Electronic Applications of Ethylene Propylene Diene Monomer Rubber and Its Composites

Anjali A. Athawale and Aparna M. Joshi

Abstract Ethylene propylene diene monomer (EPDM), due to its outstanding oxygen, ultraviolet (UV), weather, fatigue and moisture resistance, and good electrical properties, is one of the fast growing elastomer. Besides its general applications such as seals, radiator, and hose, being a flexible polymer and an electrical insulator, it is a suitable candidate for electrical cables, cable terminal protectors, bus bar shrouds, etc., and is advantageous in comparison with glass or ceramic insulators. EPDM can be made electrically conductive by incorporating conductive materials such as conductive carbon black (CCB), metals, conductive polymers, carbon nanotubes, or other nanomaterials. The electrically conductive applications of EPDM include pressure-sensitive switches, actuators, microwave absorption, EMI shielding, conductive gaskets, touch pads, biosensors, and many other fields.

Keywords EPDM · Rubber · Polymer · Insulator · Electronics · Conductor

1 General Aspects of EPDM

1.1 Chemistry and Structure

EPDM is a synthetic rubber consisting of ethylene and propylene where 'M' refers to the saturated backbone in the polymer. It is one of the most important and fastest growing synthetic rubber having both specialty and general-purpose applications.

A.A. Athawale (✉)
Department of Chemistry, University of Pune, Pune 411007, India
e-mail: agbed@chem.unipune.ac.in

A.M. Joshi
K.D. Joshi Rubber Industries Pvt. Ltd., 'A' 82-85, H Block, MIDC, Pimpri, Pune, India
e-mail: aparnamjoshi@rediffmail.com

D. Ponnamma et al. (eds.), *Flexible and Stretchable Electronic Composites*,
Springer Series on Polymer and Composite Materials,
DOI 10.1007/978-3-319-23663-6_11

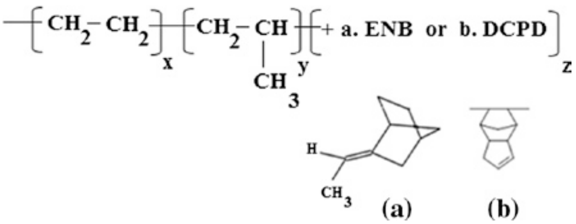

Fig. 1 Ethylene propylene diene monomer with diene as **a** ENB and **b** DCPD

EPDM is an elastic polymer or an elastomer which responds to a large, reversible, and rapid strain to stress. This property differentiates it from the rest of the materials. A broad range of EPDM elastomers can be produced ranging from amorphous and non-crystalline to semi-crystalline structures by varying the polymer composition as well as the way the monomers are combined. The chemical building blocks or monomers in EPDM polymer are similar as for polyethylene (PE) and polypropylene (PP) which combine together randomly. Terpolymerization of a third non-conjugated diene monomer is then carried out by keeping the reactive unsaturation on the side chain [1]. Two most widely used diene termonomers are primarily ethylidene norbornene (ENB) (Fig. 1a) and dicyclopentadiene (DCPD) (Fig. 1b).

1.2 Synthesis, Compounding, and Vulcanization of EPDM

Synthesis of elastomer from simple inexpensive olefins having limited functionality to accommodate vulcanization and to meet the required properties was the scientist's desire. Ziegler et al.'s breakthrough came when they pursued the matter of oligomerization with olefins and metal alkyls. However, as green chemistry as well as new regulations demands the formulations free of hazardous elements, attempts have been made toward developing lead-free EPDM to be used in wire and cable applications. Figure 2 shows the synthesis route of EPDM with Ziegler–Natta catalyst with vanadium as the metal.

EPDM rubbers are manufactured by three commercial processes with the use of catalyst such as solution, slurry, and gas-phase synthesis. Among the three, solution polymerization is the most widely used technique. Further, improvements in the catalyst and the processes have led to increased productivity while maintaining control over the polymer structure. The physical forms of the polymer range from solid to friable bales, pellets, granular forms, and oil blends.

Different materials required for the compounding and processing of EPDM include process aids, antidegradants, tackifiers, pigments, and curatives. The process aids are used to assure the easy incorporation of fillers during mixing with shorter mixing cycles and better dispersion. For the electronic applications at lower voltages, process aids such as esters, amides, and their salts are used. They tend to increase the electrical losses.

Additives such as antioxidants and antiozonants are generally required to maximize the weathering/aging resistance of EPDM for which antidegradants such as

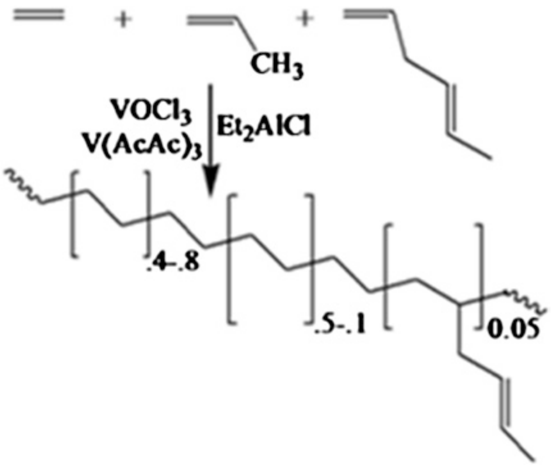

Fig. 2 Synthesis of EPDM [2]. Copyright 2015. Reproduced with permission from John Wiley & Sons. https://s100.copyright.com/CustomerAdmin/PLF.jsp?ref=ab9a5116-2468-45d6-a833-713a45162d2f

amine and phenolic groups are added to the compound. Surface tack is another important property required to improve pliability of the uncured compound. Tackifiers are usually low-molecular weight compounds. Peptizers are chain terminators and reduce the time required to lower the viscosity. Inorganic or organic pigments are another class of materials used in the compounding for improved aesthetics and color coding of products.

Fillers are the essential materials to reinforce the desired properties. The conventional fillers such as carbon black or silica must be used in high loading levels to impart good mechanical reinforcement to the compound. The choice of fillers is substantially narrowed when it comes to the electronic applications of EPDM. The filler should be selected in order to retain the physical properties, electrical losses, electrical stability, breakdown strength, moisture absorption, and increase in the voltage rating. Water-washed hard clay, calcium carbonate or whiting, barium sulfate or barytes, and various types of synthetic silica are the conventional fillers used for low-voltage applications. As the voltage requirements increase, choice of mineral fillers is substantially restricted to untreated and surface-treated calcined clays and to platy structures such as talc which are superior in electrical losses, electrical stability, and moisture absorption [3]. The common mineral fillers include hydrated alumina, precipitated silica, calcium silicate, china clay, and whiting which are used in specific applications. Calcined kaolin is the filler that can be used for insulation [4]. Silane coupling agents improve the filler–matrix interactions [5]. The electrically conductive fillers include CCB, expanded graphite (EG), metal powders, conductive polymers, and nanomaterials.

To achieve best properties in a compound, curing or cross-linking of EPDM is essential. In case of bulky polymer molecules with less sites of unsaturation, peroxide curing agents are best suited, while sulfur curing helps in comparatively simple molecular structures. For low-voltage applications of EPDM components such as insulators, cable jackets, and some molded electrical components, sulfur cure is the better option. For most electrical applications, peroxide cures are the most common curing method. The peroxides such as dicumyl peroxide and bis-(tertiary butylperoxy)-diisopropyl benzene are frequently used in thin-walled low-voltage applications or in semiconductive insulation shields. In both cases, the reaction rate is low. This helps the products to reach the cure temperatures more rapidly. The peroxide curing of elastomers requires coagents to prevent cure inhibition by oxygen or acidic compounding ingredients. Coagents are polyfunctional, unsaturated organic composites used to achieve a more versatile and efficient cure system [6–8]. Elemental sulfur is another specialized coagent. It is frequently used in molded cable accessories in which the improved hot tear strength facilitates demolding. Unfortunately, it also reduces dielectric breakdown strength because of the sulfur cross-links and creates disagreeable odors in the vulcanizate. Phenolic resins have also been used as cross-linking agents [9–11]. Electron beam induced cross-linking of elastomeric materials results in the formation of a three-dimensional network through condensation of the generated macro-radicals [12]. Cure retarders are used to prevent premature curing or scorching of compounds during processing [13, 14].

The functional characteristics of rubber composites depend largely on the mixing process; different mixing facilities are used depending on the type of compound, expected quality of the product, the type of processing method, etc. The commonly used mixing machines include two roll open mixing mill, kneader, internal mixer, and banbury. The two roll open mixing mill is the easiest method in which the mixing process can be inspected visually. The type of mixing in internal mixer is intermeshing. Banbury is used for high-volume applications. It is preferred for easy to mix formulations, sticky materials, multiple step mixing applications, high-viscosity compounds, etc. In this mixer, the rotors are designed for tangential mixing [15].

1.3 Properties of EPDM

EPDM is an inexpensive elastomer with good extendability, low-temperature properties, aging characteristics, and freedom from ozone-induced cracking. In any event, EPDM has found a niche when long-term serviceability is commencing to occupy consumer’s minds.

It is a low-cost material with very good low-temperature properties and excellent mechanical strength. The heat aging properties of EPDM are comparatively poor. However, EPDM-based compounds have better wet electrical properties. Being a non-polar elastomer, EPDM has good electrical resistivity and tracking resistance. When it comes to low-voltage application that is up to 35 kV, EPDM supersedes other elastomers and materials [16]. EPDM insulators can maintain the hydrophobicity on the surface even in the presence of pollutants [17–19].

2 General Applications of EPDM

EPDM rubber can be used for different applications in various forms, such as composites or nanocomposite with reinforcing fillers or nanofillers, as blends, coatings etc.

EPDM rubber compound could be a combination of 3–15 different ingredients obtained by mixing with a base polymer. Compound is a substance that consists of chemical bonding between two or more different elements. It has a definite proportion by mass. The bonds between these elements can be broken to get simpler molecules. Science of rubber compounding involves the use of correct ratio of ingredients for fruitful interactions. Composites are engineered materials with two or more constituent materials having significantly different physical and/or chemical properties. The materials comprising a composite remain separate and distinct. They impart the synergic enhancement in the properties of the composite.

Blending of polymers is an attractive way of producing a new material as it does not involve cost and technical uncertainties as that of synthesizing a new one. The blending of elastomers together is to improve the processing and physical properties of cured and uncured elastomers. The physical properties of the cured blends are influenced by vulcanization and filler distribution. Filler distribution in the blend affects the properties of the blend, as it is controlled by the molecular weight of the polymer and filler dispersion in each phase and chemical interaction between the polymer and filler.

The main uses of EPDM are in outdoor and in elevated temperature applications because its saturated structure provides stability under these conditions. Compounding and processing of EPDM leads to cross-linked products with excellent resistance to heat, ozone, oxygen, and weather. The ingredients in the composite play a major role for achieving the desired properties. EPDM being a non-polar elastomer has good chemical resistance towards polar solvents such as salt solutions, alkaline solutions, dilute acids, acetone, alcohols and phosphate ester-based hydraulic fluids. EPDM has poor or limited resistance to aliphatic, aromatic, chlorinated hydrocarbons or petroleum-based fluids, lubricants, and strong oxidizing acids such as nitric acid. However, it is resistant to dilute acids [20, 21].

EPDM elastomer is generally resistant to temperatures up to 121 °C in air and can tolerate higher temperatures with specific compounding. EPDM is often described as a ‘preferred’ elastomer for nuclear service due to its combined resistance to radiation, chemicals, aging, steam, heat, and other environmental factors [22–25]. Peroxide-cured EPDMs are generally preferred over sulfur-cured types for superior heat aging and radiation resistance properties. However, variations in compounding further influence this behavior.

Versatility in the design of this polymer and its performance have resulted in its broad range of applications in automotive industries, weather-stripping and seals, radiator, garden and appliance hose, tubing, belts, roofing membrane, rubber mechanical goods, plastic impact modification, thermoplastic vulcanizates, and motor oil additive applications. Properly pigmented black and non-black compounds are color stable. It has excellent low-temperature flexibility with glass transition temperature of −60 °C.

EPDM is used in several industrial segments, such as sealing, mechanical and thermal insulation, coatings, tubes, and cushions. In the aerospace sector, EPDM is very important in the development and manufacture of missiles and rockets that demand the use of highly resistant and flexible thermal protections. EPDM is a suitable candidate for these applications due to its compatibility between the materials, compounding techniques, cost of manufacture, aging process, and adhesion properties. Despite these excellent characteristics, EPDM rubber exhibits low values of surface energy, which decreases its adhesion properties to the solid propellant [26–29].

3 Applications of EPDM as Insulator in Electronic Devices

Non-ceramic insulators containing ethylene–propylene rubber (EPR) were first made by different companies in France and USA (1975–1980). In 1976, Rosenthal in Germany and Reliable in USA (1983) presented Silicone rubber (SIR). Ohio Brass produced an alloy consisting of EPDM and SIR in 1986 [30].

EPDM being a non-polar material has good surface and volume resistance, low dielectric permittivity, and high breakdown voltage. EPDM is also a cost-effective material and hence plays a major role as electrical insulator. EPDM insulators are used to support the line conductors to separate them electrically from each other. These composite insulators have substantial advantages such as lightweight, easy installation, and better voltage-withstanding capability compared to inorganic insulators. They exhibit improved contamination performance, resistance to vandalism, high hydrophobicity, and ability to withstand shock loads.

The dielectric constant of EPDM increases with the ENB content as higher number of side chains is available to create greater dipole moments or to store more charges. For example, the dielectric constants of NORDEL IP grades 3670, 4570, 5565, 4520, and 4640, at a frequency of 100 Hz and room temperature, are 1.27, 1.88, 1.92, 1.53, and 1.53, respectively. The dielectric constant of NORDEL IP 5565 is highest as it contains higher percentage of ENB. In addition to this, the dielectric constant of EDPM elastomers increases with increasing molecular weight or decreasing free volume [31].

With the advancement in the technology of large-scale dissipation of electric power through power systems such as substations, distribution, and transmission lines, it became essential that the professionals working in these places were knowledgeable about the insulating materials. In the early days, ceramic and glass materials were used as insulators. However, after 1960s, they were replaced by polymeric insulators due to their excellent insulating properties, ease in designing, manufacturing, and also economic viability. In addition to this, the performance of polymers is good in contaminated environment. They are lightweight, maintenance free, and easy to handle. The basic structure of an insulator consists of a fiberglass core rod covered by weather sheds made up of polymers such as SIR, polytetrafluoroethylene, and EPDM fitted with metal end fittings. Polymers are the commonly used dielectrics; as a result, the commercial and industrial demand for advanced polymers capable of working in harsh environments is constantly increasing [32].

Further, polymer blends are one of the major subjects in polymer industry which are suitable for distribution and transmission class insulations. Their long performance in clean environment has been successful. The purpose of blending is to gain synergistic improvement in properties at both micro- and macro-levels. Batiuk, Herman, and Healy have reported blends of EPDM especially with low-density polyethylene (LDPE) exhibiting superior tensile strength.

Though insulating composites bear several advantages, certain limitations that they pose include chemical changes on the surface due to weathering and dry band arcing together with erosion and tracking, finally leading to their failure as an insulator. It is difficult to detect faulty insulators and evaluate their life expectancy. Suspension type of composite EPDM insulators have been tested by subjecting them to accelerated stress aging as per modified IEC-61109 standards by simulating the inland arid desert's condition. The hydrophobic characteristics have been determined by measuring the contact angle along the surface before and after accelerated aging of the samples. The results show that the composite loses its hydrophobic characteristics in proportion to the intensity of the UV radiations and its rate of recovery is very slow in comparison with SIR. The performance of polymer insulators depends on the selection of materials, design, and its construction. The pollution performance of post-insulators decreases with increasing average diameter [33].

As insulator, the major applications of EPDM include communication cables, magnet wires, power wire, cable apparatus wiring, cable accessories, automotive wiring, control and signal cable and building wire, cable terminal protectors, and bus bar shroud. Due to the flexible characteristics and superior service parameters, EPDM is also widely used as outdoor HV insulator. The flexibility of EPDM has more credentials in the molding process of the complex designs of the insulator components. The complex design of the cable terminal protector can be observed from Fig. 3.

Compared to glass or porcelain insulators, the use of EPDM insulators avoids the unnecessary maintenance such as washing of the insulators and resists deliberate destructions. The ideal composition of an insulator is a resin rod, metallic end fittings, and polymeric weather sheds that protect the resin rod system from the environmental and electric surface discharges due to its water-repellent tendency [35–42]. The use of elastomeric materials in insulation systems of high-voltage apparatuses have increased during the last decades. The apparatuses and components under system voltage operation are expected to remain functional when the over voltage occurs due to unavoidable conditions such as lightning strikes, switching operations, and reversal in polarity in HV dc systems. EPDM insulators are the reliable performers when exposed to such circumstances.

Fig. 3 Cable terminal protector [34]. *Courtesy* K.D. Joshi Rubber Industries

The accumulation and relaxation of electric charges at insulator surface and interface trigger unexpected flashover during testing and operation. The temporal and spatial variations of the surface potentials correlate with the surface and volume resistivity when the surface charge is deposited on EPDM compound surface by impulse positive corona. The rate of potential decay decreases with increasing amplitude of voltage. EPDM polymer is suitable for designing and construction of high-voltage equipment [43, 44]. In comparison with polymeric insulators except silicone insulators, EPDM insulators withstand environmental temperature, pollution, UV radiations, etc., retaining its electrical, chemical, and hydrophobic properties [45]. The degradation process of EPDM is very slow even in the severe pollution conditions such as acid rain and desserts due to its chemically stable structure [46]. EPDM overcomes the leakage current, tracking resistance, and outdoor insulation erosion [47]. Contamination leading to the creepage discharge occurring at the surface is known as tracking. The surface field intensity and the magnitude of current affect the tracking resistance inducing the state of discharge resulting in the loss of its insulating property. The dc power transmission is the preferred mode of power transmission nowadays. Due to greater accumulation of contamination over the insulators under dc voltages, the problem of tracking phenomena is even more severe compared to that with ac voltage. EPDM is an excellent elastomer with its hydrophobic surface properties in the presence of pollutants over the surface of insulators to serve as an outdoor insulator.

Sarathi et al. have studied the behavior of EPDM material under ac and dc voltages, with ammonium chloride/acid rain solution as the contaminant. The tracking time depends on the conductivity and the flow rate of the contaminant. It is a surface degradation process where the tracking time is different for ac and dc voltages [48].

One of the major challenges of polymeric insulators is to minimize the flashover voltage. Its values get affected toward higher risk due to the parameters such as conductivity (μS cm^{-1}) of water droplet, number of droplets, and volume of water droplet (ml). In the field of high-voltage insulators, artificial neural network

(ANN) helps in function approximation, pattern recognition classification, estimation or prediction, etc. [49]. The ANN tool can estimate the level of pollution and flashover voltages and analyze surface tracking on polluted insulators and on hydrophobic polymer insulators [50]. Flashover voltage of hydrophobic polymer insulators has been investigated using a number of different conditions. Composites of EPDM and silicone have been tested for this purpose with silicone content varying from 0 to 100 %.

The prime and most important use of EPDM as insulator is in the wires and cables. Electrical properties that are important for wire and cable applications include resistivity, dielectric strength, dielectric constant, and dielectric loss. For certain applications, fire resistance properties are also important while selecting the material. Voltages up to 150 kV may be required in wire and cable applications; however, each application has its own specific range of voltage. For example, low power transmission cables have low frequencies and high voltages, while telephone cables operate at low voltages and high frequencies. In ultra-high-voltage transmission systems for overhead lines (~1000 kV ac and 800 kV dc) and for submarine lines (~500 and 300 kV), EPDM insulation is becoming prominent.

The construction of basic cable includes three regions. A metallic conductor is encased in a dielectric shield around the conductor system and finally a jacket material for environmental protection. EPDM elastomer due to its environmental stability can be used in many of the components, particularly for insulation and in jackets. It also withstands the temperature of the conductor which increases due to resistive heating when the current passes through the conductor. Electrical properties that are critical to wire and cable applications include resistivity, dielectric strength, dielectric constant, and dielectric loss including fire resistance properties in some applications [51]. EPDM can also accept large amounts of filler and extender oil with no significant prejudice to the final properties. Its good electrical properties make it suitable for application in wires and cables subjected to low to intermediate voltages (up to 35 kV).

As mentioned in the introductory section, some residual ions such as chlorine in the polymer synthesis are susceptible to degradation reactions at elevated temperatures and UV radiations, which cause acceleration in the degradation rate, as well as increased moisture uptake, and have reduced electrical properties. Stabilizing additives are effective in preventing further degradation and yielding reaction products that do not further destabilize the system [52, 53].

In construction wires used in buildings, communication wires, and data transfer and alarm cables, fire or flame retardancy is the most important property to avoid the fire spread through the cables. As a result, the cable materials must possess not only the required electrical properties, but also the appropriate fire resistance as well. EPDM exhibits the electrical resistivity of 10^{15}–$10^{17}\Omega$ cm, dielectric strength of ~35–41 kV mm^{-1}, dielectric constant of 3–3.5 kHz, and dissipation factor of 0.004 kHz [54]. The flame resistance of the composites of EPDM can be improved by using aluminum trihydroxide (ATH). These composites fit the national and international standards to be used for insulation in electrical wires and cables while retaining their property of fire retardancy. Around 170–180 phr of ATH is required in the composition of fire resistant cable [55]. ATH filler also improves the dry band arcing characteristics when exposed to ultraviolet (UV) light [56]. The mechanical properties such as tensile modulus and hardness increase with ATH filler, while elongation at break and tensile strength decrease when ATH (60 phr) is used as filler in the blends of EPDM with other polymers such as polypropylene for cable applications [57].

The ability of SIR insulators is excellent for transferring hydrophobicity, while in operation along with excellent electrical performance under wet and contaminated environments, they are applied widely in polluted condition. The high cost of SIR, poor mechanical properties, and tracking resistance has forced the use of EPDM in HV insulators due to its superior electrical properties, flexibility over a wide temperature range and its resistance to moisture and weather, UV radiation endurance, and hydrophobicity. The blend of EPDM and SIR exhibits excellent electrical and mechanical properties. Contact angle measurements of the blend after aging of the composite determine the surface energy as the blending offers a good degree of protection toward aging of EPDM rubber. EPDM in the blend maintains good mechanical properties such as elongation at break after heat aging [30].

LDPE, EPDM, and their blends are well-known polymers for their use as low-, medium-, and high-voltage insulators. Blends with different weight ratios of LDPE/EPDM prove to be better for mechanical properties such as increasing the tensile strength, modulus, and elongation at break. The properties depend upon the proportion of the blend [58]. Blending PP, EPDM, and thermoplastic elastomer (TPE) combines high-melting temperature and recyclability of PP with the ductility of EPDM. In addition, excellent resistance to degradation and ability to accept high filler loading by EPDM makes TPE suitable for electrical applications with ATH as a flame retarder [55, 57].

Weather sheds for polymer insulators are manufactured from materials such as bisphenol or cycloaliphatic epoxy resins, thermoplastic rubber, EPDM, and silicone elastomers. These materials are compounded with various types of inorganic fillers such as silica and hydrated alumina with concentrations ranging from a few percent to 70 % by weight. Today, the elastomeric materials of EPDM and silicone containing a minimum of 70 % by weight of hydrated alumina that are in use by most of manufacturers are favored for weather sheds with SIR clearly showing the best performance over all other types. Ehsani et al. have studied the mechanical, thermal, dynamic mechanical, and electrical properties of housing (weather shed) materials for outdoor polymeric insulators. The blends of silicone–EPDM show good breakdown voltage strength compared to SIR. Surface and volume resistance of SIR improves with EPDM content. The mechanical properties such as strength, modulus, and elongation at break are improved in the composite [58].

A new technique involving grafting of organofunctional silanes onto the polymer chain has gained importance to attain a homogeneous and maximum mixing of the two different polymers in a blend. A novel copolymer has been synthesized using dicumyl peroxide as initiator. The grafting efficiency of vinyl oxy amino silane (VOS) onto EPDM (EPDM-g-VOS) shows poor mechanical properties due to the flexibility imparted by VOS. However, thermal and dielectric properties are increased due to the introduction of VOS onto EPDM as well as the formation of thermally stable three-dimensional networks through Si–O–Si linkages. Therefore, EPDM-g-VOS could be used as low- and medium-voltage cable insulation for better performance compared to EPDM. Using optimum grafting efficiency through solution-grafting technique, EPDM-g-VOS has been developed in a Haake Rheocord-90, torque rheometer. EPDM-g-VOS can be prepared both by solution polymerization and by melt mixing techniques [59].

The development of polymeric nanocomposites is an interesting area for obtaining materials with high mechanical strength to weight ratio, resistance to vandalism, and high-voltage resistance which make them suitable for application as outdoor insulators. Nanofillers have rendered popularity to rubber nanocomposites over the past decades. These fillers have at least one of their dimensions below 100 nm and a high specific surface area. The specific surface area is responsible for different types of reinforcement in nanocomposites and is manifested even at very low filler loadings (<10 wt%). The rubber nanocomposites are comprised of nanofillers dispersed in rubber matrix. The main families of nanofillers that have become successful commercially are clays and organoclays (OC), carbon nanotubes (CNT), and nanooxides such as nanosilica, TiO_2, polyhedral oligomeric silsesquioxane (POSS), and graphene or graphitic nanofillers. Clays and organoclays are suitable for applications where electrical insulation is required and CNT and graphene are used in conducting applications [60]. Materials with a combination of nanosized organic, inorganic materials, and polymers are expected to give the properties that are synergistic combinations of the individual components with the reinforcing components, such as nanoclay or nanosilica. These are the class of organic, inorganic hybrid materials, where the inorganic components are uniformly distributed in nanometer scale (10–90 nm) within the polymer matrix. The commonly used methods for preparing the nanocomposites are solution blending/melt blending, in situ polymerization and roll milling, and high-shear mixing.

As seen in earlier section, the blend of EPDM and SIR serves the purpose of mechanical strength, tracking resistance and superior temperature stability, excellent UV resistance, better hydrophobicity, etc. However, suitable fillers play a major role in achieving the accurate desired electrical and mechanical properties. The modified inorganic fillers help in this respect. With the increase in the public environmental awareness, research on energy saving and environmentally friendly fillers have become a hot spot for polymer composites in the past two decades. Researchers have used sepiolite, montmorillonite, attapulgite, and kaolin as fillers for polymers for various composite materials with excellent performance. Among them, silica and montmorillonite with layered structure have received a wide interest [61].

Thus, the organically modified montmorillonite (OMMT) clay used in EPDM/SIR composites explores the advantage in high-voltage electrical insulators due to its enhanced mechanical, thermal, and dielectric characteristics. OMMT EPDM/silicone nanocomposites have been prepared by incorporating various phr (1–7) of OMMT onto 50/50 EPDM/SIR blends. Nanocomposites show improved mechanical, thermal, and dielectric properties [62].

4 Applications of EPDM as Conductor in Electronic Devices

4.1 Conductive Composites

By virtue of nature, EPDM is a major candidate for electrically insulating applications. However, inducing electrical conductivity into such a material has enhanced its application horizon. Flexible conductive rubbers have been a subject of interest for a long time and are growing due to their applications in newer areas such as electronic equipment, potential materials for sensors, actuators, supercapacitors, microwave absorbing materials, pressure-sensitive switches, and important strategic materials such as EMI shielding, floor-heating elements, touch-control switches, and conductive coatings for stress cone used in switchgears, applications of semiconducting materials in antistatic rollers for dissipation of static electricity [63], and sensors for vapors and chemicals. EPDM is also a suitable candidate as binder for batteries that binds the active particulate material together and adhere it to the current collector during fabrication of electrodes [64]. Electrical energy storage technologies for stationary applications draw attention to pumped hydroelectric storage, compressed air energy storage, flywheel, capacitor/supercapacitor, and thermal energy storage. The electroactive, flexible, and versatile composites of EPDM with good physicomechanical properties and weather ability serve the purpose for these applications. The piezoelectric characteristics of EPDM, its flexibility, versatility, and low cost make it a promising alternative for fabrication of energy harvesting devices. The most interesting application is a robot arm built with artificial muscles as the mechanical movement of the robot transforms into the electrical energy by piezoelectric energy harvester [65].

These materials need to attain the desired electrical properties as well as adequate mechanical properties. Various rubbers are being widely used for preparation of such composites, e.g., silicone, nitrile, butyl, natural and EPDM rubber. EPDM rubber surpasses other rubbers in these applications because of its mechanical properties and weather aging characteristics. Owing to non-polar and saturated backbone, EPDM exhibits good resistance to heat, oxidation, and polar solvents. However, due to its low crystallinity, EPDM is not self-reinforcing. Generally, there are three main ways to reinforce EPDM to obtain optimal mechanical properties: adding fillers such as carbon black, silica, and clay, blending with crystalline resin (polyethylene, polypropylene, etc.), or changing the cure systems. Adding traditional fillers has become the most significant way to enhance the mechanical properties of EPDM. In addition to traditional reinforcing fillers, there has been a growing interest in several kinds of inorganic fillers which possess excellent electromagnetic properties [66].

Conductive EPDM can be obtained by blending the insulating polymer matrix with conductive fillers. When the percolation threshold of the dispersed particles is achieved, it is possible to obtain this smart material. The conductive fillers or the combination of the conductive fillers that can be used for this purpose are

CCB, metal powders, metal-coated inorganic oxide particles, EG, graphene, carbon fibers, conductive polymers, carbon nanotubes, other nanomaterials, etc. [67]. Various electrically conductive compounds, blends, composites and nanocomposites of EPDM, their preparation techniques, and significance have been discussed in this section.

Metals are conducting due to the presence of metallic bonds in which valence electrons are completely delocalized and form an electron cloud around the metal atoms. In the covalently bonded molecules of saturated carbon compounds, there is no scope of delocalization of the valence electrons; consequently, the electron carrier path is not available. In EPDM molecule, the atoms have covalent bonding; therefore, the movement of electrons over the polymeric chain is restricted. To create the carrier path in the insulating elastomeric matrix, incorporation of conductive additives is the important method. Recent investigations on conducting polymer composites have led to some important revelations relating to attainable electrical conductivity range and trends of change in the conductivity parameter with variations in the filler loading level, nature of the matrix polymer, degree of filler dispersion, and temperature [68].

4.1.1 Composites with Carbon

As the composites of EPDM with carbon are found to be flexible, hence, they have been used for various applications such as EMI shielding, shielding effectiveness, conductive coatings, piezoelectric applications, conductive rollers and other molded components, and pressure-sensitive switches. As carbon provides reinforcement to the composites, they are found to bear superior properties. Improvement in physical and mechanical properties is the result of feasibility of homogeneous dispersion of carbon in the matrix as EPDM can absorb fillers readily. One can obtain composites with good and controllable conductivity by varying the phr concentration of carbon in EPDM.

Among the filled conducting polymer composites, however, those based on the use of different grades of carbon blacks and carbon fibers as filler have been important with reference to their physicomechanical, conducting, and non-corrosive property balance. Low cost, high flexibility, low density, and in particular, specific structures that enable the formation of conductive network inside the polymer matrix at relatively low filler concentration are the added advantages of carbon black. Carbon black is amorphous in nature. Its properties depend upon the particle size, structure, and surface properties. Small particle size and high surface area are the important features of the filler in imparting the electrical conductivity to the composite with smaller loadings. The aggregate size, shape, and the number of particles per aggregate affect the structure of carbon blacks. High structure of the primary aggregate, which is comprised of many prime particles, is important in achieving high electrical conductivity. If the primary aggregates consist of relatively few prime particles, the carbon black is referred to as a low structure black. High structure black has strong attractive forces between their aggregates. This means that the dispersion process should provide more energy to separate them. High structure black tends to produce large aggregates in contact as well as aggregates separated by smaller distance, this results in higher conductivity at the same loading level. Short carbon fibers are better choice in cases where only conductivity is important; it provides high conductivity at lower loading level [69].

Carbon blacks are classified as semi-reinforcement furnace black (SRF), fast extruding furnace black (FEF), high abrasion furnace black (HAF), CCB, and spraying carbon black (SCB). The results of the electrical tests show that the volume and surface resistivity of the EPDM composite is low in the presence of filler having a large surface area that also easily succumbs to dielectric breakdown. The composites show lowest dielectric constant and highest dissipation factor. Hence, CCB with large surface area and high content of sulfur on the surface is suitable for conductive applications; whereas, EPDM filled with other carbon blacks (SRF, SCB, HAF, and FEF) could be useful for insulation applications [70].

The properties of vulcanizates such as physical, mechanical, and DC electrical conductivity show sharp changes on addition of carbon black. When carbon black is loaded above the percolation threshold, it results in more uniform phase morphology. EMI shielding effectiveness generally increases with increase in the carbon black content. Younan et al. have found that EPDM-SRF composites show increase in tensile strength up to 60 phr, while the elongation at break and equilibrium swelling decreases. The permittivity ε' and dielectric loss ε'' increase with increasing carbon content which is abrupt at 60 phr due to the interaction between the rubber and the SRF at higher concentration. Thermal aging up to 7 days shows decrease in ε' and ε'' [71]. The resistivity is also seen to vary significantly as a function of loading level of carbon in case of NBR, EPDM, and their blends (50/50 weight ratio). At low as well as high concentrations of filler, the resistivity is affected negligibly, while in the percolation region (~60 phr), a small increase in filler concentration produces a large increase in conductivity. In the presence of low carbon content, the electrical properties are dominated by the polymer phase between the aggregates with a large distance between the filler particles and the discontinuous conductive path. As the carbon content increases, the average distance between the aggregates decreases forming a discrete chain structure between the small gaps, and at critical concentration, a small addition results in a sharp increase in the conductivity due to the formation of a continuous conductive chain and finally it gains a stable value [72].

Thus, carbon improves the physicomechanical properties of EPDM along with the desired conductivity as per the requirement of applications. However, the thermal stability of the EPDM composites with conductive carbon is comparatively poor; as a result, the concept of using different conductive materials and blends of different polymers has emerged.

The recent development of electrostrictive polymers has generated new opportunities for high-strain sensors and actuators. Recently, investigations related to the use of electrostrictive polymer for energy harvesting, or mechanical to electrical energy conversion, have begun to show its potential for these applications. Strain sensors work on the principle of change in electrical conduction under dynamic and static load. The strain sensitivity of such electrical response depends on various factors such as type of conductive filler, filler concentration, polymer matrix, method of preparation, and mode of application of stress or strain. The electrical conductivity changes significantly when compressive strain and stress are applied on the conductive rubber composites derived from NBR, EPDM, and their 50:50 blends. The resistivity increases during application of the compressive strain which could be due to the destruction of conductive networks formed by the aggregation of conductive particles during compression. When kept under constant strain (compression), there is a reorganization of conductive fillers, which results in some increase in conductivity due to slow relaxation of polymer chains. However, during deloading, there is further breakdown in the conductive networks and hence the conductivity. Conductivity is also affected (increases or decreases) with respect to pressure depending on the viscosity of the matrix. As EPDM is stiff, the relative resistivity (ρ/ρ_o) increases with pressure. Reverse trend is observed for NBR matrix since it is softer, the 50:50 blend exhibits dual behavior. Soft SIR composites also show nature similar to NBR [73].

The electrical conductivity of conductive rubber composites is also seen to vary as a function of applied stress or strain. This property has been very useful for the development of sensors and actuators. Factors such as the type of filler and polymer matrix, the amount of filler added in the composite, method of preparation of composite, and the mode of application of stress and strain affect the electrical response of the conductive rubber composites. The change in electrical conductivity is reported to be due to the change in the internal rearrangement of the conductive particles in the matrix. During the internal arrangement, formation and destruction of the transient structure occurs in the conductive particles present in the matrix together with the change in alignment of the particles. Such materials are characterized by an insulator-to-conductor transition when the concentration of conducting particles reaches a threshold value. This transition has been interpreted within the framework of percolation theory, and the percolation effect is related to the material microstructure. These materials bear the potential to constitute the new generation of sensors or strain gauges [74].

The investigations such as the effect of compression on electrical conductivity and the change in conductivity with time for compressed samples together with the effect of compressive stress on electrical resistivity of conductive rubber have also been reported. The composites are derived from four different matrices such as EPDM, NBR, 50/50 wt% blend of EPDM/NBR, and SIR. Two different loadings of conductive black have been used with 30 phr (percolation limit) and with 60 phr and 20 and 30 phr for SIR. Base polymer has been selected with reference to viscosity. As it has been found from the earlier results, the ease of conductive network formation is strongly dependent on the viscosity of the matrix polymer before vulcanization and the stiffness after vulcanization [75]. Burton and coworkers have carried out extensive work on the change in electrical conductivity and electromechanical properties of conductive black-filled rubber systems. However, they measured the change in electrical conductivity under dynamic conditions when the sample was subjected to repeat flexing.

Biopotential signals are the result of the electrochemical activity of certain cells of the nervous, muscular, or glandular tissue. When one cell is triggered, ion exchange occurs through the membrane of this cell, creating a so-called action potential. A biopotential signal is the action potential from one cell or the average electrical activity of a group of cells, and such signals can be monitored at various locations of the human body. The average activity of the brain cells can be monitored on the scalp, and this signal is called as electroencephalography (EEG). The electric activity of heart cells is monitored by electrocardiography (ECG). To avoid the drawbacks of wet electrodes, various types of dry electrodes have been introduced. Dry electrodes fabricated from flexible conductive polymers are drawing a lot of attention. To obtain optimum properties with reference to material conductivity, hardness, flexibility, and ease of fabrication, various additives have been added in the EPDM matrix and the resulting polymer has been tested as electrode material [76].

The pressure-sensitive EPDM actuators have relatively simple structure, high compliance, and water resistance. They are considered to be very promising for applications such as development of wearable power assist suits, soft handling robots, human support robots, ornamental robots, robot hands of various size say for harvesting fruits, handling animals, etc., since their movement is very smooth similar to a living species. Together with the structure, the working principle of these composites is also simple that consists of rubber structure reinforced with conductive materials or fibers that dissipate charges and have internal chambers in the rubber structure. When pressure is applied to these chamber/chambers in the composites, the rubber undergoes elastic deformation in its structure and thus works as an actuator [77].

The dielectric properties of the composites depend on the volume fraction, size, and shape of conducting fillers and also on other factors such as preparation method, curing method, interface, and interaction between fillers and polymers. It is well established that the effective utilization of filled polymers depends strongly on its ability to disperse the particles homogenously throughout the matrix. Compared to the conventional chemical vulcanizing or curing process using peroxide or sulfur, radiation cross-linking has some advantages. It results in the formation of a three-dimensional network through the union of macro-radicals generated in the system. The process is very fast and clean and requires less energy. The percolation threshold for carbon black in the composites vulcanized by chemical or γ-irradiation dose and by laser beam is different and normally is the lowest with radiation curing method. Dielectric constant (ε') and ac conductivity (σ_{ac}) of the EPDM composite vary with different carbon content. Thus, the desired conductivity can be achieved by selecting both appropriate method of curing and the value of percolation threshold. The high temperatures involved in sulfur or peroxide curing may lead to a variety of uncontrolled side reactions. On the other hand, in radiation curing, the final curing is carried out at ambient temperature under closely controlled conditions, such as radiation dose and dose rate. The type of cross-link formed in this method (–C–C–) gives rise to better mechanical properties such as hot tear strength, abrasion resistance, and superior ozone resistance at higher temperature [78].

The study of the blend of acrylonitrile–butadiene rubber and EPDM rubber (50/50) with different concentrations of HAF carbon black up to 100 phr cured by gamma irradiation indicates that both the degree of loading of the filler and the irradiation dose play an effective role in the conductive properties. Majority of the carbon blacks including HAF have an amorphous quasi-graphite structure with high electron mobility within its hexagonal layer similar to the conducting mechanism of graphite. The electrons flow from one aggregate to another by crossing two barriers such as the aggregate gap width and chemisorbed oxygen complexes existing at the particles or aggregate surfaces acting as insulators. This consumes more energy. The occurrence of the oxygen complexes is diminished to a great extent due to radiation-induced cross-linking and matrix–filler interaction. Thus, the concentration of HAF and the appropriate radiation dose together attain the semiconductive character for the EPDM/NBR blend [79].

Frequency dependence of dielectric constant ε' and ac conductivity of EPDM–HAF black composite increase with phr of HAF (~30 phr and the frequency range 100–105 Hz) and the vulcanization methods. The compound vulcanized by 5 and 10 laser shots shows minimum value of the percolation threshold.

Radiation-induced physicochemical investigations and their impact on the electrical properties of the elastomer blend are studied using FTIR by Deepalaxmi and Rajini [80]. SIR-EPDM blend having 50:50 composition shows electrical changes which reflect in the arc resistance, surface resistivity, and volume resistivity values of the blend after electron beam irradiation (dose = 5 Mrad, 15 Mrad and 25 Mrad).

E-Beam irradiation causes the elastomeric chain cross-linking and chain scission reactions. This results in the formation of new functional groups such as Si–H, Si–CH_3–CH_2, apart from the various functional groups of the component polymers. This indicates that inter molecular cross-linking takes place between SiR and EPDM. The radiation dose of 15 Mrad causes the decreasing effect on the resistivity of the blend due to molecular chain scissions. However, a 73 % increase in volume resistivity has been noticed at 25 Mrad and is attributed to the appearance of new =C–H (alkene, strong) group at 673 cm^{-1} [80].

4.1.2 Composites with Expanded Graphite

The electronic devices demand high protection from microwaves. The microwave absorbing materials have gained importance in communication industry. EPDM is a promising matrix material for this application that is used in conjugation with EG.

Among the various conducting fillers, naturally abundant graphite which possesses good electrical conductivity of about 10^4 S cm^{-1} at ambient temperature has been widely used. In most of the cases, relatively large quantities of graphite are needed to reach the critical percolation value. However, too high concentrations of conductive filler could be detrimental for mechanical properties.

Compatibilized and uncompatibilized EG-loaded EPDM/FKM (50/50, w/w) blends have been prepared and their cure characteristics, filler dispersion, limiting oxygen index, kinetics of thermal degradation, and mechanical and dc electrical properties have been evaluated. Maleic anhydride-grafted EPDM (MA-g-EPDM) has been used as compatibilizer. The dielectric properties have been measured in S (2–4 GHz) band frequency using cavity perturbation technique. The cure time decreases at high loading level due to increase in thermal transition in the presence of EG which promotes vulcanization. Cure characteristics show first order. Tensile properties of composites especially with compatibilizer are enhanced. Addition of EG improves the flame retardancy of the blends and also the ac and dc electrical conductivity due to the formation of conductive networks. The dielectric permittivity and dielectric loss increase with frequency and EG loading [23, 24].

4.1.3 Composites with Conductive Polymers

Among the conductive polymers, polyaniline is one of the most commonly used polymer and it has been evaluated for use in high-voltage engineering for power capacitors. Proposed applications include the use of polyaniline as filler in semiconducting layers as well as in the polymer films used for power capacitors. It has also been shown that polyaniline has nonlinear electrical properties (i.e., nonlinear voltage–current relationship), both when compounded with an insulating matrix and on its own. Nonlinear materials are used as field grading materials in high-voltage engineering and are commonly based on ceramic particles treated in different ways (e.g., by variation of particle size) compounded into a polymer or elastomer matrix. EPDM–polyaniline composites exhibit nonlinear properties, and the conductivity values can be controlled with the addition of carbon black without altering the mechanical strength of the composites [81].

In case of extrinsically conducting polymers, the rate of addition of fillers and the aggregation of particles is critical. The electrical conduction is through interparticle electronic transfer. Large amounts of fillers are required to achieve the conductive phase in the composites. The intrinsically conducting polymers such as polypyrrole when blended with insulating EPDM matrix provide good levels of conductivity. Such combinations are useful in EMI shielding or antistatic protections [82].

4.1.4 Composites with Ceramics

Utilization of ceramic materials as reinforcements in polymer composites is an effective solution to the challenge of developing new polymers for specific sets of properties and applications. With the increase in numerous applications of these materials, more and more knowledge is needed to gain a better understanding of their filler–matrix interaction, which can give them different physical properties. Titanium carbide (TiC) is an important material for high-temperature applications because of its high melting point, hardness, elastic modulus, and electrical conductivity as well as its relatively low coefficient of thermal expansion.

Composites of EPDM/TiC have been prepared as thermistors, with new double negative and positive temperature coefficients of conductivity (NTCC/PTCC). The concentration of TiC has been varied from 0 to 20 phr along with 50 phr HAF. TiC reduces the curing time and accelerates the driving force during the curing process. The electrical properties are also strongly affected by TiC. The dielectric constant increases linearly with temperature. PTCC can be used in antistatic materials, electromagnetic radiation shielding, and electromagnetic interface shielding. The development of NTCC and PTCC polymer composites can be considered as one of the major advances in electronic materials research [73].

Electrical stress grading materials at the insulator–conductor interface for high-voltage applications exhibit nonlinear current–voltage characteristics. Such materials are comprised of an insulating polymer matrix and semiconducting fillers such as ZnO, SiC, or conducting carbon black. One of the challenges in developing field grading materials is the ability to tailor the nonlinear behavior, the low-field conductivity, and the field at which the nonlinear behavior begins. Conductive fillers alone do not provide this tailor ability although mixtures of fillers can. The well-known nonlinear behavior of ZnO and the ability to alter the phases present by the treatment with SnF_2 to tailor the nonlinear behavior of ZnO-filled polymers can be explained on the basis of alteration of the electrical behavior between the heterogeneous particles, which in turn control the nonlinear behavior of the composite. Nonlinear behavior of metal oxide varistors is dominated by a double Schottky barrier mechanism. As such, the nonlinear behavior is controlled by the interface between the particles and the packing of the particles as well as their size. At certain filler concentrations, the resulting nanocomposites exhibit highly nonlinear I-V characteristics. SiC/polymer composites provide further insight into the mechanism leading to nonlinearity in filled polymers. It is also common to use conductive or semiconductive particles in conjunction with ceramic fillers to tailor the electric properties as reported by Wang et al. The ability to tailor the properties makes it possible to use field grading material for both ac and dc as well as for different voltage levels which is advantageous [83].

4.1.5 Composites with Inorganic Conductive Fillers

Apart from traditional fillers, there has been growing interest in inorganic fillers which possess excellent electromagnetic properties. The effect of pH level and surface treatment of samarium oxide (Sm_2O_3), samarium borate ($SmBO_3$), and Sb-doped SnO_2 (ATO) particles on peroxide-cured EPDM rubber composites have been investigated. Coupling agent such as bis-(-3-(triethoxysilyl) propyl) tetra-sulfide (KH845-4) and different level of fillers have significant effect on cure properties of EPDM composites. This is because the coupling agent introduces sulfuric linkages on the surface of the oxide particles which cleave at 170 °C and participate in vulcanization to form C–S linkages. Hence, the cross-link density and mechanical properties of the EPDM composites are enhanced. The pH values of the particles also have a significant effect on the cure and mechanical properties of the composites. The dielectric constant and the dielectric loss of the EPDM composites show an increase with filler loading from 15 to 85 phr followed by decrease at 100 phr. EPDM-ATO composite shows higher dielectric constant compared to other composites at relatively low loading level. Surface and volume resistivities decrease with increasing filler loading in the composites [84].

In another study, Su et al. have studied the cure, mechanical, and electric properties of EPDM composites with 100 phr of Sm_2O_3 treated with different coupling agents such as stearic acid (SA), isopropyl tri(dioctylphosphate) titanate (NDZ102), (KH845-4), and N-b-(aminoethyl)-g-amino propyl methyl dimethoxysilane (SG-Si602). Some functional groups are attached to the filler surface in the presence of the coupling agents. Carboxyl groups retard the EPDM cure, while amino groups, P=O bonds, and S atoms accelerate the cure. Mechanical properties of the composites are enhanced in the presence of amino groups due to the formation of additional rigid C–C linkages, while S atoms boost the mechanical properties of composite by generating flexible S–C linkages. PO bonds probably undergo cleavage during vulcanization and form flexible P–C linkage. Thus, composites with NDZ102- and KH845-4-treated filler exhibit better mechanical properties than those with SG-Si602-treated filler. Composites with KH845-4-treated Sm_2O_3 have the lowest dielectric constant because of minimum polarity of sulfuric atoms. The number of conductive channels and the current density increases with decreasing polarity resulting in low dielectric strength and volume and surface resistivity of the composites [85].

4.1.6 Composites with Steel Fibers

Composites of EPDM with steel fibers have also been reported. They are light in weight since the steel fibers affect the weight negligibly as only small additions (20–30 phr) are enough to reduce the resistivity by 1000 times. Addition of ~20–30 phr (of long as well as short fibers) reduces the resistance of the composite to ~35–40 K Ω from highly insulating electrical range. The steel fibers provide a continuous conducting network in the matrix yielding conductive composite. They can be processed easily, and it is possible to control the conductivity without compromising the physical and mechanical properties. Addition of small amounts of pigments is also permissible by retaining other properties. Important advantage of steel fibers is that they can be recycled. These results indicate that the composite has a well-organized network structure with one component (rubber) being insulating while the other (steel fibers) being conducting, which effectively leads to the induction of conductivity in the matrix. Among the two types of fibers, the SF is expected to form a better network in the matrix and hence exhibits relatively higher conductivity at lower loading levels in comparison with LF. Similar reason holds for the differences observed as a function of concentration [86]. The decreasing trend in the surface resistance can be observed from Fig. 4.

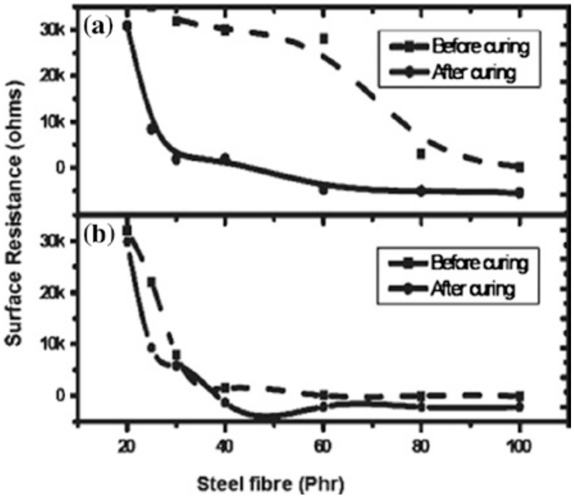

Fig. 4 Effect of **a** LF and **b** SF on electrical conductivity of composites [86]. Copyright 2015. Reproduced with permission from John Wiley & Sons. https://s100.copyright.com/CustomerAdmin/PLF.jsp?ref=14934013-b7fc-4b33-8248-8436a4b5a884

4.2 Conductive Blends

The blending of elastomers together improves the processing and physical properties which are further enhanced by vulcanization and filler distribution. Filler distribution is the important aspect in achieving the properties as it is controlled by the molecular weight of the polymer in each phase and chemical interaction between polymer and filler. Sau et al. have worked on the blends of incompatible elastomer pairs having different polarity which are also very useful for achieving a high degree of conductivity, particularly because of their well-defined interface [87].

Conductive rubber composites from EPDM and acrylonitrile blends have been prepared with acetylene black as the filler. The electrical and mechanical properties of the composites have been investigated. The results indicate that the percolation threshold of filler for achieving high conductivity varies as a function of viscosity of the blends. The conductivity shows an increase with temperature, while the activation energy of conduction is observed to decrease with decrease in filler concentration and percentage of NBR in the blend. The blends exhibit negative coefficient of temperature (NCT) effect in resistivity, and the temperature dependence becomes marginal after percolation limit. The degree of reinforcement in the presence of filler is higher in EPDM and NBR. However, the blends show lower reinforcing potential which can be attributed to the incompatibility of the two constituent polymers in the blend [88].

The service life of rubber is dependent on the behavior of fillers in rubber vulcanizates. Wakil et al. have studied the effect of calcium carbonate, Sillitin N85, and SRF black as filler on EPDM. The cross-link density of the vulcanizates was measured by using ultrasonic and pulse-echo technique. SRF enhances the mechanical properties of the vulcanizate, while Sillitin N85 shows improvement in electrical conductivity after oven aging between 2 and 10 days at 90 °C. The conductivity is basically attributed to the mobility of the free electrons taking place through the interaction between functional filler Sillitin N85 and the EPDM vulcanizate [89].

4.3 Conductive Coatings

A broad range of applications requires an effective conductive coating covering a major segment of antistatic protection such as airplane paints, magnetic tape coatings, spark resistant equipments, and primers for electrostatic spraying. EPDM-conductive filler such as carbon black is used for such applications. The stress cone used in switchgears coated with conductive EPDM filled with carbon black is the example of this application.

4.4 Conductive Foams

In recent years, the users and manufacturers of communication equipment, photographic processing equipment, and electronic devices have already recognized the need to protect their equipment and devices against electrostatic charges, particularly the adverse effects of electrostatic discharge. In order to meet this requirement, a new industry has appeared, called static control industry, and the conductive foam can be used to provide physical protection for electronic components and for electrostatic protection. The foaming conductive polymer is primarily useful for its physical properties, high thermal expansion, its buffering ability, and conductivity. It has been widely used in the detection of static electricity and the elimination of the electrostatic field. Foam composites can be prepared by melt blending and molded foam.

Liu et al. have developed CB/PVC/EPDM foam composites by melt blending and molded foam. The foam with 10 % CB content shows good bubble structure and NTC effect in the heating process. At latter stage of heating, they exhibit PTC phenomena. The DCP content in the composite has great impact on the resistance value and the composite cell formation. The foam plastic has many valuable properties; it has been widely used in industry, agriculture, transportation, military, aerospace industry, and so on. In developed countries, the growth of foam plastic production industry has been rapid and extensive [90].

EPDM structure foams with different apparent densities have been compounded by using different concentrations of foaming agent, azodicarbonamide. The electrical conductivity has been measured under different compression strains (0–60 %). The stress relaxation at different compressive stresses has also been measured. The results show decrease in dielectric permittivity with increasing frequency and foam content which could be due to carbon black dilution. At higher foam concentration, the sample loses its dielectric properties. The conductivity in foams is because of increased mobility of rubber chain molecules. The conductivity shows a sharp decrease with increase in deformation [91].

4.5 Conductive Nanocomposites

The field of nanoscience has blossomed over the last twenty years, and the importance of nanotechnology is increasing as miniaturization has become important in areas such as computing, sensors, biomedical, and many other applications. The discovery of polymer nanocomposites by the Toyota research group has added a new dimension in the field of materials science. In particular, the use of inorganic nanomaterials as fillers in the preparation of polymer/inorganic composites has attracted increasing interest owing to their unique properties and numerous potential applications in the automotive, aerospace, construction, and electronic industries [92].

Elastomer nanocomposites have established a unique position among technologically important materials because of their extensive and potential applications. The dispersion of conductive materials in an elastomer is the most important step during the fabrication of a composite. In general, elastomer nanocomposites can be synthesized in one of the three ways, viz. melt intercalation, solution mixing, and in situ polymerization. These techniques are useful for nanofillers/elastomer composite fabrication as well.

The last few years have seen the extensive use of nanoparticles with large surface area to achieve the required properties at much lower filler loadings. Nanometer-scale particles including spherical particles of silica or titanium dioxide generated in situ by the solgel process are seen to significantly enhance the physical and mechanical properties of rubber matrices. On the other hand, alternative fillers with high aspect ratio such as layered silicates, carbon or clay fibers, and single-wall carbon nanotubes (SWCNTs) or multiwall carbon nanotubes (MWCNTs) often bring about an improvement in mechanical response of the material, along with other interesting properties such as gas barrier, fire resistance, or thermal and electrical conductivities.

The effect of MWCNTs on mechanical and electrical properties of three different sulfur-cured hydrocarbon rubbers, NBR, SBR and EPDM, has been investigated by Bokobza. The composites have been prepared by solution blending using sonication process. The processing conditions have a strong effect on the electrical properties of the composite which are very sensitive to nanotube dispersion in the elastomeric matrix. The potential of CNTs as reinforcing fillers for polymeric matrices has been immediately recognized after their first observation in 1991. CNTs consist of folded graphene layers with cylindrical hexagonal lattice structure. As a result of this unique arrangement, they display exceptional stiffness and strength and remarkable thermal and electrical properties, which make them ideal candidates for the design of advanced materials. These exceptional properties are expected to impart major enhancements in various properties of polymer composites at relatively low filler loadings. The requirement of CNT having diameter of 10 nm, length of 1.5 μm, and surface area of 250–300 $m^2\ g^{-1}$ is less than 10 wt%. The composites can be prepared by solution blending using sonication process [3].

Materials with a combination of nanosized organic, inorganic materials and polymers are expected to show the properties that are synergistic combinations of the individual components with the reinforcing components, such as nanoclay, nanosilica, and nanographite. These are class of organic, inorganic hybrid materials, where the inorganic components are uniformly distributed in nanometer scale (10–90 nm) within the polymer matrix.

EPDM-CNT composites are potential materials to be used as sensors. Microscale change of interelectrical condition in EPDM matrix takes place due to deformation upon exertion of external forces as the contact resistance changes. The composite thus reveals macroscale piezoresistivity. In addition to this, proper alignment of CNT in the matrix also improves mechanical, thermal, and electrical properties [93]. These flexible strain sensors can measure large deformations on flexible structures. They are eligible to develop biomimetic artificial neuron that senses the deformation, pressure, and shear force [94].

Composites of NBR and EPDM have also been prepared by adding short carbon fibers. They are a better choice as conductive filler since they provide higher conductivity at lower loading level. The volume resistivity increase with temperature is probably due to the breakdown of conductive network. It becomes negligible at high loading levels of fillers together with a marginal degree of reinforcement. The resistivity versus temperature plot exhibits electrical set as well as electrical hysteresis during heating–cooling cycle.

Sahoo and Sahoo have synthesized EPDM–MWCNT composites. They have dispersed MWCNTs in xylene by ultrasonication, the concentration of MWCNTs was varied between 0.5 and 5 wt% in the final composite. EPDM solution was slowly poured into the dispersion of MWNTs/xylene. The individual fibrous phases had diameters of about 100 nm which must be due to the coating of EPDM layer on CNT. The nanocomposites exhibited improved mechanical properties. The electrical conductivities of EPDM/c-MWNT increased with the increase of c-MWNT content [95].

Nanocomposites of polymer/graphene have gained importance due to the excellent thermal, mechanical, and electrical properties of graphene. As graphene has a honeycomb structure, it facilitates the design of composites with superior performance at very low loading levels. However, since pristine graphene has a tendency to agglomerate, it has to be chemically oxidized so that it disperses well in the polymer matrix. High-performance nanocomposites exhibiting superior functional and environmental properties have been prepared using EPDM and graphene [96].

5 Conclusions

This chapter presents an overview of the applications of EPDM in electronic industry as electrically insulating as well as conducting material. EPDM is an ideal candidate to be used in the form of compound and blends with other polymers, composites, coatings, and nanocomposites reinforced with conductive fillers for such applications. Conductive carbon, EG, metal fibers, and conductive polymers are the excellent conductive fillers and are feasible substitutes for expensive materials. CNT, carbon fibers, graphene, and other inorganic nanomaterials are the highlights in the electrical applications in electronics. EPDM composites and nanocomposites prove to be promising as dual functional materials for applications; as insulators such as cables, cable terminals, and shrouds; and as conductors in EMI shielding, sensors and actuators, antistatic dissipation, energy harvesting devices, and microwave absorption materials.

References

1. Karpeles R, Grossi AV (2001) EPDM rubber technology. In: Handbook of elastomers, 2nd edn. Marcel Decker, Inc., New York, pp 845–876
2. Cesca S (1975) The chemistry of unsaturated ethylene-propylene-based terpolymers. J Polym Sci Part A: Polym Chem Macromol Rev 10(1):1–231
3. Bokobza L (2012) Enhanced electrical and mechanical properties of multiwall carbon nanotube rubber composites. Polym Adv Technol 23:1543–1549
4. Blodgett RB (1983) Twenty-five years of insulated wire and cable. In: Paper #37 presented at a meeting of the rubber division, ACS, Philadelphia, PA, May 1982. RUBBER CHEM. TECHNOL. 56: 270
5. Mokhothu TH, Luyt AS, Messori M (2014) Reinforcement of EPDM rubber with in situ generated silica particles in the presence of a coupling agent via a sol–gel route. Polym Test 33:97–106
6. Henning SK (2007) The use of coagents in the radical cure of elastomers. In: Proceedings of 56th international wire and cable symposium, Exton, PA, USA, pp 587–593
7. Coran AY (2005) Vulcanisation. In: Mark JE, Eirich FR (ed) The science and technology of rubber, 3rd edn. Elsevier Academic Press, pp 322–3
8. Chokanandsombat Y, Owjinda S, Sirisinha C (2012) Comparison on properties of acrylonitrile styrene butadiene rubber (NSBR) and styrene butadiene rubber (SBR)/nitrile rubber (NBR) blends. KautGummiKunstst 65(11–12):41–46
9. Calleja FJB, Bayer RK, Ezquerra TA (1988) Electrical-conductivity of polyethylene carbon-fiber composites mixed with carbon-black. J Mater Sci 23:1411
10. Genies GM, Boyle A, Lapkowski M, Tsintavis C (1990) Polyaniline: a historical survey. Synth Met 36:139
11. Mattoso LHC (1996) Polyaniline: synthesis, structure and properties. Quim Nova 19:388
12. Faez R, De Paoli MA (2001) A conductive elastomer based on EPDM and Polyaniline: II. Effect of crosslinking method. EurPolym J 37:1139
13. Walker J (2012) Elastomer engineering guide. http://www.jameswalker.biz. Accessed 10 Mar 2014
14. Bhuvaneswari CM, Kakade SD, Gupta M (2006) EPDM as futuristic elastomer for insulation of solid rocket motors. Defense Sci J 56(3):309–320
15. Moribe T (2012) Mitsubishi heavy industries. Tech Rev 49(4):38–43

16. Jl Mead, Tao Z (2002) Insulation materials for wire and cable applications. Rubber Chem Technol 75:701–712
17. Sarathi R, Rao UM, Venkataseshaiah C (2002) Investigation of surface modifications in EPDM rubber due to tracking. Polym Test 21:463–471
18. Vijayalekshmi V, Abdul SSM (2013) Mechanical, thermal and electrical properties of EPDM/silicone blend nanocomposites. Int J Eng Res Appl (IJERA) 3(2): 1177–1180. ISSN: 2248–9622
19. Delor JF, Lacoste J, Barrois ON, Lemaire J (2000) Photo-thermal and natural ageing of (EPDM) rubber used in automotive applications. Influence of carbon black, crosslinking and stabilizing agents. Polym Degrad Stab 67:469–477
20. Su J, Zhang J, Xu Z (2009) Combined effect of pH level and surface treatment of Sm_2O_3, $SmBO_3$ and ATO particles on cure, mechanical and electric properties of EPDM composites. Polym Test 28:419–427
21. Premamoy G, Bibha C, Achintya SK (1996) Thermal and oxidative degradation of PE-EPDM blends vulcanized differently using sulfur accelerator systems. Eur Polym J 32(8):1015
22. Nair AB, Philip K, Joseph R (2013) Effect of expanded graphite on thermal, mechanical and dielectric properties of ethylene–propylene–dieneterpolymer/hexafluoropropylene–vinylidenefluoridedipolymer rubber blends. Eur Polym J 49:247–260
23. Celzard A, Mareche JF, Furdin G, Puricelli S (2000) Electrical conductivity of anisotropic expanded graphite-based monoliths. J Phys D Appl Phys 33:3094–3101
24. Zheng W, Wong SC, Sue HJ (2002) Transport behavior of PMMA/expanded graphite nanocomposites. Polymer 73:6767–6773
25. Saunders DS, Galea SC, Deirmendjian GK (1993) Development of fatigue damage around fastener holes in thick graphite/epoxy composite laminates. Composite 24:309–321
26. Maia JV, Massi M, Sobrinho ASS (2013) Influence of gas and treatment time on the surface modification of EPDM rubber treated at afterglow microwave plasmas J. Appl Surf Sci 285:918–926
27. Chan CM, Ko TM, Hiraoka H (1996) Polymer surface modifications by plasmas and photons. Surf Sci Rep 24:1–54
28. Grythe KF (2006) Surface modification of EPDM rubber by plasma treatment. Langmuir 22:6109–6124
29. Dutra JN, Mello SAC, Massi M, Maciel HS (2006) Surface characterization of synthetic vulcanized EPDM rubber treated with oxygen/argon plasma. In: 41th international symposium on macromolecules, MACRO, Rio de Janeiro 18–21 Feb 2013
30. Ehsani M, Morshedian J, Bakhshandeh R (2004) An investigation of dynamic mechanical, thermal, and electrical properties of housing materials for outdoor polymeric insulators. Eur Polym J 40:2495–2503
31. Canaud C, Nunes CR (2001) EPDM formulations for electric wires and cables. Elastomers Plast 54:56–60
32. Sharma KRET (2001) Polymeric insulators. Technical Article, www.appstate.edu/~clementsjs/surfaceflashover/insulatortesting.pdf
33. ANSI/IEEE Std 4-1978—techniques for high voltage testing, 10.1109/IEEESTD.1995.81695
34. Joshi KD (2014) Rubber components. http://www.kdjoshi.com. Accessed 10 May 2014
35. Ehsani M, Borsi H, Bakhshandeh GR (2004) An investigation of dynamic mechanical, thermal, and electrical properties of housing materials for outdoor polymeric insulators. Eur Polym J 40:2495–2503
36. Tokoro T, Hackam R (2001) Loss and recovery of hydrophobicity and surface energy of HTV silicone rubber. IEEE Trans Dielectr Electr Insulat 8(6):1088–1097
37. Bernstorf RS, Zhao T (1998) Aging tests of polymeric housing materials for non-ceramic insulators. IEEE Electr Insulat Mag 14(2):26–33
38. Hackam R (1999) Outdoor high voltage composite polymeric insulators. IEEE Trans Dielectr Electr Insulat 6(5):557–585

39. Gubanski SM (2003) Modern outdoor insulation—concern and challenges. In: Proceeding of 13th international symposium on high voltage engineering (ISH), Delft, Netherlands
40. Wang X, Schadler LS, Hillborg H, Auletta T (2006) Nonlinear electrical behavior of treated ZnO-EPDM nanocomposites. ieeexplore.ieee.org/ iel5/4105355/ 4105356/ 04105460.pdf
41. Donzel L, Gramespacherz H (2004) Silicone composites for HV applications based on microvaristors. In: 2004 international conference on solid dielectrics
42. Mårtensson E, Nettelblad B, Gäfvert U, Palmqvist L (1998) Electrical properties of field grading materials with silicon carbide and carbon black. In: IEEE international conference on conduction and breakdown in solid dielectrics pp 548–552
43. Mårtensson E, Gäfvert U (2004) A three-dimensional network model describing a nonlinear composite material. J Phys D:Appl Phys 37:112–119
44. Sjöstedt H, Montaño R, Gubanski SM (2009) Charge relaxation on surfaces of polymeric insulating materials for outdoor applications. Mater Sci-Pol 27(4/2):1129–1137
45. Khan Y (2010) Degradation of hydrophobic properties of composite insulators in simulated arid desert environment. Int J Eng Technol IJET-IJENS 10(01): 64–68
46. Deng H, Hackam R (2000) Dielectr Electr Insul IEEE Trans 7(1): 84–94
47. Sarathi R, Rao UM, Venkataseshaiah C (2001) Investigations of surface modifications in ethylene propylene diene monomer (EPDM) rubber due to tracking. Polym Test 21:463–471
48. Yoshimura N, Kumagai S, Du B (1997) Research in Japan on the tracking phenomena of electrical insulating materials. IEEE Electr Insul Mag 13:8–19
49. Haykin S (1999) Neural networks: a comprehensive foundation. Upper Saddle River, Prentice Hall. ISBN 0132733501
50. Ahmad AS, Aljunid ASK (2004) Assessment of ESDD on high-voltage insulators using artificial neural network. Elsevier. Electr Power Syst Res 72(2):131–136
51. Su J, Chen S, Xu Z (2009) Comparison of cure, mechanical, electric properties of EPDM filled with Sm_2O_3 treated by different coupling agents. Polym Test 28:235–242
52. Kang D, Desai K, Lee J, Mead J (2004) Assessing the electrical properties of alternative wire and cable coatings: Metallocene EPDM. Technical report no. 56, pp 1–23
53. Bartnikas R (2000) Characteristics of cable materials. In: Power and communication cables. IEEE Press, New York. doi:10.1109/9780470545546.fmatter
54. Mead JL, Tao Z (2011) Insulation materials for wire and cable applications. Rubber Chem Technol 75:701–712
55. Cheremisinoff NP (ed) (1989) ªHandbook of polymer science and technology. Marcel Dekker, New York, Chapter 2 p 341
56. Nasrat LS, Hamed M, Ibrahim AA (2014) Effect of ultra violet on dry band arcing behavior of EPDM outdoor insulators. Int J Emerg Technol Adv Eng 4(10): 1–8. ISSN 2250-2459
57. Farzad R, Hassan A, Jawaid M, Piah MAM (2013) Mechanical properties of alumina trihydrate filled polypropylene/ethylene propylene diene monomer composites for cable applications. Sains Malaysiana 42(6):801–810
58. Ehsani M, Zeynali E, Abtahi M, Harati A (2009) LDPE/EPDM blends as electrical insulators with unique surface. Electrical and mechanical properties. Iran Polym J 18(1):37–47
59. Kumar MSC, Alagar M (2002) Development and characterisation of vinyloxyaminosilane grafted ethylene-propylene-dieneterpolymer (EPDM-g-VOS) for engineering applications. Eur Polym J 38:2023–2031
60. Galimberti M, Cipolletti V, Theonis RO, Kumar V (2014) Recent advancements in rubber nanocomposites. Rubber Chem Technol 87(3):417–442
61. Tang Q, Liang J, Zhang F (2015) Effect of coupling agent on surface free energy of organic modified attapulgite (OAT) powders and tensile strength of OAT/ethylene-propylene-diene monomer rubber nanocomposites. Powder Technol 270:92–97
62. Vijayalekshmi V, Majeed ASSM (2013) Mechanical, thermal and electrical properties of EPDM/silicone blend nanocomposites. Int J Eng Res Appl (IJERA) 3(2):1177–1180. ISSN: 2248-9622

63. Sau KP, Chaki TK, Khastgir D (1998) Carbon fibre filled conductive composites based on nitrile rubber (NBR), ethylene propylene diene rubber (EPDM) and their blend. Polymer 39(25):6461–6471
64. Morsy RM, Ismaiel MN, Yehia AA (2013) Conductivity studies on acrylonitrile butadiene rubber loaded with different types of carbon blacks. Int J Mater Methods Technol 1(4): 22–35. ISSN 2327-0322
65. Reinaldo R, João SC (2004) Electroactive polymer (EAP) actuators the artificial muscles—reality, potential and challenges, 2nd edn. SPIE Press, Washington, Yoseph Bar-Cohen, pp p1–p3
66. Ghosh P, Chakrabarti A (2000) Conducting carbon black filled EPDM vulcanizates: assessment of dependence of physical and mechanical properties and conducting character on variation of filler loading. Eur Polym J 36:1043–1054
67. Brosseau C, Boulic F, Le Mest Y, Loaec J, Beroual A (1997) Dielectric and microstructure properties of polymer carbon black composites. J Appl Phys 81:882–891
68. Norman RH (1970) Conductive rubber and plastics. EPC, New York, p 270
69. Sau KP, Chaki TK, Khastgir D (1997) Carbon fibre filled conductive composites based on nitrile rubber (NBR), ethylene propylene diene rubber (EPDM) and their blend. J Mater Sci 32:5717–5724
70. Hoffman W (1998) Rubber technology handbook. Hanser, Munich 431
71. Younan AF, Choneimt AM, Nour AE (1995) Electrical and physical properties of EPDM rubber loaded with semi reinforcing furnace black. Polym Degrad Stab 49:215–222
72. Sau KP, Chaki TK, Khastgir D (1999) Electrical and mechanical properties of conducting carbon black filled composites based on rubber and rubber blends. J Appl Polym Sci 71:887–895
73. Sau KP, Chaki TK, Khastgir D (1999) The effect of compressive strain and stress on electrical conductivity of conductive rubber composites. Rubber Chem Technol 73:310–324
74. Sahoo MK, Sahoo S (2014) Synthesis and characterization of ethylene-propylene diene monomer(EPDM)/MWCNT composites. Adv Polym Sci Technol: Int J 4(1):7–11
75. Kanamori (1986) Structural formation of hybrid siloxane-based polymer monolith in confined spaces. J Sep Sci 27(10–11): 874–886
76. Chen YH, Grundlehner B, Gadeyne S, Boon P, Hoof CV (2014) Soft, comfortable polymer dry electrodes for high quality ECG and EEG recording. Sensors 14: 23758–23780. doi:10.3390/s141223758
77. Suzumori K, Suzuki H (2007) A Bending pneumatic rubber actuator realizing soft-bodied manta swimming robot. In: IEEE international conference on robotics and automation Roma, Italy 10–14 April 2007
78. Shokr FS (2011) Dielectric properties of carbon black loaded EPDM rubber based conductive composites: effect of curing method. J Am Sci 7(9):387–397
79. Magda M, Abou Z (2007) Radiation effect on properties of carbon black filled NBR/EPDM rubber blends. Eur Polym J 43:4415–4422
80. Deepalaxmi R (2014) Property enhancement of SiR-EPDM blend using electron beam irradiation. J Electr Eng Technol 9(3):984–990
81. Sonerud B, Josefsson S, Furuheim K, Frohne C (2013) Nonlinear electrical properties and mechanical strength of EPDM with polyaniline and carbon black filler. In: IEEE international conference on solid dielectrics, Bologna, Italy 30 June–4 July 2013
82. Zoppi RA, De Paoli MA (1996) Chemical preparation of conductive elastomeric blends: polypyrrole/EPDM-II Utilization of matrices containing crosslinking agents, reinforcing fillers and stabilizers. Polymer 37(10):1999–2009
83. Gupta T (1990) Application of zinc oxide varistors. J Am Ceram Soc 73:1817–1840
84. Allen RD (1983) Fundamentals of compounding EPDM for cost/performance. J Elastomer Plast 15(1):19
85. Su J, Chen S, Zhang J, Xu Z (2009) Comparison of cure, mechanical, electric properties of EPDM filled with Sm_2O_3 treated by different coupling agents. Polym Testing 28:235–242

86. Athawale AA, Joshi AM (2011) Studies on electrically conductive composites of ethylene propylene diene monomer rubber and steel fibers. J Appl Polym Sci 120:3036–3041
87. Gessler AM (1969) Evidence for chemical interaction in carbon and polymer associations. Extension of original work on effect of carbon black structure. Rubber Chem Technol 42:850
88. Langley M (1973) Carbon fibres in engineering. Composites 5(2):84
89. Wakil AAE, Megeed AAE (2011) Effect of calcium carbonate, Sillitin N 85 and carbon black fillers on the mechanical and electrical properties of the EPDM. ARPN J of Engg and Appl Sci 6(5):24–29
90. Liu X, Xing H, Zhao L, Chen X (2012) Preparation and electrical properties of CB/PVC/EPDM conductive foam composite. In: 2nd international conference on electronic and mechanical engineering and information technology (EMEIT)
91. Lawindy AMYE (2005) Studies of electrical and physico-mechanical properties of EPDM structure, foams, Egypt. J Solids 28(1):97–107
92. Heggli M (2001) Elastomeric nanocomposites. Research plan. Institute of Polymers, ETH Zurich, Project Review. http://www.mat.ethz.ch
93. Sekitani T, Aida T, Someya T (2002) Carbon nanotubes—the route toward applications. Science 297:787
94. Kim J, Baek WK, Lim KT, Kang I (2010) Flexible strain sensor based on carbon nanotube rubber composites. Nanosensors, biosensors and info-tech sensors and system 76460 N: doi:10.1117/12.847364
95. Smith CS (1954) Piezoresistance effect in germanium and silicon. Phys Rev 94:42
96. Allahbakhsh A, Sharif F (2013) Cure kinetics and chemorheology of EPDM/graphene oxide nanocomposites. Thermochim Acta 563:22–32