Chapter 7

Conclusions and Future Work

7.1 Conclusions

Lime sludge is an industrial waste generated as a byproduct of manufacturing paper, fertilizer, sugar, carbide, and soda ash. It is usually used in illogical land filling or disposed off in dump yards causing environmental pollution. Recycling or reuse of lime sludge is of utmost importance because it can help make the environment cleaner, conserve materials, save energy and most importantly reduce the wastes affecting the environment. It consists of lime in the form of calcium carbonate ($CaCO_3$) as the major constituent along with a few other ceramic oxides in small amounts. Lime sludge is a recoverable material and can be used to produce fresh lime, which can be then reused in the parent industries. However, the cost of this process is so high that these industries dispose off as lime sludge wastes. Although various alternative uses of lime sludge waste have been suggested over the years, effective commercial re-utilization of lime sludge has not been successful till date - a reason for grave concern due to the environmental hazard it poses. Thus, in order to enhance the commercial viability and decrease the adverse environmental impact, industrial lime sludge waste is used as a filler in polymeric composites in this research. It is imperative to state that for extensive use in polymeric composites, lime sludge should not only act as a filler but also act as a reinforcing agent; thereby enhancing specific properties of the composites. This would account for three advantages - composites with superior properties, low cost of composites (since lime sludge waste is cheap) and decreased environmental pollution.

In order to study the behaviour of lime sludge waste in composites, raw lime sludge collected from waste dumpyards is ground to powdered form and used as a filler in HDPE matrix. Results revealed that addition of lime sludge in HDPE matrix significantly increased the tensile and flexural modulus of the composites. This can be attributed to increased stiffness due to the addition of rigid particulate fillers providing mechanical restraint to deformation. Additionally, the flexural strength also increased indicating better stress transfer between filler and matrix under bending stresses. Thermal stability of the composites also increased with the addition lime sludge filler due to the increase in onset temperature of thermal degradation, melting temperature, and residual content at 500 °C. Higher thermal stability, superior flexural strength and mechanical rigidity provided by lime sludge in a polymeric composite in addition to its cheapness and wide scale availability makes it an ideal filler to produce elastically rigid composites with superior thermal and flexural properties at a reduced cost. This study revealed that industrial lime sludge waste is effective as a reinforcing filler in polymeric composites. This will enhance the functionality and commercial viability of both the filler and the polymer by (a) improving composite properties upon the usage of lime sludge as filler, (b) decreasing pollution through reuse of a waste and (c) reducing the cost of polymer composites (cheap filler). However, it is also observed that properties such as tensile strength and impact strength decreased substantially due to low interfacial adhesion at the filler/matrix boundary and rigid fillers acting as stress concentration sites. Moreover, particle agglomeration at higher filler loading raised the stakes of premature failure which results in low tensile and impact strengths. Hence, it may be stated that important challenges of using inorganic raw lime sludge particulate fillers without any surface modification is that it produces composites with low strength (tensile and impact) due to unwanted particle agglomeration and low interfacial adhesion.

Homogenous dispersion of inorganic particles such as lime sludge in an organic polymer matrix is difficult due to the strong tendency of the particles to agglomerate and generate high viscosity during composite processing. Moreover, inorganic mineral fillers are hydrophilic while organic polymers are hydrophobic; this causes problems of low interfacial adhesion. In case of calcium carbonate based fillers (lime sludge, in this case), the most widely used surface modifier *i.e.* stearic acid is used where a layer of hydrophobic organic molecules is attached on to the filler surface. Hence, industrial lime sludge waste is surface modified using stearic acid before using it as a reinforcing filler in HDPE composites. The results obtained are compared to virgin polymer as well as with uncoated (raw) lime sludge filled HDPE composites. FTIR spectroscopy and SEM are adopted to ascertain the dispersability and morphology of stearic acid coated lime sludge in HDPE matrix. FTIR spectroscopy confirmed that stearic acid is successfully coated on the lime sludge particles; while SEM images showed that the modified lime sludge showed uniform dispersability in the polymeric matrix hindering particle agglomeration, even at higher filler loading. In a comparative study between stearic acid coated and uncoated lime sludge-HDPE composites, it is observed that the composites containing the modified lime sludge exhibited better mechanical properties. As stearic acid hindered particle agglomeration, the coated composites displayed better strength (tensile, flexural, and impact) and ductility than uncoated composites. The tensile and flexural modulus of the composites increased drastically with lime sludge addition. However, the rigidity of the uncoated composites is slightly higher than the coated counterparts owing to the higher mechanical restriction in chain mobility posed by the uncoated rigid lime sludge particles. Surface modification increased entanglement at the filler-matrix interface of the coated composites leading to their decomposition to residual amounts, at a temperature 100 °C higher than the uncoated composites. Stearic acid coating also reduced the water absorption rate of composites in comparison to the uncoated composites by enhancing the wettability and dispersability of lime sludge particles in the matrix. Thus, it is revealed that stearic acid is an attractive and inexpensive option to surface coat lime sludge which would improve the overall properties of the composites by hindering particle agglomeration (a factor significant in reducing the stress concentration sites which lead to premature failure upon loading; thereby reducing the mechanical properties of composites).

Additionally, the mechanical properties of both uncoated and coated lime sludge filled composites are modelled as a function of lime sludge filler loading using non linear regression analysis. The regression equations developed provided excellent fit for the variations of all mechanical properties as a function of both uncoated and coated filler loading in the composites. A consolidated model is developed using all the regression based models of individual mechanical properties. This consolidated model enabled any manufacturer to predict all the mechanical properties (all at the same time) as a function of filler loading beforehand. Moreover, the regression models of the tensile properties (tensile strength, tensile modulus and elongation at break) are compared with popular theoretical models proposed over the years. It is observed that the regression model developed for tensile strength correlated well with the theoretical model proposed by Turcsanyi, indicating lower interfacial adhesion for uncoated filler and better interfacial interaction for coated ones. In case of tensile modulus, it is found that the Sato-Furukawa model suited well for coated filler based composites while the Guth and Gold model provided better fit for uncoated lime sludge filled composites. However, the regression model developed for ductility (elongation at break) of the composites did not fit well with the proposed Nielsen model. This is due to the fact that the Nielsen model is based on perfect adhesion at the filler-matrix interface such that the polymer breaks at the same elongation in the filled system as in the neat polymer.

A commercially viable and structurally reliable filler/reinforcing agent in polymeric composites must be versatile enough to improve the properties of composites made from a variety of polymeric matrices and reinforcing agents. In order to assess this feature, lime sludge waste is used as a filler in different matrices *viz.* HDPE-PP blends, HDPE-MAPE, MAPE and epoxy and also used alongside coir fibres as a reinforcing agent in a composite. It is observed that lime sludge acts an effective reinforcing agent in all these composites up to a certain filler loading under both tensile and flexural loading conditions. Beyond a certain filler loading, the tensile strength decreased due to interfacial dewetting and particle agglomeration. Lime sludge also improved the rigidity of the composites upon its addition by increasing the tensile and flexural modulus upon the application of tensile and bending loads. Due to the increase in the rigidity and strength of composites, the ductility decreased significantly upon rigid filler addition. Additionally, it is observed that use of 5 wt % MAPE as a compatibilizer proved to an effective agent in improving the filler-HDPE interfacial adhesion, thereby improving the overall mechanical properties of the composites. Moreover, MAPE also increased the rigidity and strength of the HDPE composites which in turn decreased the ductility of the composites. Lime sludge proved to be an effective reinforcing agent up to 6 wt % in pure epoxy as well as in short and long coir fibre reinforced epoxy hybrid composites improving the mechanical properties of the composites. Moreover, addition of lime sludge also increased the thermal stability of the composites by increasing the residual weight % in lime sludge filled HDPE-PP blends and coir-epoxy composites.

It is paramount to state that this research is aimed at exploring the potential of an industrial waste to be used in an alternative application *i.e.* as filler/reinforcing agent in a polymeric matrix. Hence, the mechanical, thermal and morphological properties are studied to understand the consequence of adding lime sludge to different polymeric matrices. It is observed that addition of industrial lime sludge waste enhanced the overall properties of the composites, thereby improving the functionality and commercial viability of both the filler and the polymer. The major contribution of this research lies in the development of lime sludge filled polymeric composites - a novel idea which would focus on integrating the advantages of (i) re-utilizing industrial lime sludge waste, (ii) increasing the commercial viability of both lime sludge and the polymer, and (iii) developing novel polymeric composite with reduced cost. It is important to state that characteristics such as filler-matrix interfacial adhesion, particle agglomeration at higher filler content and effective filler dispersion in the matrix are vital factors affecting the mechanical characteristics of all these composites upon lime sludge addition.

7.2 Future research work

In order to ensure the widespread reuse and high commercial viability of industrial lime sludge waste in engineering and societal applications, the followings aspects should be further studied:

- It is observed that the particle size specifically particle agglomeration of lime sludge in a polymeric matrix plays a significant role in increasing or decreasing the mechanical properties of lime sludge filled composites. Hence, future scope of research may involve a detailed study on lime sludge particle size and its effects on the composite properties.

- Addition of lime sludge particles improved the rigidity of the composites which also results in a significant decrease in the ductility and toughness of the composites. Hence, future research should focus on developing a way of improving the ductility and toughness of the composites for further improvement of the mechanical properties.

- It is observed that addition of chemical compatibilizer such as 5 wt % MAPE improved the mechanical properties of the composites. Since, only three different MAPE contents is considered in this research, a complete study of different percentages of MAPE should be performed to identify the optimum content which can produce the highest mechanical properties. Additionally, the behaviour of lime sludge filled composites in the presence of other compatibilizers such as silanes, titanates etc. should be conducted.

- It is usually observed that the mechanical properties of polymeric composites decrease at elevated temperature. Thus, the behaviour of lime sludge filled polymeric composites at higher temperatures should be studied with a focus to improve the properties of composites at elevated temperatures by using thermal stabilizers.

- Since, commercially feasible and structurally reliable composites undergo various cycles of heating, cooling, thawing, wetting, water absorption (WA) and drying during service life. Hence, hygrothermal testing of lime sludge filled composites should also be considered in future in order to assess its reliability during service.

- Since tribological applications of composites play a significant role in defining the applications of composites for commercial use. Hence, wear resistant properties of lime sludge filled polymeric composites should be investigated.

- The design guidance and specifications for using the industrial lime sludge waste and its composites as an alternative structural material to virgin polymers and its contemporary materials should be developed.