all techniques of analysis at the 9000 hours point which is equivalent to 15 lab years. So an aging exceeding this point must be carried. To investigate this more a 30 years simulated aging is under way by same authors.

6. CONCLUSIONS

The use of thermoplastic elastomeric materials is continuously increasing for huge applications in daily life. Over molding and encapsulation are most widely used applications of TPE materials. About 85% of plastic products in the modern world are made up of TPE materials, because they provide competitive price performance as compared to other natural rubbers. The selection of a TPE material for any particular application requires a special focus on its physical, chemical, mechanical and electrical properties. The glass transition temperature T_g of a TPE material is the temperature at which many of its properties start changing. Above the T_g the polymer is most susceptible to degradation.

All TPE materials are based on two major components a hard thermoplastic and a soft elastomer. The physical properties are showing the advantages of both the rubber and plastics. TPE materials are

environment friendly and very easy to recycle. In addition to that their major disadvantages are low thermal and chemical resistance and a bit high cost. But the advantages offered by them dominate the disadvantages that's why their use is increasing day by day.

Thermoplastic elastomers are classified into following six categories, namely polystyrenes, polyolefins, polyetherimides, polyurethanes, polyesters, polyamides. Each category has a slight difference in its chemistry and therefore offers different properties. Styrenic block copolymers are cheapest and most widely used. Next popular are polyolefins and then polyetherimides. Polyamides have highest thermal resistance and cost. Polyesters have highest tensile strength.

For electrical insulation applications the surface of material is most important which is characterized in terms of its hydrophobicity, resistance and reactance. The insulation properties of a material are dependant on the physical displacement of charge in the bulk of that material upon application of a voltage. Any impurities present or contamination introduced into the system can greatly affect the dielectric characteristics of the material. TPE materials when used in electrical applications can be exposed to many kinds of stresses which include heat, UV radiation, humidity, biological degradation, mechanical stress etc. Multi-stress aging must be designed into the testing and qualification process in order to achieve a representative model of the interactions encountered. An example of a multi-stress test could include a setup which exposes a thermoplastic elastomer to temperature, humidity, UV, mechanical, and electrical stresses simultaneously. For indoor electrical insulation polyesters and polyamides are most commonly used. For outdoor insulation the most popular are blends of polyolefins. Polyetherimides are also used in high voltage switch gear application but on limited scale.

Accelerated multi stress aging has become very popular since last 15 years to investigate the long term aging and performance of any kind of insulations all over the world. Many authors have investigated the aging and electrical performance of TPE insulators in various outdoor environments to varying extents. To estimate the state of aging visual observation, hydrophobicity classification, leakage current, SEM, and FTIR are the most commonly used techniques by many authors all over the world. The results are quite satisfactory except that TPE materials cannot maintain their surface hydrophobicity. IEEE/ IEC standards have been reported by

authors to be inappropriate as they reflect only specific regional impact, and authors suggest using the individual environmental stress values instead of these standards. Maximum Multi stress aging done by any author is of 10000 hours. Maximum natural aging done is of 7 years; however various insulators tested after removing from service environments have ages of up to 20 years. The life estimation is done by some authors and ranges between 15 to 30 years with most typical value of 24 years. A very long term multi stress accelerated aging of thermoplastic insulators under varying environments is needed.

REFERENCES

- [1] *Plastic & thermoplastic elastomer materials, online technical report* (Minnesota Rubber and QMR Plastics, section 5, 2003).
- [2] *Thermoplastic elastomers: a Comprehensive Review*, ed. by N.R. Legge, G. Holden and H.E. Schroeder (Carl Hanser Verlag, Munich, vol.80, 1987), p. 574.
- [3] S.G. Chu and J. Class // *J. Appl. Polym. Sci.* **30** (1985) 805.
- [4] *Handbook of thermoplastic elastomers. 2nd ed.*, ed. by B.M. Walker and C.P. Rader (Van Nostrand publishers, Reinhold, New York, 1988).
- [5] *Thermoplastic elastomers, 2nd ed.*, ed. by G. Holden, N.P. Lagga, R.P. Qurik and H.E. Schroeder (Hanser & Hanser/ Gardener, Munich, 1996).
- [6] G. Holden, *Understanding thermoplastic elastomers* (Hanser & Hanser/ Gardener, Munich, 2000).
- [7] E.N. Kresge // *J. Rubber World* **217** (1997) 30.
- [8] Shuke Jiao, Juanlin Bing, Klaoyu Li, Dingsheng Yu // *J. Acta Polymerica Sinica* **6** (1994) 34.
- [9] R.C. Puydak, In: *Proc. 2nd International Conference on Thermoplastic Elastomer Markets and Products* (Scotland Business Research, Orlando, Fla., Mar. 15–17, 1989), p. 121.
- [10] A.J. Tinker, In: *Proc. Symposium on Thermoplastic Elastomers* (ACS Rubber Division, Cincinnati, Ohio, Oct. 18–21, 1988), p. 209.
- [11] M.G. Bouldin, J.H. Collins and A. Berker // *J. Rubber Chem. Technol.* **64** (1991) 577.
- [12] Abdou-Sabet // *J. ACS Polymeric Materials Science and Engineering* **79** (1998) 86.
- [13] *Technical Bulletin SC: 1102-89* (Shell Chemical Co., Houston, Tex., 1989).

- [14] T. Hayashi // *J. Toyoda Gosei Technical Review, Japan* **38** (1996) 2.
- [15] Krishna Venkataswamy, Rajesh Varma and Walter Ripple, online technical article *Over molding of thermoplastic elastomers: engineered solutions for consumer product differentiation* (Thermoplastic Elastomers Division, GLS Corporation, 833, Ridgeview Drive, McHenry, July 2007).
- [16] James F.B. Patterson, In: *Proc. IEEE International Symposium on Packaging Materials* (IEEE, 1991), p. 176.
- [17] *Technical Bulletin H-69216* (DuPont-Dow Elastomers, Wilmington, Del., 1996).
- [18] Lianhua Fan and C.P. Wong, In: *International Symposium on Advanced Packaging Materials* (IEEE, 2001), p. 230.
- [19] *World thermoplastic elastomers, Freedonia study report #2013* (November 2005, China).
- [20] M.J. Modic and L.A. Pottick // *J. Plast. Engg.* **47** (1991) 37.
- [21] P. Dreyfuss, L.J. Fetters and D.R. Hansen // *J. Rubber Chem. Technology* **53** (1980) 738.
- [22] A. Piazza, A. Acrozzi and C. Verga // *J. Rubber Chem. Technology* **53** (1980), p. 994.
- [23] G. Holden and K.H. Speer // *J. Autom. Polym. Des.* **8** (1988) 15.
- [24] Zheng Qingle, Pang Yongxin and Jai Demin // *J. Polymeric Materials Science & Engineering* **5** (1998) 5.
- [25] G. Holden, E.T. Bishop and N.R. Legge // *Journal of Polymer Science, Part C* **26** (1969) p. 37.
- [26] K.E. Kear, *Developments in thermoplastic elastomers* (Chemtec publishing, 2003). [27] Peter W. Dufton, *Thermoplastic elastomers* (Rapra Technology Ltd., U.K. 2001). [28] Kinsuk Naskar, *Dynamically vulcanized PP/EPDM thermoplastic elastomers* (LAP Lambert Academic Publishing, 2008).
- [29] Jiri George Drobny, *Handbook of thermoplastic elastomers* (PDL handbook series, Elsevier, 2007).
- [30] J.L. Laird, M.S. Edmonson and J.A. Riedel // *J. Rubber World* **217** (1997) 42.
- [31] M. Szycher, V.L. Poirier and D. Demsey // *J. Elastomerics* **115** (1983) 11.
- [32] *Handbook of Polyurethane Resins*, ed. I. Keiji (Nikkan Kogyo Shimbun publishers, Ltd. Japan, 1987).
- [33] B. Masiulanis and R. Zielinski // *J. Appl. Polym. Sci.* **30** (1985) 2731.
- [34] Zhongkai Yang, Hongjie Li and Xiaoning Li // *Journal of Beijing Institute of Clothing* **1** (2004) 56.
- [35] G. Rabilloud, *High performance polymers* (Technic Press, Paris, 2000).
- [36] T. Takekoshi, *Advance in polymer science* (Springer-Verlag, 1990).
- [37] *Welding Handbook: Welding science and technology* (American Welding Society, 2001).
- [38] *Plastics and composites welding handbook* (Hanser & Gardner Publications, Inc. Munich, 2003).
- [39] *Handbook of Plastics Joining, Plastics Design Library* (Norwich, New York, 2008).
- [40] Vladimir N. Khmelev, In: *Proceedings of 6th International Siberian Workshop and Tutorials (EDM'2005, July 1-5, Erlagol)*, p. 117.
- [41] (2005). *New developments in advanced welding*, ed. by Nasir Ahmed (CRC Press LLC. Boca Raton, Florida).
- [42] *Jefferson's Welding Encyclopedia* (American Welding Society, USA, 1997).
- [43] M. Amin and S. Amin // *Rev. Adv. Mater. Sci.* **13** (2006) 93.
- [44] R. Sundararajan, A. Mohammed and N. Chaipanit // *IEEE transactions on dielectrics and electrical insulation* **11** (2004) 348.
- [45] S. Grzybowski, E.A. Feilat, P. Knight and L. Doriott, In: *IEEE 1998 annual report conference on electrical insulation and dielectric phenomena* (Atlanta, Georgia, USA, October 25-28, 1998), p. 678.
- [46] S. Grzybowski E.A. Feilat P. Knight L. Doriott, In: *Proceedings of 1999 IEEE southeast conference 25-28 March, 1999* (IEEE, 1999), p. 284.
- [47] J.J. Hanrahan W.J. Hassink W.E. Kenney, In: *Electrical electronics insulation conference* (Chicago, 1993), p. 271.
- [48] Paweł Andruszkiewicz, Marta Piątek and Ryszard Ukielski // *J. Physics and Chemistry of Solid State* **7** (2006) p. 7.
- [49] Yannick Kieffel, Alain Girodet, Karsten Pohlink Salima Bouti and Dimitri Beauguitte, In: *IEEE High Voltage Engineering and Application conference (ICHVE), 11-14 Oct. 2010* (IEEE, 2010), p. 580.
- [50] J.-L. Bessede, I. Huet, Y. Kieffel, H. Aeschbach, F. Braeuer, K. Pohlink, A. Dahoun, S. Etienne and J.-M. Hiver, In: *IEEE 2005 annual report conference on*

- electrical insulation and dielectric phenomena, 16-19 Oct, 2005* (IEEE, 2005), p. 277
- [51] Sam J. Ferrito and Thomas A. Edison, In: *IEEE 1996 annual report conference on electrical insulation and dielectric phenomena, San Francisco, October 20-23, 1996* (IEEE, 1996), p. 833.
- [52] S. Grzybowski and J. Fan, In: *IEEE 1996 annual report conference on electrical insulation and dielectric phenomena, San Francisco, October 20-23, 1996* (IEEE, 1996), p. 295.
- [53] Seiichi Takei, Yasuhiro Tanabe and Yoshimichi Ohki, In: *IEEE 1998 international conference on conduction and breakdown in solid dielectrics, Vakteds, Sweden, June 22-25, 1998* (IEEE, 1998), p. 349.
- [54] P.G. Kelleher, G.H. Bebbington, D.R. Falcone, J.T. Ryan and R.P. Wenz, In: *Proc. of 37th Antec SPE* (New Orleans, 1979), p. 527.
- [55] R.J. Gardner and J.R. Martin, In: *Proc. of 37th Antec SPE* (New Orleans, 1979), p. 83.
- [56] P.G. Kelleher, R.P. Wenz, M.Y. Hellman and E.H. Gilbert, In: *Proc. of 40th Antec SPE* (San Francisco, 1982), p. 11.
- [57] M. Amin, M. Akbar and S. Amin // *Rev. Adv. Mater. Sci.* **16** (2007) 10.
- [58] R.J. Gardner and J.R. Martin // *Journal of Applied Polymer Science* **25** (1980) 2353.
- [59] M. Amin, M. Akbar and M. Salman // *Science in China Series E: Technological Sciences* **50** (2007) 697.
- [60] S.M. Oliveria and C.H. Tourreil // *IEEE Trans. on Pwr. Del.* **5** (1992) 92.
- [61] H.M. Schneider et. al. "Accelerated aging and flashover tests on 138 kv nonceramic line post insulators" *IEEE transactions on power delivery*, Vol. 8, No. 1, January 1993, p. 138.
- [62] J.L. Fierro Chavez, I. Ramirez Vazquez, G. Montoya Tena. "Online leakage current monitoring of 400 kV insulator strings in polluted areas". *IEE proceedings on Gener. Transm. Distrib.* Vol 143, No. 6 Nov 1996, p. 560.
- [63] Matsuoka K. Naito, T. Irie and K. Kondo, "Evaluation methods of Polymer Insulators under contaminated conditions" *IEEE/PES Yokohama, Japan October 2002*, p. 34.
- [64] R. Sundararajan, J. Graves, A. Mohammed, and A. Baker, "Performance Evaluation of Polymeric Insulators Aged in Lab and Field" *IEEE PES*, 13-17 July, FL, USA, 2003, p. 219
- [65] P. Cygan and J.R. Laghari, "Bull. Mater. Sci.", Vol. 27, No. 3, June 2004, p. 251.
- [66] Ali Naderian, Majid Sanaye, Hosein Mohseni, in *IEEE ISEI 2004, USA*, p-284.
- [67] C. Olave, E. Romero, P. Trinidad, R. Sundararajan, and B. Trepanier "5000h multistress aging of 28 kV TPE insulators" *IEEE PES*, 2005.12-15 June 2005. Arizona State, USA, p. 1006.
- [68] J.L. Bessedé, I. Huet and Y. Kieffel, "Suitability of thermoplastic polymer for the making of HV gas insulated substation insulator", *IEEE 2005 Annual Report Conference on Electrical Insulation and Dielectric Phenomena*. 12-15 June 2005. Arizona State, USA, p. 277.
- [69] Raji Sundararajan et. al. *IEEE trans. Dielectr. Insul.* Vol.13, No.1, Feb, 2006, p. 211.
- [70] Raji Sundararajan, "Long term acid rain multi stress performance of thermoplastic and thermoset polymeric insulators", *5th International Conference on Industrial and Information Systems, ICIIIS 2010, Jul 29 - Aug 01, 2010, India*, p. 544.