Faculty of Engineering and Science

Development of light-weight polymer composite containing solid waste fillers and its application as sub-base layer of flexible pavement.

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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Date: December 2021

ABSTRACT

This research presents an in-depth study regarding the development of polymer composite using recycled tyres crumb, recycled polyethylene terephthalate (PET), and fly ash as fillers with jute-fabric as a reinforcement. Emphasis is placed on the mix proportions, mechanical properties, and durability of the purposed composite as precast lightweight product. This study consists of four objectives. The first objective is to determine the optimum mix proportions of polymer based lightweight composites using crumb rubber as a filler to achieve a density of less than 1850kg/m^3 and compressive strength of more than 17.5MPa. The second objective is to evaluate the effect of natural jute fabric on flexural strength and toughness of above lightweight polymer composite. Consequently, the third objective is to evaluate the long-term effects of various environmental exposures e.g., acid, sulphate and chloride exposures on the above mechanical properties and micro-structure of the composites. The fourth objective of this study is to evaluate the effectiveness of the developed lightweight composite in controlling the settlement of surface layer of flexible pavement on peat soil using numerical model based on a multi-layer linear elastic theory. In the first stage of the study, effects of various volume fractions of rubber crumb, PET flakes and fly ash in different combinations on 3 days compressive strength and density of the polymer composites were studied and several optimum mixes were selected for further study. Compressive strength, flexural strength and density of the above optimum mixes were measured at 3, 14, 28, 90 and 180 days. The effect of jute fabric as a reinforcing layer on flexural strength and toughness of the polymer composite was also evaluated. Microstructure analysis was conducted to investigate the polymer matrix and matrix-fillers interface of the composites. The optimum mix proportions were developed based on the usage of least binder and high volume of filling materials, having lightweight and appreciable compressive strength properties. In the second stage of the study, long term effects of aggressive chemicals on the composites were studied.

The main outcome of this research was that the optimum mixes achieved lightweight concrete's required density of no more than 1850 kg/m3 and 28 days compressive strength greater than 17.5 MPa. The use of jute fabric significantly improved the flexural strength by more than 20% of polymer composites containing mono filler (e.g., PET flakes or crumb rubber) at all ages. Polymer composites containing mono and hybrid fillers from waste materials exhibit higher toughness by about 10–50% than the control polymer composite.

Improvement in compressive strength in the range of 5-80% was observed in many composites for exposure duration up to 6 months in H_2SO_4, $MgSO_4$ and NaCl solutions. If this composite was used as an application in the sub-base layer of the flexible pavement, the deflection of the pavement would be influenced by the sub-base thickness, elastic modulus, and contact radius. The vertical stress for the polymer composite sub-base was 32% lower than that of the conventional flexible pavement. Apart from that, the vertical strain of the polymer composite sub-base was 31.5% lower than that of the conventional flexible pavement.

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MEKP	Methyl Ethyl Ketone Peroxide
PC	Polymer Concrete
CR	Crumb Rubber
PET	Polyethylene Terephthalate
FA	Fly Ash
H_2SO_4	Sulfuric Acid
$MGSO_4$	Magnesium Sulphate
NACL	Sodium Chloride

LIST OF APPENDIXES

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List of publications form this thesis

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Attribution of Research Outputs

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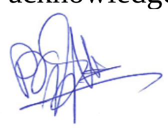
Prabir Sarker					✓	✓
I acknowledge that these represent my contribution to the above research output.  (Signature)						

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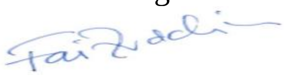
I acknowledge that these represent my contribution to the above research output.  (Signature)						
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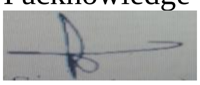
I acknowledge that these represent my contribution to the above research output.  (Signature)						

CHAPTER 1

INTRODUCTION

1.1 Background

Polymer concrete is defined as a composite material which results from polymerization of a monomer and aggregate mixture [1]. Polymer concrete was first introduced in the late 1950's and became quite popular in 1970's due to its properties such as fast curing, high compressive strengths, and resistance to chemical attacks. The properties of polymer concrete however depend on factors such as i) binder contents, ii) curing conditions, iii) aggregate size distributions and iv) content of the micro-filler. Based on literature, the most commonly used resin is i) unsaturated polyester resins, ii) epoxy resin, iii) furan resins and iv) polyurethane resin. Unsaturated polyester resins are widely used as compared to the other types because of its low cost, easy availability, and better mechanical properties.

Carrion et al. [2] studied the mechanical properties of polymer concrete developed through mixing of unsaturated polyester resin, calcium carbonate as an artificial micro-filler and waste aggregates (basalt and limestone). They concluded that the compressive and flexural strengths of the recycled polymer concrete improved as the amount of resin was increased and the particle size of the micro-filler was optimized. Kim and Soh [3] investigated the properties of unsaturated polyester mortar using crushed waste glass as a replacement for fine aggregate. The highest compressive strength was noted to be 60MPa when the fine aggregate was replaced by crushed waste glass by 50%. Similar findings were also observed by other researchers where the compressive strength was noted to be 48.90MPa when the aggregate was replaced with 50% recycled glass [4]. Majeed and Ibrahim [5] studied the mechanical properties of un-saturated polyester filled with silica fume, glass powder and carbon black. The compressive strength was increased when silica fume was added in their composite. Ali and Ansari [6] noted increase in polymer content would enhance the flexural strength however excess would reduce the compressive strength. The optimum polymer range should be 12%-14% to achieve a workable mixture with excellent mechanical properties. Scrap tires from automobiles are continuously accumulated the lands causing serious storage and disposal problem for the municipal authorities around the world.

It is estimated that about 1 billion waste tyres are produced per year globally [7]. The utilization of scrap tyre in concrete have become quite popular lately since it is lightweight and have high resistance against freeze-thaw, chloride ion penetration and acid attack [8]. The use of recycled waste tire rubber (crumb rubber) as a partial replacement of coarse/fine aggregate in Portland cement concrete has been widely investigated by many researchers [9]. Ismail and Hassan [10] noted a significant reduction in the ductility, first crack moment and toughness when crumb rubber was incorporated in conventional concrete. Similarly, Benazzouk et al. [11] stated that the elasticity of the rubber particles help improves the deformability of cement rubber mix. Rashad [12] reported that the inclusion of rubber particles improves the sound absorption, energy absorption and electrical resistance of the mix.

According to Jafari and Toufigh [13] many tyres are discarded in the environment and burning these waste tyres release harmful gases. Meanwhile landfill and burying these tyres can cause serious environmental pollution. Fiore et al. [14] concluded that cement composites containing 50% crumb rubber were light in weight, had good resistance to chloride ion, had low thermal conductivity and good freeze-thaw resistance despite there was a decrease in compressive and flexural strengths. Similar finding was also observed by Retama and Ayala [15]. However, Retama and Ayala [15] further added that the size of crumb rubber influences the elastic modulus of the concrete. To improve the mechanical properties of crumb rubber concrete, Chen and Lee [16], studied surface modifications on crumb rubber through partial oxidation reactions. The oxidation process however has improved the compressive strength by 50% according to the authors.

Another common solid waste which has become serious environmental issues lately is plastic. Polyethylene terephthalate (PET) is a thermoplastic material used in various applications such as storage containers, food wrappings and constitute a major fraction of household wastes [17]. The usage of plastic has increased dramatically in the recent years and this have produced a large amount of plastic waste [18]. A study reported that, 40% of the plastic goes to landfill, 14% is recycled and the rest 32% is dumped in the marine environment as a litter out of the annual plastic production which is 40kg for each of the 7 billion humans in this planet [19]. The utilization of plastic in concrete have become quite popular lately because plastic have high toughness, low thermal conductivity, high heat capacity and good abrasion behavior.

To minimize this waste in the environment the use of recycled PET as partial replacement of aggregates in concrete is a viable option and lots of studies are being conducted to evaluate the properties of concrete containing PET. Rahmani et al [20] investigated the mechanical properties of concrete containing waste PET. The authors replaced 5%, 10% and 15% of sand with PET and concluded that, samples containing PET particles showed lower workability, density, modulus of elasticity, splitting tensile strength with respect to conventional concrete. Similarly, Shubbar and Shadeedi [21] investigated the properties of concrete by replacing sand ranging from 1%-8% with PET. The author observed a decrease in density with the increase of the percentage of PET. Besides, the compressive strength was 41.48MPa at replacement of 2% PET. Angel and Ruiz [22], suggested that samples containing lower amount of PET aggregates produces good quality mixtures with lightweight and mechanical behavior similar to that of natural concrete. Irwan et al. [23] concluded that there is an increase in the compressive strength, modulus of elasticity and tensile strength of the concrete mix containing 0.5% PET fiber compared to normal concrete. Saikia and Brito [24], noted an increase in the toughness behavior due to incorporation of PET aggregates in concrete. Apart from that, the author also stated that the development of the compressive strength of samples containing PET particles is like that of conventional concrete, though its incorporation significantly lowers the compressive strength of the resulting concrete.

Like plastic and used tyres, fly ash is another solid waste generates abundantly around the world every year from generation of coal-fired power stations. The use of fly ash is well established in concrete as partial replacement of cement and as binder in geopolymer concrete. Significant studies have been conducted on various properties of concrete containing fly ash and fly ash geopolymer.

1.2 Research Gap and Aim

Many studies evaluated the properties of polymer concrete containing natural aggregates, glass aggregates, carbon blacks, etc. and cement concrete containing waste tyre rubber crumb and recycled PET as partial replacement of natural aggregates. However, no research attempted to evaluate the effect of two most polluting solid waste e.g., waste plastic and waste tyres as fillers in the development of lightweight composite. The development of lightweight polymer composite will have many important applications in construction industry. The construction of thick flexible pavement over soft soil or peat exhibits excessive total settlement and significant differential settlement due to very poor engineering properties of soft soil. This problem can be minimized by spreading the superimposed load if a lightweight polymer composite plate is placed on sub-grade which will minimize stress concentration and hence settlement. Higher chemical resistance of polymer makes the lightweight polymer composite plate an excellent candidate on sub-grade as ground sometimes contains various aggressive chemicals.

In most of the above polymer concrete studies one type of filler are used. However, hybridization of two or three types of fillers with various sizes can exhibit better properties than that of one type of filler in polymer concrete. Thus, the aim of this research is to develop lightweight polymer composite through formulating mix proportions of unsaturated polymer and hybrid fillers using solid waste (e.g., fly ash, recycled PET and recycled tyre rubber crumb).

1.3 Research Objectives

The purposed research is an in-depth study regarding pavement sub-base layer made by polymer composite using crumb recycled tyres, recycled PET and fly ash as fillers with jute-fabric as reinforcement. Emphasis is placed mostly on the mix proportions, mechanical and durability properties of the purposed composite as precast lightweight product. The effect of aggressive chemicals on the durability and residual mechanical properties of above composite is studied. The objectives of this research are as follows:

1. Determine the optimum mix proportion of polymer based lightweight composite using hybrid fillers e.g., recycled tyres crumb rubber, fly ash and recycled PET flakes in order to satisfy American concrete institute (ACI)’s [25] criteria for light weight concrete of density not more than 1850kg/m^3 and compressive strength more than 17.5 MPa.
2. Evaluate the effect of natural jute fabric on flexural strength and toughness of above lightweight polymer composite.
3. Evaluate long term effect of various environmental exposures e.g. acid, sulphate and chloride solutions on density, compressive and flexural strengths and micro-structural properties of above lightweight polymers composites.
4. Evaluate the effectiveness of the above lightweight composite as base layer in controlling the deflection and stress of surface layer of flexible pavement on peat soil using numerical model based on multi-layer linear elastic theory.

1.4 Scope of Work

The scope of this research is to fulfil the above objectives. Based on the first objective, the optimum mix proportion of the polymer composites containing unsaturated polyester resin as the binder, and crumb rubber, PET flakes and fly ash as the filler are investigated. A total of 50 different trial mixes are carried out before selecting the optimum mix proportion. Compressive strength and density were determined at 3 days on the trial mixes. The objective is to achieve compressive strength of more than 17.5MPa and density of less than 1,850kg/m^3. Five different types of mixes are selected based on least amount of resin and highest amount of filler usage. Consequently, after carrying out the trial mixes, compressive strength, density, flexural strength and toughness and microstructural analysis ware carried out on six different optimum polymer composites at 3, 14 and 28 days. The flexural strength and toughness were determined with inclusion of jute fabric as reinforcing layer and compared with the control composite without inclusion of jute fabric. The effect of three aggressive chemicals on above mechanical properties and microstructure of the composites is evaluated. The chemical solutions were, $MgSO_4$, H_2SO_4 and NaCl. Residual compressive strength, density, flexural strength, toughness and microstructural properties are evaluated on the polymer composites after exposure to 1, 3 and 6 months. Numerical modelling is performed on the developed polymer composites using Win-Julea, and Mich-pave software to analyse the deflection and stress distribution using multi-layer linear elastic theory.

Although, this research has reached its aim, there exist some un-avoidable limitations. Real situation of the pavement structure on soil with the developed polymer composites could be simulated in the laboratory. However, due to resource constrain, such study could not be carried out and instead its effect is evaluated using numerical model.

1.5 Thesis Outlines

This thesis is composed of five chapters, following Chapter 1, the introduction. Chapter 2 reviews previous literature published related to distress in flexible pavement, polymer composites, PET flakes and crumb rubber concretes. This chapter also discusses the mechanical, durability and micro-structure of polymer composites containing crumb rubber and PET flakes by previous researchers.

Chapter 3 discusses materials and test methods used for this research. This chapter explains in detail regarding the physical and micro-structural properties of un-saturated polyester resin, PET flakes, crumb rubber and fly ash. Consequently, the properties of the aggressive chemicals which is H_2SO_4, $MgSO_4$ and NaCl had also been discussed in detail. Mix pro potion, curing period and methods have also been discussed in this chapter. In addition to that, this chapter delivers the methodology of the compression, flexural, density and micro-structural test.

Chapter 4 discusses the results from this research such as the mechanical, durability and micro-structural tests. Results are analysed and compared with previous published works. Finally, chapter 5 presents some conclusions as well as recommendations for further research.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapters reviews the published work by previous researchers based on polymer composites containing various fillers including waste tyre crumb rubber, recycled PET flakes, fly ash and its degradation in chemical exposure. This chapter starts with discussing the properties of polymer concretes, common types of fillers used, compressive strength, and flexural strength and microstructure studies of polymer composites. After that it further discusses the use of crumb rubber, fly ash and PET plastic in polymer composites. The effect of aggressive chemicals on residual mechanical properties and microstructure of polymer composites are also discussed in this chapter. At the end of these chapter, the degradation of flexible pavement, current improvement methods and its disadvantages are discussed.

2.1 POLYMER COMPOSITES

Polymer concrete (PC) is a composite material which consists of polymeric resin acts as a binder for aggregates and micro-fillers. After the addition of different types of catalysts, the binders undergo polymerization resulting in a hardened composite. The main difference with cement-based concrete, is that polymer concrete does not contains hydrated cement, it is stronger, more durable and requires low maintenance. The advantages of polymer concrete is that its strengths can reach 4-5 times higher than cement-based concrete, meanwhile, keeping the modulus of elasticity in the similar values, have good chemical resistance and water permeability. Due to this characteristic, polymer concrete is widely used as a major component for the construction of many structures.

2.1.1 Materials used as a filler in Polymer Composites

Previous researchers used different types of waste aggregates as filler in the production of polymer composites. Hameed and Hamza [26] studied density, compressive strength, flexural strength and splitting tensile of polymer concrete produced from waste construction materials. The types of waste construction materials were demolished concrete and waste ceramic tiles. Barbuta et al. [27], studied polymer concrete through addition of different types of wastes such as argillaceous powder, calcareous powder, marble powder and fly ash. The author observed that the addition of calcareous powder decreased the mechanical strength of the concrete. Soni et al. [28], studied the synthesis and characterization of epoxy-based hybrid composites reinforced with glass fibre and milled carbon. Hybrid polymer matrix composites were fabricated by hand lay-up method. Torkittikul et al. [29] investigated the properties of polyester resin concrete containing various number of aggregates. The mixture was prepared with three different aggregates to binder ratio of 70/30, 72/25 and 80/20. Well-graded natural sand with a maximum size of 4.75 mm was used as aggregates. Barbuta and Harja [30] studied polymer composites composed of silica fume and crushed aggregates. The silica fume content varied between 6.4% and 9.6%. Kumar and Venkatesh [31], studied comparison between conventional concrete and polymer concrete with fibres of various proportions, the author performed studies of polymer resin concrete with resin percentage of 3 and 5% and compared it with the results of polymer fibre concrete with glass fibre percentage of 0.5 and 1%. Bedi et al [32], reviewed the mechanical properties of polymer concrete and stated that the most common types of aggregates used are river sand, foundry sand, crushed stone, quartz granite and gravel. The author further stated that the most common types of micro-filler used are calcium carbonate, fly ash and silica fume. Micro-filler is added to polymer concrete to reduce the void content in the aggregate and consequently increase the strength of the polymer concrete. Reddy and Santhosha [33] studied the performance of polymer concrete with fly ash as the filler and steel fibre as the reinforcement. Based on the test results, mixes with 10% fly ash and 2% steel fibres exhibited good results. Matykiewicz [34] studied the mechanical and thermomechanical properties of hybrid epoxy composites that were reinforced with carbon, glass, basalt fabric and modified with powder fillers. Sokołowska [35] studied the long-term compressive strength of polymer composites with various types of fillers. The author used quartz powder, ground sand and by-products of the combustion of polish fossil fuels (coal and lignite). Juanda et al. [36] studied the physical and mechanical properties of polymer composites with fine aggregates, epoxy resin, and foam. Four ratios of fine aggregate to the epoxy resin were used which included 1:3, 1:2.75, 1:2.5, and 1:2 of the weight of the volume of the test object while the 3 ratios of foaming agent and water used include 1:30, 1:40, and 1:50 with 50% foam of the mixed volume.

2.1.2 Compressive Strength of Polymer Composite

Hameed and Hamza [26] stated that the compressive strength of polymer composite is increased with increasing the percentage of polymer resin with all types of aggregates. The maximum value of compressive strength noted was 132 MPa for replacement of 70% ceramic waste and polyester resin of 30%. Meanwhile, the minimum compressive strength value was noted at 28 MPa when the waste of concrete at 80% was added. Torkittikul et al. [29], concluded that increasing aggregate content would result in a decrease in compressive strength of polymer concrete. The 7-days compressive strength with 70%, 75% and 80% aggregate were 56.11, 52.97 and 51.50 MPa respectively. Apart from that, the author stated that the polymer concrete containing various amount of aggregates can achieve compressive strength of 41.39-43.85 MPa within 24 hours after mixing which is 80% of the 7 days compressive strength polymer concrete. Figure 2.1 shows the compressive strength of polymer concrete found by the author, Torkittikul et al. [29]. Barbuta and Harja [30] stated that, the compressive strength of the polymer composites increased with an increase in the dosage of the silica fume dosage. The value of compressive strength varied between 51.1 MPa and 69.1 MPa. Figure 2.2 shows the compressive strength found by the author, Barbuta and Harja [30]. Ahmad et al. [37] observed that the addition of polymer had an unfavorable effect, with compressive strength declining as the polymer concentration was increased. The compressive strength of the polymer concrete declined from 34.6 MPa to 23.7 MPa and from 44.4 MPa to 31.3 MPa on sample labelled as C-20 and C-40, respectively after 28 days of curing ages. C-20 and C-40 samples consisted of different concentration of polymer addition and different water to cement ratio. Sample labelled C-20 consisted of 260kg/m3 of cement meanwhile sample labelled as C-40 consisted of 380kg/m3 of cement. Juanda et al. [36] studied the compressive strength of polymer concrete consist of fine aggregates, epoxy resin and foam. The author stated that a smaller mixture ratio of foaming agent and water produces light polymer concrete with better characteristics. The most optimum result for compressive strength was found to be 23.57 MPa with a density of 1773.76 kg/m3.

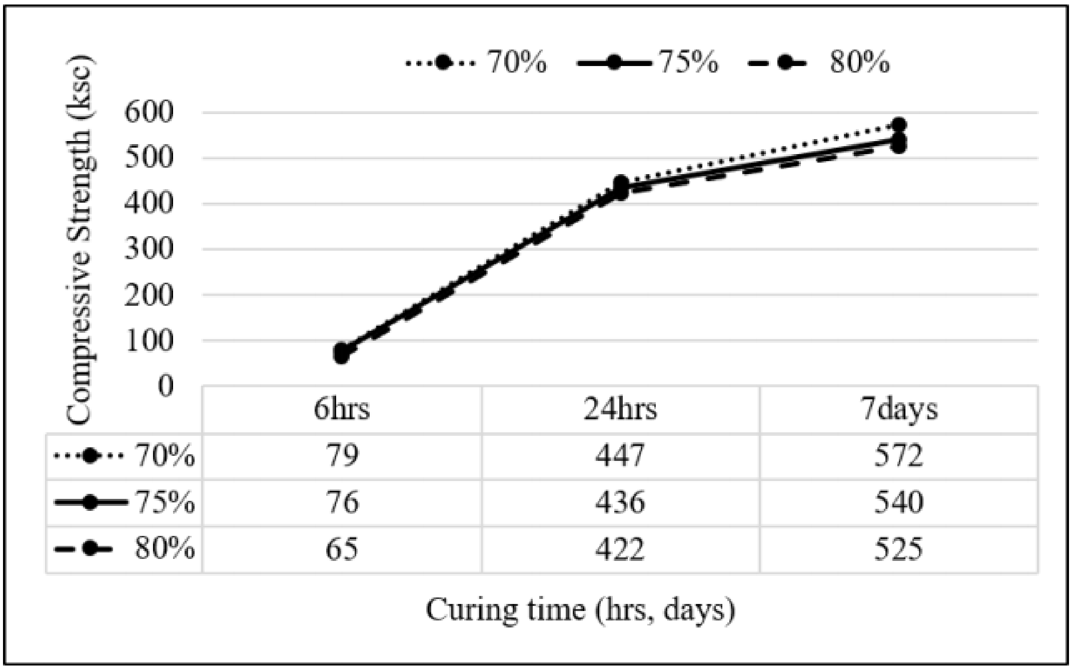


Figure 2.1: The compressive strength of polymer concrete at the age of 6hrs, 24 hrs and 7 days containing various amount of aggregate [29].

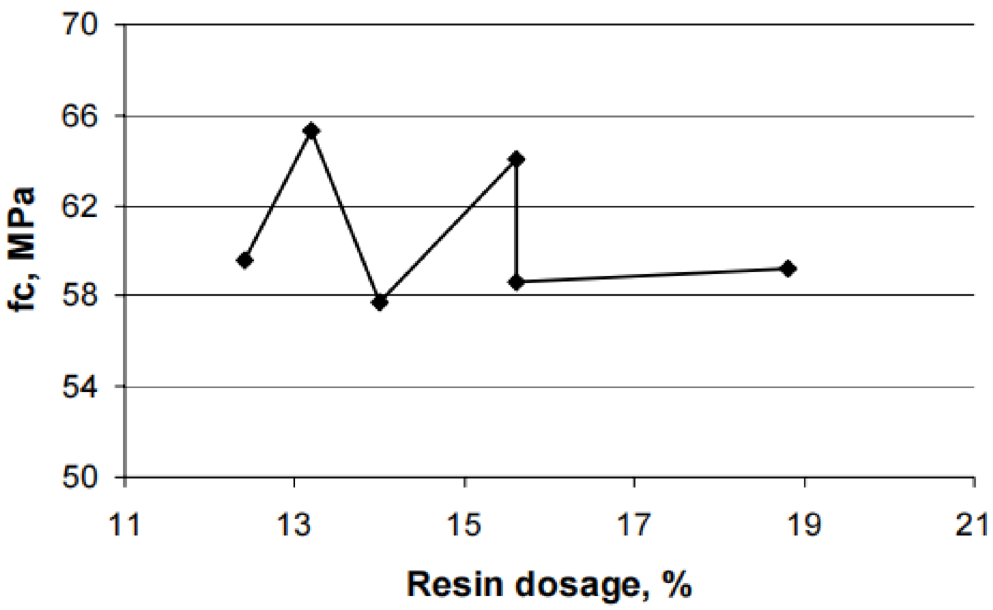


Figure 2.2: Variation of the compressive strength for BPS [30].

2.1.3 Flexural Strength of Polymer Composite

Hameed and Hamza [26] stated that the flexural strength increase with an increase in the percentage of polymer resin added to all types of aggregates. They reported the maximum flexural strength of 31.85 MPa at 30% polyester while minimum value was at 20% polyester. Soni et al. [28] stated that the maximum flexural strength was obtained for sample containing 2% milled carbon composite. Liu et al. [38] observed that load-deflection behaviour of carbon fiber/epoxy composites with different fillers shown in Figure 2.3 followed a linear elastic zone followed by non-linear behavior. However, some significant difference can be observed before and after reaching the peak load when nano-reinforcement is added. For pure sample with resin, there was no obvious plastic zone before reaching the peak load, and specimens failed rapidly after reaching the peak load. When 10 wt.% silica nanoparticles were added, a slight plastic zone in load before the maximum value was observed. When 10wt.% halloysite nanoparticles were added, an evident plain appeared after peaking then, load falled sharply.

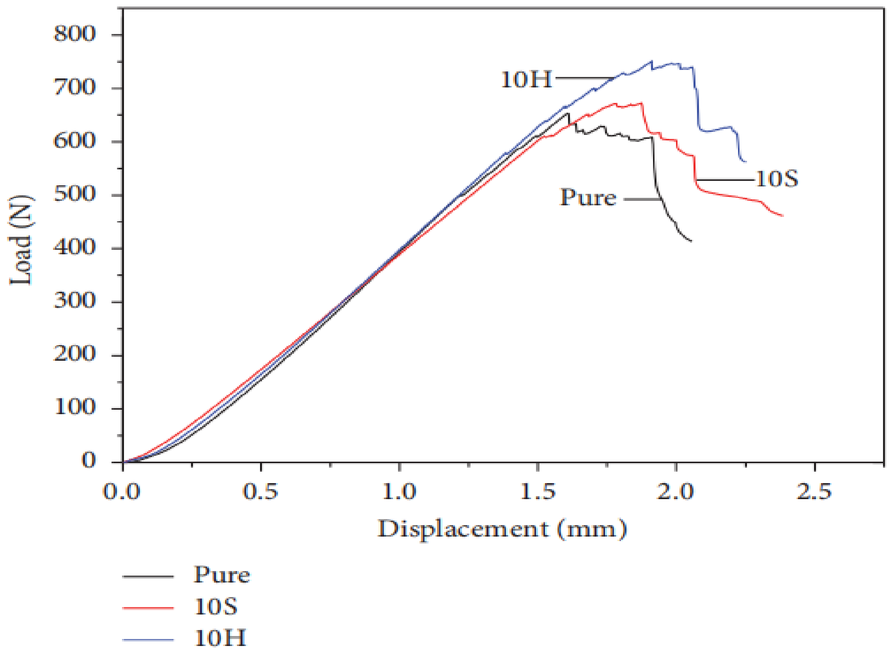


Figure 2.3: Flexural load-displacement curves of CF/epoxy composites [38].

2.1.4 Microstructures Analysis of Polymer Composites

Barbuta et al. [27] stated for samples containing calcareous powder, fly ash and resin, the mixture was homogeneous as observed through SEM image. For samples, containing argillaceous and marble powder, the addition was not homogeneous as observed through SEM image. According to Torkittikul et al. [29], micro-structural analysis through scanning electron microscopy of polymer concrete containing resin and natural aggregate, showed that the the binder was homogeneous, as the color is relatively uniform, and completely coated the natural aggregate. Figure 2.4 shows the SEM image as observed by the author. Sokołowska [35], observed that the micro-structure of vincle-ester concrete with a higher content of fly ash and lower content of quartz powder in the micro-filler fraction, were well compacted and some fine particles of fly ash were regularly distributed in the polymer phase. Consequently, for the sample's vinyl-ester concrete in which the quartz powder predominated in the micro-filler, there was large angular grains of quartz and there were spaces filled with polymer which are less saturated with mineral filler. Juanda et al. [36] observed that, foaming agents and water ratio of 1:30 produced very small pores and increased the compressive strength. Similarly, according to the author based on the micro-structural studies, bigger pores and un-dense-matrix leaded to a decrease in the density and compressive strength. In addition to that, the dehydration of concrete mixes during the curing process produced ettringite in small amounts.

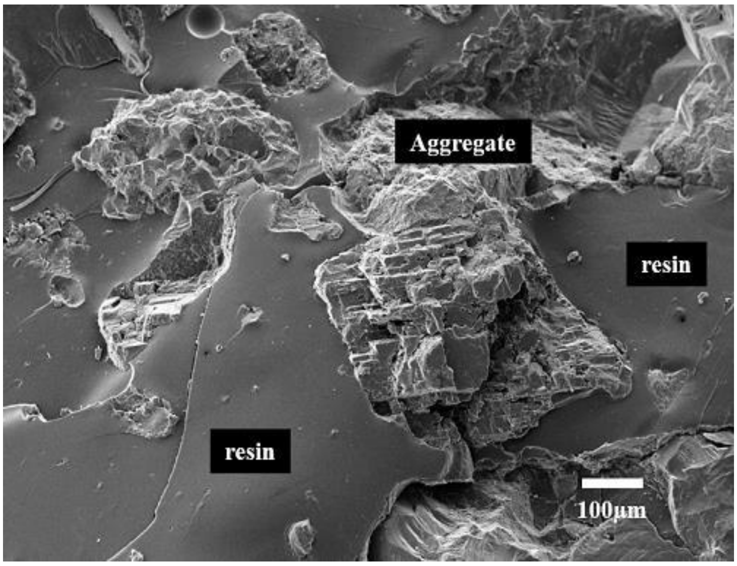


Figure 2.4: The microstructure of polymer concrete containing polyester resin and natural aggregate observed by scanning electron microscopy [29]

2.2 USE OF CRUMB RUBBER IN POLYMER COMPOSITE

The use of crumb rubbers as a construction material have been widely investigated in the past decades. There have been a number of studies conducted to introduce crumb rubber into conventional Portland cement concrete as a partial replacement of coarse and fine aggregates. According to previous researchers, it was concluded that, recycled rubber particles can modify the performance of Portland cement concrete and asphalt binder. Consequently, for rubberized concrete with replacement of rubber aggregate, the mechanical properties such as the compressive strength, splitting tensile strength and flexural strength are reduced with high percentage of rubber contents. However, the toughness and flexural displacement can be increased if compared with the conventional Portland cement concrete. Apart from that, the risk of brittle failure of concrete can also be minimized due to the addition of soft crumb rubbers. Even though, the possibility of crumb rubbers into polymer composite have showed many advantages, but the application is still limited since there is a reduction in strength.

2.2.1 Crumb rubber used in different types of concretes

Wang et al. [39] studied the mechanical and durability properties of crumb rubber-modified epoxy polymer concrete. The crumb rubber with mesh size of #50(0.279 mm) were introduced into epoxy concrete with two different contents of 5% and 10% based on the epoxy monomer weight. The compressive strength improved with the addition of 5% solid rubbers, and it reduced slightly with 10% rubber content. Retama and Ayala [40] studied the influence of crumb rubber on the mechanical properties of modified Portland cement concrete. The author stated that, replacing the aggregate with crumb-rubber modifies the energy dissipation during the cracking process and affects the concrete behaviour under monotonically increasing loads. Abusharar [41] studied the effect of particle size on the mechanical properties of concrete containing crumb rubber. The author replaced crumb rubber with 10% crumb rubber by three different particles size of crumb rubber of 1 mm crumb rubber, 0.4–1 mm fine dust crumb rubber, and 0.2–0.6 mm powder crumb rubber.

2.2.2 Compressive strength of crumb rubber polymer composite

Wang et al. [39] observed that the compressive strength of control samples was 27.49MPa. The compressive strength of samples containing 5% rubber particles were 29.99 MPa which was an increase of 9.1% compared to the control samples. When the rubber content was increased to 10%, the compressive strength of the samples was less than both the control and the samples with 5% rubber. The addition of low amount of rubber particles into the epoxy resin reduced the brittleness of the control epoxy resin and thus contributed to resist cracking when the structure deforms due to external forces. Abusharar [41] observed that strength of normal strength concrete was higher than rubberized concrete. The compressive strength for rubberized concrete with larger particles were greater than concrete containing smaller particles sizes. The compressive strength at 28 days for concrete containing 1mm crumb rubber, powder crumb rubber and fine dust crumb rubber were 19.4N/mm^2, 14.1N/mm^2 and 13.4N/mm^2. The reason for the reduction in strength is due to the reduction of quality of the solid load carrying material and lack of adhesion at the boundaries of the rubber aggregate. Diwakar et al. [42] found out that the compressive strength becomes decreasing as the amount of crumb rubber increases. Similarly, Wakili et al. [43] also notice a decrease in the compressive strength as the content of crumb rubber increased. At 28 days, the decrease for sample labelled as CR10 was found to be 16.17N/mm2 which was up to 27.81%-65.04% and MCR10 was found to be 25.0N/mm2 which was up to 11.68%-33.04% compared to the control which was 22.4N/mm2.

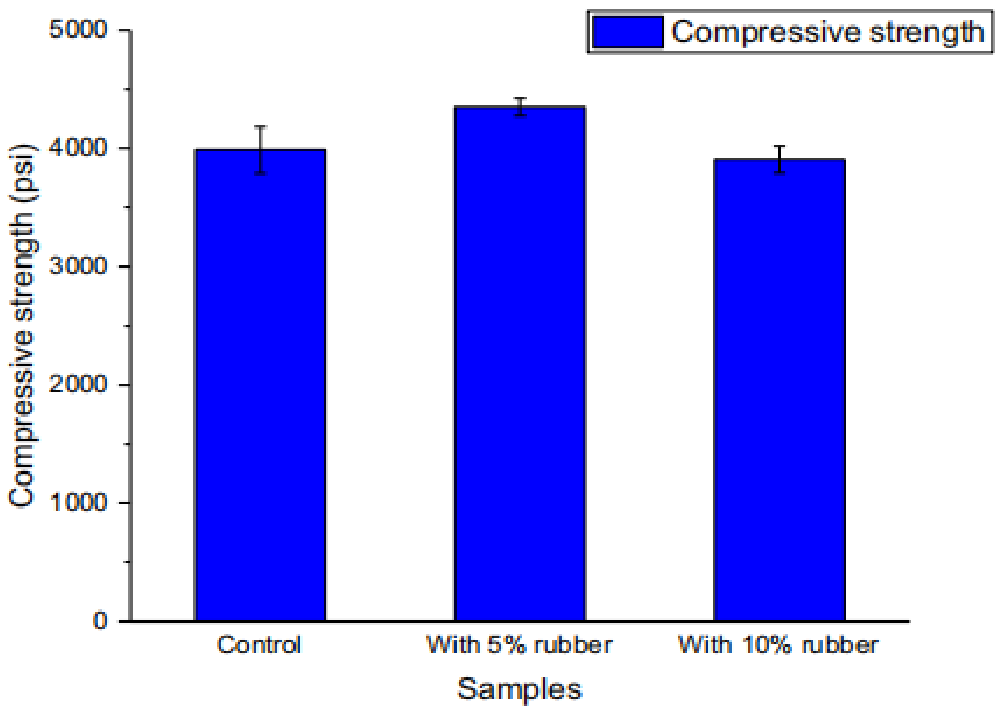


Figure 2.5: Compressive strength test results [39].

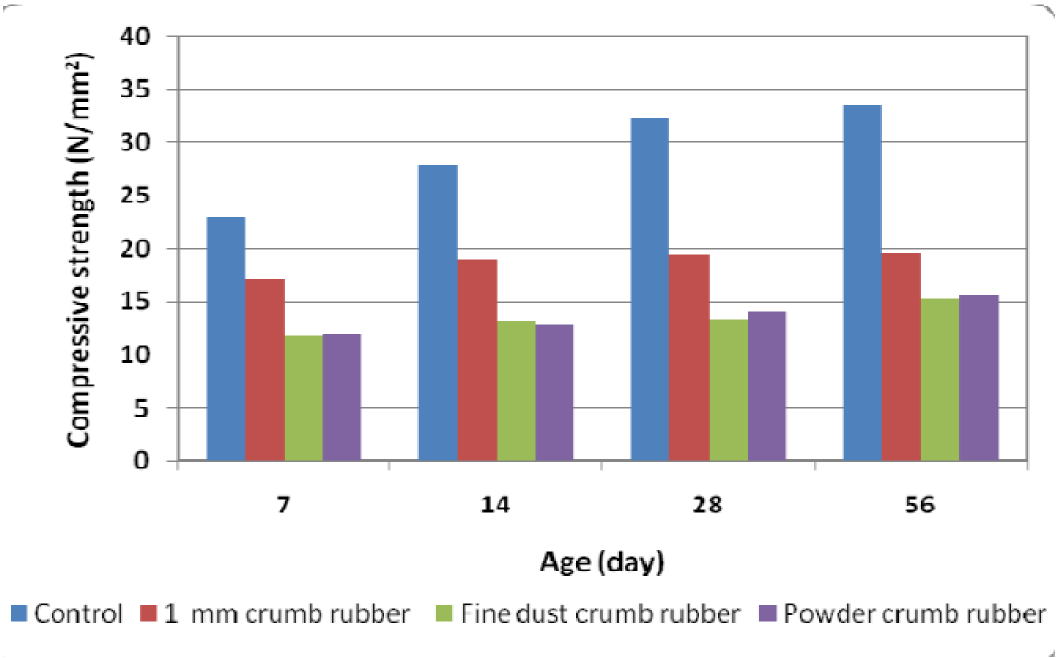


Figure 2.6: Compressive strength of crumb rubber of different size of crumb rubber composite [41].

2.2.3 Flexural strength of crumb rubber polymer composite

Abusharar et al. [41] observed that the flexural strength for rubberized concrete were lower than normal strength concrete. The flexural strength for normal concrete at 56 days were 3.71N/mm2. The maximum flexural strength for 1mm crumb rubber and fine dust crumb rubber were 2.938N/mm2 and 2.380N/mm2. The author noted that the rubberized concrete were softer than normal concrete. Concrete specimens showed early failure, because of its weakness against tension. Crumb rubber behaves like spring, and it delay the widening of the existing cracks. Ismail and Hassan [19], showed that increasing the crumb rubber appeared to narrow the crack, widths, reduce self-weight of the concrete and improve the deformability at a given load. Consequently, the addition of high percentage of crumb rubber (above 15%) showed a significant reduction in the ductility, toughness, first crack and ultimate flexural capacity of the tested beams. Benazzouk et al. [42] stated that, when crumb rubber is added more than 35%, the flexural strength decreased significantly due to the rupture of the rubber-cement matrix connection. This decrease becomes larger as the size of the rubber aggregates increases. Yilmaz and Degirmenci [43] observed that samples with waste crumb rubber showed higher flexural strength than control mix. This is due to the effect of rubber fibres. The increase in rubber content from 20% to 30% decreased the flexural strength of the mixtures. This decrease becomes lower as the size of the crumb rubber particles decreases. Kumar and Yadav [44] stated that, a replacement of up to 10% of crumb rubber can be made safely in flexural members.

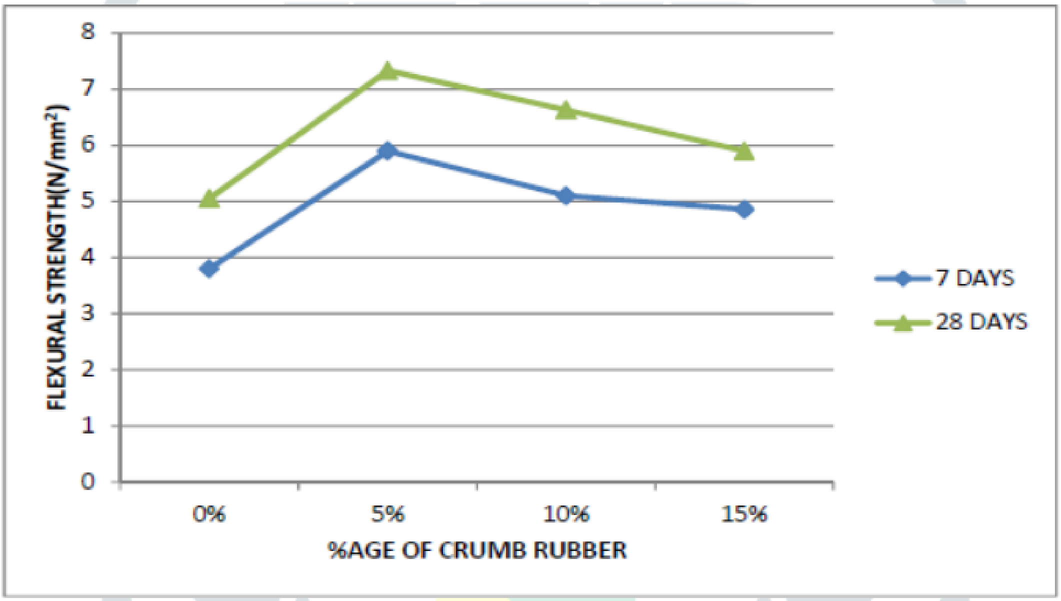


Figure 2.7: Flexural strength of crumb rubber composite [44].

2.2.4 Micro-structure studies of crumb rubber polymer composite

According to Xu et al. [45], scanning electron microscopy (SEM) image showed lack of bonding between the rubber and cement matrix at the ITZ interface. Apart from that there is also limited hydration products surrounding the rubber particles. Gaps were generally observed between the rubber particles and the cement matrix which indicated that the bond were weaker between rubber particles and the cement matrix. Figure 2.8 shows the micro-structure of the crumb rubber as described by Xu et al. [45]. Taha et al. [46] stated that the reduction in strength of sample containing rubber is due to the behaviour of the rubber particles which are soft. Thomas et al. [47], studied the micro-structure of samples with different water cement ratio, and concluded that there was more cracks in samples with higher water/cement ratio.

Chen and Lee [48] studied the effect of partial oxidation on the hydration of the cement. There was many kinds of cement crystal observed such as calcium hydroxide, calcium mono-sulfoaluminate, ettringite and calcium silicate hydrate. The author observed that, the calcium silicate hydrate on the treated rubber is much more than the calcium silicate hydrate on the received rubber. This concludes that partial oxidation contributes to the formation of calcium silicate hydrates on the rubber surfaces. Figure 2.9 shows the micro-structure of the sample as observed by the author.

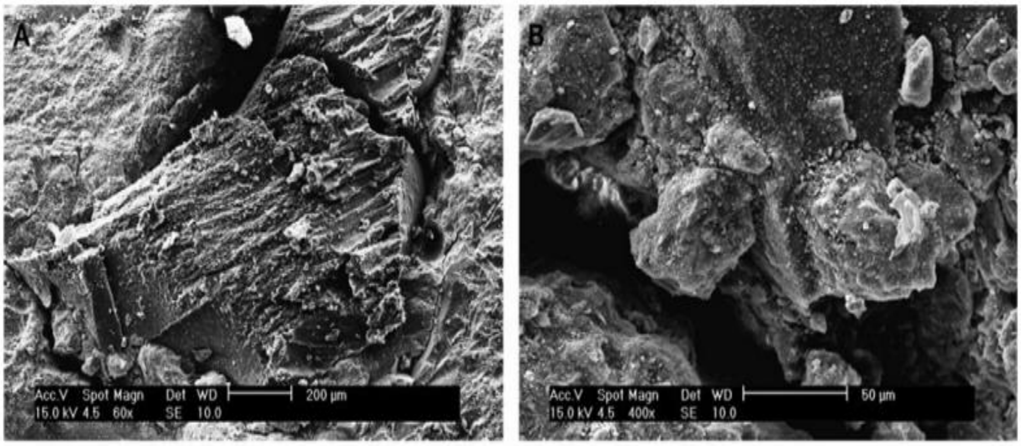


Figure 2.8: Micro-structure of crumb rubber composite [45].

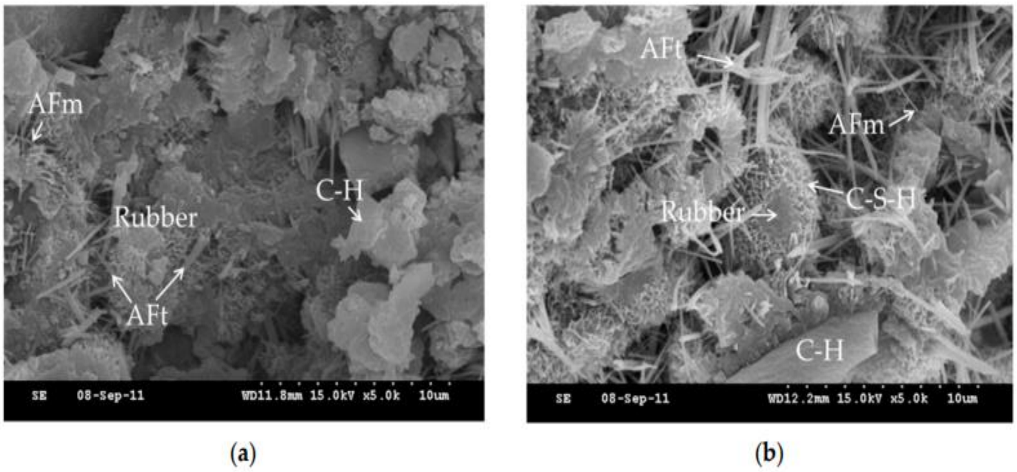


Figure 2.9: SEM image of crumb rubber composites (a) as received, (b) treated rubber [48].

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2.3 USE OF FLY ASH IN POLYMER COMPOSITE

The amount of fly ash released annually from the thermal power plant are increasing and it affects both the economy and environment. Therefore, many studies have been conducted to use this fly ash in many different fields such as chemistry, agriculture, concrete, construction, and polymer industry. According to previous studies, the use of fly ash in polymer concrete can improve their mechanical features such as tensile and impact strength.

The problem of fly ash disposal is expected to get more as the demand for energy grows. Epoxy resin is a cheap semi viscous fluid which becomes a strong matrix material when a ceramic filler like fly ash is used in it. A filler is a material which helps in increasing the mechanical, thermal and tribological properties and simultaneously helps in reduction of the cost of the component. Although fly ashes are commonly used in polymer composite, the calcium fly ashes are difficult to utilize, mainly due to the high variation in chemical composition. Figure 2.10 shows the grain size distribution for fly ash as investigated by Czarnecki et al. [49].

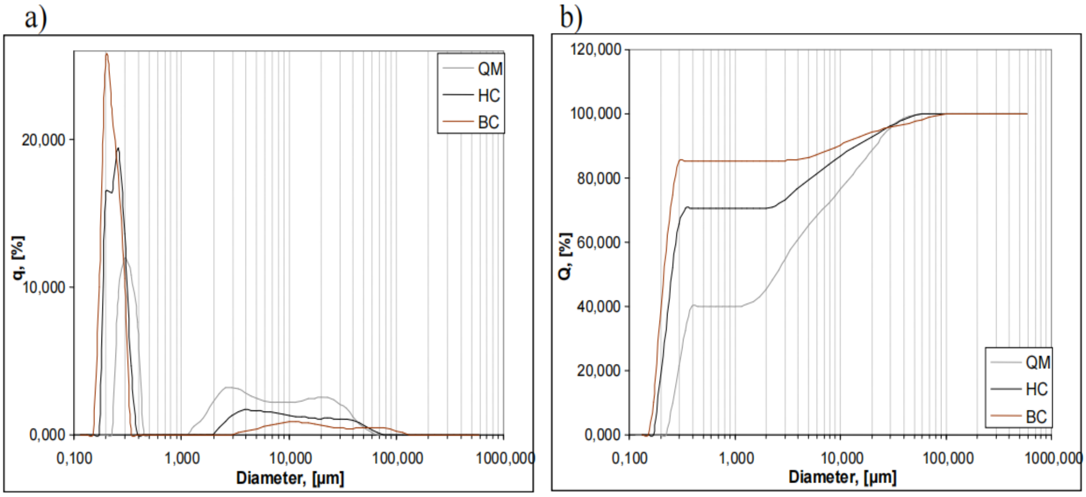


Figure 2.10: Grain size distribution curves for quartzite, calcium fly ash (a)-relative frequency, (b)-cumulative frequency plot [49]

2.3.1 Compressive strength of fly ash polymer composite

Harja et al. [50] investigated the compressive strength of polymer concrete with fly ash. The author observed that the maximum compressive strength value of 69.82MPa was obtained for dosage of 12.8% fly ash and minimum value of 57.96MPa was obtained for dosage of 6.5% fly ash. The polymer concrete with the maximum value of compressive strength had a resin content of 12.4%, aggregate content of 37.4% and fly ash content of 12.8%. In order to obtain higher compressive strength values, higher amount of fly ash and less number of aggregates must be used. Figure 2.11 shows the compressive strength at different fly ash dosage as investigated by Harja et al. [50].

Czarnecki et al. [49] stated that the compressive strength of polymer concrete containing more than 50% calcium fly ash as a micro-filler decrease significantly. Nagan and Karthiyaini [51], conducted experimental tests on fly ash-based polymer concrete columns and ordinary concrete columns, and concluded that the bonding of fly ash based polymer paste and aggregates is very strong and cohesive.

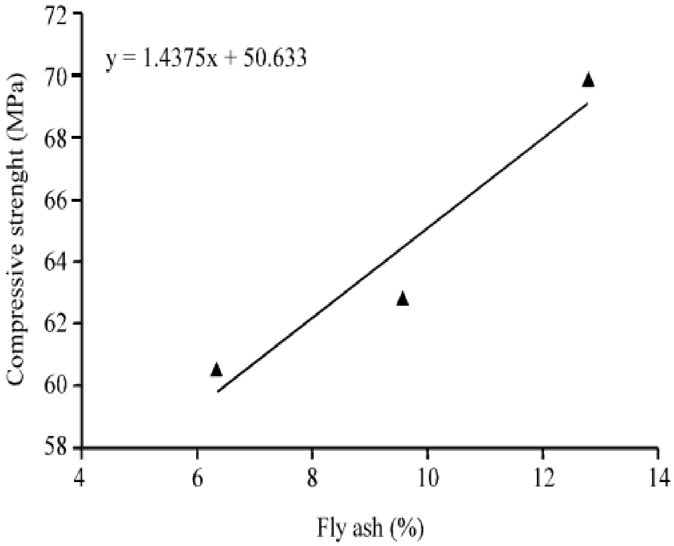


Figure 2.11: Influence of FA dosage on the compressive strength of 12.4% resin [50].

2.3.2 Flexural strength of fly ash polymer composite

Harja et al [50], observed that the maximum flexural strength value of 16.85MPa was obtained for dosage of 9.6% fly ash and the minimum flexural strength value of 13.70MPa was obtained for a dosage of 8.0% fly ash. Figure 2.12 shows the flexural strength of the sample at different fly ash dosage as investigated by the author Harja et al [50].

Raja et al [51], observed that with an increase in the fly ash content, the strength increases up to 10% of the fly ash filler. However further increase in the filler content decreases the strength of the composites. Based on the test results, the author concluded that the specimen with 70% resin, 20% fibre and 10% filler have achieved the highest value of flexural strength of 136MPa. It was further noticed that the inclusion of 10% of fly ash improves the load bearing capacity of the composites. Figure 2.13 shows the flexural strength obtained by Raja et al [51].

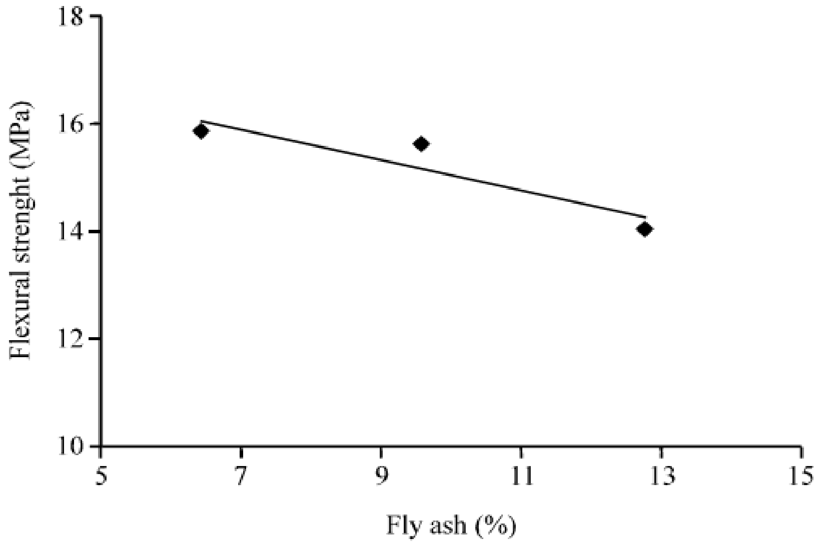


Figure 2.12: Influence of FA dosage on the flexural strength of 12.4% epoxy resin [50].

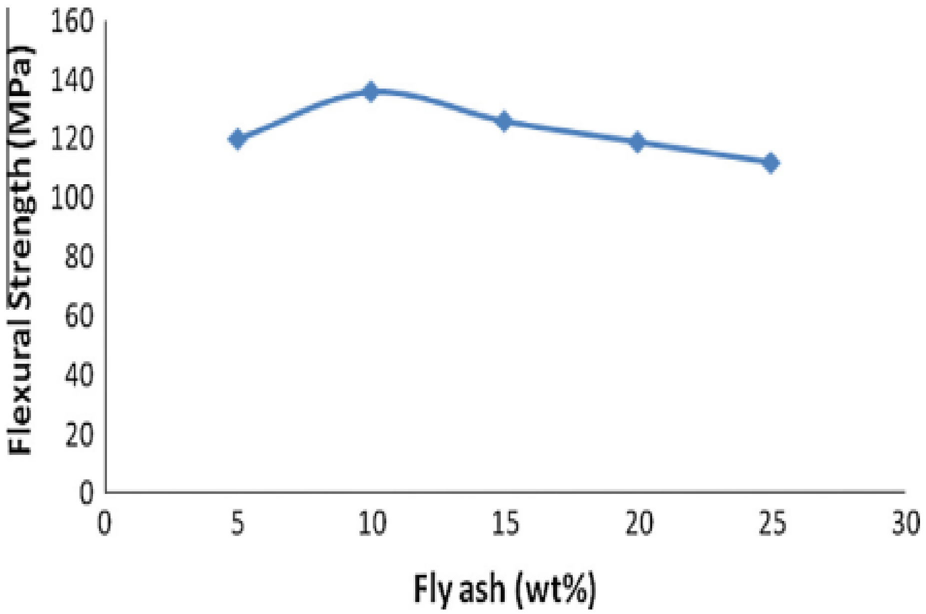


Figure 2.13: Flexural strength of fly ash composite [51].

2.3.3 Micro-structure of fly ash polymer composite

Raja et al [51] observed through SEM micrograph the fractured surfaces of fly ash impregnated glass fibre reinforced polymer composites with 10 and 25% fly ash as filler materials. The SEM observation, for polymer composites with 10% fly ash indicated that the formation of fibre pull out is arrested, which has led to better stress transfer. The stream like structure on through the analysis, indicated that, there is no crack formed due to the good bonding between the fly ash filler and the resin matrix. Further addition, of fly ash fillers would lead to poor distribution of the particles in the resin matrix. Harja et al [50], observed that, samples without fly ash, the image through SEM showed presence of voids in the polymer composites. However, for samples with addition of fly ash, the resin is not agglomerated, and the fly ash occupies the spaces among the aggregates and the structure becomes more homogeneous. Therefore, increasing the fly ash content determines the decreases of the number and size of voids. Nguyen and Pham [52] observed that, fly ash particles get on well with epoxy. Composites with fly ash have high wet ability, so the interface surface between fly ash and resin does not have any cracks. However, under effect of stress, cracks in epoxy material will appear in the most critical areas and cracks will grow when fly ash is dispersed evenly, with nanometre particles size in epoxy.

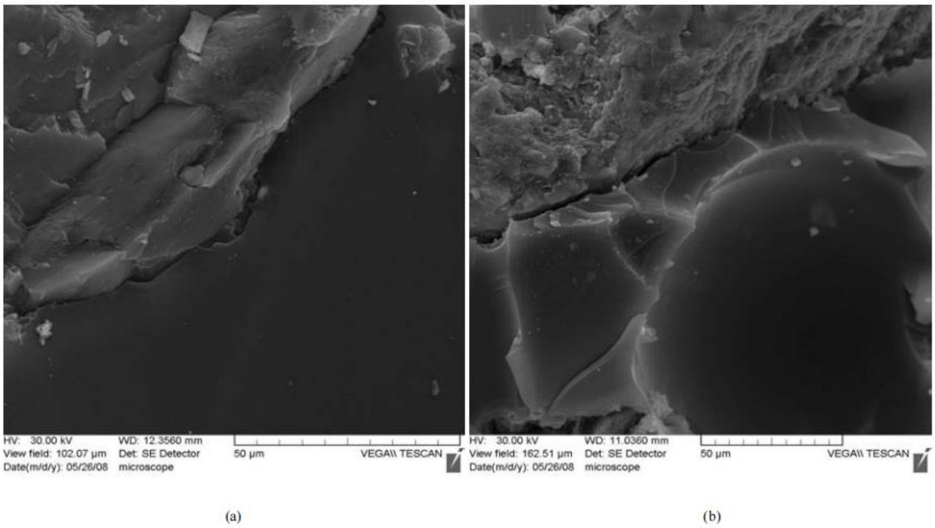


Figure 2.14: Electron microscopy for polymer composite with fly ash at the interface (a) 12.4 and (b) 14.6% resin [50].

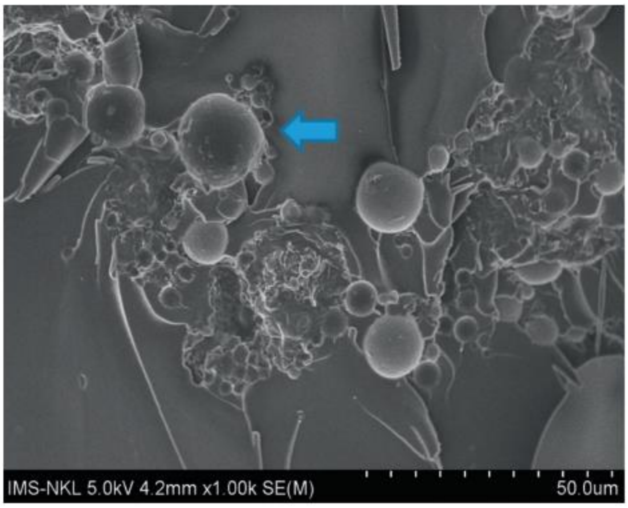


Figure 2.15: SEM image of the nanocomposite (nano-clay): with 30% fly ash, [52]

2.4 USE OF PET PLASTIC IN POLYMER CONCRETE

2.4.1 Compressive strength of PET plastic polymer composite

Rebeiz et al. [53], observed that the ultimate compressive strength of polymer concrete are about two-three times larger than those corresponding to Portland cement concrete. The author further suggested that polymer concrete using unsaturated polyester resins based on recycled PET would be suitable for field application under certain conditions. Jo et al. [54] stated that, the strength decreased with decreasing the natural aggregate contents. The compressive strength for polymer composite contains PET at resin content of 13% was in the range of 56.3-77.2MPa. Shubbar and Al-Shadeedi [55], studied the effect of using waste PET which was converted to granules and replaced different proportion of sand ranging from 1% to 8%. Samples were tested at 7 and 28 days after curing. The author concluded that, the compressive strength of the cube increases with increasing in PET waste and it gives peak value at 2% of PET replacement. Figure 2.16 shows the compressive strength of the polymer composite as found out by Shubbar and Al-Shadeedi [55]. Marsiglio et al. [56] investigated the viability of recycled plastic as a replacement for concrete masonry units as a building material. They observed that the compressive strength of sample containing PET was 80MPa meanwhile unreinforced sample were 45.2MPa. the author further stated that the presence of water in concrete can induce cracking due to thermal expansion and contraction with temperature changes, however, the porosity of PET plastic is much lower which as a result will minimize water absorption. Saikia and Brito [57] studied the compressive strength of concrete containing PET aggregates in varying amounts. It was observed that the compressive strength of concrete containing all types of PET- aggregate follows similar behavior and the incorporation of any type of PET aggregate significantly lowers the compressive strength of the concrete.

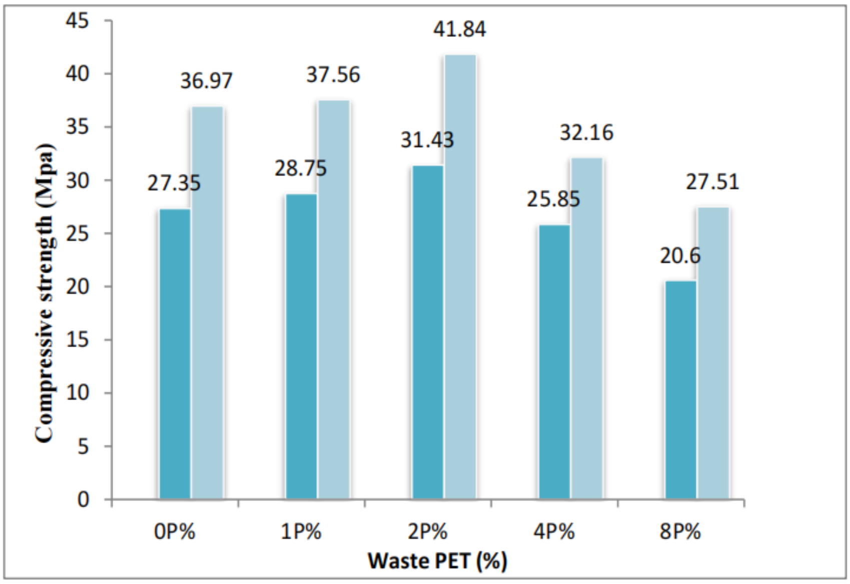


Figure 2.16: Compressive strength of PET plastic polymer composite [55].

2.4.2 Flexural strength of PET plastic polymer composite

Umasabor and Daniel [58] observed that increasing the curing duration decreases the flexural strength. At 3 days curing duration, 15% by weight of PET concrete had an increase of 20.4% over the control concrete. The early increase of flexural strength at 3 days curing duration is due to the early hydration of the cement. Wiswamitra et al. [59] observed that the flexural strength value of each concrete showed a decreasing pattern. Based on the fracture surface of beam after the flexural test, the reference concrete had the roughest fracture surface, followed by concrete using natural sand and smoothest was the concrete with all the synthetic aggregates. Rebeiz et al. [53] studied the effect of different percentages of recycled PET on the mechanical properties of the polymer concrete. The PET percentage was chosen in different percentage ranging from 15 to 40%. The flexural strength of polymer concrete increased as the amount of PET plastic residues in the resin increases.

2.4.3 Micro-structure of PET plastic polymer composite

Jo et al. [54], studied the micro-structure of polymer concrete with and without PET aggregates. Samples with PET aggregates shows compacted matrix with many voids in the surface near the aggregates, which indicates that the resin binder does not penetrate the micro-structure. Consequently, it was assumed that the properties of the aggregate-binder interfacial zone have been influenced by the presence of the porosity in the matrix and lack of adhesion. Wiswamitra et al. [59] studied the heat resistance of lightweight concrete with plastic aggregate from PET mineral filler. The test results demonstrated that heating at 100°C, fine cracks were observed which can only be seen using a digital microscope. The presence of cracks causes the mechanical characteristic of the concrete to decrease significantly. Further heating to 300 °C and 400 °C, the samples with plastic aggregate appear charred, there were holes observed due to the PET decomposition process and more cracks was observed with larger gaps. Figure 2.17 shows the micro-structures obtained by the author, Wiswamitra et al. [59].

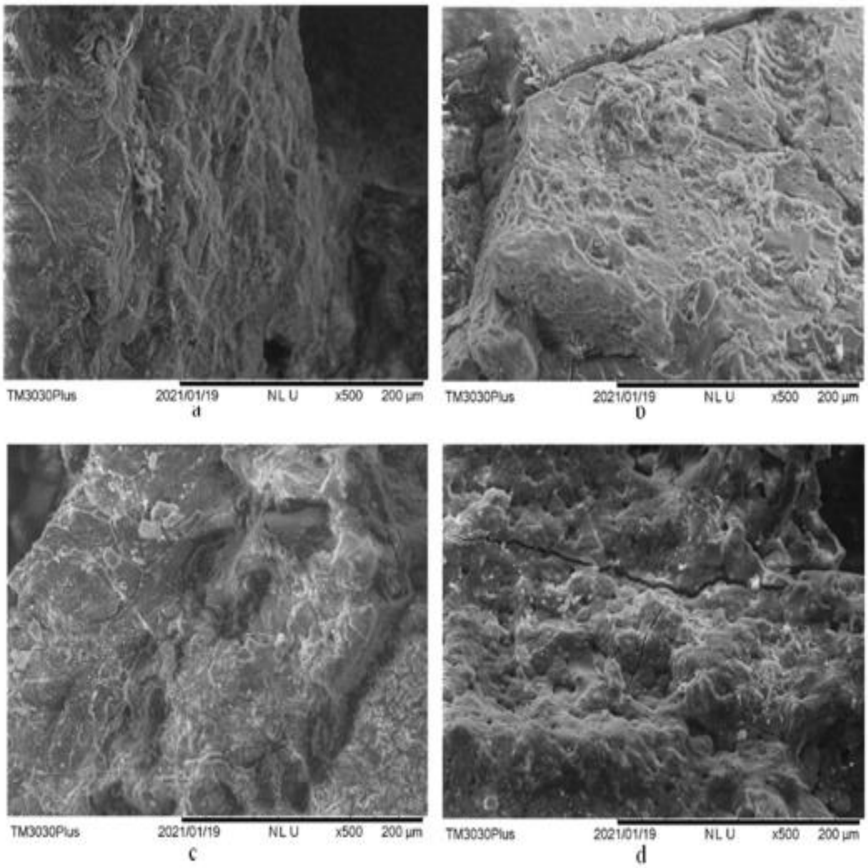


Figure 2.17. SEM photo results on FN-CPRha specimens, especially in the plastic aggregate type I/PA I (rice husk ash-PET aggregate) section at each heating temperature. (a) 100 °C, (b) 200 °C, (c) 300°C, and (d) 400 °C. [59].

2.5 POLYMER COMPOSITE IN AGGRESSIVE ENVIRONMENTS

Ghassemi and Toufigh [60] studied the durability of epoxy polymer and ordinary cement concrete in aggressive environments. According to the results, the acidic solution, was the most destructive environment for cement and polymer concrete which significantly decreased the compressive strength. Meanwhile alkaline solution had almost the same effect as the acidic solution as the ordinary Portland cement. However, epoxy polymer concrete had better performance under alkaline condition after one year of exposure. Table 2.1 shows the flexural strength of the samples after the chemical attack as summarized by the author, Ghassemi and Toufigh [60]. Figure 2.18 shows the SEM image with 8% ash in acetic acid [60].

Gorninski et al. [61] investigated the chemical resistance of eight different compositions of polymeric mortars using four different concentrations of filler, fly ash and two types of unsaturated polyester resins. Apart from that, there was no evidence of physical surface changes or weight loss. It was observed that the decrease in the flexural strength of the samples were more pronounced in the compositions with lower filler concentrations. Consequently, statistical analysis showed that the type of resin, the concentration of the filler and the type of corrosive solution have effect on the polymer mortars. Through, micro-structure analysis, it was observed that chemical attack in the polymer matrix-aggregate interface. Figure 2.19 shows the SEM image found out by Gorninski et al. [61] with 8% ash in sulfuric acid.

Table 2.1: Flexural strength of isophtalic and orthophtalic polyester after chemical attack [60].

Resin-Solution	Mean	% Strength Loss
Isophtalic – reference	24.95	-
Orthophtalic – reference	17.23	-
Isophtalic – acetic acid	24.24	2.9
Orthophtalic – acetic acid	16.41	4.7
Isophtalic – sulfuric acid	24.25	2.8
Orthophtalic – sulfuric acid	16.13	6.4
Isophtalic – cola soft drink	23.89	4.2
Orthophtalic – cola soft drink	16.79	2.6

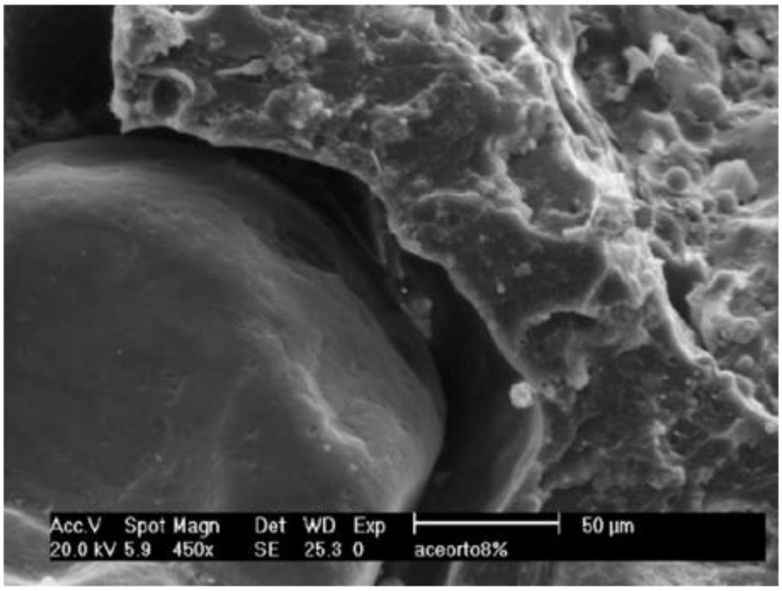


Figure 2.18: SEM image of orthophtalic PC with 8% ash in acetic acid [60].

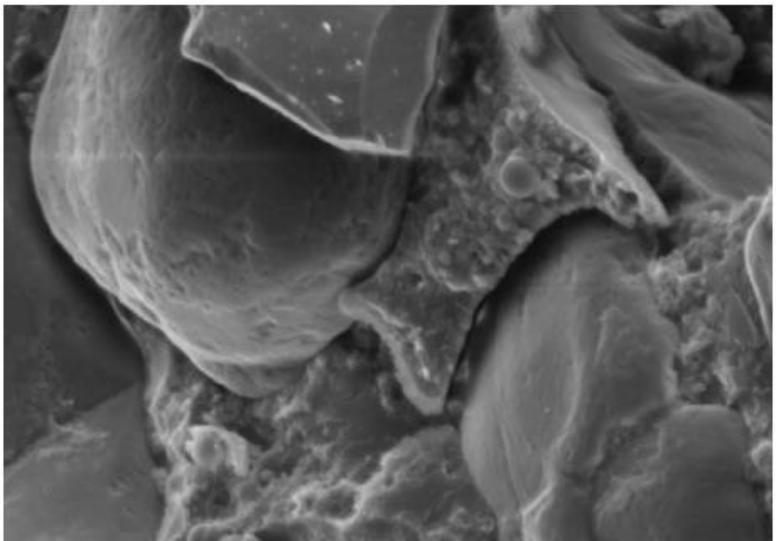


Figure 2.19: SEM image of orthophtalic PC with 8% ash in sulfuric acid [61].

2.6 USE OF NATURAL FIBER IN POLYMER COMPOSITE TO INCREASE FLEXURAL STRENGTH

Ahmadi and Dastan [62] studied, the impact and flexural properties of hybrid jute/high tenacity polyethylene terephthalate HTPET fibre reinforced epoxy composites. According to the author, high tenacity polyethylene terephthalate (HTPET) fibres also called high tenacity polyester fibres exhibit much higher tensile strength at considerably lower strains, due to their longer molecular chains with higher longitudinal orientation. Therefore, it seems that hybridizing them with a brittle fibre, like jute can have a positive effect on improving the post failure structural integrity of its composites. Based on the test results, composites with HTPET fibres do not experience catastrophic failure and retain their structural integrity after impact and bending test. Sen and Reddy [63], studied the strengthening of RC beams in flexure using natural jute fibre textile reinforced composite system and its comparative study with carbon textile (CFRP) and glass textile (GFRP) reinforced polymer composites. The author concluded that, natural jute textile have good potential in increasing the load carrying capacity of RC beams. Therefore, natural fibre in textile form like jute textile can be regarded as a suitable strengthening material for flexural strengthening of concrete structures. The average stress strain curve of jute and HTPET (b) fibres is shown in Figure 2.20 as investigated by Sen and Reddy [63].

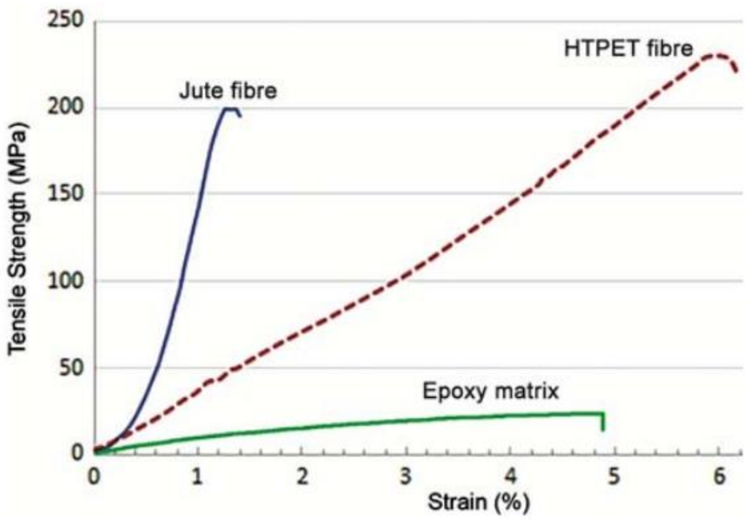


Figure 2.20: Stress-strain curve of jute and HTPET fibres [63].

2.7 FLEXIBLE PAVEMENT FAILURE, IMPROVEMENT METHODS AND DISADVANTAGES

2.7.1 Flexible Pavement Failures

Flexible pavement failure occurs when the applied load exceeds the maximum allowable limit [64]. Flexible pavement fails due to the three failures i) sub-grad failure ii) sub-base or base course failure and iii) wearing course failure [65]. The cases of flexible pavement failure have been reported in many countries particular in developing countries [65]. The four major categories of common surface distresses of asphalt pavement are i) Cracking, ii) Surface Deformation, iii) Disintegration and iv) Surface Defects [66, 67, and 68]. Generally, pavement deterioration process starts directly after opening of the road to traffics and over time accelerates at faster times. Some common types of cracking listed are a) fatigue cracking, b) longitudinal cracking, c) block cracking, d) transverse cracking, e) slippage cracking, f) edge cracking and g) reflective cracking [69, 70]. The basic type of surface deformation listed are i) Rutting, ii) Corrugations, iii) Shoving, iv) Depressions and v) Swell [71]. Meanwhile, Potholes and Patches are most common types of flexible pavement disintegration recorded. Apart from that, the most popular surface distress encountered are i) Raveling, ii) Bleeding, iii) Polishing and iv) Delamination [72]. The most common failure in flexible pavements are rutting and cracking [73 and 74]. The distress level is higher in flexible pavement in comparison with rigid pavement due to the weak inter-molecular bonding in the flexible pavement system [75, 76,]. When load is applied on flexible pavement, the molecules in the sub-base or base layer shift as they are not firmly held together causing high level of settlement and distress [77].

2.7.2 Flexible Pavement Failure Improvement

The failure of flexible pavement commonly occurs due to sub-grade failure, sub-base or base course failure or wearing course failure [78]. In order to reduce the rate of this failure, different techniques are currently applied. One common technique used in order to reduce the wearing course failure of flexible pavement is through maintenance [79]. The maintenance would consist of routine and periodic activities. Routine maintenance would include sanding, local sealing, crack sealing, filling depression, surface patching and base patching. Periodic activities would consist of surface dressing, fog spray, pavement overlaying and slurry seal.

2.7.3 Sub-base or base course deterioration improvement techniques

A study on the load carrying capacity of the flexible pavement when the gravel sub-base was reinforced with waste tyre rubber stated that total deflection of the pavement reduced when it was reinforced with waste tyre rubber in the sub-base layer [80]. At a pressure of 600kPa, the deflection was 13.25mm for rubber reinforced sub-base compared to 18.75mm for normal sub-base. An independent study on the effect of dissolving crumb rubber as binder in base layer of flexible pavement system concluded that, tyre rubber used in pavement reduces cracking, improves durability and mitigate noise [81]. Another study, on the effect of using crumb rubber in the base layer suggested that both rutting and cracking properties improved as the percentage of the crumb rubber increased [82]. Similarly, an investigation regarding the use of gravel/fly ash as the sub-base material with waste tyre rubber as a reinforcing material suggested that gravel rubber sub-base had better performance than fly ash rubber sub-base. The CBR of the gravel rubber sub-base was 13.32% at waste tyre rubber reinforcement between 5 to 6%. Meanwhile, the CBR of fly ash rubber sub-base was 8.73% at similar rubber reinforcement percentage [83]. Consequently, a study where waste tyre rubber was used as an aggregate in the base layer of the flexible pavement suggested that waste tyre rubber can be used between the ranges of 5 to 20%. Problem like rutting and cracking can be reduced particularly in hot temperature region [84]. Another study regarding the utilization of waste plastic in the base layer has stated that, it had improved the overall performance of the pavement in terms of strength and durability [85]. Similarly, another study carried out regarding the use of waste plastic as a reinforcing material for gravel/fly ash sub-base suggested that there was some improvement on the CBR of the sub-base. The CBR was 16.42% for gravel sub-base reinforced with 0.3% of waste plastic. Consequently, the CBR was 18.64% for fly ash sub-base reinforced with 0.4% of waste plastic [86].

2.7.4 Disadvantage of Current Flexible Pavement Improvement Techniques

The major problem with the surface maintenance of the flexible pavement is the cost. The maintenance cost of flexible pavement is usually 10 times more than that of rigid pavement. In many countries, about 60% from the road budget is spent on maintenance and rehabilitation [87]. Consequently, the main disadvantages with the base or sub-base reinforcement method is generally the fact that there still exist very weak inter-molecule bonds. There is a number of disadvantages of soil stabilization using lime of which are sulphate attack, carbonation and environmental impacts [88]. Soil stabilization using lime involves the calcination of calcium carbonate [88]. As the calcination occurs at a high temperature, therefore, it is responsible for the emission of large amount of carbon dioxide into the environment. Hence, the use of lime as a stabilization has negative impact on the environment [88]. Some common problems with geotextiles, geo-nets, geo-composites and geo-pipes are clogging, its long -term performance, handling, storing and installation [89]. Ground improvement using stone column is not suitable for sensitive clay. Stone columns installed at a distance of less than 3.66m can cause problem such as high lateral pressure and displacement of adjacent structures [90]. Geo-technical problems such as excessive settlement, liquefaction and low bearing capacity are usually observed with stone column [91]. In general, there is still lots of improvement needed for the current ground improvement techniques as they are very expensive and requires lots of skilled labor. Besides that, a lot of waste is also generated [92].

2.8 SUMMARY

Types	Remarks			
	Compressive Strength	Flexural Strength	Micro-structural Studies	References
Polymer Composites	1)Compressive strength of polymer composite is increased with increasing the percentage of polymer resin. 2) The compressive strength of the polymer composites increased with an increase in the dosage of the silica fume dosage. 3) Increasing aggregate content would result in a decrease in compressive strength of polymer concrete.	1) Flexural strength increases with an increase in the percentage of polymer resin added to all types of aggregates.	1)Micro-structural analysis through scanning electron microscopy of polymer concrete containing resin and natural aggregate, showed that the the binder was homogeneous.	Hameed and Hamza [26] Barbuta and Harja [30] Torkittikul et al. [29]
Crumb Rubber	1) The compressive strength improved with the addition of 5% solid rubbers, and it reduced slightly with 10% rubber content. 2) The compressive strength becomes decreasing as the amount of crumb	1) The flexural strength for rubberized concrete were lower than normal strength concrete. 2) Increasing the crumb rubber appeared to narrow the	1) Scanning electron microscopy (SEM) image showed lack of bonding between the rubber and cement matrix at the ITZ interface.	Wang et al. [39] Diwakar et al. [42] Abusharar et al. [41] Ismail and Hassan [19] Xu et al. [45] Chen and Lee [48]

	rubber increases.	crack, widths, reduce self-weight of the concrete and improve the deformability at a given load.	2) Calcium silicate hydrate on the treated rubber is much more than the calcium silicate hydrate on the received rubber	
Fly Ash	1) The bonding of fly ash-based polymer pastes and aggregates is very strong and cohesive.	1) Maximum flexural strength value of 16.85MPa was obtained for dosage of 9.6% fly ash and the minimum flexural strength value of 13.70MPa was obtained for a dosage of 8.0% fly ash.	1) Fly ash particles get on well with epoxy. Composites with fly ash have high wet ability, so the interface surface between fly ash and resin does not have any cracks.	Czarnecki et al. [49] Harja et al [50], Nguyen and Pham [52]
PET Plastic	1) The ultimate compressive strength of polymer concrete are about two-three times larger than those corresponding to Portland cement concrete.	1) Increasing the curing duration decreases the flexural strength.	1) Samples with PET aggregates show compacted matrix with many voids in the surface near the aggregates, which indicates that the resin binder does not penetrate the micro-structure.	Rebeiz et al. [53] Umasabor and Daniel [58] Jo et al. [54]

2.9 RESEARCH GAP

Previous researchers have studied the properties of polymer concrete containing mostly natural aggregates. However, there have been no research using three most generated solid wastes which are fly ash, waste plastic and waste rubber as a filler material in polymer composites. In previous studies, polymer concrete is developed using one type of filler. Hybridization of two or three types of fillers with various sizes can exhibit better properties than that of one types of filler in polymer concrete. Apart from that, there have been no research on the use of lightweight composites used as a base or sub-base course in the design of flexible pavement over peat or soft ground in controlling deflection and stress on pavement surface. Thus, the aim of this research is to develop lightweight polymer composite containing hybrid fillers such as fly ash, recycled PET and recycled tyre rubber crumb which would later be used in the application of base or sub-base layer of the flexible pavement.

2.10 Concluding Remarks

From literature review of this chapters, it is understood that polymer composite is does not contain hydrated cement, it is stronger, more durable and requires low maintenance. The advantages of polymer concrete are that its strengths can reach 4-5 times higher than cement-based concrete, meanwhile, keeping the modulus of elasticity in the similar values, have good chemical resistance and water permeability. Based on previous researchers, there have been a number of research conducted to introduce crumb rubber into conventional Portland cement concrete as a partial replacement of coarse and fine aggregates. The toughness and flexural strength of the concrete is improved due to the used of crumb rubber. Apart from that, the use of PET plastic in concrete had also shown some improvement on the compressive strength of the concrete. The target of this research study is to develop lightweight polymer composite containing waste materials such as fly ash, PET plastic and crumb rubber which would later be used as a sub-base layer of the flexible pavement.

CHAPTER 3

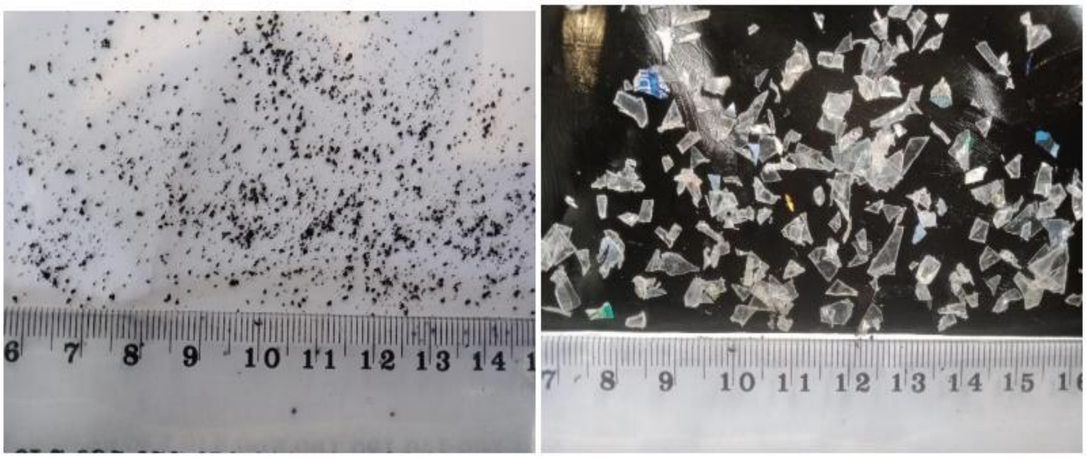
METHODOLOGY

3.1 Introduction

This chapters discusses the research approach for the development of the polymer composites and method of analysis. In the beginning of this chapter it discusses, properties of materials used in this research which are a) Unsaturated-Polyester Resin, b) MEKP (methly-ketone peroxide), c) Crumb Rubber, d) PET Flakes, e) Fly Ash, f) Sulfuric Acid, g) Magnesium Sulphate and i) Sodium Chloride are provided. Consequently, the mix proportions, curing age, specimens dimension used in this research have been discussed in detail. Details of various tests such as density, compressive strength, flexural strength and toughness carried out in accordance to Australian standard AS1012 [93] are also provided in this chapter. This chapters also discusses in depth regarding the software analysis carried out on the composites.

3.2 Materials

Unsaturated polyester resin is used as the binder of polymer composite while a small amount of about 10 mL hardener MEKP (Methyl Ethyl Ketone Peroxide) is used as a catalyst to initiate the chemical reaction of 1 kg resin. Used tyre crumb rubber, recycled polyethylene terephthalate (PET) flakes and class F fly ash are used as filler of the polymer composites. Table 3.1 summarizes the specification and properties of the resin used in this study, while Table 3.2 shows the chemical compositions of class F fly ash. Crumb rubber is produced from automotive and truck scrap tires. The crumb rubber used in this study was in powder form, whose size were less than 1mm and had bulk density of 417 kg/m^3. The average particles size of the PET flakes used in this study was 4 mm and the bulk density was 403 kg/m^3. Relatively lower bulk density of PET flakes than that of crumb rubber is due to their bigger sizes and angular shape than that of crumb rubber which contributed more voids in the bulk PET flakes than in crumb rubber. Fig. 3.1 shows the crumb rubber and PET flakes used in this study. Properties of jute fabric is shown in Table 3.3. Thus, lightweight polymer composite consisted of resin as binder and fly ash, PET flakes and crumb rubber as fillers. The chemicals used in this study were 1M H_2SO4, 1M $MgSO_4$ and 0.5M NaCl solutions [94]. According to Jakhrani et al. [95] the concentration of sodium chloride in seawater is 0.589M. Magnesium sulphate was used in order to simulate the sulphate attack from soil on polymer concrete. According to ASTM C 1012 [96], 0.352 M of magnesium sulphate is required to carry out sulphate resistance test of concrete based on real sulphate concentration in soil. For sulphuric acid, its purpose was to simulate the effect of acid rain on polymer concrete. In reality, the concentration of sulphuric acid in acid rain is 2.5 μM according to Singh and Agrawal [97]. The concentrations of all three chemical solutions used in this research were higher than the normal condition in order to accelerate the degradation of polymer composite.



(a) (b)

Figure 3.1: (a) Crumb Rubber Size (75μm - 600μm) and (b) PET flakes average size 4mm.

Table 3.1: Specification and Properties of Unsaturated Polyester Resin

Specifications and Properties of Unsaturated Polyester Resin	**Unit**	**Values**
Name		CRYSTIC 2-446 PA-45 Low Styrene Emission, Exortherm Polyester Resin
Appearance		Blue
Viscosity at 25℃(Brookfield LVT) SP3/60	Centi Poise	700
Viscosity at 25℃ (ICI C & P, 1000 sec-1)	Poise	2.5
Acid Value	mg/KOH/g	20
Non Volatile Content	%	58
Stability in the dark at 25℃	Months	3
Gel Time at 25 Resin= 100gms + Butanox M 50=1.5ml, A) QC Specification B) Gel time (aged)	Minutes Minutes	A)35 B)45
Styrene Emission - AS/NZS 4585, 1:1999	Gms/m2	<20
Interlamina adhesion test- AS/NZS 4585.2:1999		Passes

Table 3.2: Chemical composition of class F Fly Ash

Element	Percentage (%)
SiO_2	58.2
Al_2O_3	24.7
Fe_2O_3	7.18
K_2O	3.15
CaO	2.41
MgO	1.96
TiO_2	1.08
P_2O_5	0.39
Na_2O	0.31
MnO	0.91
SO_3	0.07
LOI	0.34

Table 3.3: Properties of Jute Fabric

Properties	**Unit**	**PGM 14**
Tensile Strength (md/cd)	kN/m	9
Elongation at Break	%	55
Grab Tensile Strength	N	520
Grab Elongation	%	>50
E-Modulus	MPa	12000
Melting Point	℃	165

3.3 Mix Proportion

Table 3.4 shows the mix proportions of polymer composites in the first part of this study where the effects of various volume fractions of fly ash, PET flakes, crumb rubber and the combined use of PET flakes and fly ash, crumb rubber and fly ash on 3 days compressive strength and density are evaluated.

Table 3.5 shows the mix proportions of selected polymer composites from the Table 3.4 which are considered in the second part of this study. Five different types of mixes were selected based on least resin usage and high percentage of waste material usage apart from control mix which contained 100% resin. Mix no R2-F4 was compared with mix no R4-F4. This two-mixture had similar percentage of resin and waste material usage. Mix no R3-F4 was compared with R5-F4 to observe the influence of fly ash on mixture. Mix no R6-F4 was selected to observe the influence of fly ash on mixture. Mix no R6-F4 was selected to observe the influence of all the different types of waste material on the performance of the polymer composite.The density of all composites was less than 1850kg/m^3 and exhibited more than 17.5 MPa compressive strength at 28 days and hence, satisfied the America Concrete Institute (ACI)'s [25] criteria for lightweight concrete.

Table 3.4: Mix Proportion

Filler Types	Resin	Fly Ash	Crumb Rubber	PET
	%	%	%	%
Control	100			
Fly Ash	67	33		
	50	50		
	40	60		
	33	67		
	25	75		
PET	90			10
	80			20
	70			30
	60			40
Crumb Rubber	90.9		9.1	
	87		13	
	70		30	
PET +Fly Ash	37	56		7
	36	55		9
Fly Ash +Crumb Rubber	52	35	14	
	46.5	46.5	7	

	36	55	9	
	47.6	47.6	4.8	
Crumb Rubber +PET +Fly Ash	31.25	46.9	4.7	17.2
	35.71	53.6	3.6	7.1

Table 3.5: Optimum Mix Proportion of Polymer Composites

	Resin (%)	Fly Ash (%)	Crumb Rubber (%)	PET Flakes (%)
C (Control)	100			
R2-F4	87		13	
R3-F4	38	56.6	5.7	
R4-F4	83			17
R5-F4	37	55.6		7.4
R6-F4	35.1	52.6	5.26	7

3.4 Sample Preparation and Curing

The dimension of the specimens for compressive strength and density was 50mm cubes while the dimension for flexural strength specimens were 50mm square in cross-section and 200mm in length. The fillers, resin and hardener were hand mixed in a bucket until a uniform mix was obtained. They were then placed in the Plexiglas moulds and compacted manually by using tamping rod. In the case of flexural specimen with jute fabric, the properly cut jute fabric was first placed on the bottom of the flexural mould followed by filling of freshly mixed composite. The specimens were kept in laboratory at ambient temperature of about 25℃ and tested at the stated test dates. The compressive strength and flexural strength were measured at 3, 14 and 28 days. Table 3.6 shows the chemical exposure conditions and durations.

Table 3.6: Exposure Conditions and Duration

Exposure Conditions	Chemicals	Exposure Durations
Ambient Temperature Air	None	1, 3 and 6 months
Portable Water	Tap Water	1, 3 and 6 months
Continuous Immersion in Chemical Solutions	1.0 M H_2SO_4	1, 3 and 6 months
	0.5M NaCl	1, 3 and 6 months
	1.0M $MgSO_4$	1, 3 and 6 months

3.5 Test Procedure

The compression test was carried out in accordance with the Australian Standard AS 1012 [93]. The weight of the samples was measured at every exposure duration to find the density. The flexural test of the samples was carried out according to AS1012.11 [98] standard. Four point bending test was conducted using Shimadzu testing machine. The toughness of the samples was calculated from the load displacement curves of the samples. As for the microstructure test, small pieces of samples were cleaned using ethanol and dried with nitrogen gas, before inserting inside MIRA VP-FESEM machine for the analysis.

3.6 NUMERICAL MODELLING

The evaluation of the composite pavement systems is based on mechanistic analysis. The mechanistic analysis was performed on the polymer composites through modelling. Various mechanistic analyses based on multi-linear models were performed on the polymer composite pavement and then compared with the traditional flexible pavement. The distresses of the composite were analysed by simulating real wheel loads on the pavement surfaces and modelling by Win-Julea and Mich-Pave software [99].

The numerical modelling was done based on Empirical-Mechanistic pavement design methodology which is based on the mechanism of materials which has main input value as wheel loading condition and gives output value as micro stresses and strains which are called as pavement responses. The MICH-PAVE program can perform either linear or non-linear finite element analysis of flexible pavements. It assumes axisymmetric loading conditions arising from a single circular wheel load on pavement layers of infinite horizontal extent. Consequently, in MICH-PAVE program, a flexible boundary is used instead of a fixed bottom boundary. Therefore, a mesh that is 50 radii deep is not required. Normally, when a mesh depth of 10 radii is used, sufficiently accurate results will be obtained. In general, if the flexible boundary is located too close to the top of the roadbed soil, the stress may not be accurate. If the boundary is placed too deep than, the primary advantages of using the flexible boundary are lost. The flexible boundary is usually placed at about 12 inches below the upper surface of the roadbed soil, or at a depth of 50 inches. The MICH-PAVE program includes effect of gravity and lateral stresses arising from weight of materials. At any location within the pavement, the vertical gravity stress is computed as the accumulation of the layer thicknesses multiplied by the appropriate unit weights. In case of Win-JULEA, the analysis is more simplified in comparison to MICH-PAVE. More detail of the numerical modelling is discussed in the following section.

3.6 Parametric Analysis of Pavement

A technical evaluation was performed to understand the technical advantages of the polymer composites using as a sub-base layer in the flexible pavement. The evaluation was conducted through a mechanistic modelling of the lightweight polymer composites and comparing with the conventional flexible pavement. The data were obtained by the sensitivity analysis that is performed using different parameters that influence the behaviour and response of the pavement structure.

3.7 Designed pavement

To compare the output, namely stress, strain, and deflection, it is important to design the different pavement structure so that some constant criteria can be used throughout the analysis. Although the design procedures might differ for each of the pavement types, but the structures are constructed based on the same input parameters. Table 3.7 shows the parameters that are used to design the pavements. Table 3.8 shows the design parameter input in the Mich-Pave software for analysis. Figure 3.2 shows the wheel load and the coordination of the wheels. Table 3.9 and 3.10 show the applied load and evaluation point given as input in the Win-Julea software for analysis

Table 3.7: Design Parameter for Flexible Pavement

Parameters	**Values**		
	Flexible Pavement	**Composite Pavement 1(Mix 4)**	**Composite Pavement 2 (Mix 6)**
Design Life (Years)	30		
Load	Tandem Axle Load		
Structural Number (SN)	3	None	None
Terminal Serviceability Index	3		

Table 3.8: Design Parameter for Mich-Pave Software

Parameter	Value	Unit
Wheel Load	4050	kg
Tyre Pressure	586.5	kPa
Average Annual Air Temperature	7.2	℃
Allowable Rut Depth	10.16	mm
Allowable Fatigue Damage	70	%
Kinematic Viscosity	270	Centistoke

3.7.1 Pavement Loadings

The truck used in this study was a four axle (single axle steer with single axle drive and dual tire rear tandem) 45 tons gross vehicle weight (GVW) and fitted with 10R20 tires. The truck axle configuration and GVW were chosen based on the survey done by previous researchers Haron et al (2013) and only the read tandem axle load is tested as shown in Figure 3.2. The position of each of the tire was at coordinate (0,0), (10, 0), (96, 0) and (106, 0). This coordinate was used for analysis purpose in Win-Julea software to determine the deflection, stress and strain at each of these locations.

3.7.2 Wheel Load and Position

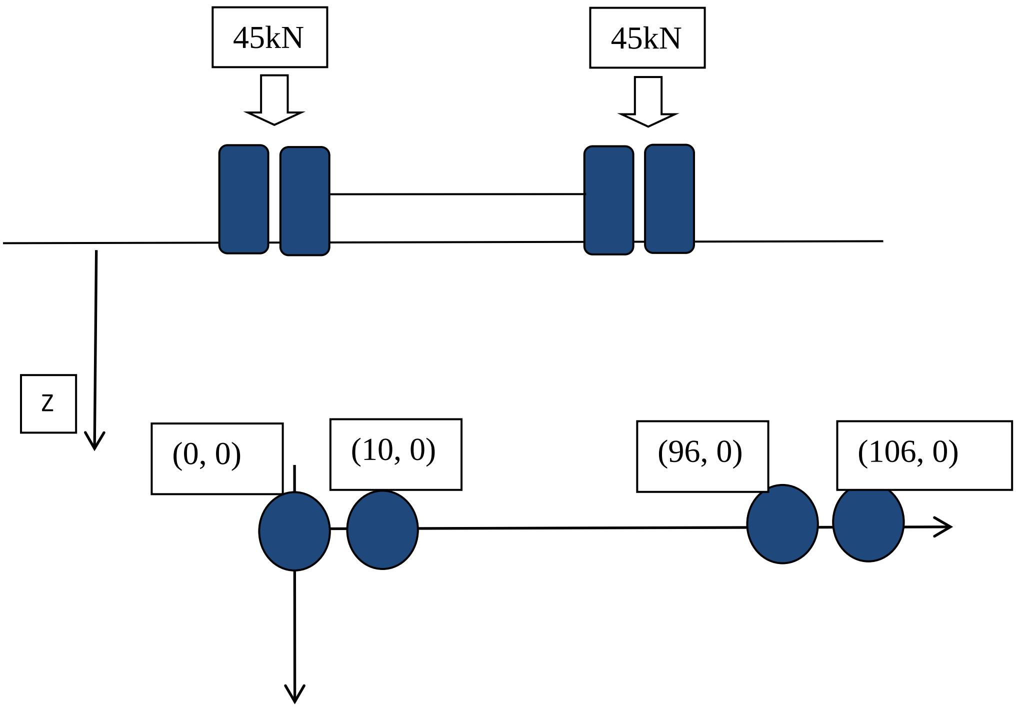


Figure 3.2: Wheel loading and Position

Table 3.9: Applied Load

Load Number	X Coordinate	Y Coordinate	Load Magnitude	Contact Area
1	0.00	0.00	4500.00	45.00
2	10.00	0.00	4500.00	45.00
3	96.00	0.00	4500.00	45.00
4	106.00	0.00	4500.00	45.00

Table 3.10: Evaluation Points

Point Number	X Coordinates	Y Coordinates
1	0.00	0.00
2	5.00	0.00
3	53.00	0.00
4	10.00	0.00

3.7.3 Properties of Flexible and Composite Pavements

There are a few common layers that have been used for the conventional depth of flexible pavement and the one used in this study was retrieved from the Austroad 2008 as shown in Figure 3.3. Table 3.11 shows the typical values used for the material properties of each layer of the conventional flexible pavement used for this study. The depth of the base layer is constant for both the mixes as the analysis is not focused here. The focus of the analysis is on the sub-base layer which consist of the different mixes of the polymer composites. The modulus of elasticity of the sub-base layer for the pavement has been obtained from lab test.

The main two parameter which were required for this study were modulus of elasticity and Poisson’s ratio. However other parameters which were also required by the Win-Julea software were the wheel loading, thickness of the layers and position of the wheel. As for the Mich-pave software, more complicated data were required such as the temperature, kinematic viscosity, and fatigue damage. This parameter and some other parameters were however automatically selected by the software. One particular reason why less parameter was required for the modelling analysis and the analysis is simplified is because these two software Win-Julea and Mich-pave were mainly designed for the pavement analysis. Therefore, the analysis is very direct.

Table 3.11: Properties of Flexible Pavement and that containing polymer composite as sub-base layer

Pavement Types	Layers	Thickness (mm)	Elastic Modulus (MPa)	Poisson's Ratio
Flexible Pavement	Asphalt Surfacing	80	1350	0.35
	Road-base	280	250	0.35
	Sub-base	100-300	170	0.35
	Sub-grade	Infinite	110	0.40
Flexible Pavement containing Mix no 4 (Resin and PET flakes) as sub-base layers	Asphalt Surfacing	80	1350	0.35
	Road-base	280	250	0.35
	Sub-base	100-300	523	0.21
	Sub-grade	Infinite	110	0.40
Flexible Pavement containing Mix no 6 (Resin, fly ash, crumb rubber and PET flakes) as sub-base layer	Asphalt Surfacing	80	1350	0.35
	Road-base	280	250	0.35
	Sub-base	100-300	4406	0.21
	Sub-grade	Infinite	110	0.40

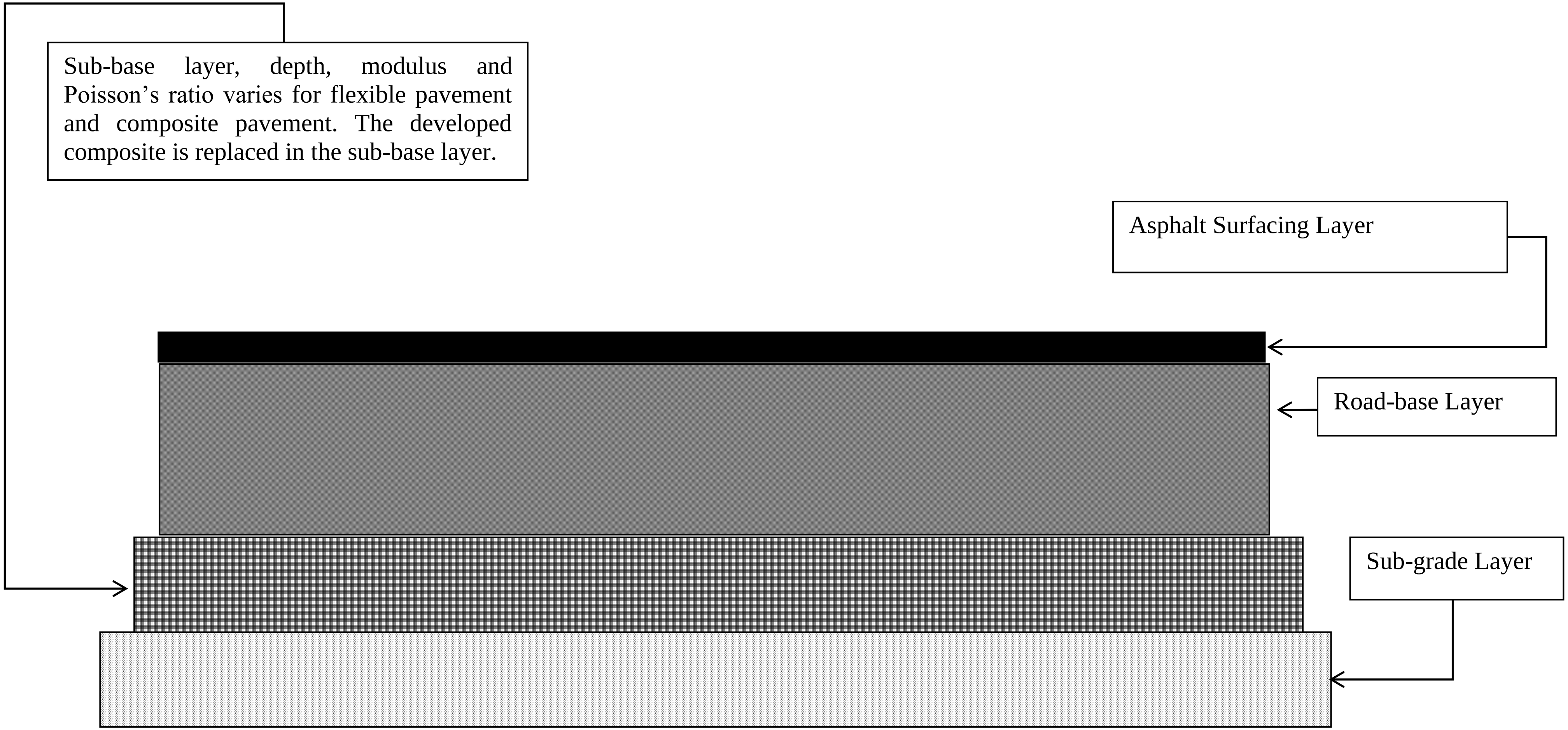


Figure 3.3: Conventional Flexible Pavement Components

3.7.4 Mechanistic Analysis

A mechanistic-based analysis based on linear elastic analysis (LEA) theory was conducted to understand and model the behaviour and responses of the pavement. The analysis of the stress, strain and deflection was obtained from the software such as Win-Julea and Mich-Pave. Win-Julea is a software developed by the Engineering Research and Development Centre (ERDC) of U.S. Army and Air Force Departments of Defence to find out the mechanistic responses of any type of pavement. This software has been used to analyse flexible pavement and the results have been promising according to previous researchers (NCHRP 2004).

Mich-pave is a user friendly, non-linear finite element analysis software developed for the analysis of flexible pavements by Ronald S. Harichandran and Gilbert Y. Baladi from Department of Civil and Environmental Engineering, Michigan State University in the year 2000. This program computes displacement, stress and strain within the pavement due to circular wheel load. Each layer in a pavement is assumed to extend infinitely in the horizontal direction and the last layer is assumed to be infinitely deep. Apart from that, all the pavement layers are assumed to be fully bonded so that no slip occurs due to applied load.

The material properties which were mainly used for analysis using this software were modulus of elasticity and Poisson's ratio of the mixes. These properties had a distinct effect on the overall test results. When the modulus of elasticity and Poisson's ratio varied, the stress, strain and deflection of the pavement layer changed. Other properties which influenced the overall test results were the wheel loadings and contact radius of the tires. All the mention properties were very sensitive to the overall results, as a slight change in values caused quite a distinct change in the overall test results. Win-Julea and Mich-pave software were designed particularly to analysis the deflection, stress and strain in pavement. This software had been used by previous researchers to analysis pavement. Other finite element (FE) simulation software such as ABAQUS and ANSYS might not provide better outcome as that software are not developed particularly for pavement but to analysis all types of structures.

3.7.5 Stress and Strain

The responses of the pavement to extremal traffic load have been mechanistically modelled by computing the stresses and strains within its layer by the Win-Julea and Mich-Pave software. Damage of pavement can occur from the stress and strain of a single wheel load. However, for repeated stress and strain, the pavement will not damage until reaches an unacceptable condition. Hence, the number and magnitude of repetitions of strain and stresses will affect the performance and determine its service life. A better pavement may be constructed with minimal distress if the pavement stress and strain can be understood in depth as the deterioration increases as the truck tyre loading and inflation pressures increase.

3.7.6 Deflection

The load transfer to the flexible and rigid pavement is usually calculated through pavement surface defection. Even though other measurements can be used to determine the structural condition of the pavement, but surface deflection is still the best pavement evaluation method. The magnitude and shape of the permanent surface deflection due to traffic load can be measured through surface deflection. The pavement structural layer stiffness and sub-grade resilient modulus can be determined through deflection measurements through back calculation methods.

3.7.7 Distress Modelling

The procedure of analysing composite pavement using multi-linear software (Win-Julea and Mich-Pave) is as follows. Firstly, a conventional pavement which is to be analysed is selected. Parameters such as the project reliability, modulus of elasticity, thickness and Poisson's ratio of each of the layer of the pavement and the contact pressure of the tyres are given as input. The standard axle wheel is located at the coordinates of (0, 0), (10, 0), (96, 0) and (106, 0) (Austroads, 2008). A vertical load of 45kN is applied at top of the wheel. The bottom of each asphalt layer and the top of sub-grade are selected as the critical locations in the pavement for the calculation of strain and stress. This is because sub-grade are able to support loads transmitted from the pavement structure without excessive deformation. The software is run for analysis and output of the result is compiled.

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

This chapter discusses the test results obtained for all the four objectives and is divided into three sections. Section 1 of this chapter discusses the development of the polymer composites with solid wastes as filler. Section 2 of this chapter discusses the long-term effect of aggressive chemicals on the developed polymer composites in section 1. The polymer composites were immersed continuously in sulphuric acid, magnesium sulphate and sodium chloride until 6 months. Section 3 of this chapter discusses in brief regarding the stress distribution pattern if this developed polymer composite is placed in the sub-base layer of the flexible pavement. Analysis is performed using Mich-pave and Win-Julea software.

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4.1 Development of Lightweight Polymer Composite

4.1.1 Influence of solid waste fillers (Fly Ash, crumb rubber and PET) on density and compressive strength of the lightweight polymer composites

Table 4.1 shows the measured 3 days compressive strength and density of lightweight polymer composites containing various amount of fly ash, recycled PET flakes and waste rubber crumb and their various combinations. It can be seen in the tables that with increase in volume fractions of fly ash the compressive strength and density are increased. However, with increase in PET flakes the density and the compressive strength of the composite is decreased. On the other hand, with increase in rubber crumb both compressive strength and density are reduced. The reduction in density of the composite containing PET and rubber crumb can be attributed to their lower density than the fly ash. Gerges et al. [100] also observed reduction in the density of the concrete when the fine aggregate in the concrete mix was replaced with crumb rubber. It can be seen that the compressive strength of composites containing fly ash is much higher than those containing PET and crumb rubber and among PET and crumb rubber the composites containing crumb rubber exhibit the lowest compressive strength. This can be attributed to the higher compressibility of crumb rubber than that of PET which damages the interface between rubber particles and polymer matrix under compression load. The weak interface between PET or rubber and polymer matrix observed in SEM analysis might be another reason for lower compressive strength of composite containing PET and crumb rubber, which will be discussed in the following section. Sofi [101] also observed the compressive strength reduction due to the addition of crumb rubber in cement concrete, while Jo et al. [102] observed a drop in the compressive strength as the PET percentage increased in resin composite. Much finer particles size and spherical shape of fly ash than those of rubber particles and PET flakes also helps in uniform dispersion of fly ash in the composite than those of rubber and PET, which also contributes in the formation of lower amount of voids and hence higher compressive strength in the former composite than the latter composites. Hybrid combinations of fly ash and PET and fly ash and rubber crumb also show higher compressive strength than the composites containing PET or crumb rubber which is believed to be due to contribution from fly ash in these composites. Nevertheless, all composites exhibited density lower than the ACI's density limit of 1850 kg/m3 for lightweight concrete. Hence, hybrid combinations of fly ash and PET flakes, fly ash and crumb rubber and fly ash, PET and crumb rubber are considered in the next part where the effect of various curing ages on density, compressive and flexural strengths, toughness, and the effect of jute fabric on flexural strength and toughness of lightweight polymer composites are evaluated.

Table 4.1: Part 1 mix proportions, compressive strength and density of polymer composites measured at 3 days.

Filler Types	Resin	Fly Ash	Crumb Rubber	PET	Compressive Strength (MPa)	Density (kg/m3)
	%	%	%	%		
Control	100				16.4	1200
Fly Ash	67	33			61.2	1328
	50	50			90.24	1472
	40	60			70	1616
	33	67			64.17	1696
	25	75			49.81	1850
PET	90			10	17.79	1136
	80			20	21.81	1136
	70			30	32.35	1088
	60			40	31	1022
Crumb Rubber	90.9		9.1		24.4	1056
	87		13		7	1045
	70		30		1.2	1015
PET +Fly Ash	37			7	40	1630
	36			9	45.04	1472
Fly Ash +Crumb Rubber	52	35	14		18.8	1376
	46.5	46.5	7		45.6	1367
	36	55	9		13	1625
	47.6	47.6	4.8		10.97	1340
Crumb Rubber +PET +Fly Ash	31.25	46.9	4.7	17.2	18.81	1400
	35.71	53.6	3.6	7.1	7.74	1550

4.1.2: Effect of curing ages and mono and hybrid fillers on density and compressive strength of lightweight polymer composites

Effects of various curing ages of 3, 14 and 28 days on density and compressive strength of polymer composites containing mono fillers (crumb rubber and PET flakes) as well as hybrid fillers (fly ash and PET flakes, fly ash and crumb rubber and fly ash, PET, and crumb rubber) are shown in Figs. 4.1 and 4.2.

The x-axis in Figure 4.1 and 4.2 shows the different types of mixes which was used for the test. R2 refers to mix no 2 meanwhile F4 refers to the initial trial mix table from where these mixes were developed. The y axis in Figure 4.1 and 4.2 shows the density and compressive strength values respectively.

It can be seen in Fig. 4.2 that the density of composite containing crumb rubber is slightly lower than that of control composite at all ages. This can be due to lower unit weight of crumb rubber than the polymer resin as 13% volume of resin is replaced by the crumb rubber. On the other hand, the density of composite containing PET flakes is slightly higher than that of control composite and that containing crumb rubber at all ages. This can be due to higher unit weight of PET than the crumb rubber and polymer resin. Slightly higher volume fraction of PET (17%) than crumb rubber is also contributed to the slightly higher density of that composite. However, the density of composites containing hybrid fillers is much higher than that of composite containing mono filler and could be attributed to the much higher unit weight of fly ash and its overall volume in the composites. Effect of curing ages did not show any significant changes in the density of the composites. The effects of curing ages on compressive strength development of polymer composites containing mono and hybrid fillers are shown in Fig. 4.2. It can be seen that the compressive strength of all composites increases with increase in curing ages irrespective of filler types and hybrid combinations.

It can also be seen that the addition of rubber crumb and PET flakes significantly reduced the compressive strength of the composites at all ages than that of control polymer composite. Among them, the addition of crumb rubber significantly reduced the compressive strength of the composite compared to that containing PET. High compressibility of rubber and poor interfacial bond of rubber particles with polymer are the reasons for such lower compressive strength. It is believed that under compression load both polymer matrix and rubber particles are compressed and due to higher compressibility of rubber than polymer matrix the rubber particles deform more and cause significant damage of rubber-matrix interface bond, as illustrated in Fig. 4.3, which adversely affects the compressive strength. Secondly, the SEM analysis revels gap between rubber particle and polymer matrix indicating poor interface of rubber with polymer matrix. Similar poor interface of PET with polymer matrix is also observed in the SEM analysis which will be discussed in the microstructural analysis section and believed to be contributed to the lower compressive strength of polymer composite containing PET flakes. It is interesting to see that the addition of fly ash significantly increased the compressive strength of polymer composites containing hybrid fillers at all curing ages and can be attributed to the much smaller particle sizes of fly ash and their spherical shape which helped in uniform dispersion of fly ash particles in the matrix of the composite as well as filling the pores and voids between rubber particles or PET flakes or both. Hence, more compact microstructure is formed and contributed to the higher compressive strength of the composite.

Interestingly, the rate of gain of compressive strength of composites containing PET flakes with curing ages is lower than those composites without PET flakes. While the reason is not clear but if the rate of strength gain of composites containing crumb rubber is compared, some reaction between polyester resin and PET might be the reason for such lower strength gain. This requires more thorough in-depth study in future on the microstructure changes of PET-polymer interface and the formation of any new reaction products in the composite, which might have contributed to this slow strength development. Nevertheless, the polymer composites containing hybrid fillers of fly ash and PET flakes, fly ash and crumb rubber and fly ash, PET and crumb rubber as well as polymer composite containing recycled PET flakes satisfied the lightweight concrete’s 28 days compressive strength and density requirement defined by ACI design guide for structural application.

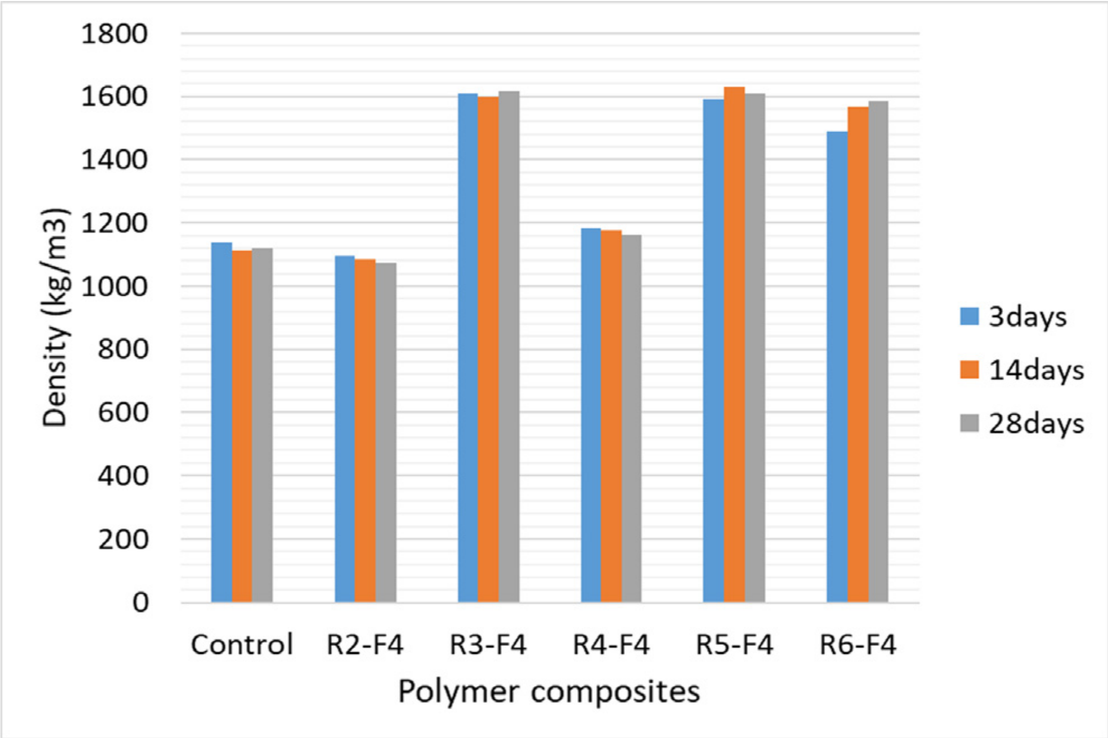


Figure 4.1: Density of Polymer Composites at 3, 14 and 28 days

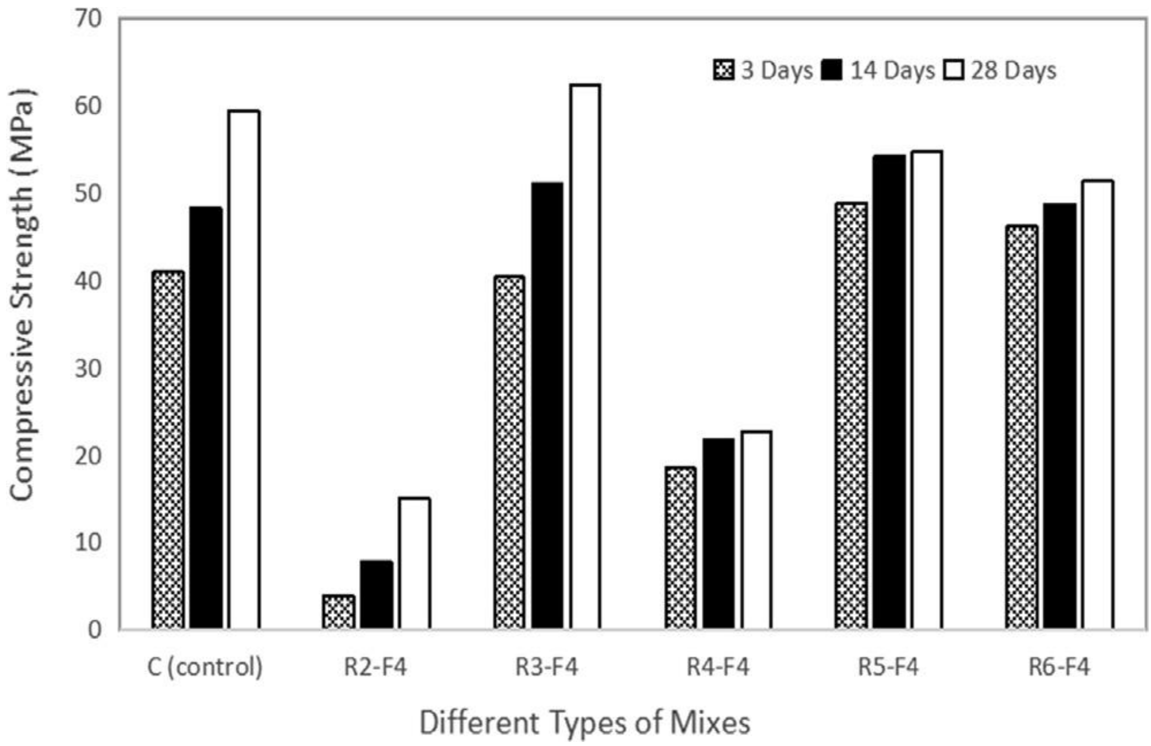


Figure 4.2: Compressive Strength of Polymer Composites Measured at 3, 14 and 28 days.

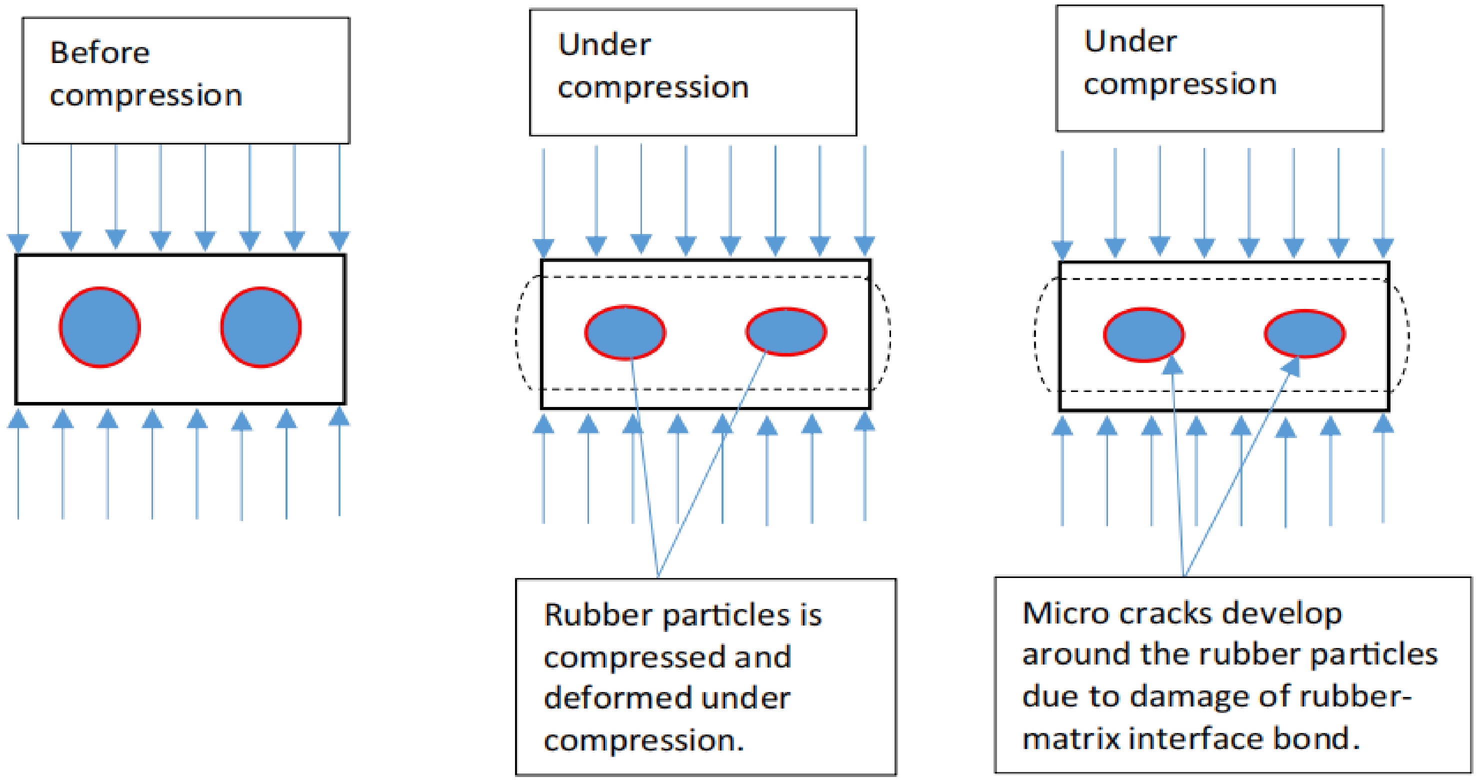


Figure 4.3: Schematic illustration of damage of interface of rubber particles-polymer matrix under compression.

4.1.3: Effect of curing ages, hybrid fillers and jute fabric on flexural strength and toughness of lightweight polymer composites.

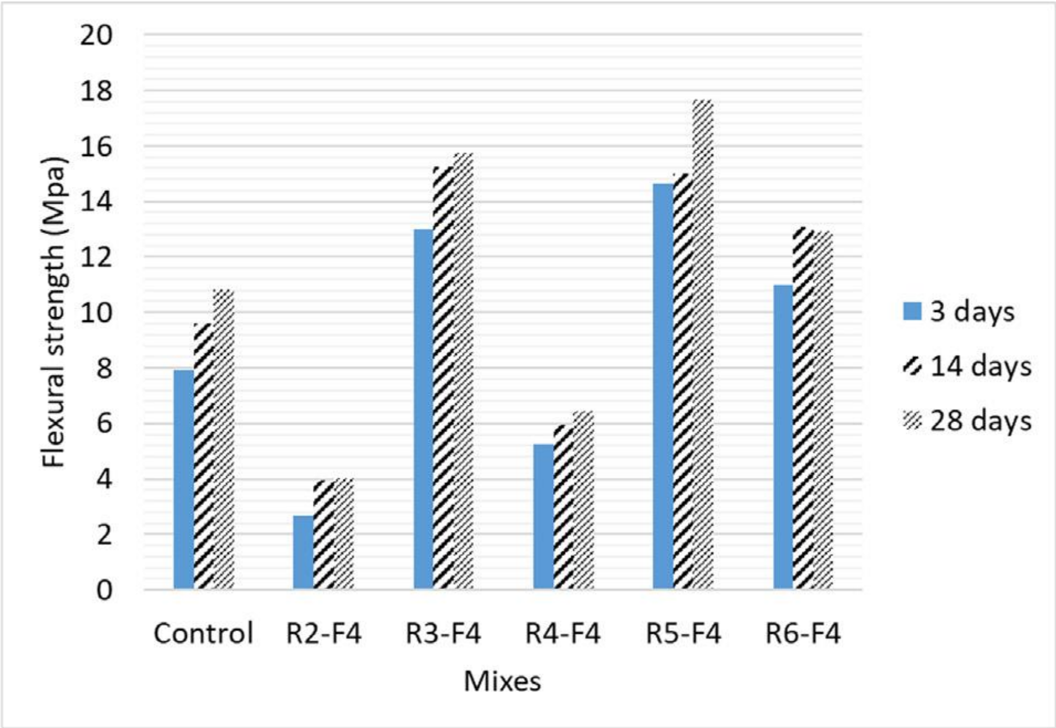
Figure 4.4 shows the flexural strength of polymer composites containing mono and hybrid fillers and reinforcement by one layer of jute fabric. The effect of curing ages on the flexural strength development of above composites is also shown in the same figure. Flexural strength results also show the similar trend of compressive strength. Polymer composites containing mono fillers (e.g., crumb rubber and PET flakes) show much lower flexural strength than that of composites containing hybrid fillers (e.g. fly ash, crumb rubber, fly ash-PET and fly ash-PET-crumb rubber). The rate of strength gain with curing ages is also very similar to that observed in the case of compressive strength. The addition of jute fabric has been found to improve the flexural strength of all polymer composites as shown in Fig. 4.4b. In particular the composites containing mono fillers exhibit much higher improvement than those containing hybrid fillers as shown in Fig. 4.5.

The deflection at peak loads of the composites is shown in Fig. 4.6 and it can be seen that the composites containing mono fillers exhibit higher deflection at peak load than that of composites containing hybrid fillers. In particular the composites containing crumb rubber (Mix R2-F4) exhibit much higher deflection capacity than that containing PET flakes and hybrid fillers. The higher deflection capacity at peak load of composites containing rubber crumb and PET flakes is attributed to their bringing effect of the micro cracks develop at the bottom of the flexural specimens of those composites. Relatively bigger size of PET flakes acted like fibres bridging the cracks in the composites which is similar to the reinforcing mechanism of fibre reinforced composite. Secondly, due to compressible nature of rubber particles, the rubber particles which were bonded with polymer matrix elongated to some extend under tension force developed at the bottom of the flexural specimens as illustrated in Fig. 4.7 and contributed to the enhanced deflection capacity at peak load. However, this phenomenon is believed to be not happened in the composites containing hybrid fillers (e.g. R3-F4 and R6-F4) presumably due to much lower volume of rubber crumb.

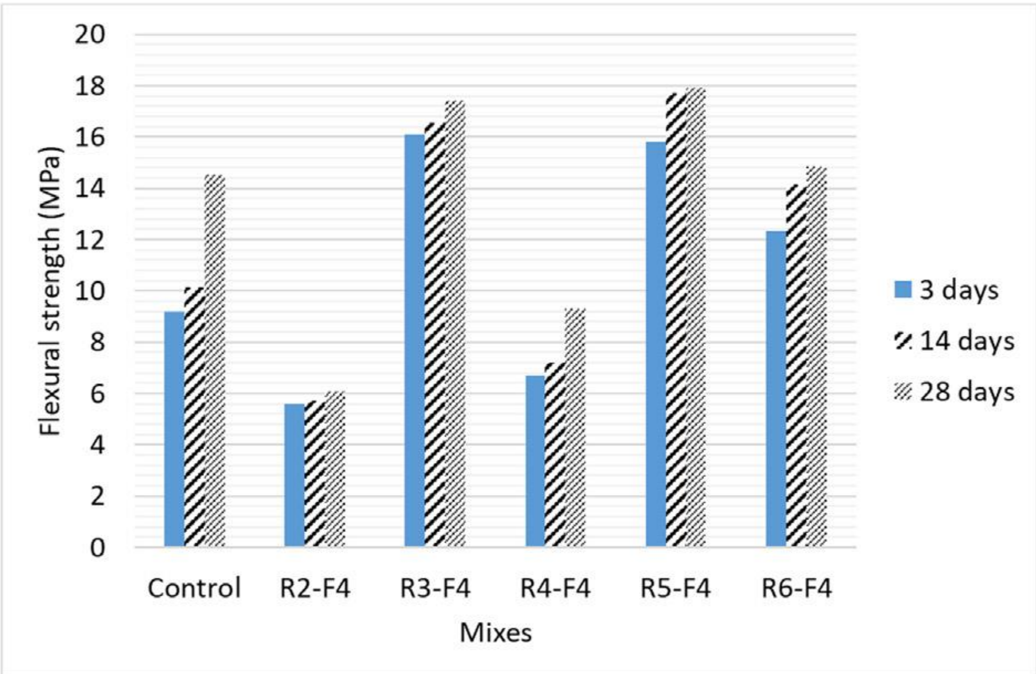
The effect of jute fabric on flexural load–deflection behavior of polymer composites cured at 3, 14 and 28 days is shown in Fig. 4.8. It can be seen that the jute fabric did not show any significant change in failure behavior of the composites under four-point bending. All composites without jute fabric show brittle failure where after the peak load the specimens load capacity is dropped to zero suddenly without increase in any deflection irrespective of curing ages. The failure pattern of the composites containing crumb rubber (R2-F4) and crumb rubber - fly ash (R3-F4) shown in Fig. 4.9 corresponds well with load–deflection behavior where complete separation of specimens can be seen indicating the brittle failure. However, the failure pattern of the composites containing PET flakes (R4-F4), PET flakes-fly ash (R5-F4) and PET flakes- fly ash crumb rubber (R6-F4) is not same as previous composites. Instead of complete separation at the middle of the beam, a crack is formed approximately in middle third of the beams (constant moment region of 4point bending load) which travelled from bottom of the beam towards the top of the beams. This type of failure pattern resembles with the softening behavior after the peak load in fibre reinforced composites where crack gradually open with increase in deflection and decrease in load.

Based on the test, sudden breakage of the samples was observed for control samples which contained 100% resin and sample labelled as R3-F4, R5-F4 and R6-F4. The fracturing of this samples occurred suddenly instead of deforming. This samples showed characterizing of brittle failure. In addition to that, the load deformation graphs for this samples deformed for shorter duration and had higher peak load for breaking. However, for sample labelled as R2-F4 and R4-F4, there was an absorption of massive amount of energy and a slower propagation was observed before the fracture occurred which shows characterizing of ductile failure. Based on the test, cracks which occurred in samples R2-F4, and R4-F4 were able to resist extension without any increase in stress. Apart from that, based on load displacement graph, the graph deformed longer for sample labelled as R2-F4 and R4-F4 as compared to the other samples. However, the load–deflection behavior of these composites does not resemble with the failure pattern which need further study by considering various sizes of PET flakes and crumb rubbers and their various amount. Nevertheless, relatively bigger size of PET flakes than other fillers in those composites might have contributed to such failure pattern through bridging the crack.

Toughness of the composites is also calculated as the area under the load–deflection curve up to peak load and is shown in Fig. 4.10. It can be seen that the use of mono and hybrid fillers improve the toughness of the polymer composites at all curing ages. The net increase in toughness of the composites containing fillers is shown in Fig. 4.11 where it can be seen that at early age (3 days) all composites show improvement in toughness due to addition of fillers. However, at later ages e.g., 14 and 28 days no such improvement is observed. In the case of jute fabric reinforced polymer composites a slightly different scenario can be seen in Fig. 4.12, where at 3 and 14 days all composites show improvement in toughness at all filler types with only exception at 28 days. The effect of jute fabric on the improvement of toughness of the composites is shown in Fig. 4.12, where mixed results can be seen. However, most of the composites show improvement in toughness due to jute fabric. By increasing the jute fabric layers or types of fibres significant improvement in toughness of the polymer composites are expected which needs further research.



(a)



(b)

Figure. 4.4: Flexural strength of polymer composites (a) without and (b) with one layer of jute fabric

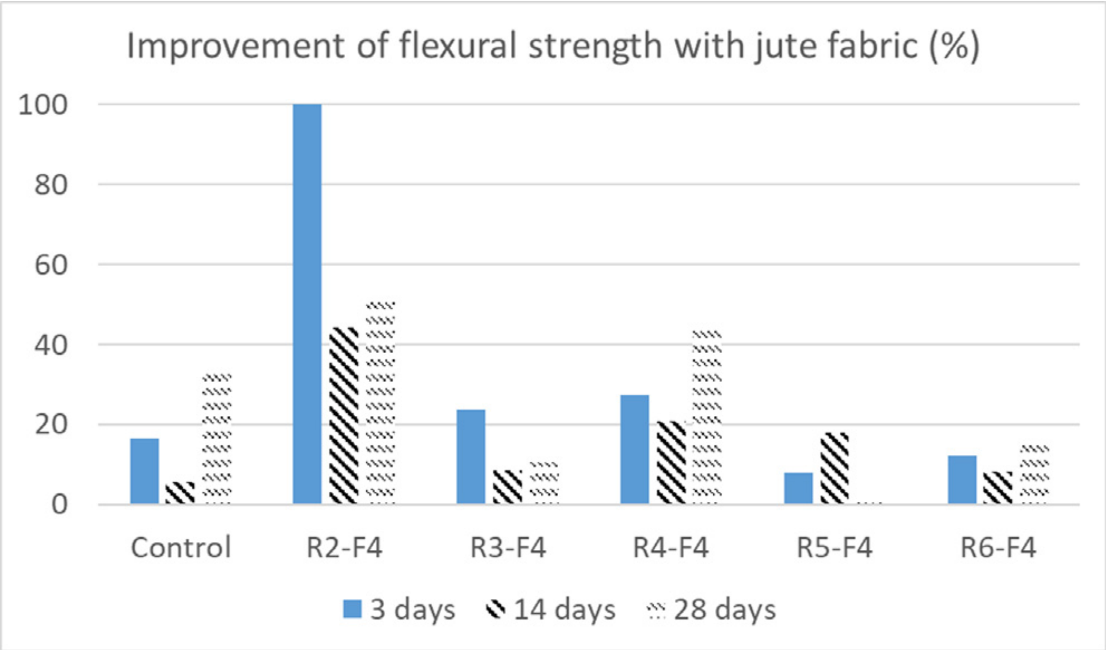
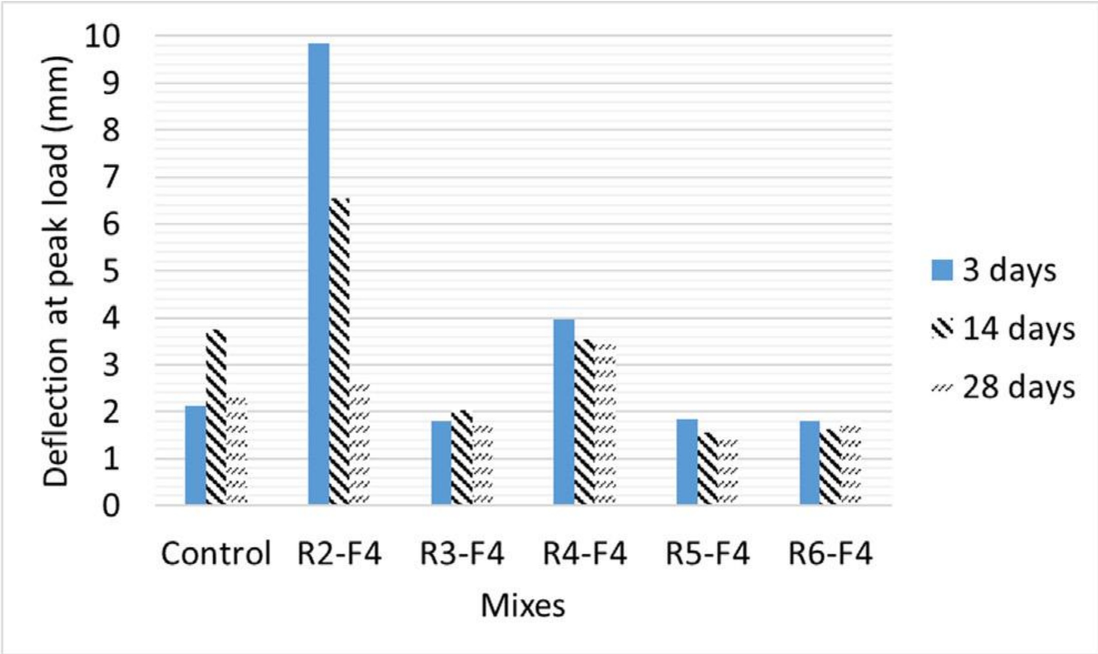
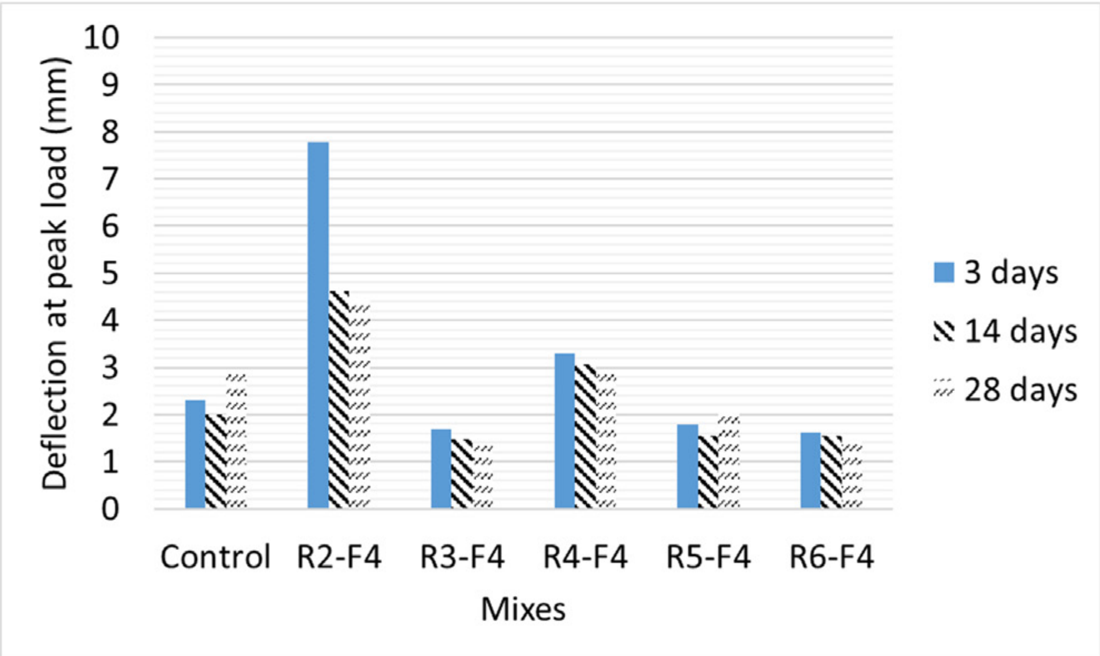


Figure. 4.5: Improvement of flexural strength of polymer composites due to addition of jute fabric.



(a)



(b)

Figure 4.6: Deflection at peak load of polymer composites (a) without and (b) with one layer of jute fabric.

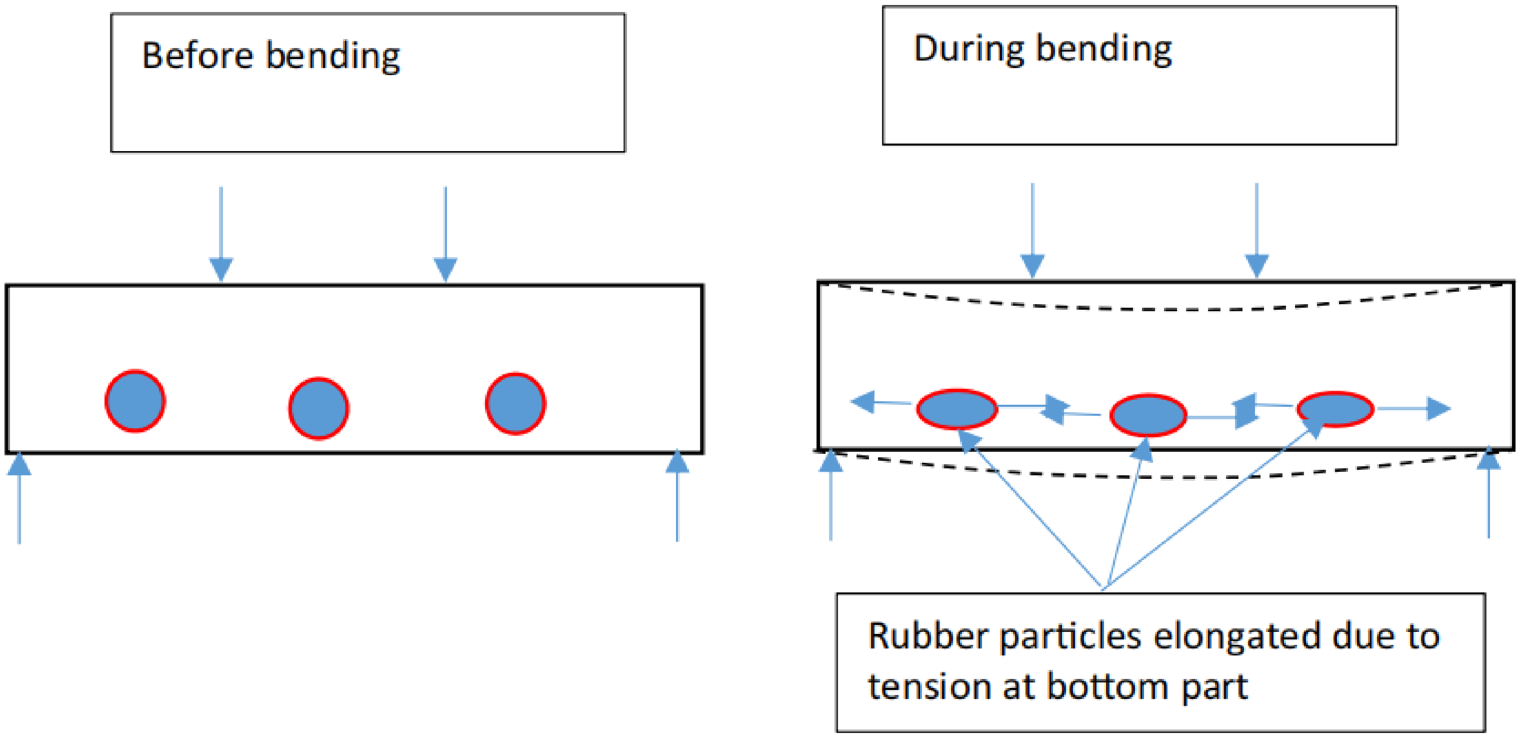
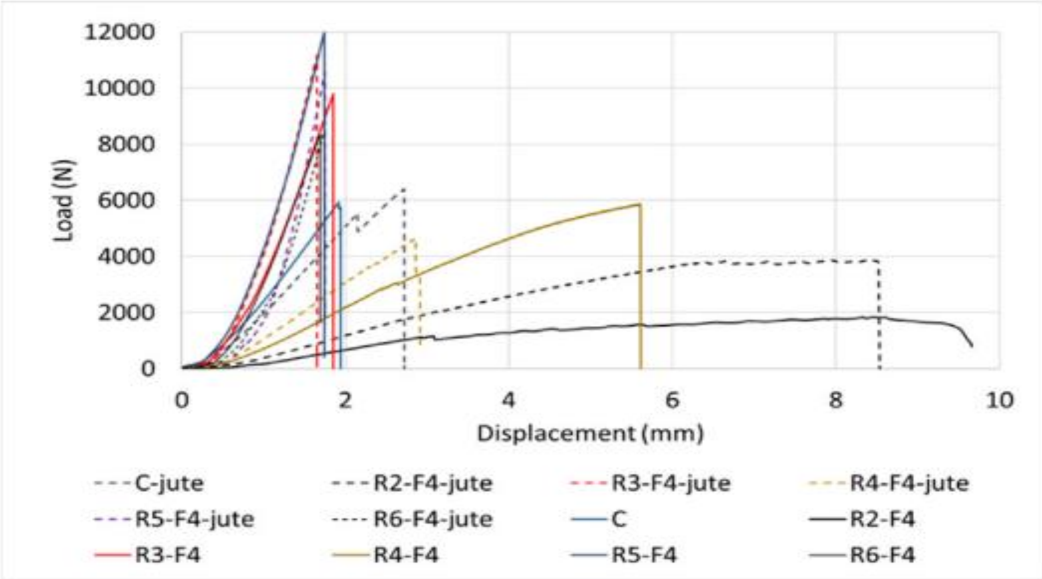
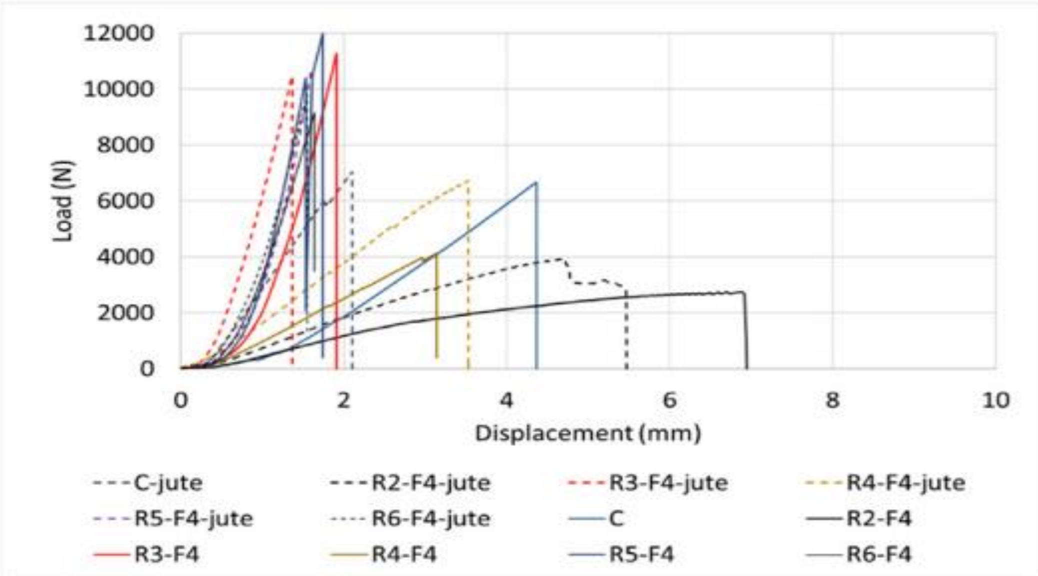


Figure 4.7:Illustration of elongation of rubber particles due to tension at bottom of the beam.


Load (N)
Displacement (mm)
C-jute
R2-F4-jute
R3-F4-jute
R4-F4-jute
R5-F4-jute
R6-F4-jute
C
R2-F4
R3-F4
R4-F4
R5-F4
R6-F4

(a)


Load (N)
Displacement (mm)
C-jute
R2-F4-jute
R3-F4-jute
R4-F4-jute
R5-F4-jute
R6-F4-jute
C
R2-F4
R3-F4
R4-F4
R5-F4
R6-F4

(b)

(C)

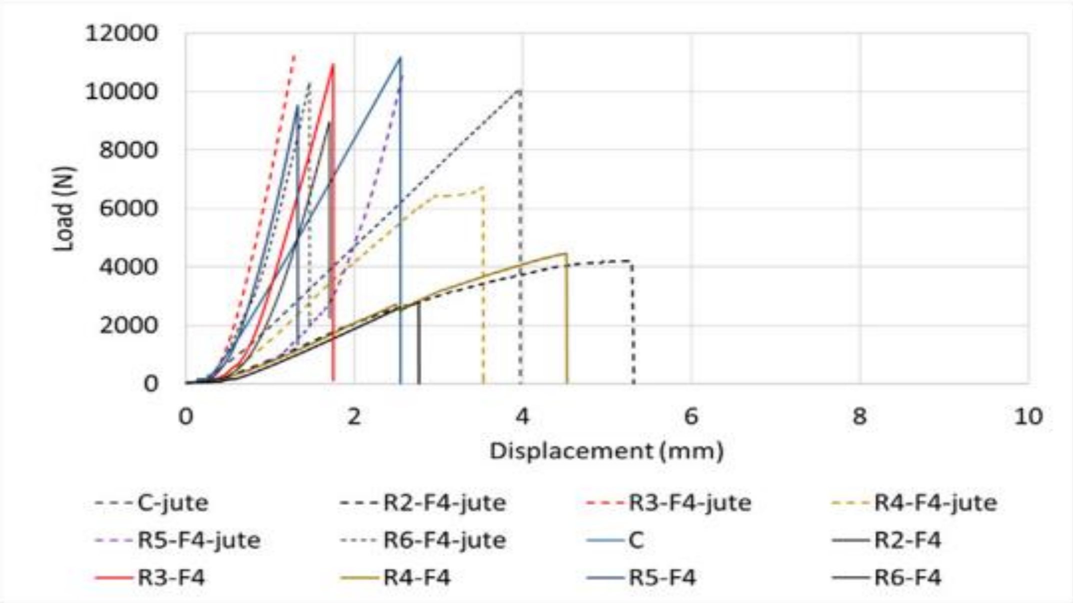


Figure 4.8: Load-deflection behaviour of polymer composites at (a) 3 days, (b) 14 days and (c) 28 days with and without jute fabric.

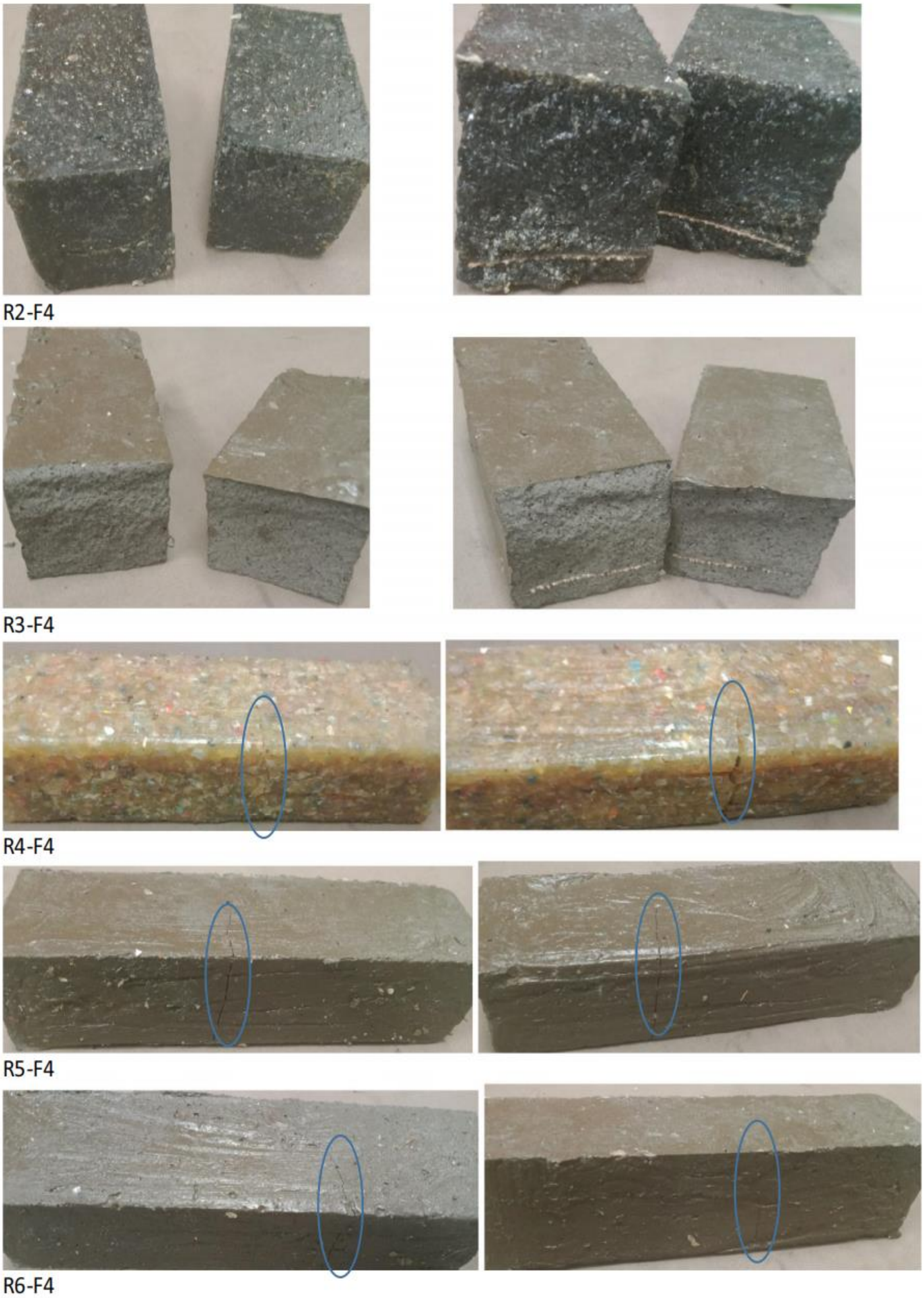
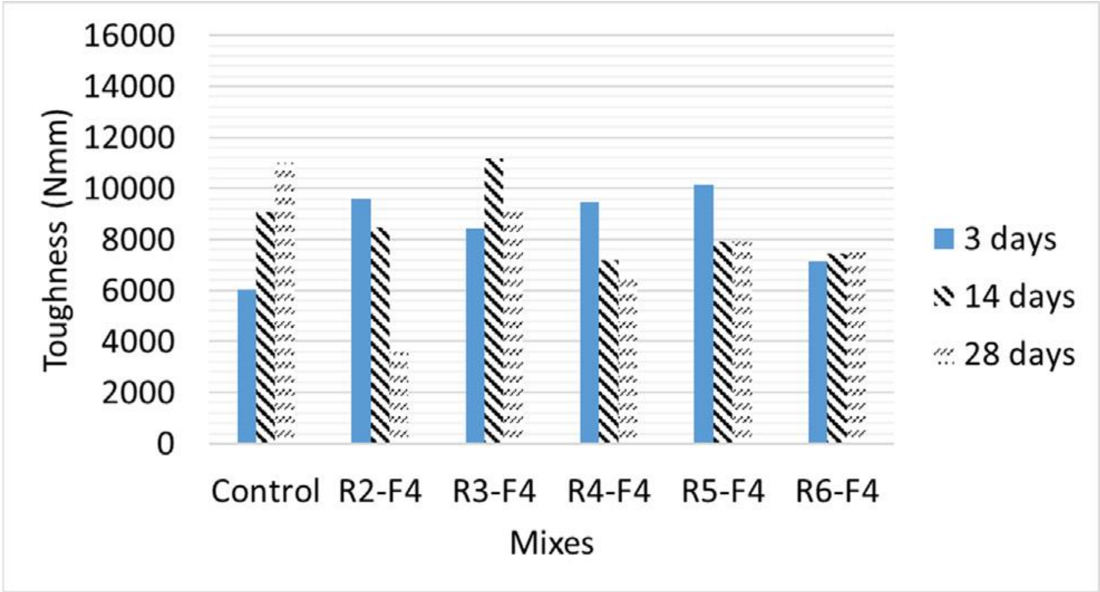
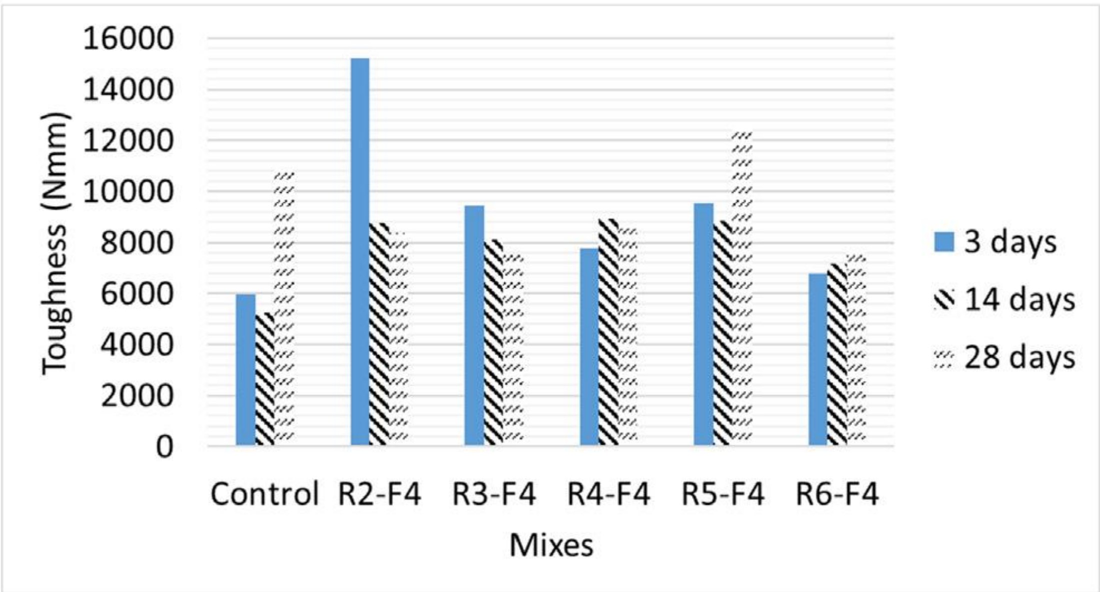


Figure 4.9: Failure pattern of polymer composites beam without jute fabric (left) and with jute fabric (right).

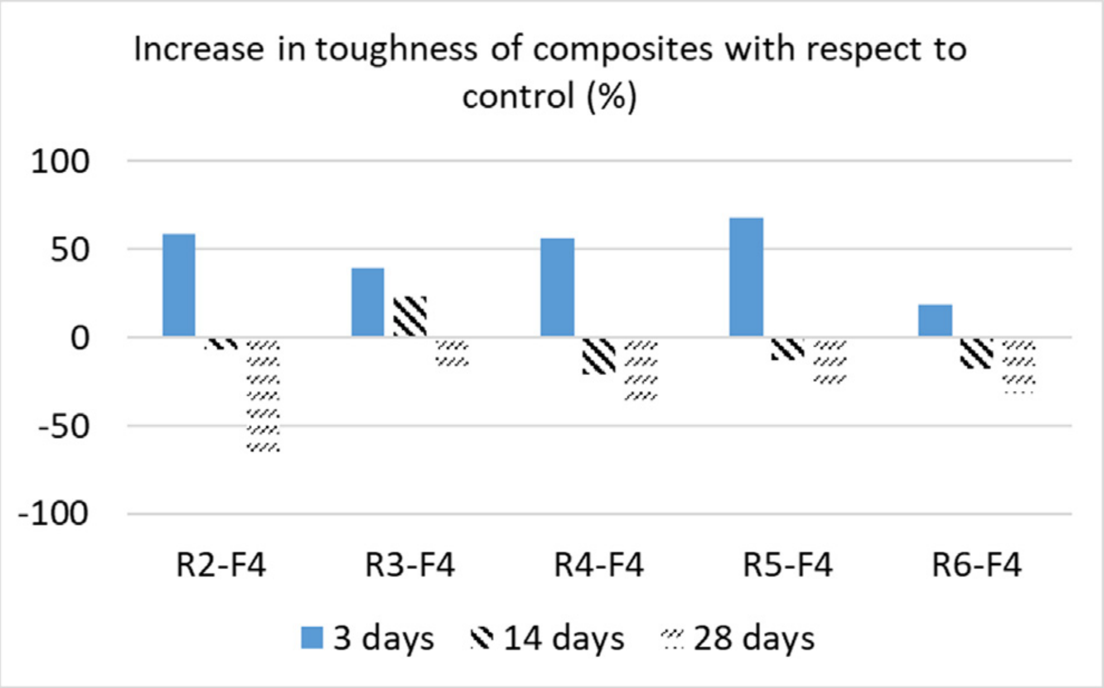


(a)



(b)

Figure: 4.10. Toughness at peak load of polymer composites (a) without and (b) with one layer of jute fabric.



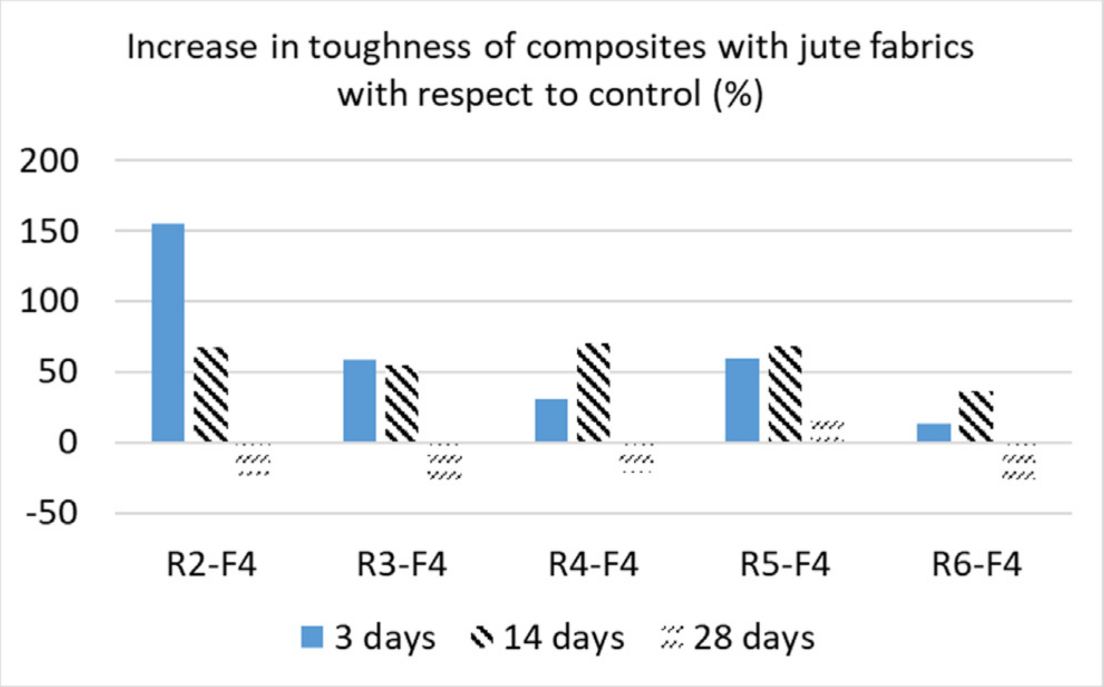


Figure 4.11: Increase in toughness of polymer composites containing mono and hybrid fillers with and without jute fabric compared to control composite.

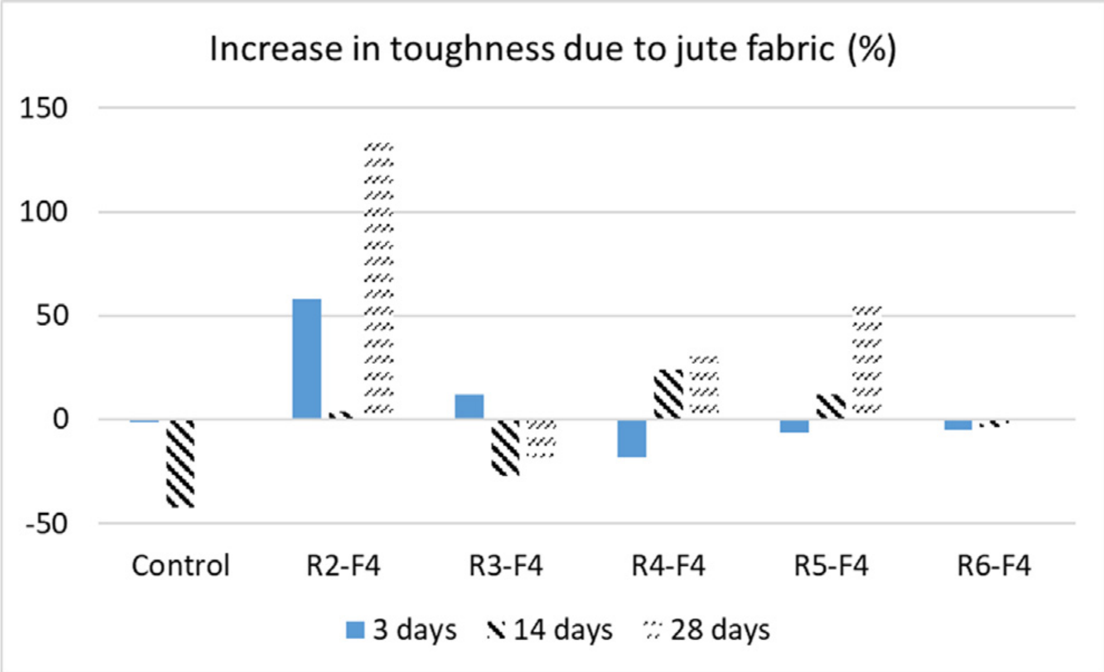


Figure 4.12: Increase in toughness of polymer composites due to jute fabric.

4.1.4: Microstructural analysis of the polymer composites

Figures 4.13 to 4.16 show the SEM images and EDS of the composites tested at 28 days. Fig. 4.13 shows the SEM image of pure resin. EDS analysis identified carbon and oxygen indicating it as polymer resin. Fig. 4.14 shows the SEM image of the composite containing crumb rubber (R2-F4) and the EDS analysis shows traces of carbon, oxygen, zinc and sulphur indicative of rubber in spectrum 16. Trace of carbon and oxygen in spectrum 17 show the evidence of polymer resin in the composite. A crack like long gap between rubber and polymer resin can also be seen in the SEM image of that composite. The SEM image and EDS shown in Fig. 4.15 of composite containing crumb rubber and fly ash show pores next to the rubber particles. Traces of carbon, oxygen, zinc and sulphur in spectrum 19 confirm it as rubber while traces of silica, carbon, oxygen and alumina in spectrum 21 show that fly ash particles are well dispersed inside the polymer resin. Good dispersion of various sizes of fly ash particles is also evident in the SEM image of this composite. Fig. 4.16 shows the SEM image of polymer composite containing PET and fly ash where good dispersion of fly ash particles in the resin can also be seen. However, porous interface between PET and matrix can be seen in the image. The trace of carbon and oxygen in spectrum 30 confirms it as PET while the traces of silica, carbon, oxygen and alumina in spectrum

31 confirm it as resin with fly ash particles. Based on the SEM images and EDS of all the composites, no formation of additional substance was identified, except for the basic materials which were used in the mix which are resin, fly ash, crumb rubber and PET.

This finding describes that there had been no reaction occur within the composites. If reaction occurred in the composites, then additional substance would have formed, and mass of the composites would have changed. The finding in this section however can be related with the finding in previous section, where no change in the density at all curing ages are observed. The increase in the compressive strength could be due to the properties of polymer composite which have a distinct change within the first 7 days.

Besides that, based on Figure 4.13-4.16 it is observed that both rubber and PET particles is not embedded well with the resin, as gaps were observed between the resin and rubber or between PET and resin. Besides that, based on Figures 4.13-4.16, it was also observed that both rubber and PET particles are irregular. The increase in compression strength of the mix when fly ash was added is due to the size and shape of the fly ash. Fly ash is finer in comparison to the rest two filler (rubber and PET). It has a spherical shape which contributed a better particle packing in the matrix.

Similar findings were also reported by previous researchers. Pihtili [103], also reported an unchanged in the composite and mass of the glass fibre polyester resin composite. Shorabi and Karbalaie [104], stated that there were voids observed between the rubber particles and the cement matrix which as a result creates weak bonds between the rubber and cement matrix. This weak bond is responsible for the faster initiation of crack.

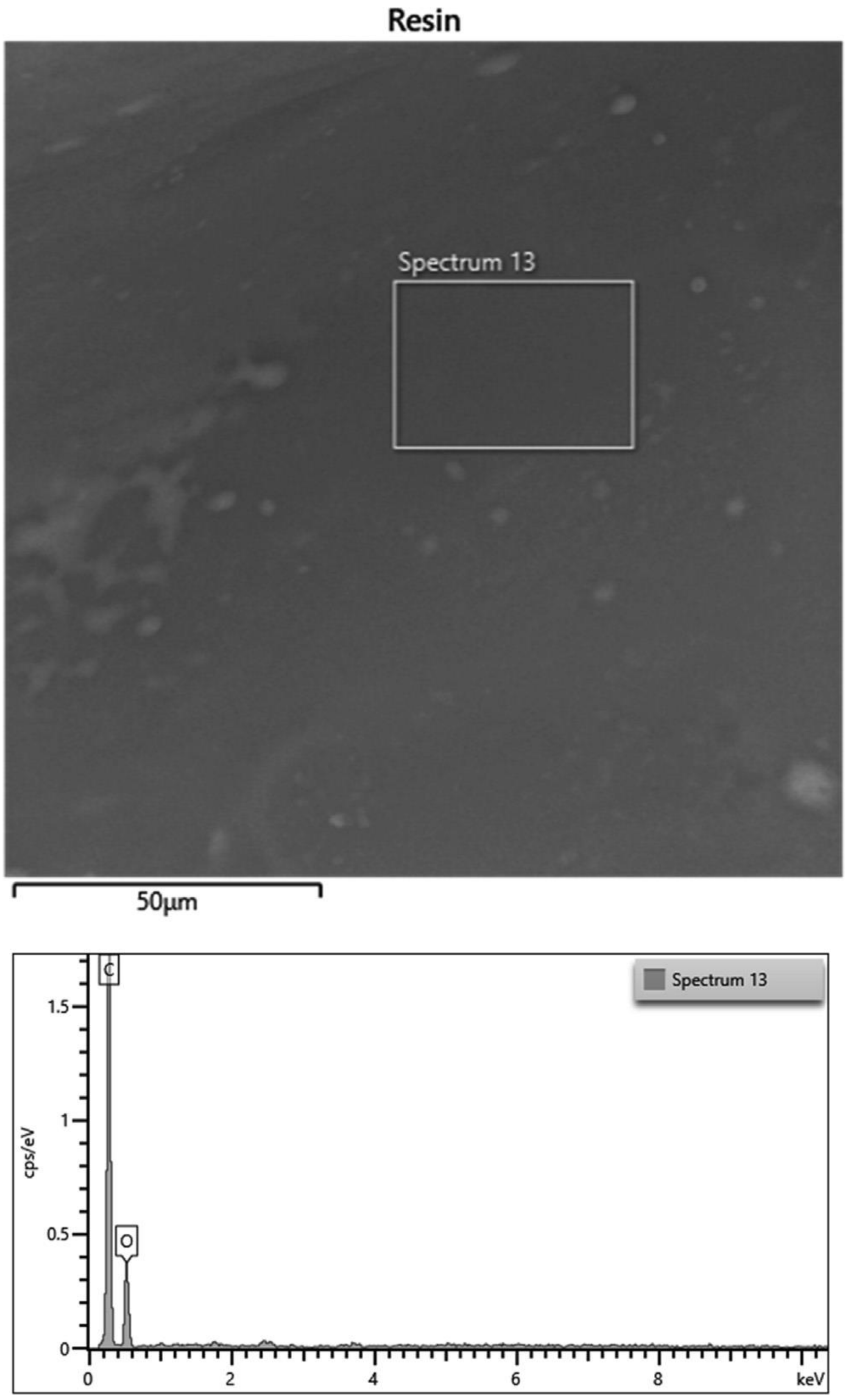


Figure. 4.13: SEM and EDS of Pure Resin Control (C).

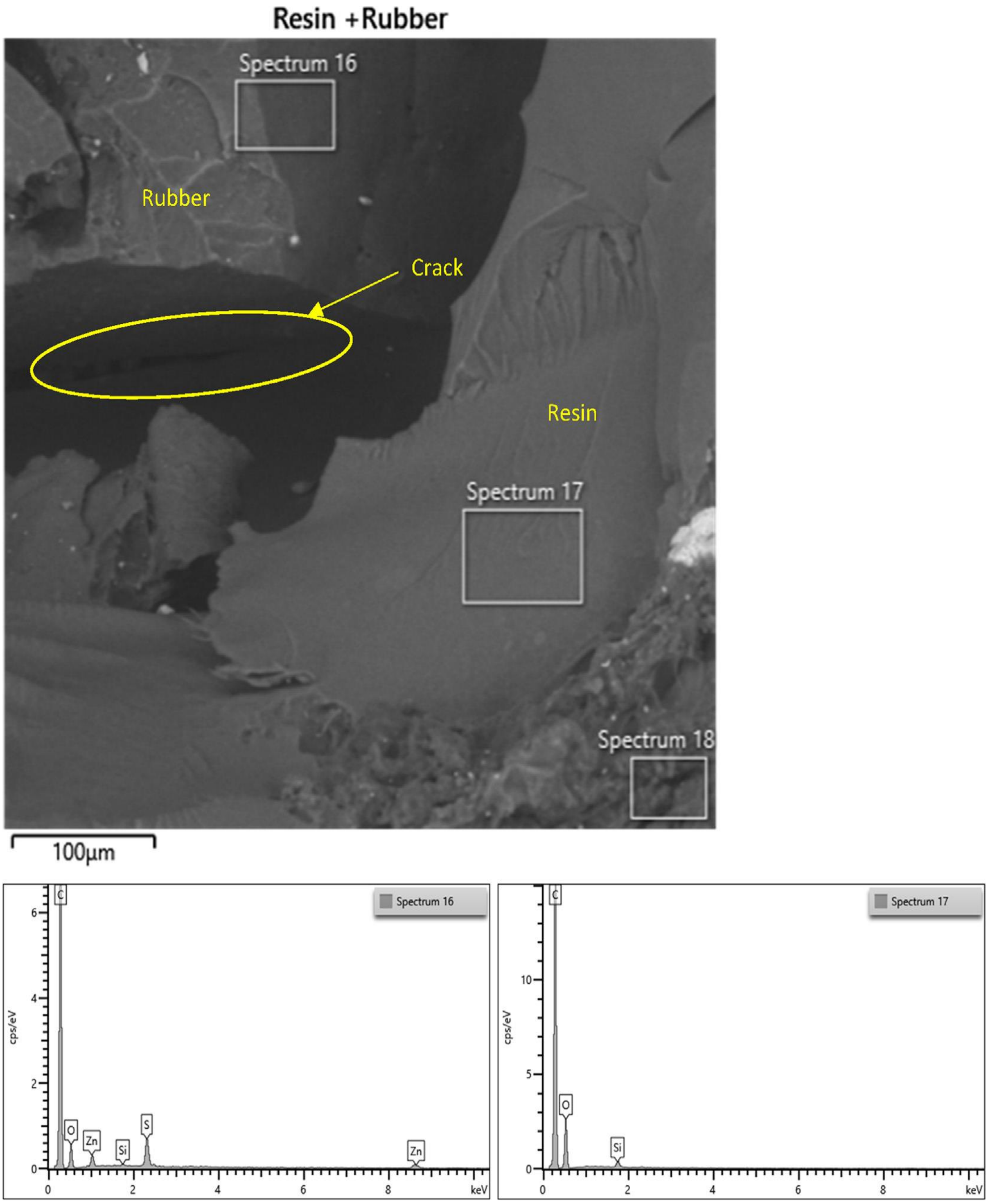


Figure 4.14: SEM and EDS images of polymer composite containing crumb rubber (R2-F4).

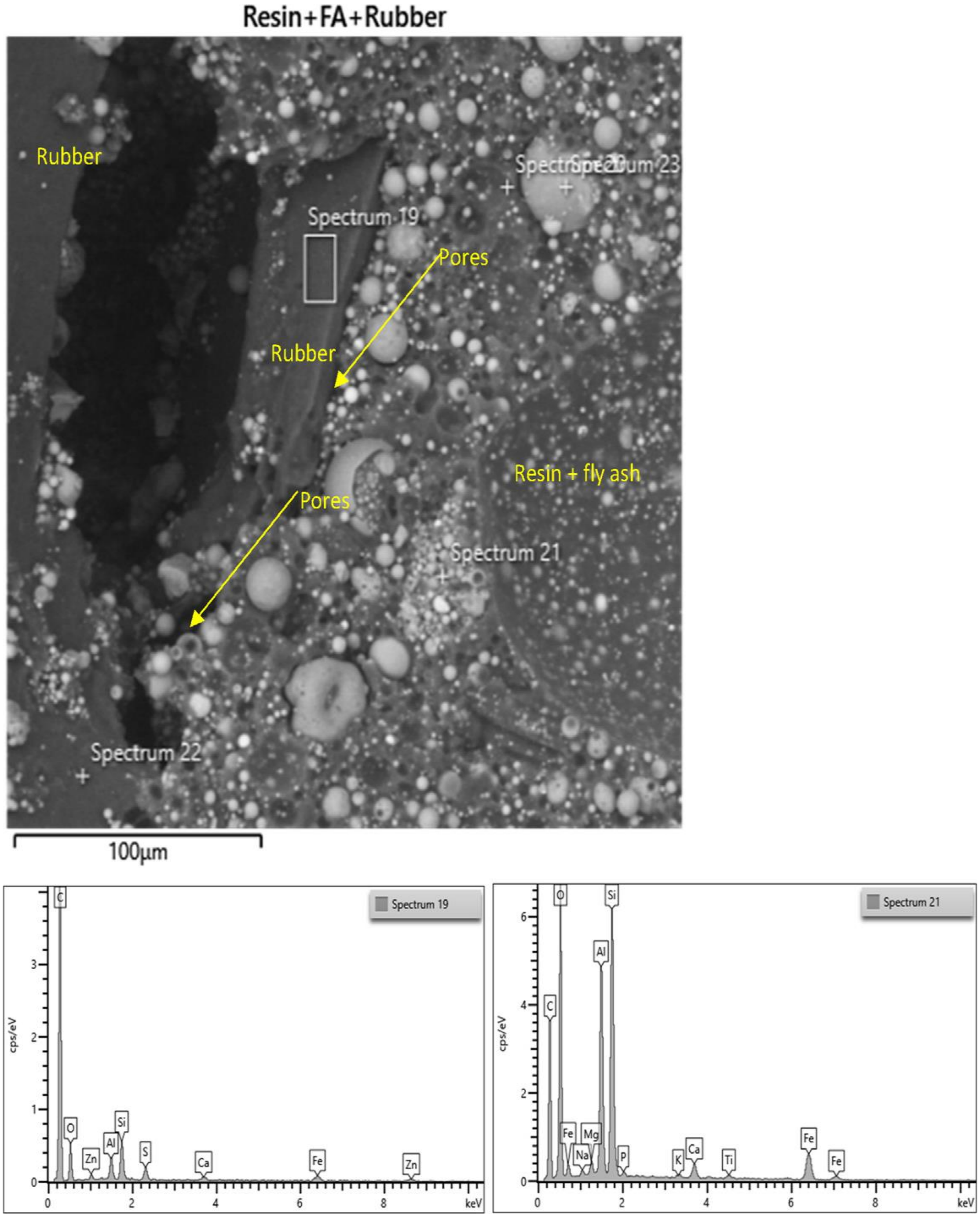


Figure.4.15: SEM and EDS images of composites containing resin, fly ash and rubber crumb (R3-F4)

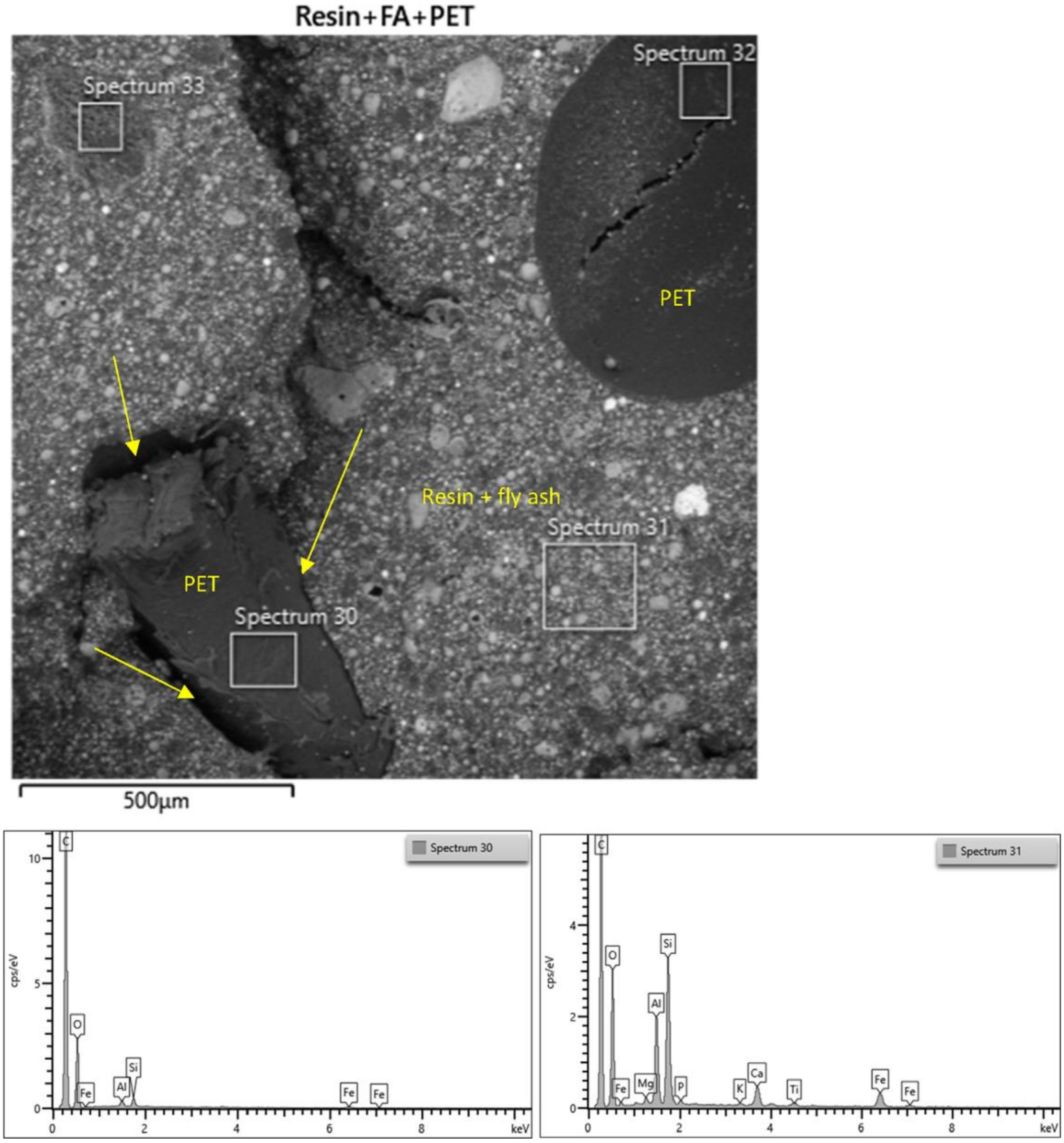
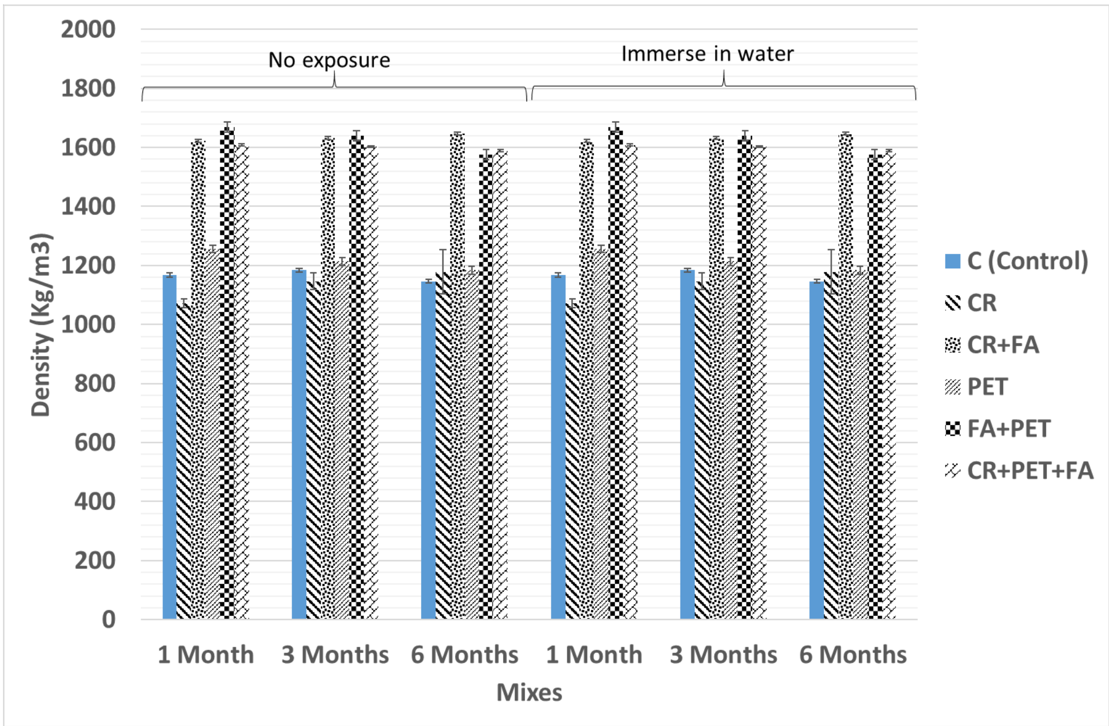


Figure 4.16: SEM and EDS images of composites containing resin, fly ash and PET (R4-F4).

4.2: SECTION 2: Effect of Aggressive Environment on the Polymer Composites

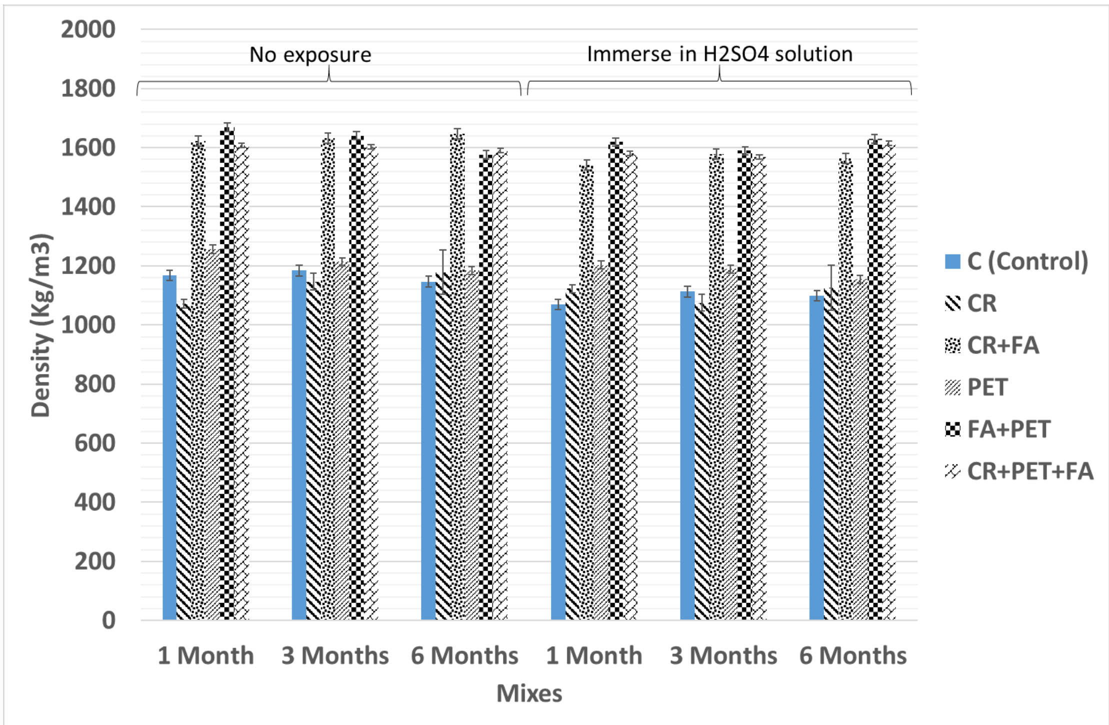
4.2.1: Effect of chemical solutions on density of polymer composites

Figure 4.17 shows the density of the polymer composites at different exposure conditions and durations. Based on the results it can be seen that the density of the mixes containing fly ash (FA) in general are higher compared to mixes without fly ash. This is due to the higher unit weight of the fly ash than rubber and PET. The lower density of those mixes is due to the lower bulk density of both crumb rubber and PET which is about 403-417kg/m^3 [20]. Figure 4.17a shows the density of the samples immersed in water. According to the figure, the density of the mixes remains almost constant for sample immersed in water for 1, 3 and 6 months. Figures 4.17b-d show the density of the samples immersed in H_2SO_4, $MgSO_4$ and NaCl solutions at 1, 3 and 6 months, which show that the densities of all composites are also almost similar to those are not exposed irrespective of chemical solutions and exposure duration. It is also interesting to see that density of polymer matrix composite (Control) is decreased after exposure to all solutions for all durations. Mix results in terms of density changes can be seen among all composites and it can be seen in Fig. 4.18a that the change in density is between +6% and -9% in all exposure durations and solutions. Figure 4.19b shows the change in density of the composites after exposure to 3 and 6 months in those solutions with respect to 1 month and it can again be seen mixed results and the change in between -5% and +11%. The significantly low change in of density of the composites can be explained due to the fact that there is no significant change in the mass of the samples due to superior resistance of polymer in those chemicals. The monomer of the polyester resins forms strong bond in the composite and produce compact composite with lesser voids which prevents the penetration of water into composite. Maksimov et al. [105] also reported that the rate of water adsorption of polymer concrete is several times smaller than the ordinary cement concrete and the reduction of mechanical characteristic of polymer concrete in very low. Better resistance of polymer mortars and concretes against chemicals are also reported in [60, 106], which agrees well with no significant changes of density of the polymer composites in this study.



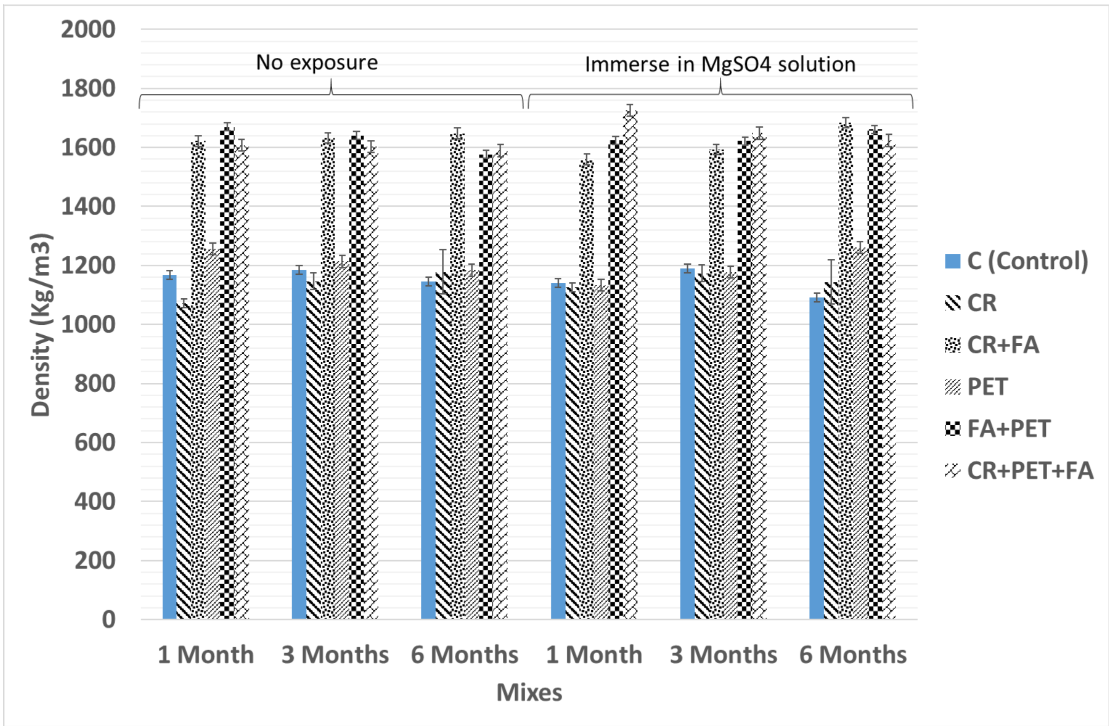
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Density (Kg/m3)
No exposure
Immerse in water
1 Month
3 Months
6 Months
1 Month
3 Months
6 Months
Mixes
C (Control)
CR
CR+FA
PET
FA+PET
CR+PET+FA

(a)

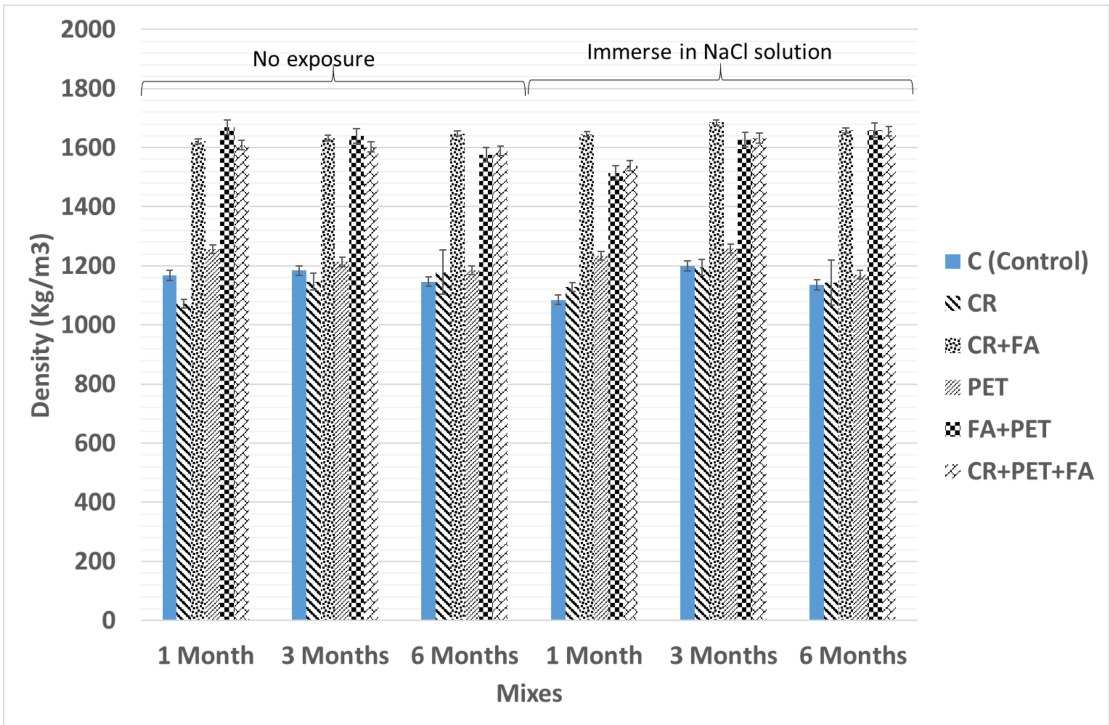


2000
1800
1600
1400
1200
1000
800
600
400
200
0
Density (Kg/m3)
No exposure
Immerse in H2SO4 solution
1 Month
3 Months
6 Months
1 Month
3 Months
6 Months
Mixes
C (Control)
CR
CR+FA
PET
FA+PET
CR+PET+FA

(b)

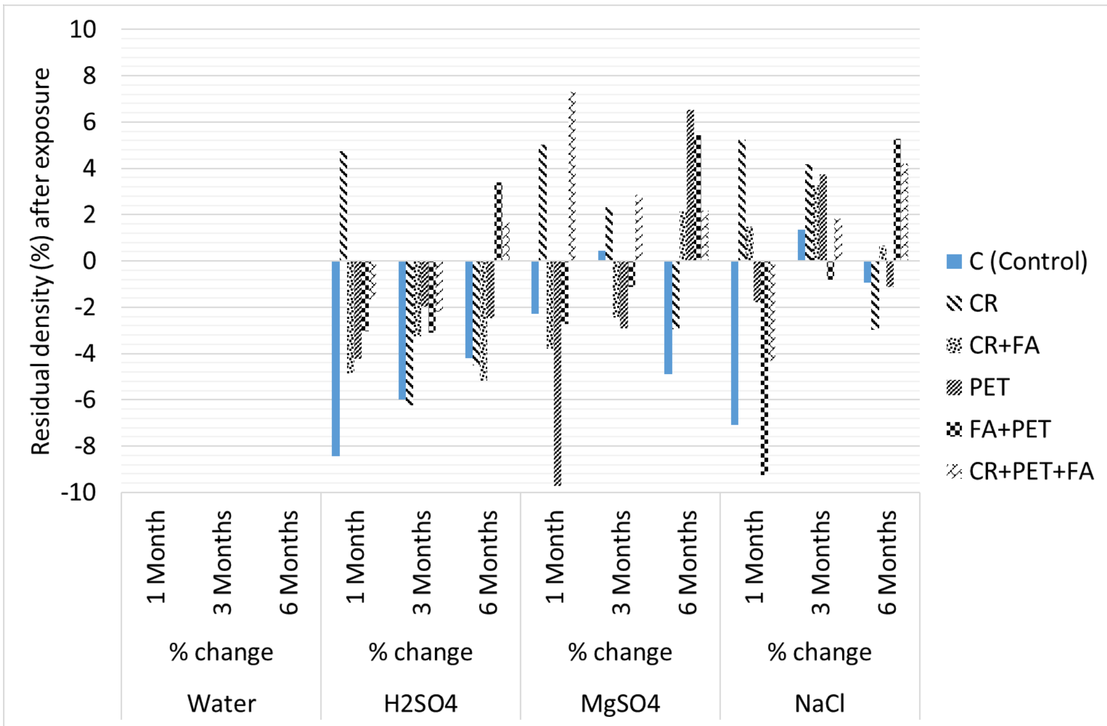


(c)



(d)

Figure 4.17: Density of polymer composites after exposure to (a) water, (b) sulphuric acid, (c) magnesium sulphate and (d) sodium chloride solutions



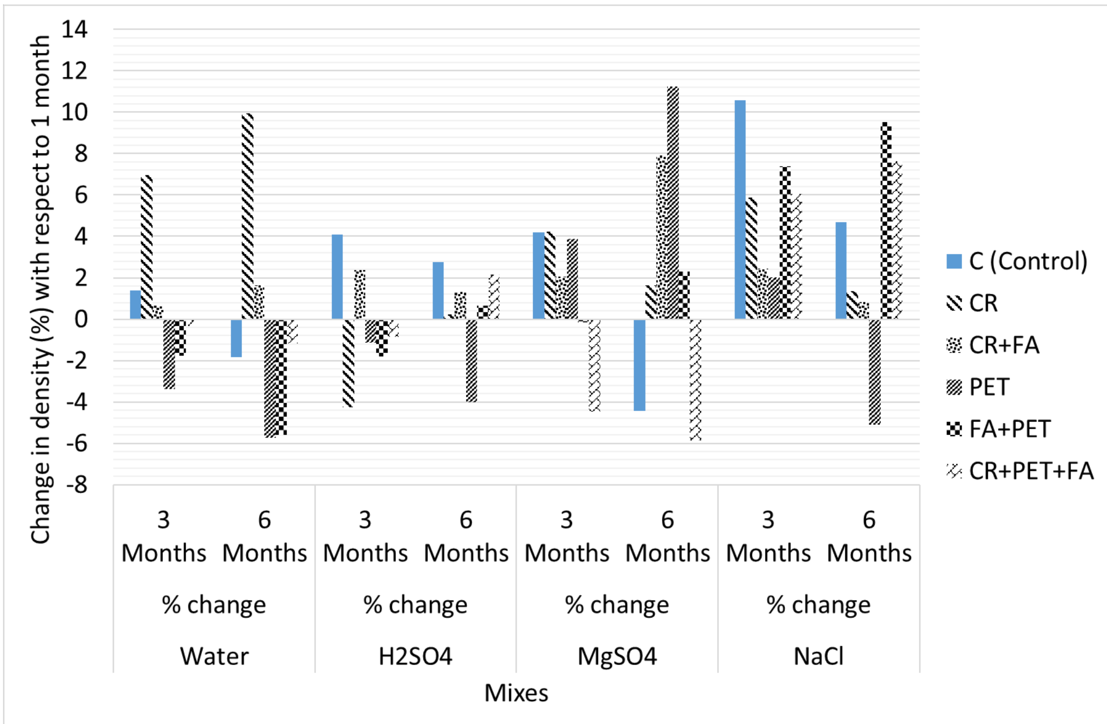


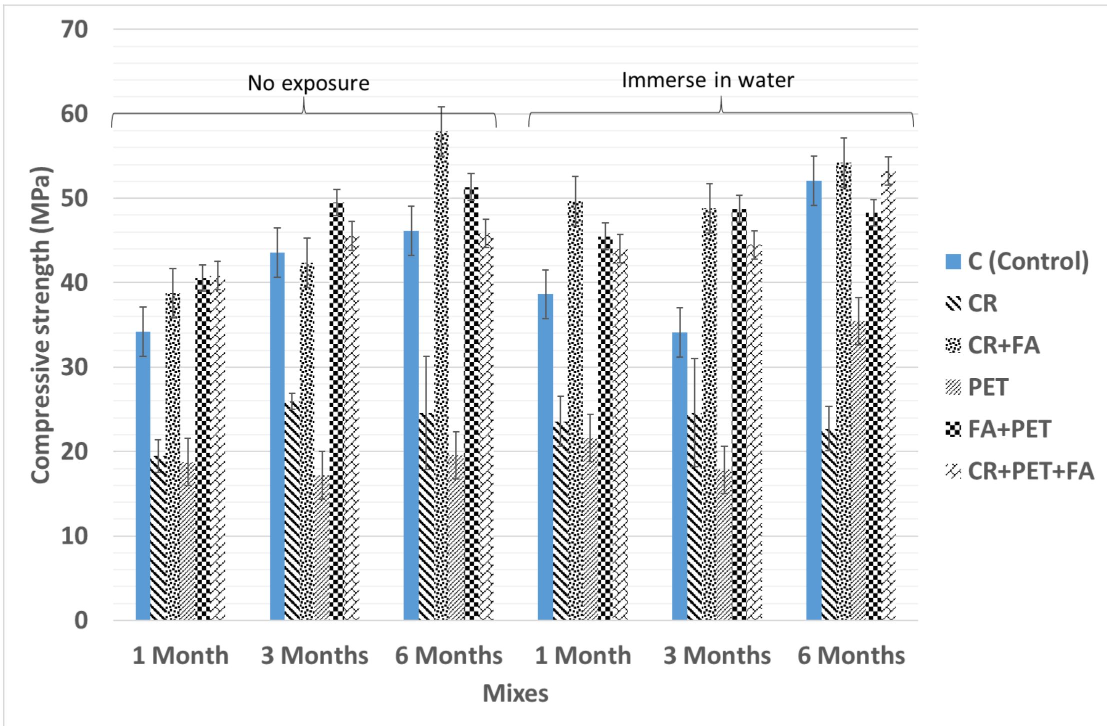
Figure 4.18: Change in density of polymer composites after exposure to chemicals.

4.2.2: Effects of chemical exposure on compressive strength of polymer composites

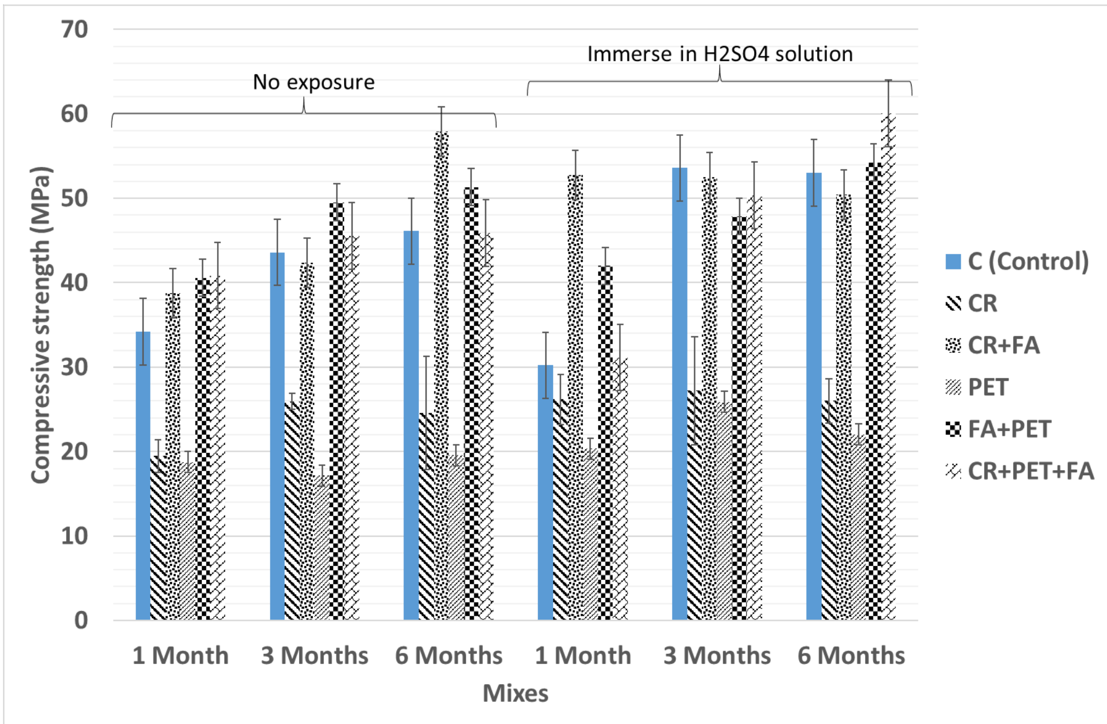
Figure 4.19 shows the compressive strength of the polymer composites after immersed in water, H_2SO_4, $MgSO_4$ and NaCl solutions for 1, 3 and 6 months. In the same figure the compressive strength values of the composites kept in ambient temperature air (no exposure) is also shown for comparison. Calculated standard deviations of the compressive strength of all composites are also shown for each composite in terms of error bar in the figures. It can be seen that the compressive strength of all the composites is increased at 3 and 6 months when exposed to ambient air. The composites containing CR plus FA, PET plus FA and PET, CR and FA as fillers exhibited much higher compressive strength than those containing PET or CR alone. This could be due to filler effect of FA in the matrix of those composites, which resulted in dense microstructure. Similar higher densities in those composites are also observed compared to those containing no fly ash. It can be seen mixed results in change in compressive strengths after exposure to above solutions for different periods.

A summary of the residual compressive strength of those composites after exposure to the chemical solutions is shown in Fig. 4.20. Generally, most composites exhibited improvement in compressive strength after exposure to those solutions for up to 6 months. It can be seen that after exposure to one month in the chemicals all composites exhibit improvement in compressive strength in water and NaCl solution with mixed results in H_2SO_4 and $MgSO_4$ solutions. The composite containing CR, PET and FA as fillers exhibited about 20% reduction in compressive strength in those solutions. Interestingly, after three months exposure the compressive strength of all composites is increased in H_2SO_4, $MgSO_4$ and NaCl solutions except the composite containing PET and FA fillers which lost about 4% of its compressive strength. However, after immersing in water for three months most of the composites exhibit reduction in compressive strength except those containing PET and CR plus FA fillers.

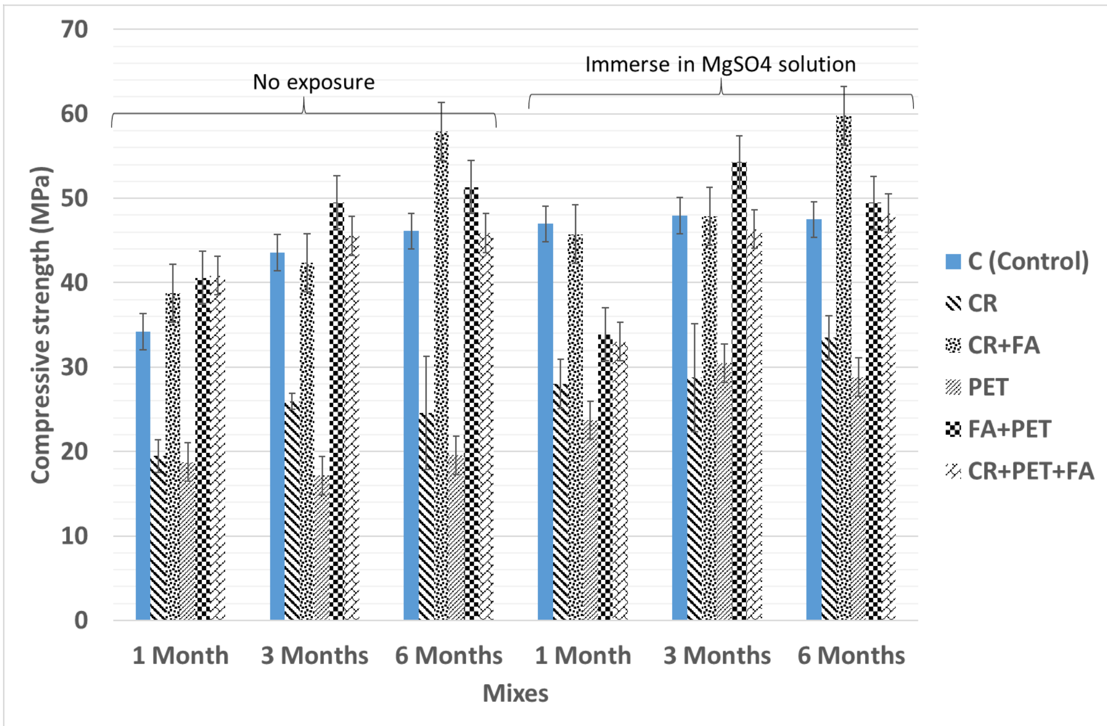
When those composites are continued to expose in the solutions for six months most of their compressive strength is increased except that containing CR plus FA fillers and PET plus FA fillers. However, all most all composites exhibited increase in compressive strength at three and six months with respect to one month in those solutions. The finding of this sections agrees with the findings of previous researchers. Ghorbel and Haidar [107] observed a small reduction of mechanical properties after polymer concrete were exposed in acid solution and the use of fillers resulted better mechanical properties and resistance to chemical attack. Lokuge and Aravinthan [108] concluded that the addition of fly ash as a filler material, resulted in a reduction in the amount of resin usage and an increase in the compressive strength of the polymer concrete. The reasons for such mixed changes in compressive strength of the composites will be discussed in microstructural analysis section.


70
60
50
40
30
20
10
0
Compressive strength (MPa)
No exposure
Immerse in water
1 Month
3 Months
6 Months
1 Month
3 Months
6 Months
Mixes
C (Control)
CR
CR+FA
PET
FA+PET
CR+PET+FA

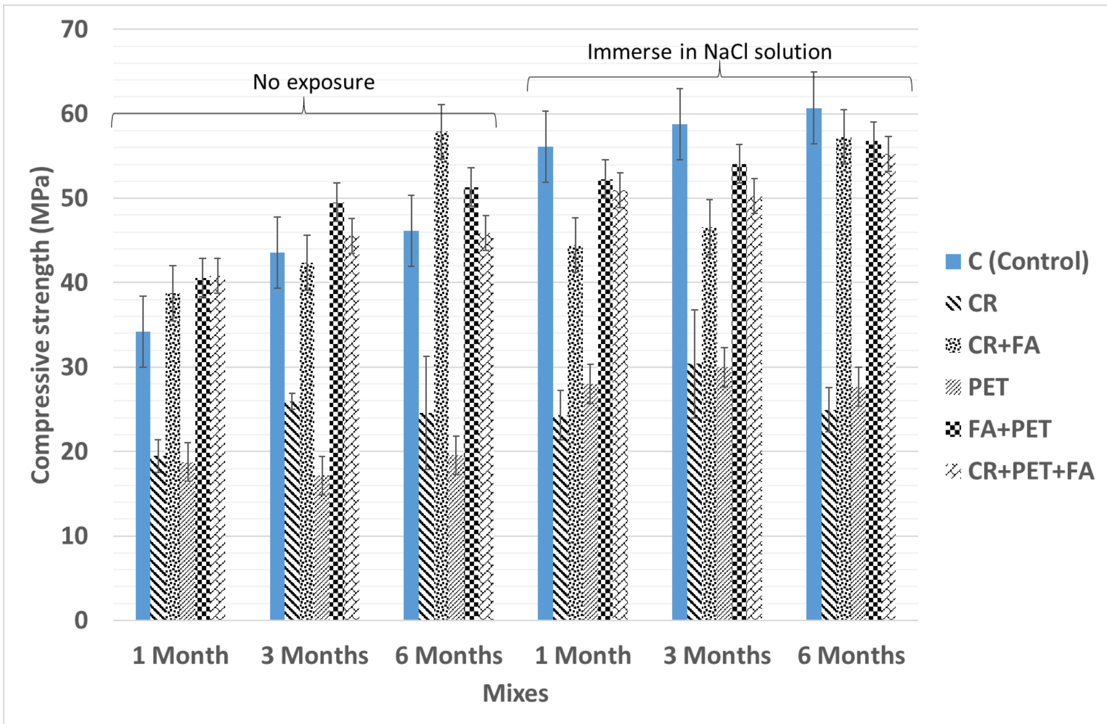
(a)


70
60
50
40
30
20
10
0
Compressive strength (MPa)
No exposure
Immerse in H2SO4 solution
1 Month
3 Months
6 Months
1 Month
3 Months
6 Months
Mixes
C (Control)
CR
CR+FA
PET
FA+PET
CR+PET+FA

(b)

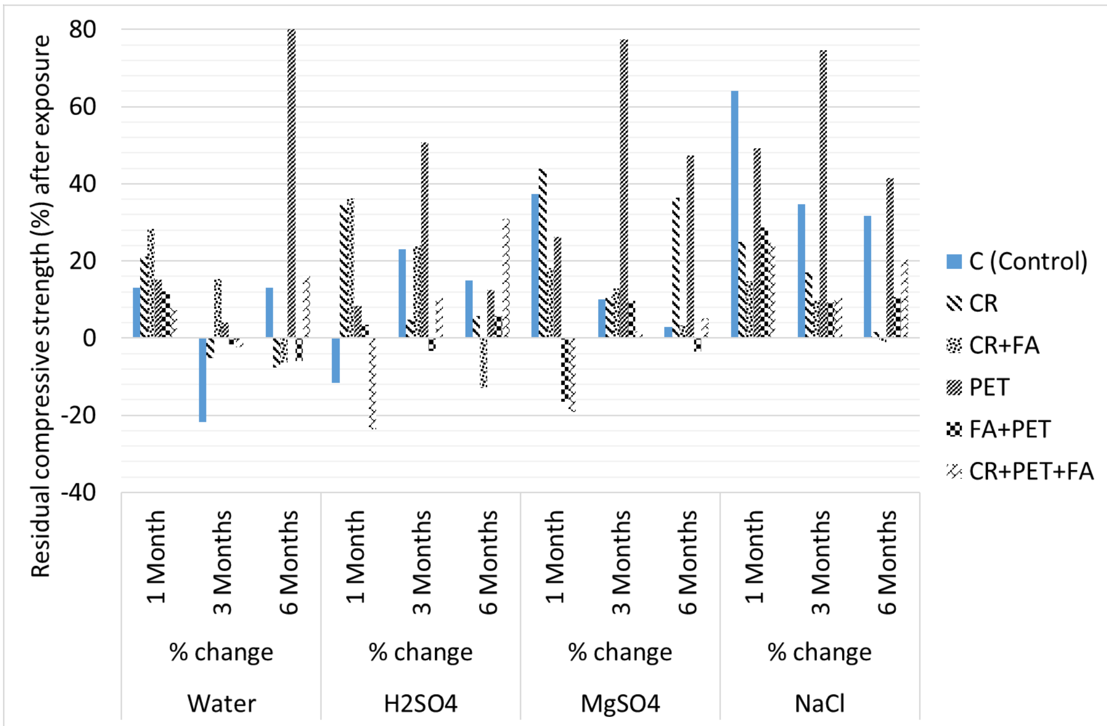


(c)



(d)

Figure 4.19: Compressive strength of polymer composites after exposure to (a) water, (b) sulphuric acid, (C) magnesium sulphate and (d) sodium chloride solutions



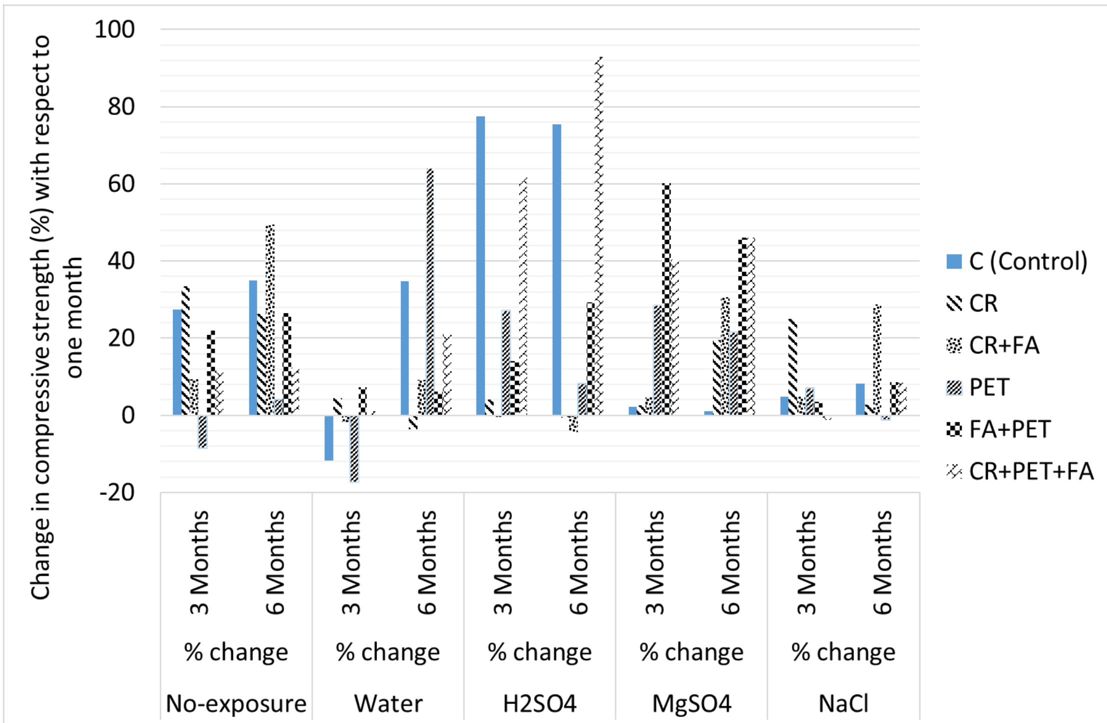
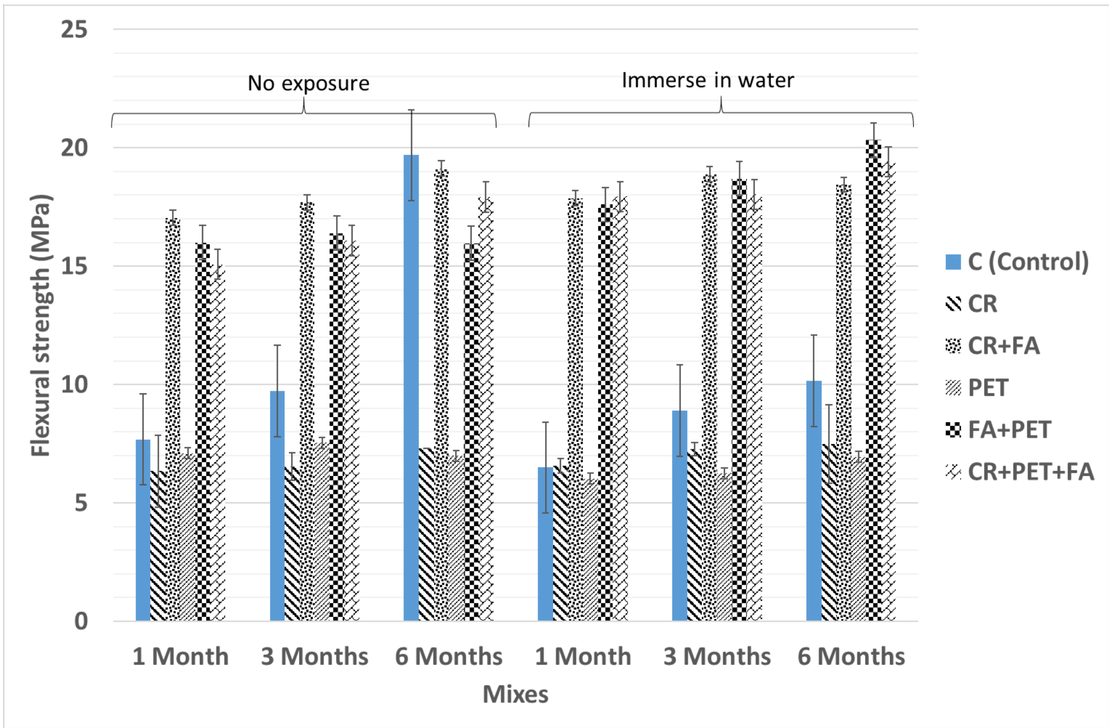


Figure 4.20: Change in compressive strength of polymer composites after exposure to chemicals.

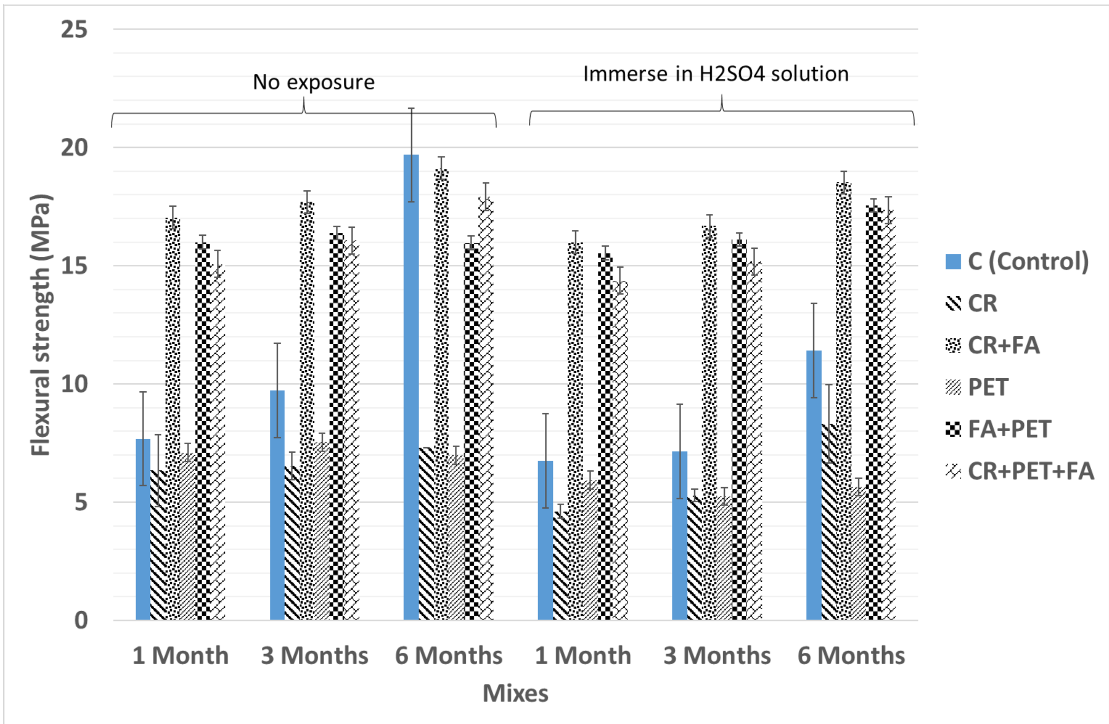
4.2.3: Effects of chemical exposures on Flexural strength of polymer composites

Flexural strength of polymer composites reinforced with one layer of jute fabric before and after exposure to chemicals are shown in Fig. 4.21. It can be seen in Fig. 4.21a that after exposure to tap water only control polymer composite and that containing PET fillers exhibited reduction in flexural strength while the rest of the composites gained the flexural strength at all exposure periods. However, when the composites are exposed to H_2SO_4 and $MgSO_4$ solutions their flexural strengths are reduced except those containing CR and PET+FA at 6 months. A different scenario is observed when exposed to NaCl solution where mixed results are obtained. A summary of the residual flexural strengths of all composites after exposure to chemical solutions is shown in Fig. 4.22a. It can be seemed mixed results with about half results are lower than the flexural strength of the composites before exposure to chemicals. However, when the effect of exposure duration is considered, all most all composites showed improvement in flexural strength at three and six months with respect to their one-month exposure irrespective of chemical type. This result also agrees well with that observed in the case of compressive strength.



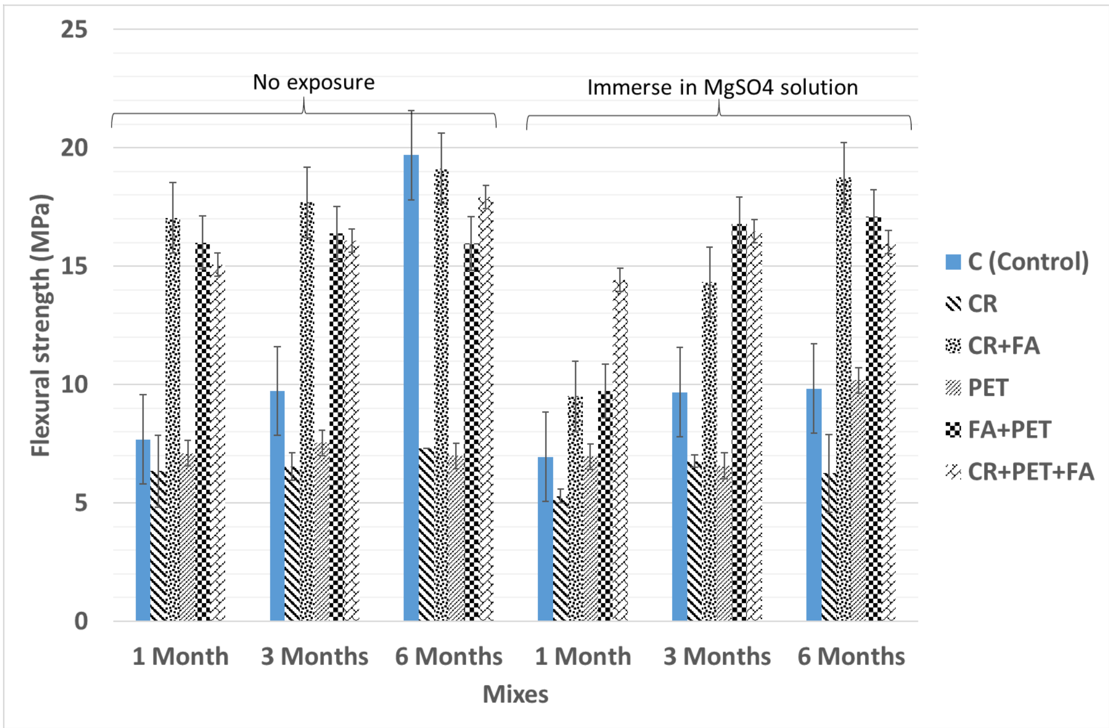
25
20
15
10
5
0
No exposure
Immerse in water
Flexural strength (MPa)
1 Month
3 Months
6 Months
1 Month
3 Months
6 Months
Mixes
C (Control)
CR
CR+FA
PET
FA+PET
CR+PET+FA

(a)

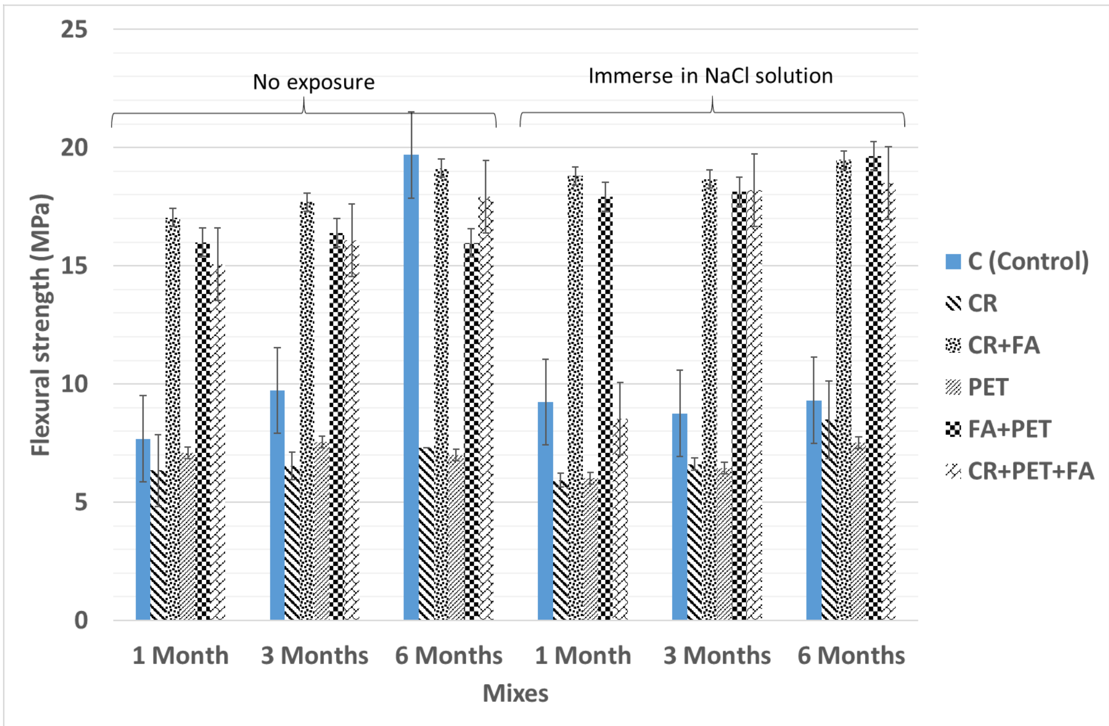


25
20
15
10
5
0
No exposure
Immerse in H2SO4 solution
Flexural strength (MPa)
1 Month
3 Months
6 Months
1 Month
3 Months
6 Months
Mixes
C (Control)
CR
CR+FA
PET
FA+PET
CR+PET+FA

(b)

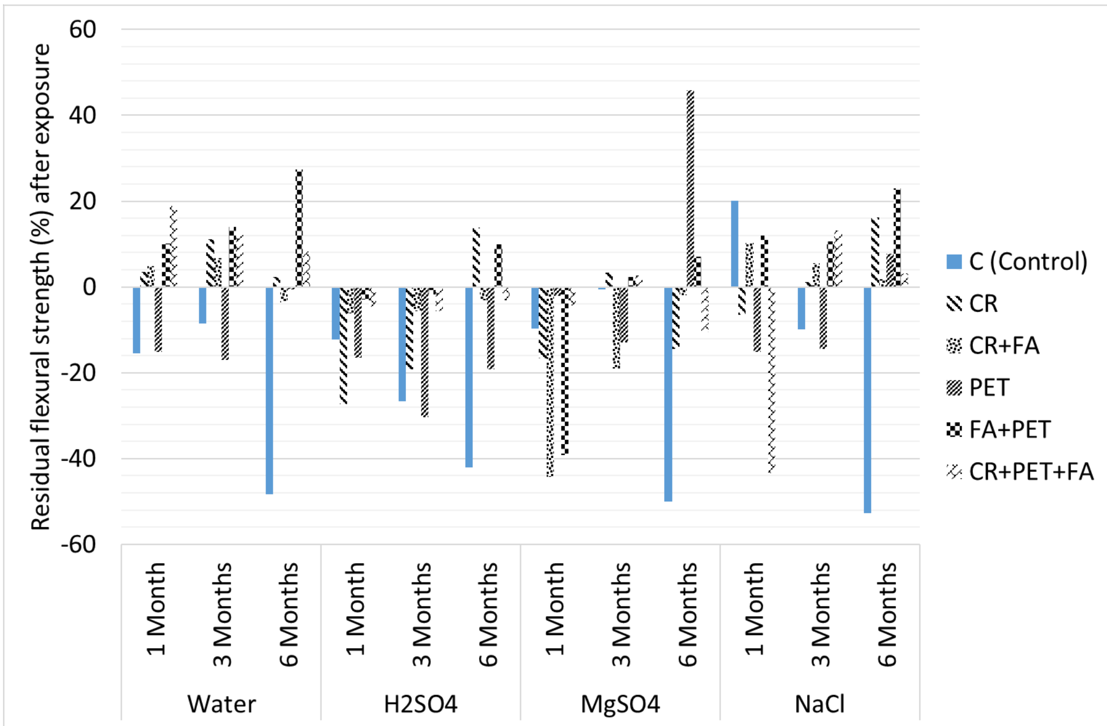


(c)



(d)

Figure 4.21: Flexural strength of polymer composites after exposure to (a) water, (b) sulphuric acid,(c) magnesium sulphate and (d) sodium chloride solutions.



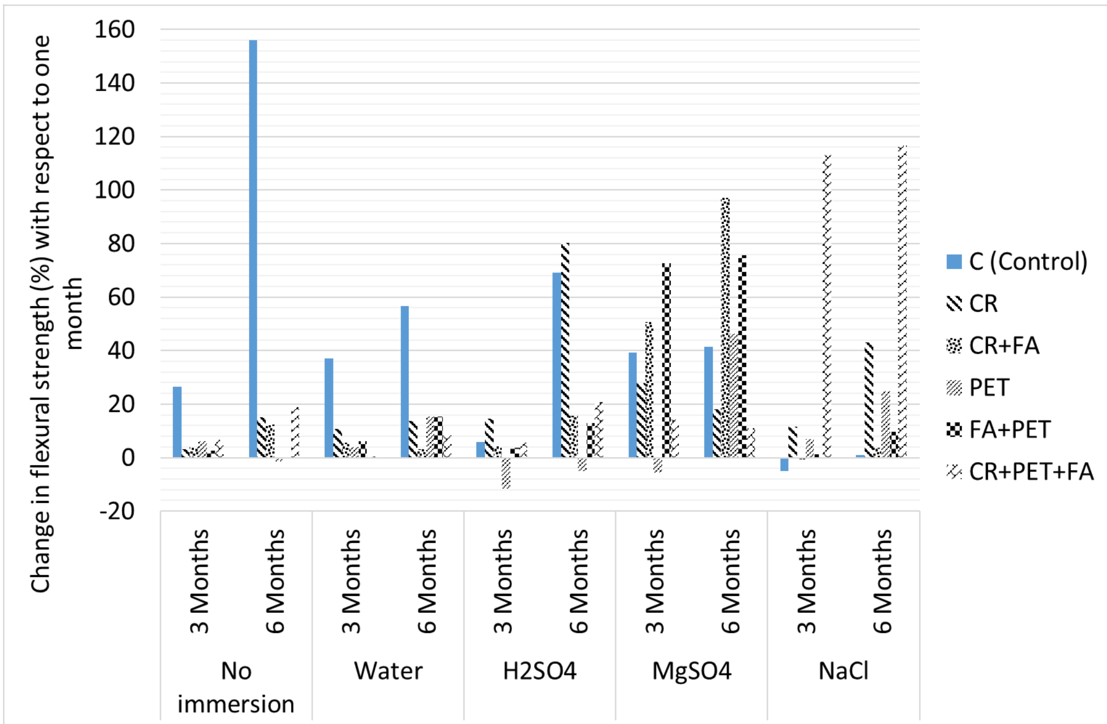


Figure 4.22: Change in flexural strength of polymer composites after exposure to chemicals.

4.2.4: Microstructural analysis of polymer composites after exposure to chemicals

Analysis of mechanical properties of lightweight polymer composites containing various solid wastes as fillers show that the polymer composite containing PET flakes as filler and the composite containing PET, CR and fly ash as fillers exhibit better properties compared to other composites. Hence, the effect of H_2SO_4, $MgSO_4$ and NaCl solutions on microstructure of these two composites is discussed in this section. Figures 4.23-25 show the SEM images of the microstructure of matrix and filler-matrix interface of those two composites after exposure to above three chemical solutions for 1, 3 and 6 months. Based on the SEM images, it is found out that the bond between PET flakes and polyester resin is not compact. Gaps are identified between the interface of these two materials which is the main reason for low compressive strength and flexural strength of this composite. It can also be seen that by increasing the exposure duration to 3 and 6 months the microstructure is not changed significantly in those chemical solutions.

On the other hand, the composite containing CR, PET and FA fillers exhibit much denser microstructure than that of composite containing PET. Signs of voids and gap between PET or CR and matrix can be seen in the figure when exposed to the three chemical solutions and with increase in exposure duration the gap between the PET or CR and matrix is widened. Fly ash particles can be seen dispersed well in the resin matrix indicating much compact matrix even after immersed in all three solutions for up to 6 months. However, compared to H_2SO_4 and $MgSO_4$ solutions the microstructure of the matrix is more compact in NaCl solution. These observations agree well with the residual compressive strength of this composite in NaCl solution. While in the SEM images the presence of any reaction products due to those three chemicals is not possible to detect, energy dispersive X-ray spectroscopy (EDS) analysis is conducted and is shown in Figs. 4.26-27. Two small areas are considered one on the matrix and one on the PET or CR surface to detect any new reaction products. It can be seen in the figures that after one- and 6-months exposure the intensive peaks of sulphur (S), magnesium (Mg), sodium (Na) and chlorine (Cl) are extremely low compared to the intensity peaks of carbon (C) and oxygen (O) for rubber or PET or polymer and silica (Si), alumina (Al) and calcium (Ca) for fly ash. These very low intensity peaks of the former elements than the latter elements indicate not significant reaction formed of the composite in those chemicals even after exposure to 6 months. These findings agree well with the findings of previous research. Shen et al [109] stated that, polymer concrete strongly resists sulphuric acid corrosion as the interiors of the specimen are un-affected by the acid based on the SEM and EDS analysis. Wang et al [39] observed gaps between rubber particles and epoxy resin.

Consequently, based on the SEM image analysis, it was noticed that grains were surrounded on each side with the polymer matrix, which indicated good mixing of the ingredients at the stage of forming of the sample. Based on Figure 4.23-4.24, in some parts, the grains were de-bonded from the resin matrix, which resulted in no structural bonding of the aggregate grains with the resin matrix. In such area, mechanism of destruction was observed during the compressive and flexural test, as the destruction ran between the grains and the polymer matrix. Apart from that, it can also be seen according to the SEM image that, the polymer matrix apart from being structurally uniform, is also very tight. The local porosity is low, and the internal cohesion of the polymer have caused the composite to have a very high flexural and compressive strength. The result of SEM test showed that, PET polymer composite and CR, PET and FA polymer composite generally have good resistance against aggressive environment. This is due to the lower content of C3A content in the composite. C3A is considered as the reactive compound responsible for ettringite formation. The substantially higher content of C3A content in the composite would make the paste more susceptible to aggressive chemical attack, particularly sulfate attacks.

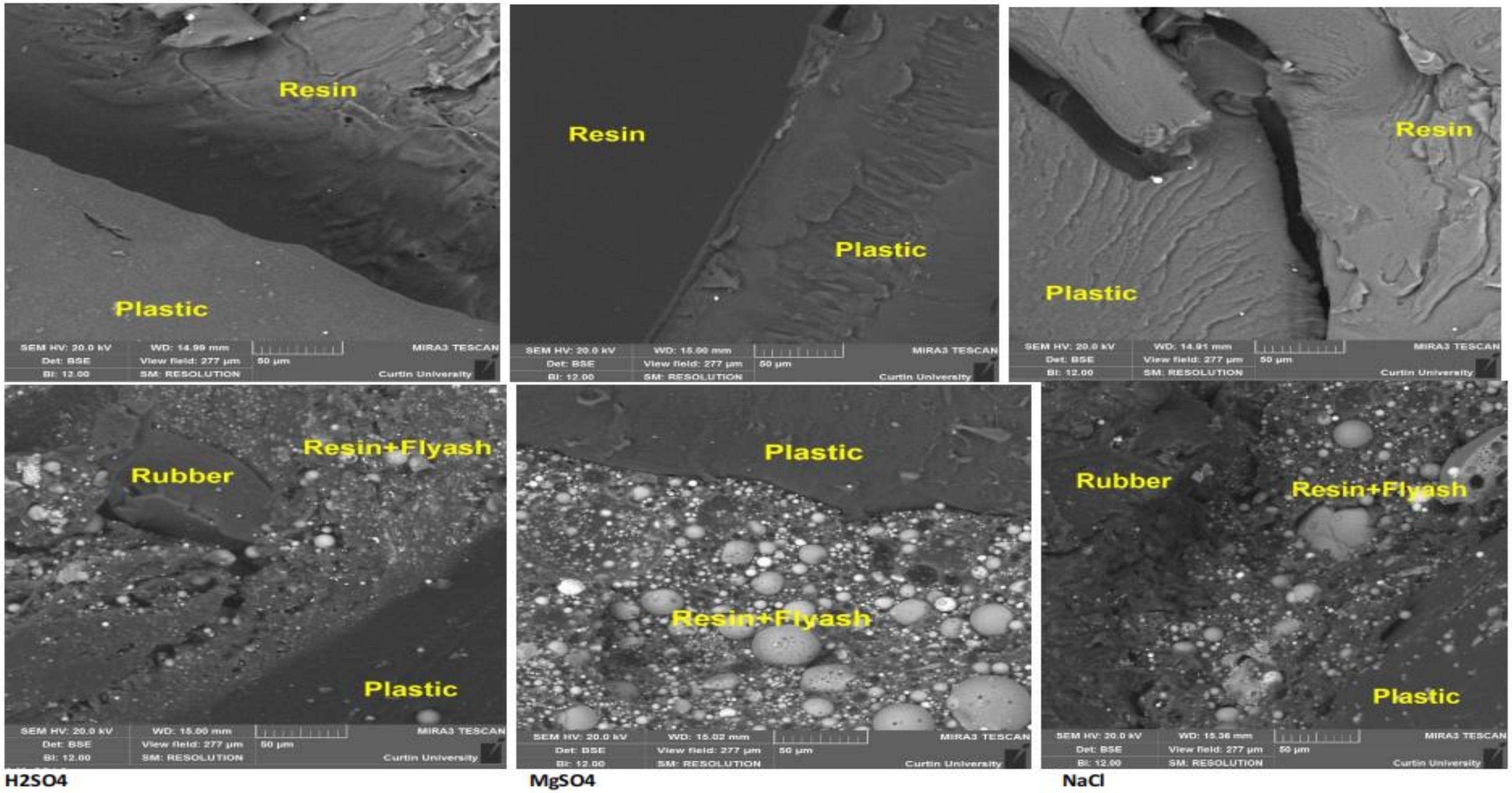


Figure 4.23: SEM image of PET polymer composites (Top) and CR, PET and FA polymer composites (Bottom) exposed to chemical solutions for 1 month

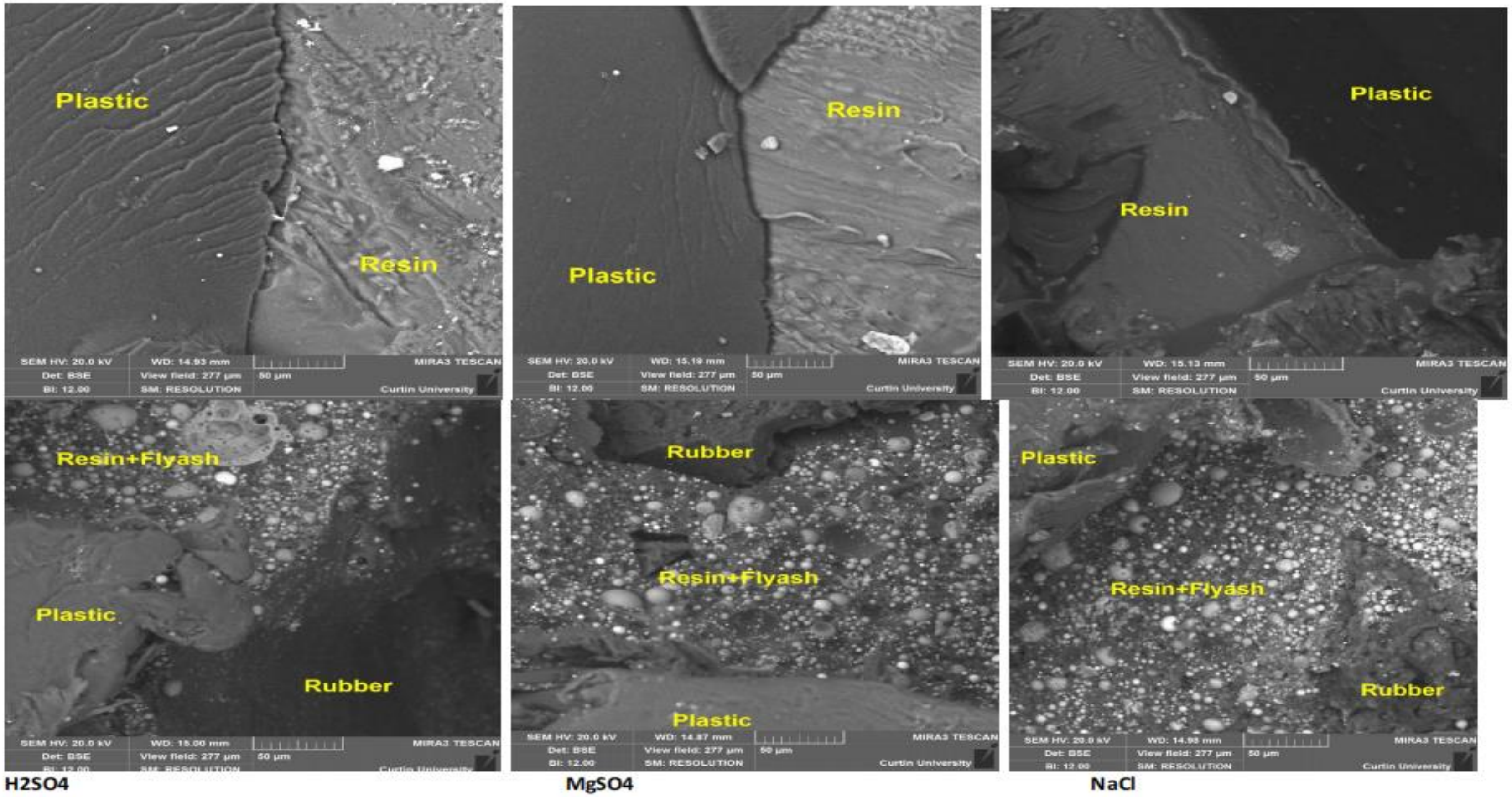


Figure 4.24: SEM image of PET polymer composites (Top) and CR, PET and FA polymer composites (Bottom) exposed to chemicals solutions for 3 months.

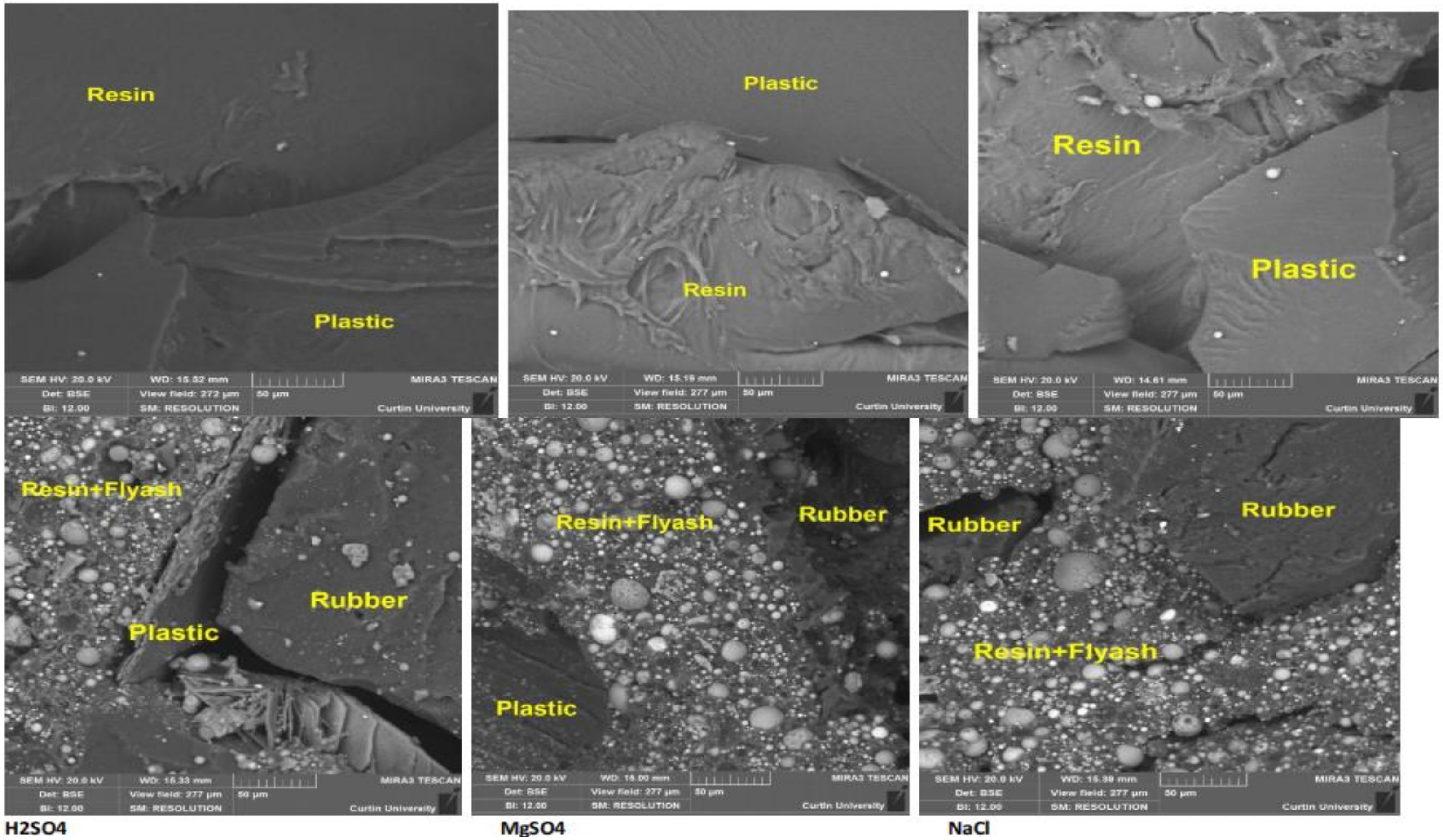


Figure 4.25: SEM image of PET polymer composites (Top) and CR, PET and FA polymer composites (Bottom) exposed to chemicals solutions for 6 months.

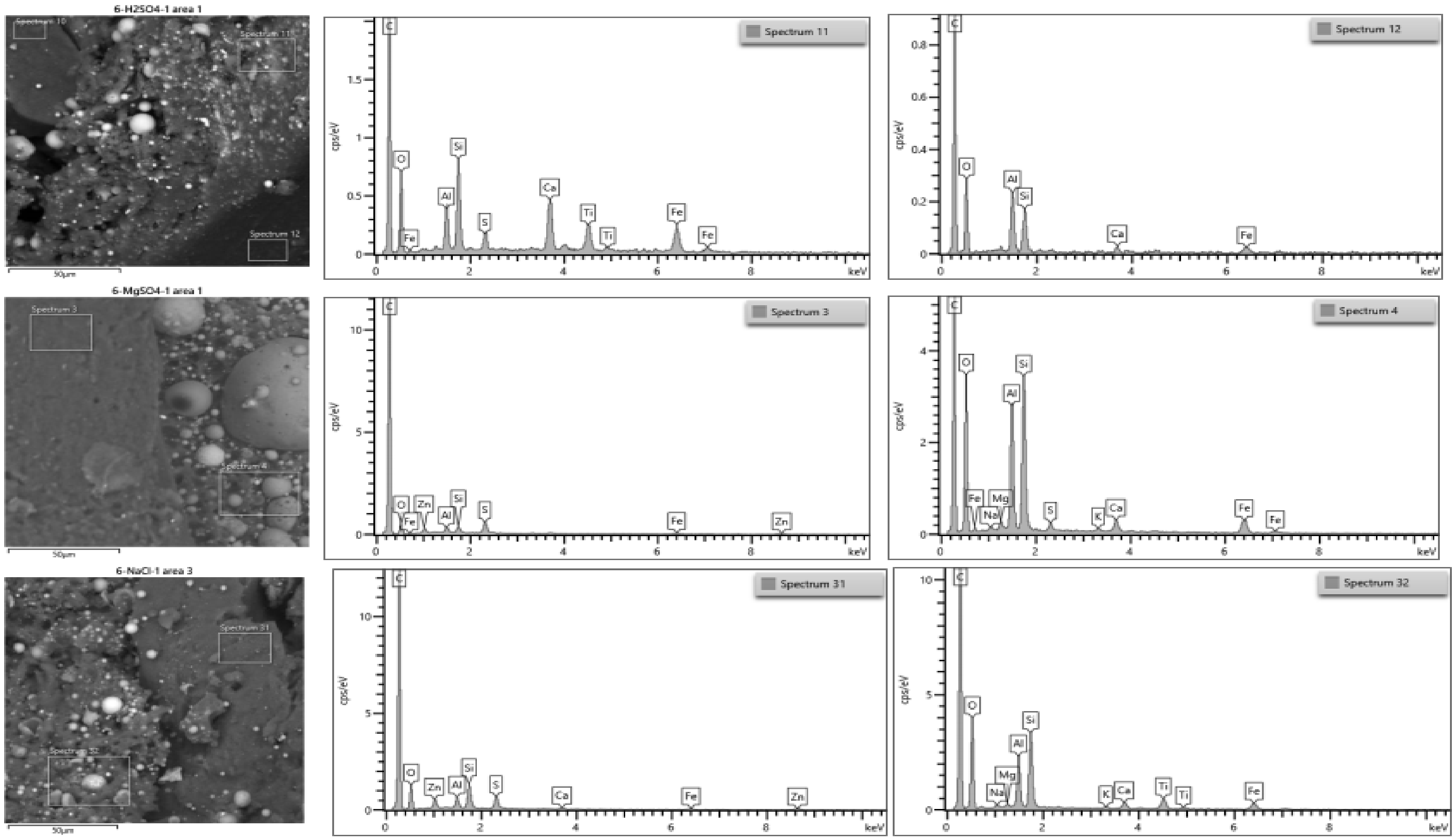


Figure 4.26: EDS analysis of polymer composites containing CR, PET and FA fillers after exposed to chemical solutions for 1 month

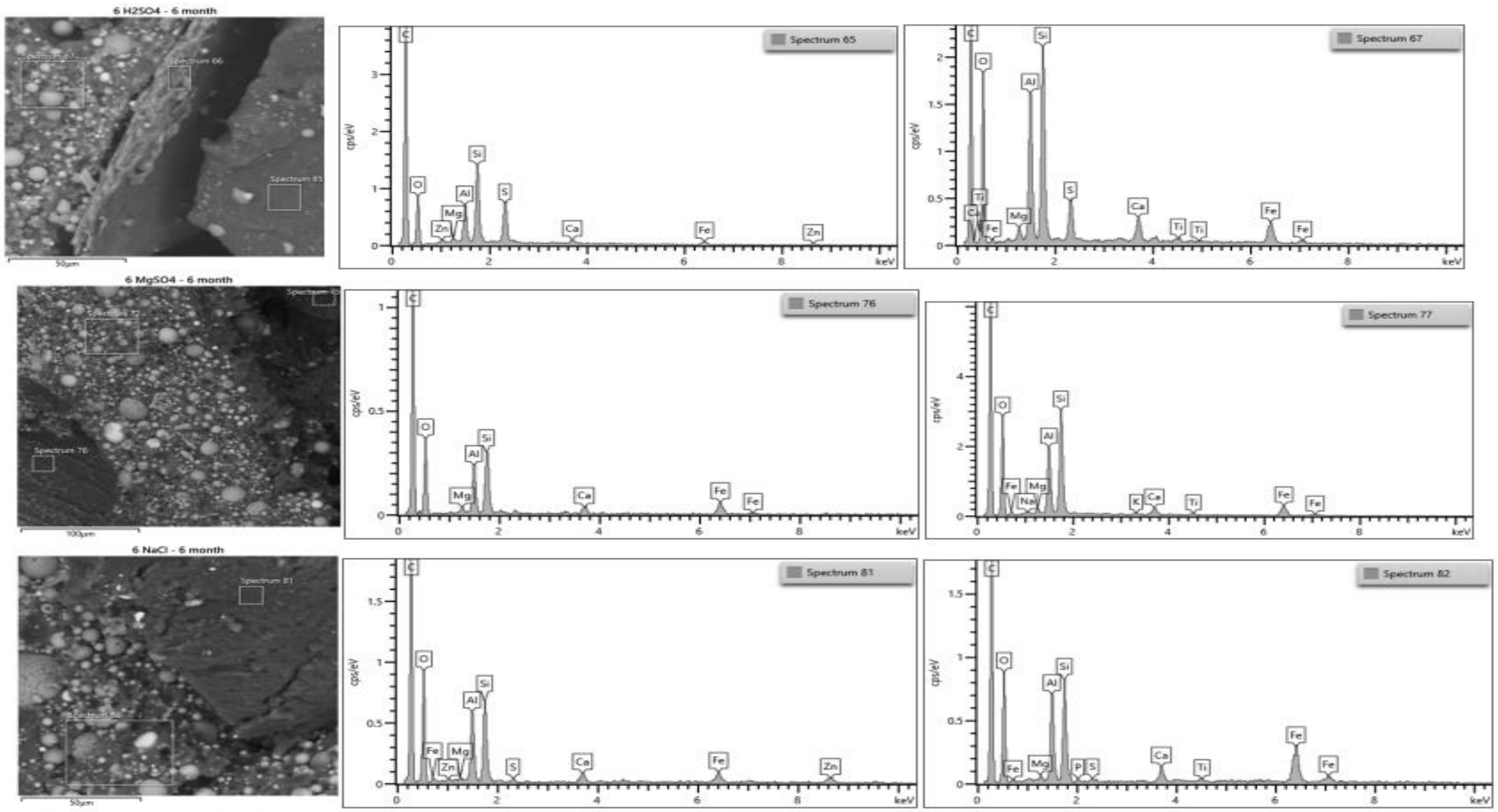


Figure 4.27: EDS analysis of polymer composites containing CR, PET and FA fillers after exposed to chemical solutions for 6 month

4.3 Numerical modelling

4.3.1: Elastic Modulus and Poisson's Ratio

Table 4.2 shows the test results obtained for elastic modulus and Poisson's ratio of polymer composite. Two different mixes of the polymer composites were tested which are mix no 4 (resin and PET flakes) and mix no 6 (resin, fly ash, PET flakes, and crumb rubber). Based on the test results it was observed that mix no 6 exhibited higher loads in comparison to mix no 4 in order to obtain the elastic modulus and the Poisson's ratio. The strength, axial elastic modulus and the lateral elastic modulus were higher for mix no 6 in comparison to mix no 4. However, according to Table 4.2, it was observed that the Poisson's ratio for both mixes were similar. The difference in the strength and modulus of the mixes is due to the composition of the mixes. The axial elastic modulus and the Poisson's ratio obtained were later on, used in the Win-Julea AASHTO 2002 and Mich-Pave Version 1.0 software for modelling. Figure 4.28 shows testing of the sample at 28 days.

Table 4.2: Elastic modulus and Poisson's ratio obtained through lab test

Description	Conventional Flexible Pavement	Mix No 4 (Resin and Plastic)	Mix No 6 (Resin, Fly ash, Plastic and Crumb Rubber)	Unit
Maximum Load	-	64.309	142.137	kN
Maximum Strength	-	6.132	18.068	MPa
Axial Elastic Modulus	170	523	4406	MPa
Lateral Elastic Modulus	-	2.468	20.704	GPa
Poisson Ratio	0.35	0.212	0.213	-

Figure 4.28: Non-destructive lab test conducted for the polymer composite at 28 days to obtained Poisson's ratio and modulus of elasticity

4.3.2: Model predicted deflection of the conventional flexible pavement and polymer composite pavement due to different sub-base layer thickness, and comparison of results between two software.

Based on the Mich-Pave software analysis, number of elements inputted in horizontal direction was 10 with contact radius ranging from a, 3a, 6a and 40a. the finite element mesh size were 14.52cm. The predicted deflection of the sub-base layer due to different thickness is shown in Figures 4.29 -4.31. Based on the analysis, it was observed mixed results for deflection at sub-base layer thickness of 100mm. It can be seen that, as the thickness of the sub-base layer increased, the maximum deflection value decreased. At sub-base layer thickness of 300mm, it was observed that sub-base made with polymer composite consisting of mix 6 exhibited the least maximum deflection of 0.0100cm. This deflection value was 50% lower than the deflection of the conventional flexible pavement having sub-base thickness of 300mm. This is due to the higher elastic modulus of mix no 6 compared to conventional sub-base/base layer of flexible pavement. The higher elastic modulus of the mix no 6 is due to the bonding of the unsaturated polyester resin which is bonded strongly with the fly ash, PET flakes and crumb rubber. Deflection of pavement are the primary mean of evaluating a pavement structure and load transfer. A pavement which encountered least maximum deflection due to wheel load, is likely to have better performance and encountered least pavement deterioration such as rutting and cracking. The deflection value obtain in this analysis is similar to the deflected values obtained by other researchers. For example, Orlando Núñez [110] stated that, as the rigidity of the layer increased, the deflections of the pavement decreased. The author obtained the maximum deflection value of 0.0489cm for granular base, 0.0104cm for soil cement, 0.024cm for cement treated base.

Table 4.3 shows the maximum deflection values obtained for the sub-base layer having different thickness. Figure 4.32 shows the comparison of maximum deflection value for Mich-Pave and Win-Julea software. The difference of the maximum deflection value when compared between the two software for flexible pavement is 20%, for mix 4 is 27%, for mix no 6 is 36%. This difference could be due to way the data are inputted for analysing. Data are inputted more directly in Win-Julea software compared to Mich-Pave software. Apart from that, the analyse in Win-Julea software is more direct as compared to Mich-pave software.

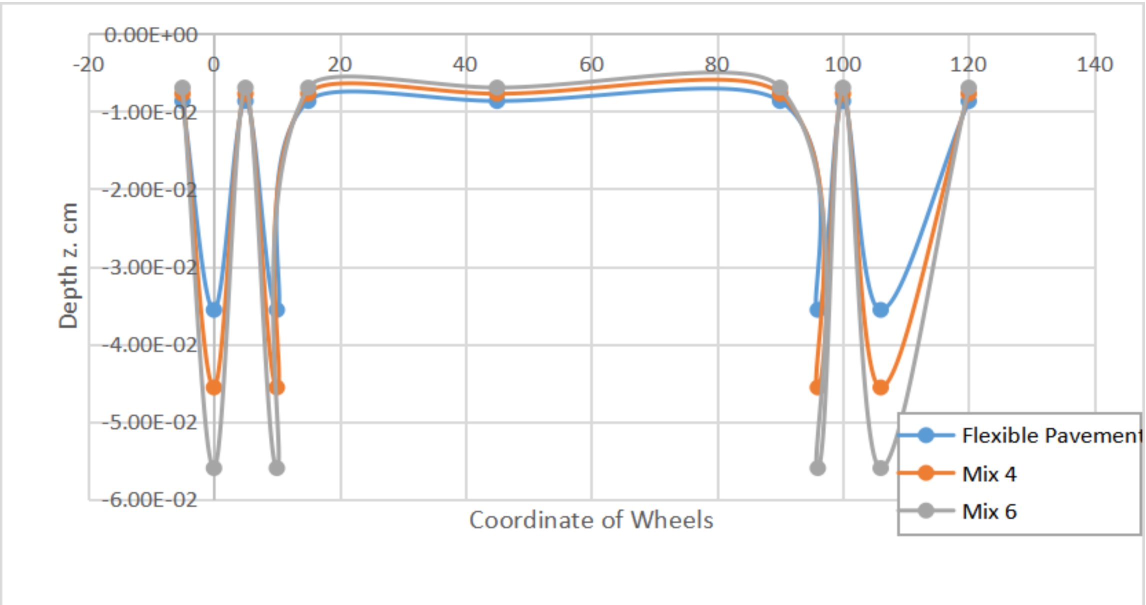


Figure 4.29: Model predicted deflection of conventional flexible pavement and flexible pavement containing 100mm thick polymer composite sub-base.

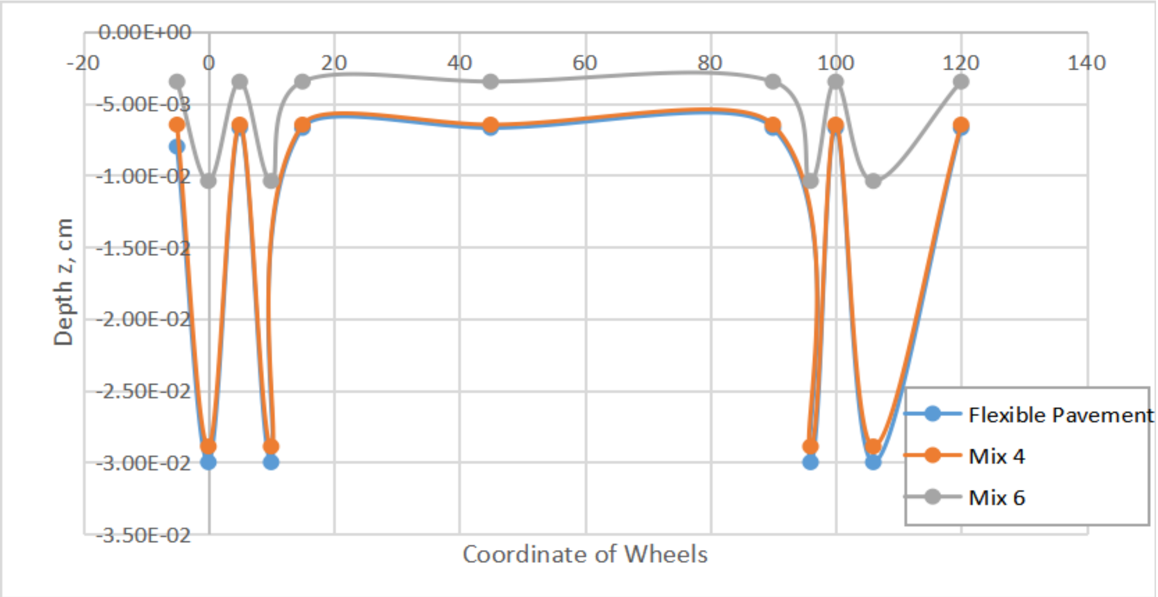


Figure 4.30: Model predicted deflection of conventional flexible pavement and flexible pavement containing 200mm thick polymer composite sub-base.

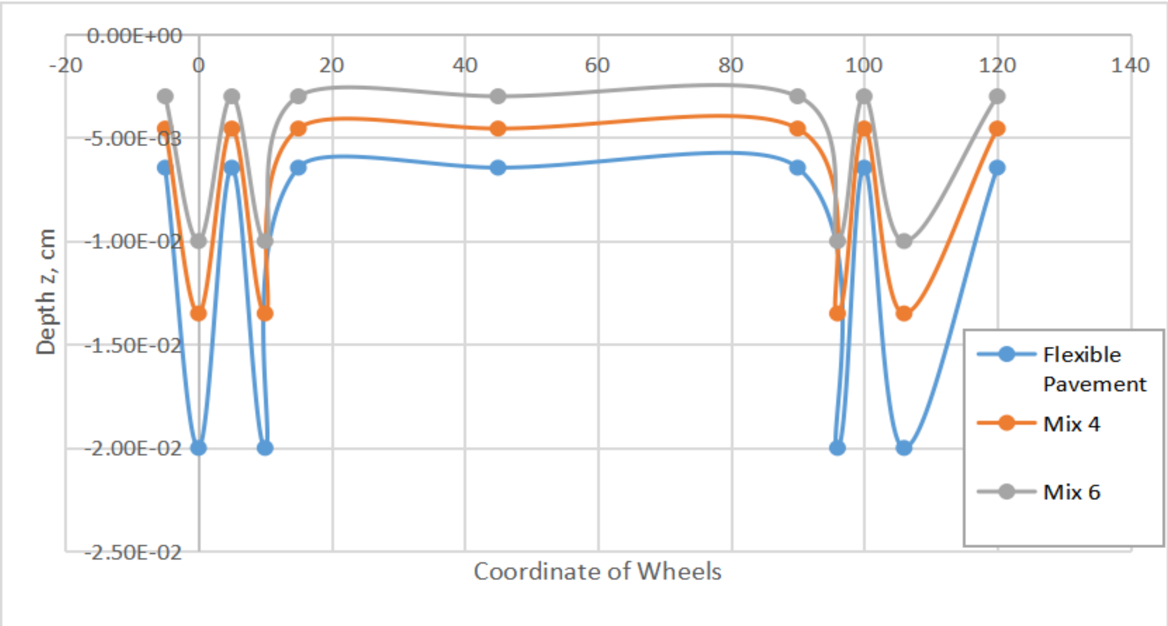


Figure 4.31: Model predicted deflection of conventional flexible pavement and flexible pavement containing 300mm thick polymer composite sub-base.

Table 4.3: Maximum deflection of pavement types with different sub-base layer thickness

Thickness of the sub-base layer (mm)	Types of Pavement/Maximum Deflection. (cm)			Percentage Different (%)		
	Flexible Pavement	Mix 4	Mix 6	Flexible pavement	Mix 4	Mix 6
100	0.036	0.0456	0.056	0	28% increased	57.3% increased
200	0.030	0.029	0.010	0	3.6% reduced	65% reduced
300	0.020	0.014	0.010	0	32.5% reduced	50% reduced

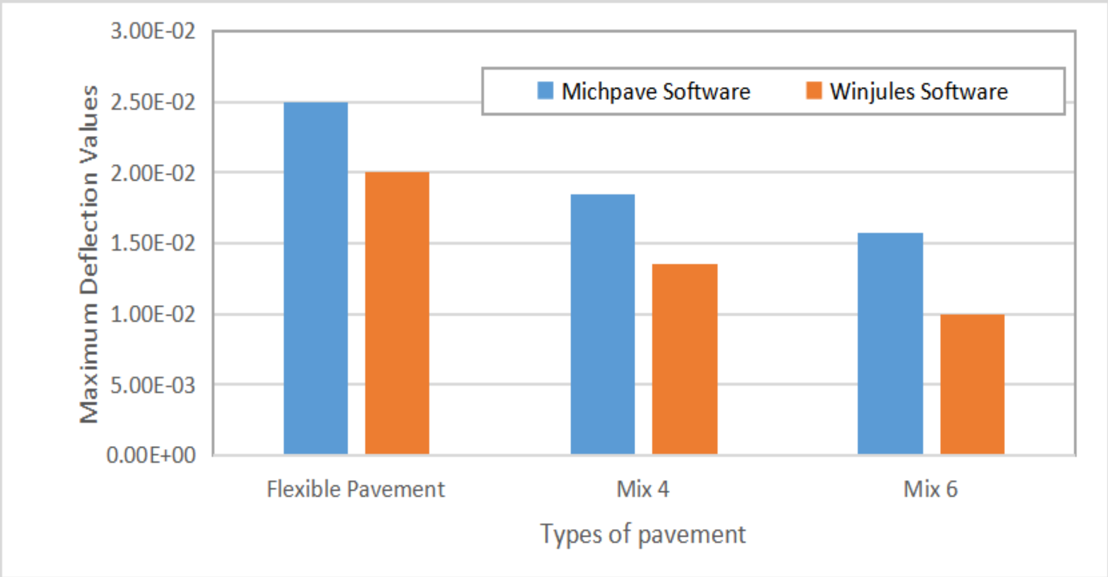


Figure 4.32: Comparison of maximum deflection value between Mich-pave and Win-Julea software at sub-base layer thickness of 300mm.

4.3.3: Model predicted deflection of the conventional flexible pavement and polymer composite pavement due to different contact radius.

A uniform circular vertical contact stress is commonly assumed in representing wheel loads in pavement analysis procedures. However, previous researchers have observed that actual loading conditions are non-uniform and depend on the tyre construction, tire load and tire inflation pressure. Table 4.4 shows the different contact radius used in this study to analysis the effect of different contact radius on the maximum deflection of the pavements. Figures 4.33-4.35 shows the deflection of the conventional flexible pavement and flexible pavement containing mix 4 and mix 6 polymer composite as sub-base layer. Based on the software analysis, it was observed that as the contact radius increased the maximum deflection decreased. Apart from that, the maximum deflection is decreased as the elastic modulus of the mix is increased. According to Table 4.5, the maximum deflection of conventional flexible pavement, flexible pavement containing mix 4 polymer composite and mix 6 polymer composite as sub-base layer at contact radius of 10.85cm was 0.024cm, 0.0174cm and 0.0120cm, respectively. Cheh [99] obtained maximum deflection value of 0.0128cm, 0.00572 and 0.0362 at a contact radius of 10.85 for flexible pavement, rigid pavement and stormpav green pavement.

Table 4.4: Tyre pressure and the contact radius used in the analysis. Haron et al [109].

Tyre pressure/Contact pressure (kPa)	Contact radius (cm)
475.74	10.85
675.69	10.67
875.63	10.40

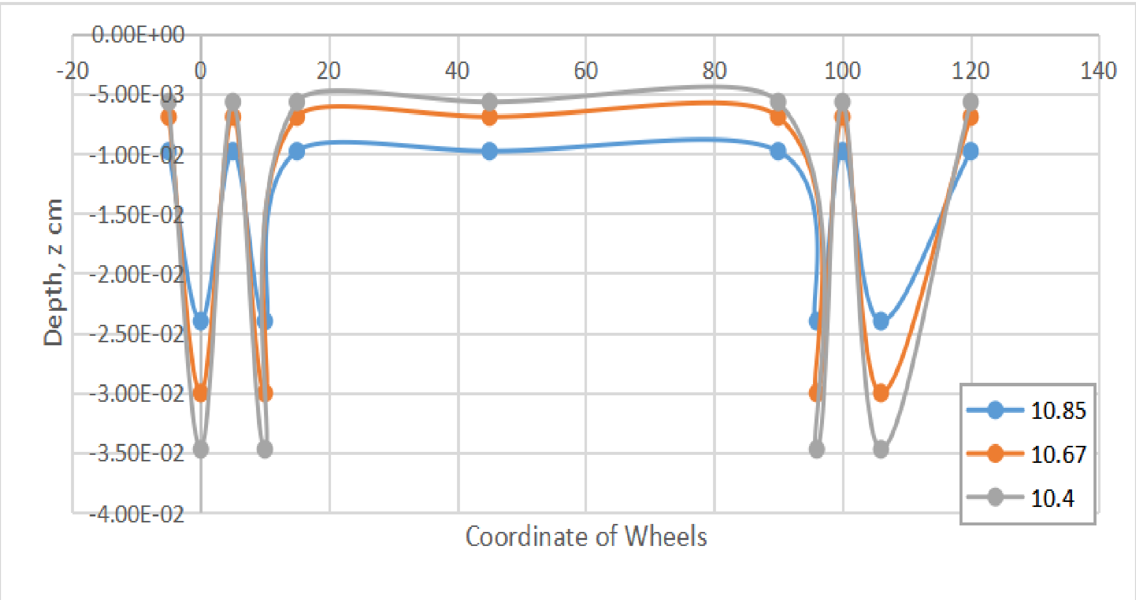


Figure 4.33: Deflection of flexible pavement due to different contact radius.

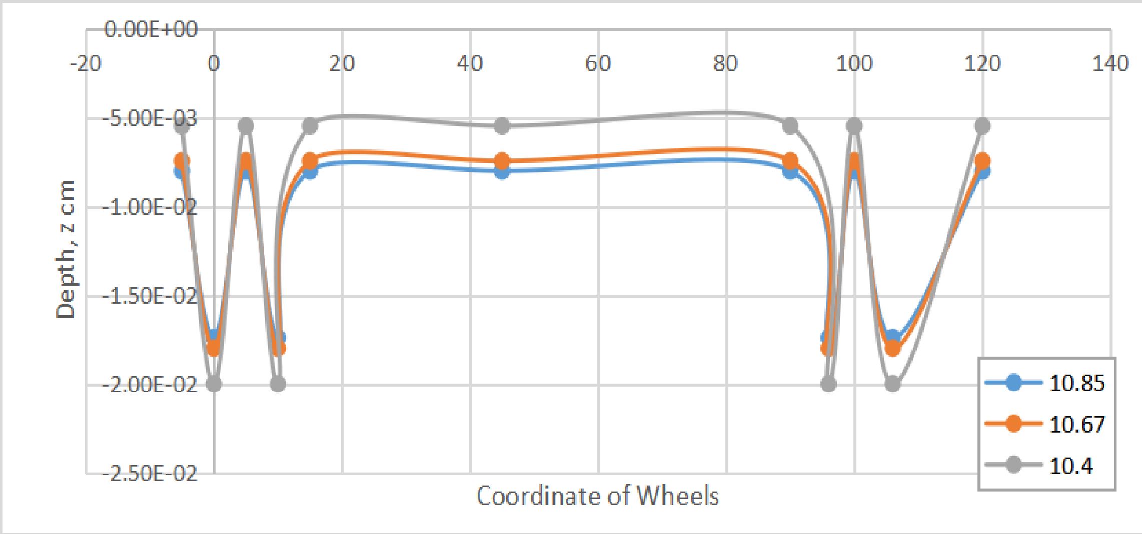


Figure 4.34: Deflection of flexible pavement containing polymer composite (Mix 4) as sub-base layer due to different contact radius.

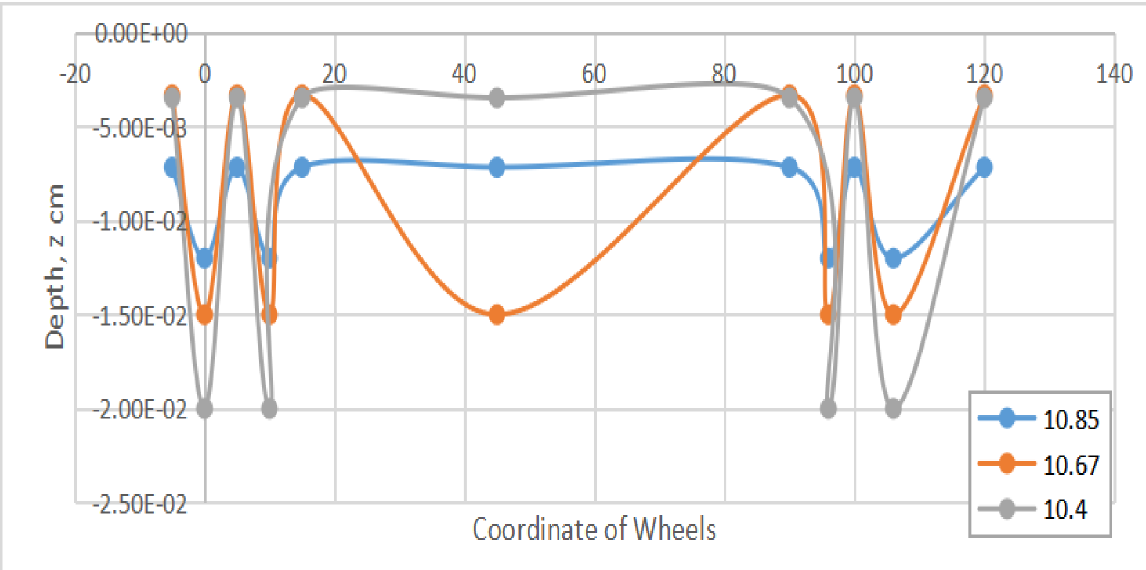


Figure 4.35: Deflection of flexible pavement containing polymer composite (Mix 6) as sub-base layer due to different contact radius.

Table 4.5: Maximum deflection value due to different contact radius

Sub-base Layer Types	**Contact Radius/Maximum Deflection (cm)**		
	10.85	**10.67**	**10.4**
Conventional Flexible Pavement Sub-base	0.0240	0.030	0.0347
Mix 4	0.0174	0.0180	0.0200
Mix 6	0.0120	0.0150	0.0200

4.3.4: Model predicted vertical stress distribution of the conventional flexible pavement and polymer composite pavement at different location and at sub-base layer thickness of 300mm.

Vertical stress is an important criteria of pavement design. When the pavement layer is subjected to vertical stress, it gets compressed. This compression leads to the crushing of the materials. Depression such as rutting are formed on the pavement surfaces. In this study, the vertical stress was analysed at two different locations of the tyres. Figure 4.36 shows two-dimension (2-D) view of the tyres. Figure 4.37 shows the two critical points of analysis for the vertical stress. Figures 4.38 show the vertical stress along the depth of conventional flexible pavement and flexible pavement containing mixes 4 and 6 polymer composites as sub-base layer. Based on the analysis, it was observed that the vertical stress decreased with depth of each of the pavement. However, the vertical stress at point 1 is higher for all three types of pavements in comparison with point 2. This is due to the fact that at point 1, the load is directly in touch with the pavement. Apart from that, it was observed that the maximum vertical stress reduced as the elastic modulus of the sub-base layer increased irrespective of the location. The maximum vertical stress at point 1 for conventional flexible pavement and flexible pavement containing mixes 4 and 6 polymer composites as sub-base layer were 905kPa, 731kPa and 620kPa, respectively. These results show that the maximum vertical stress on the surface of flexible pavement containing mix 4 polymer composite and mix 6 polymer composite as sub-base layer is about 20% and 32% lower than the conventional flexible pavement.

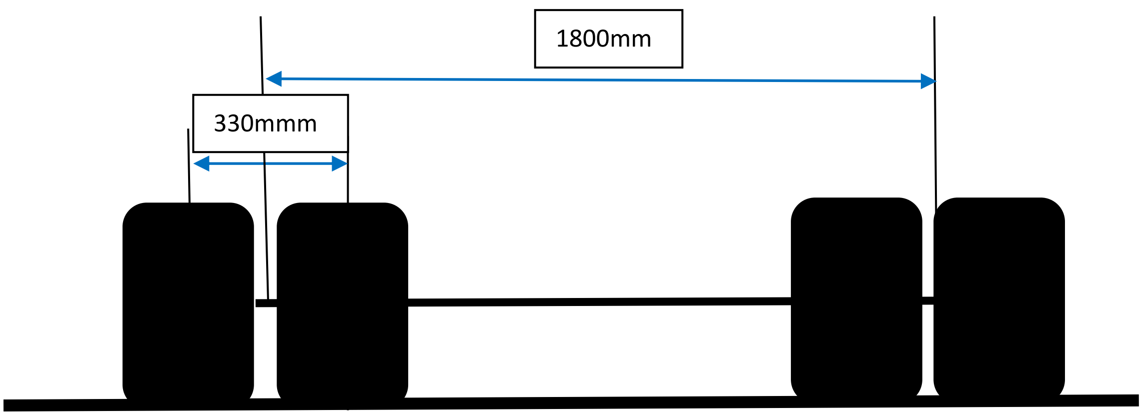


Figure 4.36: 2-D front view of a tandem axle dual wheel used in the analysis.

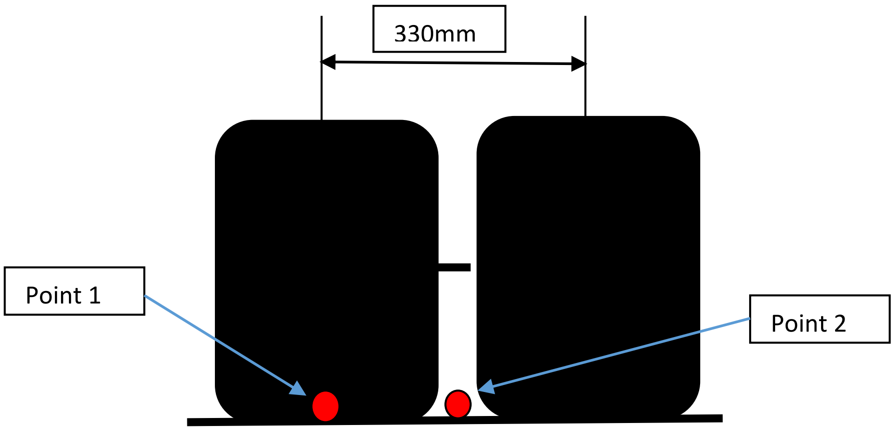


Figure 4.37: Critical point of analysis for stress and strain analysis.

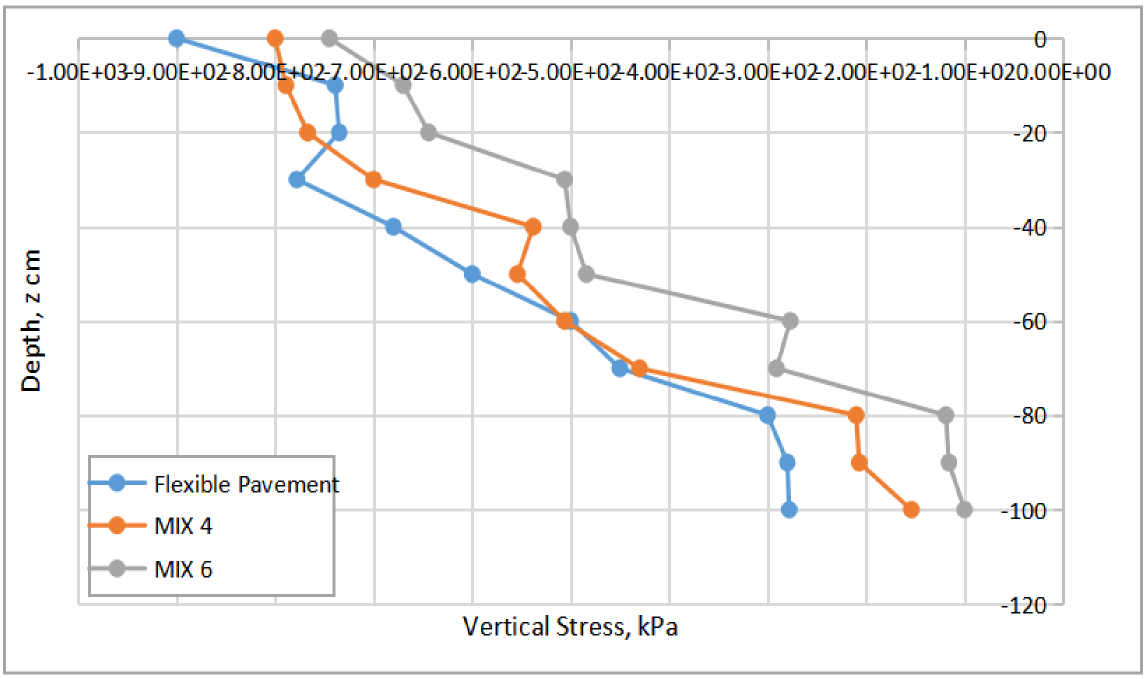


Figure 4.38: Vertical stress of the different types of pavements at point 1.

polymer composite as sub-base layer. Based on the software analysis, it was observed that as the contact radius increased the maximum deflection decreased. Apart from that, the maximum deflection is decreased as the elastic modulus of the mix is increased. According to Table 4.5, the maximum deflection of conventional flexible pavement, flexible pavement containing mix 4 polymer composite and mix 6 polymer composite as sub-base layer at contact radius of 10.85cm was 0.024cm, 0.0174cm and 0.0120cm, respectively. Cheh [99] obtained maximum deflection value of 0.0128cm, 0.00572 and 0.0362 at a contact radius of 10.85 for flexible pavement, rigid pavement and stormpav green pavement.

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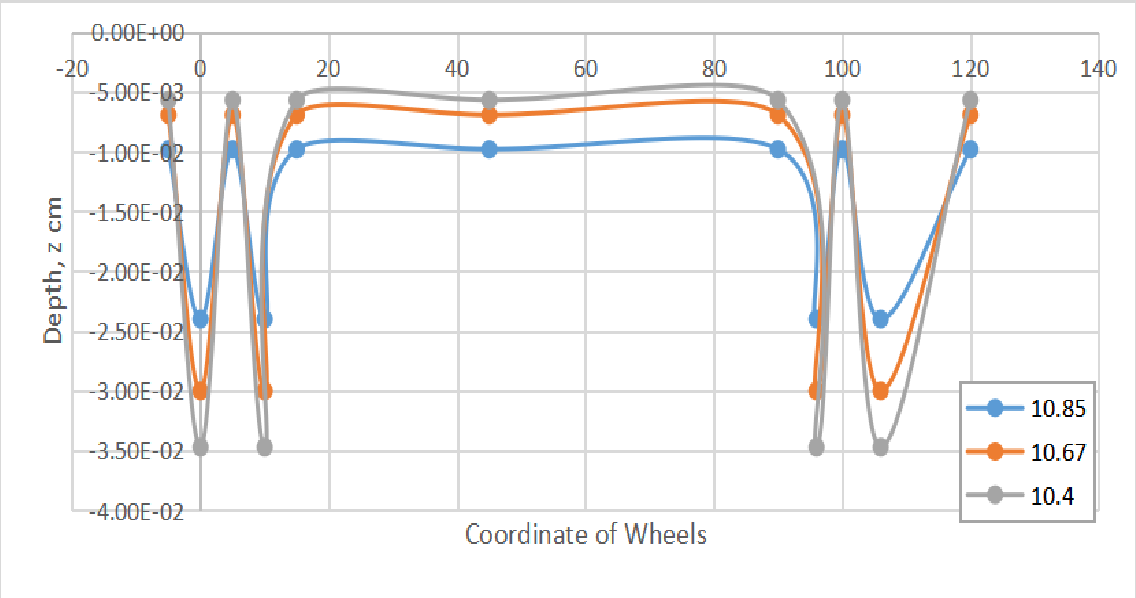

Figure 4.39: Deflection of flexible pavement due to different contact radius.

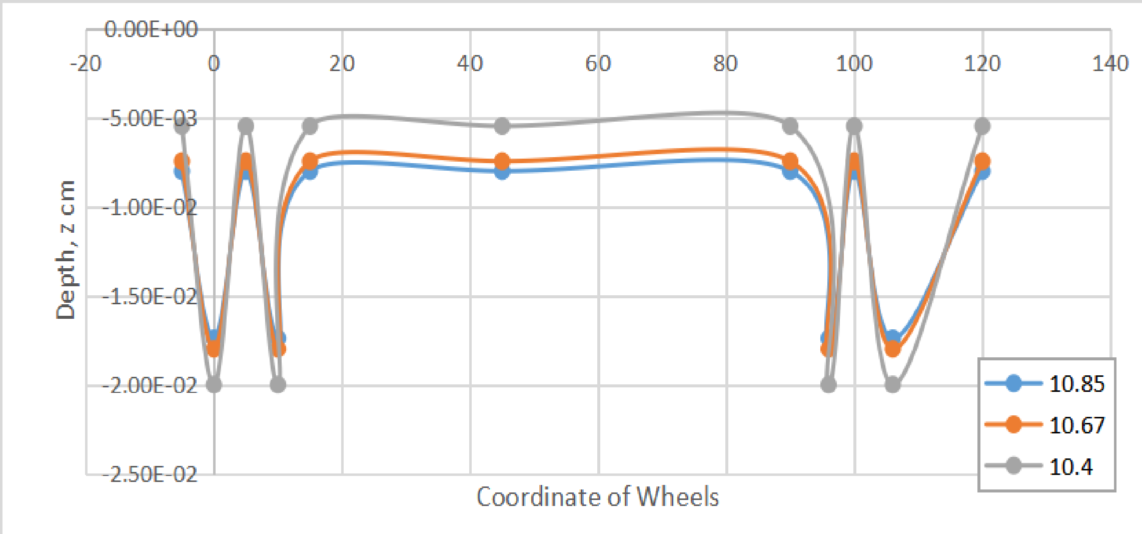

Figure 4.40: Deflection of flexible pavement containing polymer composite (Mix 4) as sub-base layer due to different contact radius.

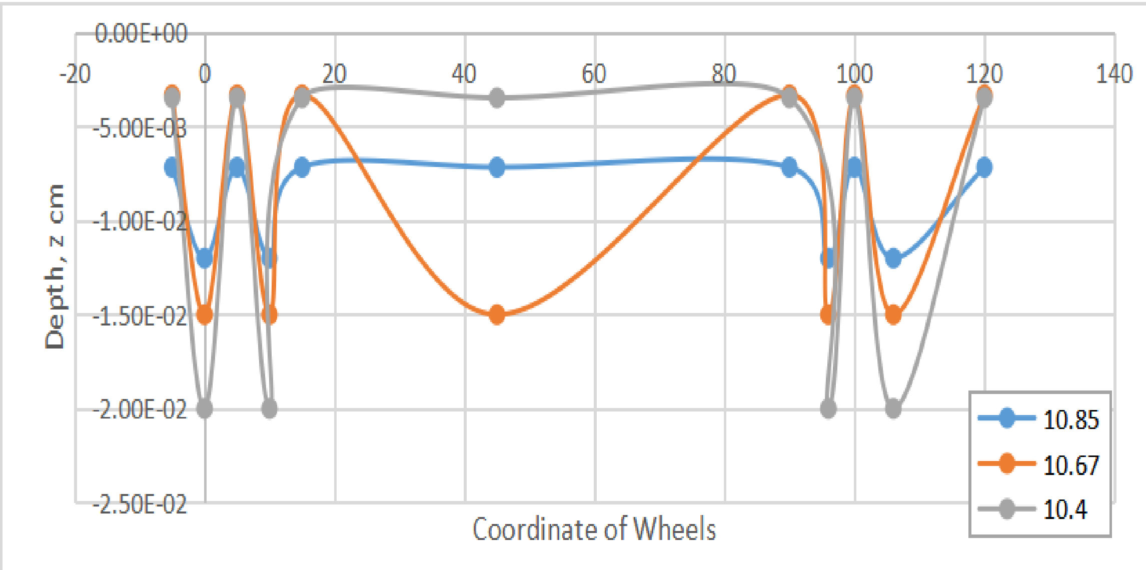

Figure 4.41: Deflection of flexible pavement containing polymer composite (Mix 6) as sub-base layer due to different contact radius.

Table 4.5: Maximum deflection value due to different contact radius

Sub-base Layer Types	**Contact Radius/Maximum Deflection (cm)**		
	10.85	**10.67**	**10.4**
Conventional Flexible Pavement Sub-base	0.0240	0.030	0.0347
Mix 4	0.0174	0.0180	0.0200
Mix 6	0.0120	0.0150	0.0200

4.3.5: Model predicted vertical stress distribution of the conventional flexible pavement and polymer composite pavement at different location and at sub-base layer thickness of 300mm.

Vertical stress is an important criteria of pavement design. When the pavement layer is subjected to vertical stress, it gets compressed. This compression leads to the crushing of the materials. Depression such as rutting are formed on the pavement surfaces. In this study, the vertical stress was analysed at two different locations of the tyres. Figure 4.42 shows two-dimension (2-D) view of the tyres. Figure 4.43 shows the two critical points of analysis for the vertical stress. Figures 4.44 and 4.45 show the vertical stress along the depth of conventional flexible pavement and flexible pavement containing mixes 4 and 6 polymer composites as sub-base layer. Based on the analysis, it was observed that the vertical stress decreased with depth of each of the pavement. However, the vertical stress at point 1 is higher for all three types of pavements in comparison with point 2. This is due to the fact that at point 1, the load is directly in touch with the pavement. Apart from that, it was observed that the maximum vertical stress reduced as the elastic modulus of the sub-base layer increased irrespective of the location. The maximum vertical stress at point 1 for conventional flexible pavement and flexible pavement containing mixes 4 and 6 polymer composites as sub-base layer were 905kPa, 731kPa and 620kPa, respectively. These results show that the maximum vertical stress on the surface of flexible pavement containing mix 4 polymer composite and mix 6 polymer composite as sub-base layer is about 20% and 32% lower than the conventional flexible pavement.

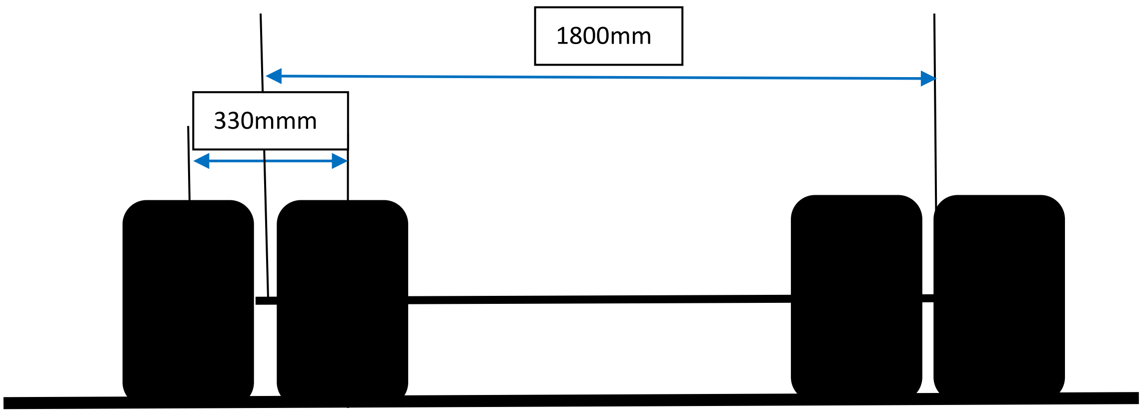

Figure 4.42: 2-D front view of a tandem axle dual wheel used in the analysis.

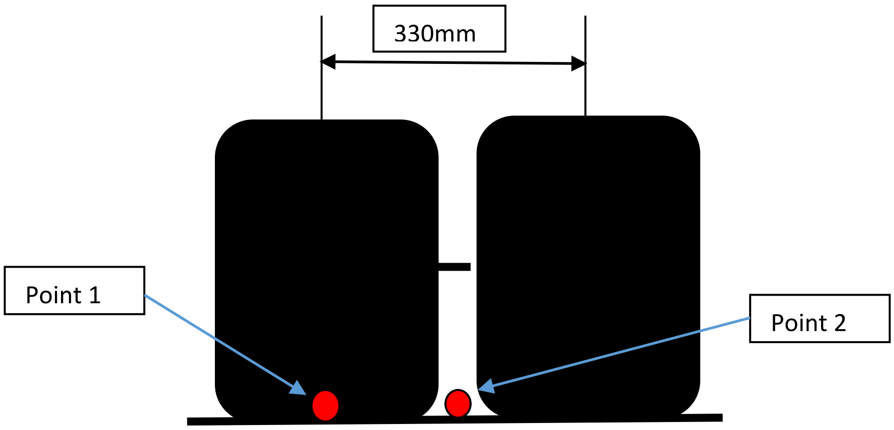

Figure 4.43: Critical point of analysis for stress and strain analysis.

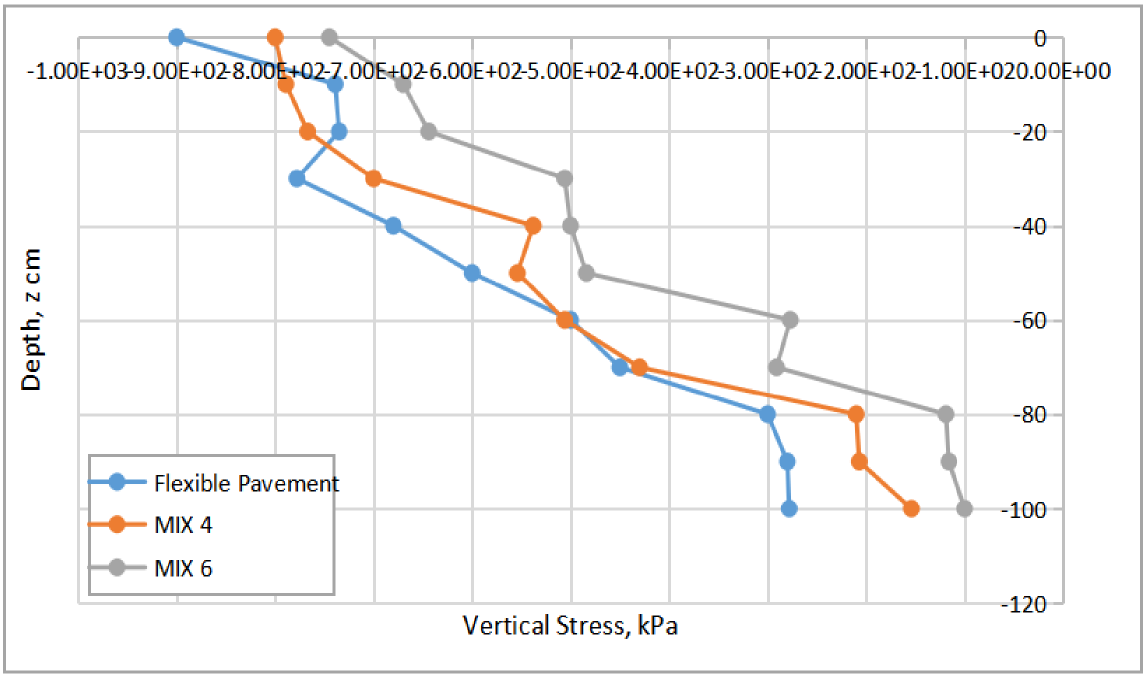

Figure 4.44: Vertical stress of the different types of pavements at point 1.

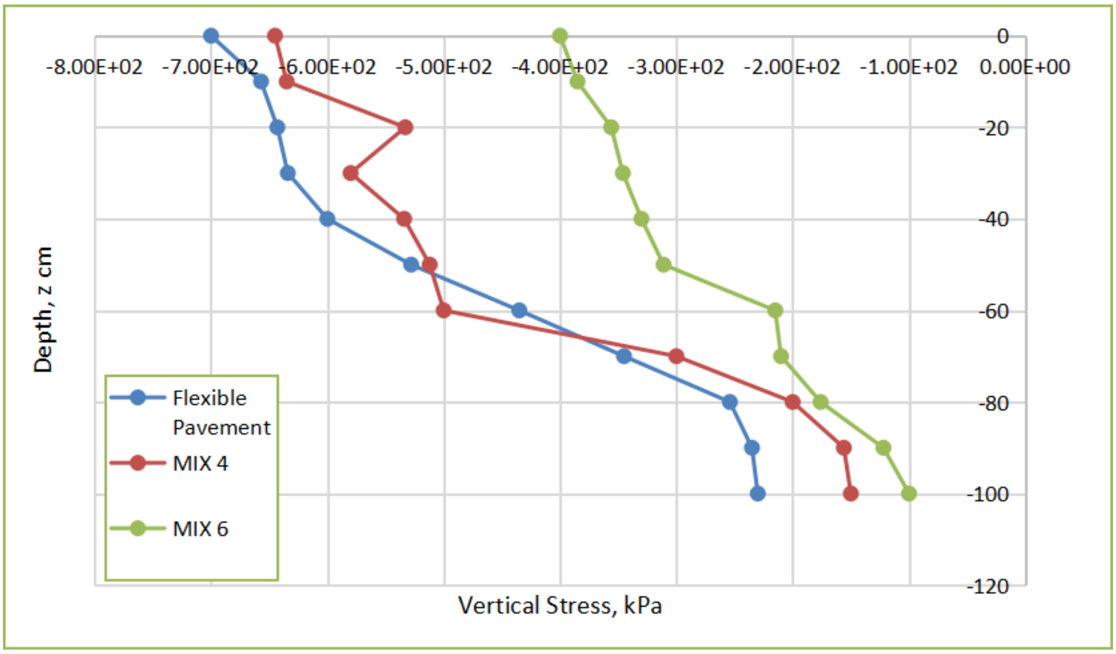

Figure 4.45: Vertical stress of the different types of pavements at point 2.

4.3.6: Model predicted vertical strain distribution of the conventional flexible pavement and polymer composite pavement at different location and a sub-base layer thickness of 300mm.

Vertical strain is also another important criterion for pavement design. The concept and the effect are similar to that of vertical stress due to the fact that vertical strain is caused due to the vertical stress. Figures 4.46 and 4.47 show the vertical strain of the conventional flexible pavement and flexible pavement containing mixes 4 and 6 polymer composites as sub-base layer at different locations. Based on the analysis, it was observed that the vertical strain is higher at point 1, where the load is directly in touch with the pavement, than point 2. Consequently, it was observed that the vertical strain reduced as the elastic modulus of the sub-base layer increased irrespective of the location. The maximum vertical strain value for the sub-base layer for the conventional flexible pavement, mix 4 and mix 6 at point 1 were 0.905, 0.731 and 0.620 respectively. These results show that the maximum vertical strain on the surface of flexible pavement containing mix 4 polymer composite and mix 6 polymer composite as sub-base layer is about 19.2% and 31.5% lower than the conventional flexible pavement sub-base.

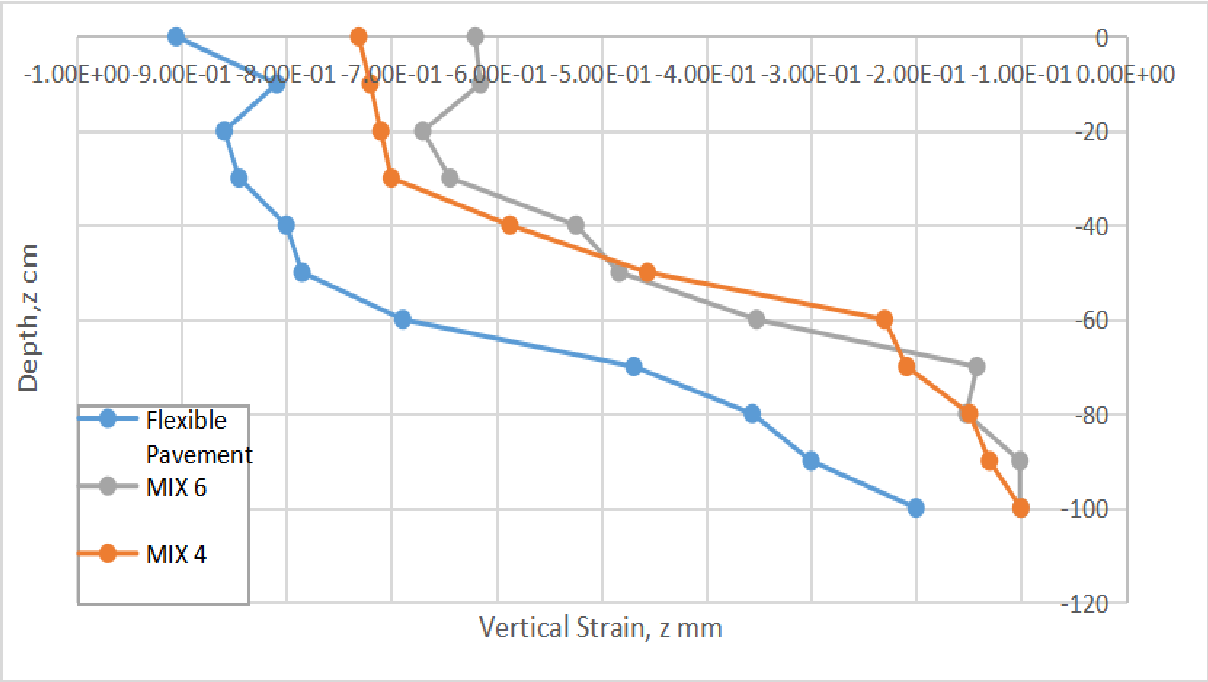

Figure 4.46: Vertical strain of different types of pavements at point 1.

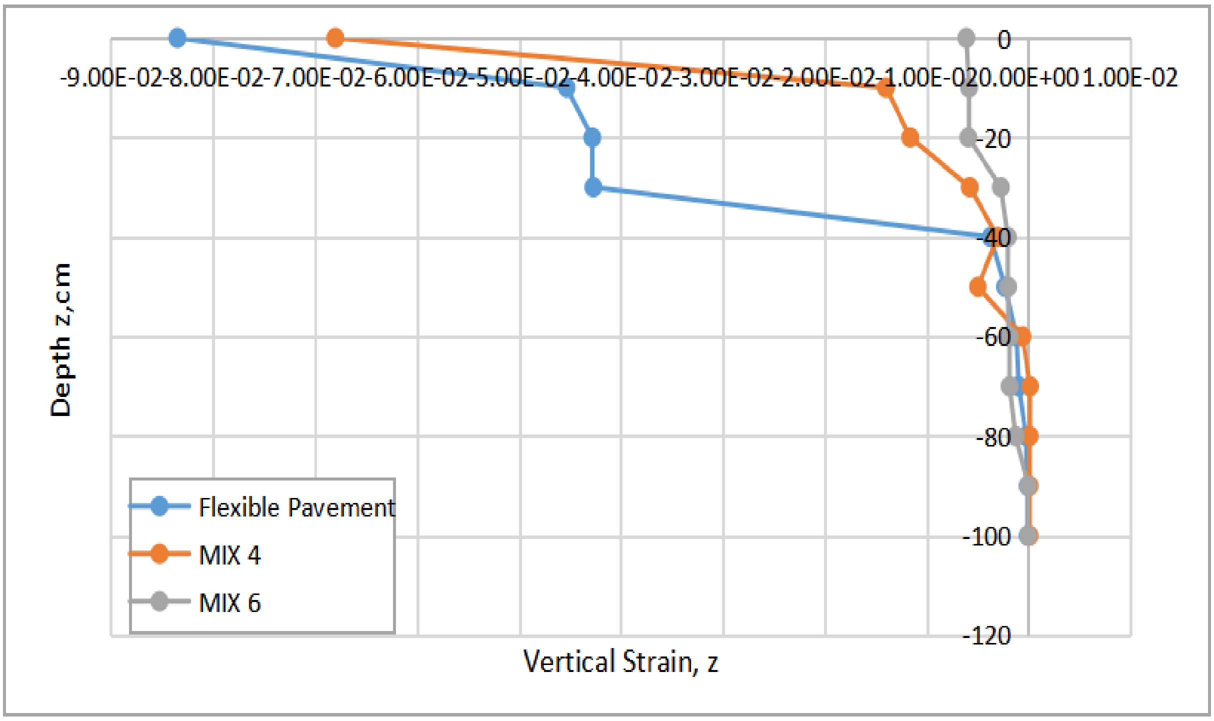

Figure 4.47: Vertical strain of different types of pavements at point 2.

4.3.7: Discussion and Comparison

In this analysis, the features and methodology used by a state-of-the-art non-linear finite element program for the analysis of flexible pavements, MICH-PAVE are described. This analysis accounts for material nonlinearity, the nature of unbound nature of granular soils, and “locked-in” lateral stresses arising from compaction. Results from the MICH-PAVE program have been compared with those from Win-Julea. For linear analysis, MICH-PAVE and Win-Julea give similar strains and displacements. The stresses computed by MICH-PAVE, however, account for the weight of pavement materials that are neglected by Win-Julea. For nonlinear analysis, displacements computed by Win-Julea are smaller than those computed by MICH-PAVE. It is believed that the use of a flexible boundary in MICH-PAVE alleviates the "stiffening" effect that results when a deep finite element mesh with a fixed boundary is used.

CHAPTER 5

CONCLUSIONS

5.1 Overview

This chapter concludes the investigation of polymer composite consisting of unsaturated polyester resin (binder), fly ash, waste tyre crumb rubber and recycled PET flakes as filler. The aim of this research was to develop a polymer composite which is light in weight, have good resistance against aggressive environment and achieve 28-days compressive strength of more than 17.5 MPa. This study was divided into three stages. In the first stage, optimum mix proportion of the polymer composite based on various trial mix were conducted. The effect of hybrid combinations on compressive and flexural strengths and density of various solid wastes as fillers in lightweight polymer composites was evaluated. The effect of curing ages on the above properties were also evaluated. The reinforcing effect of natural jute fabric on the flexural strength and toughness of lightweight polymer composites containing mono and hybrid fillers were evaluated. Microstructure of above polymer composites was also evaluated to identify any reaction products between various waste fillers and polymer matrix. In stage two, long term effect of aggressive chemicals of the developed polymer composite was investigated. Mechanical, durability and micro-structural tests were conducted at 1, 3 and 6 months. In stage three, an analysis was performed using numerical model based on multi-layer linear elastic theory. The developed polymer composites were modelled as the sub-base layer for the flexible pavement using software such as Win-Julea and Mich-pave.

5.2 Conclusions

Based on first stage of the study the following conclusions are drawn:

- Hybrid combinations of fly ash and waste rubber crumb, fly ash and recycled PET flakes and fly ash, rubber crumb and PET flakes in polymer composites exhibited lightweight concrete's requirement of density no more than 1850 kg/m3 and 28 days compressive strength greater than 17.5 MPa.

- Lightweight polymer composites containing mono and hybrid fillers show increase in compressive and flexural strengths with increase in curing ages from 3 days to 28 days irrespective of filler volumes and their combinations.
- Hybridization of fly ash, recycled PET flakes and waste rubber crumb exhibits much higher compressive and flexural strengths of polymer composites than those containing crumb rubber and PET flakes alone. The use of jute fabric significantly improved the flexural strength by >20% of polymer composites containing mono filler (e.g., PET flakes or crumb rubber) at all ages. About 5–20% improvement in flexural strength is observed in the case of hybrid fillers.
- Polymer composites containing crumb rubber and PET flakes fillers exhibit higher deflection capacity at peak load in bending than their counterpart composites containing hybrid fillers. All composites containing mono and hybrid fillers exhibit brittle failure behavior under flexure at all test ages. Failure patterns of polymer composites containing PET flakes and hybrid PET flakes and fly ash and PET flakes, fly ash and crumb rubber are different from the composites containing crumb rubber and hybrid fly ash and crumb rubber. Complete separation of samples was observed for samples containing crumb rubber and fly ash, indicating brittle failure. However, for samples containing PET flakes and fly ash, instead of a complete separation, a crack was formed in the middle third of the beam.
- Polymer composites containing mono and hybrid fillers from waste materials exhibit higher toughness by about 10–50% than the control polymer composite at early age of 3 days with no such improvement at later ages of 14 and 28 days. However, the use of jute fabric in those composites show improvement in toughness at all ages compare to the control polymer composite containing jute fabric. Jute fabric reinforcement in those composites show mixed improvement in toughness. The increase in toughness of the composite with respect to jute fabric is 60%, 50%, 70%, 70% and 40% respectively for sample R2-F4, R3-F4, R4-F4, R5-F4 and R6-F4 for 14 days test date.

- SEM images show the presence of pores/voids around rubber and PET in the polymer composite while uniform dispersion of fly ash particles are observed in the polymer matrix.

Based on second stage of the study, the following conclusions are drawn:

- The density of the polymer composites varied negligibly when kept in tap water for 1, 3 and 6 months. Mixes containing fly ash had higher density due to the higher unit weight of the fly ash. The density of most of the composites were slightly lower when immersion in H_2SO_4 solution for 1, 3 and 6 months. Mixed results were observed when exposed to $MgSO_4$ and NaCl solutions. No trend on change in density of the composites was also observed with respect to their exposure durations.
- The compressive strength is increased in most of the composites after exposure to the chemicals and tap water for duration of up to 6 months. It is found that the compressive strength of all composites is increased when immersed in NaCl solution for up to 6 months. Similar results are also observed in $MgSO_4$ and H_2SO_4 solutions with only deviation in two composites at 1 month where compressive strength is reduced by about 20%. The compressive strength in all composites is increased with exposure durations of 3 and 6 months when placed in ambient air and the improvement is in the range of 10-50%. Improvement in compressive strength in the range of 5-80% is observed in many composites for exposure duration of up to 6 months in H_2SO_4, $MgSO_4$ and NaCl solutions.
- Most of the composites exhibited up to 50% reduction in flexural strength of the composites after exposure to chemical solutions for different exposure periods up to 6 months. Significant gain in flexural strength of all composites with increasing exposure periods in the chemicals is also observed in this study.
- Scanning electron microscopy analysis shows evidence of micro gaps between fillers e.g., PET or rubber and matrix when exposed to chemicals. These micro gaps reduced in width with increase in exposure duration in those solutions. More compact microstructure of the matrix is observed when exposed to NaCl solution than the other two chemicals. In some samples, magnesium, sulphur, sodium and chlorine are identified. These elements are not reaction products of the polymer composites with the aggressive solution. The presence of these elements is due to the accumulation of the solid particles during immersion.

Based on third stage of this study, the following conclusions are drawn:

- The deflection of the pavement is influenced by the sub-base thickness, elastic modulus and contact radius. Based on the numerical modelling, at sub-base thickness of 300mm, the deflection of polymer composite sub-base was 50% less than that of the conventional flexible pavement. Apart from that, as the contact radius increased, the maximum deflection decreased. The deflection was least at contact radius 10.85cm.
- The vertical stress is influenced by the elastic modulus of the sub-base layer and due to the location of the loading. The vertical stress is higher for location where wheel load is directly in contact with the pavement. The vertical stress for the polymer composite sub-base is 32% lower than that of the conventional flexible pavement. Lower vertical stress is an indication of lower possibility of deterioration.
- The vertical strain is caused by the vertical stress. The vertical strain is influenced by the location of the loading and by the elastic modulus of the sub-base layer. Based on the analysis, the vertical strain of the polymer composite sub-base is 31.5% lower than that of the conventional flexible pavement.

5.3 Recommendation for Future Work

The following areas of research are recommended for future study:

- Continue and study more in depth the numerical modelling of this composite for application in flexible pavement system.
- Continue this research by creating thin sheet of this composite and replacing the sub-base layer of the flexible pavement and investigate in laboratory the effect of the wheel loads on the settlement of pavement in soft soils to verify the numerical modelling study.
- Continue this research by formulating the polymer composite consisting of different lightweight materials.

- Continue this research by investigating the effect of higher concentration of the aggressive chemicals and longer exposure duration of this polymer composite in the aggressive environment.
- Continue this research in other application field such as building or bridge components as this a newly developed light weight composite which consist of high waste materials and have good compressive and flexural strength. This composite could also be tested to be used as building components in aggressive environment as it has good resistance against aggressive solutions.

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APPENDIX A- Flexural Strength Test Results

1 Month Flexural Strength Test Results

	Max_Force Calc. at Entire Areas	Max_Stress Calc. at Entire Areas	Max_Disp. Calc. at Entire Areas	Max_Strain Calc. at Entire Areas
	N	N/mm2	mm	%
	5115.86	7.36684	2.11334	1.76111
	5561.07	8.00793	1.64588	1.37157
	5154.36	7.42228	2.56497	2.13747
	3662.90	5.27457	3.37806	2.81505
	12019.2	17.3076	1.58705	1.32254
	12560.9	18.0876	1.66154	1.38462
	4930.43	7.09981	3.38943	2.82453
	4685.47	6.74707	2.52644	2.10536
	11112.7	16.0023	1.38093	1.15077
	13514.9	19.4614	1.52004	1.26670
	10978.5	15.8090	1.45781	1.21484
	9963.97	14.3481	1.33134	1.10945

	Max_Time Calc. at Entire Areas
	sec
	430.300
	470.900
	443.300
	321.000
	1031.00
	1083.20
	438.400
	393.700
	951.100
	1159.10
	940.400
	856.300

	Max_Force Calc. at Entire Areas	Max_Stress Calc. at Entire Areas	Max_Disp. Calc. at Entire Areas	Max_Strain Calc. at Entire Areas
	N	N/mm2	mm	%
	7942.56	11.4373	3.64695	3.03913
	6170.27	8.88518	2.98131	2.48443
	4710.52	6.78314	2.94066	2.45055
	4417.23	6.36081	2.70686	2.25571
	14269.1	20.5476	2.38279	1.98566
	11949.5	17.2073	2.07423	1.72852
	14565.3	20.9740	1.81731	1.51442
	13671.8	19.6874	1.87315	1.56096
	12474.6	17.9634	2.52051	2.10043
	12442.8	17.9177	2.20223	1.83519
	4139.41	5.96075	2.08753	1.73961
	5516.47	7.94372	2.61952	2.18293
	3639.57	5.24098	2.45919	2.04932
	6806.94	9.80199	2.62175	2.18479
	4522.51	6.51241	4.27158	3.55965
	4327.89	6.23217	4.19166	3.49305
	13721.2	19.7585	2.11713	1.76428
	1520.66	2.18975	0.93536	0.77946
	4586.77	6.60495	3.53814	2.94845
	5925.56	8.53281	3.29557	2.74631
	12034.3	17.3294	1.66923	1.39103
	10222.9	14.7210	1.32990	1.10825
	147.963	0.21307	0.28854	0.24045
	10479.8	15.0909	1.94574	1.62145

	Max_Time Calc. at Entire Areas
	sec
	686.900
	531.600
	405.700
	379.000
	1230.40
	1032.20
	1254.40
	1178.90
	1076.20
	1072.80
	355.300
	474.500
	312.900
	586.100
	389.500
	380.500
	1185.10
	127.300
	392.700
	510.900

3 Months Flexural Strength Test Results

Max_Force Calc. at Entire Areas N	Max_Stress Calc. at Entire Areas N/mm2	Max_Disp. Calc. at Entire Areas mm	Max_Strain Calc. at Entire Areas %
5470.67	7.87777	3.40899	2.84082
4031.41	5.80523	2.18589	1.82157
4315.53	6.21436	2.77996	2.31663
4640.71	6.68263	3.30838	2.75698
14842.8	21.3737	1.94377	1.61981
12484.2	17.9773	1.77239	1.47699
5667.95	8.16185	3.14028	2.61690
4753.17	6.84456	3.30474	2.75395
14791.2	21.2993	1.77844	1.48203
14010.7	20.1754	1.67856	1.39880
11651.6	16.7782	2.29014	1.90845
14486.0	20.8598	2.23644	1.86370
7063.41	10.1713	2.71731	2.26443
5750.58	8.28084	2.30539	1.92116
3987.67	5.74225	2.93676	2.44730
4251.85	6.12267	2.78145	2.31788
11982.7	17.2551	2.14916	1.79097
14128.6	20.3452	1.70033	1.41694
3707.84	5.33929	3.25881	2.71567
4663.60	6.71558	2.68164	2.23470
10853.8	15.6294	2.03129	1.69274
14035.0	20.2103	1.69201	1.41001
317.311	0.45693	0.47233	0.39361
11542.9	16.6217	1.63406	1.36172

Max_Time Calc. at Entire Areas sec
476.600
348.100
371.200
400.600
1280.00
1079.30
489.000
413.000
1283.90
1208.70
1004.40
1246.00
608.300
498.900
345.100
366.400
1033.30
1218.60
345.100
401.700

	Max_Force Calc. at Entire Areas	Max_Stress Calc. at Entire Areas	Max_Disp. Calc. at Entire Areas	Max_Strain Calc. at Entire Areas
	N	N/mm2	mm	%
	6767.55	9.74527	2.63173	2.19311
	9080.91	13.0765	2.95109	2.45925
	3133.29	4.51194	1.95406	1.62839
	4207.82	6.05926	2.70245	2.25204
	12392.1	17.8446	2.10579	1.75483
	9833.89	14.1608	1.72592	1.43827
	3714.79	5.34930	2.13786	1.78155
	4118.90	5.93122	2.25868	1.88223
	10820.1	15.5809	2.20129	1.83441
	11547.1	16.6279	1.90640	1.58867
	10158.0	14.6275	1.75146	1.45955
	10927.8	15.7360	2.38860	1.99050
	5644.53	8.12812	2.85176	2.37647
	4274.94	6.15591	1.89515	1.57929
	5901.97	8.49884	2.77877	2.31564
	5653.06	8.14040	2.52898	2.10748
	12496.2	17.9945	2.72771	2.27309
	13230.7	19.0522	2.30131	1.91776
	3462.15	4.98549	2.17503	1.81252
	3822.10	5.50383	2.01791	1.68159
	11743.5	16.9106	1.48460	1.23717
	12630.3	18.1876	1.68890	1.40742
	1040.84	1.49881	0.66878	0.55732
	12057.3	17.3626	1.68266	1.40221

	Max_Time Calc. at Entire Areas
	sec
	584.000
	778.300
	270.000
	363.200
	1066.60
	842.400
	318.600
	351.000
	933.600
	995.400
	870.000
	943.300
	486.600
	367.800
	503.700
	487.100
	1077.90
	1136.80
	297.400
	326.900

6 Months Flexural Strength Test Results

Max_Force Calc. at Entire Areas	Max_Stress Calc. at Entire Areas	Max_Disp. Calc. at Entire Areas	Max_Strain Calc. at Entire Areas
N	N/mm2	mm	%
9349.95	13.4639	2.78631	2.32192
4084.03	5.88100	1.46999	1.22499
4580.11	6.59536	2.50439	2.08699
4810.65	6.92734	2.10184	1.75153
11653.8	16.7815	1.79048	1.49206
14383.3	20.7119	1.84443	1.53702
4609.55	6.63776	1.93881	1.61568
4511.25	6.49620	1.96321	1.63601
10038.2	14.4549	1.89519	1.57933
13262.0	19.0973	1.88046	1.56705
11451.7	16.4904	1.98101	1.65084
12165.5	17.5183	1.80084	1.50070
5657.37	8.14661	1.64685	1.37238
3987.05	5.74135	1.82961	1.52467
3711.30	5.34428	2.09291	1.74409
4964.94	7.14951	2.19694	1.83079
9523.42	13.7137	2.05226	1.71021
10376.7	14.9424	1.23434	1.02862
4545.74	6.54586	1.73764	1.44804
5114.75	7.36523	2.18264	1.81886
12223.8	17.6023	1.59821	1.33184
11504.1	16.5659	1.25146	1.04288
10174.4	14.6511	2.29719	1.91433
12067.7	17.3775	2.07281	1.72734

Max_Time Calc. at Entire Areas
sec
807.800
355.900
395.800
413.500
999.500
1231.60
385.100
387.800
865.100
1143.90
987.700
1047.60
487.000
339.000
318.200
419.200
819.700
887.400
383.200
435.000

24	Qty/Batch:

Max_Force Calc. at Entire Areas N	Max_Stress Calc. at Entire Areas N/mm2	Max_Disp. Calc. at Entire Areas mm	Max_Strain Calc. at Entire Areas %
6770.77	9.74991	2.30174	1.91812
4567.09	6.57661	2.06137	1.71781
5510.94	7.93575	2.44158	2.03465
5553.87	7.99757	2.32789	1.93991
12865.5	18.5264	2.38467	1.98722
12382.5	17.8308	2.34795	1.95663
4348.30	6.26155	2.39536	1.99614
4795.12	6.90498	2.62884	2.19070
12868.8	18.5311	1.66021	1.38351
12807.3	18.4425	2.06441	1.72034
11610.4	16.7190	2.60367	2.16972
11934.2	17.1853	1.72774	1.43979
8370.26	12.0532	3.26643	2.72203
7382.99	10.6315	2.33949	1.94958
5957.33	8.57856	2.77969	2.31641
6190.65	8.91454	2.89699	2.41416
11733.2	16.8958	2.41953	2.01628
9728.69	14.0093	1.83289	1.52741
4139.08	5.96028	2.16508	1.80423
3874.93	5.57990	2.34130	1.95108
116.261	0.16742	0.11533	0.09611
9850.32	14.1845	1.67569	1.39641
11661.9	16.7931	2.11681	1.76401
11810.6	17.0072	1.90354	1.58629

Max_Time Calc. at Entire Areas sec
583.000
394.600
469.800
476.500
1111.60
1064.30
397.200
413.100
1110.80
1106.70
1002.20
1028.30
722.500
637.000
512.600
532.600
1011.00
838.200
355.600
336.100

APPENDIX B-Flexural Strength Graph

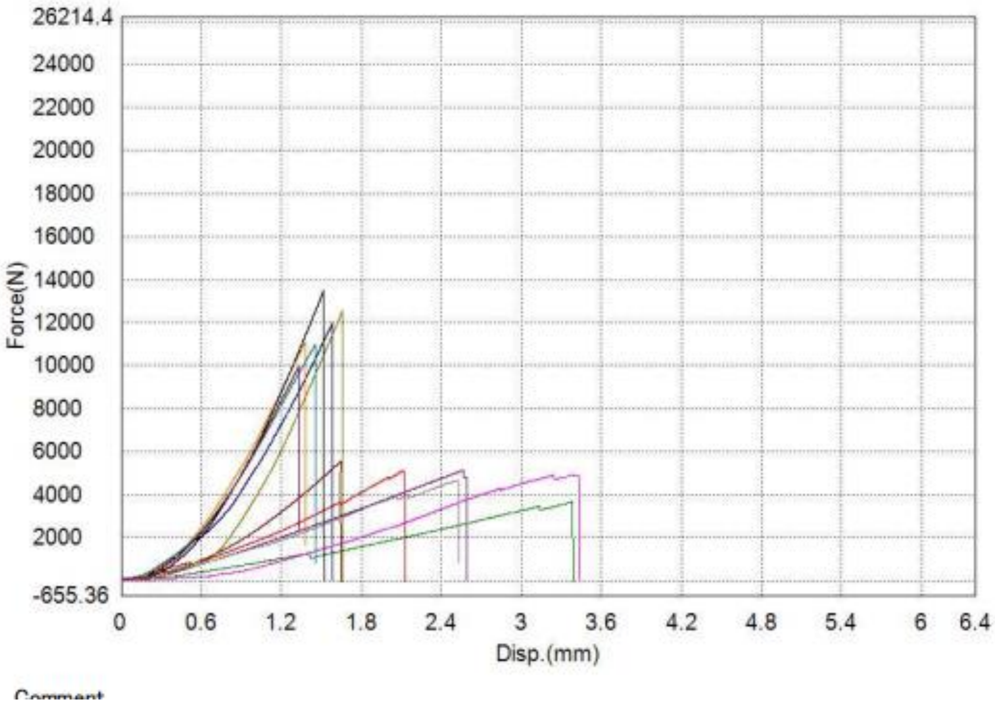


Figure 1: 1 Month Force Displacement Graph

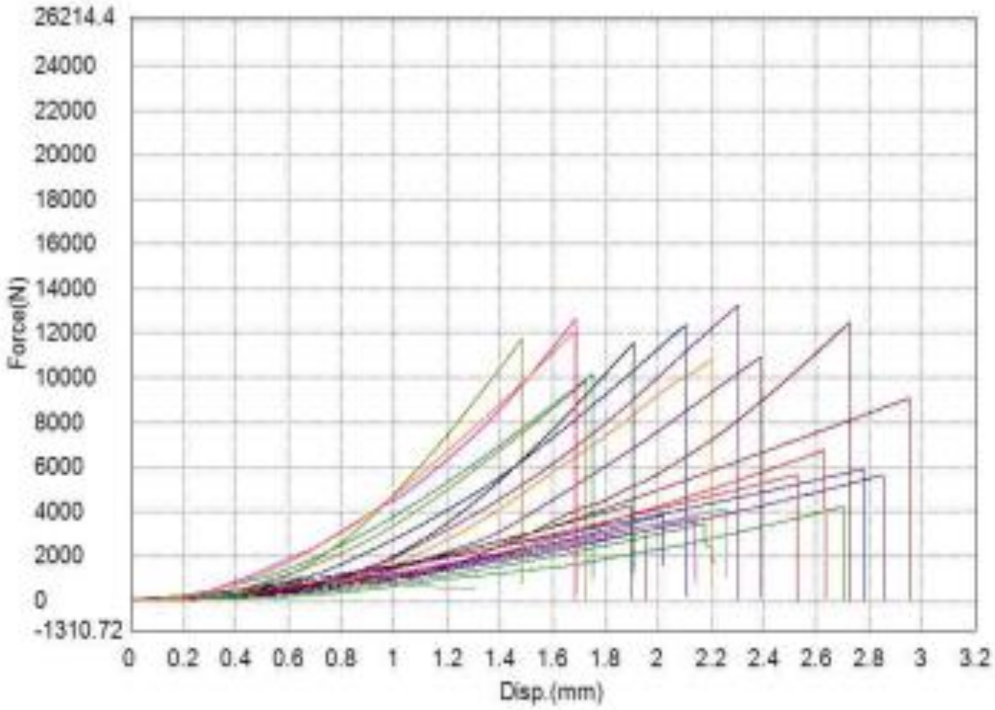


Figure 2: 1 Month Force Displacement Graph

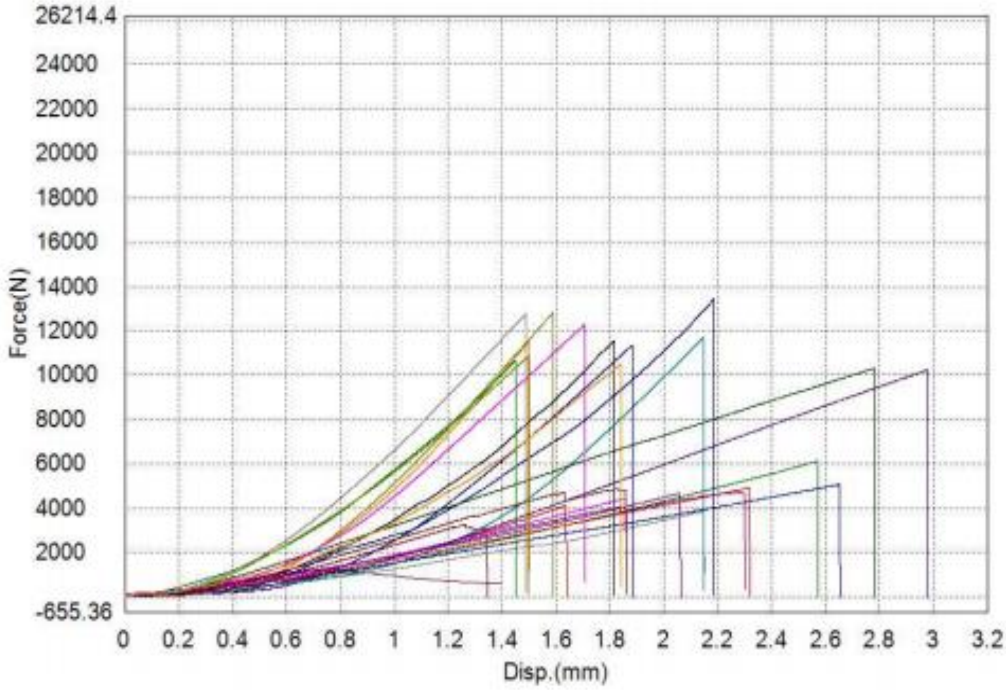


Figure 3: 1 Month Force Displacement Graph

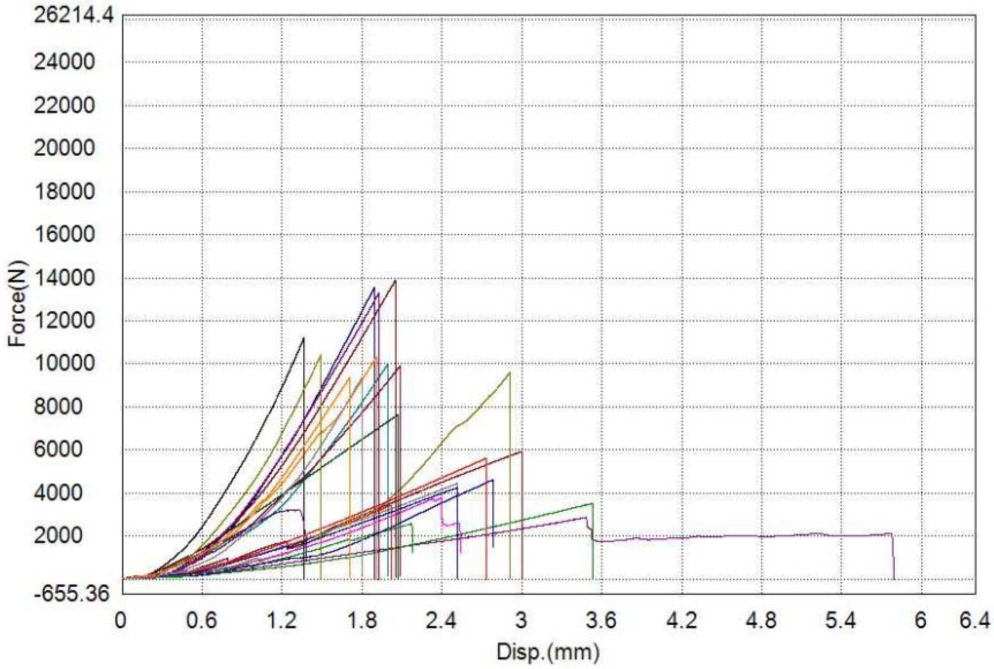


Figure 4: 3 Month Force Displacement Graph

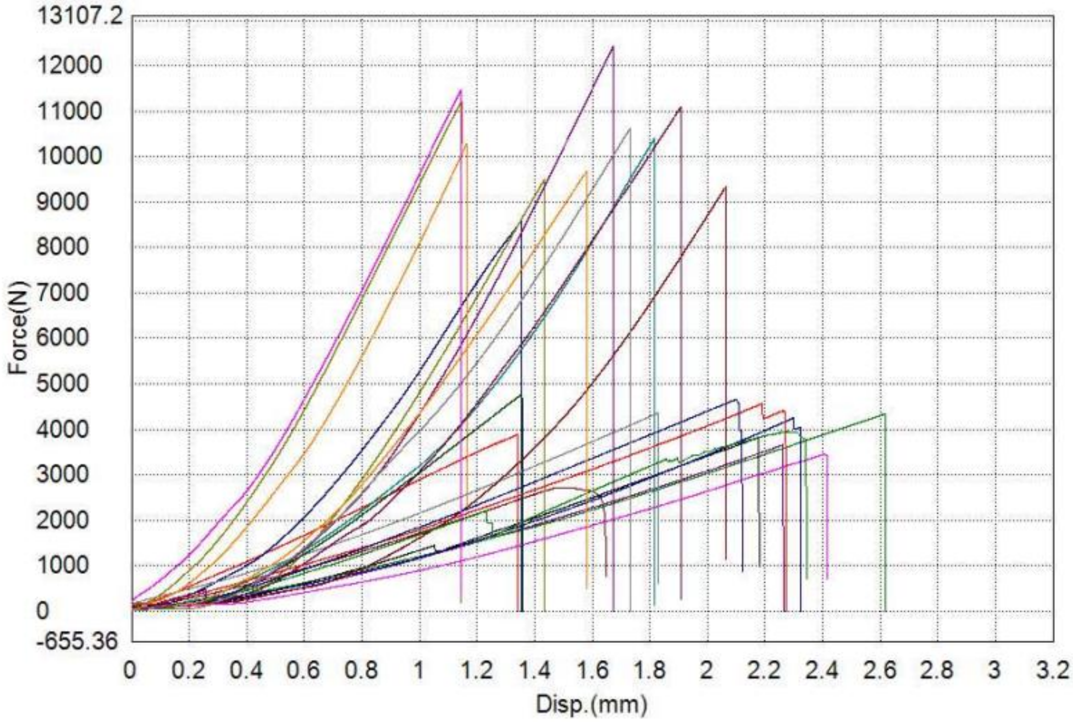


Figure 5: 3 Months Force Displacement Graph

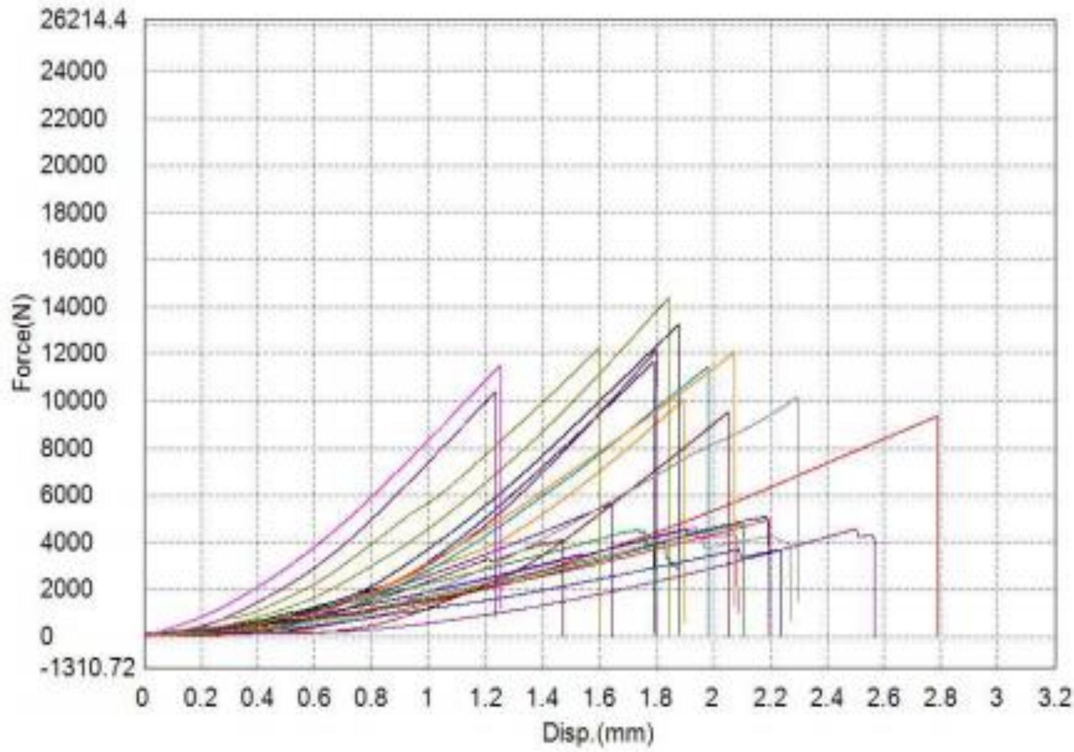


Figure 6: 3 Months Force Displacement Graph

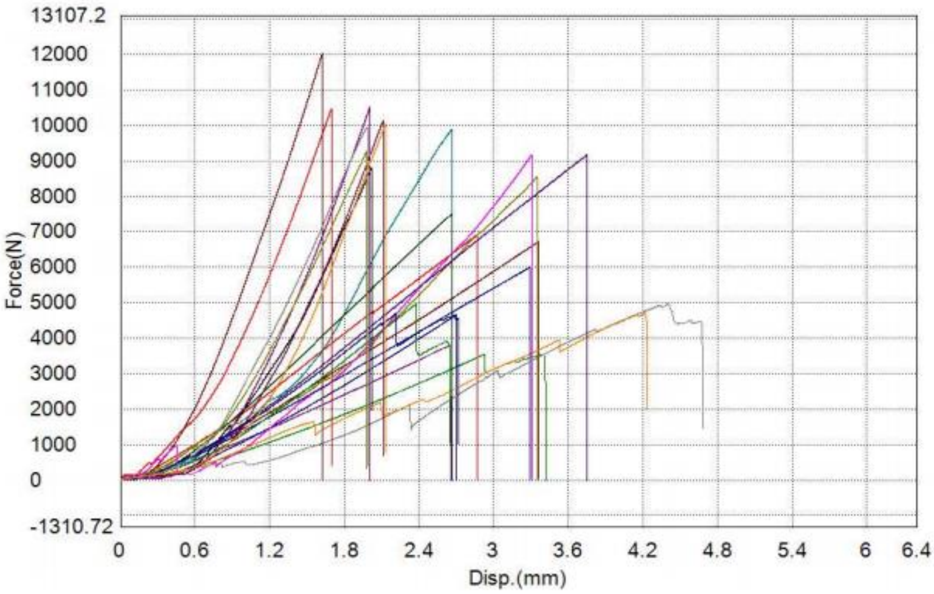


Figure 7: 6 Month Force Displacement Graph

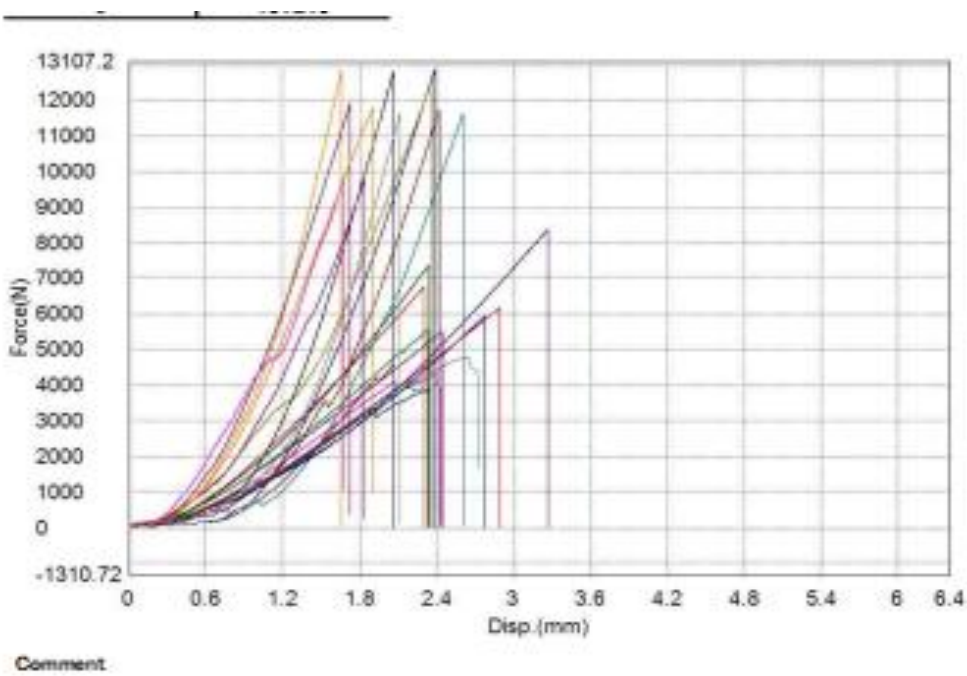


Figure 8: 6 Months Force Displacement Graph

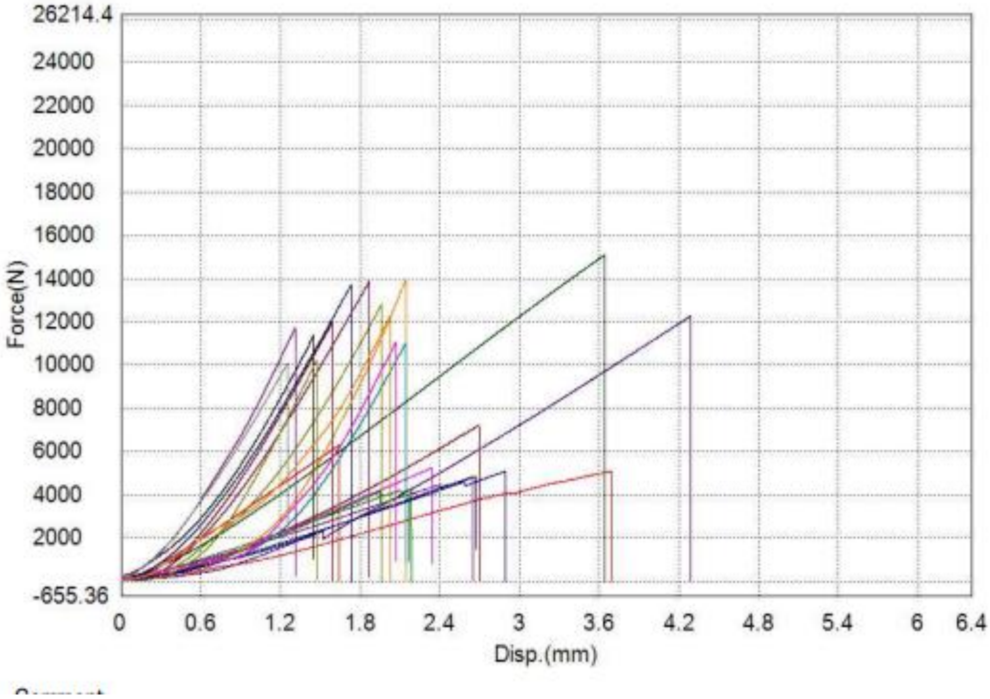
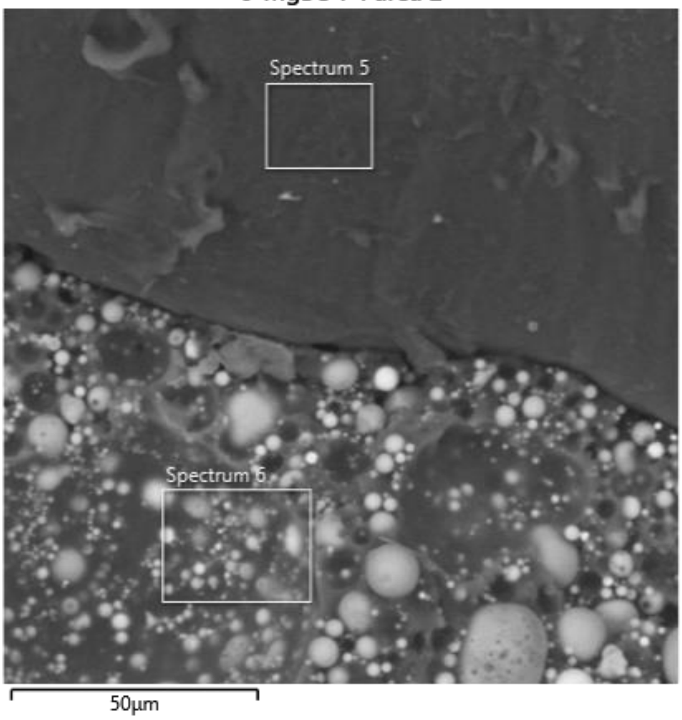


Figure 9: 6 Months Force Displacement Graph

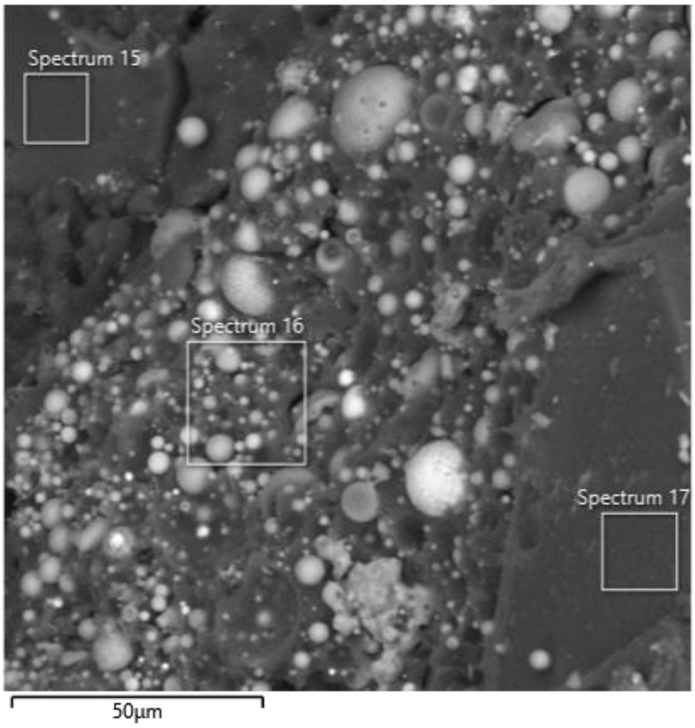
APPENDIX C- SEM Image of Samples

1 Month SEM Image in Aggressive Environment

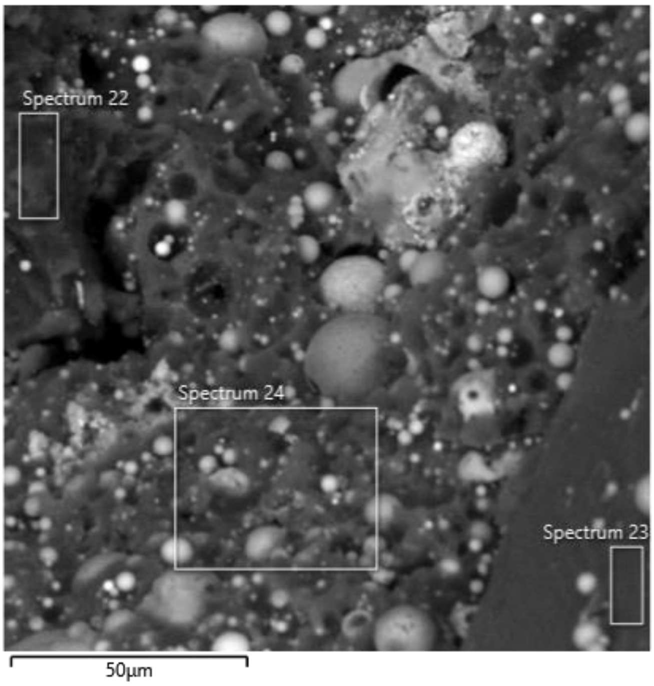
6-MgSO4-1 area 2



6-H2SO4-1 area 2

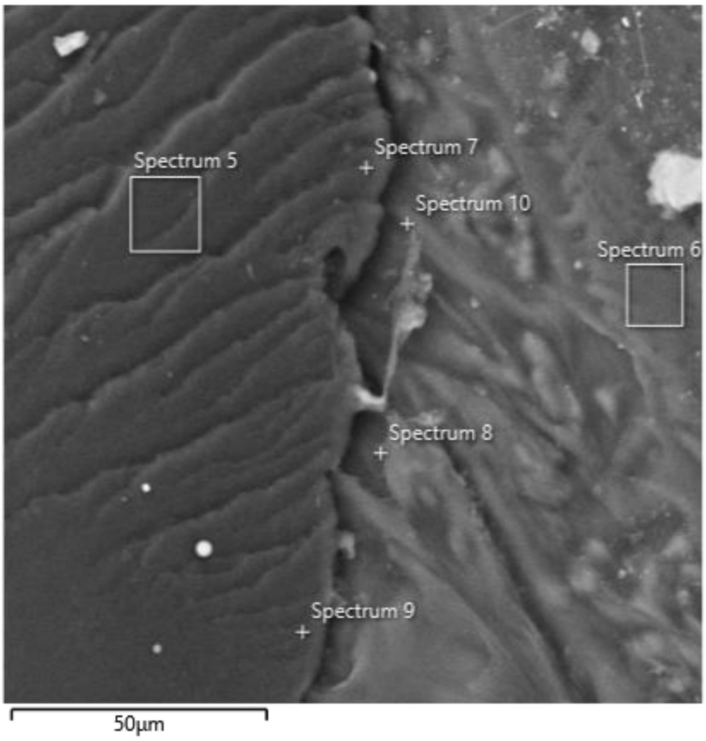


6-NaCl-1 area 1

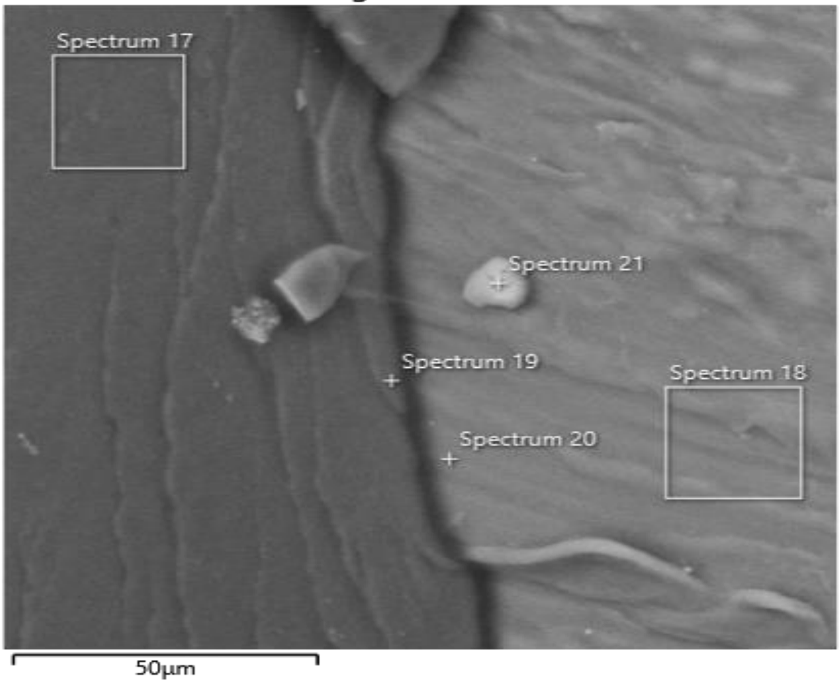


SEM Image 3 of Months in Aggressive Environment

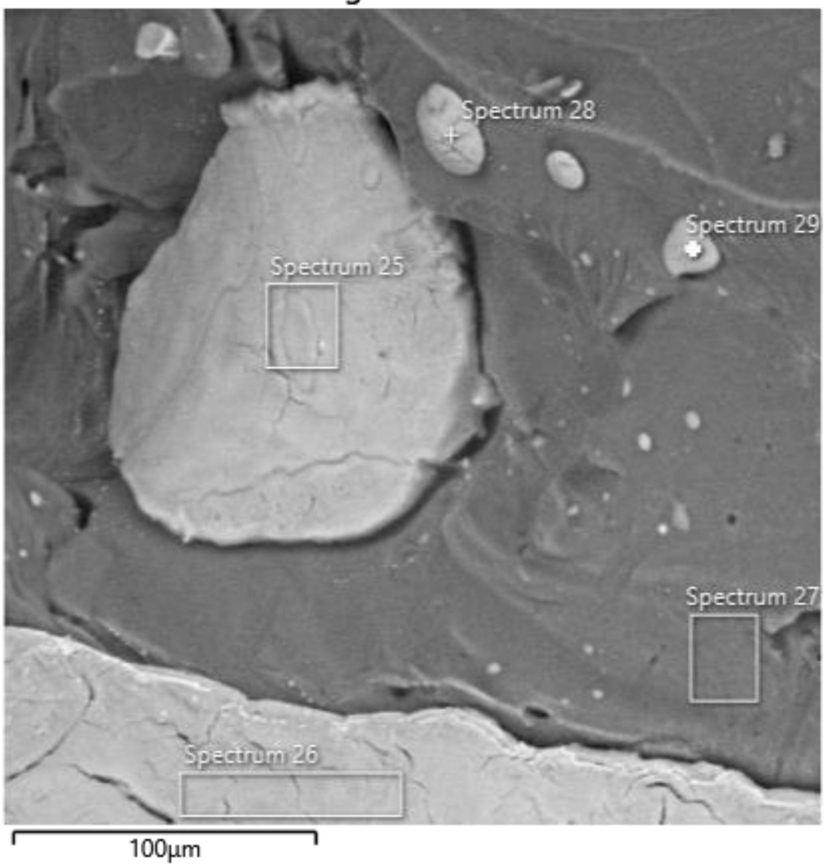
4 H2SO4 3 month



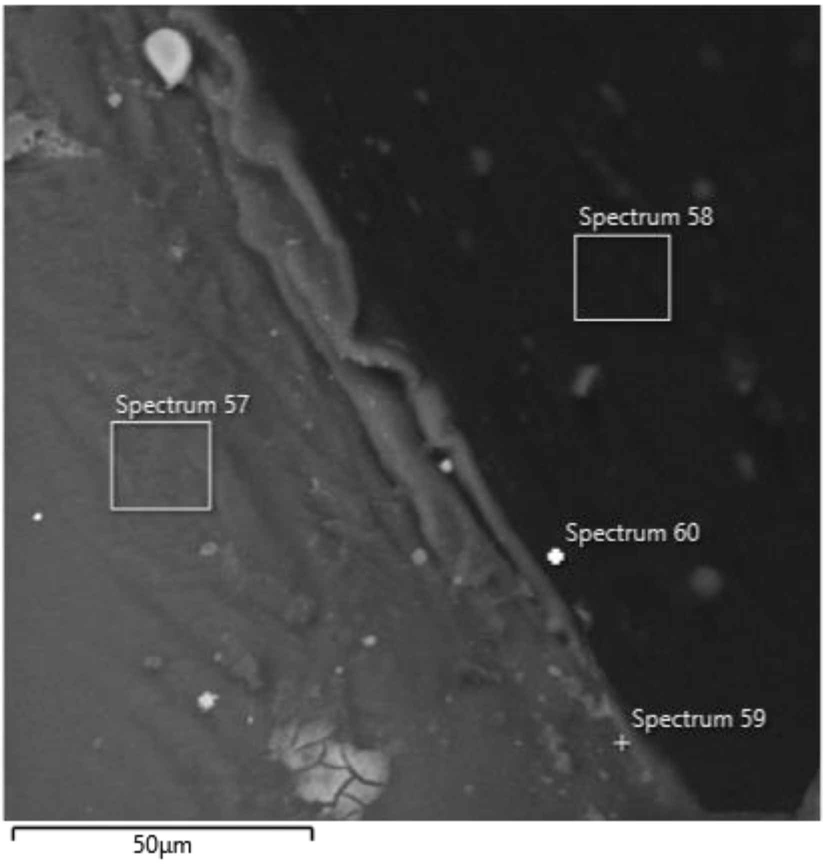
4 MgSO4 3 month



4 MgSO4 3 month

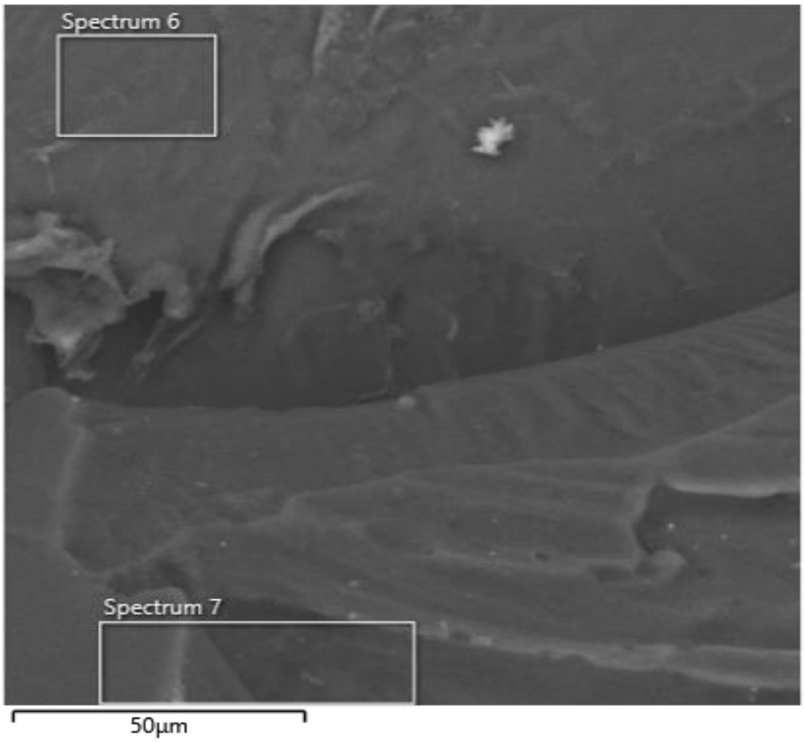


4 NaCl 3 month

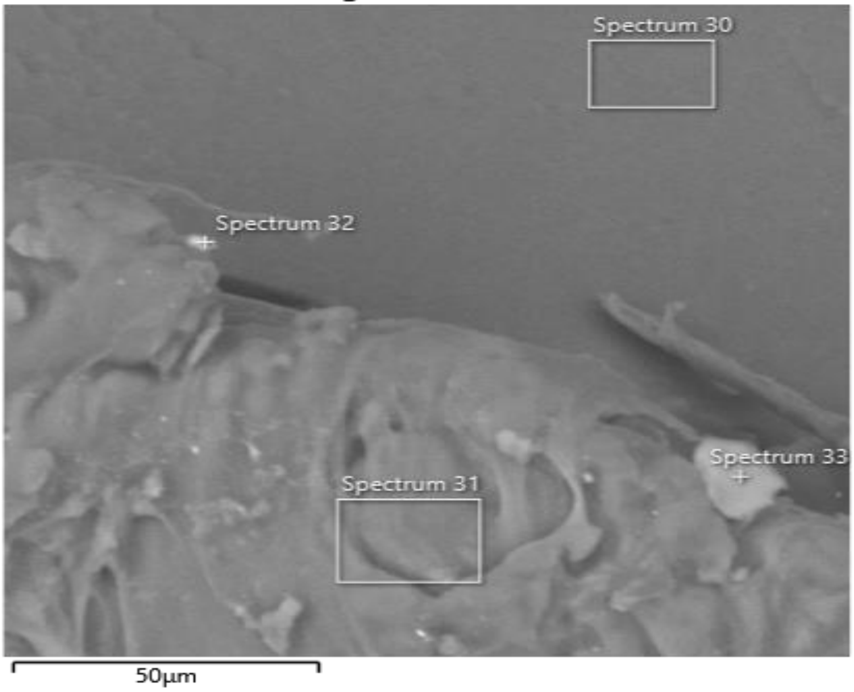


SEM Image of 6 Months in Aggressive Environment

4 H2SO4 - 6 month



4 MgSO4 - 6 month



4 NaCl - 6 month