CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

A study of the literature provides the knowledge on the background and current trends on the related aspects to draw attention to the significance of current investigation. This chapter highlights different facets of PMCs covering their physico-mechanical, thermal and tribological performances. The topic comprises the study on

- Fiber reinforced polymer composites
- Particulate filled polymer composites
- Hybrid polymer composites
- Mechanical properties of fiber reinforced, particulate filled and hybrid polymer composites
- Thermal properties of fiber reinforced, particulate filled and hybrid polymer composites
- Tribological properties of fiber reinforced, particulate filled and hybrid polymer composites
- Implementation of statistical tools like design of experiments and optimization techniques

2.2 Fiber reinforced polymer composites

For most applications neat polymers are not the right choices mainly because of their poor strength. Reinforcements for polymers are available in various forms. Fiber (short, long, woven, nonwoven, etc.) is one among them and is
preferred depending on prerequisite application. Short fibers offer easy injection mould ability for thermoplastic composites. The strength offered, however, is moderate and depends on fiber orientation. Long fibres on the other hand offer very high strength, but only in one direction and that too at the cost of easy processability. These are generally processed by compression moulding and hence fiber handling is a tough job. For tribo—materials, most popular fibrous reinforcements consists of glass, carbon, graphite, aramid etc. Again each has its own advantages and limitations. Glass fibers are least expensive and offer moderate strength and wear resistance at the cost of increased friction coefficient, damage of the counterface by abrasion generally and are used in combination with solid lubricants. Aramid fibers are of moderate cost, offer considerable wear resistance and strength without excessive incremental increase in the coefficient of friction value and neither damages the counterface. However, their temperature resistance is poor. On the other hand carbon/graphite fibers are most expensive with excellent; specific strength, thermal conductivity and self-lubricity properties. Table 2.1 provides few characteristics of these fibers as reported by Lee (1991).

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Tensile Strength (GPa)</th>
<th>Specific Strength (GPa)</th>
<th>Modulus of Elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aramid (Kevlar 49)</td>
<td>1.44</td>
<td>3.6-4.1</td>
<td>2.5-2.85</td>
<td>131</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.78-2.15</td>
<td>1.5-4.8</td>
<td>0.7-2.7</td>
<td>228-724</td>
</tr>
<tr>
<td>E-glass</td>
<td>2.58</td>
<td>3.45</td>
<td>1.34</td>
<td>72.5</td>
</tr>
<tr>
<td>Boron</td>
<td>2.57</td>
<td>3.6</td>
<td>1.4</td>
<td>400</td>
</tr>
</tbody>
</table>

2.3 Particulate filled polymer composites

Fillers improve the performance of PMCs in different ways. Filler behaviour in these compounds is governed by parameters such as particle-size, particle dispersion, surface area, shape, colour and surface chemistry. The
commonly used materials in everyday life are the composites filled with particulate fillers. Such materials are available at low cost. When working with micro-scale particles it must be taken into account that the mechanical behaviour of the particulates are likely to follow the one of the bulk filler material. The particle angularity plays a decisive role for such compounds. Therefore, it is expected that the smaller the particle size, the more efficient their reinforcing action should be. By scaling the particle size down to a nanometre range the influence from the particle’s angularity gets reduced drastically. Nanoparticles possess a huge surface-to-volume relation and are referred to as being “interface-dominated” materials. Because of their small sizes, it is extremely difficult to disperse nanoparticles uniformly. Nanoparticles agglomeration arises normally as a result of van der Waals bonding. This problem is even more complicated for high filler loadings. Hence, it is reported that low nano filler loading (1-4 vol. %), have yielded significant improvement in PMC performance.

2.4 Hybrid polymer composites

The word “hybrid” is of Greek-Latin origin. Hybrid polymer composites are multi-phased composites comprising of primary reinforcement in the form of fibers and secondary reinforcement in the form of particulate fillers. Reinforcements have been incorporated either by:

(i) Intermixing of more than one type of short fibers systematically before combining them into the polymer in a mixer, or included consecutively into the matrix material with or without surface alteration of the reinforcements.
(ii) Sandwiching of fibers or their mats or fabrics or
(iii) Using non-woven or woven fabrics of both types of reinforcements.
The behaviour of hybrid PMCs depends on the balanced quantity of the single constituents. Their performances are absolutely controlled by the span of single fiber, orientation, fiber to matrix bonding, degree of intermixing of fibers, and array of both of the fibers/fillers or combination of both. Rule of mixtures (ROM) can be used to conclude the behaviour of the hybrid material system comprising of two or more constituents. Furthermore, effective use of hybrid PMCs is concluded by the mechanical, chemical, and physical steadiness of the fiber/filler/matrix system.

2.5 Mechanical performance of fiber reinforced/particulate filled hybrid polymer matrix composites

2.5.1 Mechanical behaviour of fiber reinforced PMCs

The mechanical behaviour of the PMCs are governed by the type of matrix, the reinforcement and the interface. Hence there are many variables to be considered in the design which includes the type of matrix material and reinforcement, their relative weight percent, shape and size of the reinforcement and the quality of the interface. Discontinuous short fibers/particles reinforced thermoplastic composites have become attractive engineering materials since they offer improved performance over unreinforced materials at limited incremental cost. When these fibers are employed for reinforcement, the performance of the PMCs tend to be anisotropic as the fiber reinforcements are randomly oriented. They lack the excellent strength of continuous-fiber reinforced composites. However, they can be easily fabricated at cheaper cost. The continuous-fiber reinforcement gives a directional property, called isotropy. PMCs exhibit greater strength when they are subjected to load along the fibers and weak across the fibers.
Mallik (2007) reported that the fibers (glass, carbon and aramid) reinforced polymer composites demonstrated high stiffness and strength to weight ratio contrasted to traditional metals. The fibers can be incorporated into the matrix either in continual (single direction) or in spasmodic lengths (short fibers). One of the important modification of the polymer composites is the inclusion short fibers in the matrices. The mechanical behaviour of short fiber reinforced polymer composites (SFRPCs) have been studied since from two decades. Compared to continuous fiber composites, SFRPCs combine simpler manufacturability with low processing cost. Hence, in modern days the use of SFRP composites grew swiftly in many engineering appliances in automotive and other industries. Fu et al. (2000) reported their findings involving short glass fiber (SGF) and short carbon fiber (SCF) reinforced polypropylene (PP) composites, the mechanical behaviours such as strength, modulus and toughness increase commonly with increase in length of fiber and fiber loading. The applied load on the reinforced composites will be distributed and transmitted across fiber matrix interfaces. Hence a strong bonding improves the mechanical properties of composites. Clark and Secrist (1998) investigated the mechanical properties of injection-moulded, carbon fiber (CF) reinforced Nylon 66 (PA 66). Composites were characterized for four different fiber surface treatments. They demonstrated that, for similar fiber length distributions, improvements in both ultimate and impact strengths can be affected by increasing the degree of fiber-to-resin bonding through modification of the surface treatment. Harsha and Tewari (2003) in their work confirmed that the mechanical performances of polyether-ether-ketone (PEEK) are enhanced by reinforcing SGF and SCF which is in accordance with general observations in fiber-reinforced thermoplastic composites. Cao et al. (2011) investigated the influence of basalt fiber (BF) in ultra-high molecular weight polyethylene (UHMWPE). They reported that increase in BF content resulted in reduced toughness and enhanced strength, hardness, and creep resistance properties. Qiang et al. (2008) investigated the mechanical performance of SCF reinforced PEEK composites, where SCF is made from polyacrylonitrile (PAN) and pitch (Pitch-SCF). The crystallinity of PAN-
SCF/PEEK increased with the content of SCF, whereas the crystallinity of Pitch-SCF/PEEK was not changed with variation of SCF content. The storage tensile modulus of PAN-SCF/PEEK composite is greater than that of pitch-SCF/PEEK material. Impact strength of PAN-SCF/PEEK increased with the inclusion of SCF and was greater than that of Pitch-SCF/PEEK, since PAN-SCF has strong bonding with the PEEK matrix. Liang (2011) investigated the dynamic mechanical properties of glass bead filled low density polyethylene (LDPE) composites. It is inferred that the storage modulus increased nonlinearly with an increase of the glass bead weight fraction. Mondadori et al. (2011) investigated the mechanical behaviour of reused poly (ethylene terephthalate) (PET) reinforced with SGF and revealed that increase in fiber content in various weight percentages increases the mechanical properties of the PET/SGF composites. Arsad et al. (2010) revealed that the tensile and flexural performance enhanced upon the addition of maleic anhydride grafted acrylonitrile-butadiene-styrene (ABS-g-MAH) at different weight percent composition into the polyamide 6 (PA6)/acrylonitrile-butadiene-styrene (ABS) blends, whereas toughness diminished with the inclusion of SGF in the composites. Jin et al. (2001) conducted the study on dynamic mechanical analysis (DMA) of multi-processed multi-walled carbon nanotube (MWCNT) /polymethylmethacrylate (PMMA) composites to determine storage and loss moduli and Tan δ. Hassan et al. (2011) reported the dynamic mechanical property of injection moulded SGF/polyamide 66 (PA66) composite. They revealed that the Tan δ of the virgin and filled material under dry and 50% relative humidity (RH) and wet condition. Kushwaha et al. (2011) studied the characterisation of nickel coated SCF reinforced polycarbonate (PC) composites. They revealed that increase in SCF enhanced the tensile and flexural properties and hardness of the PC composites, sacrificing the toughness. They also determined the storage and loss moduli, which increases with the increase in fiber content, indicating that nickel coating on CFs had no effect on the mechanical properties.
2.5.2 Mechanical properties of particulate filled PMCs

Bijwe et al. (2005) studied mechanical behaviour of PEEK-polytetrafluoroethylene (PTFE) (7.5 to 30 wt. %) blends. They revealed that 30 wt. % PTFE into PEEK outpaced the impact strength and other mechanical properties were found to be reduced. Chun and Xia (2004) determined that the ekonol filled in PEEK was favourable for improving the compressive strength and the hardness, however it was not advantageous for flexure and impact strength. Tham et al. (2010) revealed that the flexural modulus of PMMA was enhanced with the inclusion of hydroxyapatite. Ghazanfari et al. (2008) revealed that the tensile and flexure strength and strain of high density polyethylene (HDPE)/date pit particle filled composites reduced with increase in date pit flour content. Joseph et al. (2011) studied the influence of nanoplatelet chains and nanoalumina on mechanical behaviour of PEEK matrix. They inferred that the nanoalumina filled PEEK composite exhibited higher mechanical properties than that of the nanoplatelet chains filled PEEK composites. Tarawneh et al. (2011) revealed that the tensile properties and impact strength are enhanced appreciably while sacrificing high elongation at break by incorporating multi-walled carbon nanotubes (MWCNTs) as filler in thermoplastic natural rubber (TPNR) compared to pure TPNR. Micron sized calcium carbonate (CaCO₃) filled polypropylene (PP) composites offer higher strength at a given particle loading was reported by Lau et al. (2006). Also, the micron sized particles resulted in enhancement of fracture toughness of CaCO₃ filled HDPE composite was reported by Bartczak et al. (1999). Zhu et al. (1999) revealed that the strength of the polyimide (PI)/silicon dioxide (SiO₂) composites increases with particle loading upto 10 wt. % and decreased with further increase in loading of SiO₂. However, their modulus increases monotonically with SiO₂ loading. Sreekanth et al. (2011) investigated the role of mica and fly ash fillers filled in polyester TPE composites. They concluded that there is a substantial rise in the flexural properties with an increase in the filler loading. The impact strength reduced with the addition of filler and this is due to the decrease of elasticity of
material and thereby reducing the deformability of matrix and its ability to absorb deformation energy. Yadav and Rao (2012) investigated the mechanical and thermal behaviour of hybrid nanoclay and nanoalumina filled PP composites. They revealed that nanocomposites with 4 wt. % clay along with modifier and coupling agent have shown best mechanical property, while the nanocomposite with 4 wt. % alumina along with modifier and coupling agent have shown better thermal properties over the other composites. Riley et al. (1990) confirm that the inclusion of nano sized particles with low aspect ratio are beneficial to impact properties of polymers. Further they revealed that larger aspect ratio particles are detrimental as they stimulate high stress concentrations near their edges. In contrast, increase in silicon nitride (Si$_3$N$_4$) filler content in polyethersulfone (PES) composites resulted in the decrease of tensile strength and elongation was reported by Dai et al. (2012). They also reported that rise in filler concentration increases the hardness of the PMCs. Huang et al. (2006) reported that the modulus of PTFE filled silica composites decreased with an increase in silica concentration in the PTFE composites.

### 2.5.3 Mechanical behaviour of hybrid polymer matrix composites

Bose et al. (2005) studied the mechanical performance of poly methyl methacrylate (PMMA) filled with talc and synthetic aluminium silicate (SSAS) with different proportions. They revealed that the impact strength of PMMA was enhanced with the addition of talc and SSAS up to 20 wt. % and subsequently it deteriorated continuously. Impact strength was higher in talc filled PMMA compared to that of SSAS filled PMMA. They also revealed that the addition of fillers (talc and SSAS) resulted in deterioration of tensile strength and elongation at break. Alhareb and Ahmad (2011) investigated the mechanical behaviour of PMMA reinforced Al$_2$O$_3$/ZrO$_2$ composite. They revealed that the incorporation of Al$_2$O$_3$/ZrO$_2$ into PMMA improved the tensile and flexural properties of the PMMA composite. Further they revealed that 5 wt. % filler (80/20; Al$_2$O$_3$/ZrO$_2$)
demonstrated the better mechanical behaviour amongst the materials in the group. Mohan and Kanny (2011) investigated the effect of nanoclay on SGF reinforced PP composites. They revealed that inclusion of nanoclay decreases the melt flow rate. On the other hand, it enhanced the crystallinity of the composite due to the nucleating effect. Further, nanoclay filled SGF reinforced PP composite exhibited better tensile properties. Rahman et al. (2012) studied the micro-structure, thermal and mechanical performance of glass fiber (GF)/nanoclay/PP composites. They concluded that inclusion of nanoclay enhances the mechanical performance of traditional fiber reinforced composite. Bijwe et al. (2001) demonstrated that inclusion of fillers (PTFE, MoS$_2$, and graphite) in GF reinforced poly ether imide (PEI) hybrid composite showed improved flexural modulus, but reduced strength compared to PEI+GF composite. Thongsang et al. (2012) investigated the dynamic mechanical performance of fly ash silica (FASi)/precipitated silica (PSi) filled natural rubber (NR) composites by modifying the silica contents in NR hybrid composites. They concluded that optimal mechanical performance can be achieved with 75 % PSi content in FASi/PSi-filled NR hybrid composites.

2.6 Thermal behaviour of particulate filled and fiber reinforced polymer matrix composites

2.6.1 Thermal properties of fiber reinforced PMCs

Poomalai et al. (2011) studied the thermal and mechanical behaviour of PMMA copoly ether-ester (COPE) blends and revealed that the existence of COPE increases the thermal stability of PMMA. DSC and DMA test data revealed two $T_g$’s for all blends indicating incompatible two phase system and compatibility reduces with increase in COPE content. Their investigation also revealed that the damping characteristics also show two peaks each for COPE and PMMA in which higher broadening of damping peaks for the blends with higher COPE content indicates incompatibility. Mani and Singh (1993) concluded that crystallinity of
poly (ether ester) depends upon preceding thermal/polychromatic irradiation of the specimen. Irradiation improves compatibility between the phases and hence the dispersion of soft segment domains in poly (tetramethylene terephthalate) matrix. On prolonged irradiation, a soft segment acts as a compatibilizer for a hard segment and selectively extracts steric defects leaving a matrix of hard segment which causes higher crystallinity. Samakrut et al. (2008) studied the rheological and thermo-mechanical behaviour of SGF reinforced PC/ABS blends. They revealed that addition of SGF in PC/ABS blends has resulted in enhancement of viscosity and storage modulus of the composite. Hassan et al. (2011) studied thermal and mechanical behaviour of GF reinforced PP composites compatibilized with maleic anhydride grafted PP. They revealed that the incorporation of coupling agent and with increase in fiber content the mechanical properties were improved, while a slight shift in $T_g$ was observed with a drastic reduction in $\tan \delta$ values.

2.6.2 Thermal properties of particulate filled polymer matrix composites

Nalini et al. (2011) studied the morphological, thermal and mechanical performance of PP thermoplastic elastomer with sodium montmorillonite (Na-MMT) using PP grafted maleic anhydride as a compatibilizer in thermoplastic olefins (TPO) nanocomposites. They revealed that the TPO with 5 wt. % Na-MMT showed the higher melting point and thermal degradation temperature, good thermal stability, increase in $T_g$ and storage modulus. Ghazanfari et al. (2008) studied the thermal and mechanical characteristics of HDPE/date pit filled composites. They revealed that addition of date pit flour enhanced the thermal conductivity and specific heat, with decrease in melt flow index (MFI), tensile and flexural properties. Benjamin et al. (2000) studied the thermo-mechanical properties of nanoalumina ($n$-$\text{Al}_2\text{O}_3$) filled PMMA nanocomposites. They revealed that inclusion of nanoparticles to a brittle matrix led to ductile-type behaviour in which
nanocomposite yields by shear through the suppression of craze formation or through the delocalization of homogeneous yielding throughout the matrix.

2.6.3 Thermal behaviour of hybrid polymer matrix composites

Chan et al. (2014) studied the thermal, electrical and mechanical behaviour of silicon carbide (SiC) and hexagonal boron nitride (hBN) filler reinforced linear low density polyethylene (LLDPE) composites. They revealed that the inclusion of ceramic fillers effectively enhanced the thermal conductivity without giving up their electrical resistivity. It also resulted in declination of coefficient of thermal expansion and enhanced mechanical performance.

2.7 Tribological performance of fiber reinforced/particulate filled/hybrid polymer matrix composites

2.7.1 Tribological behaviour of fiber reinforced polymer matrix composites

Lucas and co-workers (2011) investigated the two-body abrasive wear (2-BAW) performance of HDPE/ultra-high molecular weight polyethylene (UHMWPE) blends and concluded that addition of UHMWPE into HDPE improves the wear resistance to abrasive paper, with an augmentation in mechanical properties. Harsha and Tewari (2002) studied the mechanical, thermal and tribological characteristics of various polyaryletherketone (PAEKs) and their composites. They concluded that the tougher matrices of PAEKs demonstrated higher wear resistance to abrasion compared to their composites under multi-pass (MP) conditions against SiC abrasive paper. Further, they demonstrated that the variables such as sliding distance, abrasive grit size and load have a major impact
on abrasive wear behaviour of composites. Friedrich (1985) studied the single-pass (SP) 2-BAW behaviour of unfilled polyethylene terephthalate (PET), GF reinforced PET and glass-sphere filled PET and revealed that the wear resistance decreases with increasing size of abrasive grains and a higher hardness of the abrasive grains leads to additional cracking of the rigid fillers per unit time, thus leading to decreased wear resistance. Harsha and Tewari (2002) conducted a study on MP 2-BAW behaviour of polysulfone (PSU) filled with varying proportions of GF. They concluded that the resistance to abrasive wear of PSU filled with GF (i.e. with 20 wt. % and 30 wt. %) was deteriorated compared to that of unfilled PSU. They also observed that the load, sliding velocity and abrasive grain size as significant parameters effecting the abrasive wear. Unal and co-workers (2005) studied the 2-BAW performance of aliphatic polyketone (APK), polyoxymethylene (POM), UHMWPE, PA 66 and 30 wt. % GF reinforced polyphenylenesulfide (PPS) polymer composites at room temperature and concluded that POM and UHMWPE has the highest and lowest specific wear rates ($K_s$) respectively in the group. They also observed in their investigation that the $K_s$ decrease with the increase in sliding distance and grit grade number of abrasive paper. Bijwe et al. (2002) investigated the 2-BAW performance of CF filled PTFE and neat PTFE and concluded that CF reinforced PTFE exhibited little higher wear rate than the neat PTFE indicating slight deterioration in wear characteristics, which is due to CF reinforcement. Suresha et al. (2007) studied the three-body abrasive wear (3-BAW) performance of SGF reinforced polyurethane (PU) composites and revealed that the wear volume increased with the addition in SGF content in the composite. Decrease in $K_s$ with increase in abrading distance at higher load was observed. Kushwaha et al. (2011) conducted abrasion wear test on PC reinforced with and without nickel coated CF. Inclusion of CF in the composite decreases the wear resistance of the composites. Nickel coating enhanced the abrasion resistance of composites compared to uncoated CF composites and pure PC.
2.7.2 Tribological behaviour of particulate filled polymer matrix composites

Ravikumar et al. (2009) studied the 2-BAW behaviour of nanoclay filled low density polyethylene (LDPE)/ethylene vinyl acetate (EVA) composites with and without compatibilizer. They concluded that LDPE/EVA blend reinforced with nanoclay with compatibilizer demonstrated superior wear resistance to abrasion. They also observed in their experiments that wear rate increases with increasing size of abrasive particles. Bijwe et al. (2005) investigated the mechanical and tribop-erformance of PEEK-PTFE blends in various wear modes and concluded that inclusion of PTFE in PEEK, the $K_s$ increases by 2-3 times that of neat PEEK. On the other hand they observed decrease in $K_s$ with an increase in load.

2.7.3 Tribological performance of hybrid polymer matrix composites

The effect of CF and nano SiO$_2$ filled POM composites were investigated by Zhaohong et al. (2014). They revealed that POM with 3 vol. % nano SiO$_2$ with CF presence, enhances the toughness and modulus of POM composites. However the content of nano SiO$_2$ upto 3 vol. % with CF reinforcement demonstrated reduced friction coefficient and smaller wear volumes of the composite. Jian and Tao (2014) investigated the mechanical and tribological performance of CF/PPS composite filled with PA6. The addition of PA6 in varying volume percent increases the bending strength and decreases the wear loss and friction coefficient of CF/PPS composites. It is a well-known fact that, inclusion of fillers/fibres as reinforcement into most of the thermoplastic composites will enhance the mechanical behaviour, however the same does not augment the wear resistance if the wear mechanisms are highly abrasive in nature, as reported by Voss et al. (1986). However the findings of Bahadur et al. (1992, 1993, 1984, 1992, 1992, 1996) revealed that the wear rate was substantially condensed by the accumulation
of CuO and CuS to PTFE, CuS, CuF₂, CaO, and PbS to polyamide 11 (PA 11), and CuO, CuS, and CuF₂ to PEEK. Conflicting to the above findings, they also found that wear rate enhanced when the polymers were filled with particulate materials such as BaF₂, CaF₂, ZnF₂, SnF₂, ZnS, SnS, ZnO, and SnO (1992, 1992). Bijwe et al. (2001) examined the neat PEI, PEI filled with SGF and PTFE, molybdenum disulphide (MoS₂), and graphite in various wear modes. They reported that neat PEI exhibits better resistance under 3-BAW. These findings have revealed that the fibers and fillers are detrimental for 3-BAW behaviour and are in good match with the above listed outcomes of Voss and Friedrich (1986) and Bahadur et al. (1992, 1992). Li and Xia (2010) investigated the tribological performance of PA 6 and CF reinforced composites with varying fiber content under dry sliding wear situation. They noticed the optimum wear resistance of composites at 20 vol. % of CF content. Increase in coefficient of friction and wear volume of PA 6 and their composites with the increase in load was observed. Li (2010) investigated the impact and adhesive wear behaviour of polytetrafluoroethylene (PTFE) and PTFE/PA 6 blends, with PA 6 in varying vol. %. His investigation revealed that 30 vol. % PA 6 in PTFE demonstrated momentous results with impact, friction and wear behaviour of PTFE/PA 6 composites. Ravikumar et al. (2009) investigated the mechanical and 3-BAW performance of PA 66/PP blend and its composites filled with nanoclay and reinforced with and without SCF. They concluded that the PA66/PP blend filled with nanoclay showed reduction in tensile strength, strain and increase in hardness. But, PA 66/PP + nanoclay, reinforced with SCF exhibited better tensile strength, reduction in strain and increase in hardness. However, the same is not true with 3-BAW behaviour of the composites under study. From this the investigators inferred that inclusion of nano filler is not beneficial to wear behaviour and inclusion of SCF to the nanocomposite is more unfavourable to the abrasive wear behaviour of the composite under investigation.

Budinski (1997) studied abrasion resistance of twenty one polymers and revealed that the PU had outstanding abrasion resistance over other polymers.
Briscoe et al. (1986) investigated the abrasive wear behaviour of PEEK filled PTFE and PTFE filled PEEK. Sole and Ball (1996) investigated the influence of fillers such as CaCO₃, BaSO₄, and fly ash on abrasive wear behaviour of PP. They revealed that inclusion of mineral fillers to the PP matrix reduces the wear resistance under harsh abrasion situation. Liu et al. (1999) studied the abrasion resistance of UHMWPE with and without quartz particles as reinforcement under 3-BAW conditions. Pettarin et al. (2010) studied the wear behavior of high molecular weight high density polyethylene (HMWHDPE)/MoS₂ composites under adhesive and abrasive wear situations. They inferred that, inclusion of 10 wt. % MoS₂ to HMWHDPE enhances the adhesive and abrasive wear performance of the composite. Tong et al. (2003) noticed that the friction coefficient of UHMWPE was enhanced with the inclusion of wallastonite fibers. They also observed highest wear resistance, when the fiber content was about 10 wt. % in the composite. Voss and Friedrich (1987) investigated the adhesive and abrasive wear behavior of SGF and SCF reinforced PEEK composites at room temperature. They concluded that, addition of SGF to PEEK showed marginal improvement in the abrasion resistance. Wei (2014) investigated the friction and wear performance of SCF/PA/PTFE hybrid composites under adhesive wear. Research findings revealed that the tribological performance enhanced with an increase in the SCF content in SCF/PA 6/PTFE systems due to the synergetic effect. Further, 30 vol. % SCF in the composite demonstrated least wear and friction among all the hybrid composites under study. The friction and wear rate reduced with sliding distance and then levelled off under dry sliding wear situation.

2.8 Implementation of statistical tools

Statistical tools have been well accepted and recognised for analysis, predicting/estimating and/or process optimization of a number of engineering/research activities. These tools are also beneficial in determining the
influence of individual test parameters in various experimental processes. Wear is a complicated phenomenon governed by a number of test parameters/control factors. Hence, it is necessary to use statistical tools for the critical analysis of experimental data in order to determine the influence of control factors on wear performance of newly designed material.

Statistical tools help the researchers to predict the results based on available research data by generating the mathematical model associated with the parameters influencing the processes. The mathematical model can be formulated by response surface method (RSM). It is a robust mathematical and statistical technique employed to formulate mathematical models considering multiple parameters, which may influence responses. In many instances, the relationship between the response and independent parameters/variables is not known. This approach is normally designed using central composite design (CCD) in which the design is to explore the effect of variables on the response in the region of investigation. The CCD with RSM has been used to evaluate the effects of multiple parameters on tribological behaviour of composites by Mishra (2012); Thakre (2014); Kumar and Balasubramanian (2010); Suresha and Sridhara (2010); Chauhan and Dass (2013) and Rajesh et al. (2012).

Taguchi (1986) devised a new experimental design that applied signal to-noise (S/N) ratio with orthogonal arrays (OA) to the robust design of products and processes. This also minimises the amount of work, time, energy, or other limited resources as reported by Montgomery (2001). Phadke (1989); Wu and Moore (1986); Logothesis and Haigh (1987 and 1988); Shoemaker and Kackar (1988); Phadke and Dehnad (1988) have subsequently applied this method, to design the products and process parameters. Also, DOE have been successfully employed for parametric appraisal in tribological behaviour of polymer composites by Cho et al. (2005), Sudheer et al. (2012), Agarwal et al. (2012) and Chand et al. (2000).
Grey relational analysis (GRA) was proposed by Deng (1989) and is suitable for solving problems with complicated inter relationships between multiple factors and variables according to Moran et al. (2006). Grey relational analysis solves multi-attribute decision making problems by combining the entire range of performance attribute values being considered for every alternative into one single value. This reduces the original problem into a single decision making problem, was reported by Biswas and Alok (2009). GRA quantifies the influences of various factors and their relation which is called the whitening of factor relation. Black is represented as lack of information. Thus the information that is either incomplete or undetermined is called grey. Subbaya et al. (2012); Ramesh and Suresha (2014) implemented the GRA to optimize the tribological behaviour of polymer composites. Ramesh and Suresha (2014) investigated the optimization of tribological parameters in abrasive wear mode of carbon-epoxy (C-E) hybrid composites. They implemented Taguchi’s DOE, Analysis of Variance (ANOVA) to conclude the importance of control factors effecting wear and grey relational grade (GRG) to optimize the tribological parameters having multiple responses. They concluded that filler loading and abrasive particle size have more momentous effect on the $K_s$ of the composite and are therefore ranked first and second.

2.9 The Knowledge gap in earlier Investigations

The literature survey portrayed above exposes the subsequent knowledge gap in the research reported so far:

- A number of research efforts have been devoted to the mechanical and wear performance of either fiber reinforced or particulate filled composites. However, a probability that the inclusion of both particulates and fibers in polymer could deliver a synergism in terms of enhanced performance has not been effectively attempted so far.

- Though much work has been done on a wide variety of polymers as matrix materials, very little has been reported on thermoplastic elastomers (TPE) in
general. Very few findings have been explored with polyester based thermoplastic elastomer as matrix material.

- Very few researchers have explored the thermoplastic copolyester elastomer (TCE) as modifiers to improve impact strength, as blends and matrix material reinforced with mica and fly-ash; and are characterised to understand its thermal, mechanical and electrical properties.
- There are no reports available in the literature on the mechanical, thermal and tribological characterisation of TCE (Arnitel EM740) composites reinforced with glass fiber and particulate fillers.

### 2.10 Objectives of the Present Work

The knowledge gap in the present literature summarized above has facilitated to fix the objectives of this research work which are defined as follows:

2. Evaluation of mechanical, thermal and tribological characteristics of TCE composite and TCE hybrid composites.
3. Statistical analysis based on Taguchi DOE, RSM and GRA for parametric appraisal of the wear process in the composites under study and development of predictive equations.
4. Suggesting the possible end applications of the composite material system under study.
2.11 Chapter summation

This chapter has catered

- An extensive review of research works on diverse facets of polymer composites reported by previous researchers
- The knowledge gap in earlier investigations
- The objectives of the present work

The next chapter describes the materials and methods used for the processing of the composites, the experimental planning, different statistical methods and multi objective optimization technique.