INVESTIGATION ON THE PROPERTIES OF ACRYLIC EMULSION POLYMER BASED ORDINARY PORTLAND CEMENT CONCRETE REINFORCED WITH HOOKED STEEL FIBER

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DAYANG SITI HAZIMMAH BINTI ALI

Thesis submitted in fulfillment of the requirements for the award of the degree of Doctor of Philosophy of Engineering in Civil (Construction Materials)

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JANUARY 2015

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy of Engineering in Civil (Construction Materials).

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DEDICATION

I wish to dedicate this thesis to my late father, **Ali bin Abang Haji Amin**. He taught me to persevere and prepared me to face challenges with faith and humility. He was a constant source of inspiration to my life. Although he is not here to give me strength and support I always feel his presence that used to urge me to strive to achieve my goals in life. This thesis is also dedicated to all my family members especially my loving husband Mohd Nazri bin Che Hassan, who has supported me all the way since the beginning of my studies. Also, this thesis is dedicated to my children, Danish Nabil, Nisrina Habriyah, Darwisy Naufal and Dhamin Nashshar who have been a great source of motivation and inspiration. They were my own "soul out of my soul," who kept my spirits up when the muses failed me. Without their lifting me up when this thesis seemed interminable, I doubt it should ever have been completed. Finally, this thesis is dedicated to all those who believe in the richness of learning.

ACKNOWLEDGEMENTS

I am heartily thankful to my supervisor, Dr Khairunisa binti Muthusamy, whose encouragement, guidance, and support from the initial to the final level enabled me to develop an understanding of the research. Her sage advice, insightful criticisms, and patient encouragement aided the writing of this thesis in innumerable ways. She has always impressed me with her outstanding professional conduct, her strong conviction for civil engineering, and her belief that a PhD program is only of a life-long learning experience. I would also like to thank Professor Dato' Dr Sabarudin bin Mohd as my ex-supervisor whose steadfast support of this project was greatly needed and deeply appreciated. I also sincerely thank him for the time spent proofreading and correcting my many mistakes. I would like to express the deepest appreciation to Professor Dr. Prakash R. Apte, who has the attitude and the substance of a genius: he continually and convincingly conveyed a spirit of adventure in regard to research. Without his guidance and persistent help this research would not have been possible. Professor Dr. Prakash R. Apte, played a major role in Taguchi Method, both in his initial direction in a seminar as I tried to figure out and showing me places where I had strayed from the straight path and gently leading me back in the proper direction.

I would also like to thank Prof. Engr. Dr. Zularisam bin Abd Wahid, whose steadfast support of this project was greatly needed and deeply appreciated. Also warmest thanks must go to Dean of Faculty of Civil Engineering and Earth Resources, En Fadzil bin Mat Yahaya, whose patience, support, and impeccable understanding allowed me to write this thesis. I would like to thank all vocational training officers who demonstrated me everything that concerning lab facilities. This project would not have been possible without the support from Kolej Poly-Tech MARA by giving me 3 and a half years study leaves with full salary payment that enable this study to be carried out. My sincere thanks go to all my lab mates and members of the staff of Civil Engineering and Earth Resources, UMP, who helped me in many ways and made my stay at UMP pleasant and unforgettable.

I am most especially grateful to my husband, Mohd Nazri bin Che Hassan, for his guidance, support and extraordinary courage. My loving husband also assisted me in my research. I acknowledge my sincere indebtedness and gratitude to my family for their love, dream and sacrifice throughout my life. I am also grateful to my daughter and sons for their sacrifice, patience, and understanding that were inevitable to make this work possible. I would like to thank many friends, relatives, and supporters who have made this happen. Finally, thanks go out to the Universiti Malaysia Pahang Library for providing a clean, quiet, and well-equipped repository to work. Financial support was provided by Graduate Research Scheme, Universiti Malaysia Pahang. I cannot find the appropriate words that could properly describe my appreciation for their devotion, support, and faith in my ability to attain my goals. Lastly, I offer my regards and blessings to all those who supported me in any respect during the completion of the thesis.

ABSTRACT

Polymer modified cement-based materials and fiber reinforced cementitious composites are both widely used in civil engineering applications. Both show great advantages, especially in repair and rehabilitation. The work reported here, however, deals with polymer modified fiber reinforced cement based composites (PM-FRC) that is, combined used of fibers and polymers in the same system. This paper reports the quantitative study of all the three additives each taken with three settings, namely, steel fiber (1.0%, 1.5% and 2.0%), acrylic emulsion polymer (1.0%, 2.5% and 4.0%) and silica fume (5.0%, 6.0% and 8.0%). The other two control variables were chosen as water-cement ratio (0.42, 0.50 and 0.60) and aging (3, 7 and 28 days). In this study, steel fiber reinforced polymer modified concrete (SFRPMC) was produced with the addition of acrylic emulsion polymer (<4%) into steel fiber reinforced concrete which enhance the workability, strength and thermal properties. The unique properties of steel fiber qualify it to be the best option as reinforcement in acrylic polymer cement composite. However, uniform dispersion is the biggest challenge in generating a composite with an optimum performance. Hence, acrylic emulsion polymer and silica fume with different percentages was used to improve the quality of steel fiber reinforced concrete. In this study, we have used a comprehensive approach known as Design of Experimental (DoE) which had been applied efficiently from the material formulation and processing stage until the material characterization. Through verification experiment, the compressive strength had increased by as much as 59% compared to control concrete specimen. To optimize other mechanical properties such as flexural strength, splitting tensile strength and modulus of elasticity, the L9 array method was used. Variant analysis and average analysis were then used to get the optimum formulation and through the X-ray diffraction analysis, the dispersion of acrylic polymer is slightly improved when combined with steel fiber reinforced concrete. From morphology observation, the dispersion of steel fiber with acrylic polymer addition showed a better uniformed dispersion in SFRPMC. Through thermal analysis, optimum specimen was proven to own good thermal stability than the other specimens. Steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC) were produced based on the significant parameters suggested by Taguchi Analysis that was performed earlier. SFRPMC had improved the dispersion of steel fiber and acrylic polymer in matrix composite due to the presence of a few functional groups of elements from different materials, as observed through the morphology examination through SEM-EDX analysis. Synergistic effect between the fibers and the polymer were observed in most of the composites as long as suitable polymer dosages were used. It is concluded that a high performance composites with 2.5% acrylic emulsion polymer, 8% silica fume, 1.5% steel fiber and water-cement ratio 0.50 at 28 days curing could be a promising material for both structural and repair purposes.

ABSTRAK

Bahan simen berasaskan polimer modifikasi dan komposit simen diperkuatkan gentian digunakan secara meluas di dalam aplikasi kejuruteraan awam. Kedua-dua bahan ini mempunyai banyak kelebihan khususnya dalam kerja pembaikan dan rehabilitasi. Walau bagaimanapun, penyelidikan ini adalah mengenai komposit berasaskan simen dimodifikasikan polimer dan diperkuatkan gentian (PM-FRC) iaitu gabungan gentian dan polimer serta simen dalam sistem yang sama. Melalui penyelidikan ini, kajian secara kuantitatif bagi tiga (3) bahan tambahan dengan tiga (3) pembolehubah kawalan telah ditentukan iaitu gentian keluli (1.0%, 1.5% dan 2.0%), polimer akrilik emulsi (1.0%, 2.5% dan 4.0%) dan wasap silika (5.0%, 6.0% dan 8.0%). Dua (2) pembolehubah kawalan yang lain telah dipilih dengan nisbah simen air (0.42, 0.50 dan 0.60) dan tempoh awetan (3, 7 dan 28 hari). Dalam kajian ini, fabrikasi komposit polimer akrilik emulsi diperkuatkan gentian keluli (SFRPMC) ini dihasilkan dengan penambahan polimer akrilik emulsi (< 4%) ke dalam konkrit diperkuatkan gentian keluli yang berupaya meningkatkan sifat kebolehkerjaan, kekuatan dan sifat terma. Sifat gentian keluli yang sangat unik menjadikan ia pilihan terbaik sebagai penguat di dalam matriks konkrit simen dimodifikasi polimer akrilik emulsi. Namun begitu, penyerakan yang seragam merupakan cabaran terbesar dalam menghasilkan komposit berprestasi yang optimum. Justeru itu, polimer akrilik emulsi dan wasap silika dengan peratusan yang berbeza telah digunakan untuk meningkatkan kualiti konkrit diperkuatkan gentian keluli. Dalam kajian ini, pendekatan yang lebih menyeluruh yang dikenali sebagai rekabentuk eksperimen (DoE) telah diaplikasikan secara efisien daripada formulasi bahan dan tahap pemprosesan bahan sehingga pencirian bahan. Menerusi eksperimen penentusahihan, kekuatan mampatan telah meningkat sebanyak 59% berbanding spesimen konkrit kawalan. Untuk mengoptimakan sifat mekanik yang lain seperti kekuatan lenturan, kekuatan tegangan koyak dan modulus kenyal, tatasusunan L9 telah digunakan. Analisis varian dan analisis purata digunakan untuk mendapatkan formulasi optimum dan menerusi analisis pembelauan sinar-X, penyerakan polimer akrilik menunjukkan sedikit peningkatan apabila digabungkan dengan gentian keluli di dalam komposit. Daripada pemerhatian morfologi, penyerakan gentian keluli lebih seragam dengan penambahan polimer akrilik emulsi. Menerusi analisis terma, spesimen optimum mempunyai kestabilan terma yang lebih baik berbanding spesimen yang lain. Komposit konkrit polimer akrilik emulsi modifikasi diperkuatkan gentian keluli dihasilkan berdasarkan parameter yang signifikan yang disarankan melalui analisis Taguchi yang telah dijalankan sebelumnya. SFRPMC yang dihasilkan telah mempertingkatkan penyerakan polimer emulsi akrilik dan gentian keluli kerana kehadiran beberapa kumpulan unsur fungsian daripada bahan yang berlainan, seperti yang diperhatikan daripada pemeriksaan morfologi melalui analisis SEM-EDX. Kesan sinergi di antara polimer dan gentian boleh diperhatikan dalam kebanyakan komposit selagi sukatan polimer yang sesuai digunakan. Kesimpulan boleh dibuat bahawa satu komposit berprestasi tinggi dengan 2.5% polimer akrilik emulsi, 8% wasap silika, 1.5% gentian keluli dan nisbah simen air sebanyak 0.50 pada 28 hari tempoh penuaan merupakan satu bahan komposit yang berpotensi digunakan untuk tujuan struktur dan pembaikan.

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LIST OF SYMBOLS

%	Percentage
Å	Angstrom
Ac	Various acrylics
At%	Atomic %
b	Width
cm	centimetre
d	Depth
dB	Decibel
DF	Degrees of freedom from each source
Eta	S/N ratio
f_b	Bending stress / modulus of rupture
g	gram
GPa	Giga Pascal
K	Kelvin
keV	kiloelectron-volt
kg	kilogram
kN	kilo Newton
kPa	kilo Pascal
L	Length
l/d	Fiber length by its diameter
L27	Orthogonal array 27
L9	Orthogonal array 9
M	Maximum bending moment

min	minute
ml	millilitre
mm	millimetre
MPa	Mega Pascal
MS	Mean squares
MSD	Mean squared deviation
Mstd	Reference/ standard value of the signal strength
N	Newton
Nm	Newton metre
ov	overall
p/c	polymer-cement ratio
ro	Number of samples tested under each signal level
s	second
S/N	Signal to noise
T_{di}	Decomposition Temperature
T_g	Glass Transition Temperature
T_m	Melting Temperature
Vf	Volume fraction of fiber
Vm	Volume fraction of matrix
w/c	water-cement ratio
Wt%	Weight %
δ	Delta
μm	micrometre
°C	degree Celcius

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
AEP	Acrylic Emulsion Polymer
AEPMC	Acrylic Emulsion Polymer Modified Concrete
ANOM	Analysis of Mean
ANOVA	Analysis of Variance
AR	Aspect Ratio
ASTM	American Society for Testing and Materials Standards.
BS	British Standards
DoE	Design of Experiment
DTA	Differential Thermal Analysis
EDX	Energy Dispersive X-ray Analysis (EDAX)
FRC	Fiber Reinforced Concrete
FRP	Fiber-reinforced Plastic or Fiber-reinforced Polymer
FRPMC	Fiber Reinforced Polymer Modified Concrete
FT	Fine Tuning
ITZ	Interfacial Transition Zone
MFT	Minimum Film-forming Temperature
MMA	Methacrylate Monomer
OA	Orthogonal Array
OPC	Ordinary Portland cement
PC	Polymer Concrete
PCC	Polymer Cement Concrete
PIC	Polymer Impregnated Concrete

PMC	Polymer Modified Concrete
PPCC	Polymer-Portland Cement Concrete
QC	Quality Characteristics
RC	Reinforced Concrete
RCC	Roller Compacted Concrete
SBR	Styrene-butadiene-rubber
SEM	Scanning Electron Microscopy
SF	Steel Fiber
SFRC	Steel Fiber Reinforced Concrete
SFRPMC	Steel Fiber Reinforced Polymer Modified Concrete
TGA	Termogravimetric Analysis
UHPC	Ultra High Performance Concrete
XRD	X-ray Diffraction

CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

Developing countries are trying their best to achieve rapid progress in the fields of industry and housing. Progress involves large-scale construction activities. Cement concrete; hitherto has been one of the important materials of construction, in spite of its many drawbacks. The newly developed "Polymer Concrete" possessing many superior properties over conventional cement concrete, renders itself as one of the most versatile construction materials. Polymer concrete in particular, is highly suitable in case of pre-fabricated building industry, irrigation structures, marine structures, nuclear power production and desalination plants (Abdulkader et al., 2005)

Composite polymer which contains fiber as reinforcement is one of the research which gives the results that is encouraging in advanced material field (Ohama et al., 1982). The advantage of this material is its low density, simple processing and the nature that easily changed match. There are many polymers such as thermoset or thermoplastic in the market that can be made into a choice as matrix. Polymer latex is most commonly used in polymer modified concrete (PMC). The concept of polymer latex modified concrete is not new; 1923 saw the first patent involving natural rubber latexes used in paving materials (ACI Committee 548, 1995).

In early 1930's, synthetic latex was suggested in concrete use. But practically applications of PMC only increasingly became widespread in early 1960's. By now, thousands of projects, such as bridge deck construction or repair, and parking garage repairs, have been completed in North America using styrene-butadiene latex. Acrylic

latex and epoxy modifiers have also been developed and have been instrumental in project repair. Many studies and construction experience showed that cement-based composites with suitable polymer latex display good bond to old concrete and to rebar steel, good ductility, lower permeability and resilience features that are better to freeze thaw action, reduce carbonation depth and reasonable chemical resistance. Latex modified concrete also provides higher strength and impact resistance. Apart from that steel fiber usage as reinforcement also increase the flexural and compressive strengths of steel fiber reinforced polymer modified concrete (Ohama et al., 1982).

There are many studies which reported that usage of polymer and fiber reinforcement that are suitable can produce composite polymer with better performance and reduction in production cost and raw material. There are various parameters that changed match in effort to increase fracture toughness of the composite polymer. The parameters studied were filler volume fraction, particle size, filler strength, bonding between filler and resin and resin viscosity. Differences of parameter that had been reported give improvement in various attributes studied such as mechanical and thermal strength (Miyamoto et al., 2002).

Addition of steel fiber was conceded can enhance the fracture toughness of the composites. Steel fibers and synthetic fibers (such as polypropylene, polyethylene, PVA and carbon fibers) are now the most common fiber types. Their performance depends on their elastic modulus, aspect ratio, surface texture, and also on the matrix type and the bonding properties between the fibers and matrix. In recent years, researchers have begun to transfer the benefits of fiber reinforced concrete (FRC) to structural applications, especially for seismic structures (ACI Committee 544, 1997).

Nowadays, due to the high demand on light materials which have good mechanical and thermal properties, the polymer composites reinforced with fiber increasingly developed and carried out actively. Polymer composite gives better improvement in mechanical properties and good thermal compared to common composites. In this research an investigation was done on steel fiber reinforced concrete containing acrylic emulsion polymer (AEP) as one of the mixing ingredient. Some

properties such as mechanical strength, thermal properties and bonding performances through interfacial transition zone (ITZ) were studied for this composite.

1.2 PROBLEM STATEMENT

A full understanding of the combined use of fibers and polymers in one system (PM-FRC) is still not available. Progress in the area of PM-FRC has been fairly slow, partly due to the high material cost which may discourage industrial applications, and due to the lack of experimental data on the new composites; thus, the potential high performance of these materials has been neglected. Now, however, concretes, and particularly high strength concrete, containing polymers and fibers are of growing interest (Xu, 2003).

Polymer cement concretes have high tensile strength, good ductile behavior and high impact resistance capability due to the formation of a three dimensional polymer network through the hardened cementitious matrices (Sakai and Sugita, 1995). Steel fiber reinforced concretes are structural materials that are gaining importance quite rapidly due to the increasing demand of superior structural properties. These composites exhibit attractive tensile and compressive strengths, low drying shrinkage, high toughness and high energy absorption (Li et al., 2007). Unfortunately, fiber balling, due to fiber interlocking and poor dispersion, can also detrimentally affect the hardened properties of concrete, which in turn will reduce the durability of the concrete (Xu, 2003). Polymer modification is one of the methods which can improve both the properties of the fresh concrete and the hardened concrete matrix, thereby enhancing the life span of the structure. Thus polymer modified concrete can be reinforced by short fibers, (or fiber reinforced concrete can be modified with polymers), and a composite with the beneficial effects of both fibers and polymers may be useful for more extensive applications.

On overall, this research proposes to investigate the properties of steel fiber reinforced concrete produced by integrating acrylic emulsion polymer (AEP) as one of the mixing ingredient. An acrylic emulsion polymer is incorporated to improve ductile behavior and flexural strength of steel fiber reinforced concrete (SFRC). Silica fume is

also used to enhance the densification of cementitious matrix. The mechanical properties that is better is discovered by varying the factors namely the acrylic emulsion polymer content, steel fiber content, silica fume content, water-cement ratio and curing time. Although studies about this composites from previous researchers was being conducted widely, the differences of polymer types and synergy between steel fibers and polymer for low strength matrices needs to be investigated including its excellent bonding properties to other materials. Bonding between polymer modified and fiber reinforced concrete and substrate must be studied.

1.3 AIM AND OBJECTIVES

Both polymer modified concrete (PMC) and fiber reinforced concrete (FRC) have many advantages over plain concrete and both have been applied in the field. However, the combination of fibers and polymers has not been investigated extensively. The main objective of this research is to develop very high performance cement-based composites using polymer modification, focusing particularly on high mechanical strength. The target compressive strength of the polymer concrete matrix was in the range of 68- 90 MPa. The related objectives of the present research are as follows:

i) To determine the optimum mix proportion in producing a high strength composite by determining the major parameter in compressive strength of steel fiber reinforced polymer modified concrete (SFRPMC) through experimental design method, namely Taguchi method.

ii) To study the effect of various acrylic emulsion polymers and steel fibers combinations on the workability of fresh concrete and the mechanical properties of hardened concrete, mainly compressive strength, splitting tensile strength, flexural strength and modulus of elasticity of steel fiber reinforced polymer modified concrete (SFRPMC).

iii) To evaluate the roles of crystal structure of SFRPMC in the strength development of SFRPMC systems.

iv) To study the effect of acrylic emulsion polymer and steel fiber on the strength performances of SFRPMC through microstructure observation of specimens.

1.4 SCOPE OF RESEARCH

The scope of research for this project involves the discussion on the effect of polymer on the mechanical strength of concrete. Strength characteristic is important because it is related to several other important properties which are difficult to be measured directly. This study concentrates mainly on the strength and characterization of concrete. With regard to this matter, the improvement of compression strength of polymer concrete was studied.

In this research, 30 different mixes were cast and examined; including one mix of plain concrete, one mix of PMC and one mix SFRC and twenty seven mixes of SFRPMC were preliminary studied for strength performance. The effects of adding of acrylic emulsion polymer by 1.0%, 2.5% and 4.0% by weight of cement in SFRC mix on compressive, tensile and flexural performance of the mix is studied. Concrete tests were conducted on the concrete samples at the specific ages. All the strength tests were limited to the ages of 3, 7 and 28 days.

The current study was also carried out to examine the behavior of steel fiber, the product from Stahlcon which is made from cold drawn high tensile steel wires, in accordance to ASTM A820 type 1 with different percentages by 1.0%, 1.5% and 2.0% (by weight of cement), in high performance concrete when subjected to compressive, tensile and flexural tests. Besides, silica fume meeting the requirement of ASTM C1240 was used in this study to increase the strength of concrete, improve abrasion resistance as well as reduced the permeability of concrete.

With the same percentages of mix proportions in different curing aging of 1 hour, 24 hours and 168 hours, a few of small specimens of SFRPMC with 1 mix of basic concrete were also tested for microstructural performance by using SEM-EDX, XRD and TGA. Through this examination, the bonding performance of acrylic emulsion polymer and strength performance of steel fiber reinforced concrete (SFRC) in SFRPMC were studied.

1.5 SIGNIFICANCE OF RESEARCH

From previous published studies, gaps in research of polymer modification and fiber reinforcement are seen, as explained below:

1. There is no research conducted on the effect of acrylic emulsion polymer (AEP) on the properties of steel fiber reinforced concrete (SFRC). An optimum volume fraction of polymers is needed to design the steel fiber reinforced polymer modified concrete mix. Addition of polymer improves strengths and also workability. Pavements, tunnel linings and bridge deck applications require high workability and it was necessary to determine the volume fraction of polymers to accommodate the mix within specified specification for slump. A comprehensive set of mechanical tests (compression, tensile, flexure, fracture, etc) is required to be conducted to help us better understand the properties of SFRPMC under different condition of stress.

2. Researchers such as Bayasi (1989) did not recommend the use of aggregates in fiber reinforced cement, since they could disturb fiber distribution in the matrix and increase fiber spacing. However, polymer has shown to improve dispersion. Thus, further studies were needed to determine whether there was sufficient fiber distribution to cause significant improvement in mechanical properties in the polymer modified concrete. Abrasion of fibers was also a reason for not incorporating aggregates to the cement fiber matrix. Hence this study would also investigate proper mix methods and mixing times to ensure that fibers are not degraded.

Findings from this research study would contribute towards the advancement of knowledge on the use of acrylic emulsion polymer with cement as matrix reinforced with steel fiber for producing composites possessing enhanced mechanical strength in comparison to Steel Fiber Reinforced Concrete (SFRC) and Polymer Modified Concrete (PMC). Furthermore, outcome of the study would also provide more information on the performance of Steel Fiber Reinforced Polymer Modified Concrete (SFRPMC)

specimens in terms of mechanical properties when subject to different variables of curing age, water-cement ratio, acrylic emulsion polymer, silica fume and steel fiber content.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter introduced literature that contains the main principles underlying the use of concrete, SFRC and PMC. The properties of SFRC-PMC composites are then reviewed, focusing on mechanical properties, as well as the mechanisms of the improvement bond properties for steel fibers and matrices. This review also described the formation mechanisms and the microstructure of interfacial transition zone (ITZ) which is around the aggregate and caused the different microstructure of the surrounding hydrated cement paste. Lastly, this chapter described generally on Taguchi experimental design that had been widely utilized in engineering analysis and consist of a plan of experiments with the objective of acquiring data in control way, in order to obtain the behavior of a given process.

2.2 FIBER REINFORCED CONCRETE (FRC)

According to ACI Committee 544 (1982), fiber reinforced concrete (FRC) is concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibers. It contains short discrete fibers that are uniformly distributed and randomly oriented. Fibers include steel fibers, glass fibers, synthetic fibers and natural fibers – each of which lends varying properties to the concrete. One aspect of serviceability that can be enhanced by the use of fibers is control of cracking. In addition to crack control and serviceability benefits, use of fibers at high volume percentages (5 to 10% or higher with special techniques) can substantially increase the matrix tensile strength (Shah,

1991). Basically, fiber reinforced concrete is concrete containing fibrous materials which can increase its structural integrity.

2.3 STEEL FIBER REINFORCED CONCRETE (SFRC)

Steel fiber reinforced concretes are structural materials which can exhibit attractive tensile and compressive strength, low drying shrinkage, high toughness, high energy absorption and durability due to their tendency of propagating micro-cracks in cementitious matrices to be arrested by fibers (Bentur and Mindess, 2006). Studies show that fiber-matrix interfacial bond is provided by a combination of adhesion, friction and mechanical interlocking (Li et al., 2007). Thus SFRC has superior resistance to cracks and crack propagation and all these results are to impart to the fiber composite pronounced post-cracking ductility which is unheard of in ordinary concrete (Bentur and Mindess, 2006).

2.3.1 Production of Steel Fiber Reinforced Concrete

The mechanistic mix proportioning design method, introduced by the Portland Cement Association in 1977 (Hanna, 1977) was based on three principles:

(a) The addition of steel fibers should be accompanied by the addition of an amount of cement paste sufficient to coat the fibers and to ensure their bond in the concrete mix.

(b) The added fibers and cement paste should be treated as a replacement for an equivalent volume of the plain concrete mix and

(c) Water-cement ratio in both plain and SFRC mixes remain unchanged.

The concept of coupling is used to design mixes having steel fibers. In other words, normal concrete mix proportioning criteria's can be used for the designing of trial mix; then the workability can be adjusted when adding steel fibers. Generally, SFRC mixes contain higher cement contents and higher ratios of fine to coarse aggregate than do ordinary concretes, and so the mix design procedures the apply to

conventional concrete may not be entirely applicable to SFRC. Commonly, to reduce the quantity of cement, up to 35% of the cement may be replaced with fly ash (Bentur and Mindess, 2006). In addition, to improve the workability of higher fiber volume mixes, water reducing admixtures and in particular, super plasticizers are often used, in conjunction with air entrainment.

The main objective in designing a structural fiber concrete mix is to produce adequate workability, ease of placing and efficient use of fibers as crack arrestors, besides the other objectives desired in any normal concrete (Li et al., 2010). Preliminary trial mixes indicated that the addition of steel fibers to a properly designed concrete mix reduced the slump. To maintain the level of workability and to ensure adequate bond of fibers to the concrete matrix, it was concluded that the addition of steel fiber to the concrete mix should be accompanied by the addition of cement paste. The amount of added cement paste depends on three principal factors as follows (Hanna, 1977):

- Amount of fibers
- Shape and surface characteristics of the fibers
- Flow characteristics of the cement paste

SFRC delivered to projects should conform to the applicable provisions of ASTM C1116 (2004). It is recommended that the method of introducing the steel fibers into the mixture be proven in the field during a trial mix. Steel fibers should be dispersed with care to avoid clumping and non-homogeneity. The possible non-problematic sequences were given by the ACI Committee 544 (1982) and its procedure is summarized in the diagram in Figure 2.1.

The ACI Committee 544 (1993) has given following guidelines to serve purpose of SFRC mix design:

- Coarse aggregates should be limited to 55% of total aggregate.
- W/c should be kept below 0.55 (0.35 is recommended).
- Minimum cement content of 320 kg/m^3 should be used.
- Reasonable sand content of 750 – 850 kg/m^3 is recommended.

- The workability could be improved by increasing the cement paste, which is possible by addition of slag or fly ash to replace the cement.
- Maximum aggregate size is to be 9 mm.

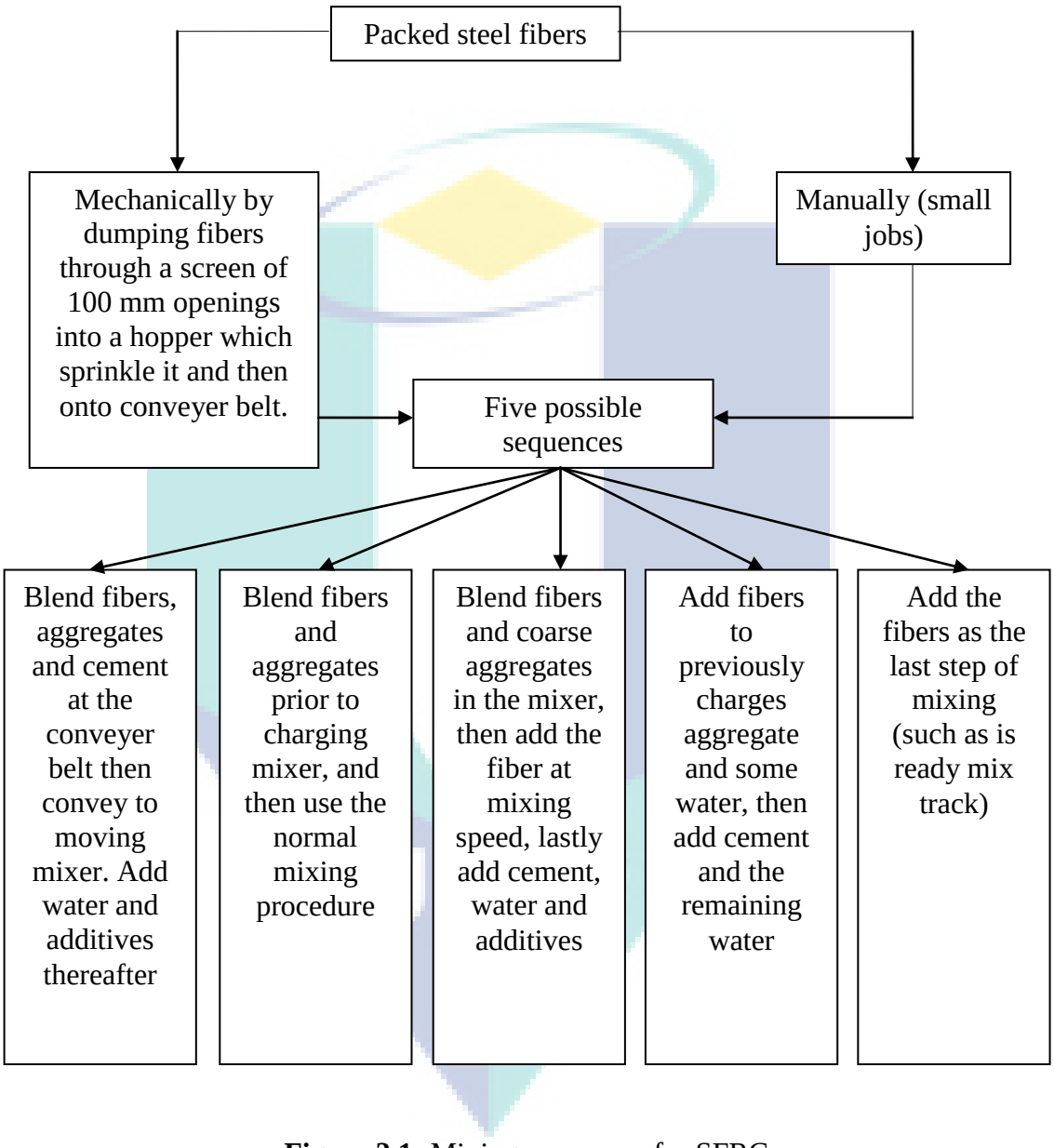


Figure 2.1: Mixing sequences for SFRC

Source: ACI Committee 544 (1982)

2.3.2 Types of Steel Fibers Used in SFRC

There are a number of different types of steel fibers with different commercial names. Basically, steel fibers can be categorized into four groups depending on the manufacturing processes such as cut wire (cold drawn), slit sheet, melt extract and mill cut. It can also be classified according to its shape and/ or section (JSCE, 1983). Figure 2.2 shows the various types of steel fiber geometries.

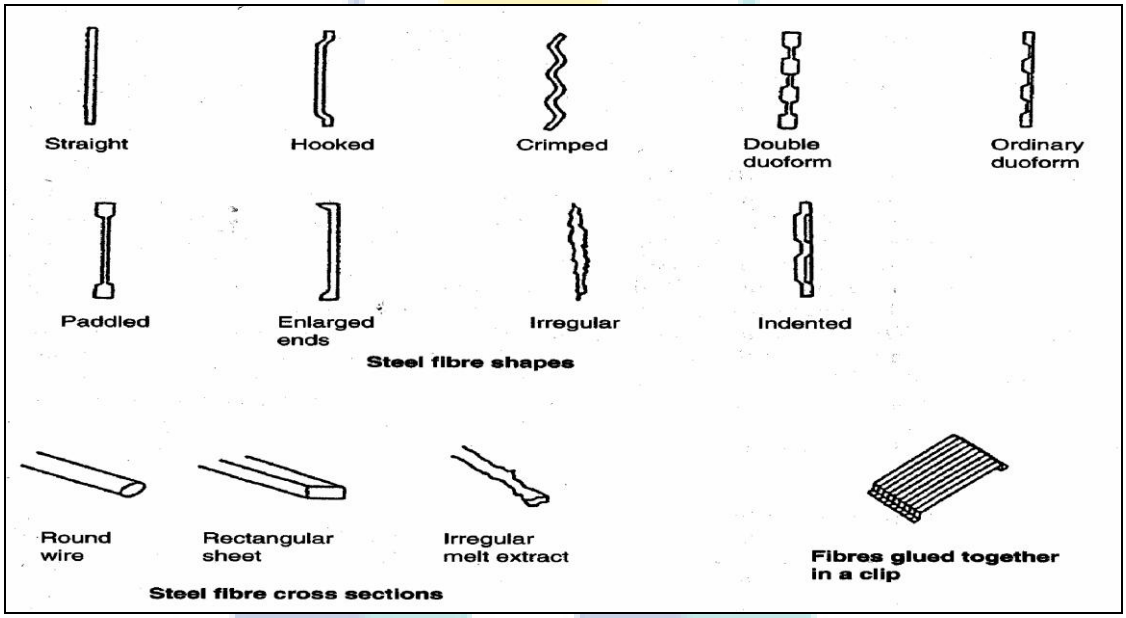


Figure 2.2: Various steel fiber geometries

Source: Knapton (2003)

2.4 PROPERTIES OF STEEL FIBER REINFORCED CONCRETE

The fiber strength, stiffness and the fibers capacity to bond with the concrete are important fiber reinforcement properties. Bond depends on the aspect ratio of the fiber. Steel fibers have a relatively high strength and modulus of elasticity, protected from corrosion by the alkaline environment of the cementitious matrix, and their bond to the matrix can be improved by mechanical anchorage or surface roughness. Various grades of stainless steel, available in fiber form, respond somewhat differently to exposure to elevated temperature and potentially corrosive environments (Lankard and Sheets,

1971). ASTM A820 (1998) establishes minimum tensile strength and bending requirements for steel fibers as well as tolerances for length, diameter (or equivalent diameter), and aspect ratio. The minimum tensile yield strength required by ASTM A820 is 345 MPa, while the JSCE Specification (1983) requirement is 552 MPa.

2.4.1 Properties of Freshly-Mixed SFRC

The properties of SFRC in its freshly mixed state are influenced by the aspect ratio of the fiber, fiber geometry, its volume fraction, the matrix proportions, and the fiber-matrix interfacial bond characteristics (Paul et al., 1981). For conventionally placed SFRC applications, adequate workability should be insured to allow placement, consolidation, and finishing with a minimum effort, while providing fiber distribution that is uniformed with minimum segregation and bleeding. For a given mixture, the degree of consolidation influences the strength and other hardened material properties, as carried out in plain concrete.

Studies have established that a mixture with a relatively low slump can have consolidation properties under vibration (Morgan et al., 1984). Slump loss characteristics with time for SFRC and non-fibrous concrete are similar (Schneider et al., 1984). On the other hand, short fibers, with an aspect ratio less than 50 are not able to interlock and can be easily dispersed by vibration (Hannant, 1978). However, aspect ratio of steel fiber greater than 100 is not recommended, as it will cause inadequate workability, formation of mat in the mix and also non uniform distribution of fiber in the mix. As stated in ACI 544 (2008), fiber volume fraction used in producing steel fiber reinforced concrete should be within 0.5% to 1.5% as the addition of fiber may reduce the workability of the mix and will cause balling or mat which will be extremely difficult to separate by vibration.

2.4.2 Mechanical Properties of Hardened SFRC

Steel fibers improve the ductility of concrete under all modes of loading. This material is also effective in improving the compression, tension, shear, torsion, and flexure strength of concrete. Improvement in ductility depends on type and volume

percentage of fiber used in concrete mix (Johnston and Coleman, 1974 and Johnston, 1982). Fibers with enhanced resistance to pull out are fabricated with a crimped or wavy profile, surface deformations, or improved end anchorage provided by hooking, teeing or end enlargement. These types are more effective than equivalent straight uniform fibers of the same length and diameter. Consequently, the amount of these fibers required achieving level of improvement in strength and ductility is usually less than the amount of equivalent straight uniform fibers (Brandshaug et al., 1978; Balaguru and Ramachandran, 1986 and Johnston and Gray, 1986).

However higher percentage of fiber can be used with special fiber adding techniques and also placement procedures. According to ACI 544 (2002), aspect ratio is referred to the ratio of fiber length over the diameter. The normal range of aspect ratio for steel fiber is from 20 to 100. To avoid any honeycombing, bleeding, segregation and heterogeneous features by improving the workability, less water and paste is used. Rui et al. (2005) varied the percentage of volume of fiber in the concrete up to 1.5%. Their results indicate that the addition of fibers to concrete enhances its toughness and strength and peak stress, but can slightly reduce young's modulus.

2.4.2.1 Compressive Strength

Fibers enhance the static compressive strength of concrete, with increase in strength ranging from essentially nil to 25%. Even in members that contain conventional reinforcement in addition to the steel fibers, the fibers have little effect on compressive strength. However, the fibers substantially increased the post-cracking ductility, or energy absorption of the material (Bentur and Mindess, 2006). Influence of steel fibers on compressive strength can be observed in Figure 2.3. In an experimental work conducted in India, for the range of fiber content ranges between 0% and 3% by volume, the compressive strength was increased insignificantly which is about 40% increase when using 3% fiber content (Elsaigh and Kearsley, 2002).

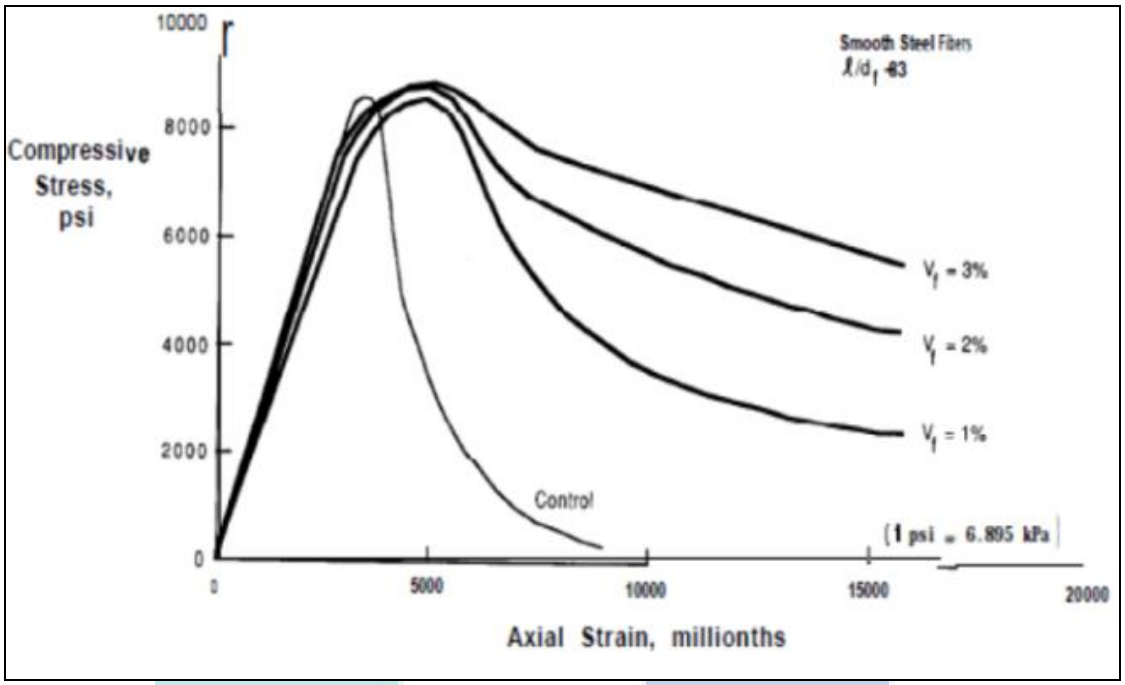


Figure 2.3: Influence of amount steel fibers on compressive stress behaviour

Source: Fatih et al. (2005)

A test in Australia, (Fibresteel, 1981) showed that, the addition of steel fiber to concrete matrix may produce marginal gains in compressive strength at constant water-cement ratio. At steel fiber concentrations of (50 to 90 kg/m^3), the increase in compressive strength is not usually statistically discernible. In South Africa, the tests revealed that the addition of steel fibers with various contents may increase the compressive strength slightly (approximately 10%) and the highest occurred at low steel fiber contents (up to 20 kg/m^3). An excessive increase of fiber content will not affect the compressive strength as prior to that limit. On top of that, the addition of steel fibers is not a cost effective way of improving the compressive strength of concrete (Burgess, 1992).

2.4.2.2 Splitting Tensile Strength

In direct tension, the improvement in strength is significant, with increases of the order of 30% to 40% reported for the addition of 1.5% by volume fibers in mortar or

concrete (Williamson, 1974 and Johnston and Gray, 1978). Fibers aligned in the direction of the tensile stress may bring about very large increases in direct tensile strength. However, for more or less randomly distributed fibers, the increase in strength is much smaller, ranging from as little as no increase in some instances to perhaps 60%. Splitting-tension test of SFRC showed similar result. Thus, adding fibers merely to increase the direct tensile strength is probably not worthwhile.

2.4.2.3 Flexural Strength

Flexural strength is the stress capacity determined through a third-point loading test, which strive to find the stress at maximum load that can be sustained by a prismatic beam. The increase in flexural strength is particularly sensitive, not only to the fiber volume, but also to the aspect ratio of the fibers, with higher aspect ratio leading to larger strength increases (Johnston, 2001). Main factors influencing the flexural strength of SFRC (Snyder and Lankard, 1972) are:

i) Degree of consolidation of the matrix, which is a function of water to cement ratio, consolidation technique, and type and content of the steel fiber.
ii) Uniformity of fiber distribution, which is mainly influenced by the workability and mixing procedure used.
iii) The surface conditions of the steel fibers, which relates to the bond stresses generated between steel fibers and the concrete, for instance a hydrophobic film on the steel fiber surface can prevent the development of an adequate fiber bond.

2.4.2.4 Modulus of Elasticity

The inclusion of steel fibers in concrete influences the modulus of elasticity. Uniaxial tensile stress-strain measurements on (100x100x500 mm) plain and fiber reinforced specimens showed an increase of 7.5% for the specimens having a dosage of 2.7% by volume of straight steel fibers (Edgington et al., 1974). Similar results were gained from a third-point test carried out on beam specimens, where it was found that

the calculated modulus of elasticity increased very little relative to plain concrete (Fibresteel, 1981). Other studies also showed that 0.76% weight of hook-ended and crimped steel fiber has a positive effect with increase in E-value ranging between 0% and 2.8% (Armelin and Helene, 1995).

2.5 MECHANISM OF STEEL FIBER REINFORCED CONCRETE

The composite will carry increasing loads after the first cracking of the matrix if the pull-out resistance of the fibers at the first crack is greater than the load at first cracking. At the cracked section, the matrix does not resist any tension and the fibers carry the entire load taken by the composite. With an increasing load on the composite, the fibers will tend to transfer the additional stress to the matrix through bond stresses. This process of multiple cracking will continue until either fibers fail or the accumulated local debonding will lead to fiber pull out. The pull out mechanism of SFRC can be seen in Figure 2.4 (Bayasi and Gebman, 2002).

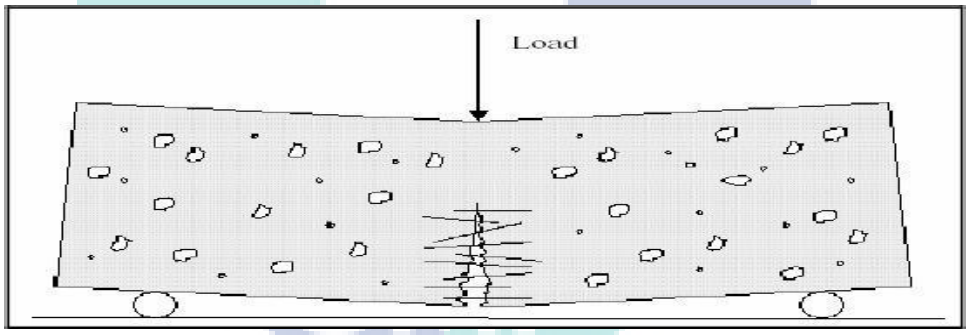


Figure 2.4: Pull out mechanism of fiber reinforced concrete

Source: Bayasi and Gebman (2002)

Pullout resistance of fibers (dowel action) is important for efficiency. Pullout strength of fibers significantly improves the post-cracking tensile strength of concrete. As an FRC beam or other structural element is loaded, fibers bridge the cracks. Such bridging action provides the FRC specimen with greater ultimate tensile strength and, more importantly, larger toughness and better energy absorption (Jyoti et al., 2013). The randomly-oriented steel fibers assist in controlling the propagation of micro-cracks

present in the matrix, first by improving the overall cracking resistance of matrix itself, and later by bridging across even smaller cracks formed after the application of load on the member, thereby preventing their widening into major cracks (Figure 2.5) (Mehta and Monteiro, 2011).

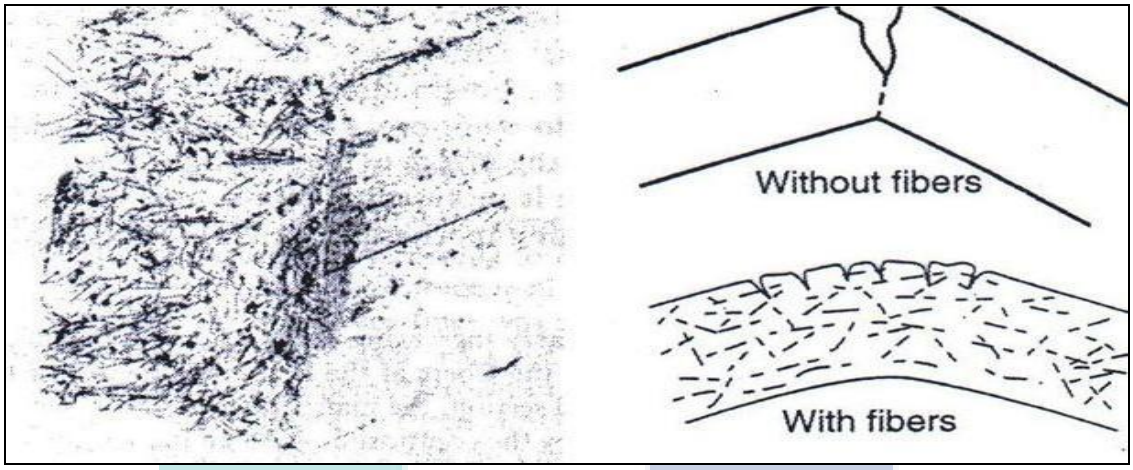


Figure 2.5: Failure mechanism and the effect of fibers

Source: Mehta and Monteiro (2011)

2.5.1 Spacing Mechanism

When a fiber-reinforced specimen is subjected to a tensile load, the tensile stresses are transmitted from the matrix to the fibers and the fibers undergo tension. Depending on the strength of the bond between the fiber and the matrix, the bond may or may not fail under a given load. It is possible that the following happens before cracking of the matrix (Banthia, 2012):

1. The load is so low (or the chemical adhesion is so strong) that the adhesive bond does not break, and there is no relative displacement between the fiber and the matrix.
2. The load breaks the chemical adhesion between the matrix and the fiber; however the bond strength of the fiber is not attained, so that a condition of elastic bond prevails along the interface.

2.5.2 Bridging Mechanism

Bond remains a very important factor in determining the properties of a composite even in its post-cracking stage, but its function changes. The change is most significant in the case of discontinuous fibers (Banthia, 2012). In the pre-cracking stage, when the elastic shear bond was intact, the maximum shear flow occurred at the ends of the fibers. The stresses were transferred from the matrix to the fibers. In the post-cracking stage, the fibers bridging a crack are pulled out and the interfacial shear stress changes; the maximum stress now occurs at the point where the fibers enter the matrix for example at the crack. If the frictional shear bond is perfectly plastic before the start of the cracking, it is likely to stay this way in the post cracking stage. Multiple cracking of matrix occurs as indicated in Figure 2.6 (Bayasi and Gebman, 2002).

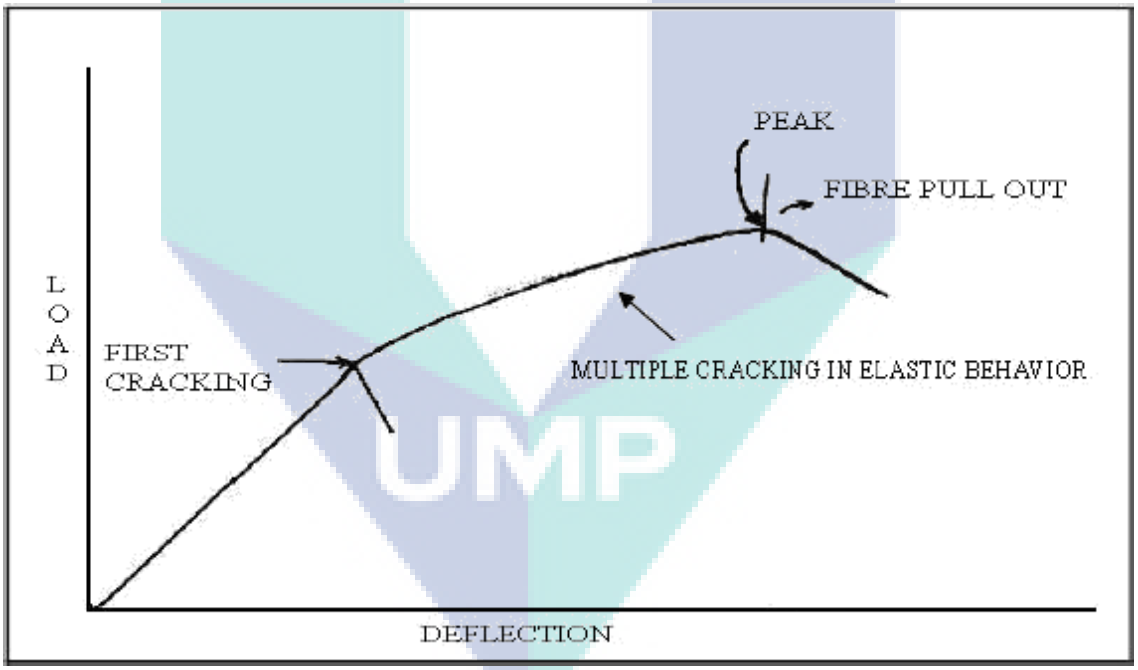


Figure 2.6: Fiber reinforced concrete mechanism

Source: Bayasi and Gebman (2002)

2.6 APPLICATION OF STEEL FIBER REINFORCED CONCRETE

Steel Fiber Reinforced Concrete or shotcrete have been used in various applications throughout the world. The principal advantages of SFRC versus plain or mesh/bar reinforced concretes are; cost savings of 10% - 30% over conventional concrete flooring systems and reinforcement throughout the section in all directions versus one plane of reinforcement (sometimes in the sub-grade) in only two directions (Nataraja et al., 1999). Besides, SFRC improved ultimate flexural strength of the concrete composite. The ability to absorb energy, impact resistance and thus reduced chipping and joint spalling are also the benefits of using SFRC. The most important benefits of SFRC are that they increased shear strength that makes it able to transfer loads across joints in thin sections; and increased tensile strength and tensile strain capacity that allowing increased contraction/construction joint spacing. The six major areas in which steel fibers can be used to achieve hi-strength, durable and economical concrete are overlays, pre-cast concrete products, hydraulic and marine structures, defence and military structures, shotcreting applications and special structures (ACI Committee 544, 2005).

2.7 POLYMER IN CONCRETE

The introduction of polymers into cementitious material in order to improve the bond adhesion, flexibility, and workability of resultant composite first occurred in the 1930s where naturally rubber was utilized. Polymers are now commonly used in conjunction with concrete or cement based material to produce a variety of polymer-modified cementitious products. The resulting physical and chemical properties of the final product are dependent upon the nature of the polymer material and the actual quantity used in relation to the cement phase (Miller, 2005). An improvement in the workability and bond adhesion was seen along with an increase in durability and water resistance hence the addition of polymer into the cementitious system enabled its use in more complex structure and situations (Miller, 2005).

Polymer in concrete is part of group of concretes that use polymers to supplement or replace cement as a binder. The types include polymer-impregnated

concrete (PIC), polymer concrete (PC), and polymer-Portland-cement concrete (PCC or PMC). The general concept of concrete-polymer materials, from technical point of view, involves a process by which chemicals (monomers, oligomers, prepolymers polymers) introduced into a concrete mix are subjected to polymerization and polycondensation by thermo-catalytic or other systems (Czarnecki, 2001). Thus, concrete-polymer materials can be considered as hybrid composites of concrete using polymers.

Polymer impregnated concrete (PIC) is produced by infusing a monomer into the cracks and voids of already hardened concrete. The monomers are polymerized after they enter the voids by the action of a chemical hardener or the application of heat. Polymer concrete (PC) is a material made of aggregate and a polymer binder. There is no Portland cement in polymer concrete. The polymer matrix binds very well to the aggregate particles with no transition zone, unlike polymer cement concrete (Rebeiz et al., 1994). Polymer modified concrete (PMC) or polymer Portland cement (PCC) is normal Portland cement concrete with a polymer admixture. The polymer and the cement hydration products create two interpenetrating matrices, which work together, resulting in an improvement in the material properties of PCC alone (Chandra and Ohama, 1994).

2.8 POLYMER MODIFED CONCRETE (PMC)

Polymer modified cementitious mixtures (PMC) have been called by various names such as polymer Portland cement concrete (PPCC) and latex modified concrete (LMC) (ACI Committee 548, 2003). Polymer modified cementitious mixtures includes polymer modified cementitious slurry, mortar and concrete. The improvement from adding polymer modifier to concrete include increased bond strength, freezing and thawing resistance, abrasion resistance, flexural and tensile strength and reduced permeability and elastic modulus (ACI Committee 548, 2003). A reduced elastic modulus will result in reducing the stresses developed due to differential shrinkage and thermal strain that would reduce the tendency of the material to crack. PMC can also have increased resistance to penetration by water and dissolve salts and reduced need

for sustained moist curing. The improvements are measurably reduced when PMC is tested in the wet state (Popovics, 1987).

2.9 PRODUCTION OF POLYMER MODIFIED CONCRETE

According to ASTM C1438 (2013), whenever preparing a polymer modified cement mix, the amount of polymer modifier either 0.15 gram or polymer solids per 1 gram of cement or as otherwise specified is added. The water portion of the polymer modifier added to the mix shall be included in the calculation of the water-cement ratio. For mixing mortar, following ASTM C1438, the entire polymer modifier is mixed with water in the bowl. The cement is added to the polymer modifier and water, and then starts the mixer and mix at the slow speed (140±5revolution/min) for 3 second. Lastly, the entire quantity of sand is added slowly over a 30-s period, while mixing at slow speed.

For mixing concrete, following ASTM C192 (2006), prior to starting rotation of the coarse aggregate, polymer modifier, and approximately half of the water is added into the mixer. The mixer is turned in a few revolutions and the fine aggregate, cement and remaining water is then added. The concrete is mixed for 3 minutes, followed by a 1 minute rest, and 1 minute final mixing. The mixer is then covered during the rest period to prevent evaporation. Precautions have to be taken to compensate for mortar retained by the mixer so that the discharged batch, as used, will be correctly proportioned.

For curing process, all specimens made of polymer modified mortar and concrete shall be covered immediately with polyethylene film and cured at 23 ± 2^{o}C for 24 ± 1 hours. The polyethyelene cover is then removed and the specimens cured at 23 ± 2^{o}C and 50 ± 10 R.H., until time of test. Non-polymer control specimens shall be cured according to ASTM C109 (2012) or C192, as appropriate.

2.9.1 Materials of Polymer Modified Concrete

By introducing polymer materials into concrete and cement-based compounds, the physical characteristics of the cementitious systems are modified. Riley and Razl (1974) stated that the mixing polymer emulsion such as SBR and acrylics with cementitious materials reduced the risk of cracking in the hardened structure due to ambient temperature. During their research, the workability and bond adhesion were improved that seen along with an increase in flexural and tensile strengths as compared to plain concrete. Polymer modified cementitious also showed an increase in durability and water resistance. In the addition of polymer into the cementitious system, it enabled its use in more complex structures and situations.

Table 2.1 is a listing of the various polymers that have been used with hydraulic cements. The major polymers used for modification of cementitious mixtures are acrylic polymers and copolymers (PAE), styrene-acrylic copolymers (S-A), styrene-butadiene copolymers (S-B), vinyl acetate copolymers (VAC), and vinyl acetate homopolymers (PVA).

Table 2.1: Polymers used to modify hydraulic cementitious mixtures

Elastomeric	Natural rubber latex	
	Synthetic latexes	Styrene-butadiene, polychloroprene (neoprene), acrylonitrile-butadiene
Thermoplastic	Polyacrylic ester, styrene-acrylic, polyvinyl acetate, vinyl acetate copolymers, polyvinyl propionate, vinylidene chloride copolymers, polypropylene	
Thermosetting	Epoxy resin	
Bituminous	Asphalt, rubberized asphalt, coal-tar, paraffin	
Mixed latexes		

Source: ACI Committee 548 (2003)

2.9.1.1 Styrene –Butadiene Latex (SBR)

Styrene-Butadiene Latex (SBR) has been widely used for floor and bridge overlays, although the minimum thickness is usually about 30 mm. The advantages are excellent bond strength to concrete, higher flexural strength, and lower permeability (Fowler, 1999). The inclusion of styrene-butadiene latex in Portland cement mortar and concrete results in less water required for a given consistency. Component in the latex function as dispersants for Portland cement and, thus increase flow and workability of the mixture without additional water (ACI Committee 548, 2003). Although a versatile and useful material, SBR will form a skin or crust on the surface if exposed to dry air for prolonged periods and only suitable for low to moderate chemical exposure.

2.9.1.2 Acrylic Polymers

An acrylate polymer belongs to a group of polymers which could be generally referred to as plastics. They are noted for their transparency and resistance to breakage and elasticity and also commonly known as acrylics or polyacrylates. Typical acrylate monomers used to form acrylate polymers are: acrylic acid, methyl methacrylate and acrylonitrile (Asua, 2007). Acrylic polymers are thermoplastic in nature hence their flexibility increases when exposed to heat (Daintith, 1990 and Shaw et al., 1994). They do not show any deterioration when exposed in UV radiation. The stability of this polymer to oxidation and discoloring makes its use in external coatings favorable (Walters, 1997). This is a plastic, which has no natural colour and exhibits a good resistance to weathering and impact when compared other polymers such as polystyrene (Daintith, 1990). Acrylic polymers are typically manufactured by the reaction of an acrylic ester monomer for example methyl acrylates and ethyl acrylates, with itself or another monomer species such as styrene, butadiene, and acrylonitrile by free radical polymerization. Free radical polymerization of MMA results in the formation of polymethyl methacrylate (Ebewele, 2000).

Acrylic polymers are commonly used to modify cement based-systems which will be exposed to a variable environment along with a high degree of moisture (O'Brien et al., 1984 and Walters, 1997). Unlike PVA homo-polymers, acrylics do not

undergo further hydrolysis upon contact with water (Shaw et al., 1994). Acrylic polymer has been used in polymer cement concrete and these polymers are utilized in flooring compounds and mortars where the highest level of physical performance of the modified compound is required (Nelson, 1997). Acrylic monomers have also been combined with aggregates to produce a resin-bound concrete suitable for use as repair mortar as an overlay for bridge decks (Kirhikovali, 1981; O'Brien et al., 1984; Ellis, 1989 and Miller, 2005).

Acrylic emulsions (or acrylic lattices) are characterized as high-solids polymers having a film-forming temperature at or below room temperature (Lavelle, 1986). From the previous research stated above, acrylic polymers have excellent hydrolysis resistance compared with other resins and are well suited as modifiers for Portland cement mortars. However, acrylic polymer has not yet been investigated in the production of steel fiber reinforced concrete (SFRC). Hence, the mechanical properties of SFRC containing acrylic polymer is also remain unknown.

2.9.2 Mix Design

The materials used in polymer modified mortars and concrete are the same as those employed in ordinary Portland cement mortar and concrete.

2.9.2.1 Cements

Ordinary Portland cement is widely used for polymer-modified mortar and concrete. Other Portland cement such as high-early-strength Portland cement, ultra high-early strength Portland cement, sulphate resisting Portland cement, moderate heat Portland cement and white Portland cement, blend cement and super high-early-strength cement can also be employed. Air-entraining cement should not be used because of air-entrainment due to polymer addition (Kaushal, 1991).

2.9.2.2 Polymer Latexes

In particular, the commercial latexes widely used in the world are styrene-butadiene rubber (SBR). It is estimated that over 9000 bridge decks alone in USA are protected with SBR Latex system, polychloroprene rubber (CR), polyacrylic ester (PAE), Poly (ethylene-vinyl accetate) (EVA) and poly (vinylidene chloride-vinyl chloride) (PVDC) copolymers. Most commercial polymer latexes for cement modifiers contain proper antifoaming agents, and can be generally used without addition of the antifoaming agents during mixing.

2.9.2.3 Aggregate

Fine and coarse aggregates such as river sand and gravel, crushed sand and stone, silica sands and artificial lightweight aggregate recommended for ordinary cement mortar and concrete, are used for polymer modified mortar and concrete. For the purpose of corrosion resistance silica sand and siliceous crushed stones may also be used. The use of aggregates with excessive water content should be avoided because the required polymer-cement ratio will not be achieved.

2.9.2.4 Mix Proportioning

The mix proportions of most polymer modified mortars are in the range of the cement; fine aggregate ratio = 1:2 to 1:3 (by weight), the polymer-cement ratio 5% to 20% and the water-cement ratio of 30% to 60%, depending on their required workability. The mix proportions of most polymer modified concretes cannot be easily determined in the same manner as those of polymer modified mortars, because of many factors are to be considered in the mix design. Generally, polymer modified concrete have polymer cement ratio ranges from 5% to 15%, and water-cement ratio ranges from 30% to 50%. The mix design is described by Ohama (1981) in Table 2.2 and 2.3.

Table 2.2: Types of materials used in polymer modified concrete

Types of cement	**OP cements 53 Grade as per I.S: 12269-1987.**
Types of aggregates	River sand of Zone II & III as per IS: 383-1970. It should not contain particles coarser than 2.5 mm.
River gravel	5-20 mm and 5-10 mm for example 20 and 10 mm graded uncrushed aggregate as per IS: 383-1970. (both the above aggregates saturated and surface dry)
Polymer latexes	Commercial polymer latexes, irrespective polymer types (containing antifoamers)

Source: Ohama (1981)

Table 2.3: Range of proportions in practical use

Unit cement content	From 250 to 400 kg/m^3 for 20 mm maximum size of aggregate
Polymer-cement ratio	From 0.05 to 0.20 (5 to 20% by wt. of polymer with respect to cement)
Water-cement ratio	From 0.30 to 0.50 (30 to 50% by wt. of water with respect to cement)
Slump	50 mm to 200 mm
Compressive strength	From 200 to 600 kg/cm^2
Air (by Volume)	2% in 20 mm maximum size aggregate 3% in 10 mm maximum size aggregate

Source: Ohama (1981)

2.10 PROPERTIES OF POLYMER MODIFIED CONCRETE

It is characteristic of polymer modified concrete which is produced by mixing polymer-based admixture with cement concrete, to possess co-matrix phases. The properties of the polymer modified concrete is characterized by such co-matrix phases, and markedly improved over conventional cement concrete. The properties of the fresh and hardened concrete are affected by a multiplicity of factors such as polymer type, polymer-cement ratio, water-cement ratio, air content and curing conditions.

2.10.1 Properties of Fresh Polymer Modified Concrete

Generally, polymer modified concrete provide an improved workability over conventional cement concrete. This is mainly interpreted in terms of improved consistency due to "ball bearing" action of polymer particles, the entrained air and the dispersing effect of surfactants in the polymers. The water-cement ratio of polymer modified concrete at a given consistency (flow or slump) is reduced with an increase in polymer-cement ratio (Chandra and Ohama, 1994; Ramakrishnan, 1994 and Su, 1995). This water reduction effect is found to contribute to a strength development and drying shrinkage reduction.

In most polymer modified concrete, a large quantity of air entrained is used compared with an ordinary cement concrete because of the action of surfactants contained as emulsifiers and stabilizers in the polymer modified. Some air entrainment is useful to obtained improved workability. An excessive amount of entrained air caused a reduction in strength and is controlled by using proper antifoaming agents. Therefore, antifoaming or air reducing compounds are often added to PMC in order to limit air entrainment to a maximum of 6.5% (Ramakrishnan, 1994 and Su, 1995).

According to Ramakrishnan (1994), hydration is somewhat slowed by polymer modification because of the dispersing effect of the polymers and because of the absorption of surfactants on the developing cement matrix. A sufficient amount of water required for cement hydration is held in the concrete and for most polymer modified concrete, dry cure is preferable to wet or water cure. The excellent water retention of the polymer modified concrete contributes to an increase in the long term strength in dry curing (Chandra and Ohama, 1994). Hence, the transition zone in PMC is refined due to the coating of the developing hydration products with the polymer, which affects ettringite and large CH crystal growth, and also due to coalescing of the polymer film in the transition zone voids (Su, 1995). Moreover, in contrast to ordinary cement concrete, which cause bleeding and segregation, the resistance of polymer modified concrete to bleeding and segregation is excellent, despite of their improved flowability. This contributes to higher strength and lower permeability of the concrete (Ramakrishnan, 1994).

2.10.2 Properties of Hardened Polymer Modified Concrete

Generally, polymer modified concrete shows a noticeable increase in tensile or flexural strength but no improvement in compressive strength compared with ordinary cement concrete (Ohama, 1998). This is interpreted in terms of the contribution of high tensile strength by the polymer themselves and an overall improvement in cement hydrate-aggregate bond. The main factors that influence the strength properties of polymer modified concrete are nature of materials, cements and aggregates, controlling factors for mix proportions for example polymer-cement ratio, water-cement ratio, binder-void ratio, air content, curing methods and testing methods (Ohama, 1998).

2.10.2.1 Mechanical Properties of PMC

Polymer modified concrete (PMC) exhibits superior bonding to all concrete which is very attractive for concrete repairs (Ohama, 1992). Another advantage of PMC, compared to the unmodified concrete is its enhanced mechanical properties. Though the compressive may be decreased, the flexural strength and toughness are generally higher for concretes of the same consistency (Ohama, 1981). The modulus of elasticity may be lower than that of plain concrete because of the addition of the much softer polymer phase. For normal concrete, the decrease in modulus of elasticity (E) is generally less than 15% (Ohama, 1992).

2.10.2.2 Durability Properties

Much research has shown that the durability of PMC is greatly improved, due to its lower permeability; therefore PMC is especially suitable for severe conditions (Hashimoto and Ohama, 1987). The result of all these developments is that Dow styrene butadiene latex modified concrete has become a standard material of construction in the United States and Canada, and one that has an extensive history of high performance on bridge decks (Kuhlmann, 1981). It is used not only for repair, but also to protect decks in new construction. The primary properties of latex modified concrete such as bond, impermeability, and freeze/thaw durability, as well as its compatibility with conventional concrete, make it an ideal material to repair old concrete and protect new

research and field evaluations continue to be conducted on this material by highway departments as well as Dow (Kuhlman and Foor, 1985).

2.10.2.3 Other Properties

The drying shrinkage of polymer modified concrete is lower than that of conventional concrete, though this depends on the polymer type, polymer-cement ratio, and water-cement ratio, cement content and curing conditions. However, the creep of PMC is highly temperature sensitive; it may be much more than that of ordinary concrete. Meanwhile, other mechanical properties such as flexural strength and elastic modulus decrease with the increase of temperature. This temperature dependence is due to the nature of polymer such as Tg (transition temperature) and Tm (melting point).

2.11 MECHANISM OF POLYMER MODIFIED CONCRETE

For fresh polymer modified concrete, two processes govern the effects of polymer on cement mortar and concrete, i.e., cement hydration and polymer coalescence. Generally, cement hydration occurs first, and as the cement particles hydrate and the mixture sets and hardens, the polymer particles become concentrated in void spaces. With continuous water removal due to cement hydration, evaporation, or both, the polymer particles coalesce into a polymer that is interwoven in the hydrated cement, giving a co-matrix that coats the aggregate particles and lines the interstitial voids (Ohama, 1995). The hydration and co-matrix formation mechanism of cement with polymers is shown in Figure 2.7 (Ohama, 1995).

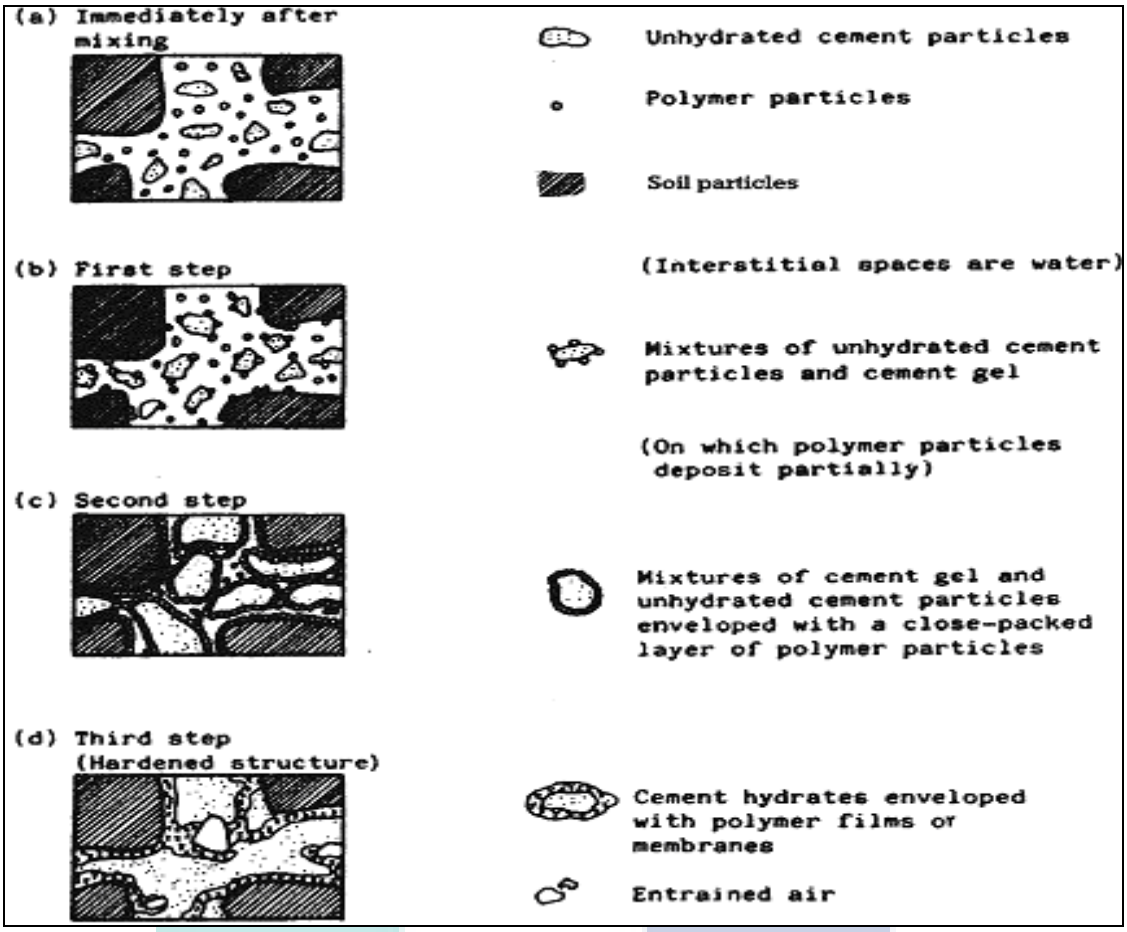


Figure 2.7: Model of formation of polymer-cement-co-matrix (Mechanism of polymer modification in concrete)

Source: Ohama (1995)

If re-dispersible polymers are mixed in concrete with water, the polymer powders are re-emulsified in the modified mortar and concrete, and behave, in the same manner as latexes, as cement modifiers. For resin modified concrete, polymerisable low molecular weight polymers or pre-polymers are added in a liquid form to mortar or concrete. The polymerization process or cross linking is initiated in the presence of water to form a polymer phase, and simultaneously the cement hydrates. Therefore, a co-matrix phase, similar to latex modified concrete, is formed with a network structure of interpenetrating polymer and cement hydrates phases. Thus, the properties of the hardened concrete or mortar are improved in the same way as those of polymer modified systems (Ohama, 1995). A model of the composite mechanism of PMC (Etsuo

and Jun, 1995) is shown in Figure 2.8. With cement hydrate as matrix, a microstructure with soft polymer particles distributed in it is formed, an interfacial layer with different microstructure from the case where no admixture is used form at the surfaces of cement particles and aggregates.

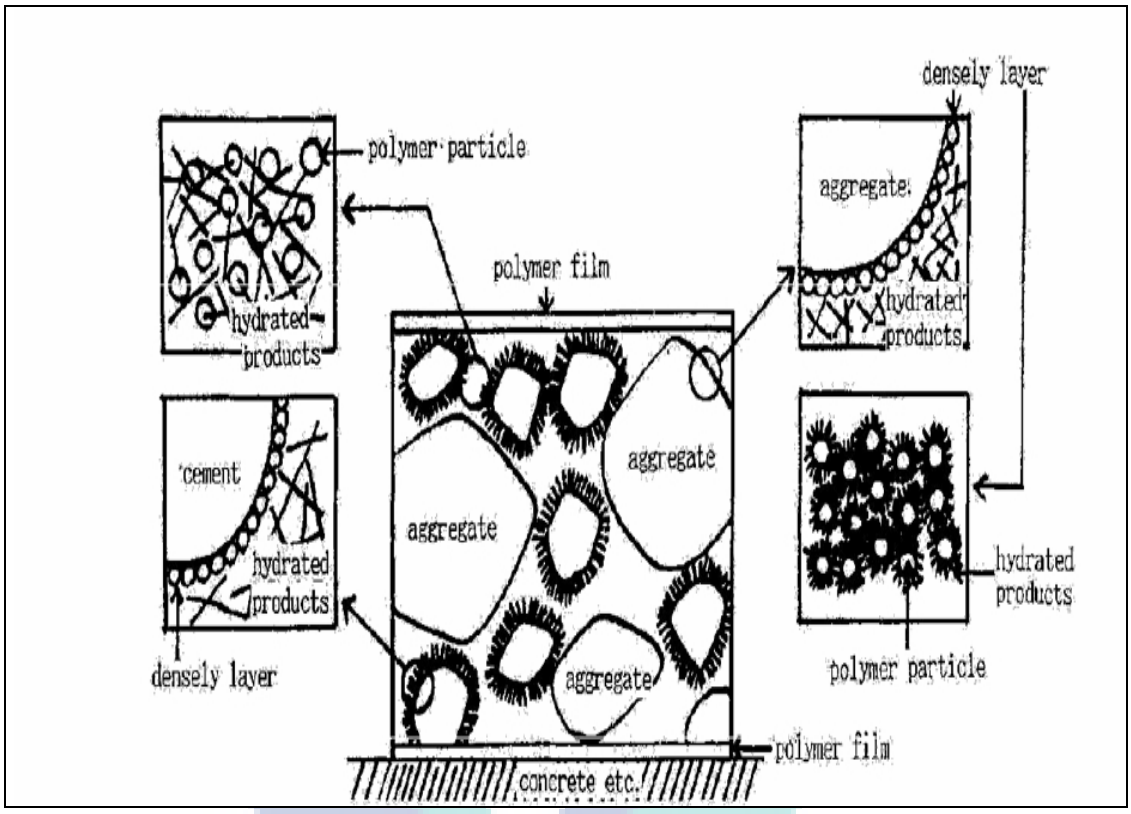


Figure 2.8: Model of composite mechanism of PMC concrete

Source: Etsuo and Jun (1995)

2.12 APPLICATION OF POLYMER MODIFIED CONCRETE

Polymer modified concrete have superior properties such as high tensile and flexural strengths, excellent adhesion, high waterproofness, high abrasion resistance and good chemical resistance, compared with ordinary cement mortar and concrete (Ohama, 1998). PMC are primarily used as overlays on roadways and bridges, both as new construction and as repairs of existing deteriorated structures (Darwin, 1984). PMC is also being used in flooring, water tanks, swimming pools, septic tanks, silos, drains,

pipe and ship decks (Ohama, 1978 and Su, 1995). Two very promising and relatively new applications of PMC is used in combination with fiber reinforcing (Gerwick and Ben, 1978; Souroshian et al., 1993. and Chen and Chung, 1996). It is also used as pneumatically applied material or shotcrete (Schorn, 1985).

The combination of improved workability, adhesion, and curing performance allows using polymer-modified mortar in several applications that would otherwise be difficult or impossible. PMC is applied mainly in bridge deck overlays, road surfacing, corrosion resistant overlays, floor toppings, and also for repair and rehabilitation. This type of concrete is also often used in laying bricks, in fabricated panels and with stone and ceramic tile because of its excellent adhesive properties.

2.13 ACRYLIC EMULSION POLYMER CONCRETE

Acrylic emulsion polymer is a co-polymer water dispersion of methacrylic acid, acrylonitrile or acrylic acid. Emulsions of this kind dry through the processes of water evaporation and film coalescence. Studies have shown that certain acrylic lattices impart excellent workability at lower water demand, thin section adhesion and toughness, improved flexural strength and tensile strength and outstanding adhesion (Lavelle, 1983). Commercial grades are designed for specific end uses and cement systems modified with acrylic emulsions are used in numerous applications such as patching repair mortars, floor underlays and overlays, terrazzo floorings, ceramic tile adhesives, precast architectural building panels, grouts, cementitious coatings, highway and bridge deck repair products (Irfan, 1998).

Apart from that, acrylic polymer concrete has several benefits as a structural material due to its ease of viscosity adjustment to a variety of levels, excellent weather, chemical and abrasion resistances and high bond strength (Seung and Jung, 2012). When acrylic polymers are added into a cement mortar or concrete, their sphere coalesce to form a continuous polymer matrix which coats the hydrating cement grains and aggregates (Irfan, 1998). This polymer matrix acts as a barrier which helps to improve the hydration of the cement and also provides a polymeric network which increases the toughness and durability of the finished product (Rohm and Haas, 1991).

2.14 SILICA FUME CONCRETE

Silica fume is an ultrafine material with spherical particles less than 1 μm in diameter, the average being about 0.15 μm. This makes it approximately 100 times smaller than the average cement particle (Siddique and Iqbal, 2011). The bulk density of silica fume depends on the degree of densification in the silo and varies from 130 kg/m^3 (undensified) to 600 kg/m^3. The specific gravity of silica fume is generally in the range of 2.2 to 2.3. Because of its extreme fineness and high silica content, silica fume is a very effective pozzolanic material (Luther, 1990). Inclusion of this material in concrete contributes towards densification of concrete internal structure through pozzolanic reaction and filler effect.

When added as mineral admixture, this material would take part in pozzolanic reaction consuming large quantity of $Ca(OH)_2$, a by-product from hydration process of to form secondary calcium-silicate-hydrate (C-S-H) gel which fills in the voids existing in the concrete. As a result, the concrete with silica fume consist larger amount of (C-S-H) gel than plain concrete produced using 100% ordinary Portland cement which makes the concrete denser and stronger than the latter. Neville (2000) added that the filler effect with improved particle distribution causes by silica fume results in reduction of the thickness of transition zone and leads to densely packed stronger and less permeable concrete (Neville, 2000). In addition, the amount of $Ca(OH)_2$, which is vulnerable to aggressive environment is also reduced assisting the concrete to possess higher durability. The positive contribution of silica to properties enhancement of concrete has been highlighted by Detwiler and Mehta (1989) who stated that integration of silica fume in Portland cement concrete improve its properties, in particular its compressive strength, bond strength, and abrasion resistance.

Looking at the effects of silica fume on properties of fresh concrete, the slump loss with time is directly proportional to increase in the silica fume content due to the introduction of large surface area in the concrete mix by its addition (ACI 234, 2006). Although the slump decreases, the mix remains highly cohesive. Silica fume reduces bleeding significantly because the free water is consumed in wetting of the large surface area of the silica fume and hence the free water left in the mix for bleeding also

decreases. Silica fume also blocks the pores in the fresh concrete so water within the concrete is not allowed to come to the surface.

Since pozzolanic reaction is controlled by the $Ca(OH)_2$ formation and depends on the available amount of $Ca(OH)_2$ (Siddique and Iqbal, 2011), only a suitable integration of silica fume would assist the concrete to achieve optimum strength. So far, silica fume has been used as an addition to concrete up to 15% by weight of cement, although the normal proportion is 7% to 10% (EN 13263, 2005). At a typical dosage of 8% by weight of cement, it will fill the water spaces in fresh concrete. This eliminates bleed and the weak transition zone between aggregate and paste found in normal concrete (Verma et al., 2012). With an addition of 15%, the potential exists for very strong, brittle concrete (Heidari and Zabihi, 2013). It increases the water demand in a concrete mix; however, dosage rates of less than 5% will not typically require a water reducer. High replacement rates will require the use of a high range water reducer.

2.15 FIBER REINFORCED POLYMER MODIFIED CONCRETE (FRPMC)

Fiber reinforced polymer modified concrete (FRPMC) is produced when polymer is added to the concrete reinforced by fiber. This production process of this composite is known as polymer modification. Study on polymer modification start since 1920s when the first patent of the concept had already been issued to Cresson (1998) that referred to paving materials with natural rubber latexes and in the patent, cement was used as a filler. The first patent with the present concept of polymer modification was published by Lefebure in 1924. Since then, considerable research and development of polymer modification for cement mortar and concrete have been conducted in various countries for 70 years or more. As a result, many effective polymer modification systems for cement mortar and concrete have been developed, and currently used in various applications in the construction industries. The research on polymer modification then continuously investigated by various researchers (Fukuchi et al., 1978; Ohama et al., 1985; Soroushian et al., 1991; Reis, 2004) into fiber reinforced concrete by using different polymers and fibers to improve mechanical, thermal and durability properties of FRPMC.

2.15.1 Performance of Fiber Reinforced Cement Concrete Modified With Polymer

Fiber reinforced concrete (FRC) is an alternative building material as it can strengthen the crack resistance and the toughness of the concrete effectively, and it is capable of reinforcing the impermeability and effectively eliminating the stress concentration of concrete as well (Banthia, 2012). Whereas, with the progression of the research and application, the existing issues of FRC are equally striking. Inside FRC, especially in the interface transition zone (ITZ) between fiber and cement substrate, there tend to be a large quantity if harmful pores, giving rise to the weak bonding among cement hydrates, fibers and aggregates. Herein, the role of the fiber is deteriorated in enhancement (Viktor and Flavio, 2012; Wang and Meyer, 2012).

Fortunately, with the polymeric materials science and in-depth insights of the correlations and causations between material structures and properties progressing, large quantities of excellent properties possessed by polymer, such as waterproof, filling, flocculation and thickening effects were discovered. It is to be noted that polymer has been already implemented or gradually applied to concrete field currently (Zhong and Yuan, 2003; Ohama, 2000). With the purpose of making concrete capable of meeting the requirements of structural applications, the inclusion of polymer in concrete has become one of the focused research topics in engineering circles (Dionys and Lech, 2005).

In Xu et al. (2014) research study, for the purpose of effectively dealing with brittleness and inferior dynamics performance of cement concrete road overlay material composed of polyester fiber and SBR latex, which is called fiber and polymer compound modified concrete (FRPMC), they conclude that the mechanical properties of fiber reinforced polymer modified concrete (FRPMC) were the most optimal at 0.14 vol.% of polyester fiber and at 90 kg/m^3 of SBR latex. There is an obvious compound effect of polyester fiber and styrene-butadiene-rubber (SBR) latex on the mechanical properties of FRPMC correspondingly. The results of microscopic tests obtained showed that SBR latex took no significant effect on cement hydration in the long-term. Besides, continuous SBR latex films formation presented in cement substrate makes it possible to raise toughness and compact degree of interface transition zone (ITZ).

Furthermore, SBR latex trigger fiber and cement paste to lead to a tight mutual connection.

The research conducted by Al-Gassani (2007) discovered that steel fibre reinforced concrete (SFRC) containing polymer which known as FRPMC showed improvement in all mechanical properties as compared to plain SFRC. In compressive strength, the increase was (14.2% - 29.2%) for steel fiber concrete, while the increase was (44.8% - 86.64%) for steel fiber concrete containing polymer. In splitting tensile strength, the increase was (50% - 91%) for steel fiber concrete, while the increase was (102.4% - 124.7%) for steel fiber concrete containing polymer. For flexural strength, the increase was (24.2% - 48.3%) for steel fiber concrete, while the increase was (62% - 78%) for steel fiber concrete containing polymer.

2.15.2 Influences of Superplasticizer and Polymer Latexes on Modified Cement Concrete

Recently, many investigations have been conducted to improve the durability of concrete (Dhir et al., 1989; Aitcin, 2000; Czarneki and Justnes, 2012; Singh and Garg, 2012; Hassan et al., 2012 and Somna et al., 2012). It has been well accepted that most issues regarding concrete durability are related to the permeability of concrete, such as freeze-thaw deterioration, chloride ingress, sulfate attack, and carbonation (Basheer et al., 2001). Basically, the key to enhance durability of concrete is to increase the concrete impermeability. The impermeability of concrete is primarily determined by the pore structure of cement pastes, and is also affected by cracks and interfaces between the cement pastes and aggregates (Nilsen and Monteiro, 1993 and Zhang and Li, 2011).

Various polymers have been incorporated in modern concrete in order to achieve desired properties. Adding superplasticizers into fresh cementitious materials can improve their rheological properties and thus in the premise of satisfying the construction requirements, lower water to cement ratio (w/c) could be achieved. As well known, the lower W/C is required to produce concrete with higher strength, lower permeability and higher durability (Gagne et al., 1996 and Malhotra, 1999). Polymer latexes are often used as cement mortars and concrete modifiers to improve mortars and

concrete properties such as adhesion, fracture toughness, flexural strengths, crack resistance and waterproof (Jenni et al., 2005; Kong and Li, 2009).

Ohama and Demura (1991) revealed oxygen diffusion resistance of the polymer-modified mortars is larger than that of unmodified mortars, and is markedly increased with an increase in polymer to cement ratio. Moreover, Gao et al. (2002) found that the pore volume and the pore size of latex-modified cement pastes tended to become smaller with an increase in latex to cement ratio because the capillary pores of the hardened cement pastes were filled in with the polymer particles of the polymer membrances form by agglomeration of the polymer particles. Meanwhile, the polymer latex film could effectively compact the interfacial zones between fine aggregates and cement pastes (Beeldens et al.,2005; Czarnecki and Schorn, 2007; Knapen and Gemert, 2007), enhancing the impermeability of hardened mortars (Beeldens et al., 2001).

Polyacarboxylate (PC) superplasticizer usually has a hydraulic radius of 10 – 100 nm in aqueous solution and the particle size of polymer latexes ranges from 100 to 1000 nm. Although much research on the cement mortar with superplasticizer, polymer latex have been conducted, few studies dwell on their impacts on the pore structure and the impermeability from the viewpoints of microstructure in the fresh state of cement paste, especially their different impacts originating from particle size. Specifically, the formation of the pores may be affected by addition of these polymers due to their impacts on the rheological properties of fresh pastes, cement hydration, and the shrinkage of hardened pastes. Furthermore, the type of polymers with varied particle size also plays an important role in changing the pore structure and the impermeability. It is supposed that these polymers may affect the pore structure and the impermeability from three perspectives: (1) changing the flocculation microstructure of cement grains, which is demonstrated by the variations of the fluidity of fresh pastes in macro scales; (2) altering cement hydration process; (3) filling the pores and the cracks in the transition zones and forming films in many cases.

Zhang and Kong (2014) studies showed that the incorporation of superplasticizer obviously reduces the average pore size and enhances impermeability. The polyacrylate latexes also lead to the decline in pore size and consequently the

enhanced impermeability at dosage higher than 3%. At the same dosage, latex with smaller polymer particle size is more effective in reducing the average pore size and enhancing the impermeability than that with larger particle size due to its better plasticizing effect. In the case of polymer latexes and emulsion polymer, the plasticizing effect contributes actively at low dosage and the filling effect is dominant at high dosage in terms of declining pore size and augmenting impermeability.

2.15.3 Characterization of Modified Cement Concrete with Polymer

Many effective polymer modification systems for mortar and concrete have been developed and intensively applied because of their improved properties compared with conventional cement mortar and concrete (Kong et al., 2014). Previous studies have shown that the incorporation of polymers into cement mortar or concrete often leads to an improved workability and mechanical properties, especially higher flexural strength and decreased elastic modulus (Ohama, 1994; Folic and Radonjanin, 1998; Jenni et al., 2006; Pascal et al., 2004), improved impermeability such as lower chloride diffusivity (Zhong and Chen, 2002; Yang et al., 2008), higher frost resistance (Mirza et al., 2002), reduced shrinkage rate (Wang and Wang, 2010), and eventually improves the durability (Al-Zahrani et al., 2003; Ohama, 1996; Sakai and Sugita, 1995) of the concrete structure. The mechanism of polymer modification is related to the influences of polymers on the microstructures of hardened cement mortar and concrete, cement hydration process and pore size distribution (Ohama, 1987; Sakai and Sugita, 1995; Afridi et al., 2003; Schulze, 1999). The addition of polymers is a very effective way to improve the performance of cement mortar and concrete in terms of either mechanical properties or durability aspects.

Different amounts of polymer addition are required to gain various improved properties of mortar or concrete. As far as mechanical properties or impermeability is concerned, a polymer addition of 3% – 20% is usually needed. With less than 3% of polymer addition, the mechanical properties of impermeability hardly changes. Impermeability can only be improved when the polymer forms a semi-continuous film in the matrix of hardened cement hydrates. Hence, a minimum polymer addition is required to ensure film formation, which is usually larger than 3% of p/c ratio (Kong et

al., 2014). After the film formation of the polymer and the hardening of the mortar, a gradient polymer distribution is generated from the surface to the interior region of the mortar. A significantly condensed surface is obtained *in situ*, which provides a radically effective protective layer. The gradient distribution of the polymer was confirmed by thermogravimetric analysis (TGA) and X-ray diffraction (XRD) analysis.

2.15.4 Effect of Polymers on Hydration Process of Modified Cement Concrete

Polymers are very important means to the adjustment of the properties of a number of concrete products, such as self-compacting concrete and ultra high performance concrete (UHPC) (Jansen et al., 2013). When developing and manufacturing concrete, it is always important to know whether the polymers and additives such as superplasticizers have an impact on the hydration process of the inorganic binders which are used. Specific knowledge of the interaction between polymers and other additives, and of hydration reactions of cementitious systems, might also be important in order to understand an unsatisfactory performance of cementitious products in application such as they are setting too quickly, or an unintended retardation. This is the reason why the influence of different polymers has already been examined by numerous authors and has also been reviewed (Chandra and Flodin, 1987).

The phase development of cement hydration can be traced by means of X-ray diffraction (Jansen et al., 2001). Heat flow curves and data from XRD experiments can be combined and the early heat flow during cement hydration can be related to different specific reaction (Jansen et al., 2013). In Jansen et al. (2013) research study, it was shown that the influence of the cationic polymer on the hydration of the cement will tend to be strongly dependent on the nature of the anionic counter ion. In case of OH^-, more calcium sulfate will tend to be dissolved in the early stages, which acts in turn as an accelerator for the hydration of the C_3S phase. In case of SO_4^{2-}, it will tend to produce a secondary gypsum precipitation, which will in turn act to lower the Ca^{2+} content in the mix water, leading to a retardation of the hydration process compared to the hydration in absence of polymer.

Plank and Gretz (2008) investigated the influence of superplasticizers as well as anionic and cationic latexes on the hydration behavior of Portland cements, measuring zeta potential and absorption isotherms. It was shown that the charged latex particled absorb selectively on the surfaces of those hydrating cement particles which display an opposite charge. Additionally it was shown that the anionic latexes absorb a considerable amount of Ca^{2+} from pore solution. Larbi and Bijen (1990) examined the pore solution during cement hydration and the influence of different polymers on the composition of the pore solution. They showed that there is an interaction between polymers and ions (Ca^{2+}, SO_4^{2-}, OH^-) released by the cement during hydration. The carboxylic groups of the polymer appear to interact with the positive Ca^{2+} in pore solution.

Su et al. (1991) worked out that acrylic polymers tend to retard cement hydration and related this retardation either to the formation of a skin of the polymer around the cement grains, which then acts to restrict water access. The interaction between cement hydration and ethylene/vinyl acetate copolymers (EVA) has been investigated in detail by Silva and Monteiro (2005). They discovered an interaction between the ester groups of the polymer and Ca^{2+} from the pore solutions, resulting in the formation of calcium acetate and therefore a retardation of the cement hydration. Moreover, the amount of portlandite was discovered to decrease where EVA is added, due to the consumption of Ca^{2+} by the polymer (Silva and Roman, 2002). In addition, it was also discussed whether polymer particles might possibly act as a nucleation site for the C-S-H phase (Silva and Monteiro, 2006). The fact that the polymer modification delays and slows the reaction of the clinker phases, alternatively the precipitation of ettringite and C-S-H phase.

2.16 TAGUCHI EXPERIMENTAL DESIGN

In an experimental study, in order to determine the effects of various factors, which are affecting the results of experiment, different methods, and approaches are used. The fundamentals of these methods are the full factorial design and fractional factorial design (Montgomery and Runger, 2006). In the traditional approach, which is also known as full factorial design, the experiments are performed for each condition,

which consists of all factors. The number of possible design N (number of trials) shall be expressed in equation (2.1):

$$N = L^m \tag{2.1}$$

where L= number of levels for each factor, m= number of factors involved

Assume an engineering experiment study requires six control factors and three control levels per control factor to understand the influence and interaction of its input data on the output results. By using a traditional experimental process, usually at least all the possible 3^6 = 729 tests need to be carefully conducted and finished before an optimal performance can be concluded. The number of tests can get very large really fast. A complete factorial design requires experiments including all levels of possible combinations of the factors, which can be very expensive and time-consuming. Therefore, Taguchi design can be used as an efficient alternative. A Taguchi design requires running only a fraction of experiments in the complete factorial design. They also help to identify factors that have significant effects.

Taguchi's approach to parameter design provides the design engineer with a systematic and efficient method for determining near optimum design parameters for performance and cost. The objective is to select the best combination of control parameters so that the product or process is most robust with respect to noise factors. The Taguchi method utilizes orthogonal arrays from design of experiments theory to study a large number of variables with a small number of experiments. Using orthogonal arrays significantly reduces the number of experimental configurations to be studied (Unal and Dean, 1991).

To get the combination of mechanical properties and better performances in producing PMC-SFRC, there are several factors that need to be considered. Therefore, optimization process which is known as design of experiment (DoE) has been utilized. DoE is an engineering methodology to improve the production and research development in order to produce high quality and lower cost product within a short period of time. This method is implemented with planned experimental production

where the control parameter can be varied. For each control parameter in the experiment, the performance features or processes will be calculated to get the results from the production variation effects.

2.16.1 Factor Classification

The number of parameters or factors can affect the product response. These factors can be divided into three namely:

a. Control factor (Z)
b. Signal factor (M)
c. Noise factor (X)

Figure 2.9 showed the parameter diagram which gives various factors that influenced the quality and the reaction of products. A product or process is robust if the product is very insensitive with all the factors

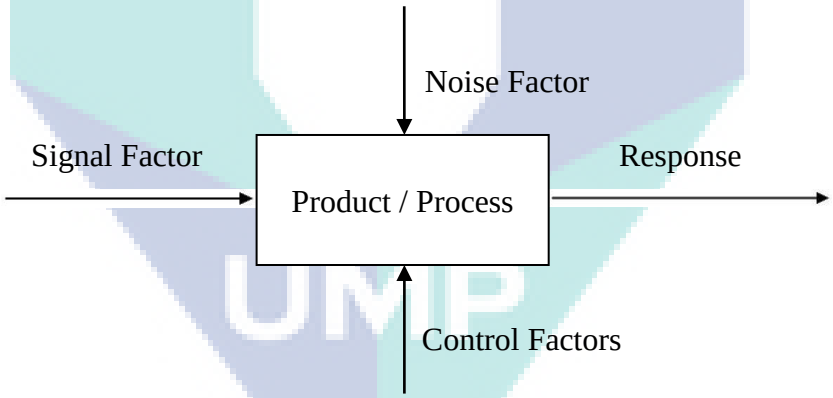


Figure 2.9: Block diagram of a product/process: P diagram

Source: Phadke (2008)

2.16.2 Taguchi Method

Taguchi method is a method that has been utilized before. However, this method is still relevant with recent research because it is a modern robust design process based on the statistic experimental design. This method gives optimal decision which included

all noise that involved in the process. Besides, this method also can reduce the production cost and improve product quality that is produced. This method was elected to be applied in this project because it can give main parameter that can enhance the composite mechanical properties with a few series of experiments that has been planned meticulously.

Taguchi method is a design method that has been prepared efficiently and systematically to optimize ability design, quality and manufacturing cost (Gustri, 2008 and Ranjit, 2001). Apart from facilitating experiment planning, the relationship between parameter also can be determined (Bernadous and Vosniakos, 2002). The number of experiment and processing costs could be reduced (George at al., 2004 and Ghani et al., 2004). According to Phadke (2008) and Park (1996), two important matters that should be considered in Taguchi experiment are:

- Signal ratio on interference which measures quality
- Orthogonal array that can use many factors by methodical

The following steps are used for the Taguchi experiment (Antony and Anthony, 2001):

1. Objective of the experiment
2. Identification of the control factors and their levels
3. Selection of most suitable response for the experiment
4. Choice of orthogonal array (OA)
5. Preparation of experimental layouts and run
6. Statistical analysis and interpretation of experimental results

The Taguchi method is based on the design which follows the statistical method and it can give satisfaction economically on issue solution and gives optimum results. By using this technique, the duration for testing experiments can be reduced until effecting testing can be done (Park, 1996 and Ranjit, 2001). In this methodology, there are EIGHT (8) steps that should be followed to obtain good results. It can be shown in Figure 2.10.

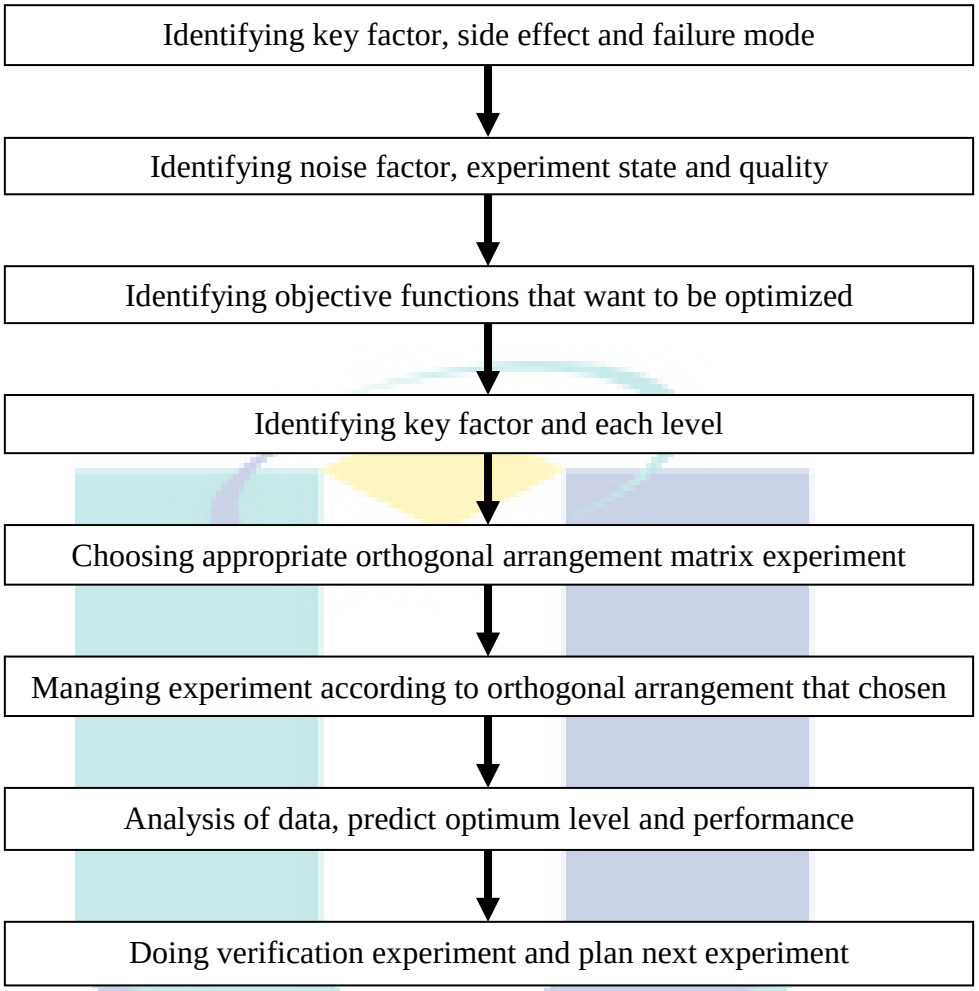


Figure 2.10: Taguchi experimental design process step

Source: Park (1996) and Ranjit (2001)

2.16.3 Orthogonal Array, Loss Function and Signal Ratio/ Noise

The robust design is a technique that is effective to reduce cost and improve product performance or process. Three types of tools used in Taguchi method are orthogonal array, loss function and signal ratio/noise. Specific test characteristics for each experimental evaluation are identified in the associated row of the table. Thus, L_{18} means that eighteen experiments are to be carried out to study eight variables at three levels. The number of columns of an array represents the maximum number of parameters that can be studied using that array. Note that this design reduces 6561 (3^8) configurations to 18 experimental evaluations. There are greater savings in testing for

the larger arrays. For example, using an L_{27} array, 13 parameters can be studied at 3 levels by running only 27 experiments instead of 1,594,323 (3^{13}).

The Taguchi method can reduce research and development costs by improving the efficiency of generating information needed to design systems that are insensitive to usage conditions, manufacturing variation, and deterioration of parts. As a result, development time can be shortened significantly and important design parameters affecting operation, performance, and cost can be identified (Unal and Dean, 1991).

(a) Orthogonal array

Orthogonal array is an experiment matrix or experiment set where several of control factors with different levels are arranged according to matrix arrangement. Orthogonal array is matrix which contains the number arranged in line and column. In this matrix, the column contains control factors that interchangeable which depend on the experiment while the line column on the other hand contains control factors level to each experiment. The level of various control factors is balance and the factor's effect can be divided from other factors in the same experiment. By this method, the control factors contribution can be determined and key factors are identified (Ranjit, 2001). Generally there is standardized orthogonal array and it is shown in Table 2.4. The layout can be used according to every researcher. However it may be modified to increase the total of control factors level in process of product manufacture.

Table 2.4: Orthogonal standard layout

Level 2	**Level 3**	**Level 4**	**Level 5**	**Combination Level**
L_4 (2^3)	L_9 (3^4)	L_{16} (4^5)	L_{25} (5^6)	L_{18} (2^1 X 3^7)
L_8(2^7)	L_{27} (3^{13})	L_{64} (4^{21})	-	L_{32} (2^1 X 4^9)
L12(2^{11})	L_{81} (3^{40})	-	-	L_{36} (2^{11} X 3^{12})
L16(2^{15})	-	-	-	L_{36} (2^3 X 3^{12})
L_{32}(2^{31})	-	-	-	L_{54} (2^1 X 3^{25})
L64(2^{63})	-	-	-	L_{50} (2^1 X 5^{11})

Source: Ranjit (2001)

In this study, L_{27} layout is used in initial studies and $L_{9\ is}$ used in next study. L_{27} orthogonal layout template is a combination of control factors with different level. In this L_{27} layout (9^1 x 3^9), 10 columns are labeled from A to J which is control factors that has to be investigated in this study. Each column consists of control factor level which has been fixed at this column. Hence, the first experiment will consist of combination of level 1 for all control factors. Template for this array is shown in Table 2.5 (Ranjit, 2001).

(b) Loss Function

The performance of product or process is considered to be of more quality if the deviation value is minimum from the target value. If the product quality characteristic is y and m is the best value for y. the quality loss can be stated as:

$$L(y) = k(y-m)^2 \tag{2.2}$$

Where, k is a constant called quality loss coefficient. Three such loss function characteristics are:

- Better nominal: nominal value is the best because it fulfills consumer target value that is needed. The value in both sides of target value is unwanted and the value can become positive or negative.
- Smaller-the better: smaller value had better and the larger value is unwanted.
- Larger-the better: larger value had better while smaller value does not require.

If better nominal is taken as example, assume deviation in failure of certain product or process is $m\pm\Delta_0$ and loss in $m\pm\Delta_0$ is A_0. Substituting equation 2.2 will obtain

$$k = \frac{A_0}{\Delta_0^2} \tag{2.3}$$

Thus, better nominal loss function may be written as (Ranjit, 2001):

$$k_N = \frac{A_0}{\Delta_0^2}(y-m)^2 \tag{2.4}$$

Table 2.5: L_{27} Orthogonal Array that carry out for earliest analysis

EXP. NO.	CONTROL FACTORS									
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
1	1	1	1	1	1	1	1	1	1	1
2	1	2	2	2	2	2	2	2	2	2
3	1	3	3	3	3	3	3	3	3	3
4	2	1	1	1	2	2	2	3	3	3
5	2	2	2	2	3	3	3	1	1	1
6	2	3	3	3	1	1	1	2	2	2
7	3	1	1	1	3	3	3	2	2	2
8	3	2	2	2	1	1	1	3	3	3
9	3	3	3	3	2	2	2	1	1	1
10	4	1	2	3	1	2	3	1	2	3
11	4	2	3	1	2	3	1	2	3	1
12	4	3	1	2	3	1	2	3	1	2
13	5	1	2	3	2	3	1	3	1	2
14	5	2	3	1	3	1	2	1	2	3
15	5	3	1	2	1	2	3	2	3	1
16	6	1	2	3	3	1	2	2	3	1
17	6	2	3	1	1	2	3	3	1	2
18	6	3	1	2	2	3	1	1	2	3
19	7	1	3	2	1	3	2	1	3	2
20	7	2	1	3	2	1	3	2	1	3
21	7	3	2	1	3	2	1	3	2	1
22	8	1	3	2	2	1	3	3	2	1
23	8	2	1	3	3	2	1	1	3	2
24	8	3	2	1	1	3	2	2	1	3
25	9	1	3	2	3	2	1	2	1	3
26	9	2	1	3	1	3	2	3	2	1
27	9	3	2	1	2	1	3	1	3	2

Source: Ranjit (2001)

Based on equation 2.3, better nominal loss function is plotted in Figure 2.11. Loss, L (y) decreases slowly when the quality value, y approaches, m but if it distances m, loss, L (y) rapidly increased. Equation 2.8 and 2.9 is function of better smaller and better larger. Both of these loss functions are plotted in Figure 2.12 and 2.13.

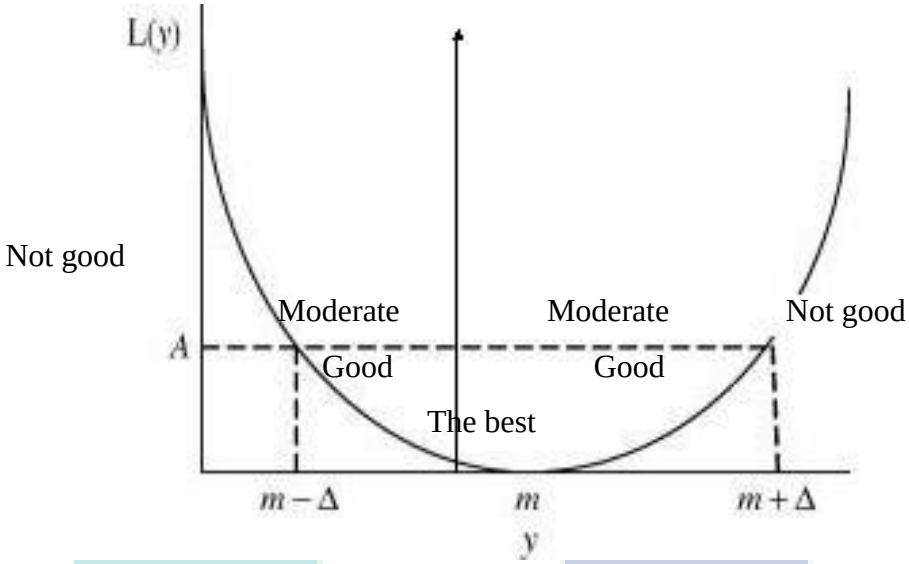


Figure 2.11: Nominal- the better

Source: Ranjit (2001)

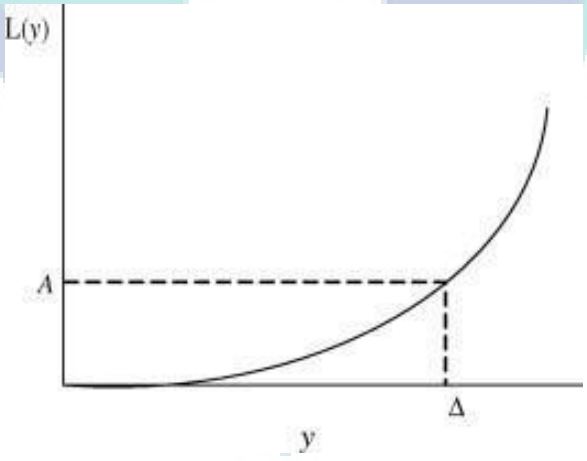


Figure 2.12: Smaller-the-better

Source: Ranjit (2001)

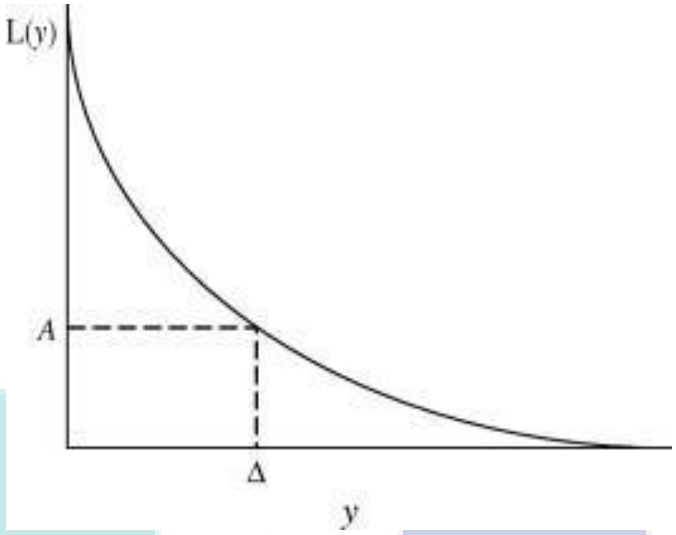


Figure 2.13: Larger-the-better

Source: Ranjit (2001)

(c) Signal ratio / noise factor

Signal ratio / noise are strength index which measures transformation of energy quality that exists in design and stated as:

$$\eta = signalpower/noisepower = \mu^2/\sigma^2 \tag{2.5}$$

Signal ratio / noise are used to maximize the characteristic function. For example, the higher the value of S/N ratio, the quality will be higher. In common practice, S/N ratio is counted in log and stated in decibel scale (dB):

$$\eta = 10\log_{10}\frac{\mu^2}{\sigma^2} \tag{2.6}$$

If there are set of characteristics y_1, y2, y3 ...yn, S/N ratio for these three types of quality characteristics are:

(i) Nominal-the-best type problem

$$\eta = 10 \log_{10} \frac{\mu^2}{\sigma^2} \tag{2.7}$$

(ii) Smaller-the better type problem

$$\eta = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^{\eta} y_1^2 \right] \tag{2.8}$$

(iii) Larger-the better type problem

$$\eta = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^{\eta} \frac{1}{y_1^2} \right] \tag{2.9}$$

There are FOUR (4) steps to optimize the product performance process:

1. Control factor effect assessed by considering η and function average.
2. For factor with main effect on η, choose level that maximizes η.
3. Choosing which factor that has no effect on η but have effect in function average as adjustment factor. It is used to obtain function average to target.
4. For factor which has no effect on η and also function average; choosing which level with consideration that is suitable.

2.16.4 Analysis in Taguchi Method

In Taguchi method, there are two types of analysis used after decision found from orthogonal array which are average analytical method and S/N ratio analysis method. The average analytical method is calculated from the average value from experiments that had been carried out while S/N ratio analysis method is determined from S/N ratio calculation. The average analytical method is much easier because it requires only one value from the experiment for calculation while S/N ratio analysis method depends on S/N ratio that calculated from a few of serial experiments. Both of

these two methodologies can be calculated through the interaction table that is very simple or variant analytical method that is more complex.

(a) Interaction Table

Mean value and S/N ratio can be calculated after the results from experiment are obtained. The level effect for each control factor also can be compared by taking average for each experiment results. For example, in this study, by taking a factor A in L27 (9^1 x 3^9) orthogonal array from Table 2.6, the average effect from Level 1 to 9 can be stated as:

$\breve{y}_{A1}$ = mean effect (or S/N ratio) for experiment 1 to 3
$\breve{y}_{A2}$ = mean effect (or S/N ratio) for experiment 4 to 6
$\breve{y}_{A3}$ = mean effect (or S/N ratio) for experiment 7 to 9
$\breve{y}_{A4}$ = mean effect (or S/N ratio) for experiment 10 to 12
$\breve{y}_{A5}$ = mean effect (or S/N ratio) for experiment 13 to 15
$\breve{y}_{A6}$ = mean effect (or S/N ratio) for experiment 16 to 18
.
.
$\breve{y}_{A9}$ = mean effect (or S/N ratio) for experiment 25 to 27

Meanwhile for three level of factor B are:

$\breve{y}_{B1}$ = mean effect (or S/N ratio) for experiment 1, 4, 7, 10, 13, 16, 19, 22 and 25
$\breve{y}_{B2}$ = mean effect (or S/N ratio) for experiment 2, 5, 8, 11, 14, 17, 20, 23 and 26
$\breve{y}_{B3}$ = mean effect (or S/N ratio) for experiment 3, 6, 9, 12, 15, 18, 21, 24 and 27

Table 2.6 is L27 (9^1 x 3^9) orthogonal array. Variation value can be determined from the highest and the lowest differences for each factor. Based on quality characteristic that is chosen namely smaller-the better or larger-the better, optimum factor can be determined from interaction table. Based on selection criteria, the highest or lowest value is chosen and optimum condition is then carried out.

Table 2.6: Interaction table of factor effect for $L_{27}(9^1 \times 3^9)$ Orthogonal Array

	Control Factor									
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
Level 1	$\breve{y}_{A1}$	$\breve{y}_{B1}$	$\breve{y}_{C1}$	$\breve{y}_{D1}$	$\breve{y}_{E1}$	$\breve{y}_{F1}$	$\breve{y}_{G1}$	$\breve{y}_{H1}$	$\breve{y}_{I1}$	$\breve{y}_{J1}$
Level 2	$\breve{y}_{A2}$	$\breve{y}_{B2}$	$\breve{y}_{C2}$	$\breve{y}_{D2}$	$\breve{y}_{E2}$	$\breve{y}_{F2}$	$\breve{y}_{G2}$	$\breve{y}_{H2}$	$\breve{y}_{I2}$	$\breve{y}_{J2}$
Level 3	$\breve{y}_{A3}$	$\breve{y}_{B3}$	$\breve{y}_{C3}$	$\breve{y}_{D3}$	$\breve{y}_{E3}$	$\breve{y}_{F3}$	$\breve{y}_{G3}$	$\breve{y}_{H3}$	$\breve{y}_{I3}$	$\breve{y}_{J3}$
Level 4	$\breve{y}_{A4}$	-	-	-	-	-	-	-	-	-
Level 5	$\breve{y}_{A5}$	-	-	-	-	-	-	-	-	-
Level 6	$\breve{y}_{A6}$	-	-	-	-	-	-	-	-	-
Level 7	$\breve{y}_{A7}$	-	-	-	-	-	-	-	-	-
Level 8	$\breve{y}_{A8}$	-	-	-	-	-	-	-	-	-
Level 9	$\breve{y}_{A9}$	-	-	-	-	-	-	-	-	-
Difference	-	-	-	-	-	-	-	-	-	-
Level	-	-	-	-	-	-	-	-	-	-
Optimum	-	-	-	-	-	-	-	-	-	-

Source: Ranjit (2001)

(b) Analysis of Variance (ANOVA)

Table 2.6 also can give relative magnitude of control factor effect. However, better approach on different control factor effects that is more available can be determined from variant analysis known as ANOVA.

i. Equation for ANOVA calculation

ANOVA can ensure main relative of various factors, error variant for factor effect and predictive error variant. ANOVA calculation uses a few basic equations shown as below:

- Sample mean, $\breve{y}$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{2.10}$$

Where y_i is set of numbers n that selected randomly

- Sum of squares in sets of number n, SS

$$SS = \left[\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \right]^2$$

$$= (y_1 + y_2 + y_3 + \ldots\ldots\ldots\ldots + y_n^2)^2 \qquad (2.11)$$

- Large number of sum of squares in sets of numbers n, SST_{grand}

$$SST_{grand} = \sum_{i=1}^{n} y_i (y_1 + y_2 + y_3 + \ldots\ldots\ldots\ldots + y_n^2 \qquad (2.12)$$

The large number of sum of squares can be separated to total sum of squares to average and total sum of squares.

- Mean sum of squares, SSM known as error factor

$$SSM = n\bar{y}^2 = nX \frac{\left[\sum_{i=1}^{n} y_i \right]^2}{n^2} = \frac{\left[\sum_{i=1}^{n} y_i \right]}{n} \qquad (2.13)$$

- Total sum of squares, SST

$$SST = \sum_{i=1}^{n} (y_i - \bar{y})^2 \qquad (2.14)$$

- If equation 2.14 combine with equation 2.9, it will become

$$SST = \sum_{i=1}^{n} (y_i^2 + \bar{y}^2 - 2y_i \bar{y}) = \sum_{i=1}^{n} y_i^2 + n\bar{y}^2 - 2n\bar{y}.\bar{y})$$

$$= \sum_{i=1}^{n} y_i^2 - n\bar{y}^2 \qquad (2.15)$$

Hence, equation 2.13 also can be stated as

$$SST = SST_{grand} - SSM \tag{2.16}$$

- Summation of square factor A, SA according to equation 2.14

$$S_A = \frac{\left(n_{A1} - \bar{y}_{A1}\right)^2}{n_{A1}} + \frac{\left(n_{A2} - \bar{y}_{A2}\right)^2}{n_{A2}} + \ldots\ldots\ldots + \frac{\left(n_{Am} - \bar{y}_{Am}\right)^2}{n_{An}} - SSM \tag{2.17}$$

Or can be stated based on equation 2.13

$$S_A = n_{A1}(\bar{y}_{A1} - \bar{y})^2 + n_{A2}(\bar{y}_{A2} - \bar{y})^2 + \ldots\ldots\ldots + n_{Am}(\bar{y}_{Am}(\bar{y}_{Am} - \bar{y})^2 \tag{2.18}$$

Where *m* is number of level for control factor A. n_{Am} is a result number / observation for certain level for example m is for factor A.

- Sum of squared errors of prediction, SSE can be stated as:

Total sum of squares = explained sum of squares + residual sum of squares (2.19)

Hence, for L_{27} (9^1 x 3^9) orthogonal array layout may be written as

$$SSE = SST - (S_A + S_B + S_C + \ldots\ldots\ldots .. + S_J) \tag{2.20}$$

- Degree of Freedom, D

Degree of freedom, D is parameter number which is not dependent for entity such as matrix experiment or factor or Reciprocal Square. Mean total have one degree of freedom equivalent to total sums of squares. Based on equation 2.18, the relationship of various degrees of freedom is:

Degree of freedom of total sum of squares, D_{SST}
= (total degree of freedom of various factors, $D_A + D_B + D_C$
$+ \ldots\ldots + D_J$) + (Degree of freedom for error)

(2.21)

(c) F- Ratio and F –Test

There is F–ratio calculation method which gives results in confidence level although the variance of second sample is different. F-ratio is used to calculate variance ratio for particular factor on variance error, V_e. F-ratio for factor A, F_A is stated as:

$$F_A = \frac{\text{exp}\,lained\,\text{var}iance}{un\text{exp}\,lained\,\text{var}iance}$$

$$F_A = \frac{V_A}{V_e} \qquad (2.22)$$

(d) P% Contribution

Total of variation that is observed in the experiment and contributed by each factor are indicated by contribution of percentage value, *P%*.

- Contribution of percentage of factor A, $P_A\%$

A factor contribution on total of sum of squares is:

P_A = sum of squares for factor A – (degree of freedom of factor A) x (Error of Mean square)

$$S_A - D_A x EMS \qquad (2.23)$$

Hence, percentage contribution for factor A can be inscribed as:

$$P_A\% = \frac{P_A}{SST} x100 = S_A - D_A x \frac{EMS}{SST} x100 \qquad (2.24)$$

Contribution of percentage for other factors (for example factor B, C until J in L_{27} orthogonal array (9^1 x 3^9) is determined with the same method.

- Error percentage contribution, $P_e\%$

P_A = (error sum of squares) – (total degree of freedom of various Factor) x error mean square

Error contribution on total sum of squares is:

$$SSE + (D_A + D_B + ... + D_J)xEMS \tag{2.25}$$

Hence, contribution of error percentage can be inscribed as:

$$P_A\% = \frac{P_A}{SST} x100 = SSE + \frac{(D_A + D_B + ……..+ D_J)xEMS}{SST} x100$$

Due to total of percentages contribution that is 100%, error percentage contribution can be calculated by subtracting all resources from 100%.

Experimental design using Taguchi method has been successfully applied to many research of civil engineering material in the last decade. Srinivasan et al. (2003) use Taguchi method based on orthogonal array technique in L_9 array with three factors, namely ordinary Portland cement (OPC), fineness of the cement, and type of additives, at three levels each. They need 9 number of experiment. They can reduce number of experiment 60% from 3^3= 27 number of experiment in factorial method. Tahyildizi and Coskun (2008) adopted Taguchi approach with an L_{16} (4^5) to reduce the numbers of experiment. They studied the effect of silica fume on compressive and splitting tensile strength of lightweight concrete after high temperature. The mixes have two control factors (variables); percentages of silica fume with 4 level and heating degree with 3 level.

2.17 SUMMARY

Fiber reinforced composites of steel fibers and glass particles are applied to civil and building projects. All these innovations have compounded an accelerating change in the nature of the industrial material world. Designers of every stripe have shown a growing interest in learning more about new materials. So, in construction of civil engineering composite construction has developed significantly. The utilization of composite action has been recognized as an effective way of enhancing structural performance.

In order to provide a focus for this present investigation, this chapter presents the overview on the advantages and superior properties of the fiber reinforced cement concrete and polymer modified concrete. Generally, polymer concrete (PC) performed better than conventional concrete because of its relatively high strength, greater resistance to chemical and corrosive agent, durability and it's fast curing. Furthermore, this chapter also presents the possibility of using fiber reinforced polymer cement concrete system as few studies were reported in the success of using FRC and PMC in strengthening reinforced concrete (RC) structures.

Numerous studies had been reported a wrapping for beam or column and an external strengthening for beam, slabs and column. Therefore, it would be possible to combine together cement and emulsion polymer as a matrix of the fiber reinforced concrete. It is to produce other alternative or version of composite material at a much lower cost with similarly quality properties, perhaps of FRC and PMC. Besides, this chapter also discusses details about acrylic polymer and steel fiber in concrete and their effects to concrete strength and concrete durability and performance studies on bonding and interfacial transition zone characteristic of the composites/concretes.

During construction, all the composite construction such as steel fiber reinforced concrete and polymer modified concrete are very versatile and important. Each of these materials has their own advantages, disadvantages and own characteristics for any purposes. The study of the engineering properties of composite construction during the experiments can be done to improve the advantages and

disadvantages of each composite construction by using Taguchi method for optimization of various parameters with regard to performance, quality and cost.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter details the procedures followed in the preparation of the concrete specimens. The materials used and corresponding specification are outlined. The various test methods and test procedures are also detailed and explained. The preparation of steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC) was carried out carefully to achieve the required quality of final matrix. In this research study, three different percentages volume of steel fibers (1.0%, 1.5% and 2.0%), silica fume (5%, 6% and 8%), acrylic emulsion polymers (1.0%, 2.5% and 4.0%) and water cement ratio (0.42, 0.50 and 0.60) were used. The ordinary Portland cement corresponding to ASTM Type I cement was used in all mixture proportions. The acrylic polymer resin system that was used in this research was emulsion polymer that can be mixed with water and cement as matrix.

The mixing and casting of the specimens were done according to BS5328: 1988. The specimens also were cured according to BS1881: Part 3 (1983). Design of a trial mix was very important to ensure the design characteristic strength achieved. The purpose of this trial mix was to determine the best mix proportion of acrylic emulsion polymer as partial cement replacement to be used and also steel fiber as reinforcement non-load-bearing element. Curing condition was very important in gaining the designed strength of concrete. After demoulding specimens were cured in water in curing tank before testing for 3 days, 7 days, and 28 days. Figure 3.1 shows the outlines for overall research design methodology.

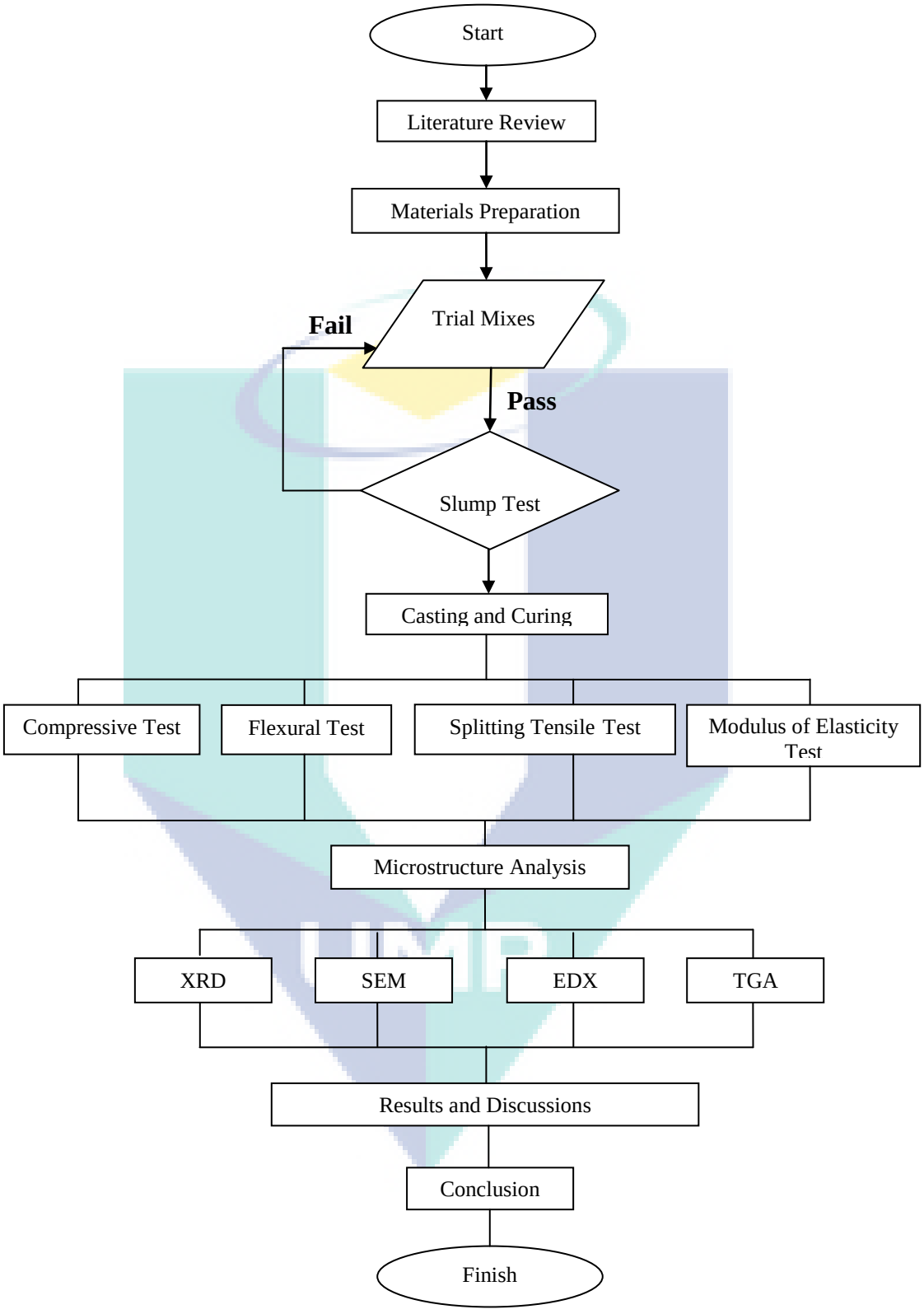


Figure 3.1: Research methodology flow chart

3.2 SELECTION OF MATERIALS

Materials listed below were used in the preparation of the specimen in this study.

3.2.1 Cement

The cement used in this study was ordinary Portland cement Type I (ASTM C150) which is general–purpose cement suitable for all uses. The cement was kept in an airtight container and stored in the humidity controlled room to prevent cement from being exposed to moisture.

3.2.2 Acrylic Emulsion Polymer

Acrylic Emulsion Polymer (Figure 3.2), a product from Tufbond Technologies is synthetic acrylic latex intended for manufacturer of cement products. This material provides excellent water resistance. It has a fine particle size, good water resistance, excellent adhesion to concrete and excellent UV resistance. It is milky white and has 43% – 46% non-volatile solids, has 100 cps maximum of viscosity and 18^{o} C of *Tg (glass transition temperature)*.

Figure 3.2: Acrylic emulsion polymer

Source: Tufbond Technologies

3.2.3 Silica Fume

Silica fume meeting the requirement of ASTM C1240 was used in this study. It is a new generation concrete additive in loosely agglomerated particles form based on silica fume technology. It is a highly effective additive for the production of high performance concrete. Silica Fume is used to increase the durability and strength of concrete, improve abrasion resistance as well as reduced the permeability of concrete. It is grey in color, specific gravity – 2.2 (approximately). Silica fume that was used in this research is shown in Figure 3.3.

Figure 3.3: Silica Fume

Source: Sika Product

3.2.4 Water

Water is needed for the hydration of cement and to provide workability during mixing and for placing. In this study, normal tap water was used. Almost of any natural water that is drinkable and has no pronounced taste or odor can be used as mixing water for making concrete. However, some waters that are not fit for drinking may be suitable for use in concrete. Water of questionable suitability can be used for making concrete if mortar cubes (ASTM C109) made with it has 7-days strength equal to at least 90% of companion specimens made with drinkable or distilled water.

3.2.5 Coarse Aggregates

Coarse aggregate are materials retained on 5 mm test sieve and containing only so much finer material as permitted from various sizes as specified by ASTM C33 and the results data is shown in Appendix E. In this research, type of uncrushed gravel having maximum 14 mm was used as a coarse aggregate. The grading limit of coarse aggregate is shown in Figure 3.4.

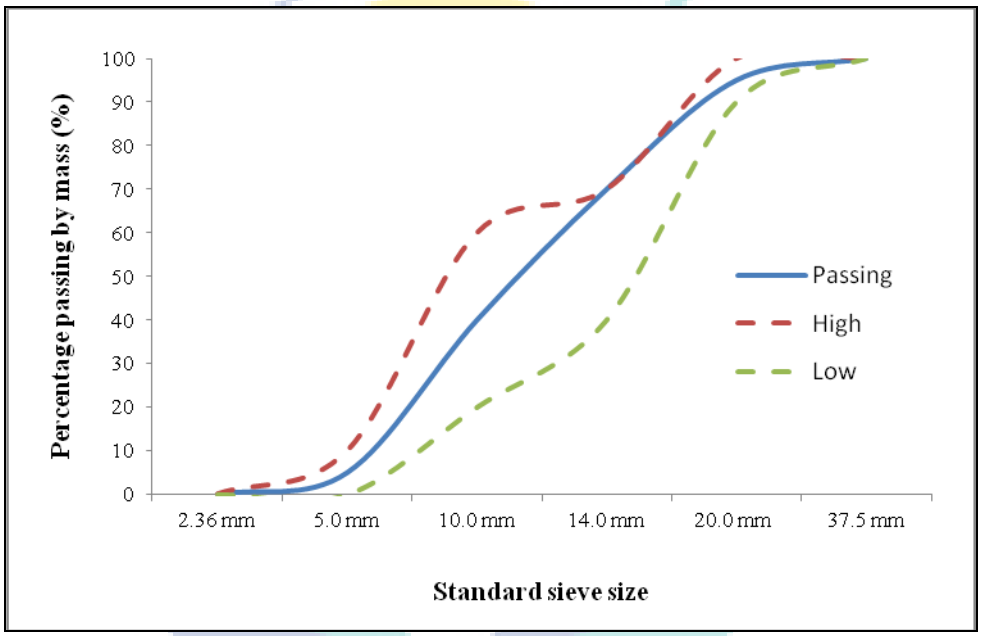


Figure 3.4: Grading chart of coarse aggregate. Dashed line indicate limits specified in ASTM C33 for coarse aggregates

3.2.6 Fine Aggregates

In this research, sand passed through a 5 mm ASTM C33 test sieve was used. The results data is shown in Appendix E. The material used was having diameter smaller than 5 mm which is 1.18 mm. It must be cleaned and not contaminated by lumps of clay or coating of clay and also clean from salt ingredient. The grading limit of sand is shown in Figure 3.5.

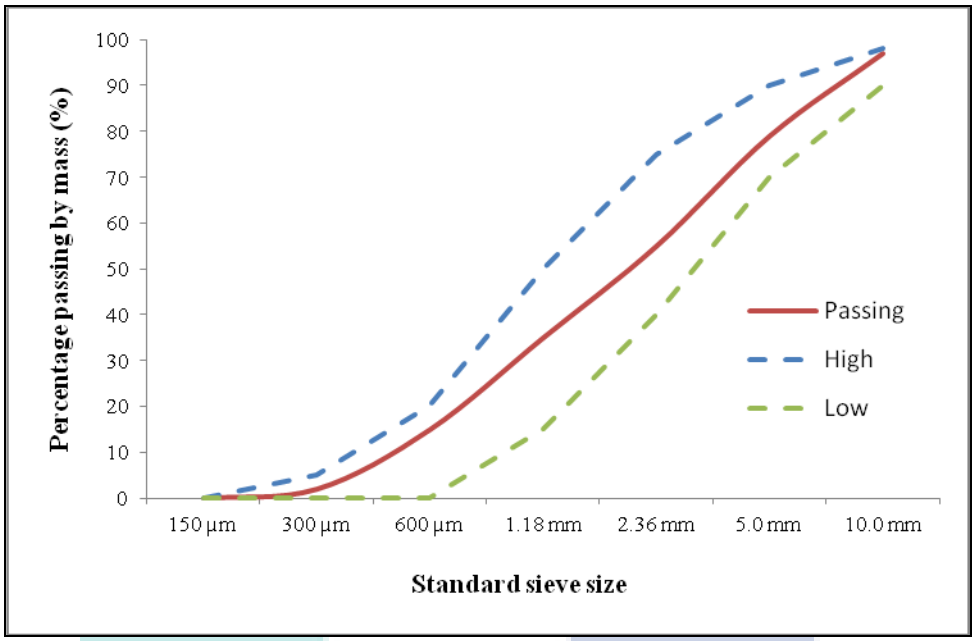


Figure 3.5: Grading chart of fine aggregate. Dashed line indicate limits specified in ASTM C33 for fine aggregates

3.2.7 Steel Fiber

The steel fiber used in this research is a product from Stahlcon. It is made from cold drawn high tensile steel wires, in accordance to ASTM A820 type 1 and shall have a minimum tensile strength 1100 N/mm^2. The specification of steel fiber is shown in Table 3.1 and Figure 3.6 shows a picture of steel fiber.

Table 3.1: Specification of steel fiber

Code	HE 0.75/60
Aspect Ratio	80
Fibre Length	60 mm
Equivalent Diameter	0.75 mm
Pieces per kg	4,600
Deformation	Hooked end with round shaft

Source: Stahlcon Product

Figure 3.6: Steel fibers

3.3 MIX PROPORTION OF STEEL FIBER REINFORCED ACRYLIC EMULSION POLYMER MODIFIED CONCRETE (SFRPMC)

In this research, steel fiber reinforced acrylic emulsion polymer modified concrete comprised of three different percentages of steel fibers; silica fume, acrylic emulsion polymers and water-cement were used. Detail of mix proportion of SFRPMC specimens is shown in Table 3.2. Among these parameters, the compatibility is dominated by the chemical composition of the reinforcing fiber together with their surface properties (Jarabo et al., 2012). Due to the parametric dependence of so many factors, the wide scattering in the mechanical properties of SFRPMC seems to be obvious. The optimization of mix design for SFRPMC had been explained in Appendix D.

Table 3.2: Mix proportion of SFRPMC and control specimens

Category	Code	Water-Cement Ratio	Polymer (%)	Silica Fume (%)	Steel Fiber (%)
Concrete with silica Fume	PCS	0.50	0.0	8.0	-
PMC			0		
AEPMC	PMC1.0	0.50	1.0	8.0	-
AEPMC	PMC2.5	0.50	2.5	8.0	-
AEPMC	PMC4.0	0.50	4.0	8.0	-
FRC					
SFRC	SFRC1.0	0.50	-	8.0	1.0
SFRC	SFRC1.5	0.50	-	8.0	1.5
SFRC	SFRC2.0	0.50	-	8.0	2.0
AEPM-SFRC					
Mix 1	SFRPMC1-3	0.42	1.0	5.0	1.0
	SFRPMC1-7	0.42	1.0	5.0	1.0
	SFRPMC1-28	0.42	1.0	5.0	1.0
Mix 2	SFRPMC15-3	0.42	2.5	6.0	2.0
	SFRPMC15-7	0.42	2.5	6.0	2.0
	SFRPMC15-28	0.42	2.5	6.0	2.0
Mix 3	SFRPMC26-3	0.42	4.0	8.0	1.5
	SFRPMC26-7	0.42	4.0	8.0	1.5
	SFRPMC26-28	0.42	4.0	8.0	1.5
Mix 4	SFRPMC32-3	0.50	1.0	6.0	1.5
	SFRPMC32-7	0.50	1.0	6.0	1.5
	SFRPMC32-28	0.50	1.0	6.0	1.5
Mix 5	SFRPMC43-3	0.50	2.5	8.0	1.0
	SFRPMC43-7	0.50	2.5	8.0	1.0
	SFRPMC43-28	0.50	2.5	8.0	1.0
Mix 6	SFRPMC48-3	0.50	4.0	5.0	2.0
	SFRPMC48-7	0.50	4.0	5.0	2.0
	SFRPMC48-28	0.50	4.0	5.0	2.0
Mix 7	SFRPMC63-3	0.60	1.0	8.0	2.0
	SFRPMC63-7	0.60	1.0	8.0	2.0
	SFRPMC63-28	0.60	1.0	8.0	2.0

Table 3.2: Continued

Mix 8	SFRPMC65-3	0.60	2.5	5.0	1.5
	SFRPMC65-7	0.60	2.5	5.0	1.5
	SFRPMC65-28	0.60	2.5	5.0	1.5
Mix 9	SFRPMC76-3	0.60	4.0	6.0	1.0
	SFRPMC76-7	0.60	4.0	6.0	1.0
	SFRPMC76-28	0.60	4.0	6.0	1.0

In this research, the most important objective is to investigate the effect of acrylic emulsion polymer and steel fiber as reinforcing agent into steel fiber reinforced concrete (SFRC). For homogeneous distribution of steel fiber into cement matrix, the modification to both chemical composition as well as surface properties of steel fiber by a combined dilute acrylic emulsion polymer is done. The effect of steel fiber on the physical and mechanical properties of cement mortar has been investigated. Finally the plausible mechanism of steel fiber controlling the physical and mechanical properties of cement mortar is elucidated.

Preparation of steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC) specimens is shown schematically in Figure 3.7. Portland cement confirming with Type I (ASTM C150) was used as the binder material for the preparation of cement mortar. The local river sand was used for the preparation of cement mortar did not contain any organic substances which might affect cement hydration reaction. To evaluate grading zone and average particles sizes of aggregates, sieve analysis was performed. The use of steel fiber as reinforcement in cement composite is made from cold drawn high tensile steel wires, in accordance to ASTM A820 type 1. Next, the respective amount of silica fume containing acrylic emulsion polymer with water and added to the alkali cement paste. The fresh concrete thus prepared was cast immediately in different moulds for mechanical strength specimens. The samples allowed setting in the moulds for 24 hours at ambient temperature. The specimens after setting were removed from the mould after cured for 3, 7 and 28 days.

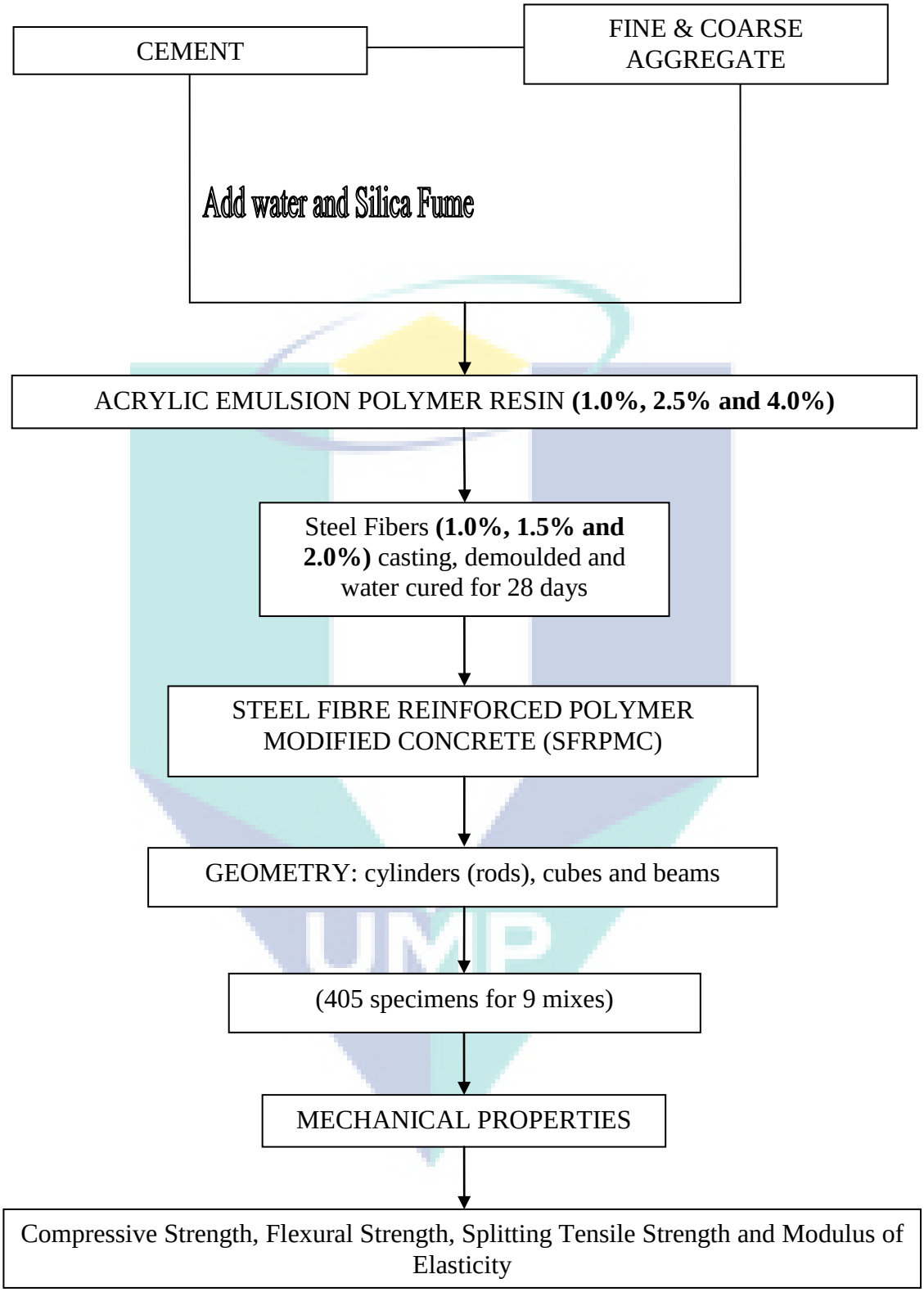


Figure 3.7: Flow chart to produce steel fiber reinforced polymer modified cement concrete (SFRPMC) specimens for mechanical testing

3.4 SAMPLE PREPARATIONS

3.4.1 Samples for Mechanical Properties Testing

The process of mixing and casting of the composites were carried out following Aziz et al. (1981). The amount of acrylic emulsion polymer was kept ready in suitable container. The quantity of water was then measured with a measuring cylinder and kept in suitable container. All polymers were mixed with half of water that measured into other container and put into the pan mixer. The mixing time was let to be 1 minute to 2 minutes.

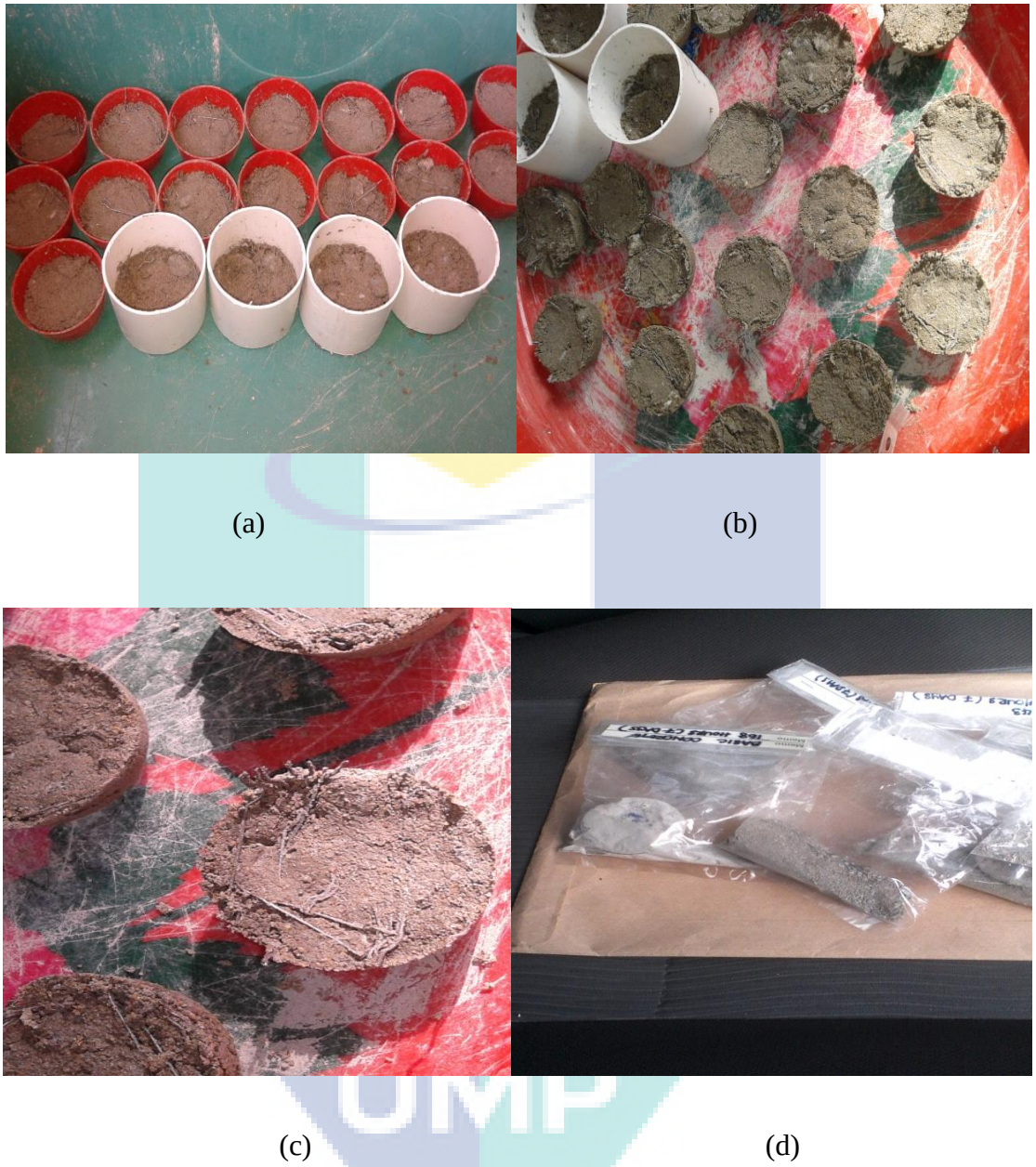
Then the amount of cement, silica fume and aggregates was kept ready in suitable container. Sand was fed into the pan mixer, a part of the coarse aggregates, cement, silica fume and the materials were mixed for 2 minutes. The other half of water with some of the remainder of the coarse aggregates was fed so as to break up any modules of mortar. After all ingredients were added, the mixing time was set to be 3 to 5 minutes till homogeneous obtained. The calculated steel fibers were measured and kept in suitable container. The steel fibers with 60 mm length sized hooked end were added in percentage by weight (of total wet solid). The fibers were added in small increments by sprinkling them onto the surface of the mix until all the fibers absorbed into the matrix. This technique was performed to prevent ‘balling’ or ‘interlocking’ of the fibers.

From each experiments of steel fiber reinforced polymer modified cement concrete, three cylinders (150 x 300 mm), three cubes (100 mm) and three beams (100 x 100 x 500 mm) were prepared. After conducting slump test, the concrete mix is placed inside the prepared moulds. Then, all specimens were compacted by means of a vibrating table. After that, the specimens were demoulded after 24 hours and subjected to water curing until the testing date. Figure 3.8 shows the mixing process and sample preparations of steel fiber reinforced polymer modified concrete (SFRPMC).

Figure 3.8: SFRPMC sample preparations: (a) mixing process (b) slump test (c) molding process after mixing, (d) compacting process, (e) molding for 24 hours before curing (f) curing process

3.4.2 Samples for Microstructural and Performance Analysis

With the same percentages of mix proportions in different curing aging of 1 hour, 24 hours and 168 hours, a few small specimens of SFRPMC with 1 mix of basic concrete were also tested for microstructural performance by using SEM-EDX, XRD and TGA. Figure 3.9 shows the specimens preparation for microstructural and performance analysis. In this experiment, for each formulation 6 specimens were fabricated for each test. The structural and thermal characteristics of specimens were investigated using an X-ray diffractometer (Rigaku MiniflexII model) and Mettler Toledo TGA/DSC 1 model. Diffraction parameter involved was CuKα source with wavelength 1.5148 Å. The scan step size was $0.02^{o,}$ the collection time 1s and in the range 2θ scanning temperature range is $5^{o} – 65^{o}$. For TGA testing, the specimen with 3 mg – 5 mg was heated at temperature range between 30^{o}C until 500^{o}C with temperature rise at 10^{o}C/mean in nitrogen flow. The micrographs of the specimens of were recorded using scanning electron microscope (Hitachi with S-3400N) and ZEISS SUPRA 55VP connected to an analysis system with Energy Dispersive X-ray (EDX).



(a) (b)

(c) (d)

Figure 3.9: Specimens' preparation for microstructural and performance analysis (a) molding process after mixing (b) demolding process (c) specimens for SEM-EDX testing (d) powdered specimens for XRD and TGA testing

3.5 EXPERIMENTAL PROGRAM

Figure 3.10 shows the process flow for the overall experimental programs.

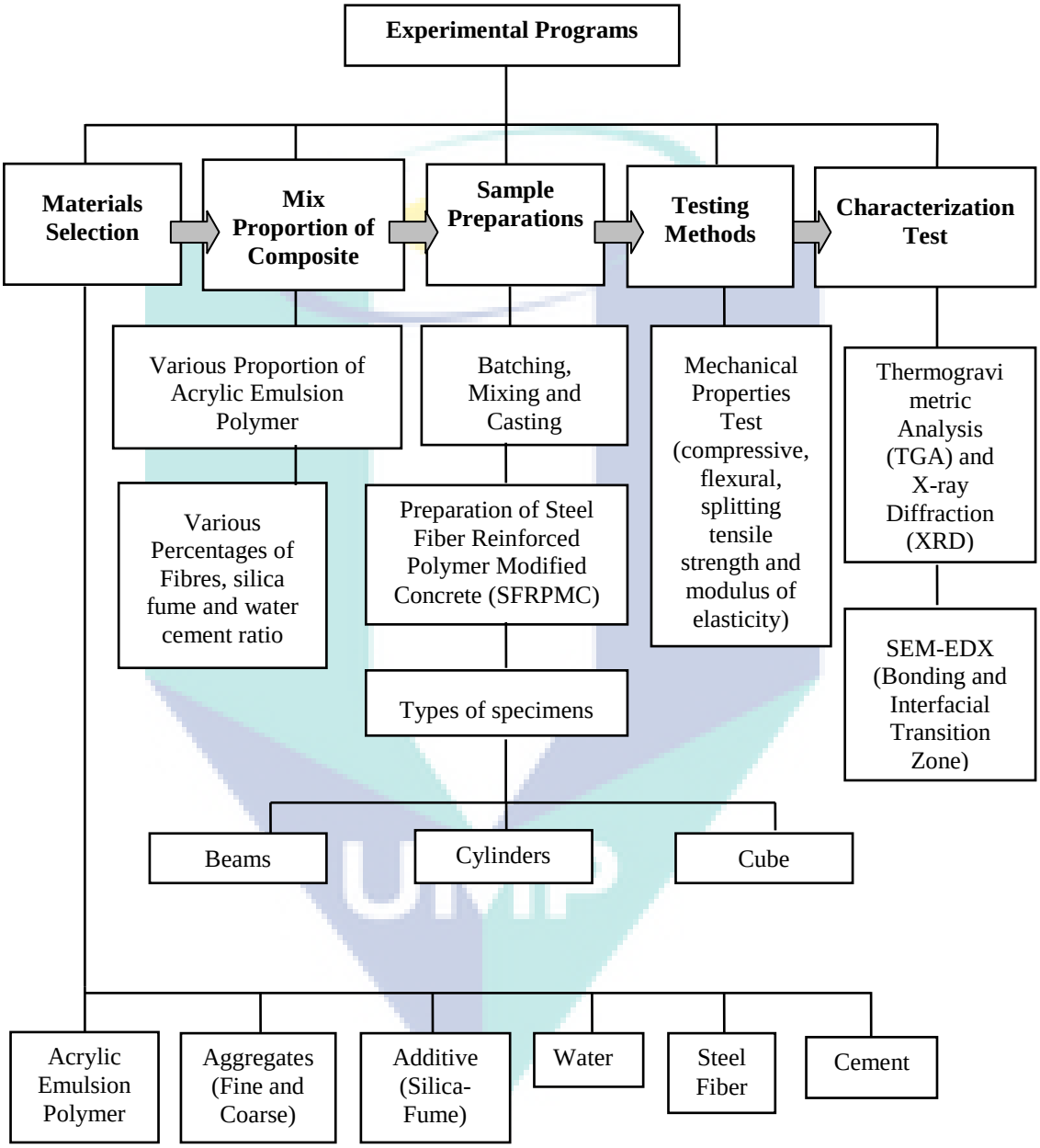


Figure 3.10: Process-flow for the experimental programs

3.6 TEST ON FRESH CONCRETE

After mixing 3 minutes, tests of fresh concrete were conducted as shown in Figure 3.11. Slump test was carried out according to ASTM C143. Sampling of the fresh concrete was performed in accordance with ASTM C172.

Figure 3.11: Slump test

3.7 TEST ON HARDENED CONCRETE

The objective of the research was to study the mechanical properties of hardened steel fiber reinforced concrete with polymer modification. All specimens followed guidelines from relevant ASTM standards where applicable, and tested according to ASTM standards.

3.7.1 Compressive Strength Test

The compressive strength of the concrete was obtained using the procedures in ASTM C109 (2012) for cube specimens**.** Generally, concrete specimens for compressive strength determination were cast in 100 mm cube moulds. These were greased with diesel prior to batching to facilitate the samples' removal. The moulds

were removed at about one day after batching. All specimens were tested in ELE compression testing machine; neoprene caps set in metal plates were used to provide an even loading surface. The load was applied at the rate of 0.3 N/mm^2/s. These tests were run at 3, 7, and 28 days. Figure 3.12 shows compression test setup. The compressive strength is calculated using Equation 3.1 shown below.

$$f_C = \frac{P}{A} \tag{3.1}$$

where:

f_c = compressive strength (N/mm^2)

P = maximum applied load (N)

A = cross sectional area of specimen (in mm^2)

Figure 3.12: Compression strength test setup

3.7.2 Flexural Strength Test

Flexural strength is also known as modulus of rupture. The test was intended to determine the flexural strength of concrete in tension. The specimens used were 100 x 100 x 500 mm. Three specimens were tested at each testing time. These tests were also run at 3, 7 and 28 days. The flexural strength was conducted according to ASTM C78

(1998). Flexural strength was determined using (50kN) capacity (ELE) machine. The average modulus of rupture was obtained for each testing age (3, 7 and 28 days).

In the flexural strength test, a concrete beam that was subjected to third point loading, right until failure occurs. However, for short-fiber reinforced beams, the loading allowed for a longer period of time after the failure of concrete occurs to observe the post-crack behavior of the concrete specimen. The specimens were rejected if the edges of the beams were chipped, surface cracking occurs and honeycomb can be obviously seen everywhere on the specimens. Furthermore, surfaces of the specimens had to be in the plane so that the lines of contact between the bearing surfaces where the rollers bear would not be out of the plane more than 1 mm. The flexural strength was calculated using Equation 3.2.

$$f_r = \frac{PL}{bd^2} \tag{3.2}$$

where:

f_r = modulus of rupture (N/mm^2)

P = maximum applied load indicated by testing machine (N)

L = distance between supports and equal to (450mm)

b = average width of specimen (mm)

d = average depth of specimen (mm)

3.7.3 Splitting Tensile Strength Test

Tensile strength of the concrete was found using the splitting tensile test following the procedures in ASTM C496 (1998). All cylinders batched were used for this test, three at each testing time. These tests were also run at 3, 7, 28 days. The ELE machine was again used, but the loading apparatus was changed. One-inch-wide strips of a thin fiberboard material were cut to provide a yielding bearing surface for the cylinders. One of these strips was placed on a steel plate on the bottom loading platen, and taped down to prevent movement. The cylinder was then laid down on the strip. Another plate with a strip of the wood was placed on top of the cylinder, with the strip

resting along the cylinder and the steel plate spreading the load from the upper loading platen 92 to the strip and cylinder. The load was applied at the rate of 0.094 N/mm^2/s. Figure 3.13 shows a splitting tensile test at completion. The splitting tensile strength was calculated using Equation 3.3.

$$f_s = \frac{2PL}{\Pi dL} \tag{3.3}$$

where:

f_s = splitting tensile strength (N/mm^2)

P = maximum applied load (N)

L = length (mm)

d = diameter (mm)

Figure 3.13: Splitting tensile strength test

3.7.4 Modulus of Elasticity (Young's Modulus)

Modulus of elasticity is also known as Young's Modulus. It is defined as the ratio of stress over strain. The test setup in the present study used a modified compressometer as per ASTM 469-94 (1994). The modulus of elasticity of concrete E_c adopted in modified form by the ACI Code can be calculated using Equation 3.4.

$$E_c = 0.043 w_c^{1.5} \sqrt{f_c'} \quad \text{MPa in SI units} \tag{3.4}$$

where

E_c = modulus of elasticity of concrete (MPa)

f'_c = specified 28 days compressive strength of concrete (MPa)

w_c = weight of concrete (kg/m^3)

3.7.5 X-ray Diffraction (XRD) Analysis

X-ray diffraction analysis was carried out on selected specimens from all composites that were produced in this research study. This test was carried out to know the element dispersion effect especially acrylic emulsion polymer and cement matrix. Diffractometer machine used in this research study is Rigaku MiniflexII model. Diffraction parameter involved was CuKα source with wavelength 1.5148 Å. The scan step size was $0.02^{o,}$ the collection time 1s and in the range 2θ scanning temperature range is 5^o – 65^o. The apparatus for x-ray diffraction analysis is shown in Figure 3.14.

Figure 3.14: Equipments used for X-ray diffraction testing

3.7.6 Thermogravimetric Analysis (TGA)

This analysis is thermal analysis which the research is done by studying the specimen changing with temperature changes. This analysis can be used to study specimen thermal stability. When temperature was levied at specimens, the particle energies in tested specimens will also increase with the increasing of temperatures. When temperature increases, chemical attraction will become weak and material that volatile easily and humidity will be removed from specimens. This will cause weight loss of the specimens. The specimens will have thermal decomposition and this temperature is known as decomposition temperature, T_{di} and at this moment the weight loss will become greater. In this experiment, the specimen with 3 mg – 5 mg was heated at temperature range between 30^{o}C until 500^{o}C with temperature rise at 10^{o}C/mean in nitrogen flow. The machine used in this study is Mettler Toledo TGA/DSC 1 model shown in Figure 3.15. From this analysis, heavy percentage graph versus composite decomposition temperature was determined.

Figure 3.15: Thermogravimetric analysis (TGA) apparatus

3.7.7 Scanning Electron Microscopy Test (SEM) and Energy Dispersive X-ray Analysis (EDX or EDAX)

The microstructure of specimens was examined with a Scanning Electron Microscope Hitachi with S-3400N (Figure 3.16) and ZEISS SUPRA 55VP connected to an analysis system with Energy Dispersive X-ray (EDX). All small specimens of 40 x 40 x 15 mm and 50 x 50 x 20 mm cylinders were prepared in small plastic molds. Tests were conducted on specimens prepared 1 hour, 6 hours, 1 day and 7 days before testing. Backscattered and secondary electron images were obtained from polished sections. Quantitative analyses of X-rays were performed at points located in the interfacial transition zone (ITZ). At each point, quantitative analyzes of Na, Mg, Al, Fe, S, Ca, Si, Mn and K (Oxygen was stoichiometrically calculated) were made. All the specimens were used for each type of concrete, and all the points of ITZ, region of the specimens were arbitrarily chosen. Analyzes of the compositions of the main cement hydration products (CSH, CH, Af_m and Af_t) were used to compare the characteristics of the ITZ of the concretes.

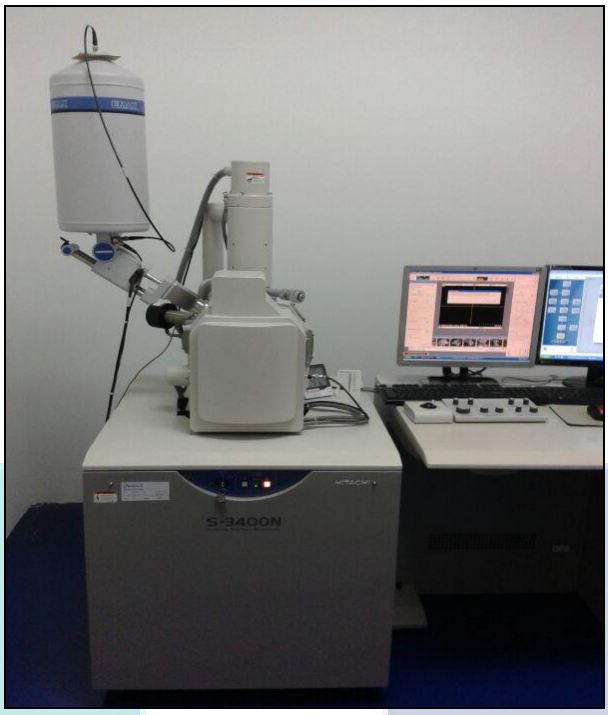


Figure 3.16: Equipments used for SEM-EDX testing

CHAPTER 4

RESULTS ON PRELIMINARY STUDIES ON MATERIAL FORMULATION BY USING EXPERIMENTAL DESIGN (DoE)

4.1 INTRODUCTION

Firstly, the objective of this research is to determine the major parameter to determine compressive strength of the steel fiber reinforced polymer modified concrete (SFRPMC) by using experimental design method (DoE) called Taguchi method. The composite that produced is using the experimental design and all the specimens are tested by using compressive test. The major parameter for composite system production is determined through ANOVA and ANOM analysis. The research results are obtained during validation experiment.

By using 5 parameters (control factors), L27 array is chosen. During L27 orthogonal array, no or negligible interaction between parameters is observed. There is no use of a noise factors because the cubes, cylinders/ other-shapes for testing the compressive/tensile/flexural of steel fiber reinforced concrete had been done during trial mixes. Noise is not required when there is more than 1 sample and there are 2 or 3 samples had been done for each testing after 3 days, 7 days and 28 days curing. A noise factor also can be done by taking segregation (fine and coarse) is most suitable and this two factors also had been considered during mix design process. And then the confirmation or verification also known as a "fine tuning" experiment using an L9 array with the above 4 parameters with 3 levels was done.

4.2 TAGUCHI METHOD

There are ten steps in a systematic approach to the use of Taguchi's parameter design methodology (Aloia and Cordin, 2006). Figure 4.1 shows the detail procedure of Taguchi design methodology. The significant difference between the Taguchi's approaches with classical methodology is in step 7 of Figure 4.1 where the orthogonal matrix is set by parameters and levels.

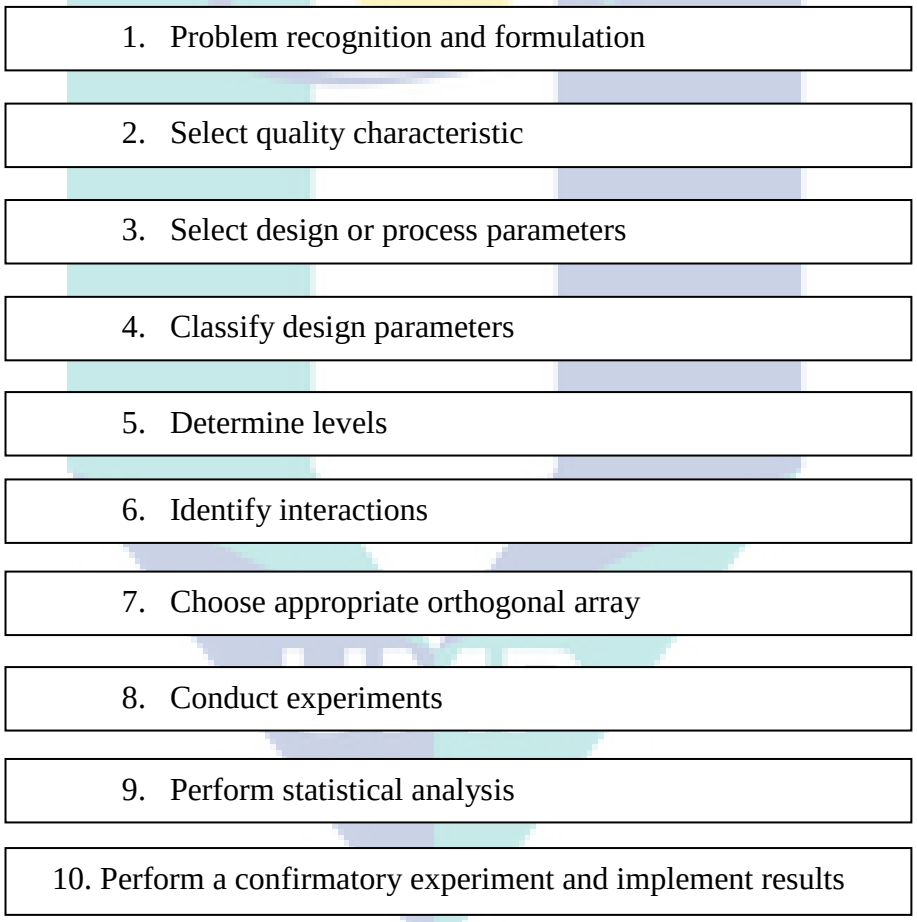


Figure 4.1: Taguchi method algorithm

4.3 L27 PRELIMINARY EXPERIMENTAL DESIGN

4.3.1 Parameter Selection

In this research, during the preliminary design, there were five control parameters selected. This control parameter selection was made after some considerations. Consideration was made based on laboratory works and information obtained from various journals. Various factors were selected so that the process of control factor determination that was not significant can be found in the beginning of the experiment. There are a few composite study that has been conducted by using experimental design by Nuruddin and Bayuaji, 2007; Muhammed et al., 2009; Majzadeh et al., 2010 and Khosrokhavar et al., 2011. However, experimental design has not been used for steel fiber reinforced acrylic emulsion polymer modified concrete.

Water-cement ratio, percentage of acrylic emulsion polymer, percentage of steel fiber and percentage of silica fume and curing time (aging) were the selected parameters. All the parameter was selected in three levels. All control factor and level for each are shown in Table 4.1. Besides of control parameter selection, the noise factor was also deliberated in this experiment. In Taguchi design, a measure of robustness is used to identify control factors that can reduce variability in a product or a process by minimizing the effects of uncontrollable factors (noise factors). Variation reduction is universally recognized as a key to reliability and productivity improvement. There are many approaches to reduce the variability, each one having its place in the product development cycle. By addressing variation reduction at a particular stage in a product's life cycle, one can prevent failures in the downstream stages. The robustness strategy is to prevent problems through optimizing product designs and manufacturing process designs (Phadke, 2008).

In this experiment, there were two noise factors considered which cause segregation such as fine and coarse aggregates. However these noise factors already considered in mix design optimization (trial mixes). Therefore, only one mix has been made for each row of the L_{27} orthogonal array concrete mix. Thus, mix concrete was not robust against noise factor and the "fine tuning" experiment around the best level of water-cement ratio was performed. Fine tuning is a verification experiment repeated

until five times to get precise results while robust is a repeated experiment to get same result because of all factors and noise factor had been used during analyses.

The Orthogonal array (OA) experimental design method was chosen to determine the experimental plan, L_{27} (3^5) is one of the standard experimental plans improved by Taguchi (Genichi Taguchi and Taguchi, 2000) (see Table 4.2) since it is the most suitable for the condition being investigated, i.e. four parameters with three levels (values). In Table 4.2, it should be noted that the parameter variable 1, 2, 3 and 4 were acrylic emulsion polymer, silica fume, steel fiber, water-cement ratio and curing time all have three levels respectively.

Five parameters which were acrylic emulsion polymer, silica fume, steel fiber, water-cement ratio and curing time, each at three levels were considered in this study in accordance with L_{27} ($_3^{13}$) orthogonal design. Finally, L_{27} Orthogonal array was selected according to the suitable control parameter that had been selected. This orthogonal array is shown in Table 4.2. For the easiest analysis, the assumption of the interaction between parameter does not depend with each other must be made. Besides, the selection of the control parameter, the noise factors with two levels were considered in this experiment during mix design optimization (refer Appendix C). All the samples that produced from this orthogonal array were tested with compressive test.

Table 4.1: Control parameter and level that used in L_{27} Orthogonal Array

Control Parameter	**Level**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Water-Cement Ratio	0.4	0.5	0.6	-	-	-	-	-	-
Steel Fiber (%)	1.0	1.5	2.0	-	-	-	-	-	-
Acrylic Emulsion Polymer (%)	1.0	2.5	4.0	-	-	-	-	-	-
Silica Fume (%)	5	6	8	-	-	-	-	-	-
Curing Time (Day)	3	7	28	-	-	-	-	-	-

Table 4.2: Standard L_{27} orthogonal array

Experiment No	Water-Cement Ratio	Acrylic Emulsion Polymer %	Silica Fume %	Steel Fiber %	Age	Performance parameter value
1	1	1	1	1	1	SFRPMC-1
2	1	1	1	1	2	SFRPMC-2
3	1	1	1	1	3	SFRPMC-3
4	1	2	2	2	1	SFRPMC-4
5	1	2	2	2	2	SFRPMC-5
6	1	2	2	2	3	SFRPMC-6
7	1	3	3	3	1	SFRPMC-7
8	1	3	3	3	2	SFRPMC-8
9	1	3	3	3	3	SFRPMC-9
10	2	1	2	3	1	SFRPMC-10
11	2	1	2	3	2	SFRPMC-11
12	2	1	2	3	3	SFRPMC-12
13	2	2	3	1	1	SFRPMC-13
14	2	2	3	1	2	SFRPMC-14
15	2	2	3	1	3	SFRPMC-15
16	2	3	1	2	1	SFRPMC-16
17	2	3	1	2	2	SFRPMC-17
18	2	3	1	2	3	SFRPMC-18
19	3	1	3	2	1	SFRPMC-19
20	3	1	3	2	2	SFRPMC-20
21	3	1	3	2	3	SFRPMC-21
22	3	2	1	3	1	SFRPMC-22
23	3	2	1	3	2	SFRPMC-23
24	3	2	1	3	3	SFRPMC-24
25	3	3	2	1	1	SFRPMC-25
26	3	3	2	1	2	SFRPMC-26
27	3	3	2	1	3	SFRPMC-27

4.3.2 Determination of Parameter Effect

Calculation of signal to noise ratio for compressive strength:

Based on 27 experiments of compressive strength that had been carried out, the statistical formula η_i for experiment *i*, can be summarized as:

$$\eta_i = -10 \log_{10} (\text{mean square reciprocal number for experiment } i)$$

Calculation of signal to noise ratio (SN) for compressive strength:

Calculation 1:

Determine reciprocal of sum of square (SSQ) to all values (Y) measured by

$$SSQ = Y1^{\wedge} - 2 + Y2^{\wedge} - 2 + Y3^{\wedge} - 2 + Y4^{\wedge} - 2 \tag{4.1}$$

Calculation 2:

Determine reciprocal mean square

$$\text{MSSQ} = (\text{SSQ}) / \text{number of measurement} \tag{4.2}$$

Calculation 3:

For the case of maximizing the performance characteristic, the following definition of the SN ratio should be calculated:

$$n = 10\log 10\left[\frac{1}{n}\sum\left(\frac{1}{Y_1^2} + \frac{1}{Y_2^2} + \frac{1}{Y_3^2}\right)\right] \tag{4.3}$$

The effect of each parameter was chosen from the obtained value of 27 experiments. The total average value, η for all parameters and level in Table 4.1 is given by:

$$m = \frac{1}{27}\sum_{i=1}^{27}\eta_i \tag{4.4}$$

$$= \frac{1}{27}(\eta i + \eta i + \ldots\ldots\ldots\ldots + \ldots\ldots\ldots\ldots \eta i_{27}) \tag{4.5}$$

If the column of each parameter had been scrutinized in Table 4.2, the numbers of levels of each parameter are also present is same as in 27 experiments that had been carried out. Therefore, m is the overall factor mean that was equal in experiment that carried out. From this study, the effect of parameter level can be defined as deviation from overall mean. For example, the effect of water-cement ration will exist in experiment 1, 4, 7, 10, 13, 16, 19, 22 and 25. Hence,

$$mB1 = 1/9 * (\eta_1 + \eta_4 + \eta_7 + \eta_{10} + \eta_{13} + \eta_{16} + \eta_{19} + \eta_{22} + \eta_{25}) \tag{4.6}$$

So, mB3 is mean η for water-cement ratio in level 3 where this mean was done in equal state for all levels of each parameter that had been considered. Hence, the effect of parameter B3 = b3 = mB3-m.

All parameters and level are repeated by using equation 4.4

- mA1, mA2, mA3 ……mJ3

By taking all values that had been calculated, mean η for each level for five parameters were determined and the value can be shown in Appendix A. This value can be described graphically in Figure 4.2. Analysis that had been carried out is known as mean analysis (ANOM). The effect of each parameter is plotted and is known as S/N chart or factor effect plot chart.

Overall mean,

$$m = 1/27(\eta_1 + \eta_2 + \eta_3 + \eta_4 + \ldots\ldots\ldots \eta i_{27}) = 26.53dB \quad (4.7)$$

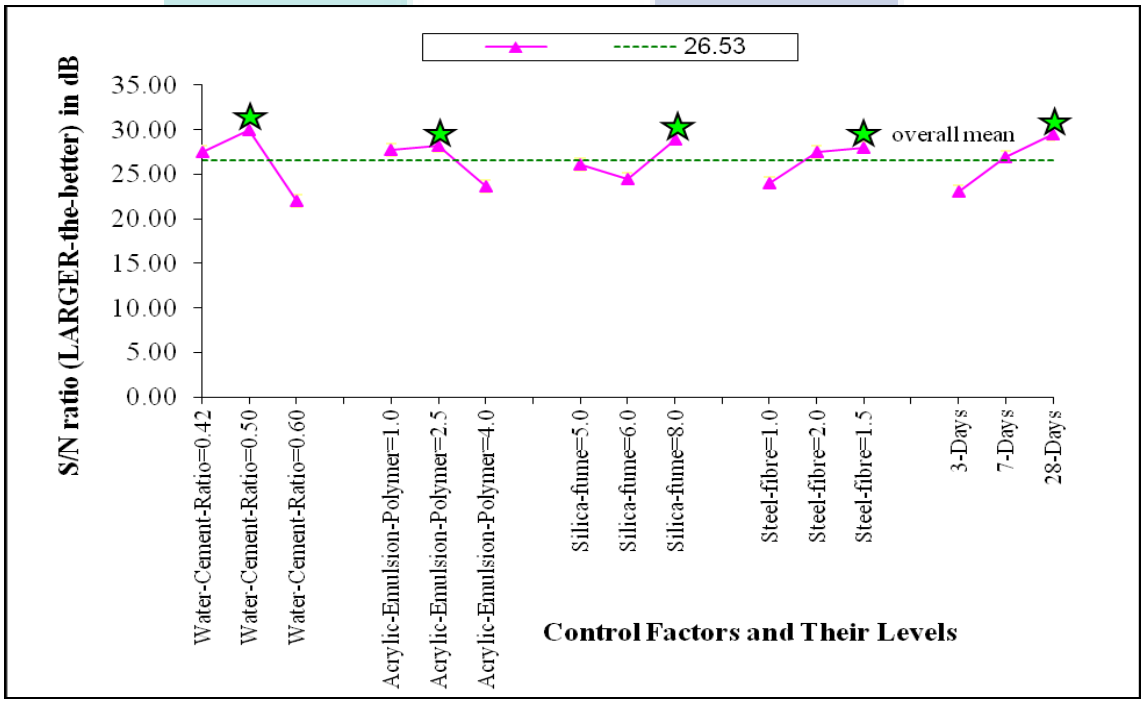


Figure 4.2: Factor effects for cube compressive strength of steel fiber reinforced polymer modified concrete (SFRPMC) mixes

Based on S/N ratio chart, the optimum level of control parameter for compressive strength can be obtained. The optimum level of each control parameter is summarized in Table 4.3.

Table 4.3: Optimum level for production of maximum cube compressive strength of SFRPMC

Control Parameter	**Optimum Level**
water-cement ratio	0.5
Percentage of acrylic emulsion polymer (%)	2.5
Percentage of silica fume (%)	8
Percentage of steel fiber (%)	1.5
Curing time (day)	28

Through variance and mean analysis, contribution of each control parameter was determined and parameter that gives less contribution (refer Appendix A) was ignored during preparation of sample for the next verification process. Figure 4.3 showed that the water-cement ratio was the main control parameter with 39% contributions followed by curing time with 24% contribution. Apart from that, silica fume, acrylic emulsion polymer and steel fiber are factors which give effect on compressive strength of the specimens.

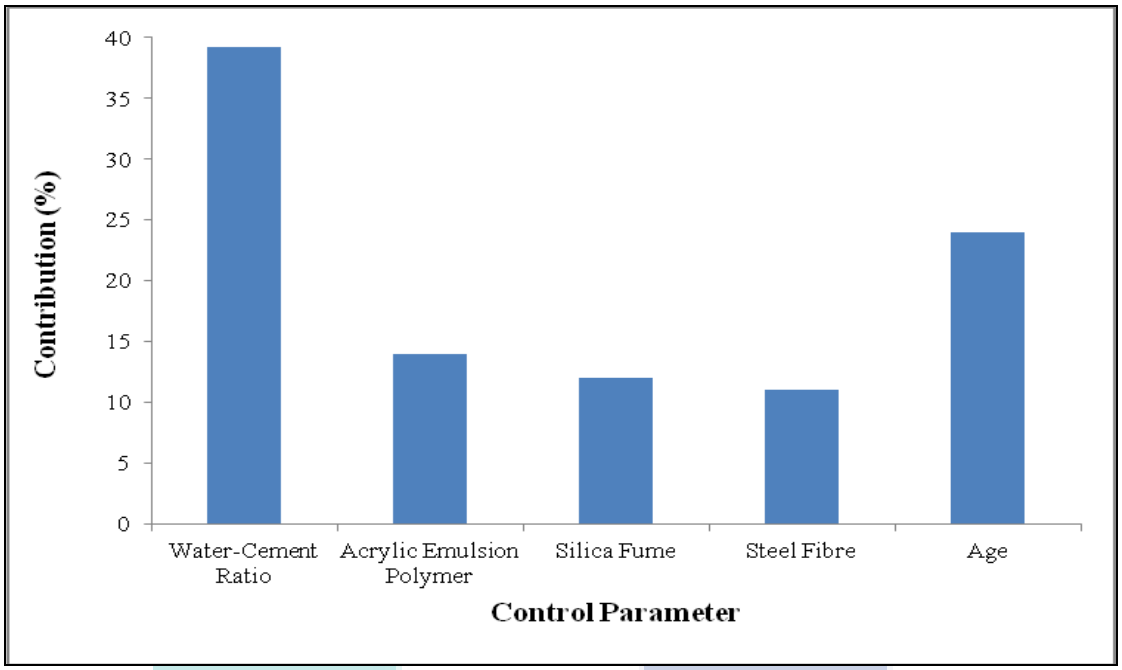


Figure 4.3: Plot of ANOVA analysis for cube compressive strength of steel fiber reinforced polymer modified concrete (SFRPMC) mixes

4.4 ADDITIVE MODEL

Additive model are also known as superposition model where it gives relationship between interaction product variable and control factor. In this model, level effect for each parameter that had been studied was evaluated separately. Predicted results can be determined by including specific factor level value. This additivity is influenced by selected quality characteristic, S/N ratio, control parameter and level. If the additivity and additive model had been verified, it is legalized prediction for laboratory and production benefit.

The model produced gives justification for calculation of factor effect as mean from the experiments that had been carried out. The competitive model is approximation

$$\eta = \mu + a_i + b_j + c_k + d_l + ... + \varepsilon \quad (4.8)$$

Deviation due to A_i level from μ was given by a_i, B_j was from μ as b_j and further on. ε is an error due to additivity approximation and also error in calculation.

The total of deviation due to each level in each parameter is zero. If parameter are considered in three level, thus for this parameter:

$$B = b_1 + b_2 + b_3 = 0 \tag{4.9}$$

Mean of parameter effect for all parameters is equivalent to μ.
The relationship between control parameter and performance characteristics should be additive. The additivity ensured the design stability in laboratory, production and consumer's use.

4.4.1 Determination of Parameter Effect by Using Additive Model

From this study, the example of water-cement ratio in level 3 is

$$mA3 = 1/3*(\eta_7 + \eta_8 + \eta_9) = m + a_3 \tag{4.10}$$

Meanwhile percentage of acrylic emulsion polymer in level 3 is

$$mB3 = 1/9*(\eta_3 + \eta_6 + \eta_9 + \eta_{12} + \eta_{15} + \eta_{18} + \eta_{21} + \eta_{24} + \eta_{27}) = m + b_3 \tag{4.11}$$

All parameter effect in each level is calculated and variance analysis was carried out. Variance analysis (ANOVA) is needed to determine variance error for parameter effect and variance for prediction.

In ANOVA analysis, some calculation has to be done namely:
Largest Overall Square:

$$G_T = \sum_{i=1}^{27} \eta_i^2 \tag{4.12}$$

Overall mean square:

$$S_M = 27 * m^2 \tag{4.13}$$

Sum overall square
= GT – ST and also

$$= \sum_{i=1}^{27} \eta_i^2 - 27 * m^2 \tag{4.14}$$

Sum of squares (SSQ) referring to each parameter. Sum of squares referring to parameter A;

SSQ A = 3 ($a_1^2 + a_2^2 + a_3^2 + a_4^2 + a_5^2 + a_6^2 + a_7^2 + a_8^2 + a_9^2$) (4.15)

Sum of squares referring to parameter B; SSQ B = 9 ($b_1^2 + b_2^2 + b_3^2$) (4.16)

Sum of squares referring to parameter C; SSQ C = 9 ($c_1^2 + c_2^2 + c_3^2$) (4.17)

All the parameter results of sum of squares were calculated. Hence, the percentage of contribution of each parameter is calculated with (sum of squares/total of sum of squares) x 100 = percentage of contribution (refer Appendix A).

4.5 EVALUATION OF MAJOR PARAMETER EFFECT ON COMPRESSIVE STRENGTH

The effect of each parameter used in this experiment study was analyzed. The compressive strength (signal/noise ratio) of each parameter and level was plotted in signal/noise chart. Each reading in this plot was average in reading, at least five specimens were prepared for cube compressive strength.

4.5.1 Water-Cement Ratio

From Figure 4.4, the optimum water-cement ratio is 0.50. The compressive strength shows improvement from 0.42 until 0.50 followed by reducing of compressive

strength at 0.60 of water-cement ratio. When the initial value of the water cement-ratio > 0.50, there is an excess of water and then the capillary pores are large and probably cannot be filled completely. Otherwise, for a water-cement ratio < 0.50 only reduced water flow is possible. Then there is enough water for hydration and also enough space for hydration products, which swell during the process so that the capillary pores may have reduced permeability. These values for mortars and concretes depend on the mixture proportions and quality of components, and also on special admixtures added to modify the fluidity of the fresh mix (Brandt, 2009).

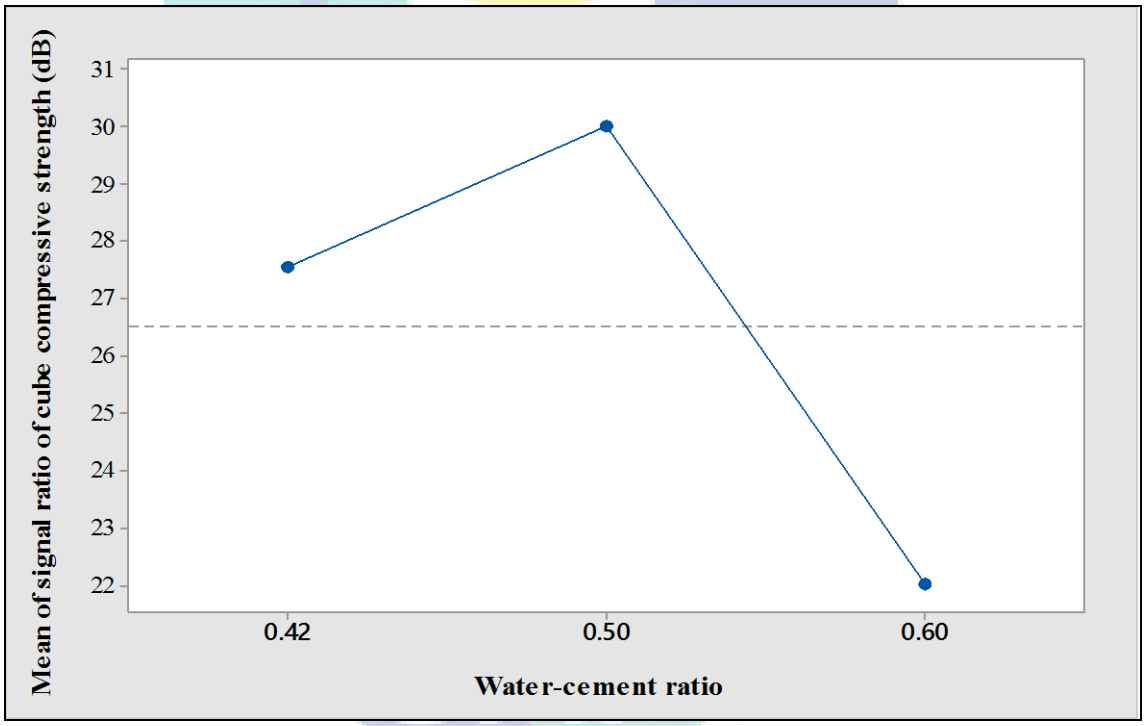


Figure 4.4: Main effect plot for signal ratio of water-cement ratio on cube compressive strength of SFRPMC mixes

4.5.2 Acrylic Emulsion Polymer

Figure 4.5 illustrate the effect of acrylic emulsion polymer (AEP) content on compressive strength of SFRPMC mixes. After an initial increase in compressive strength there is a marginal decrease at higher percentages of polymer/cement. Evidently, only suitable acrylic emulsion polymer content which is 2.5% would be able to assist the SFRPMC mix to achieve optimum compressive strength. Too much of AEP

decreases the strength of concrete. This was probably due to the decrease in the rate of hydration of cement particles which in turn due to the presence of the polymer in the cement-polymer matrix. Similar observation has been made by Beeldens et al. (2003) who reported that the excessive use of polymer more than 15% could be inefficient for strength development of acrylic emulsion polymer concrete.

The polymer particles coalesce to form a film around the cement particles (Lavelle, 1986). This films either retards or prevents the percolation of water to the cement particles thereby decreasing or preventing hydration. The thickness of the film and its permeability to water molecules depend mainly on the type and percentage of the polymer used (Dennis and Dong-Tsai, 1992). In polymer dispersions, the surfactants hold the water for hydration more compactly since their hydrophilic parts are partially bound to the water molecules; the presence of surfactants tends to entrap air which decreases the strength of the composites (Miller, 2005).

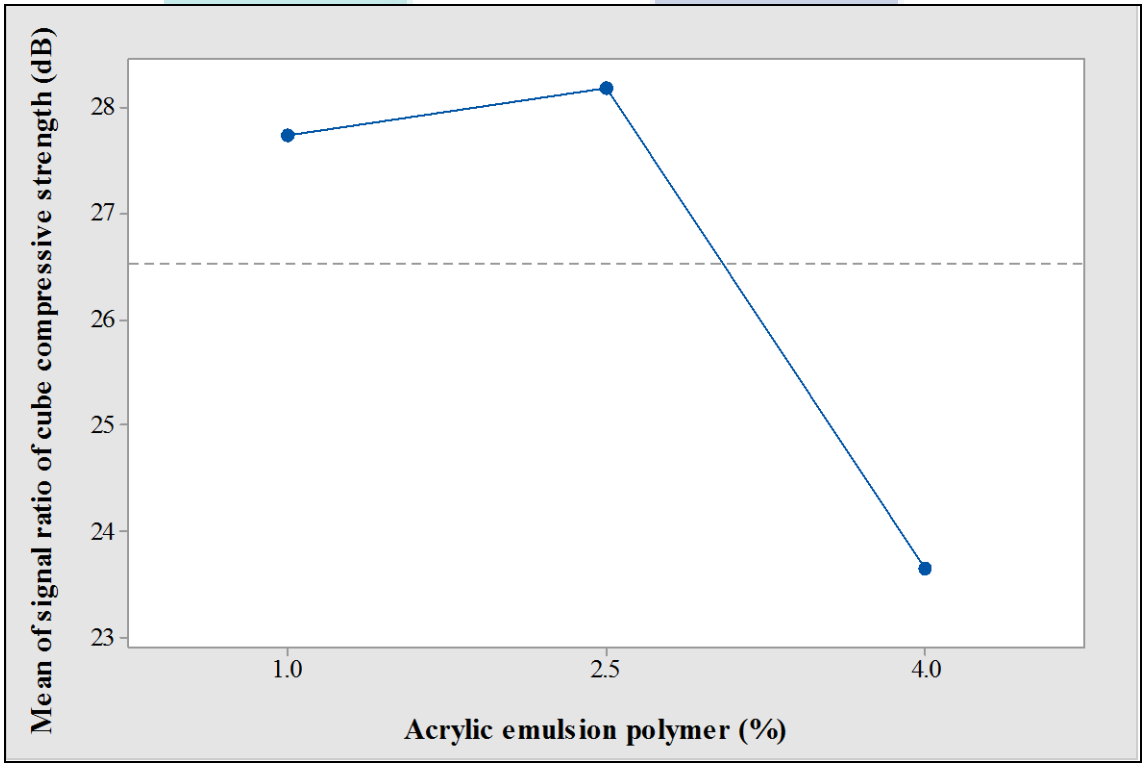


Figure 4.5: Main effect plot for signal ratio of acrylic emulsion polymer (%) on cube compressive strength of SFRPMC mixes

4.5.3 Silica Fume

Silica fume caused a slight increase in contact resistivity, indicating no decrease of the interfacial void content. In this research, 8% of silica fume is the optimum content of mix proportion as can be observed in Figure 4.6. The small microsilica particles fill spaces between cement particles and between the cement paste matrix and aggregate particles. Microsilica also combines with calcium hydroxide to from additional calcium silicate hydrate gel through pozzolanic reaction. Both of these actions results in a denser, stronger and less permeable material (Heidari and Zabihi, 2013). Fu and Chung (1998) also reported that the effectiveness of silica fume in combination with polymer as admixtures is due to the combined effect in which silica fume causes an increase in the matrix modulus (rather than interfacial void content decrease) while polymer improves adhesion. The content of silica fume is usually between 7% and 15% of cement mass as an addition or replacement and in most cases 8% is considered as optimum (Brandt, 2009).

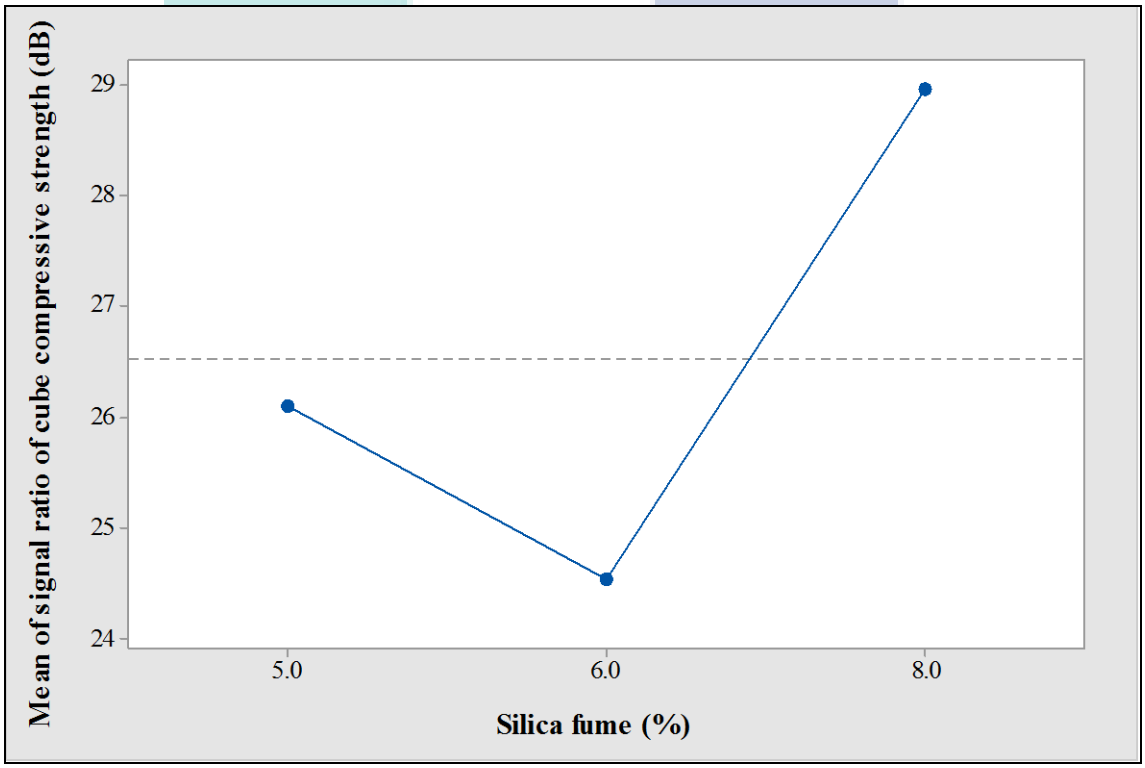


Figure 4.6: Main effect plot for signal ratio of silica fume (%) on cube compressive strength of SFRPMC mixes

4.5.4 Steel Fiber

The influence of steel fiber content towards compressive strength of SFRPMC mixes is illustrated in Figure 4.7. Compressive strength shows improvement when the percentage of steel fiber integrated in the concrete mix becomes higher. This is probably due to the characteristic of steel fiber which is high strength. The positive contribution of steel fiber to concrete strength enhancement has been highlighted by Johnston (1982). However, adding too much of steel fiber does not cause significance increase in the compressive strength. Previous researchers, Atis and Karahan (2009) also reported that increasing steel fibers content results in small increase in compressive strength (up to 10%). Evidently, addition of 1.5% of steel fiber contributes to significant compressive strength achievement as compared to 2%. Therefore, in this research the optimum percentage of steel fiber that had been chosen is 1.5%.

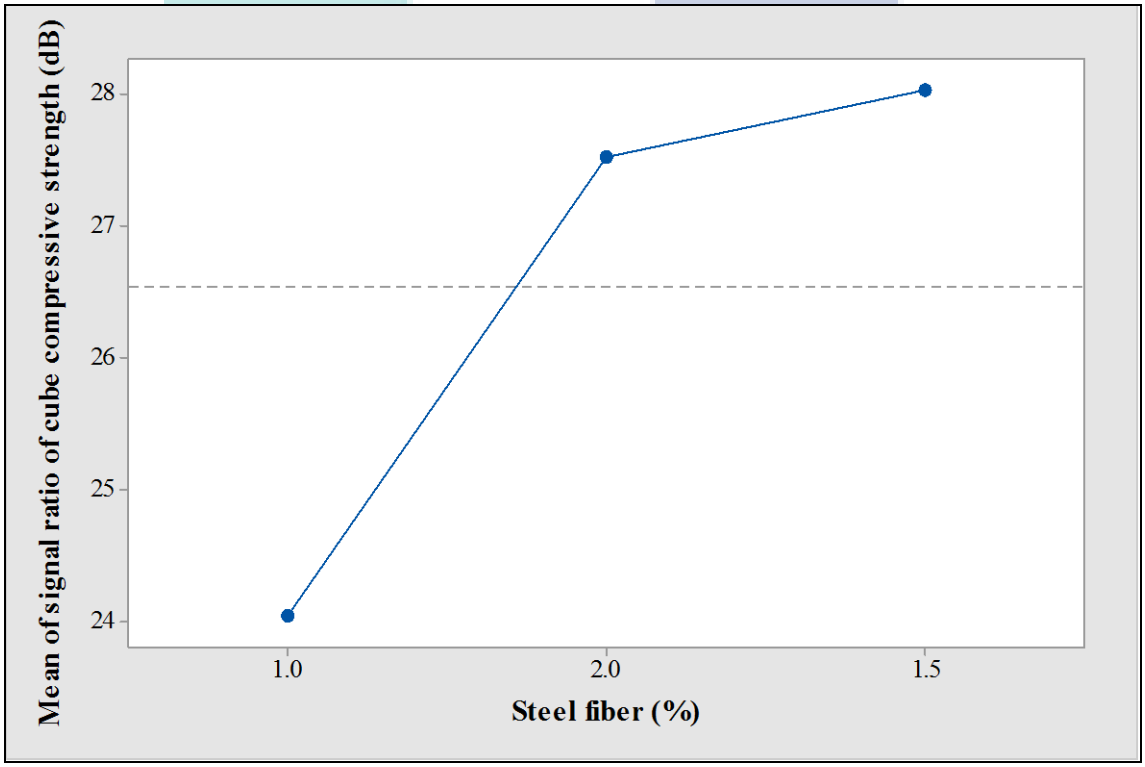


Figure 4.7: Main effect plot for signal ratio of steel fiber (%) on cube compressive strength of SFRPMC mixes

4.5.5 Curing Time

Curing is the process of controlling the rate and extent of moisture loss from concrete during cement hydration. As displayed in Figure 4.8, compressive strength of steel fiber reinforced polymer modified concrete (SFRPMC) increasing drastically from 3 to 28 days. Prolonging the water curing period allows better hydration process to take place in the concrete mix. Continuous availability on moisture prolongs hydration process which produces more C-S-H gel that is responsible to enhance the concrete strength. In other words, longer curing time enables production of large amount of C-S-H gel from hydration process that fills in the pores inside concrete making it denser and stronger compared to the one subjected to shorter curing age. From Krishna et al. (2010) study, compressive strength increased with age (curing time). The optimal curing time that achieved is 28 days, showing the highest value of compressive strength.

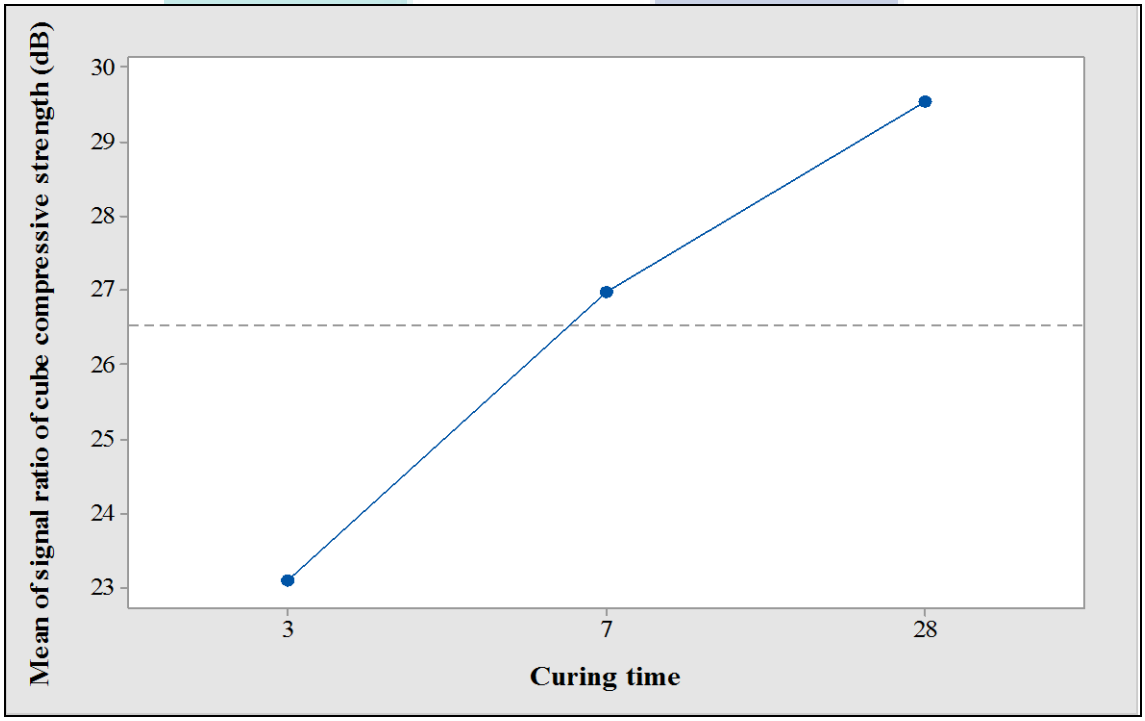


Figure 4.8: Main effect plot for signal ratio of curing time (days) on cube compressive strength of SFRPMC mixes

4.6 SUMMARY

In this chapter, steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC) were generated through solution mix design and molding techniques and effect of various control parameter on compressive strength of SFRPMC were analyzed by using Taguchi method approach. Conclusion can be made after verification experiment:

- Compressive strength is influenced by water-cement ratio, percentage of acrylic emulsion polymer, silica fume, steel fiber and curing time (aging).
- Optimum condition for SFRPMC are as follows:
    - Water-cement ratio: 0.50
    - Percentage of acrylic emulsion polymer (%): 2.5
    - Percentage of silica fume (%): 8
    - Percentage of steel fiber (%): 1.5
    - Curing time (day): 28
- Verification experiment that had been carried out had confirmed the additive model that built. The results of verification experiment had been in the analysis range that predicted by ANOVA and ANOM analysis.

CHAPTER 5

RESULTS AND DISCUSSION

MATERIAL FORMULATION BY USING EXPERIMENTAL DESIGN (DoE) FOR OPTIMIZATION OF MECHANICAL PROPERTIES OF STEEL FIBER REINFORCED ACRYLIC EMULSION POLYMER MODIFIED CONCRETE (SFRPMC)

5.1 RESULTS AND ANALYSIS

From the results in Chapter 4, by looking at the factor effects plots, the water content is at center level which was the best and effect reduces on either side or produces “BELL shaped” or “maxima at central level type. The polymer content is similar to this which also produces “BELL shaped”. For steel fiber plot it also produced “maxima at central level” type. The important property of this “maxima at central level” type plot was the results that “insensitive” to small variations around the center values of these control factors. Thus, this composite was “insensitive” or robust with respect to variations in water content, polymer content and steel fiber content. Hence, the verification experiment also called a “fine tuning” experiment by using L9 orthogonal array with three control parameters with three levels. This experiment also called as “fine tuning” because of the small changes on either side of the BEST levels.

5.1.1 Analysis on Results of L27 Orthogonal Array

By using ANOVA and ANOM analysis, main control parameter and interaction between each parameter can be traced. This criterion is determined based on cumulative

contribution (%) approximately 90%. This analysis is done for all mechanical properties that involved in this research study. ANOVA analysis diagram are indicated in Figure 5.1 to 5.4.

From Figure 5.1 to 5.4 shown below, to achieve the maximum strength, the water-cement ratio is the main effect. This parameter contributes more than 30% on all mechanical strength. The second main effect is curing time (aging) which contributes more than 20% on mechanical strength. Curing time contributes 30% on splitting tensile strength. Besides, acrylic emulsion polymer content contributes more than 10% on all mechanical strength that involved in this research. Then, silica fume is the fourth key factor that affects the mechanical strength and it contributes 12% to 17% on mechanical strength of this composite that had been produced. Lastly, steel fiber contributes less effect on mechanical strength with 8 % to 11% contribution.

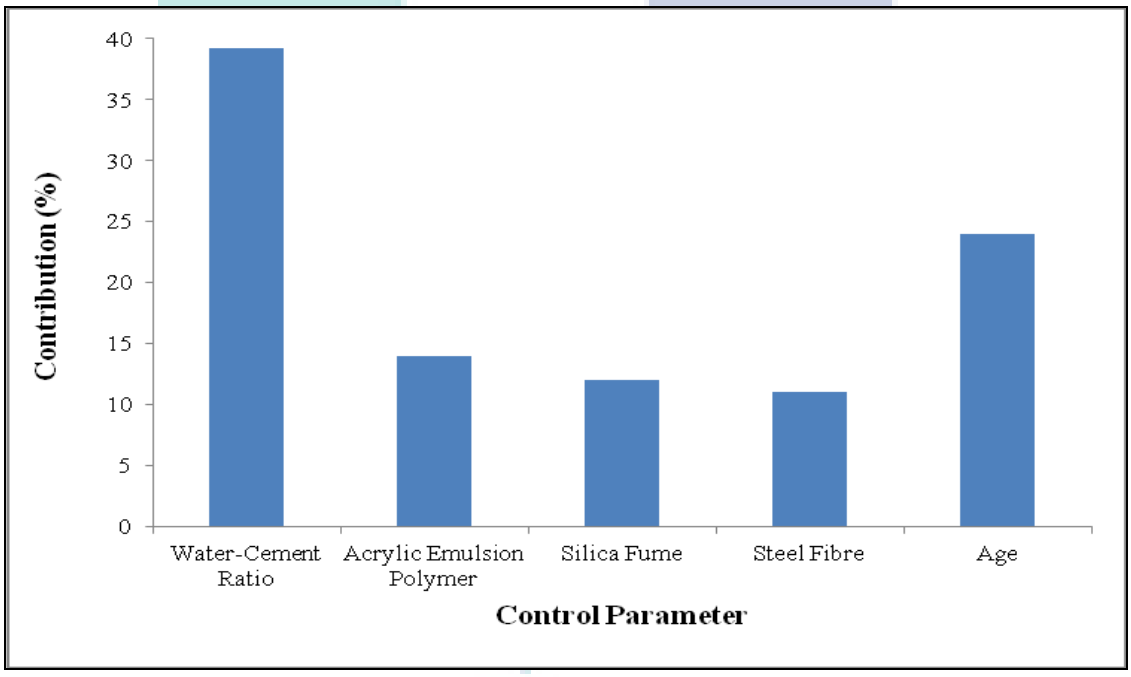


Figure 5.1: ANOVA analysis diagram that shows control parameter influence cube compressive strength of 27 SFRPMC mixes specimens

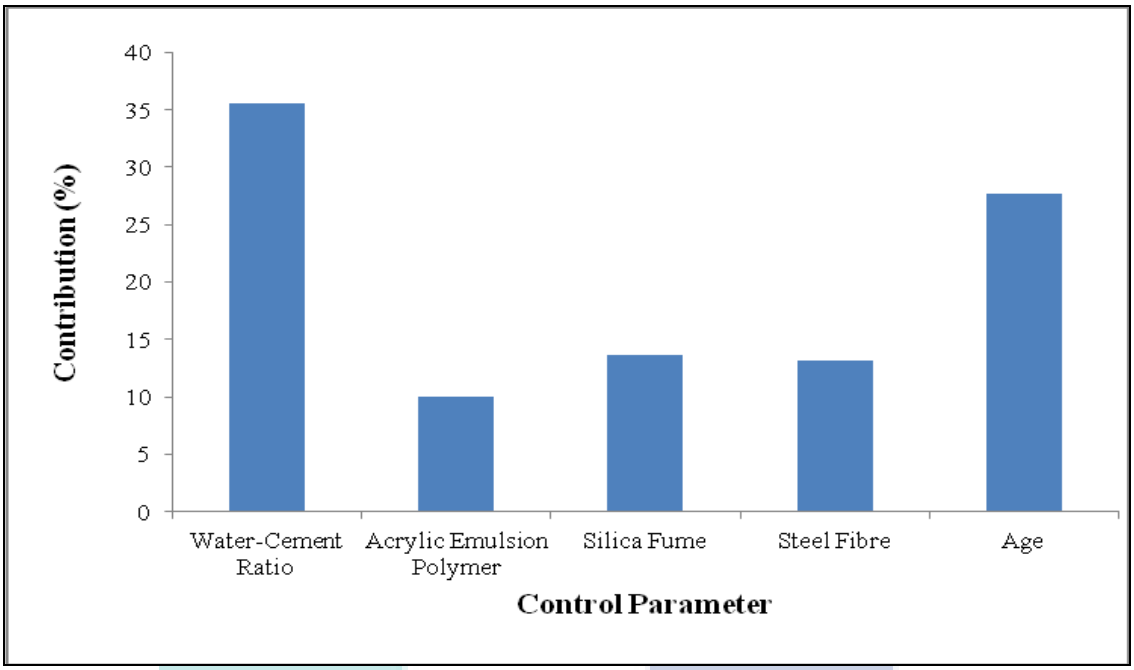


Figure 5.2: ANOVA analysis diagram that shows control parameter influence flexural strength of 27 SFRPMC mixes specimens

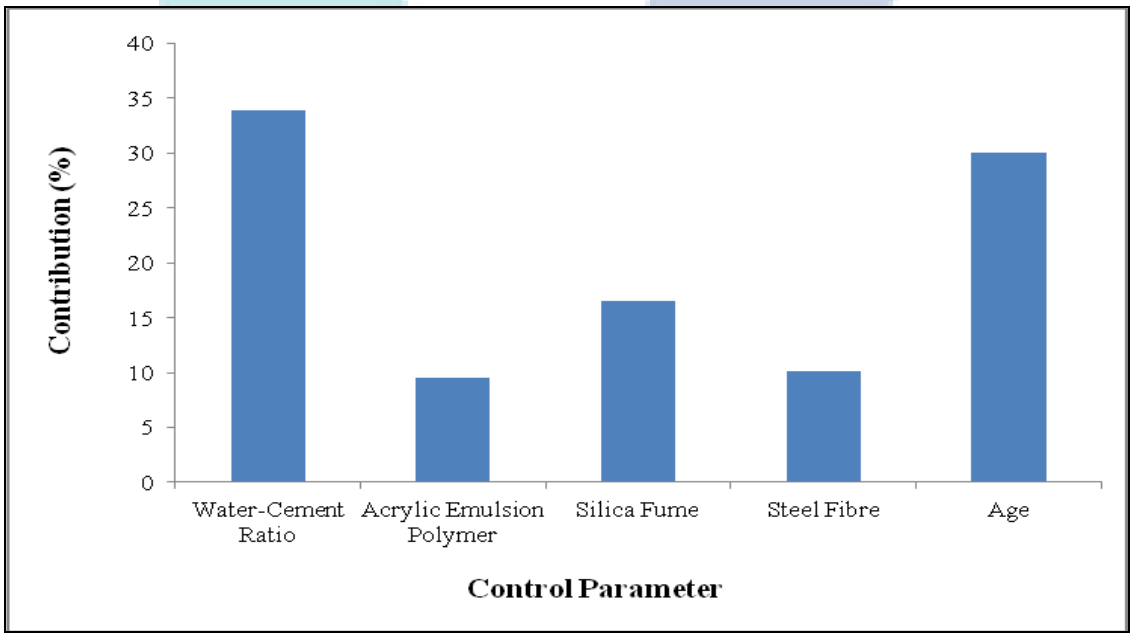


Figure 5.3: ANOVA analysis diagram that shows control parameter influence splitting tensile strength of 27 SFRPMC mixes specimens

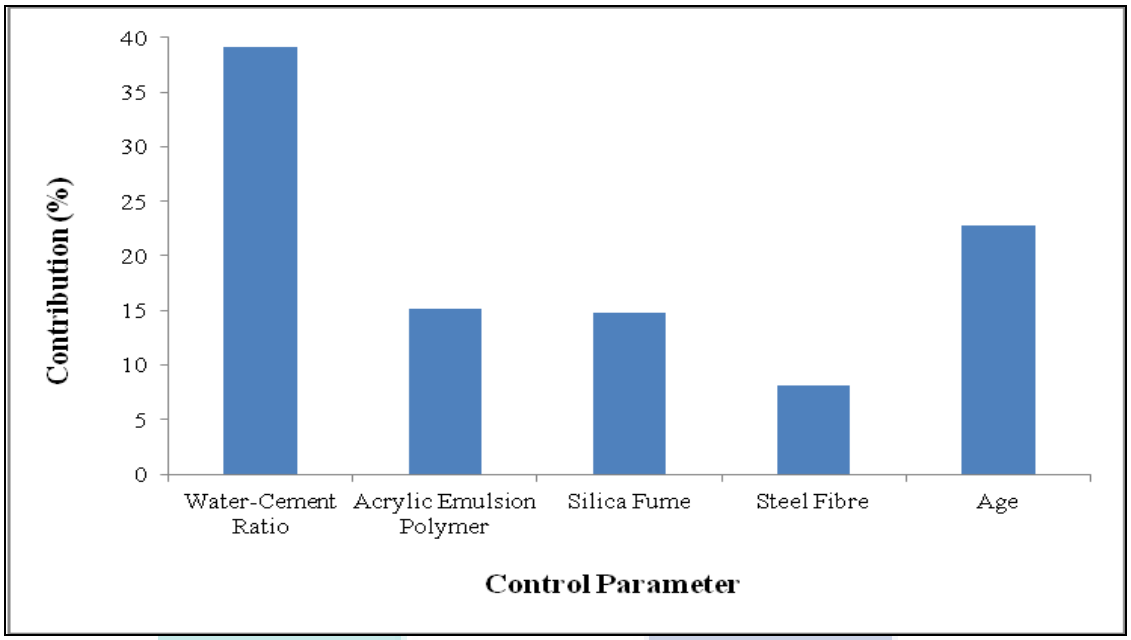


Figure 5.4: ANOVA analysis diagram that shows control parameter influence Young's modulus of 27 SFRPMC mixes specimens

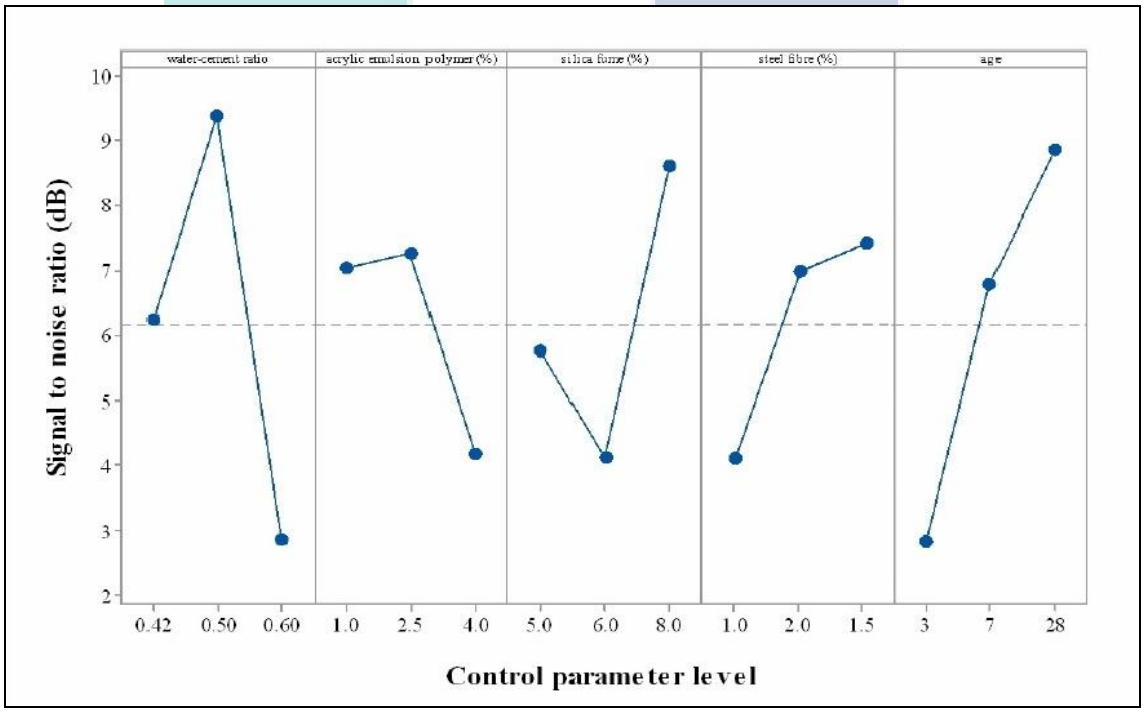


Figure 5.5: Plot of signal to noise ratio achieved from cube compressive strength of 27 SFRPMC mixes

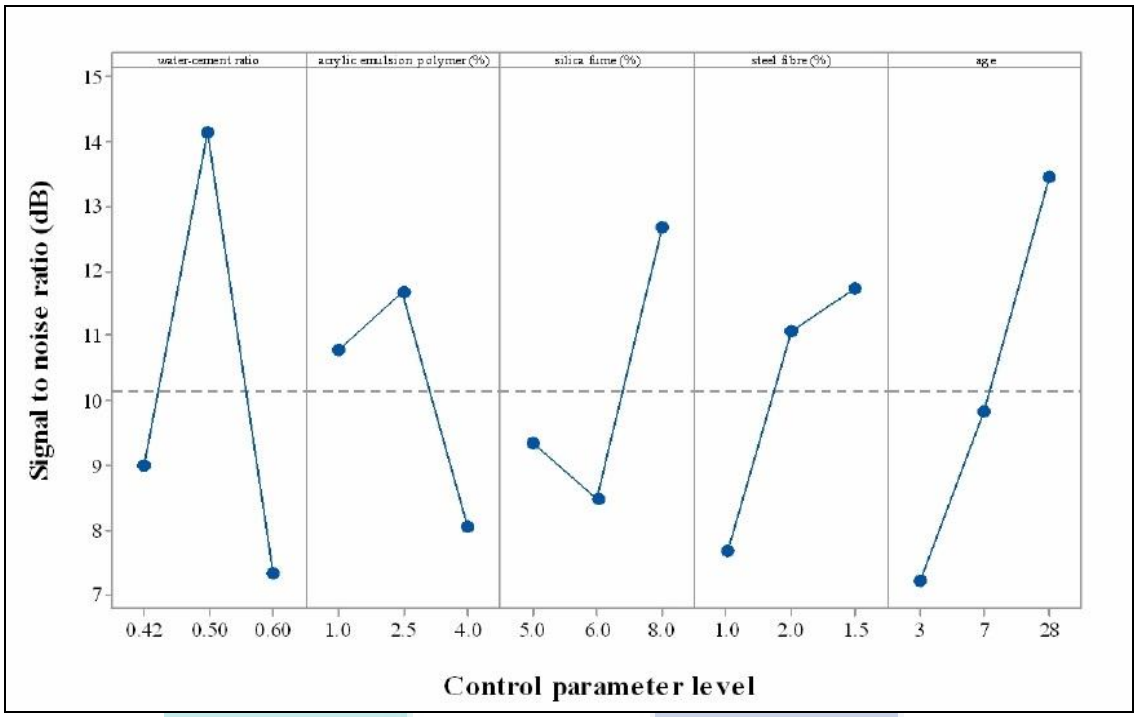


Figure 5.6: Plot of signal to noise ratio achieved from flexural strength result of 27 SFRPMC mixes

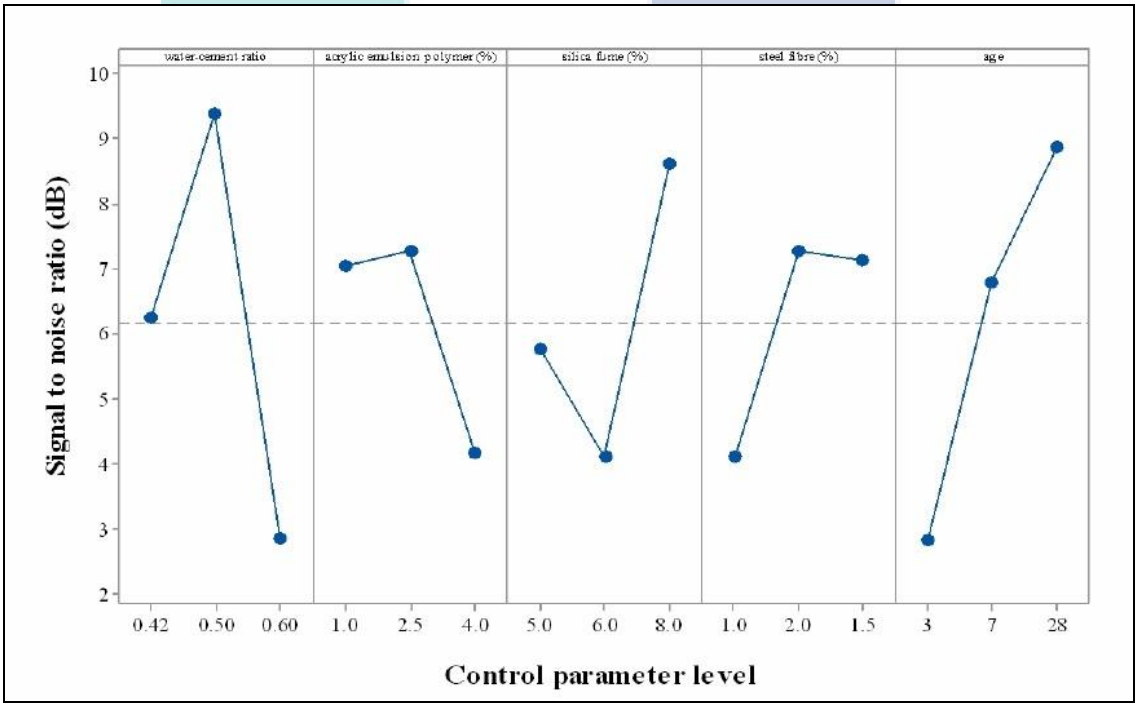


Figure 5.7: Plot of signal to noise ratio achieved from splitting tensile strength result of 27 SFRPMC mixes

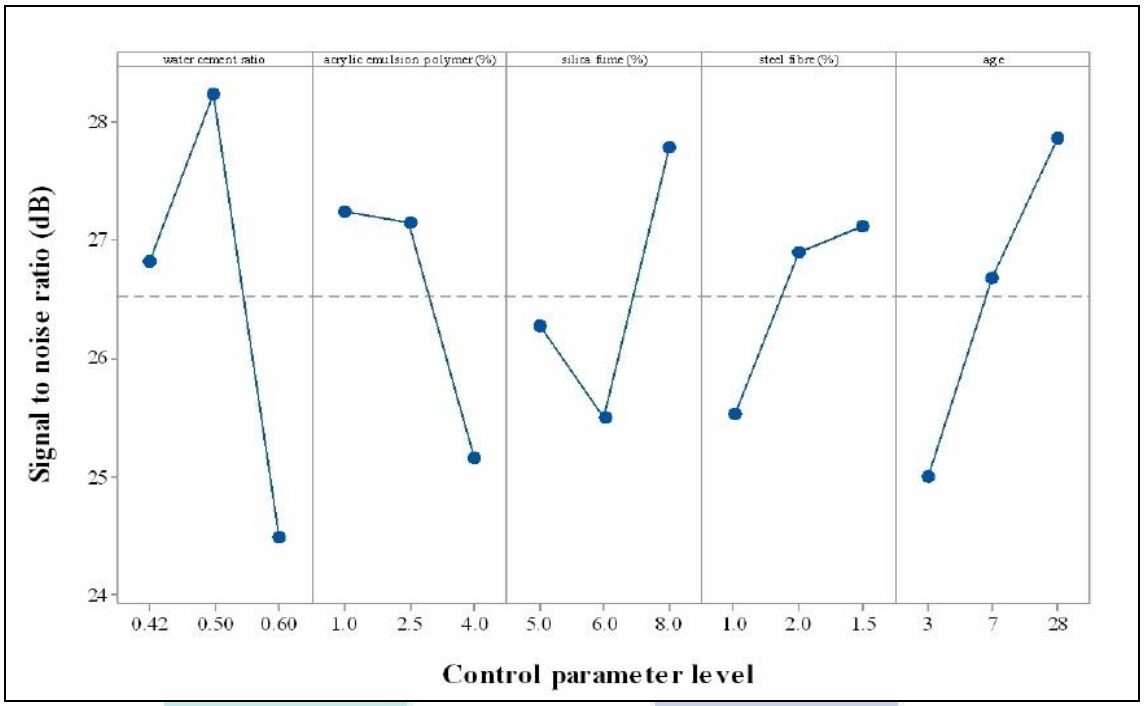


Figure 5.8: Plot of signal to noise ratio achieved from Young's modulus result of 27 SFRPMC mixes

After contribution of each control parameter on mechanical properties is determined, signal to noise ratio chart is plotted for each mechanical properties that had been tested. From this chart, the level of each optimum control parameter is determined and is used to verify the fine tuning experiment results that is conducted. Based on signal to noise ratio chart that had been obtained from cube compressive strength results (Figure 5.5), the optimum formulation for cube compressive strength is water-cement ratio (A2); acrylic emulsion polymer with 2.5% (B2); 8% of silica fume (C3), 1.5% steel fiber (D3) and curing time of 28 days (E3). After that, for optimum formulation of flexural strength, splitting tensile strength and modulus of elasticity (Young's modulus), and optimum formulation is identified based on maximum level of each parameter that is shown in Figure 5.6 to 5.8 and summarized in Table 5.1.

Table 5.1: Optimum formulation on mechanical strength from 27 mixes of steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC)

Mechanical Properties	Optimum Formulation
Cube compressive strength	$A_2B_2C_3D_3E_3$
Flexural strength	$A_2B_2C_3D_3E_3$
Splitting tensile strength	$A_2B_2C_3D_2E_3$
Young's modulus	$A_2B_1C_3D_3E_3$

5.2 L9 ORTHOGONAL ARRAY DESIGN

After major control parameter is chosen, steel fiber reinforced acrylic emulsion polymer modified concrete is produced by using orthogonal array design that is smaller because major parameter is being constant (refer Appendix B). In finding the major parameter that influenced the mechanical properties of composite that is produced, four parameters was selected namely water-cement ratio, percentage of acrylic emulsion polymer, percentage of silica fume and percentage of steel fibers. All parameters are considered in three levels and this is indicated in Table 5.2. After all these parameters were considered, orthogonal array that is suitable was chosen to study the effect of mechanics of produced composite (Table 5.3).

Table 5.2: Control factors and levels that used in L_9 orthogonal array

Control Parameter	Level 1	Level 2	Level 3
Water-Cement Ratio	0.48	0.50	0.52
Steel Fiber (%)	1.4	1.5	1.6
Acrylic Emulsion Polymer (%)	2.3	2.5	2.7
Silica Fume (%)	7.5	8.0	8.5

Table 5.3: L_9 orthogonal array layout that is used in mechanical properties testing

Expt. No.	Control Factors			
	Water-Cement Ratio	**Acrylic emulsion polymer (%)**	**Silica fume (%)**	**Steel fiber (%)**
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Degree of freedom of each parameter in each stage is calculated as below (Phadke, 2008). The degree of freedom associated with the total sum of squares is 9-8=1.

Degree of freedom (DOF) = number of levels – 1 (5.1)

For each parameter, degree of freedom is equivalent to:

For (A); DOF = 3-1 = 2

For (B); DOF = 3-1 = 2

For (C); DOF = 3-1 = 2

For (D); DOF = 3-1 = 2

Total degree of freedom is calculated based on;

Total DOF = number of experiments – 1 (5.2)

Total degree of freedom for this experiment is;

Total DOF = 9 – 1 = 8

In this orthogonal array, nine experiments were being conducted with different parameter and all samples were tested on mechanical properties through compressive strength test, flexural strength test and splitting tensile test. Table 5.4 is the analysis that had been carried out to determine the key factor on mechanical strength of specimens.

Table 5.4: ANOVA analysis for three control parameter with three levels

Parameter		**A**	**B**	**C**	**D**	**E**	**T**
Total of parameter level	1	ΣA_1	ΣB_1	ΣC_1	ΣD_1	ΣE_1	T
	2	ΣA_2	ΣB_2	ΣC_2	ΣD_2	ΣE_2	
	3	ΣA_3	ΣB_3	ΣC_3	ΣD_3	ΣE_3	
Difference of sum of squares		S_A	S_B	S_C	S_D	S_E	S_T
Degree of freedom		2	2	2	2	2	8
Contribution ratio/100		S_A/ S_T	S_B/S_T	S_C/S_T	S_D/S_T	S_E/S_T	1

From Table 5.3, all values are calculated based on equation below:

$$T = \Sigma A_1 + \Sigma A_2 + \Sigma A_3 \quad (5.3)$$

$$S_A = (\Sigma A_1 - \Sigma A_2)^2 + (\Sigma A_1 - \Sigma A_3)^2 + (\Sigma A_2 - \Sigma A_3)^2 \quad (5.4)$$

$$S_B = (\Sigma B_1 - \Sigma B_2)^2 + (\Sigma B_1 - \Sigma B_3)^2 + (\Sigma B_2 - \Sigma B_3)^2 \quad (5.5)$$

$$S_C = (\Sigma C_1 - \Sigma C_2)^2 + (\Sigma C_1 - \Sigma C_3)^2 + (\Sigma C_2 - \Sigma C_3)^2 \quad (5.6)$$

$$S_D = (\Sigma D_1 - \Sigma D_2)^2 + (\Sigma D_1 - \Sigma D_3)^2 + (\Sigma D_2 - \Sigma D_3)^2 \quad (5.7)$$

$$S_E = (\Sigma E_1 - \Sigma E_2)^2 + (\Sigma E_1 - \Sigma E_3)^2 + (\Sigma E_2 - \Sigma E_3)^2 \quad (5.8)$$

$$S_T = S_A + S_B + S_C + S_D + S_E \quad (5.9)$$

5.2.1 Verification Experiment Analysis

To verify the analysis that had been made, fine tuning experiment is done based on control parameter and level that is chosen according to signal to noise ratio chart and ANOVA and ANOM analysis. Verification experiment is done at least five times for verification purposes. Since all 27 experiments are done with one mix for each row of the L_{27} orthogonal array concrete mix, thus mix concrete is not robust against any noise factor. Formulation of fine tuning experiment is done by using L9 orthogonal array (Table 5.5).

Table 5.5: Formulation of fine tuning experiment by using L_9 orthogonal array

	Control Factors Assigned to Columns			
Experiment No.	**Water Cement Ratio**	**Acrylic emulsion polymer (%)**	**Silica Fume (%)**	**Steel Fiber (%)**
FT1	0.48	2.3	7.5	1.4
FT2	0.48	2.5	8.0	1.5
FT3	0.48	2.7	8.5	1.6
FT4	0.50	2.3	8.0	1.6
FT5	0.50	2.5	8.5	1.4
FT6	0.50	2.7	7.5	1.5
FT7	0.52	2.3	8.5	1.5
FT8	0.52	2.5	7.5	1.6
FT9	0.52	2.7	8.0	1.4

Table 5.5 shows a few of optimum formulations for each of mechanical strength to achieve the maximum value. However, the fine tuning experiment must be undertaken to confirm or verify the prediction analysis that had been done. Thus, a series of experiments have to be done and mechanical testing is carried out. To produce the results that are more accurate, a set of experiments called as fine tuning had been done. Table 5.6 shows robust experiment to determine the mechanical strength for several specimens according to the design method. Since water-cement ratio has a large effect (20% to 50%), the process robust called fine tuning experiment against variations in water-cement ratio is done. The specimens are tested and the experiment result is shown in Figure 5.9.

Table 5.6: Robust experiment for mechanical properties of SFRPMC

Expt. No.	Water-cement ratio	Acrylic Emulsion Polymer (%)	Silica Fume (%)	Steel Fiber (%)
1	0.47	2.5	8.0	1.5
2	0.48	2.5	8.0	1.5
3	0.50	2.5	8.0	1.5
4	0.51	2.5	8.0	1.5
5	0.53	2.5	8.0	1.5

Figure 5.9 shows cube compressive strength value from fine tuning is more robust with respect to small variations and gives improved values of strength. Nevertheless, some of fine tuning experiment giving the cube compressive value that relatively low compared to L9 experiment. FT5 specimen gives the best combination of cube compressive strength value which is 87.68 MPa.

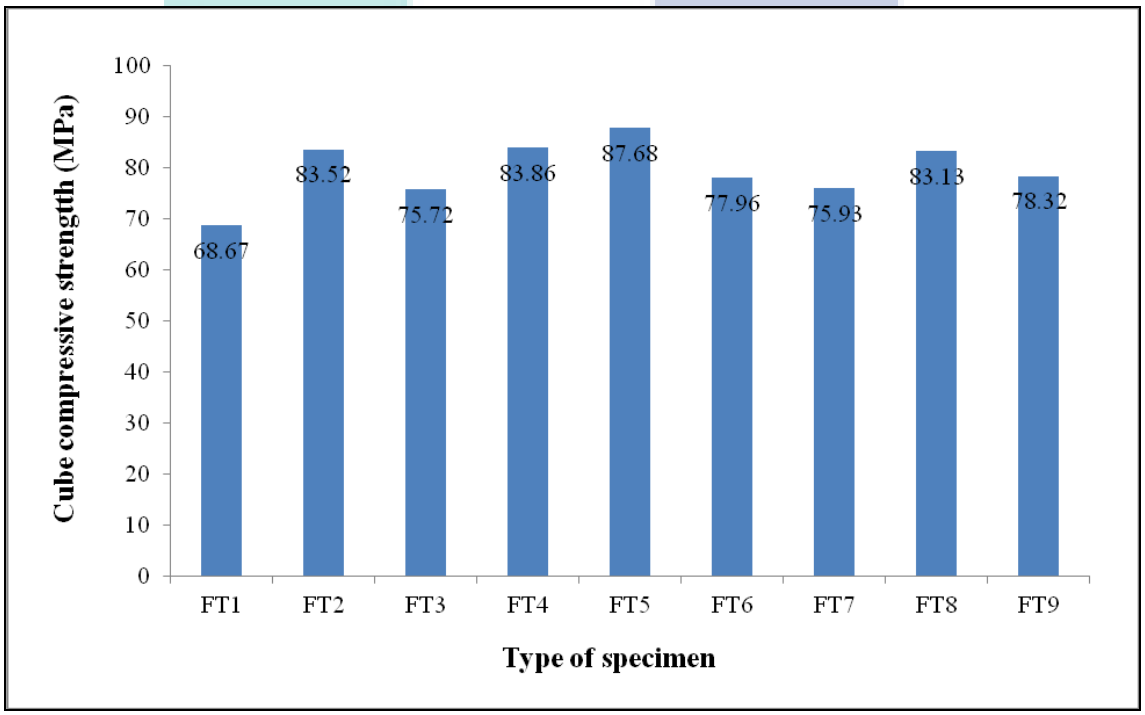


Figure 5.9: Cube compressive strength from L9 verification experiment

Based on robust experiment, effect of water-cement ratio is figured out. Figure 5.10 shows the effect of water-cement ratio on all mechanical strength of SFRPMC that had been done. The development of all mechanical strength for all samples is almost the same. After optimum water-cement ratio is about 0.50 had been achieved, second two attributes of cube compressive strength decreases. The compressive strength of concrete is known to decrease with an increase in water-cement ratio due to an increase in porosity.

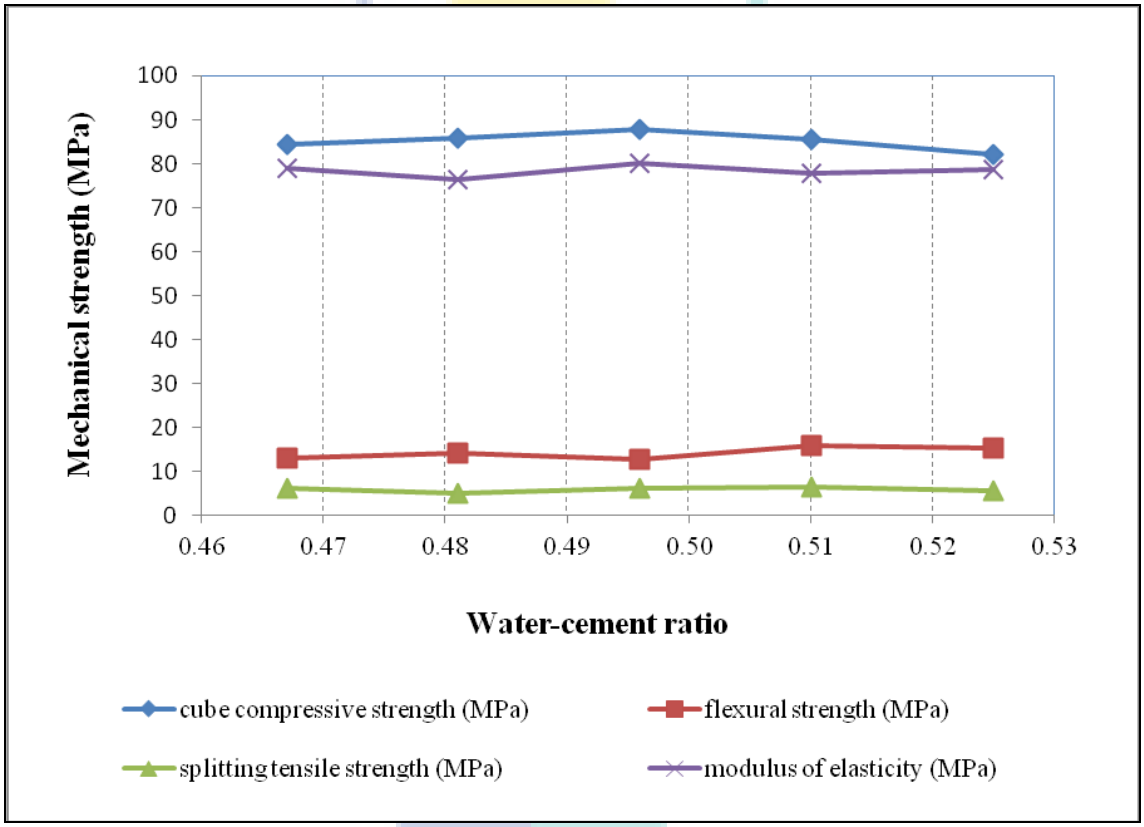


Figure 5.10: Effect of water-cement ratio on mechanical strength results for 5 SFRPMC mixes of robust experiment

The maximum compressive strength is obtained when the mix containing 0.50 of water-cement ratio, 2.5% acrylic emulsion polymer, 8% of silica fume and steel fiber with 1.5% at 28 days curing. Table 5.7 shows summary of results that is found from fine tuning experiment that was being conducted. The best optimum specimen from fine tuning experiment (Appendix F) have cube compressive strength (87.68 MPa), flexural

strength (13.83 MPa), splitting tensile strength (6.49 MPa) and modulus of elasticity (80.67 MPa).

Table 5.7: Fine tuning experiment results

Mechanical Properties	**Range of Prediction**	**Experiment Range**
(MPa)	**Taguchi Analysis**	**Fine Tuning**
Cube compressive strength	68-102	68-90
Flexural strength	9-19	10-17
Splitting tensile strength	5-9	4-7
Modulus of elasticity	77-83	76-83

To compare the optimum properties of SFRPMC that is produced in this experiment, some of the specimens with different codes at 28 days curing are selected for the comparison such as:

1. Plain concrete with 8% silica fume and 0.50 water-cement ratio --- **PC**
2. Acrylic emulsion polymer modified concrete with 1.0% polymer --- **AEPMC 1.0%**
3. Acrylic emulsion polymer modified concrete with 2.5% polymer --- **AEPMC 2.5%**
4. Acrylic emulsion polymer modified concrete with 4.0% polymer --- **AEPMC 4.0%**
5. Steel fiber reinforced concrete (SFRC) with 1.0% steel fiber, 8% silica fume and 0.50 water-cement ratio ---**SFRC 1.0%**
6. Steel fiber reinforced concrete (SFRC) with 1.5% steel fiber, 8% silica fume and 0.50 water-cement ratio --- **SFRC 1.5%**
7. Steel fiber reinforced concrete (SFRC) with 2.0% steel fiber, 8% silica fume and 0.50 water-cement ratio --- **SFRC 2.0%**

8. SFRPMC (1.0% acrylic emulsion polymer, 8% silica fume, 1.5% steel fiber and 0.50 water-cement ratio) --- **SFRPMC 1.0AEP (Mix 26)**
9. SFRPMC (2.5% acrylic emulsion polymer, 8% silica fume, 1.5% steel fiber and 0.50 water-cement ratio) --- **SFRPMC 2.5AEP (OPTIMUM-Mix 43)**
10. SFRPMC (4% acrylic emulsion polymer, 8% silica fume, 1.5% steel fiber and 0.50 water-cement ratio) --- **SFRPMC 4.0AEP (Mix 63)**
11. SFRPMC (2.5% acrylic emulsion polymer, 8% silica fume, 1.0% steel fiber and 0.50 water-cement ratio) --- **SFRPMC 1.0SF**
12. SFRPMC (2.5% acrylic emulsion polymer, 8% silica fume, 1.5% steel fiber and 0.50 water-cement ratio) --- **SFRPMC 1.5SF**
13. SFRPMC (2.5% acrylic emulsion polymer, 8% silica fume, 2.0% steel fiber and 0.50 water-cement ratio) --- **SFRPMC 2.0SF**

5.3 COMPRESSIVE STRENGTH TEST

The cube compressive strength test result of selected specimens that is produced is shown in Figure 5.11. From the figure, the similar trend is shown by all tested specimens. It also shows the optimum with 2.5% acrylic emulsion polymer, 8% silica fume, and 1.5% steel fiber and water-cement ratio of 0.50 produces the highest mechanical strength of the composites. Compared to plain concrete with 8% silica fume, the compressive strength of an optimum specimen increases by 13%. For SFRC with 8% silica fume, it also shows improvement of SFRPMC ranges from 77.98 MPa to 87.68 MPa.

Other result shows that the acrylic emulsion polymer concrete exhibit high compressive strength, it's quite high compressive strengths even at low water-cement ratio content (0.50). From Beeldens et al. (2003) study, the finding also implied that the compressive strength development ratio quite depends on the acrylic emulsion polymer but the higher polymer content, the higher the strength development ratio. However, at same curing time (28 days) indicated that the excessive use of polymer (MMA more than 2.5%) could be inefficient for the strength improvement of acrylic polymer concrete. The reduction of the compressive strength of the composite specimens with fiber is more obvious. The reason may be that the aging of the interface between fibers

and the concrete matrix leads to a drop in the substrate's bonding capacity. The reason also proof that with the increase of fiber length, it is more difficult for fiber to distribute uniformly in cementitious composites, which is harmful for the development of strength (Bentur and Mindess, 2006).

From the results in Appendix F, it shows that the performance and structural characteristic of steel fiber reinforced acrylic emulsion polymer modified concrete is superior to conventional concrete. Compressive strength results envisage that the modification at optimum dosages of 2.5% polymer is well advantageous and attaining superior results at 28 days curing to achieve complete polymerization and subsequent improvement in performance. The compressive strength for the mixes in this study are summarized in Appendix F and Figure 5.12, in which results are organized based on polymer content (from 1% to 4%), compared to plain concrete without acrylic polymer.

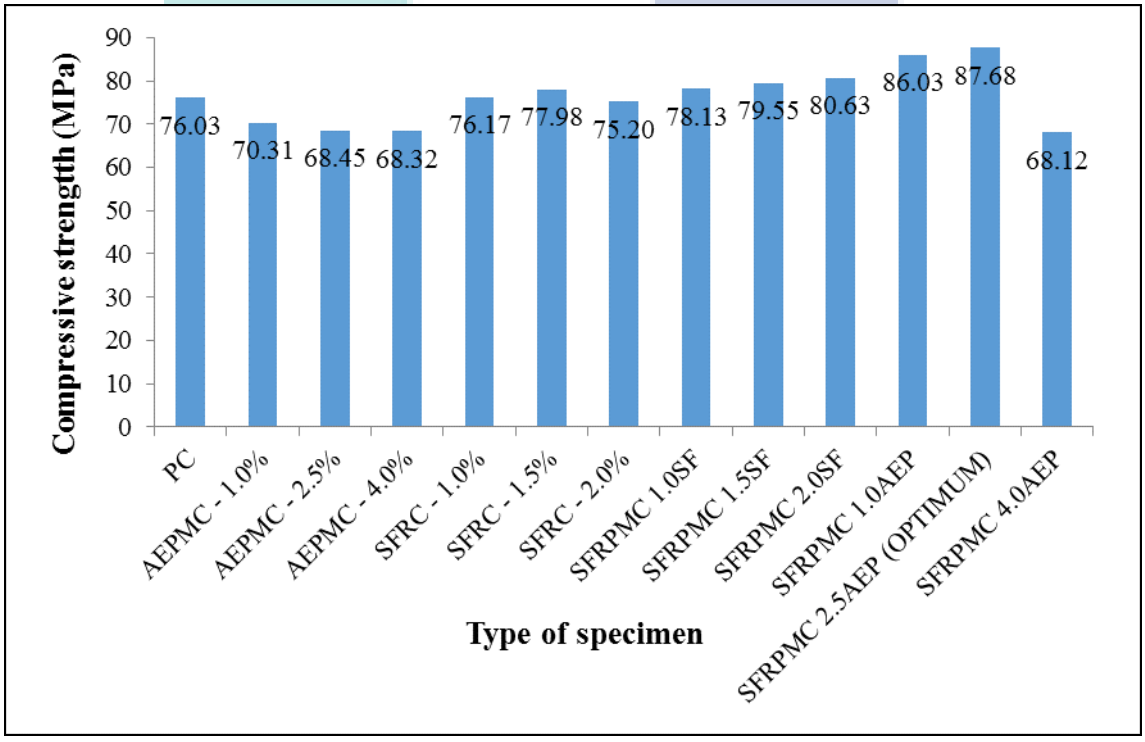


Figure 5.11: The result of cube compressive strength of tested specimens at 28 days curing

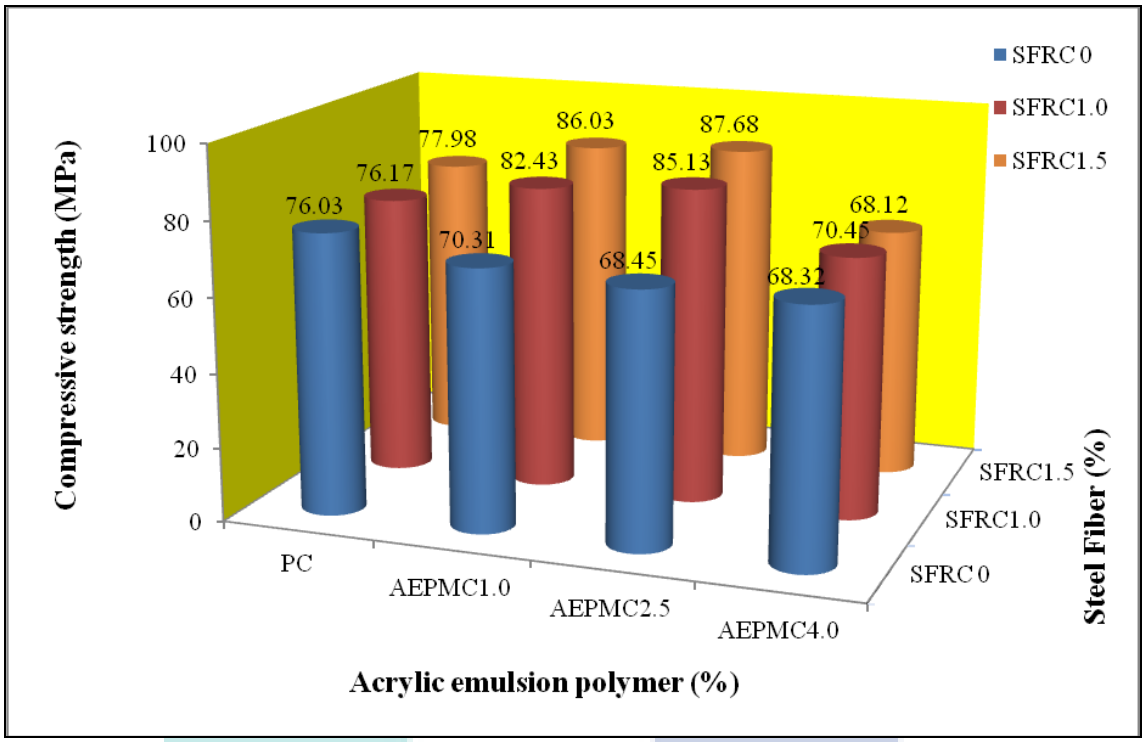


Figure 5.12: Compressive strength of concrete with steel fiber and acrylic emulsion polymer

These results indicate that at the same water-cement ratio, the compressive strength decrease with acrylic emulsion polymer additions. At polymer cement ratio greater than 2.5%, this trend becomes particularly clear. This is due to the fact that the polymer film itself has a low compressive strength, as well as a low stiffness to the cement paste and aggregate (Su, 1995). When the polymer cement ratio is 4% or more, this dosage is sufficient for the polymer to form continuous phase with lower elastic modulus. When the concrete is under load, the differences of the deformation of this extra "soft" phase (cement paste with polymer) and other component could lead to high stress concentrations though the bonding may be improved in the interface. Consequently, a significant compressive strength will occur, even though enough silica fume is used.

When steel fibers were incorporated, the compressive strength increased, but there was no significant effect on the concrete when polymer is used. For acrylic emulsion polymer modified steel fiber reinforced concrete, the compressive strength

ranged from 68 MPa – 102MPa, which fit the design objective of this research program. SFRPMC 2.5AEP (OPTIMUM) showed the highest compressive strength value with 87.68 MPa and SFRPMC 4.0AEP showed the lowest value, 68.12MPa. Overall, all the polymer content played the most important role in determining the compressive strength.

5.4 FLEXURAL STRENGTH TEST

It is commonly accepted that the flexural behavior of a fiber reinforced concrete beam can be described as consisting of three stages (Balaguru and Shah, 1992): first, the load increases almost linearly with the displacement up to some critical value near to the peak load at which the first major crack occurs. Second, either strain-softening or strain-hardening behavior is then observed after the first crack. The strain hardening occurs if there are enough fibers, if they are well anchored into concrete matrix, and if their ability to transfer load across cracks is higher than that of the matrix itself. That is, a multiple cracking process occurs, due to the ease of formation of the new cracks compared to the difficulty of propagating the existing cracks where fibers play a bridging role. The third step involves the post-crack behavior, which depends strongly on both the fibers and the matrix.

The result of flexural strength test is shown in Figure 5.13. From the figure, the optimum specimens show the large amount of improvement in flexural strength and modulus of elasticity. This figure showed variation in flexural strength with addition of silica fume at different water-cement ratio. By addition of 1.0% of steel fiber with acrylic emulsion polymer content (2.5%), the flexural strength increases. After the steel fiber with 2.0% is added and with higher percentage of acrylic emulsion polymer with 4.0 % shows reduction in flexural strength but the value is still high compared to other specimens. Kader and Ghassan (2014) reported that the specimen which containing steel fiber showed degree of ductility that is higher before failure and steel fiber did not start to pull out from fractures surface until the maximum load is reached.

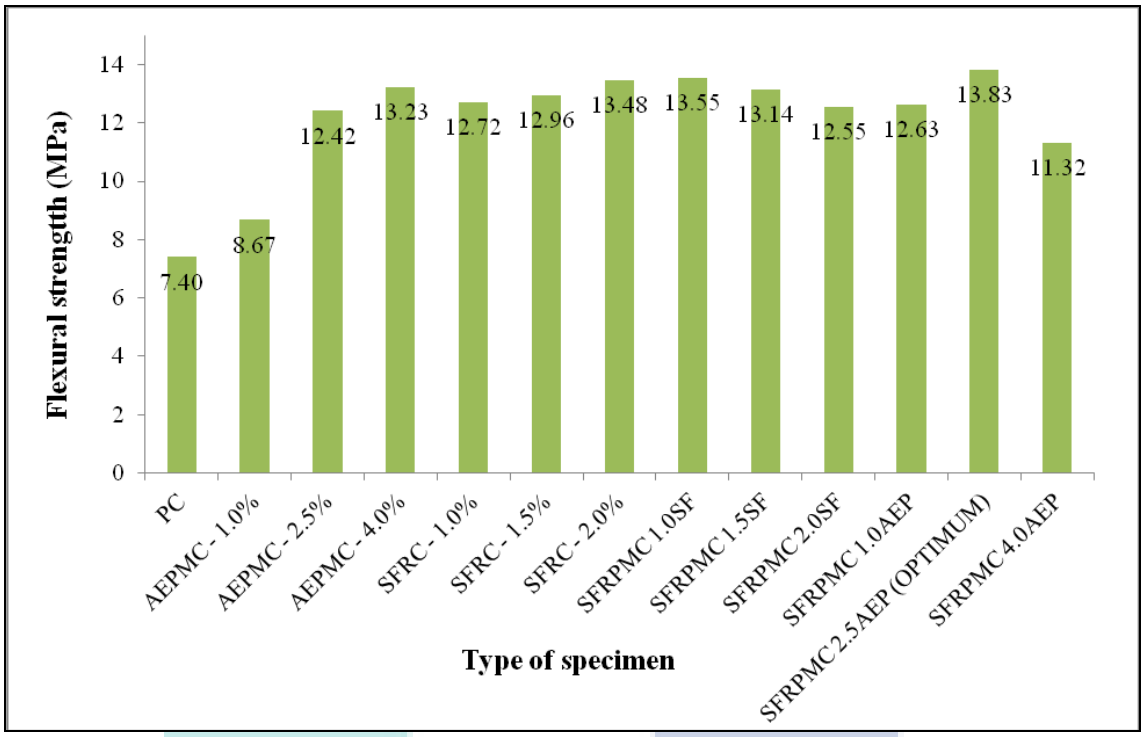


Figure 5.13: The result of flexural strength of tested specimens

The flexural strength improvement percentage is more compared to the compressive strength by adding acrylic emulsion polymer. Decrease and increase in the strength is due to the development of polymer film on the surface that retains the internal pressure for continuing cement hydration. In addition to this, polymers require time for the progress of polymer structure and formation of cement matrix. This polymer film matures with age; this is the reason that at 28 days of age, increase in compressive and flexural strength is registered with the addition of polymer (Kapil and Joshi, 2014).

5.5 SPLITTING TENSILE STRENGTH TEST

Based on Figure 5.14 and the results data in Appendix F, the splitting tensile strength show the same trend when acrylic emulsion polymer is added to steel fiber reinforced concrete. By addition acrylic emulsion polymer, it can be seen that the splitting tensile strength increases when the polymer is added to SFRC-1.0% specimen. This specimen shows the increment of 7.4% of splitting tensile strength. Nevertheless, the excessive of polymer (4%) with water-cement ratio (0.50) decreases the splitting

tensile strength drastically. The similar observation also reported by other researchers highlighting that the addition of polymer into concrete improved the splitting tensile strength and decreases later with excessive dosage of polymer (Sivakumar, 2011 and Kader and Ghassan, 2014). From the results it is evident that the performance and structural characteristics of polymer modified concrete is superior to conventional concrete.

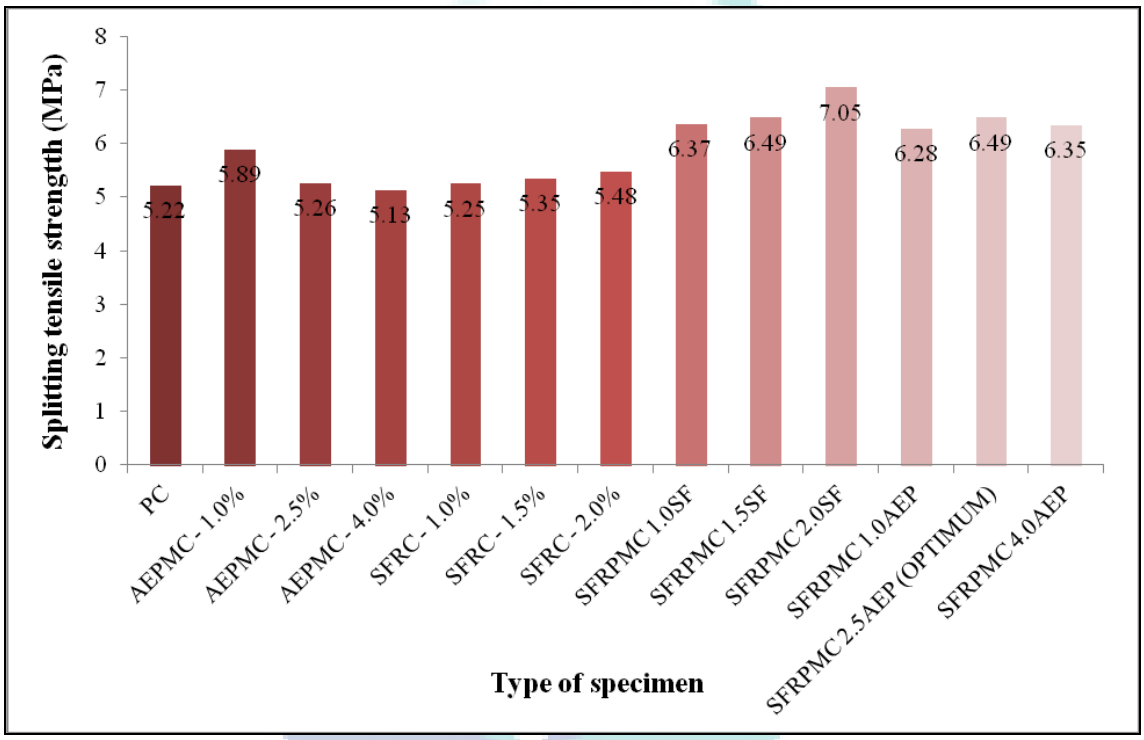


Figure 5.14: The result of splitting tensile strength of tested specimens

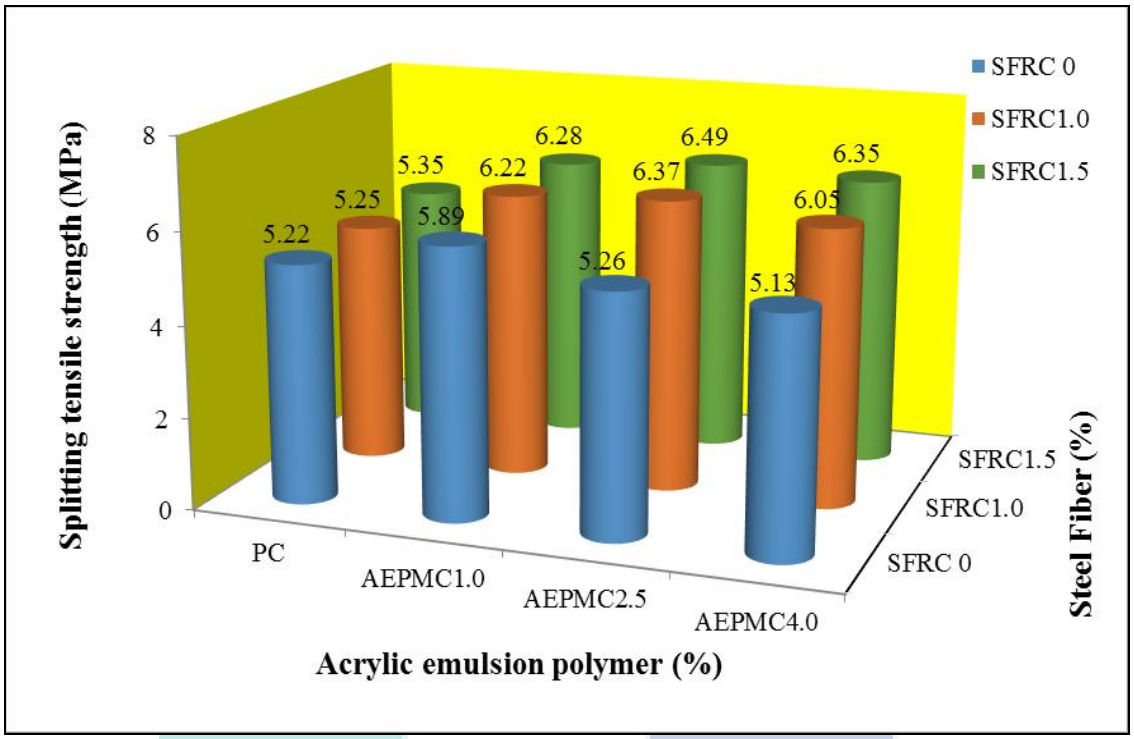


Figure 5.15: Splitting tensile strength of concrete with steel fiber and acrylic emulsion polymer

5.6 MODULUS OF ELASTICITY (YOUNG'S MODULUS)

Based on Figure 5.16, the modulus of elasticity shows the same trend as splitting tensile strength when acrylic emulsion polymer is added to steel fiber reinforced concrete. By addition of acrylic emulsion polymer, it can be seen that the modulus of elasticity increases when the polymer is added to SFRC-1.0% specimen. The excessive of polymer (4%) with water-cement ratio (0.50) decreases modulus of elasticity drastically. The similar observation also reported by various other researchers (Sivakumar, 2011 and Kader and Ghassan, 2014) which reported that the addition of polymer into concrete improved the modulus of elasticity and decreases later with excessive dosage of polymer.

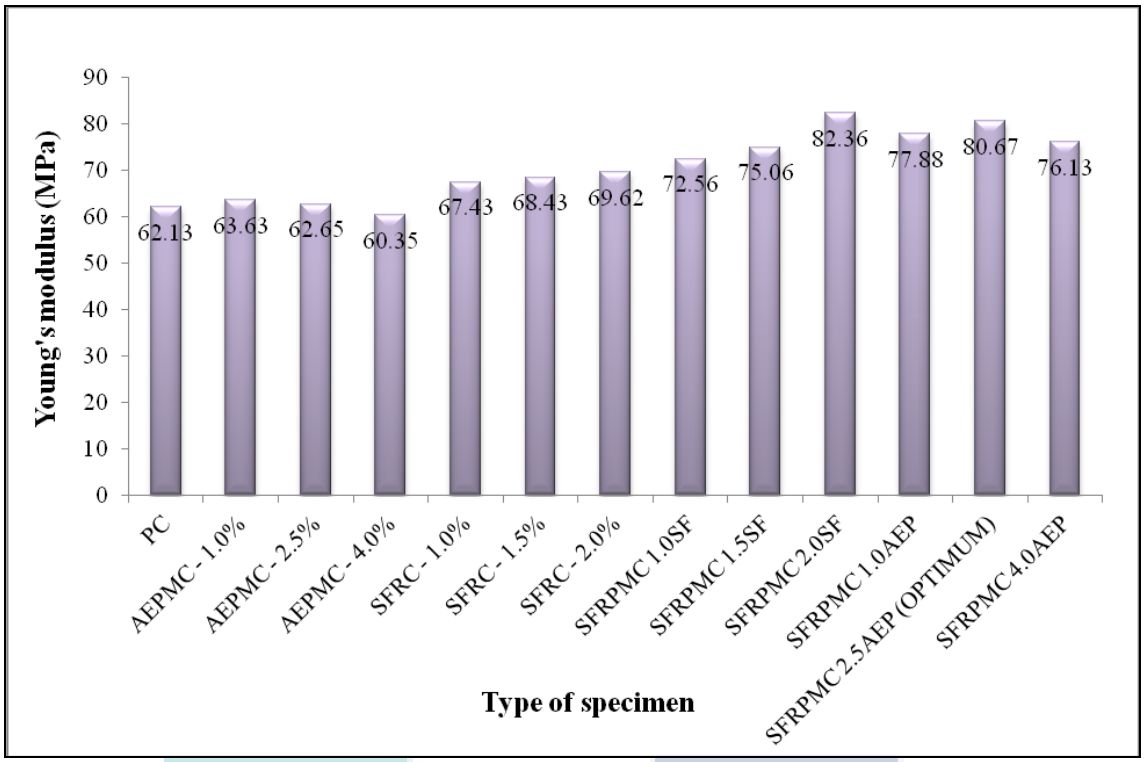


Figure 5.16: The result of modulus of elasticity on tested specimens

5.7 SUMMARY

From mechanical properties testing such as compressive strength test, flexural strength test and splitting tensile strength test, the major parameter that influences mechanical properties is achieved. Based on mean analysis and variance analysis, the optimum parameter level is obtained in order to maximize the mechanical strength of the produced composites. To get equal combination of mechanical properties, fine tuning test is being conducted and the combination that is suitable is obtained to get the optimum specimen with better mechanical properties. This specimen produced from 2.5% acrylic emulsion polymer, 8% silica fume, and 1.5% steel fiber and water-cement ratio 0.50 at 28 days curing.

CHAPTER 6

RESULTS AND DISCUSSION

CHARACTERIZATION OF STEEL FIBER REINFORCED ACRYLIC EMULSION POLYMER MODIFIED CONCRETE (SFRPMC) THROUGH X-RAY DIFFRACTION (XRD) AND THERMOGRAVIMETRIC (TGA) ANALYSIS

6.1 RESULTS AND ANALYSIS

The results show the effect of polymer modification on the behavior of $Ca(OH)_2$ in steel fiber reinforced concrete. The steel fiber reinforced polymer modified concrete were prepared using acrylic emulsion polymer at various polymer-cement ratios; moulded into specimens and cured. The cured specimens were subjected for compressive strength, flexural strength, splitting tensile strength and modulus of elasticity. The small specimens that moulded were subjected to X-ray diffraction (XRD), different thermal analysis (DTA) and thermogravimetric analysis (TGA). From the test results, it is concluded that formation of $Ca(OH)_2$ in the polymer modified concrete reinforced with steel fiber is reduced possibly because of the absorption of $Ca(OH)_2$ on polymer films formed in the concrete. The extent of reduction in the quantity of $Ca(OH)_2$ depends upon the polymer-cement ratio. Generally SFRPMC of mix 43 with 2.5% polymer-cement ratio were found to be more effective than other SFRPMC with 1.0% and 4.0% acrylic emulsion polymer in reducing the quantity of $Ca(OH)_2$ in SFRPMC. The cement modifiers did not cause any detrimental effect on the degree of hydration as indicated by their higher compressive strength. Estimation of the

quantity of calcium hydroxide in the polymer modified concrete therefore, does not provide a proper means for predicting their degree of hydration.

6.2 X-RAY DIFFRACTION (XRD) ANALYSIS

X-ray diffraction (XRD) has been used for the characterization and identification of the crystalline phases. Four different samples at 7 days (168 hours) curing are analyzed using powder X-ray diffraction technique, comprising plain concrete, SFRPMC/ mix 26 (P1.0%F8%S1.5%W0.50), SFRPMC/ mix 43 (P2.5%F8%S1.5%W0.50) and SFRPMC/ mix 63 (P4.0%F8%S1.5%W0.50).

From Figure 6.1, it shows XRD patterns for six specimens that had been tested. According to Antonovič et al. (2009), from their study, Nano clusters and Nano layers of only amorphous hydrates of aluminate cement are formed in the hardened structure of complex binder. However, main crystalline phases such as $CaO.Al_2O_3$ (CA), $CaO.2Al_2O_3$ (CA_2), $3Al_2O_3.2SiO_2$ (A_3S_2), γ-$2CaO-SiO_2$ (γ-C_2S) and SiO_2 and no hydrates were indicated by X-ray analysis of the dry specimens. Fiber and silica fume content variations do not affect the composition of the refractory concrete; therefore XRD patterns of specimen with the highest amount of additives are presented. Due to CA_2 slow reaction with water at early age of hydration, the mechanical strength of the dry specimens is relatively low (Zawrah and Khalil, 2007).

It also shows that the ratio of pulse count of cement specimens at 2θ angles, 30^o and 22.5^o has an almost linear relationship with the mix proportion in cements. From the whole graphs, the larger particles are thought to be composed of α alumina, berlinite and cristobalite while the clusters of small particles surrounding are likely high-phosphate products (MAP, ATH or meta-B as identified by XRD). The main compounds observed are $Ca(OH)_2$ resulting from carbonation of $Ca(OH)_2$ and calcium silicate anhydrous. The peak intensity in the region $2\theta = 26.75^o$ has been considered as a measure of the quantity. It is also noted here that at a polymer-cement ratio of 2.5%, a slight increase in the peak intensity compared to plain concrete is observed in Figure 6.1. Further, $Ca(OH)_2$ produce sharper reflection in the presence of acrylic emulsion polymer due to change in the orientation pattern of the crystals. This sharper reflection

offsets the effect gained by lowered quantity of $Ca(OH)_2$ (Almeida and Sichieri, 2006) and the peak intensity at polymer content of 2.5% and 4% appears at an increased level compared to that of plain concrete. These results are in line with those of some previous research (Soufiane et al., 2012).

With more hydration, it is anticipated that the relative surface area of the peak due to $Ca(OH)_2$ will increase and that of C_3S will decrease. It is seen that the $Ca(OH)_2$ peaks for mix 43 displays the sharpest peak display the highest $Ca(OH)_2$ peak accompanied by a largest C_3S peak amongst the four spectra. This indicates that the highest hydration occurred in this sample. It is conceivable that a long lasting close contact of water molecules with cement granules is required for the hydration to occur. In case of presence of polymer molecules, they could be gathering around cement granules to form a surfactant layer, in which the hydrophobic ends of the surfactant molecules are in contact with the cement granules surface, and their hydrophilic heads to the picture of polymer micelles and that of polymer stabilized latex particles. The polymer molecules in such a conceived orientation are surely less packed or less organized compared with the structure in other latex; nevertheless, it might well act as barrier keeping part of water molecules away from cement granules' surface (Wang et al., 2005). This can serve to explain the lower hydration degree in mix 43.

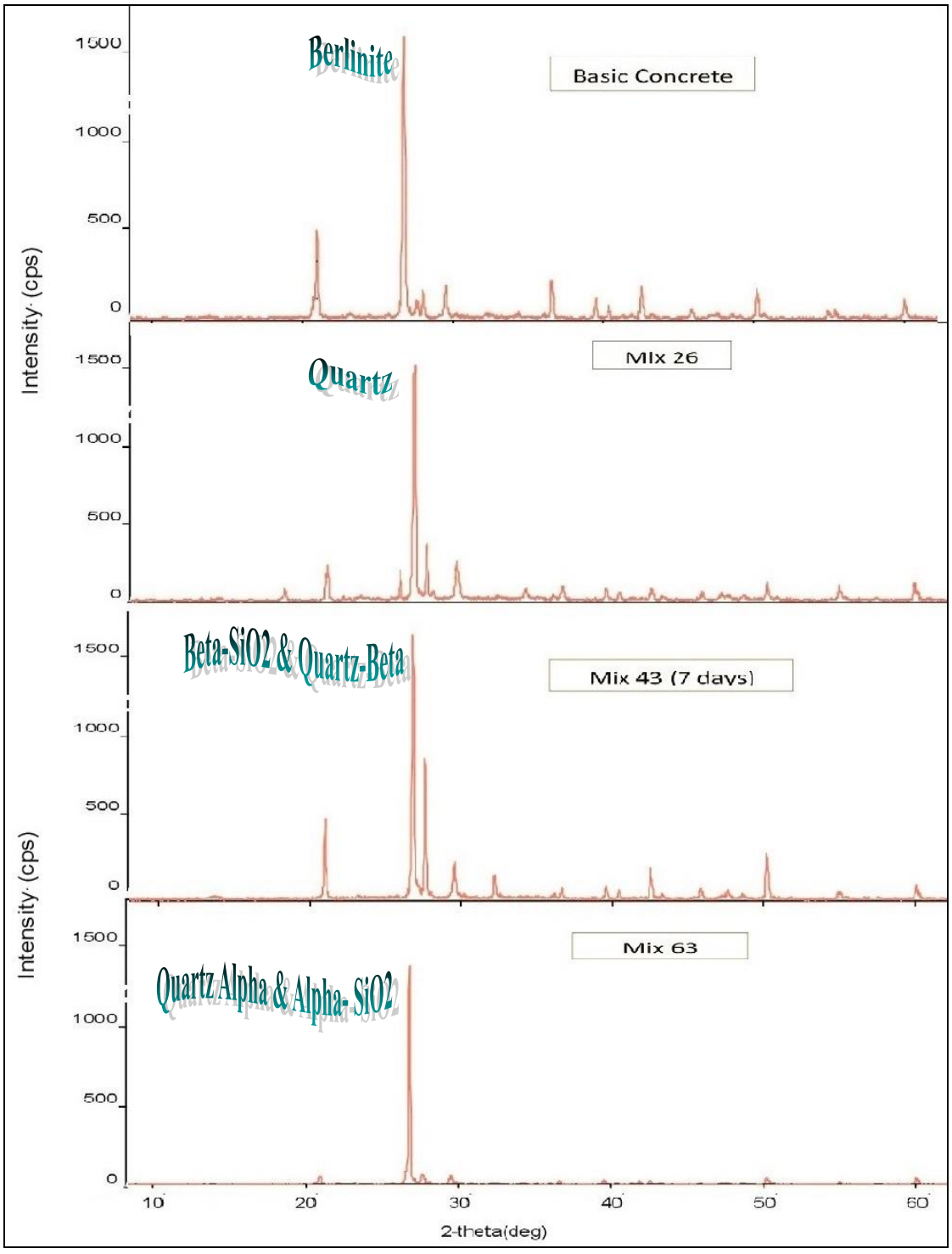


Figure 6.1: XRD patterns of steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC) compared to plain concrete at 7 days curing

Figure 6.2 shows the XRD pattern for optimum specimen, mix 43 with different curing time. In the hydration of cement, the chemical reactions that take place between anhydrous cement and water are generally complex in nature because of their multiphase nature and also simultaneously effects of many variables. The silicate phases that is shown in Figure 6.2 for optimum specimens lead to the formation of CH and C-S-H, the latter being generic name for armophous or poorly crystalline calcium silicate hydrates.

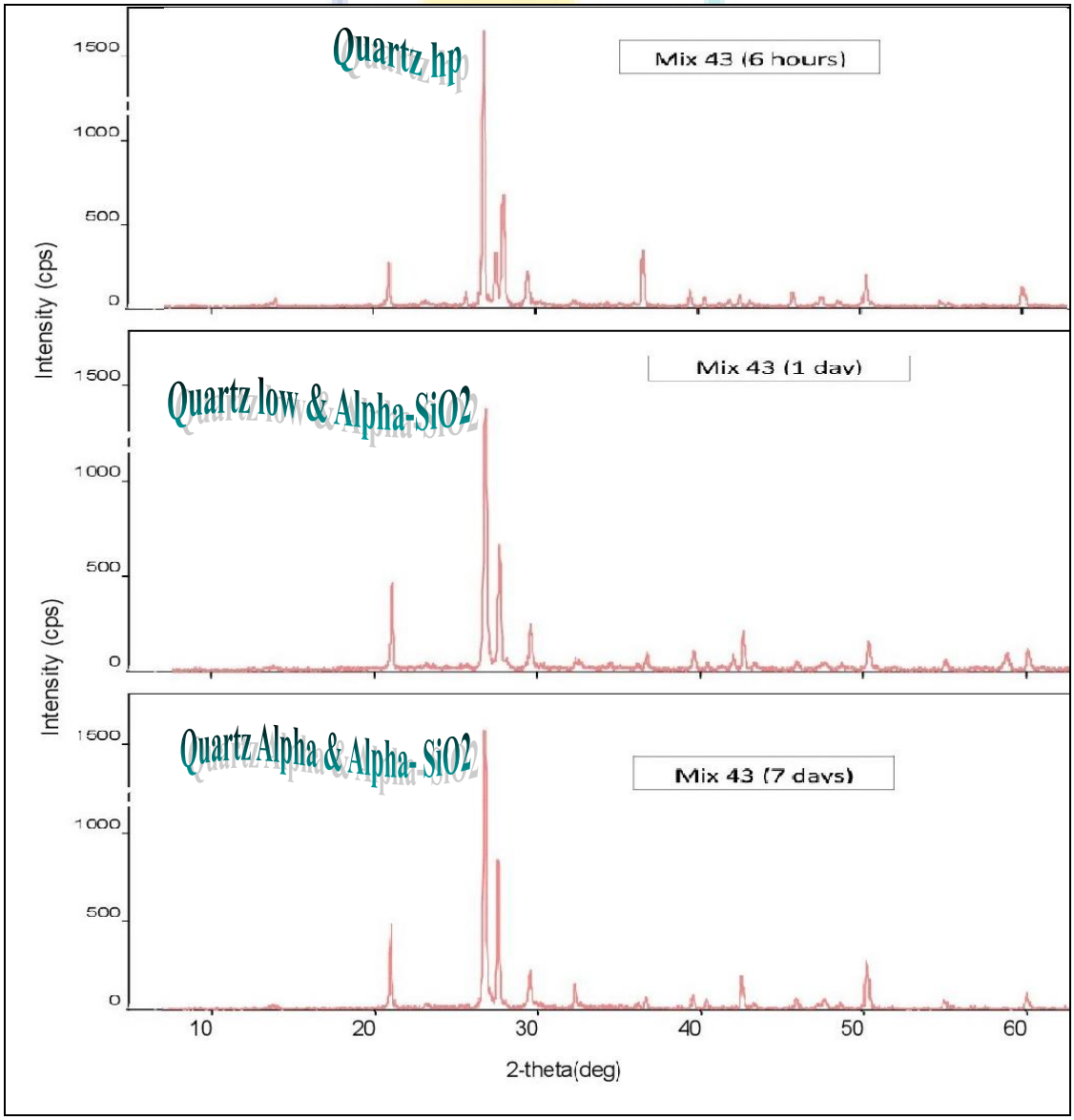


Figure 6.2: XRD patterns of steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC) for mix 43 (optimum) with different curing time

Xu et al. (2014) showed that the diffraction peak of the XRD patterns that appeared near 27^{o} (2θ) was regarded as a measurement of the intensity of $Ca(OH)_2$ crystal. The diffraction peak of $Ca(OH)_2$ was quantitatively by the CuKα source and the results is presented in Table 6.1. Through the analysis of the characterization of the diffraction peak, it could be observed that with the extension of cement hydration in the cement paste, the production of $Ca(OH)_2$ in the control specimen (plain concrete), mix 26, mix 43 and mix 63. Due to the addition of acrylic emulsion polymer, the production of $Ca(OH)_2$ in all specimens reduced and its decline rate reduced by degrees with the extension of the cement hydration.

Table 6.1: Integrated results of XRD peak of $Ca(OH)_2$ cement paste samples

Sample	Curing Time	d (ang.)	FWHM(deg)	Int. I(cps¥deg)
Plain Concrete	7 days	3.3232(7)	0.146(5)	193(3)
Mix 26	7 days	3.3331(7)	0.152(5)	205(3)
Mix 43	6 hours	3.3224 (9)	0.175(6)	486(17)
Mix 43	1 day	3.3308(7)	0.139(5)	615(22)
Mix 43	7 days	3.32971(15)	0.0920(10)	437(5)
Mix 63	7 days	3.3311(6)	0.099(7)	210(4)

When hydration occurred unremittingly after 6 hours, the production of $Ca(OH)_2$ in SFRPMC of mix 43 was only 19.9% of that in plain concrete specimen, as hydration continues after 1 day and 7 days, the production of $Ca(OH)_2$ in SFRPMC of mix 43 was 24.7% and 56.8% of that in plain concrete respectively. It demonstrated that acrylic emulsion polymer apparently delayed the cement hydration in the early curing time (within 1 day). However, with the extension of maintenance, the delay action of polymer on the cement hydration depressed by degrees, which was in accordance with the results concluded from the analysis of chemical combined water amount (Xu et al., 2014).

Meanwhile, Figure 6.3 to 6.6 shows the XRD pattern for plain concrete, mix 26, mix 43 and mix 63 respectively with different mix proportion of water-cement ratio, acrylic emulsion polymer content, silica fume and steel fiber content. From the graph, it shows that the addition of acrylic emulsion polymer with silica fume into SFRPMC determines the formation of lower phases, such as quartz and silica. For basic concrete specimens, it shows the formation of berlinite ($AlPO_4$) at $2\theta = 26.8$. Unfortunately the data obtained from plain concrete with silica fume and other samples are not sufficient for phase analysis, due to either a lack of crystalline phases of $Ca(OH)_2$ in the samples, or the crystalline atoms are reduced by other elements in the powder. C-S-H, particularly, is a very poor crystalline material and if this is dominant in the powder then we would not expect to see a spectrum (Regina et al., 2012). Three distinct phases are identified for the plain concrete; berlinite ($AlPO_4$), caminite ($Mg_3(SO_4)_2$ $(OH)_2$ and calcite ($CaCO_3$).

For mix 26 with 1.0% polymer shows the obvious content of silica when formation of quartz (SiO_2) take place during the mixing process. Two distinct phases are identified for this sample which namely quartz (SiO_2) and calcite, magnesian ($(Mg.064.Ca.936)(CO_3)$. Based on Figure 6.5, there are three phases that have been identified; beta-SiO_2, quartz beta (SiO_2), caminite ($(Mg_3(SO_4)_2$ $(OH)_2$) and calcite, magnesian $(Ca, Mg)CO_3$ in mix 43 samples. The presence of caminite and beta silica and quartz beta in mix 43 with glassy phases shows the process of modifying additives, acrylic emulsion polymer into SFRC which partially fills pores and cavities in the materials resulting in decrease of porosity accompanied with little shrinkage and can be observed in SEM-EDX microstructure. For sample 63 (Figure 6.6) with 4.0% acrylic emulsion polymer, 8% silica fume, 1.5% steel fiber and water-cement ratio (0.50) have two distinct phases namely quartz alpha, alpha-SiO_2 and calcite, magnesian (MgO.03 CaO.97) (CO_3).

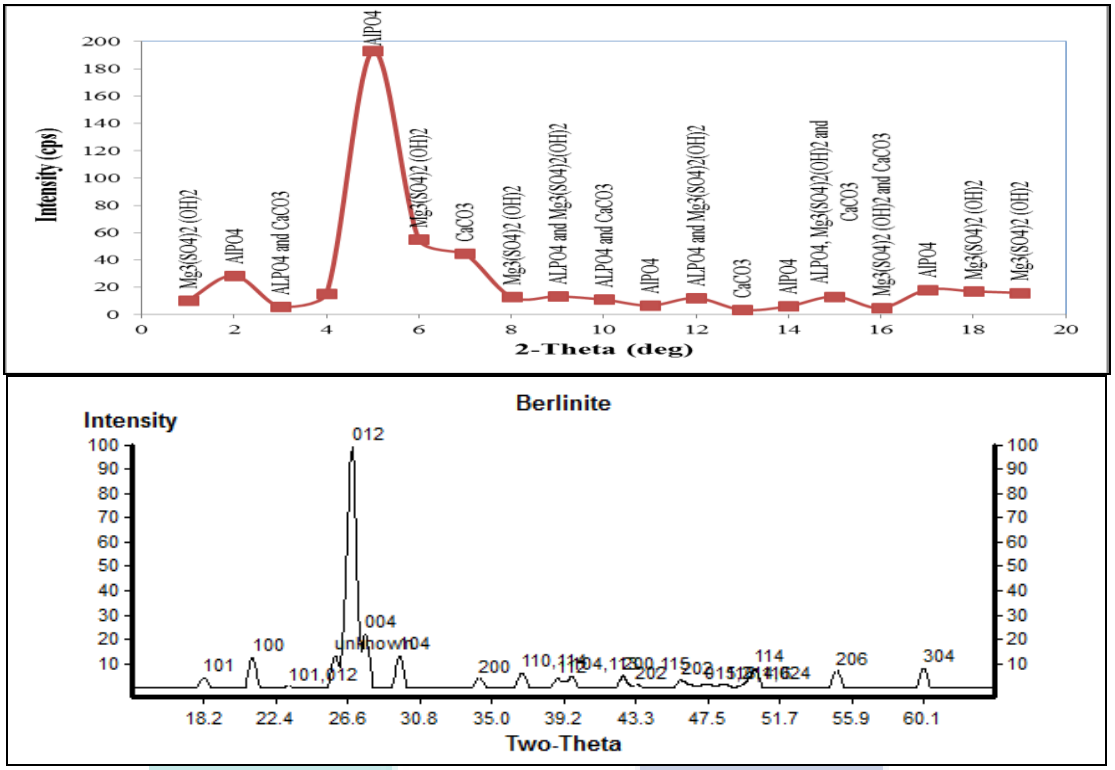


Figure 6.3: XRD patterns of plain concrete

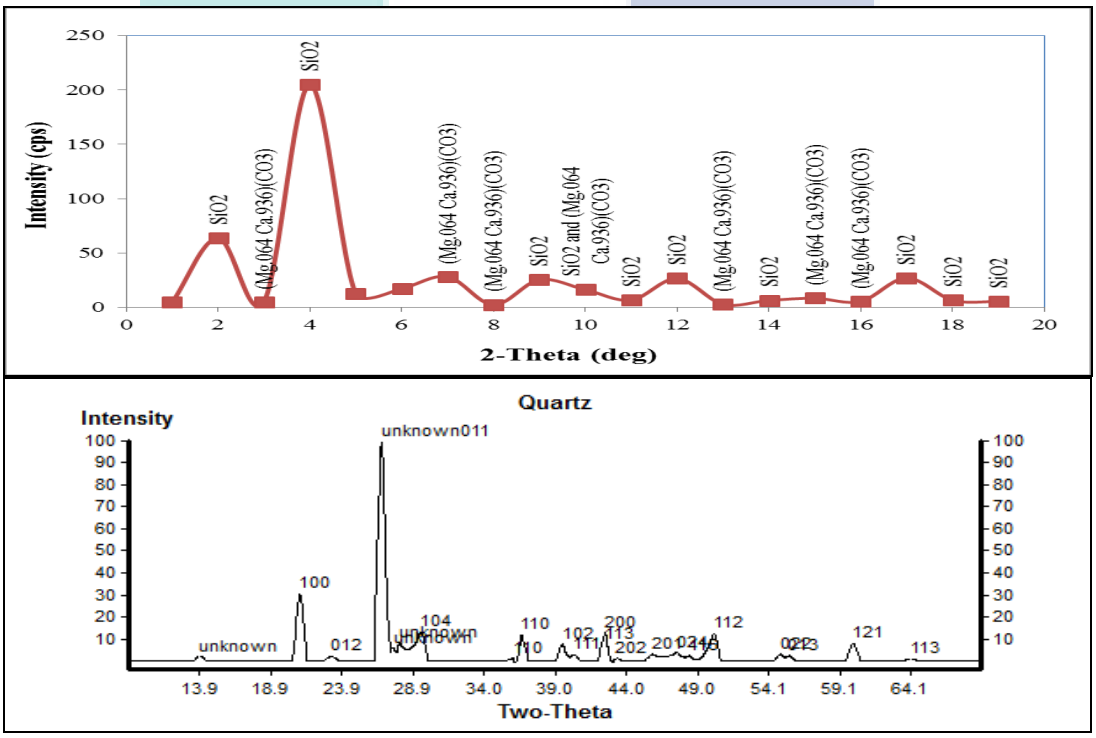


Figure 6.4: XRD patterns of mix 26

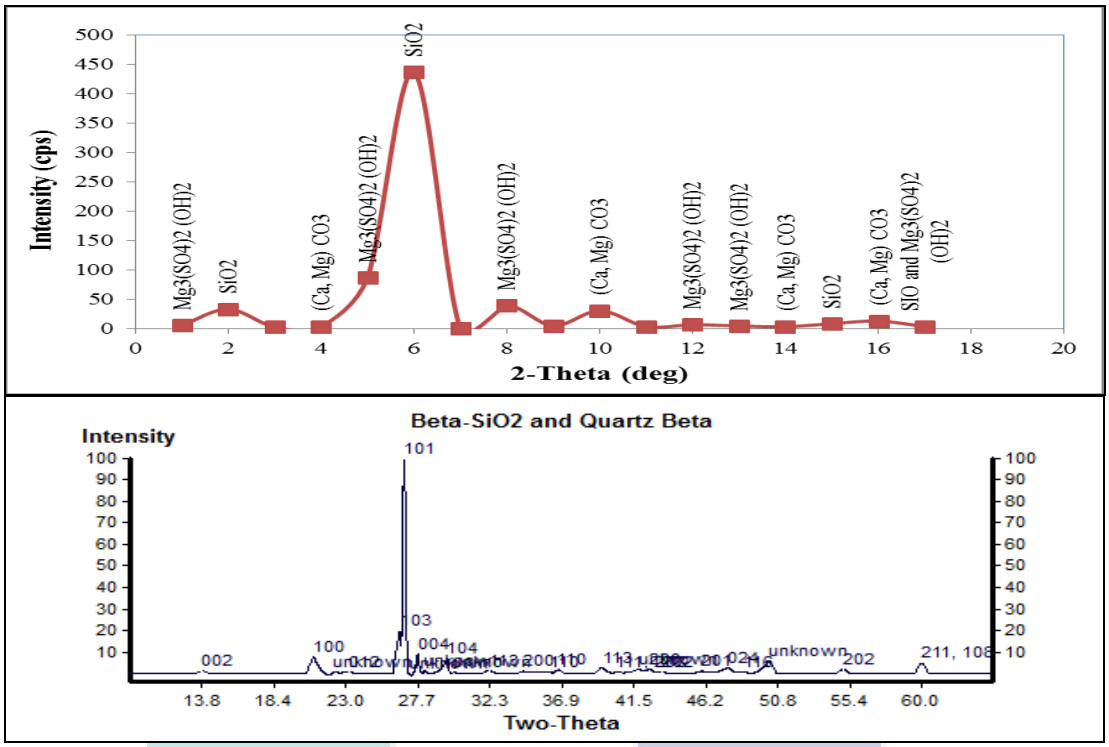


Figure 6.5: XRD patterns of mix 43 (optimum specimen)

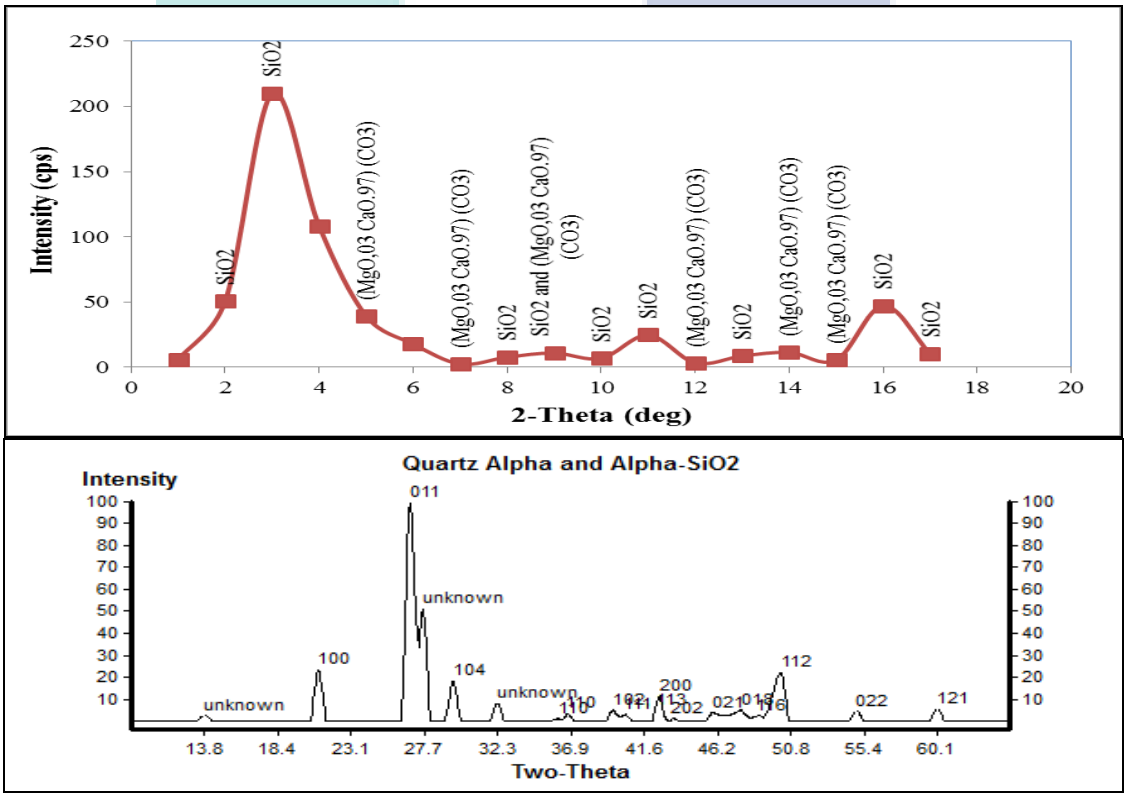


Figure 6.6: XRD patterns of mix 63

As seen in Figure 6.7, where the plots of X-ray diffraction patterns for the characterization of $Ca(OH)_2$ in acrylic emulsion polymer modified concrete have been depicted in comparison with plain concrete. It is apparent that raising polymer-cement ratio causes a gradual decreases of the quantity of $Ca(OH)_2$ in the systems, and at a polymer-cement ratio of 2.5% (mix 43) is higher to that of the plain concrete. On the basis of the experience gained by DTA/TGA analysis, it is possible to explain this variations in terms of the fact that the capability to arrest $Ca(OH)_2$ in hydrated cementitious systems is generally lower in mix 63 (4.0% AEP) compared to mix 26 (1.0% AEP) and mix 43 (2.5% AEP).

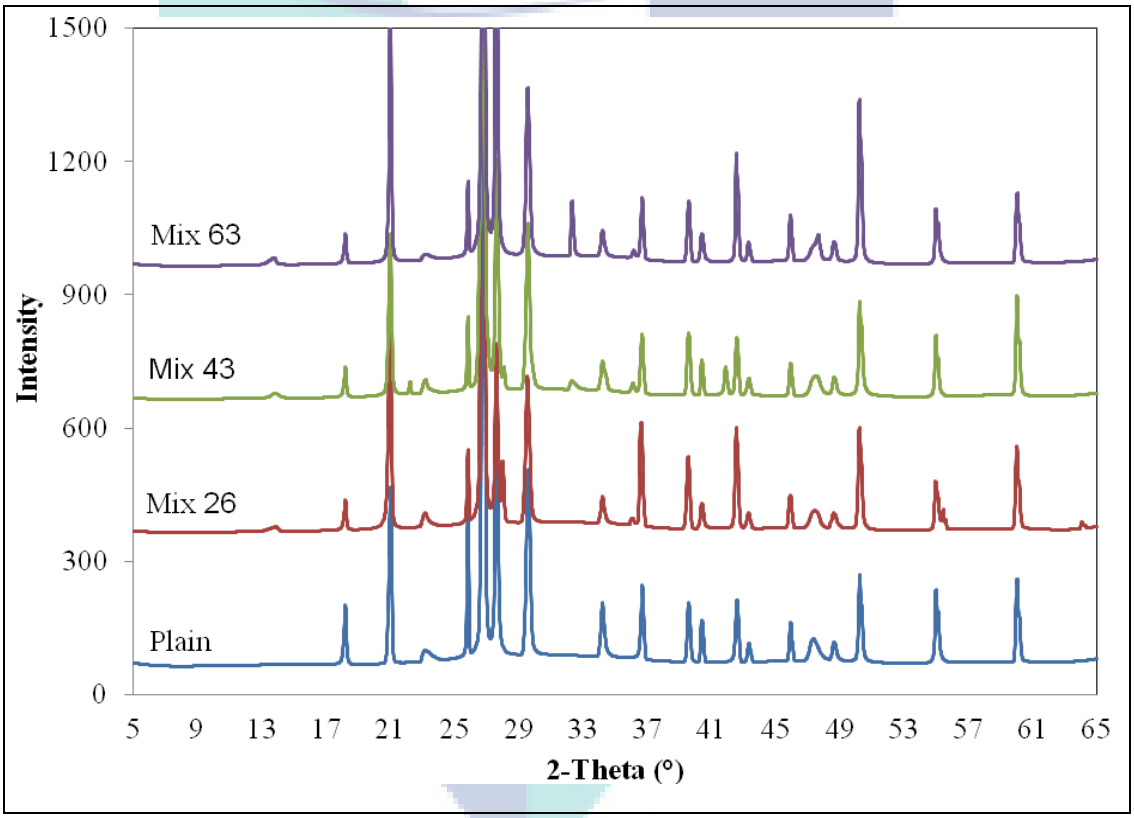


Figure 6.7: Plots of X-ray diffraction patterns for the characterization of $Ca(OH)_2$ in plain concrete and SFRPMC at varying polymer cement ratio

Further, $Ca(OH)_2$ crystals may possibly produce sharper reflections in the presence of 2.5% of acrylic emulsion polymer due to a change in the orientation pattern of the crystals. This sharper reflection offsets the effect gained by the lower quantity of $Ca(OH)_2$ and so the peak intensity at a polymer-cement ratio of 1.0% SFRPMC of mix

26 with a polymer – cement ratio of 2.5% SFRPMC of mix 43 is nearly equal to that of the plain concrete, in spite of the fact that the quantity of $Ca(OH)_2$ is gradually reduced in both these cases compared to plain concrete. Similar observation has been reported by Afridi et al. (2003).

6.3 THERMOGRAVIMETRIC ANALYSIS (TGA)

From earlier thermal analysis, the same specimens as tested for XRD in different temperature are analyzed. To know the thermal stability of specimens, a few degradation level, temperature peak and mass loss are determined. Thermal stability is characterized by on set temperature in loss of 5% bulks, T5%. Thermal degradation is taken in T50% temperature (^oC) namely loss of 50% bulks or peak in DTG curves matches to arc counter in TG curve. Table 6.2 shows the second thermal stability of SFRPMC systems which determined the weight loss of specimens at heated temperature. Increasing temperature in this system does not display effect on thermal stability although there is an increase in early decomposition temperature and degradation temperature.

Table 6.2: Weight loss of specimens during TG/DTA analysis

Reaction Zone	Mix 26	Mix 43 (OPTIMUM)	Mix 63
	Weight Loss (mg)		
Dehydration of pore water	0.0002	0.0003	0.003
Dehydration of calcium silicate hydrates	0.0001	0.0001	0.001
Dehydroxylation of calcium hydroxide	0.0006	0.0004	0.003
Enlargement of the endothermic peak intensity	0-0.0002	0.0001	0.004
Decarbonation of $CaCO_3$	0.0008	0.0012	0.008

The DTA and TG curves obtained in all the tests are typical in hydrated cement composites containing carbonate phases. Figure 6.8 shows the thermal stability plots for all SFRPMC specimens and plain concrete. The weight versus temperature plot for all specimens shows that the curves have almost the same pattern. All specimens decompose in temperature range 650^{o}C – 750^{o}C and fully decompose around 800^{o}C.The percentage of decomposition of specimens does not gives too obvious differences. Early decomposition of all specimens is shown in Table 6.3.

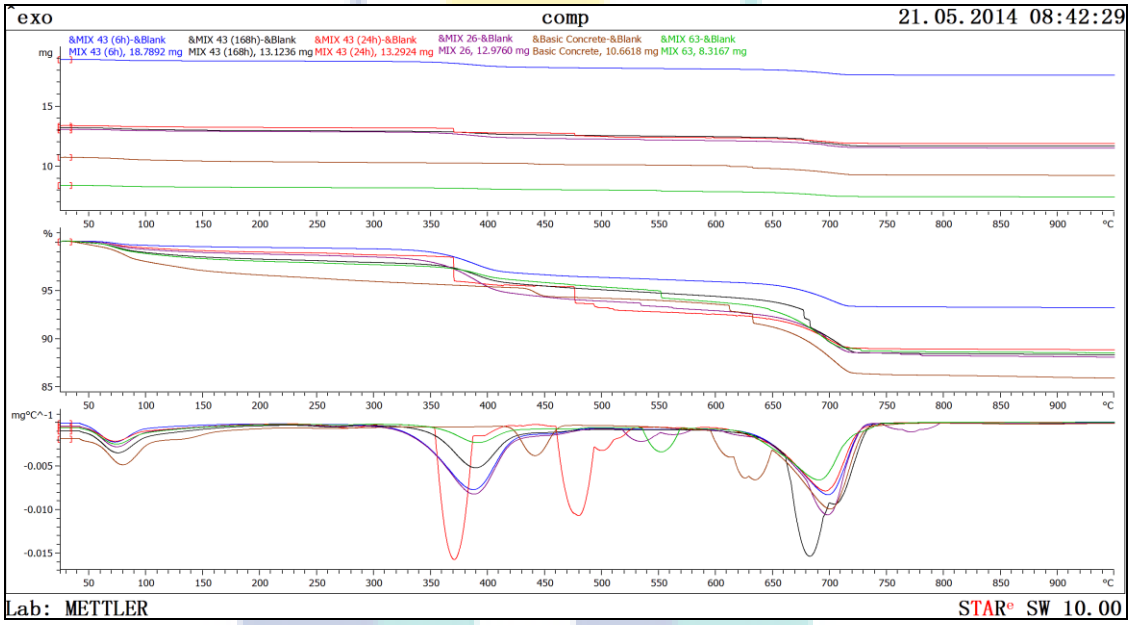


Figure 6.8: TG/DTA plots for all SFRPMC specimens and plain concrete

Table 6.3: Thermal stability for all specimens

Specimen	Early Decomposition Temperature (^{o}C)
Plain Concrete	450
Mix 26	390
Mix 43 (6 hours)	385
Mix 43 (24 hours)	370
Mix 43 OPTIMUM (168 hours)	390
MIX 63	390

Figure 6.9 shows the TGA curves of plain concrete without acrylic emulsion polymer. It can be seen that TG/DTG curves for this plain concrete consist of four zones:

1. Dehydration of pore water ($60^{o}C$ – $100^{o}C$)
2. Dehydration of calcium silicate hydrates ($100^{o}C$ – $420^{o}C$)
3. Dehydroxylation of calcium hydroxide ($420^{o}C$ – $470^{o}C$)
4. Decarbonation of $CaCO_3$ ($700^{o}C$)

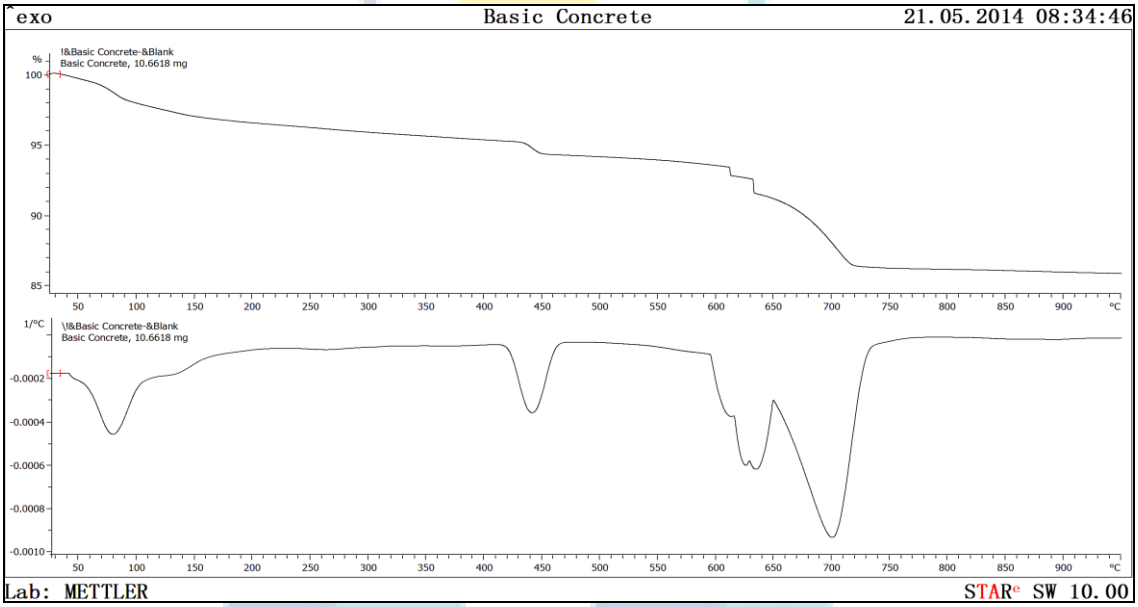


Figure 6.9: TG/DTA plots for plain concrete

Figure 6.10 – 6.14 show TG curves of composites with acrylic emulsion polymer addition of 1.0%, 2.5% and 4.0%. The TG curves obtained in these tests are typically of hydrated cement composites containing carbonate phases and acrylic emulsion polymer modification influences.

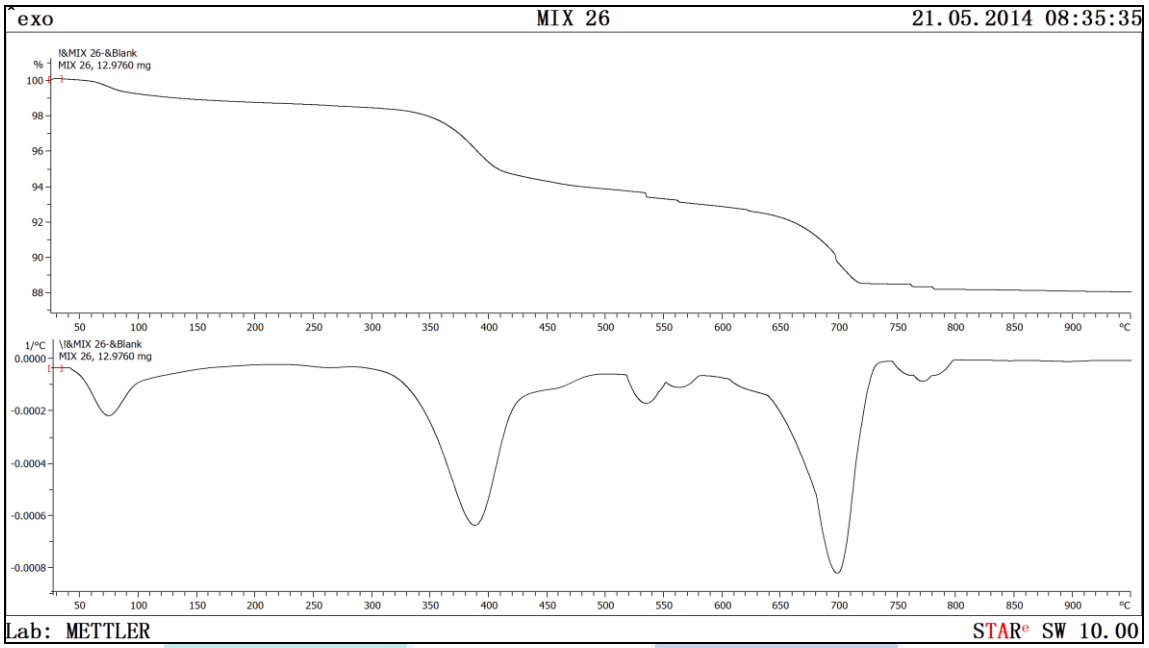


Figure 6.10: TG/DTA plots for mix 26

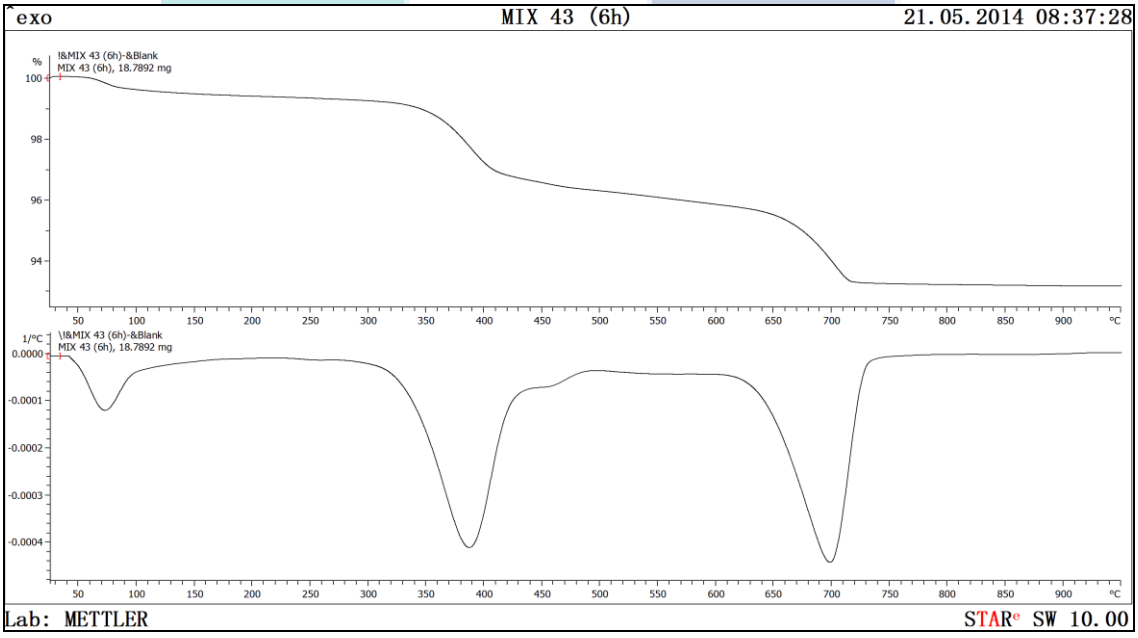


Figure 6.11: TG/DTA plots for mix 43 (6 hours curing)

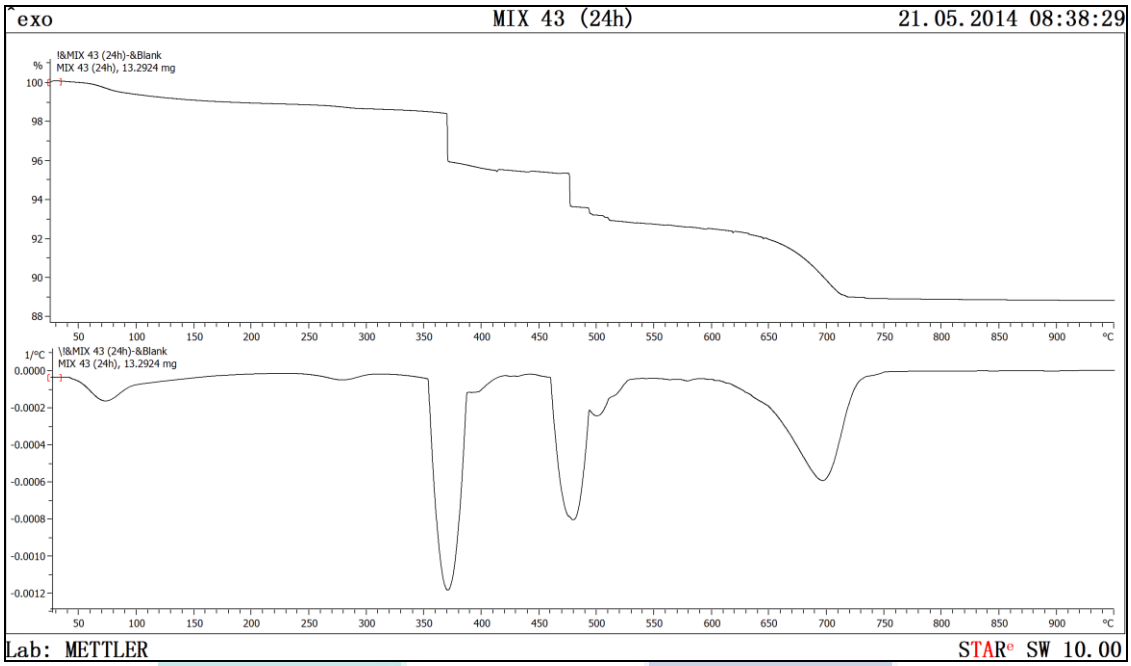


Figure 6.12: TG/DTA plots for mix 43 (24 hours curing)

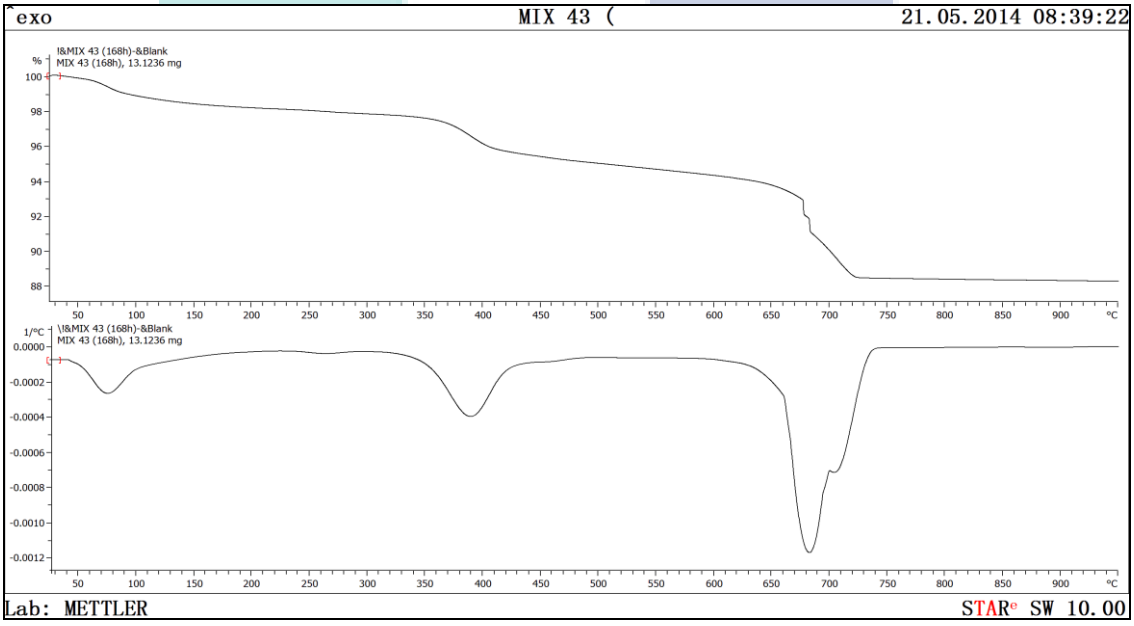


Figure 6.13: TG/DTA plots for mix 43 (168 hours curing)

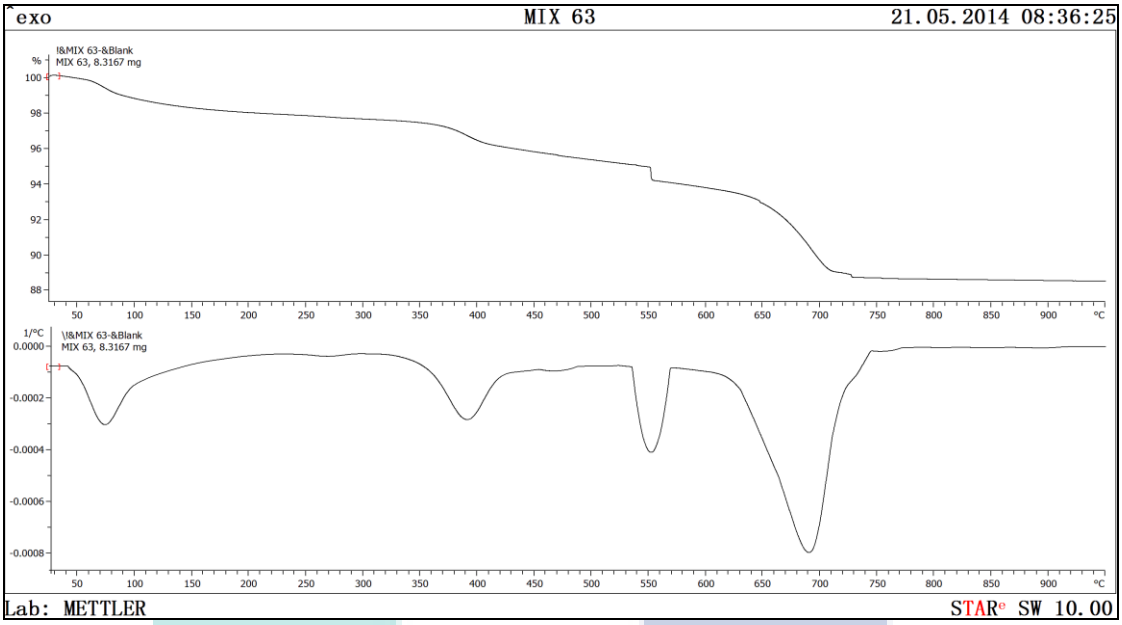


Figure 6.14: TG/DTA plots for mix 63

The curves can be divided into five major parts, according to different reactions. It is summarized in Table 6.4:

Table 6.4: TG/DTG temperatures for SFRPMC with different mix proportion of acrylic emulsion polymer content

Reaction Zone	Plain Concrete	Mix 26	Mix 43 (OPTIMUM)	Mix 63
	Temperature (^{o}C)			
1. Dehydration of pore water	60 – 100	50 – 100	50 – 100	48 – 100
2. Dehydration of calcium silicate hydrates	100 – 420	100 – 300	100 - 350	100 - 350
3. Dehydroxylation of calcium hydroxide	420 – 470	300 – 435	350 – 430	350 – 420
4. Enlargement of the endothermic peak intensity	470 – 600	435 – 650	430 – 630	420 – 630
5. Decarbonation of $CaCO_3$	700	700	670	690

All the weight loss data are expressed as function of the ignited weight of the sample as suggested by Silva et al. (2001). The calcium hydroxide content is determined from the Equation 6.1.

$$CH(\%) = WL_{CH}(\%)\, x \frac{MW_{CH}}{MW_{H}} \tag{6.1}$$

Where CH(%) is the content of $Ca(OH)_2$ (in weight basis), WL_{CH} (%) is the weight loss occurred during the dehydration of calcium hydroxide (in weight basis), MW_{CH} is the molar weight of calcium hydroxide and MW_H is the molar weight of water. Since the exact stoichiometry of decomposition reactions of the carbonate phases is not known, the results are expressed in function of the weight of CO_2 gas released during the decomposition, and not as carbonate phase's content (Silva et al., 2001). Based on Figure 6.8, it can be seen that acrylic emulsion polymer sharply decreases the quantity of carbonate phases in the composites. When the rate of substitution of acrylic emulsion polymer increases, there is less formation of portlandite, $Ca(OH)_2$. This is mainly the results of the following reaction (Soufiane et al., 2012):

$$C_3S + C_2S + H_2O \rightarrow C-S-H + Ca(OH)_2 \tag{6.2}$$

From the results, the plots of typical $Ca(OH)_2$ endotherms obtained from different mixes with various of polymer-cement ratio in the temperature range to 300 to 500^{o}C. In Figure 6.15, endothermic peak area due to the decomposition of $Ca(OH)_2$ has been plotted against the polymer-cement ratio. These results show that as the polymer-cement ratio is increased, both the peak intensity and the peak area are decreased in each case in comparison to plain concrete. Table 6.5 shows the analytical data from thermal analysis and also contains data on the quantity of $Ca(OH)_2$ in each system. The results confirm the previous finding of X-ray diffraction analysis, and suggest that as the polymer-cement ratio is increased, the quantity of $Ca(OH)_2$ is gradually decreased in SFRPMC.

Table 6.5: Analytical data from thermal analysis

Type of concrete	Polymer-cement ratio	Peak Temperature	Peak Area (cm)	Weight Loss of Ca(OH) (mg)
Plain Concrete	0.0	440	0.2	0.0035
Mix 26	1.0	390	0.6	0.0006
Mix 43	2.5	390	0.3	0.0004
Mix 63	4.0	390	0.2	0.0003

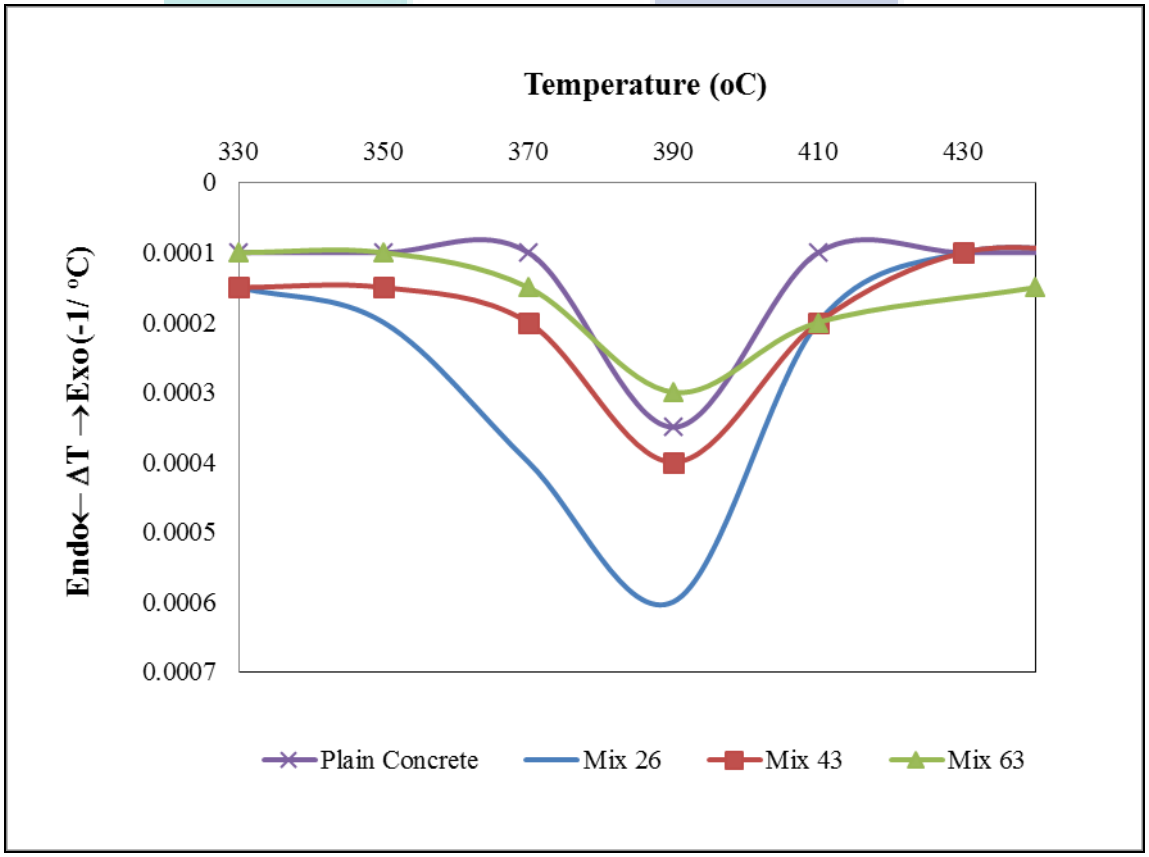


Figure 6.15: DTA plots of $Ca(OH)_2$ estimation for plain concrete and SFRPMC at varying polymer-cement ratios

The data also show that generally there is less capability of arresting $Ca(OH)_2$ with acrylic emulsion polymer. At a polymer-cement ratio of 4.0%, acrylic emulsion

polymer was so effective that it was impossible to measure the quantity of $Ca(OH)_2$ thermogravimetrically because of the negligible weight loss. The smallest endothermic peak in Figure 6.14 and the lowest peak intensity in Figure 6.6 also confirm this behavior of SFRPMC with a polymer-cement ratio of 4.0%.

6.4 SUMMARY

The qualitative XRD investigation revealed that a lower intensity of $Ca(OH)_2$ (in the region $2\theta = 26.8^o$) is obtained in the presence of acrylic emulsion polymer, compared to plain concrete. Similarly, a decrease in the $Ca(OH)_2$ content is found in the TG analyses for the modified specimen with polymer addition. As it can be seen, composite with 4.0% polymer content presents the lowest $Ca(OH)_2$ compared with the other composites. The addition of cement modifiers reduces the formation of $Ca(OH)_2$ possibly due to absorption of $Ca(OH)_2$ on the polymer films. However, the magnitude of reduction in the quantity of $Ca(OH)_2$ is affected by the polymer-cement ratio. Generally an increase in polymer-cement ratio meets with a decrease in the quantity of $Ca(OH)_2$.

CHAPTER 7

RESULTS AND DISCUSSION

PERFORMANCE OF STEEL FIBER REINFORCED ACRYLIC EMULSION POLYMER MODIFIED CONCRETE (SFRPMC) MIXES

7.1 INTRODUCTION

This research objectives are to study the effect of acrylic emulsion polymer and steel fiber addition on mechanical properties and thermal properties of steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC). The main key in this high well-performed composite production is the cement-based composite that can scattered perfectly in polymer-cement matrix with steel fiber. Hence, the parameter that is used in this composite is selected based on Taguchi analysis that is being conducted previously. 28 days curing time and water-cement ratio of 0.50 have been constant in this SFRPMC composite production. In this chapter, analysis on the properties of the various composites is presented; focusing on the influence of fibers and polymers on the properties of hardened concrete namely compressive strength, flexural strength and splitting tensile strength.

7.2 FRESH CONCRETE

7.2.1 Workability

Good workability is essential for high strength concrete because less efficient compaction may lead to loss of strength. Many factors, such as total content, water/cement ratio, acrylic emulsion polymer, and aggregate shape and size, effect workability. For ease of achieving the strength objective, the basic parameters such as

cement content, silica fume and water content are fixed for the reference plain concrete. Only the following parameters are varied:

7.2.1.1 Ratio of sand/total aggregate

For high strength concrete, the ratio of sand to total aggregate recommended by Cai (1998) ranges from 0.34 to 0.42 for crushed stone and 0.26 to 0.36 for gravel. An optimum sand content exists, which may not be sensitive for normal strength concrete. When the same water/cement ratio is maintained, an increase of fine aggregate content may reduce both workability and strength (unless more chemical admixture is applied), because the specimen may not be easy to compact when still in its fresh state. Very high mortar content may also lead to increase in shrinkage and creep properties. In this research, ratios of 35%, 38% and 43% are tried. The result shows that the concrete with 43% sand had the best results when workability, strength and lower admixture dosage are considered. However, a slightly higher sand content is helpful for fiber dispersion. Suitable adjustment is made when fibers are incorporated.

7.2.1.2 Polymer/cement ratio

Polymer content is the dominant factor influencing the workability of AEPMC. Table 7.1 shows the workability of AEPMC by slump test.

Table 7.1: Workability of polymer modified concrete (w/c = 0.42)

Index	**Polymer/Cement Ratio (%)**			
	0	1	2.5	4
Slump (mm)	0	12	50	185
Appearance	Very dry	dry	Medium sticky	Viscous and flow

7.2.2 Results for composites with polymer and/or fibers

7.2.2.1 Workability of fresh concrete

The workability of fiber reinforced concrete, which is important for practical applications, has different characteristics from that of conventional concrete (Bentur and Mindess, 1990). In order to achieve good workability for this part of investigation, some adjustments are made to these SFRC and AEPM-SFRC composites. First, the sand content (sand/total aggregate) is adjusted from 42% to 50%, which effectively improved fiber dispersion in the fresh concrete; no superplasticizer is added to compensate for the workability loss due to fiber addition and the increase in fine aggregate. Workability data for all the 35 mixes are shown in Table 7.2 below:

Table 7.2: Workability data

Category	Code	Water-Cement Ratio	Polymer (%)	Silica Fume (%)	Steel Fiber (%)	Slump (mm)
Concrete with silica Fume	PCS	0.50	0.0	8.0	-	70
AEPMC	PMC1.0	0.50	1.0	8.0	-	80
AEPMC	PMC2.5	0.50	2.5	8.0	-	95
AEPMC	PMC4.0	0.50	4.0	8.0	-	200
SFRC	SFRC1.0	0.50	-	8.0	1.0	65
SFRC	SFRC1.5	0.50	-	8.0	1.5	60
SFRC	SFRC2.0	0.50	-	8.0	2.0	55
AEPM-SFRC						
MIX 1	SFRPMC 1.0SF	0.50	1.0	8.0	1.0	60
MIX 2	SFRPMC 1.5SF	0.50	2.5	8.0	1.5	85
MIX 3	SFRPMC 2.0SF	0.50	4.0	8.0	2.0	75
MIX 4	SFRPMC 1.0AEP	0.50	1.0	8.0	1.5	75
MIX 5	SFRPMC 2.5AEP (OPTIMUM)	0.50	2.5	8.0	1.5	90
MIX 6	SFRPMC 4.0AEP	0.50	4.0	8.0	1.5	165

The results indicated that most mixes has slumps ranging from 60 – 90 mm when lower dosages of polymer are added. For higher polymer additions, says 4.0%, the slump values are much higher, ranging from 145 mm to 200 mm due to the water-reducing property of the polymer. Even for mix 3, where much higher total volume fraction V_f = 2.0% of fiber is used, the polymer is able to provide an acceptable workability. Figure 7.1 shows the effect of polymer dosage on the slump when the water-cement ratio was held constant.

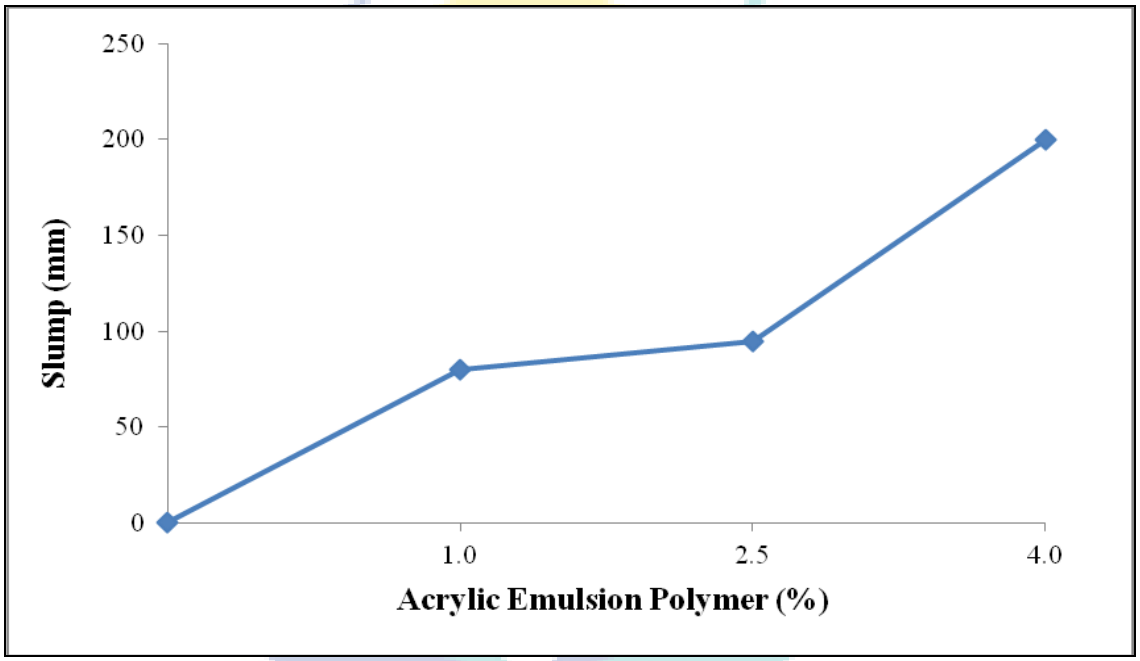


Figure 7.1: Effects of polymer dosage on workability of AEPMC

The workability of SFRC and SFRPMC mixes is summarized in Figure 7.2. The results indicate that steel fiber and acrylic emulsion polymer have significant influences on the SFRC-AEPMC mixes studied here. The effects of different fibers on workability can be evaluated by comparing the polymer dosage and/or workability data for similar mixes such as SFRC1.0, SFRC1.5, SFRC2.0, and SFRPMC with different fibers and acrylic emulsion polymer dosage. When polymers were added to the SFRCs, as expected and better characteristics resulted, such as less mixing friction, the greater ease of casting and better finishability is obtained. The effective effect of polymer in SFRC-AEPMC is observed when high workability (165 mm) was observed when 4.0%

polymer was added. This may be because of the polymer not only increased the workability but also led to better distribution and decreased of balling of the fibers.

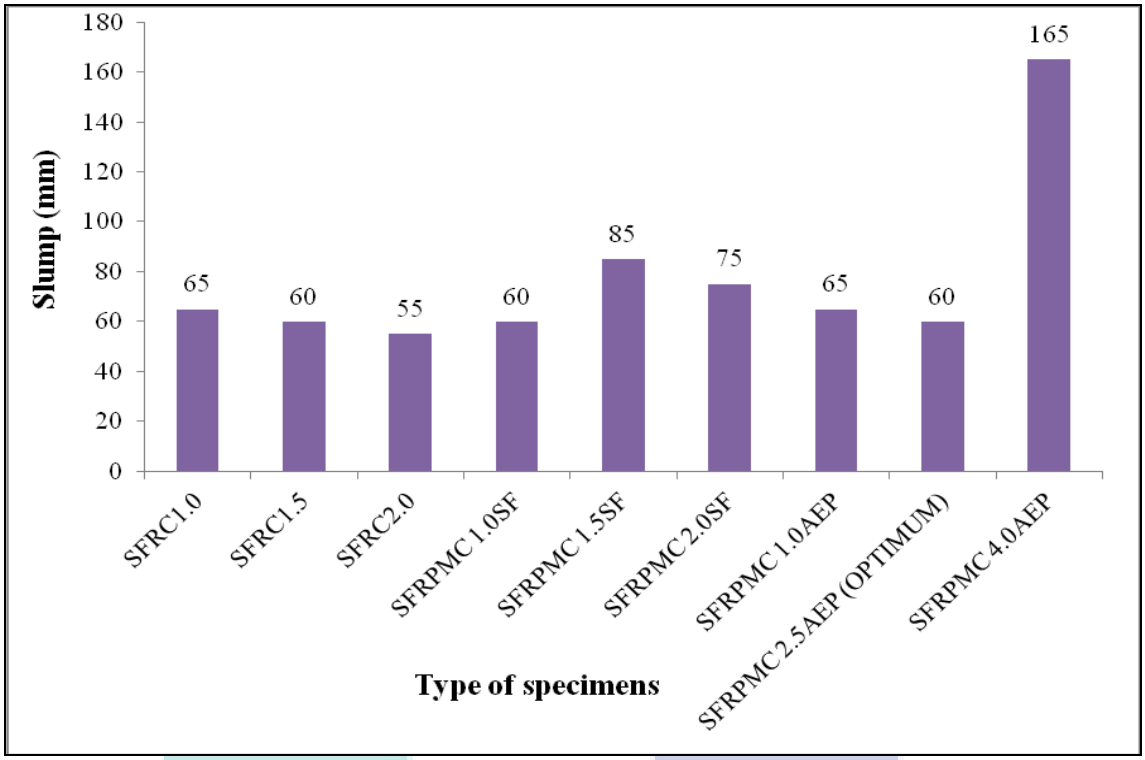


Figure 7.2: Workability of SFRC and SFRPMC mixes

It has been often reported that some polymer latexes also have plasticizing effect in fresh cementitious mixtures due to the adsorption of polymer particles on the surface of cement grains and the consequently better dispersion of cement grains (Ohama, 1998 and Kong and Li, 2009). Basically, the incorporation of acrylic emulsion polymer has significant influences on the fluidity of SFRPMCs. Similar to superplasticizer, the influences of acrylic emulsion polymer on the pore structure of hardened cement pastes that originates from the changes in the coagulated structure of cement grains should be expected. On the other hand, different from superplasticizer, acrylic emulsion polymers exist in a condensed state with particle size, which are impossible to be integrated into cement hydrates during cement hydration. During cement pastes hardening, the polymer particles of the polymer films formed by the agglomeration of polymer particles fill in the capillary pores. In this way, the impermeability of hardened cement pastes may be more remarkably enhanced by adding polymer than adding superplasticizer due to

combination of plasticizing effect and filling effect (Knapen and Gemert, 2007; Huang et al., 2010).

7.3 HARDENED CONCRETE

Several parametric studies including the content of polymer, cement and water-cement ratio were fixed as mentioned in Chapter 5 for specimen 11-13 (refer Page 113), and they were performed through the variable of fiber volume fraction. In this scenario, the content of polymer and cement constantly was 4 kg/m^3 and 343 kg/m^3. Meanwhile, the water-cement ratio was fixed to 0.50. As can be observed in Table 7.3, integration of suitable content of steel fiber and acrylic emulsion polymer are able to enhance the compressive strength and flexural strength of the concrete mix.

Table 7.3: The influence of polymer and fiber content on the strength properties of SFRPMC

Specimen code	compressive strength (MPa)	flexural strength (MPa)	splitting tensile strength (MPa)
PC	76.03	7.40	5.22
AEPMC - 1.0%	70.31	8.67	5.89
AEPMC - 2.5%	68.45	12.42	5.26
AEPMC - 4.0%	68.32	13.23	5.13
SFRC - 1.0%	76.17	12.72	5.25
SFRC - 1.5%	77.98	12.96	5.35
SFRC - 2.0%	75.20	13.48	5.48
SFRPMC 1.0SF	78.13	13.55	6.37
SFRPMC 1.5SF	79.55	13.14	6.49
SFRPMC 2.0SF	80.63	12.55	7.05
SFRPMC 1.0AEP	86.03	12.63	6.28
SFRPMC 2.5AEP (OPTIMUM)	87.68	13.83	6.49
SFRPMC 4.0AEP	68.12	11.32	6.35

To be more specific, flexural strength (σ_f) of mix 43 cured 28 days were better than AEPMC specimens by 11.4%, whereas the compressive strength (σ_c) increased by 28% and σ_f/σ_c decreased by 16.7%. The flexural strength of specimens decreased at

2.0% volume of steel fiber. It could be concluded that fiber is not sufficient to exert a continuous toughening effect inside the specimens in inadequate fiber included. However, excessive fiber would as well result in dispersed an uneven surface, which is prone to agglomerate. Therefore, the macroscopic defects will appear, giving rise to the dispersion of the strength performance (Xu et al., 2014). All the results through SEM-EDX are also shown in Appendix G.

7.3.1 Compressive Strength

The relationship between compressive strength at different ages and various ratios of steel fiber and several polymer/cement ratios (p/c) is shown in Figure 7.3. It can be seen that the compressive strength of SFRC increases with the increase of steel fibers. However, when 2.0% of steel fiber is used, the compressive strength of the concrete mix drops. The reason of this is the fiber after which 2.0% had formed bulks and segregate on mix. This will form stiff bond about this bulks. When acrylic emulsion polymer is added to mix, the compressive strength increases with the increase of polymer content but after (p/c = 4.0%) the compressive strength decreases. The increase in compressive strength may be due to three facts. The first is that PMC has less w/c ratios, which gives higher strength. Secondly, the use of polymer leads to form continuous three dimensional networks of polymer molecules throughout concrete which increases the binder system due to good bond characteristic of polymer. The last is the partial filling of pores with polymer which reduces the porosity, and hence increases the strength (Letif, 1998). The maximum compressive strength is obtained when the concrete mix produced by adding 1.5% steel fibers by volume and 2.5% acrylic emulsion polymer.

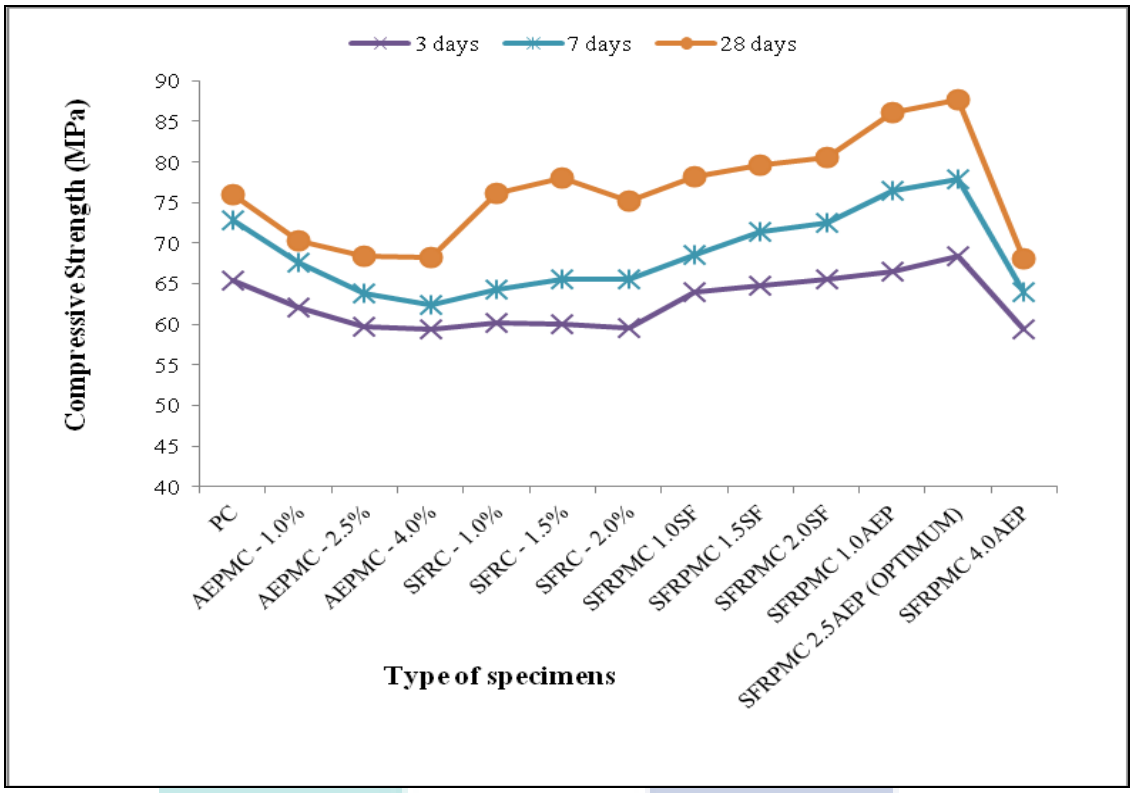


Figure 7.3: The development of compressive strength with age for all concrete mix

7.3.2 Flexural Strength

The relationship between flexural strength and various ratios of steel fiber and various ratios of polymer/cement is shown in Figure 7.4. The addition of steel fiber leads to remarkable increase in flexural strength for plain concrete as well as SFRPMC. The increase is due to the same reasons mentioned for the compressive strength and splitting tensile strength. It can be noted that the specimens containing steel fiber shows higher degree of ductility before failure and steel fiber does not start to pull out from fractures surface until the maximum load is reached. Similar observation has been observed by Ghassan (2007). The maximum flexural strength is obtained when the mix content of 1.5% steel fiber by volume and 2.5% acrylic emulsion polymer.

Use of acrylic emulsion polymer in plain concrete and SFRC also improves the flexural strength of concrete. Despite this, the flexural strength of SFRPMC showed a faster response to the growth of acrylic emulsion polymer content as the addition of

steel fiber. Or rather, the flexural strength of mix 43 cured in 28 days was larger than SFRC by 6.7% indicating that the steel fiber was conducive to the enhancement modification effects possessed by acrylic emulsion polymer.

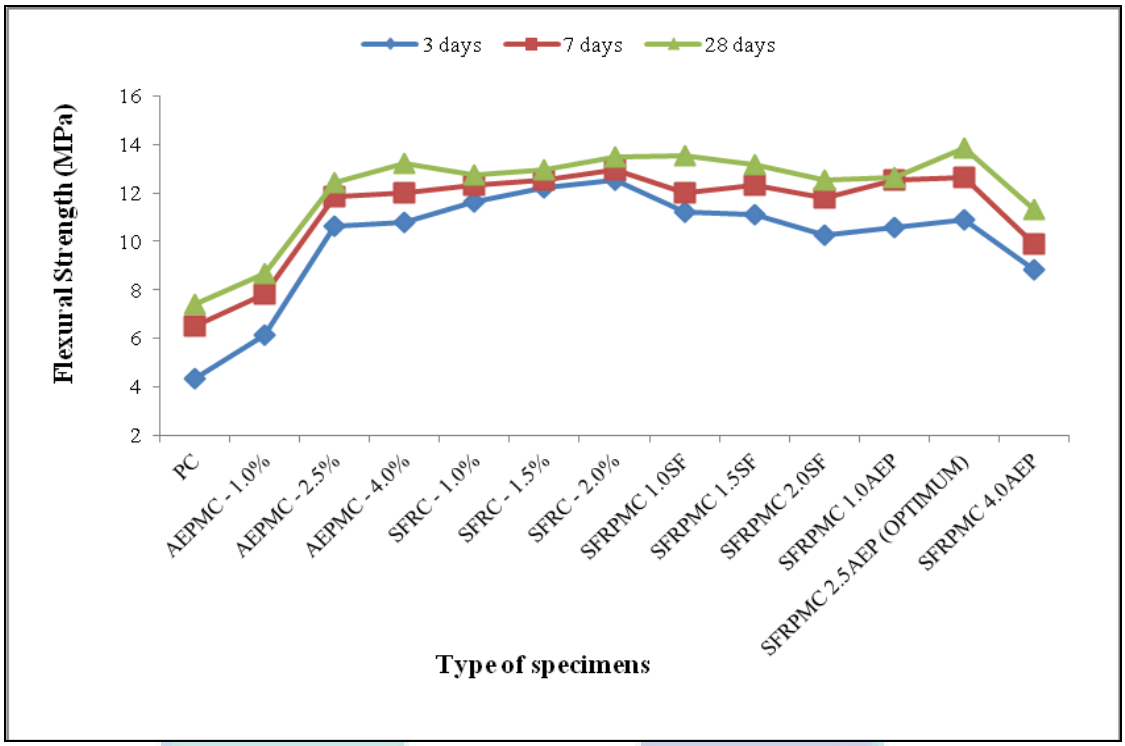


Figure 7.4: The development of flexural strength with age for all concrete mix

7.3.3 Splitting Tensile Strength

The relationship between splitting tensile strength and various ratios of steel fiber and various ratio polymers is shown in Figure 7.5. It can be seen that the addition of steel fiber leads to increase of remarkable splitting tensile strength. The increase is due to the fact that the presence of steel fibers arrests cracks progression. The tensile strength of the concrete mix increases with the increase of the polymer content. The increase may be due to the reduction in water-cement ratio (Ghassan, 2007). The maximum splitting tensile strength is obtained at mix containing 1.5% steel fiber by volume and p/c = 2.5%. However, using too much of polymer (4.0%) causes the tensile strength to decrease.

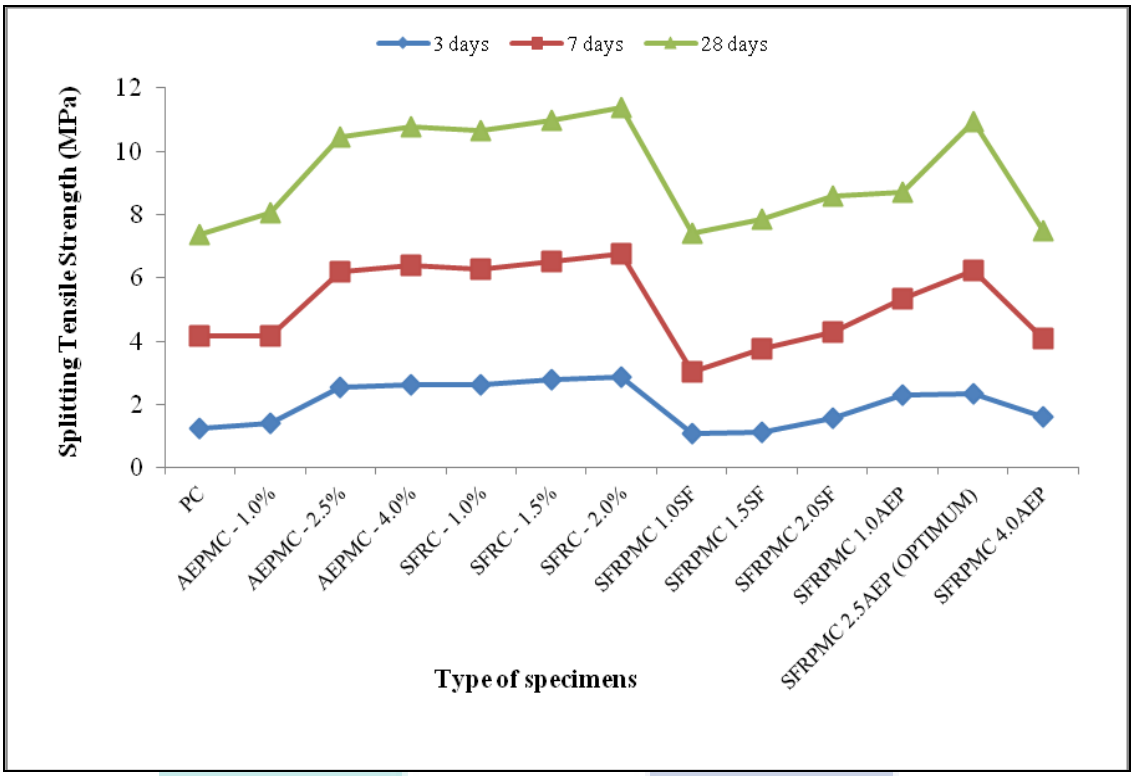


Figure 7.5: The development of splitting tensile strength with age for all concrete mix

7.4 MORPHOLOGY EXAMINATION

Morphology examination by using scanning electron microscopy (SEM) has been conducted on composite system that had been produced. The microstructures of tested specimens are shown in Figure 7.6 to 7.8. It can be seen that due to the presence of polymer film in all the specimens, the bond among steel fibers, aggregates and cement is greatly improved. Obviously, the porosity and pore size distribution are influenced by the corporation of polymer. The overall porosity increases with the increasing dosage of polymer (Li et al., 2010).

The SEM image of polymer modification cement shows a quite different morphology. It can be seen the fracture surface has more fibrillar outgrowths, or more recticular networks. Figure 7.6 shows well defined hydrates with some C-S-H gel and the $Ca(OH)_2$ crystals in the layer form, some C-S-H gel in the fiber form. It seems that they spread into the pore space, but do not completely fill the space and leave large voids.

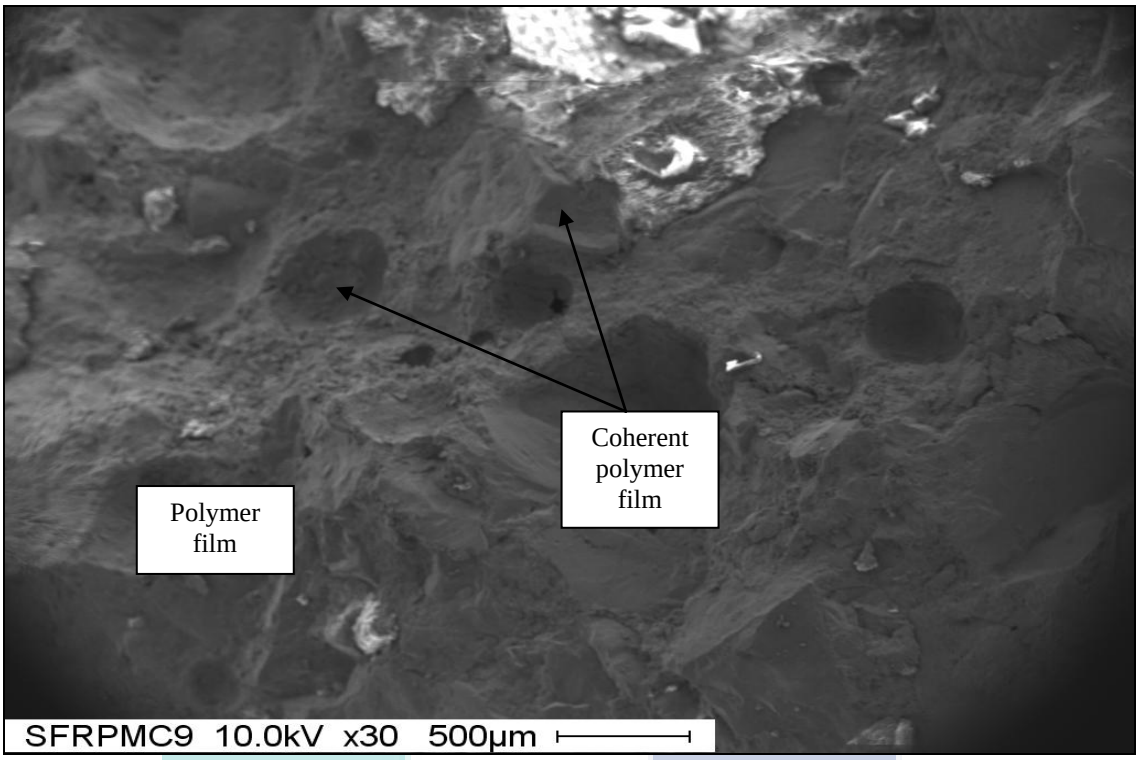


Figure 7.6: Microstructure on mix 26 (1.0% acrylic emulsion polymer, 8.0% silica fume, 1.5% steel fiber and 0.50 w/c ratio)

Figure 7.7 shows the gross structure of polymer-cement paste that can be seen and the C-S-H gel in this structure is finer and more acicular. It seems that some polymer adheres or deposit on the surfaces of the C-S-H gel. Needles of C-S-H appear to spread out from a cluster of hydrates and interweave together forming a crossing network. An additional observation of these figures is the morphology and dimension of $Ca(OH)_2$ crystals is shown in Figure 7.7. A group of fine $Ca(OH)_2$ crystal are observed in the limited areas. The presence of polymer confines the ionic diffusion so that the $Ca(OH)_2$ crystallized locally to form fine crystals. The void in the structures seems to be smaller, but no polymer films appears to be bridging the walls of the pores although many polymer bonds or C-S-H gel spread into the pore space. Due to the presence of polymer films in specimens, the bond among steel fibers, aggregates and cement is greatly improved (Li et al., 2010) and leads to the highest strength for mix 43.

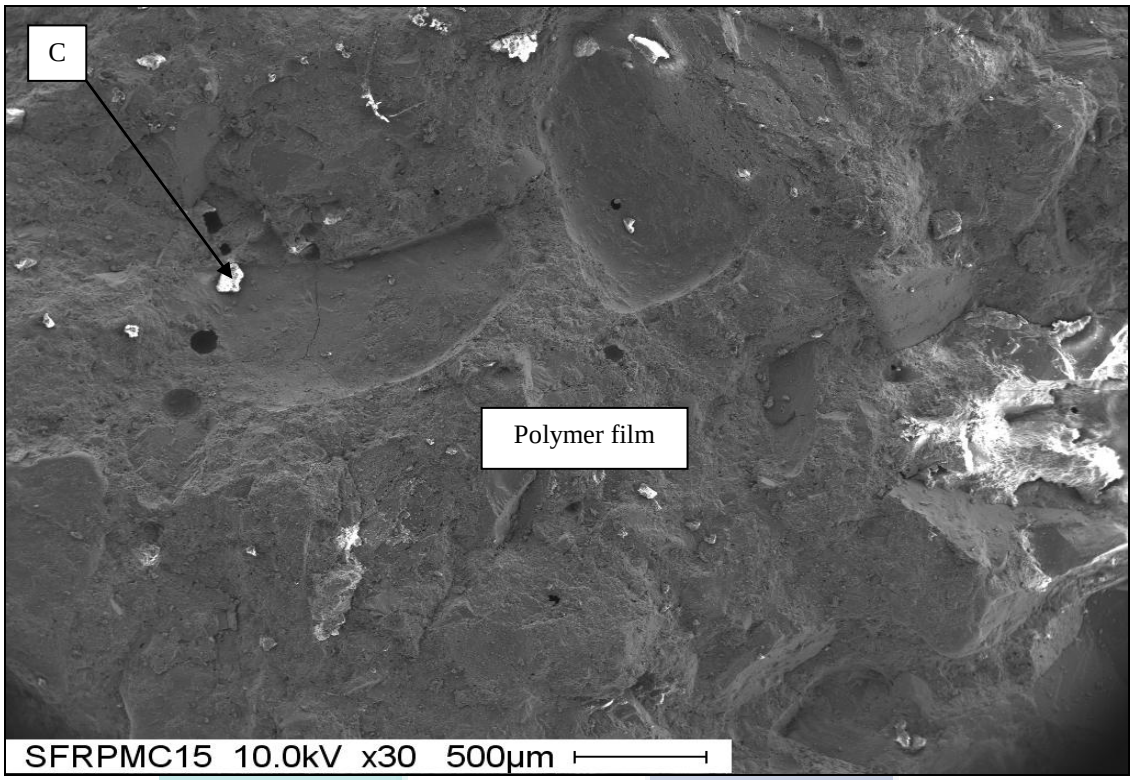


Figure 7.7: Microstructure on mix 43 specimen (2.5% acrylic emulsion polymer, 8.0 silica fume, 1.5% steel fiber and 0.50 w/c ratio)

As shown in Figure 7.8, the concrete constituents are not compactly joined leads to lower flexural strengths. The acrylic emulsion polymer cement paste (Figure 7.8) displays a fishing-net or honeycomb structure. There are ettringite or big pores are present. Furthermore, the polymer films in Figure 7.8 are thicker and more coherent than Figure 7.7. Thus steel fibers can be pulled out more easily in SFRPMC-21 (mix 63), and flexural strengths then become lower.

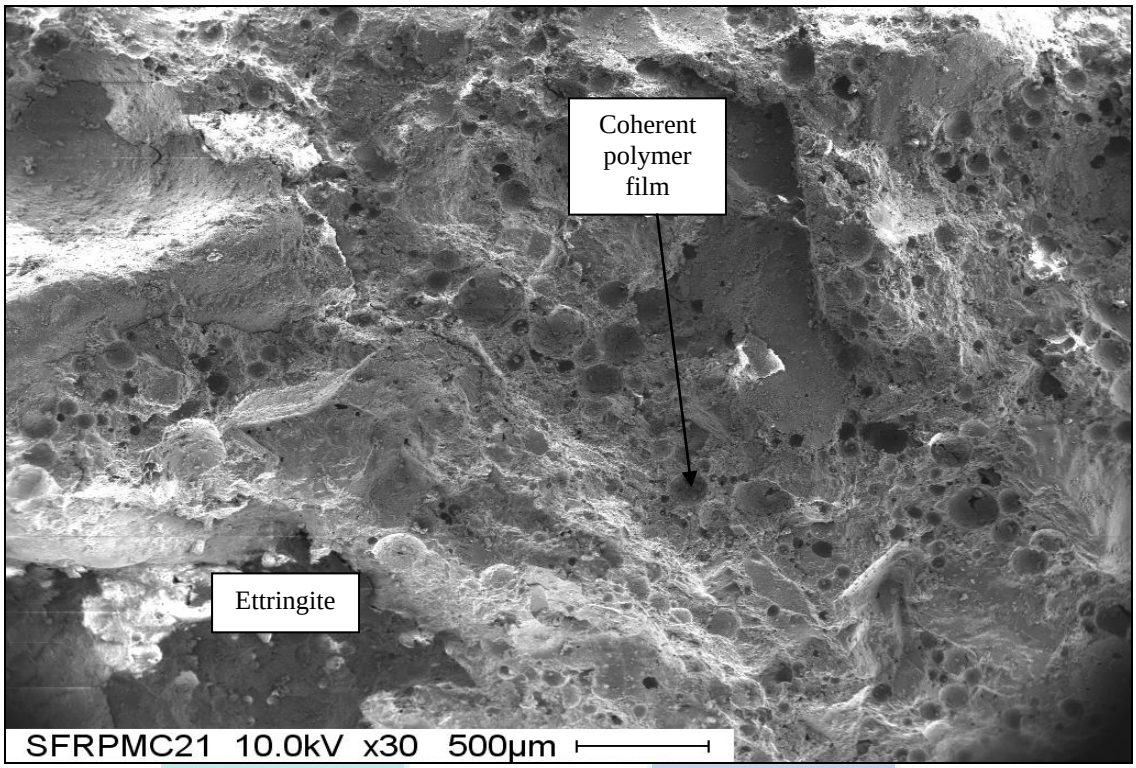
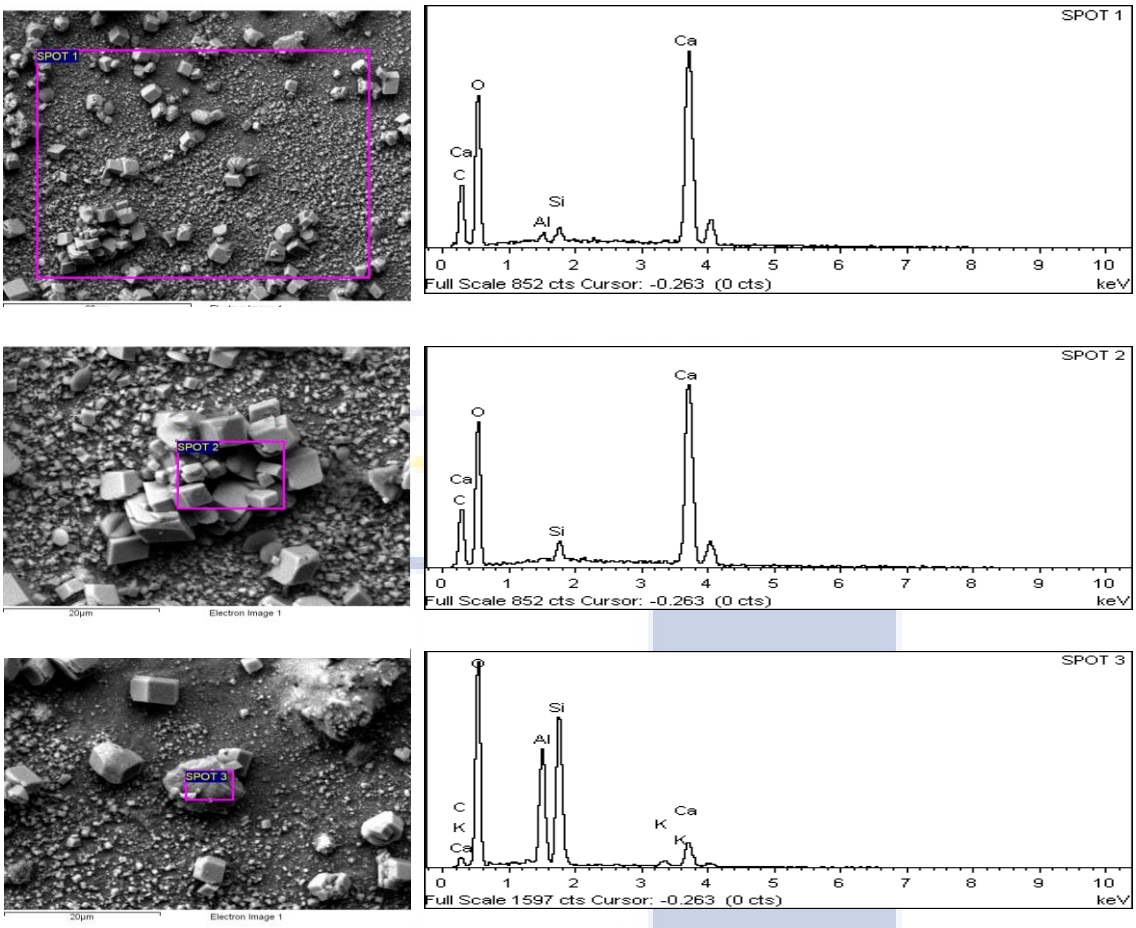


Figure 7.8: Microstructure on mix 63 (4.0% acrylic emulsion polymer polymer, 8% silica fume, 1.5% steel fibre and 0.50 w/c ratio)

Three spot spectra are carried out on the plain concrete specimen with a magnification of 2500x. This analysis aims to get information about general constituent in the cement matrix with silica fume. Table 7.4 gives a summary of the element present for each of the three spots spectra. In addition, to identify cement phases present in this specimen, Figure 7.9 shows reference EDX spectrum for calcium hydroxide and C-S-H for plain concrete specimens. All three spectra of plain concrete have significant calcium peaks at 3.7 keV. However, spot 3 in Table 7.4 exhibits a significantly smaller Ca peak, suggesting this spectrum may be taken from a phase containing silica fume. All spots in the table, as well as the C-S-H spectrum of Figure 7.9, also exhibit large silica peaks at around 1.7 keV which suggests that both spots contain C-S-H, and possibly unreacted cement grains. Table 7.4 shows that there are distinct differences between the three analyzed spots. However, most of the phases contain similar elements, but in slightly different proportions.



(a) (b)

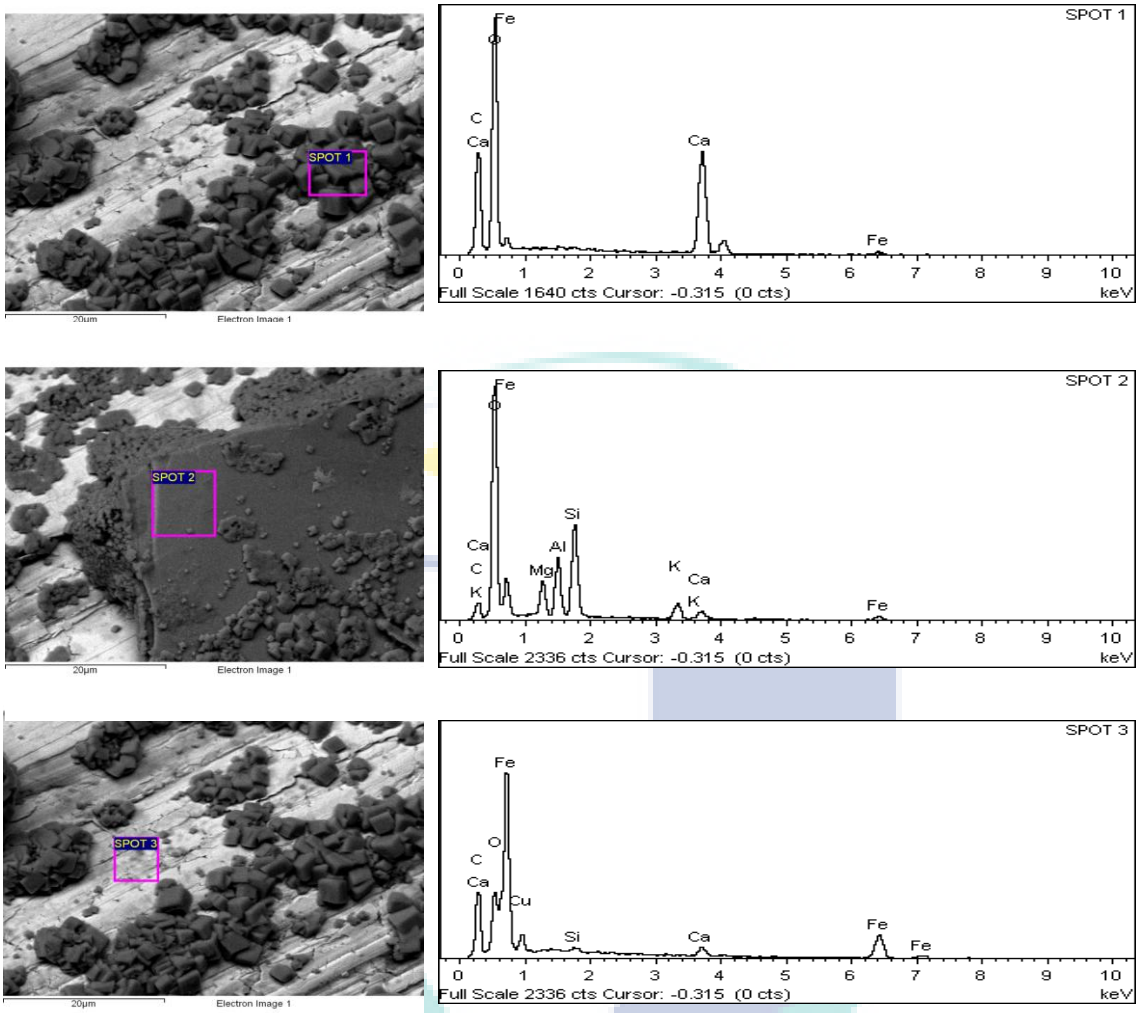
Figure 7.9: Spot 1 for plain concrete at 2500x magnification. (a) Image of the surface with the position at which the spectra taken marked. (b) Elemental peaks are shown to represent the elements present at the marked point.

Table 7.4: Element present in three spots spectra and the weight percentage of each for plain concrete at 2500x magnification

	Spot 1		Spot 2		Spot 3	
Element	**Weight%**	**Atomic%**	**Weight%**	**Atomic%**	**Weight%**	**Atomic%**
C K	6.49	12.27	6.72	12.73	5.78	9.61
O K	40.28	57.17	39.73	56.46	47.65	59.47
Al K	0.57	0.48			12.41	9.18
Si K	1.04	0.84	1.81	1.47	22.10	15.71
K K					1.73	0.88
Ca K	51.62	29.24	51.73	29.34	10.33	5.15

The expected phases in the cement are (i) inner C-S-H, (ii) calcium hydroxide; (iii) unreacted cement grains and (iv) silica fume derivate (Gallucci et al., 2010). It can be seen in Table 7.4 that there are trace amounts of Potassium present at spot 3, which may contain trace amounts of K_2O. However, for the composition of silica fume it would appear the ratios of the element at spot 3 are considerably different. It could be that the EDX spectrum taken at spot 3 has a larger interaction volume, and other phases combined with silica fume are detected, distorting the ratios. The ratio of Ca/Si peak in the inner C-S-H phase is expected to be around 1.5 to 2 (Richardson, 1999), whereas the calcium hydroxide phase should only have small amounts of Si (Figure 7.9). Of spot 1 to 3, only spot 3 have a ratio close to the correct ratio for inner C-S-H with a value of Ca/Si of 0.47 by weight. Based on this, it is inferred that spots 1 and 2 are more likely to contain higher volume fractions of calcium hydroxide and spot 3 is more likely to contain a higher fraction of inner C-S-H. Again, the ratios may be offset due to the interaction volume of the specimens which may include other phases.

For optimum specimens (mix 43), the EDX spectrum for calcium hydroxide and C-S-H are shown in Figure 7.10. All spots in the Table 7.5, as well as the C-S-H spectrum of Figure 7.12, also exhibit large silicon peaks at around 1.7 keV which suggests that spot 2 and 3 contain C-S-H, and possibly unreacted cement grains with polymer matrix. Table 7.5 shows that there are distinct differences between the three analyzed spots. Figure 7.12 shows the SEM images of the microstructure of fiber surface and hydrated cement matrix with acrylic emulsion polymer. It can be seen that steel fiber and polymer have been covered with densely hydrated cement matrix. This phenomenon implies a good bond between fiber and hydrated cement matrix in the early age. From this figure, the steel fiber pulled out from the cement matrix presents a smooth surface. This indicated a debonding cement matrices and fibers may occur in the long term. The aging phenomenon may result in a decrease in compressive strength at the late age (Xu, 2003).



(a) (b)

Figure 7.10: Spot 1 for mix 43 (optimum) at 2500x magnification.

From Table 7.5, there are trace amounts of Potassium present at spot 3, which may contain trace amounts of Cu. However, for the composition of acrylic emulsion polymer it would appear the ratios of the element at spot 3 are considerably different. It could be that the EDX spectrum taken at spot 3 has a larger interaction volume of C, and other phases combined with acrylic emulsion polymer are detected, distorting the ratios. Figure 7.11 presents the microstructure analysis of SFRPMC – mix 43 by SEM. It shows that the dense ITZ of specimens with the addition of polymer and the steel fiber, and in the ITZ, that are barely apparent defects, indicating that the inclusion of acrylic emulsion polymer could effectively fill the internal macro and micro defects of cement matrix, thus improving the degree of density into the ITZ. The role of polymer

and fiber can be explicitly explained through the microstructure figures. For one thing, acrylic emulsion polymer could shape continuous polymer films inside the concrete so that the flexibility and bonding capacity of polymer could enhance toughness and compact degree of ITZ. It could trigger steel fiber and the cement paste to a tight mutual connection. In addition, it could relieve the macro and micro defects of interface transition zone between fibers and cement paste, thereby boosting toughness and crack resistance (Xu et al., 2014).

Table 7.5: Element present in three spots spectra and the weight percentage of each for mix 43 (optimum specimen) at 2500x magnification

	Spot 1		Spot 2		Spot 3	
Element	**Weight %**	**Atomic %**	**Weight %**	**Atomic %**	**Weight %**	**Atomic %**
C K	12.66	21.29	5.89	11.14	12.35	35.59
O K	47.43	59.88	40.09	56.87	6.36	13.75
Mg K	0.00	0.00	3.53	3.29	0.00	0.00
Al K	0.00	0.00	5.61	4.72	0.00	0.00
Si K	0.00	0.00	11.37	9.18	0.36	0.44
K K	0.00	0.00	4.48	2.60	0.00	0.00
Ca K	30.96	15.60	2.49	1.41	2.12	1.83
Fe L	8.95	3.24	26.54	10.79	72.87	45.15
Cu L	0.00	0.00	0.00	0.00	5.93	3.23

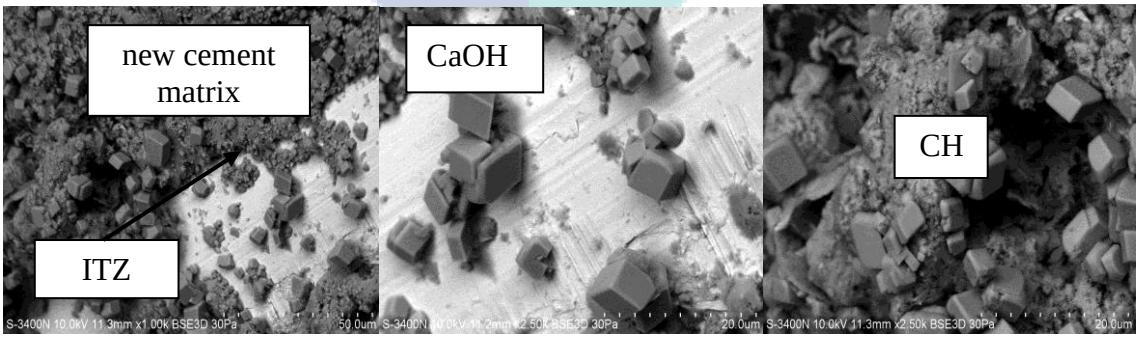


Figure 7.11: Spot 1 for mix 43 (optimum) at 1 day curing with three different spots

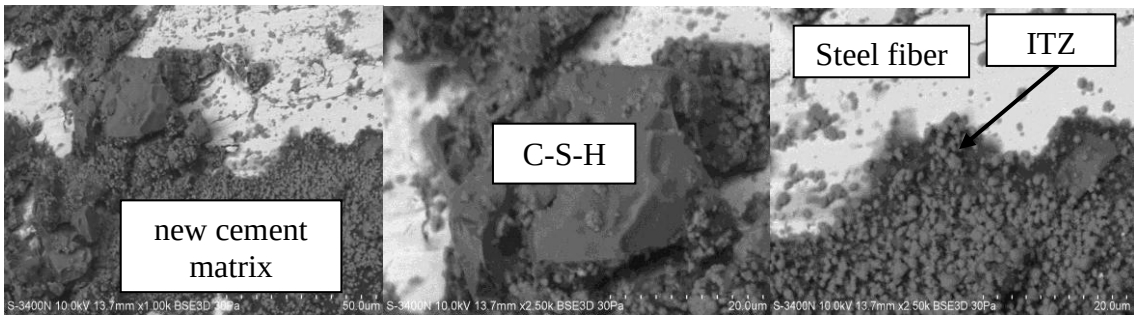


Figure 7.12: Spot 1 for mix 43 (optimum) at 7 days curing with three different spots

Figure 7.11 and Figure 7.12 show typical SEM microstructures through the combination of several photos, and some inkling of transition zone (ITZ) can be discovered. The results for various ages from SEM are explained as follows (Kuo et al., 2004):

1. At the edge of the aggregate, there are much unhydrated cement particles and products of initial hydration. From SEM inspection, a few C-S-H gels can be seen, but the hydration products of C-S-H increases quickly with the increase in curing age.

2. At age of 7 days, the unhydrated cement particles and products at the age of 1 day are transformed into C-S-H at the age of 7 days. The needle-shaped C-S-H increased and gradually formed the gel, with needles growing into the pore space just like mesh. At this age, silica fume particles still does not react, but among the hydration products, pore existed.

3. At the edge of the aggregate, there will still much hydration products caused by the pozzolanic reaction. Due to the mutual stack of these hydration products, it contained plenty of pores. Beyond this range, it can be found that the previous pores are now filled with the hydration products of pozzolanic reaction, making the previous mesh structure turn into plain structure. This phenomenon is more obvious as curing age increased. Moreover, from SEM microstructures, the porosity decreased as the distance from the aggregate edge increased. From the observation silica

fume particles kept on breaking and dropping off, and needle-shaped C-S-H is growing in it, in addition of acrylic emulsion polymer into the concrete.

The addition of emulsion polymer causes a plasticizing effect on the cement paste to some extent. Along with cement hydration, the agglomeration of emulsion polymer particles and film formation absorbed on cement occur, which effectively changes the microstructure by compacting the interfacial zones among phases. Finally, a structure of dense interpenetrating network is formed, involving cement hydrates, fine aggregates, and emulsion polymer membranes. From the microstructural analysis of composite, it is observed that using acrylic emulsion polymer modification, through application of high performance 8% of silica fume, caused a reduction in the porosity of aggregate-matrix ITZ region, compared to unmodified concrete.

7.5 SUMMARY

Based on mechanical analysis and thermal carried out, the addition of acrylic emulsion polymer gives apparent effect on mechanical and thermal properties of steel fiber reinforced acrylic emulsion polymer modified concrete. Generally addition of 2.5% of acrylic emulsion polymer had improved most mechanical properties and more addition of polymer has blighted mechanical on the tested specimens. When acrylic emulsion polymer is added as modifier, compressive strength, flexural strength and splitting tensile strength and thermal properties shows better improvement. With the increase of steel fiber content, the mechanical properties of SFRPMC showed a trend of improvement as well. It is interesting to note that SFRPMC possessed the optimal strength properties, flexural strength at 1.5% volume of steel fiber. Combination of steel fiber and suitable content of polymer produced SFRPMC mix having enhanced mechanical strength than plain concrete, AEPMC and SFRC.

In addition to porosity reduction, it is observed that polymer modified the hydration products in the steel fiber-matrix ITZ. The modification is simpler in concrete with richer cement matrix that is concrete elaborated with silica fume and steel fiber reinforcement improve the bonding strength and this influences directly on mechanical properties of SFRPMC specimens. In addition, the acrylic emulsion polymer can form

continuous polymer films inside the concrete, which boosted toughness and compact degree of interface transition zone. The acrylic emulsion polymer could trigger steel fiber and the cement paste to a tight mutual connection. It as well alleviated the macro and micro defect of interface transition zone between fiber and cement paste, strengthening the role of fiber regarding toughness and crack resistance properties. For the SFRC with acrylic emulsion polymer, the impermeability is modified due to the combined effects of plasticizing and filling. At very low p/c (<2.5%), adding emulsion polymer has little effect on the impermeability. Further addition of emulsion polymer leads to a significant increase in the impermeability. It is believed that the filling effect plays a dominant role in increasing the impermeability when their dosages are high.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

Overall, conclusion that can be made is by using experimental design in producing the composite of steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC) gives encouraging results. The additions of steel fiber and acrylic emulsion polymer into concrete have successfully improved the mechanical properties and performance of the composite such as compressive strength, tensile strength and flexural strength of the composites.

1. From the earliest studies of experimental design that was being conducted, there are five factors which give large effect on steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC) such as water-cement ratio, acrylic emulsion polymer content, silica fume content, steel fiber content and curing time. Apart from that, curing time is the factor that gives more contributions on compressive strength of the composite. Steel fiber reinforced acrylic emulsion polymer modified concrete (SFRPMC) were produced through solution mix design and molding techniques and effect of various control parameter on compressive strength of SFRPMC were analyzed by using Taguchi method approach.

2. From mechanical properties testing such as compressive strength test, flexural strength test and splitting tensile strength test, the major parameter that influences mechanical properties is achieved. Based on mean analysis and variance analysis, the optimum parameter level is obtained in order to maximize

the mechanical strength of the produced composites. To get equal combination of mechanical properties, fine tuning test is being conducted and the suitable combination is obtained to get the optimum specimen with better mechanical properties. This specimen produced from 2.5% acrylic emulsion polymer, 8% silica fume, and 1.5% steel fiber and water-cement ratio 0.50 at 28 days curing. Combination from a few fine tuning experiment has been successful in obtaining the optimum specimens with the largest and better mechanical properties. There are 30% of water-cement ratio effect on cube compressive strength, 20% on flexural strength, 15% on splitting tensile strength and 58% on modulus of elasticity.

3. From XRD analysis, optimum specimen shows the chemical reactions that take place between anhydrous cement and water are generally complex in nature because of their multiphase nature and also simultaneously effects of many variables. In the early of age 1 hour, a peak intensifies in a day's time. After 1 day, the appearance of monocarboaluminate hydrate and calcite is appears and the C-S-H cryptocrystalline phase with quartz low, alpha-SiO_2 is then exists. From TGA analysis, the curves are typically of hydrated cement composites containing carbonate phases and acrylic emulsion polymer modification influences. The different reactions are divided into 5 zones by starting with dehydration of pore water, followed by dehydration of calcium silicate hydrates, dehydroxylation of calcium hydroxide, enlargement of the endothermic peak intensity and lastly decarbonation of $CaCO_3$. Acrylic emulsion polymer sharply decreases the quantity of carbonate phases in the composites compared to plain concrete.

4. Based on mechanical analysis and thermal carried out, the addition of acrylic emulsion polymer gives apparent effect on mechanical and thermal properties of steel fiber reinforced acrylic emulsion polymer modified concrete. Generally addition of 2.5% of acrylic emulsion polymer had improved most mechanical properties and more addition of polymer has blighted the mechanical properties of the tested specimens. When acrylic emulsion polymer is added as modifier, compressive strength, flexural strength and splitting tensile strength and thermal properties shows better improvement. The modification is simpler in concrete

with richer cement matrix that is concrete elaborated with silica fume and steel fiber reinforcement improve the bonding strength and this influences directly on mechanical properties of SFRPMC.

For optimum dosage of acrylic emulsion polymer with 2.5%, the C-S-H gel in this structure is finer and more acicular. Some polymer adheres or deposit on the surface of the C-S-H gel. The presence of acrylic emulsion polymer confines the ionic diffusion so that the $Ca(OH)_2$ crystallized locally to form fine crystals. The void in the structures seems to be smaller but no polymer films appears to be bridging the walls of pores although many polymer bonds or C-S-H spread into the pore spaces.

In addition to porosity reduction, acrylic emulsion polymer modified the hydration products in the steel fiber –matrix ITZ. The hydration product C-S-H appeared as a needle like shape. The needle-shaped C-S-H increases and gradually formed the gel, with needles growing into the pore space. The phenomenon is more obvious as curing age increased.

8.2 RECOMMENDATION FOR FURTHER INVESTIGATION

To stabilize further investigation on fiber reinforced polymer modified concrete research; there are many spaces for following research that can be probably extended in the future. It is recommended that further research be undertaken in the following areas:

1. Composite production on steel fiber reinforced polymer modified concrete by using acrylic emulsion polymer as modification is an attractive study because they have apparent effect between cement, aggregates and steel fibers. It is proven that integration of suitable content of hooked fiber could increase the strength and durability aspect of SFRPMC. It would be interesting to assess the effect of using different types of steel fiber to strength and durability performance of SFRPMC.

2. One of the areas that can be looked into is the possibility of integrating another type of waste material that can be found in Malaysia such as rice husk ash (RHA) or timber industrial ash (TIA) as partial cement substitute in SFRPMC mix in order to enhance the mechanical and durability aspect of this composite.

3. Fatigue nature and creep on structural members using SFRPMC is also one of the areas that can be investigated. Increasing temperatures also gives high impact on mechanical properties of this composite.

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APPENDIX A

L27 LARGER THE BETTER FOR COMPRESSIVE STRENGTH - FOR PRELIMINARY EXPERIMENTALTAGUCHI DESIGN

	LEVELS													
Control Factors and Levels	**1**	**2**	**3**	**check mean**	**check mean =**	**Degrees of Freedom**	**Sum of Squares**	**Mean Square**	**Factor Effect (percent)**	**F before pooling**	**empty**		**empty or pooled F=<1.5**	**F After pooling**	**Error Bar on each CF Level**
				26.53											
Water-Cement Ratio	27.56	30.01	22.02	**26.53**	**26.53**	2	301	151	39	15247	no		no	**152**	+- 0.66 dB
Acrylic Emulsion Polymer %	27.74	28.19	23.66	**26.53**	**26.53**	2	112	56	14	5680	no		no	**57**	+- 0.66 dB
Silica Fume %	26.10	24.53	28.96	**26.53**	**26.53**	2	91	45	12	4601	no		no	**46**	+- 0.66 dB
Steel Fibre %	24.04	27.52	28.03	**26.53**	**26.53**	2	85	43	11	4301	no		no	**43**	+- 0.66 dB
Age	23.10	26.96	29.52	**26.53**	**26.53**	2	188	94	24	9496	no		no	**95**	+- 0.66 dB
-	26.02	27.09	26.47	**26.53**	**26.53**	0	0	0	-	0	yes		yes	-	+- 0.66 dB
-	26.29	26.50	26.80	**26.53**	**26.53**	0	0	0	-	0	yes		yes	-	+- 0.66 dB
-	26.72	26.43	26.44	**26.53**	**26.53**	0	0	0	-	0	yes		yes	-	+- 0.66 dB
-	26.93	25.99	26.66	**26.53**	**26.53**	0	0	0	-	0	yes		yes	-	+- 0.66 dB
-	26.51	26.46	26.62	**26.53**	**26.53**	0	0	0	-	0	yes		yes	-	+- 0.66 dB
-	26.72	26.40	26.47	**26.53**	**26.53**	0	0	0	-	0	yes		yes	-	+- 0.66 dB
-	26.73	26.04	26.82	**26.53**	**26.53**	0	0	0	-	0	yes		yes	-	+- 0.66 dB
-	26.76	26.42	26.40	26.53	26.53	0	0	0	-	0	yes		yes	-	+- 0.66 dB
check OV MEAN =	26.53			Total DF =		10			100						
Ov-Mean	26.53	26.53	26.53						**NO. OF unpooled 3-LEVEL CFs =**				**5**		
Total sum of Squares due to Factor Effects							777	389							
Total sum of Squares = grand Total - 27*mean sq							793								
Error Variance (unpooled)						16	16								
Error Variance (unpooled) per degree of freedom								0.99							
(Error Variance pooled))						16	16								
Error Variance per degree of freedom								0.99							
Error Bar for each 3-Level CF = 2*SQRT(error var. per DF / repetition of each level) =								0.66	**1/n = 1/(nexpts for mean) + (no of unpooled CF)/(nrepeat for each level) =**						**0.59**

Prediction error variance (for 5 to 6 repititions) = sum of sq for error /neff =								0.78	**nr = no of repeat expts =**	**5**			
95% confidence interval for pred. err = +-2*sqrt(pred err) =								1.77			**1/neff = 1/n + 1/nr therefore neff =**		**1.26**
OV-MEAN	26.53		26.53				26.53						

APPENDIX B

L9 LARGER THE BETTER - FOR VERIFICATION EXPERIMENTALTAGUCHI DESIGN

	LEVELS												
CONTROL FACTORS \ LEVELS	**1**	**2**	**3**	**Degrees of Freedom**	**Sum of Squares**	**Mean Square**	**Factor Effect (percent)**	**F before pooling**	**empty**		**empty or pooled F=<1.5**	**F After pooling**	**Error Bar on each CF Level**
water cement ratio	-1.78	-1.09	-1.05	2	1	1	19	9	no		no	**13**	+- 0.22 dB
acrylic emulsion polymer (%)	-1.84	-0.66	-1.41	2	2	1	40	20	no		no	**28**	+- 0.22 dB
silica fume (%)	-1.74	-0.62	-1.55	2	2	1	40	20	no		no	**28**	+- 0.22 dB
steel fibre (%)	-1.27	-1.43	-1.21	2	0	0	1	1	no		pooled	-	+- 0.22 dB
Ov-Mean	-1.31	-1.31	-1.31					**no. of unpooled CFs =**			**3**		
Total sum of Squares due to Factor Effects					5								
Total sum of Squares = grand Total - 9*mean sq					5								
Error Variance (unpooled)				0	0								
Error Variance (unpooled) per degree of freedom						0.05		**Since DF-for-error = zero, Error has been assumed to be 1% of Total sum of squares**					
(Error Variance pooled))				2	0								
Error Variance per degree of freedom						0.04							
Error Bar for each CF level = 2*SQRT(error var. per DF / repetition of each level) =						0.23							
Prediction error variance (for 5 to 6 repititions) = sum of sq for error /neff =						0.05		1/n = 1/(nexpts for mean) + (no of unpooled CF)/(nrepeat for each level) =					**1.11**
95% confidence interval for pred. err = +-2*sqrt(pred err) =						0.45		nr = no of repeat expts =		**5**	1/neff = 1/n + 1/nr therefore neff =		**0.76**
								prediction error = error variance per degree of ffreedom/neff					0.0502007
OV-MEAN	-1.31	-1.31	-1.31		-1.31								

APPENDIX C

OPTIMIZATION OF SFRPMC BY TAGUCHI METHOD

By using 5 parameters (control factors), L27 array is chosen. During L27 orthogonal array, no or negligible) interaction between parameters is observed. There is no used of noise factors because the cubes, cylinders/ other-shapes for testing the compressive/tensile/flexural of steel fiber reinforced concrete had been done during trial mixes. Noise is not required when there is more than 1 sample and there are 2 or 3 samples had been done for each testing after 3 days, 7 days and 28 days curing. A noise factor also can be done by taking segregation (fine and coarse) that is most suitable and this two factors had also been considered during mix design process.

Then, 5 specimens with slightly different water content is done as follows:

--> fine-tune mix#1 160 (Kg/m3)
--> fine-tune mix#2 165 (Kg/m3)
--> fine-tune mix#3 170 (Kg/m3) --> (this is the best level identified in the result)
--> fine-tune mix#4 175 (Kg/m3)
--> fine-tune mix#5 180 (Kg/m3)

=====> If all the strengths are close to the predicted results

==> Then the concrete is ROBUST against small variations of water content

Discussion on Robustness with respect to small

variations in control factors
==========

Looking at the factor effect plots we see that we have
--> Water content --> center level is best (and effect reduces on either side)
==> This shape is called "BELL Shaped" or "maxima at central level" type
--> Polymer content --> similar to above --> "maxima at central level"

====> Important property of "maxima at central level" type plot is
==> The results will "insensitive" to
==> Small variations around the center values of these 3 control factors

====> so in this sense the concrete is "insensitive" or ROBUST with respect to
--> Variations in water content
--> Variations in polymer content
--> Variations in steel fiber content

And then the confirmation or verification also known as “a "fine tuning" experiment using a L9 array is done.
--> With the above 3 parameters with 3 levels

--> water content --> 0.49, 0.50, and 0.51
--> Polymer content --> 2.4, 2.5, 2.6
--> Steel Fiber Content --> 1.4, 1.5, 1.6

==> NOTE: It is called "fine tuning" because of the small changes on either side of the BEST levels

==> There will be 3 advantages in conducting "fine tuning' experiments

(1) --> supposed to conduct many repeats with best settings

(2) --> Able to show ROBUSTNESS with respect to small variations in one or more of the above 3 control factors

(3) --> one of these 9 experiments may give IMPROVED values of strengths

From L27 experiments

--> All 'empty' columns show negligible factor effects

ROBUST: A process is called ROBUST if its response outputs (in various strengths) are "insensitive" to noise factors.

--> Since there is no noise factors for the L27 experiments
--> The process is NOT robust with respect to any noisy parameter

Fine Tuning: (just as fine-tune a string instrument ==> instrument is 'fine-tuned')
=========

Once the best settings are obtained by the Taguchi analysis are obtained
(In the case these are A2 B2 C3 D3 E3),

--> Then "verification" experiments can be done "around" these values, for example
--> 3-levels of Water-Cement-Ratio as --> 0.48, 0.50, and 0.52 (much smaller difference)
--> 3-Levels of Acrylic . . . as --> 2.3, 2.5, 2.7
--> 3-levels of silica fume . . . as --> 7.5, 8.0, and 8.5
--> 3-Levels of steel fiber . . . as --> 1.4, 1.5, and 1.6
==> keep aging constant at 28 hours

--> Now "fine Tuning" experiments is done with above 4 control factors with their 3-levels using L9 array
==> The whole set of 9 experiments will be called "Fine Tuning"
==> Advantages of fine tuning experiments are
--> (1) might get a Better result in one of the rows of 9 experiments
--> (2) If all strength values will be close to predicted values
==> Then Verification experiment is considered successful

The new L9 orthogonal array can be used as following below for verification experiments:

Water cement ratio	"0.48	"0.50	"0.52
Acrylic emulsion polymer (%)	"2.3	"2.5	"2.7
Silica fume (%)	"7.5	"8.0	"8.5
Steel fiber (%)	"1.4	"1.5	"1.6

CUBE --> best settings are 2 2 2 - ==> 0.50, 2.5, 8.0 and (pooled)
Cylinder --> best settings are 3 2 2 - ==> 0.52, 2.5, 8.0 and (pooled)
Flexural --> best settings are 3 2 2 - ==> 0.52, 2.5, 8.0 and (small effect)
Splitting --> best settings are 2 2 2 - ==> 0.50, 2.5, 8.0 and (pooled)
Modulus -->best settings are 3 2 2 - ==> 0.52, 2.5, 8.0 and (pooled)

Conclusion from above:

Water cement ratio Best setting between "0.50 "0.52 --> try "0.51

Acrylic emulsion polymer (%) Best setting "2.5

Silica fume (%) Best setting "8.0

Steel fiber (%) Best setting "1.5

Effect of Water Cement Ratio
==========

The effect of water-cement-ratio is
(1) CUBE --> 30% --> best level is 2 --> "0.50
(2) Cylinder --> 58% --> best level is 3 --> "0.52
(3) Flexural --> 20% --> Best level is 3 --> "0.52
(4) Splitting --> 15% --> Best level is 2 --> "0.50
(5) Modulus --> 58% --> best level is 3 --> "0.52

The effect of 50% or more has best level 3, and effect of 30% or less has best level 2
==> So, it can be concluded that the best level for water-cement ratio should be 'closer' to level 3
==> say "0.515 +- "0.005 or "0.51 to "0.52

ROBUST EXPERIMENTS
==========

Since water-cement-ratio has a LARGE effect (20% to 50%),
--> The process ROBUST against variations in water-cement-ratio cannot be done

However, rows 3, 4 and 5 of "ROBUST EXPERIMENT %" --> give very good results
--> Row 3 corresponds to water-cement-Ratio at level 2 of "0.50

APPENDIX D

OPTIMIZATION OF MIX DESIGN FOR STEEL FIBER REINFORCED POLYMER MODIFIED CONCRETE (SFRCPMC)

Mix design of plain concrete

By using DoE mix design method the proportion of concrete mix without silica fume for an application requiring a characteristic strength if 35 MPa at 28 days and a slump of 60 – 90 mm is determined**.** The materials available are ordinary Portland cement, and crushed fine and coarse aggregate of specific gravity of 2.51 and 2.60 respectively. The maximum nominal size of aggregate is 20 mm and fine aggregate conforms to the grading zone II with percentage passing 600 micron sieve being 43 percent.

IS: 450-2000 is the recommended silica fume as a replacement of cement in the proportion of 5 to 10 percent of the cementitious materials. In proportioning the companion mixes containing different percentages of silica fume replacing the cement, though the total content of cementitious materials remains constant but the volumes of cement, silica fume and hence of total cementitious materials change. However volumes of coarse aggregate, water and air per cubic meter of concrete are same as in the basic mixture, but the required weight of sand changes. With the increase in the percentage replacement of cement by silica fume, the total volume of cementitious materials increases and consequently the required weight of dry sand decreases. The dosage of chemical admixtures may or may not change (Gambhir, 2006). To produce steel fiber reinforced concrete (SFRC), the typical mix proportions by mass are cement: water/cement ratio:sand:aggregate (1:0.4-0.6:2-3:0.8-3).

Mix design of Steel Fiber Reinforced Concrete (SFRC)

As with any other type of concrete, the mix proportions for SFRC depend upon the requirements for a particular job, in terms of strength, workability, and so on. Several procedures for proportioning SFRC mixes are available, which emphasize the workability of the resulting mix. However, there are some considerations that are particular to SFRC. In general SFRC mixes contain higher concretes, and so the mix design procedures application to conventional concrete may not be entirely applicable to

SFRC. Commonly to reduce the quantity of cement, up to 35% of the cement may be replaced with superplasticizer (Nguyen, 2010).

In mix design for steel fiber reinforced concrete according to Ghambir (2006), the mix should contain minimum fiber content and maximum aggregate for the specified strength and workability. For the commonly encountered SRFC mixes, the following range parameters is mentioned in Table below:

Parameter	Range for common SFRC (theoretical)	Experimental (Trial Mixes)
Cement content (kg/m^3)	300 – 500	428.57
Water-cement ratio	0.45 - 0.60	0.49
Ratio of sand to total aggregate (%)	50 - 100	43
Maximum size of aggregate	10 and 20 mm	20 mm
Fiber content (%)	1.0 – 2.5	1.5
Fiber-aspect ratio	50 - 1000	80

For modification of steel fiber reinforced concrete, the quantities of acrylic emulsion polymers required for are relatively small (Ghambir, 2006), being in the range of 1 to 4 percent by mass of the composite.

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APPENDIX E

TEST DATA ON SIEVE ANALYSIS OF COARSE AGGREGATES AND FINE AGGREGATES

Grading limit of coarse aggregates

Sieve Size	Percentage passing	Percentage passing	Total % retained
ASTM C33		**Results from experiment**	
37.5 mm	100	100	0
20.0 mm	90-100	95	5
14.0mm	40-80	60	40
10.0 mm	30-60	30	70
5.0 mm	0-10	5	95
2.36 mm	-	0	100

Grading limit of fine aggregates

Sieve Size	**Percentage passing**	**Percentage passing**	**Total % retained**
ASTM C33		**Results from experiment**	
10.0 mm	100	100	0
5.0 mm	95-100	98	2
2.36 mm	80-100	85	15
1.18 mm	50-85	65	35
600 µm	25-60	45	55
300 µm	10-30	21	79
150 µm	2-10	3	97

APPENDIX F

TEST DATA ON MECHANICAL STRENGTH TESTING

Specimen code	compressive strength (MPa)	flexural strength (MPa)	splitting tensile strength (MPa)	Young's Modulus (MPa)
PC	76.03	7.40	5.22	62.13
AEPMC - 1.0%	70.31	8.67	5.89	63.63
AEPMC - 2.5%	68.45	12.42	5.26	62.65
AEPMC - 4.0%	68.32	13.23	5.13	60.35
SFRC - 1.0%	76.17	12.72	5.25	67.43
SFRC - 1.5%	77.98	12.96	5.35	68.43
SFRC - 2.0%	75.20	13.48	5.48	69.62
SFRPMC 1.0SF	78.13	13.55	6.37	72.56
SFRPMC 1.5SF	79.55	13.14	6.49	75.06
SFRPMC 2.0SF	80.63	12.55	7.05	82.36
SFRPMC 1.0AEP	86.03	12.63	6.28	77.88
SFRPMC 2.5AEP (OPTIMUM)	87.68	13.83	6.49	80.67
SFRPMC 4.0AEP	68.12	11.32	6.35	76.13

VERIFICATION EXPERIMENT (BY PERCENTAGE)

verification experiment no.	water cement ratio	acrylic emulsion polymer (%)	silica fume (%)	steel fibre (%)	compressive strength (MPa)	flexural strength (MPa)	splitting tensile strength (MPa)	modulus of elasticity (MPa)
1	0.48	2.3	7.5	1.4	68.67	10.47	4.82	76.45
2	0.48	2.5	8.0	1.5	83.52	14.29	6.84	80.75
3	0.48	2.7	8.5	1.6	75.72	12.93	4.89	76.96
4	0.50	2.3	8.0	1.6	83.86	14.86	6.80	78.34
5	0.50	2.5	8.5	1.4	87.68	13.83	6.49	80.67
6	0.50	2.7	7.5	1.5	77.96	12.85	5.21	77.87
7	0.52	2.3	8.5	1.5	75.93	12.05	4.39	81.23
8	0.52	2.5	7.5	1.6	83.13	14.20	5.84	81.83
9	0.52	2.7	8.0	1.4	78.32	16.58	6.06	82.46

Concrete compressive strength (MPa)

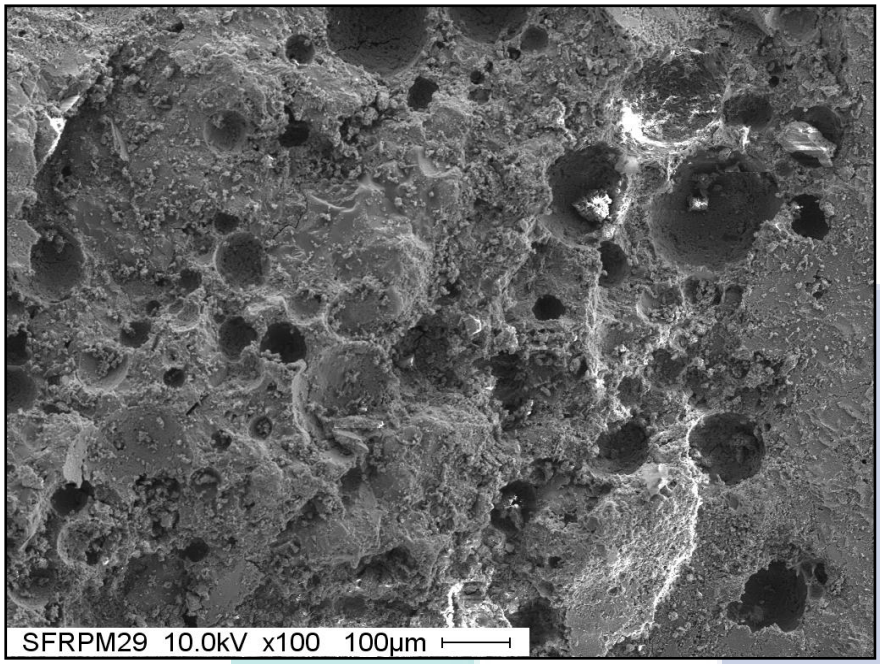
Volume fraction of fiber (%)		Acrylic emulsion polymer (%)			
		0.0	1.0	2.5	4.0
Fiber	**Vf**	**PC**	**AEPMC1.0**	**AEPMC2.5**	**AEPMC4.0**
No	0.00	76.03	70.31	68.45	68.32
Fiber	**Vf**	**SFRC 0**	**AEPMC1.0-SFRC**	**AEPMC2.5-SFRC**	**AEPMC4.0-SFRC**
SFRC1.0	1.0	76.17	82.43	85.13	70.45
SFRC1.5	1.5	77.98	86.03	87.68	68.12
SFRC2.0	2.0	75.20	-	-	-

Splitting tensile strength (MPa)

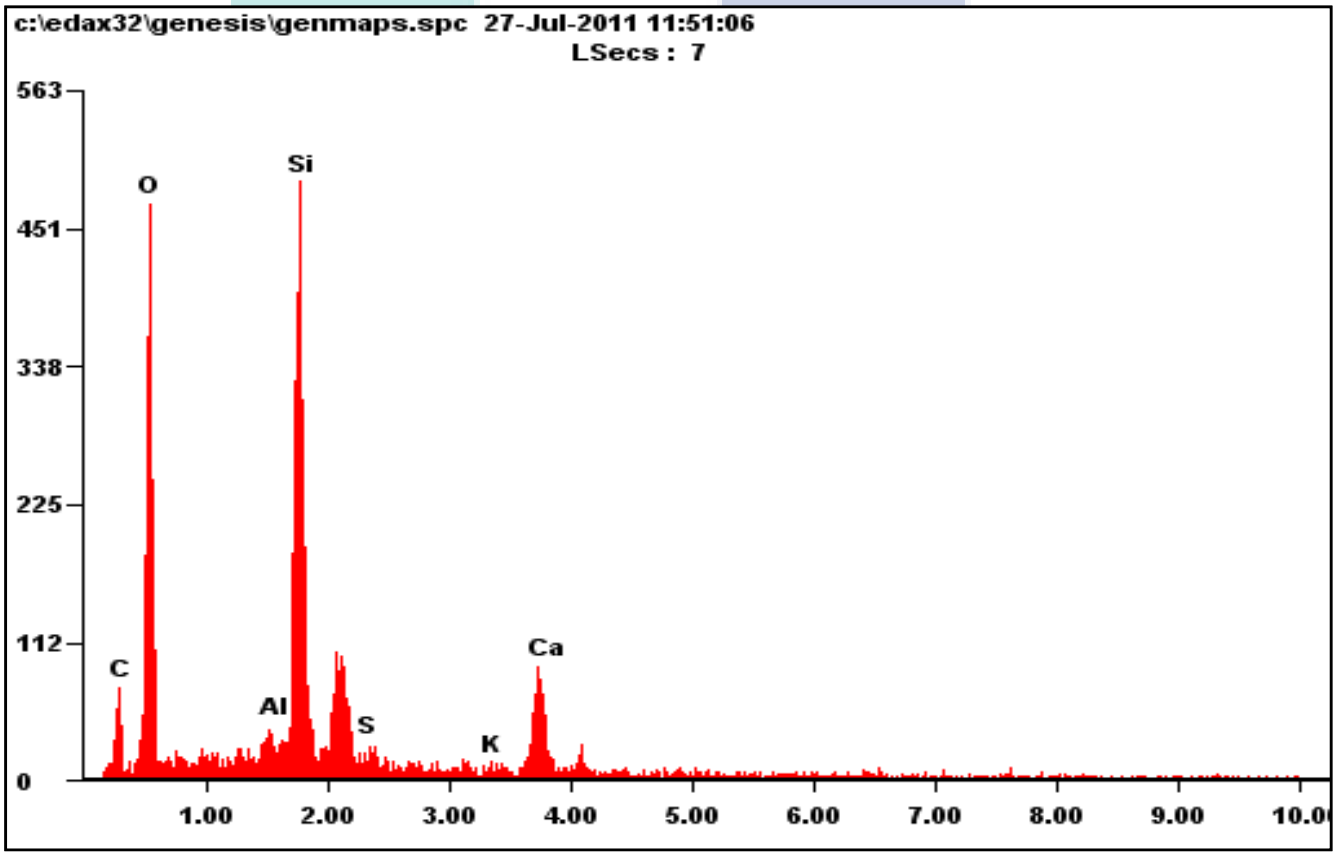
Volume fraction of fiber (%)		Acrylic emulsion polymer (%)			
		0.0	1.0	2.5	4.0
Fiber	**Vf**	**PC**	**AEPMC1.0**	**AEPMC2.5**	**AEPMC4.0**
SFRC0	0.0	5.22	5.89	5.26	5.13
Fiber	**Vf**	**SFRC 0**	**AEPMC1.0-SFRC**	**AEPMC2.5-SFRC**	**AEPMC4.0-SFRC**
SFRC1.0	1.0	5.25	6.22	6.37	6.05
SFRC1.5	1.5	5.35	6.28	6.49	6.35
SFRC2.0	2.0	5.48	6.31	7.05	5.43

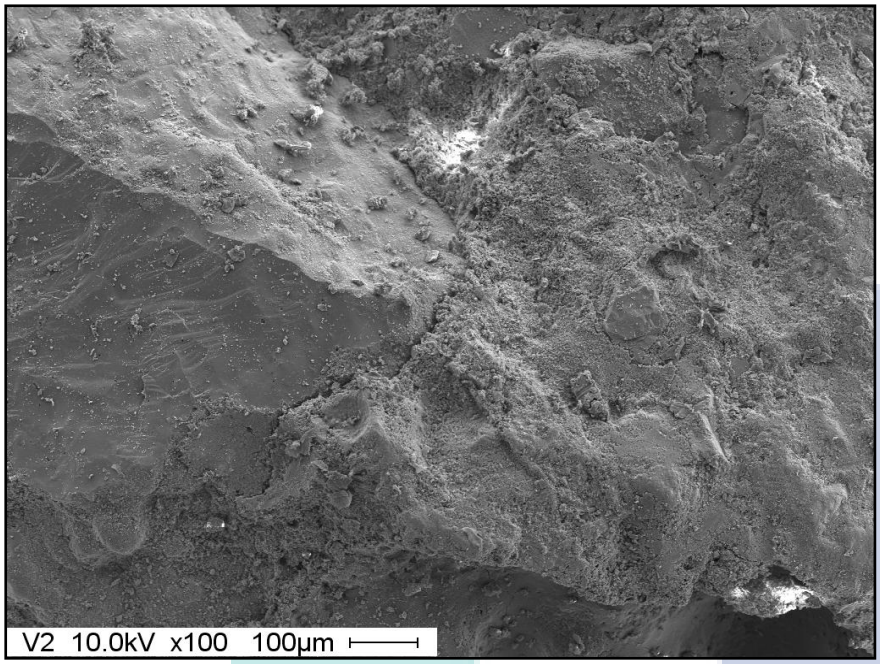
APPENDIX G

TEST DATA ON SPECIMEN MICROSTRUCTURE (SEM) AND EDAX ANALYSIS

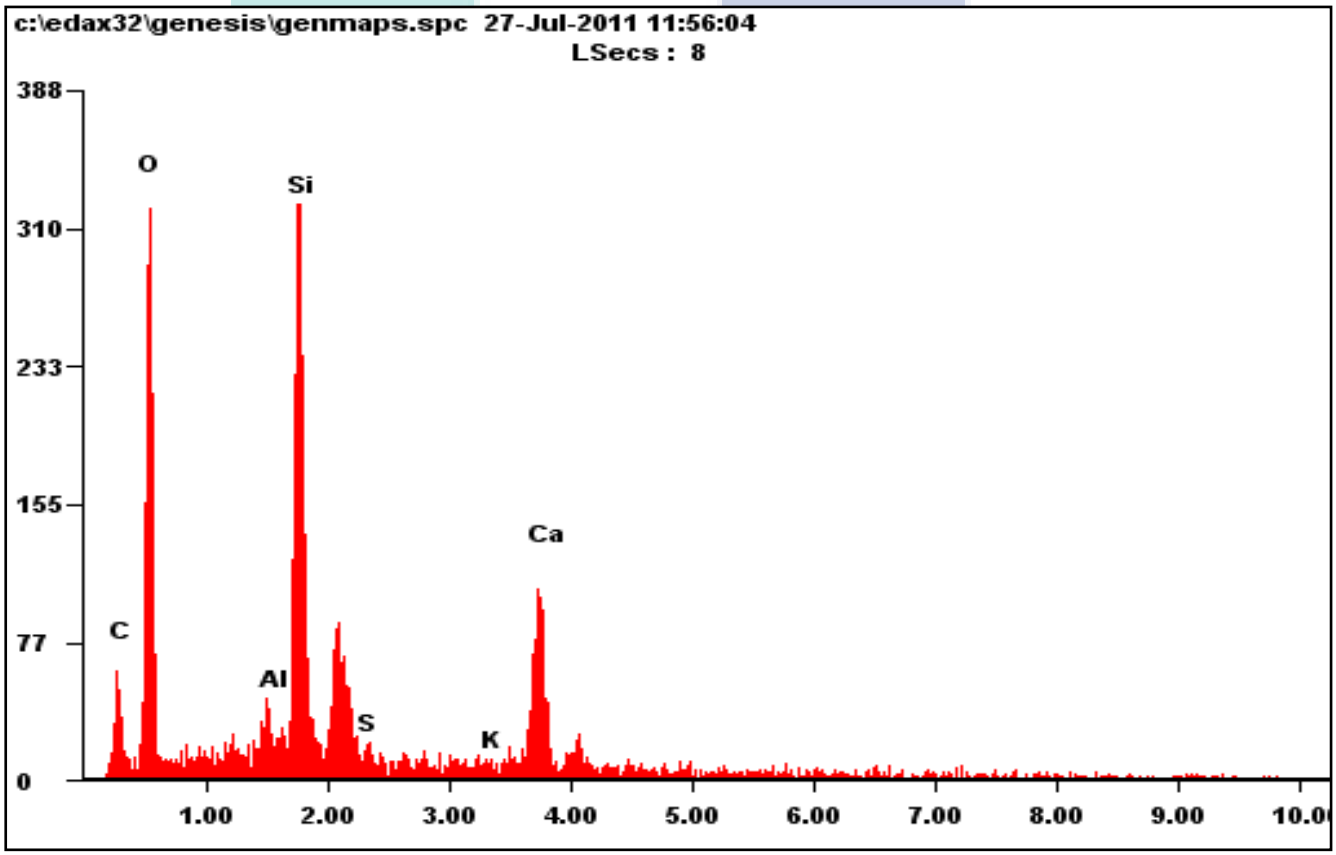


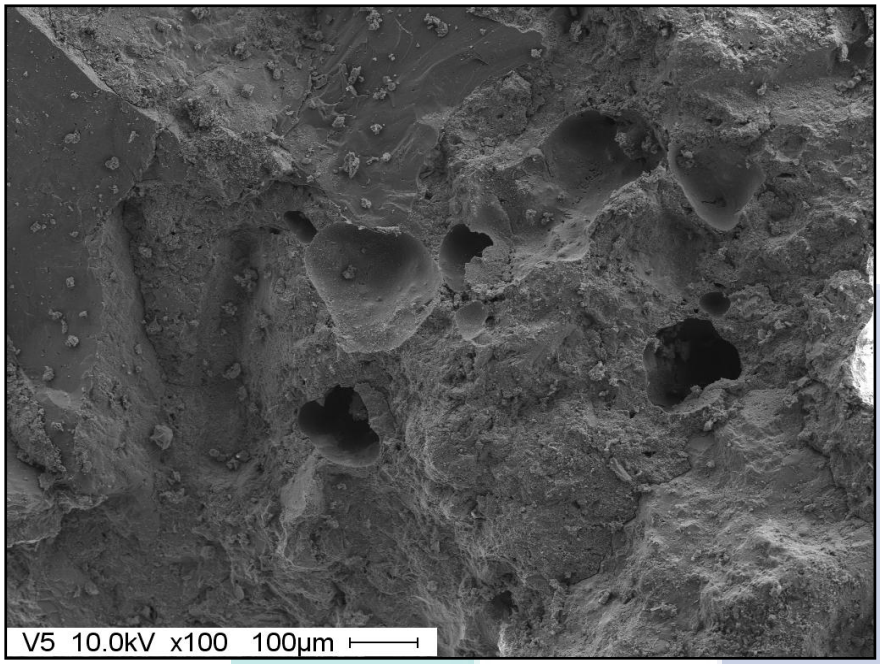
Element	Wt%	At%
C K	09.58	17.49
O K	35.19	48.21
NaK	00.38	00.36
AlK	02.27	01.84
SiK	13.56	10.58
S K	01.13	00.77
K K	01.50	00.84
CaK	36.40	19.91



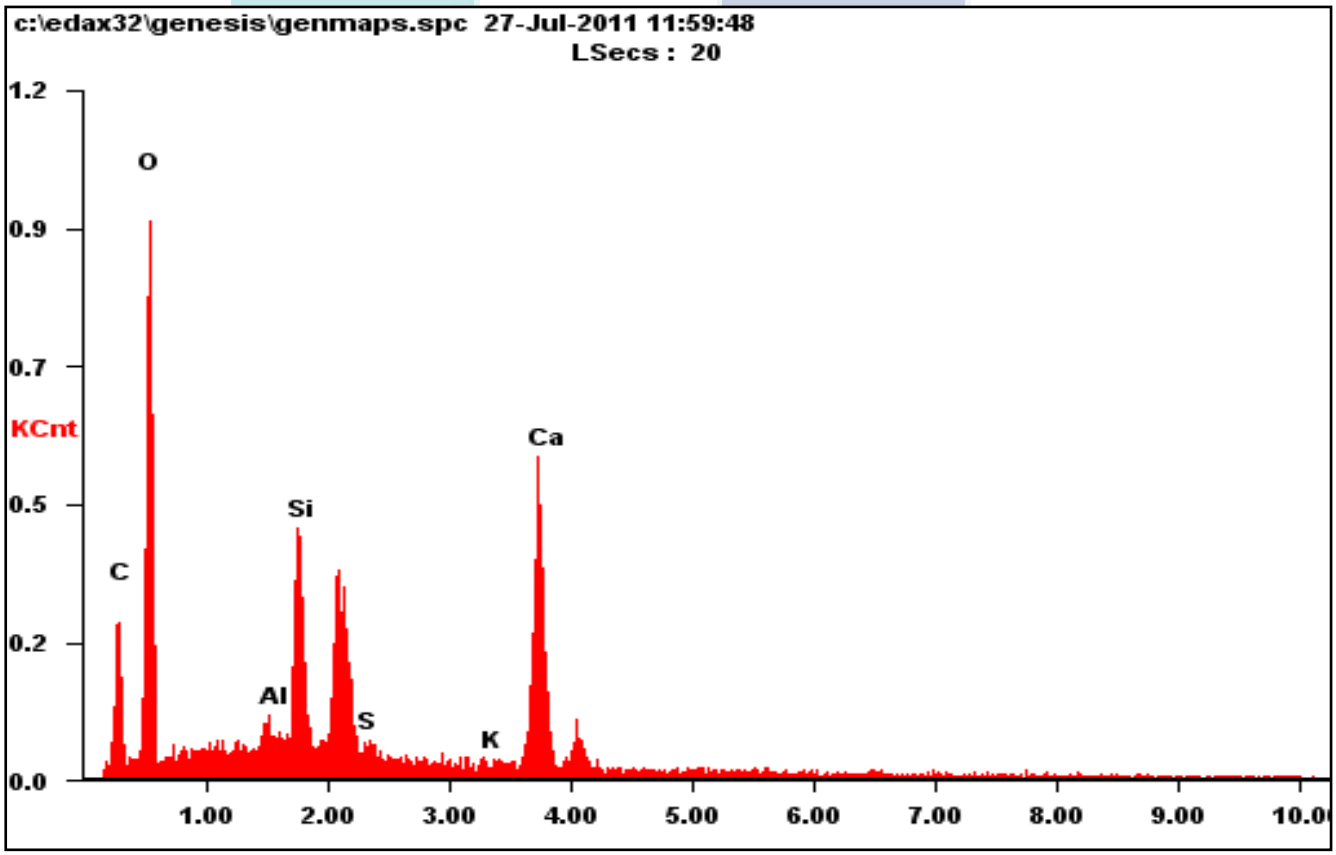


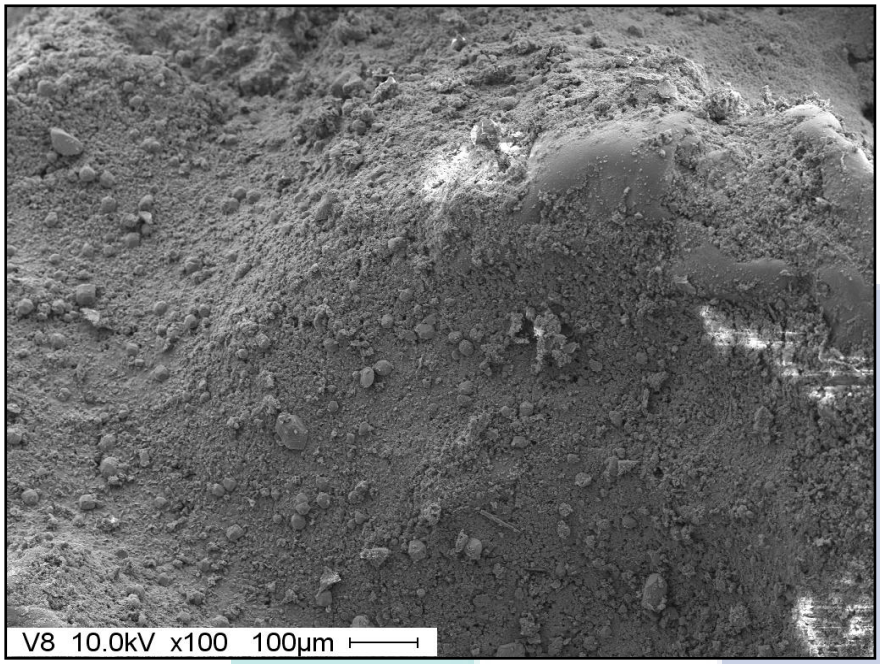
Element	Wt%	At%
C K	13.60	22.77
O K	36.13	45.44
AlK	01.25	00.93
SiK	28.65	20.52
S K	00.86	00.54
K K	00.26	00.14
CaK	19.25	09.66



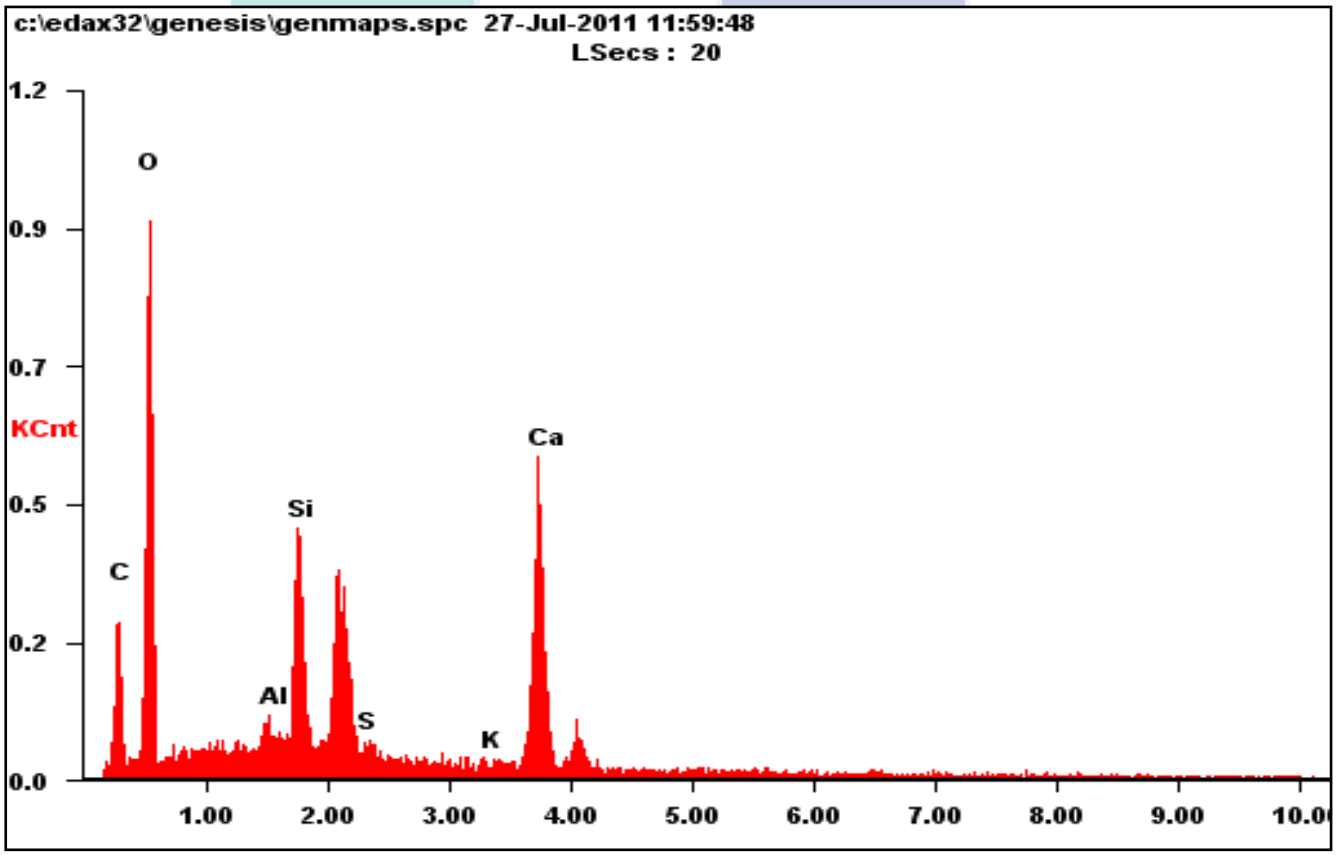


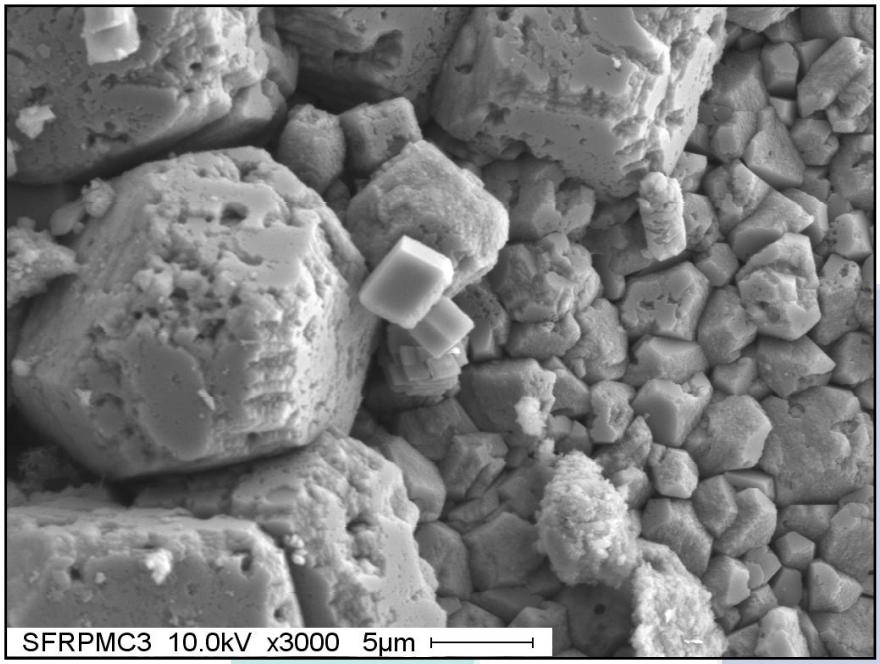
Element	Wt%	At%
C K	12.81	22.13
O K	34.83	45.16
AlK	01.73	01.33
SiK	22.89	16.90
S K	00.94	00.61
K K	00.28	00.15
CaK	26.51	13.72



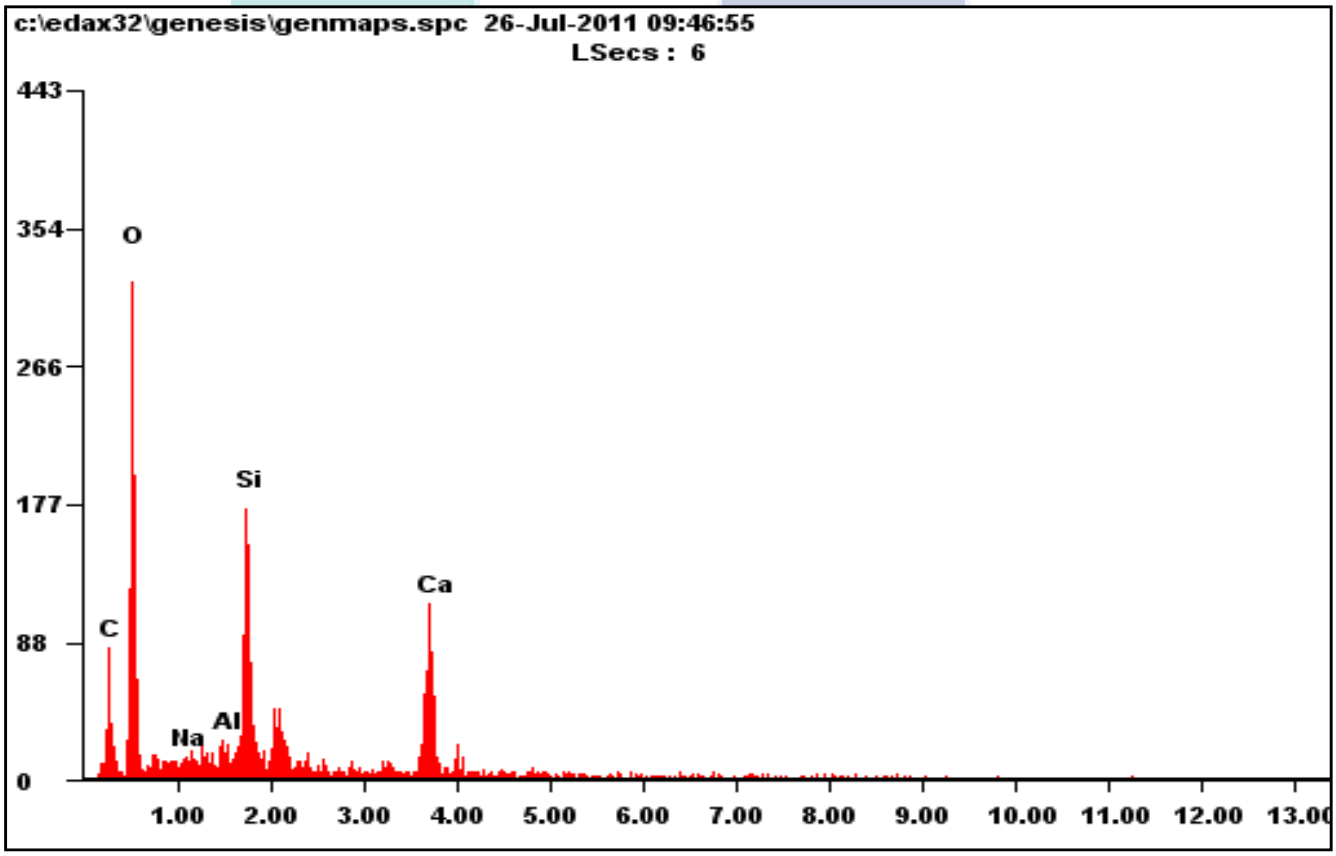


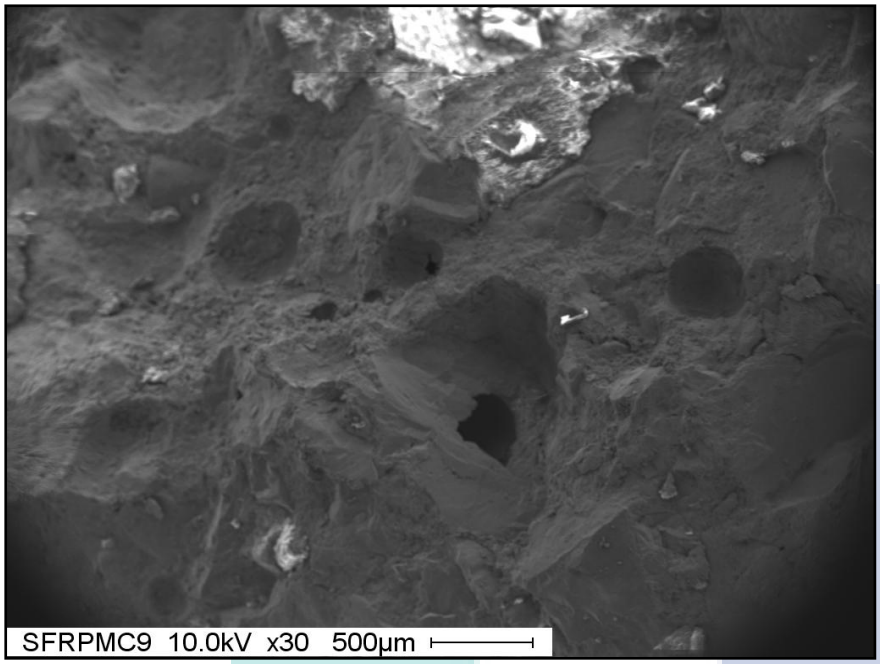
Element	Wt%	At%
C K	13.92	24.05
O K	37.17	48.22
AlK	01.14	00.88
SiK	09.13	06.75
S K	00.75	00.48
K K	00.41	00.22
CaK	37.48	19.41



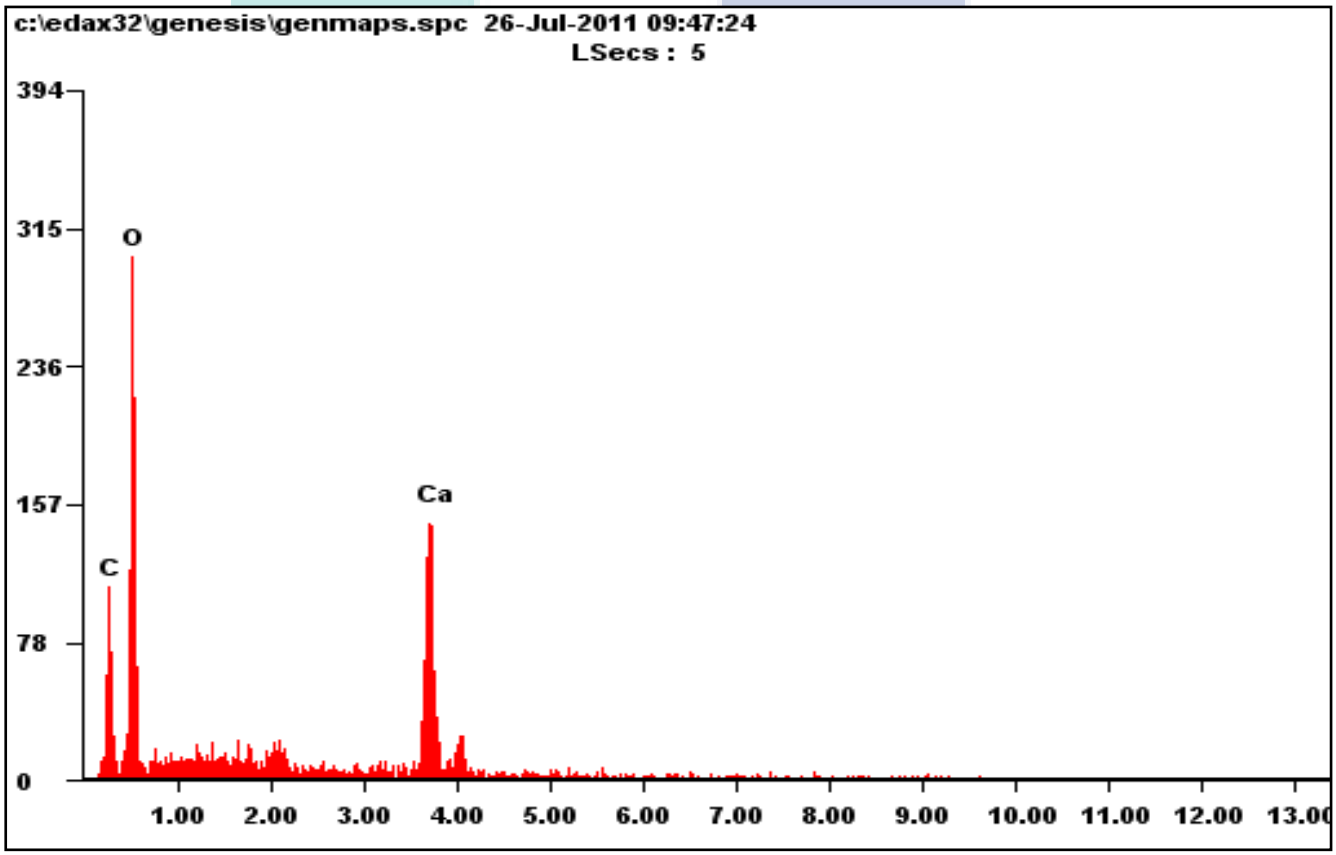


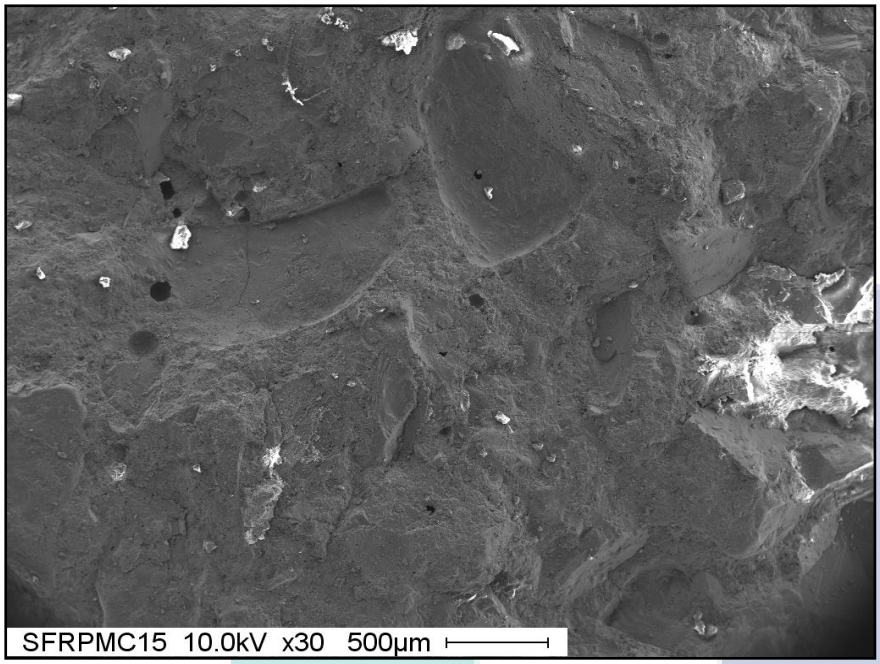
Element	Wt%	At%
C K	11.12	20.40
O K	36.47	50.25
NaK	00.37	00.36
AlK	00.45	00.37
SiK	01.04	00.82
CaK	50.54	27.80



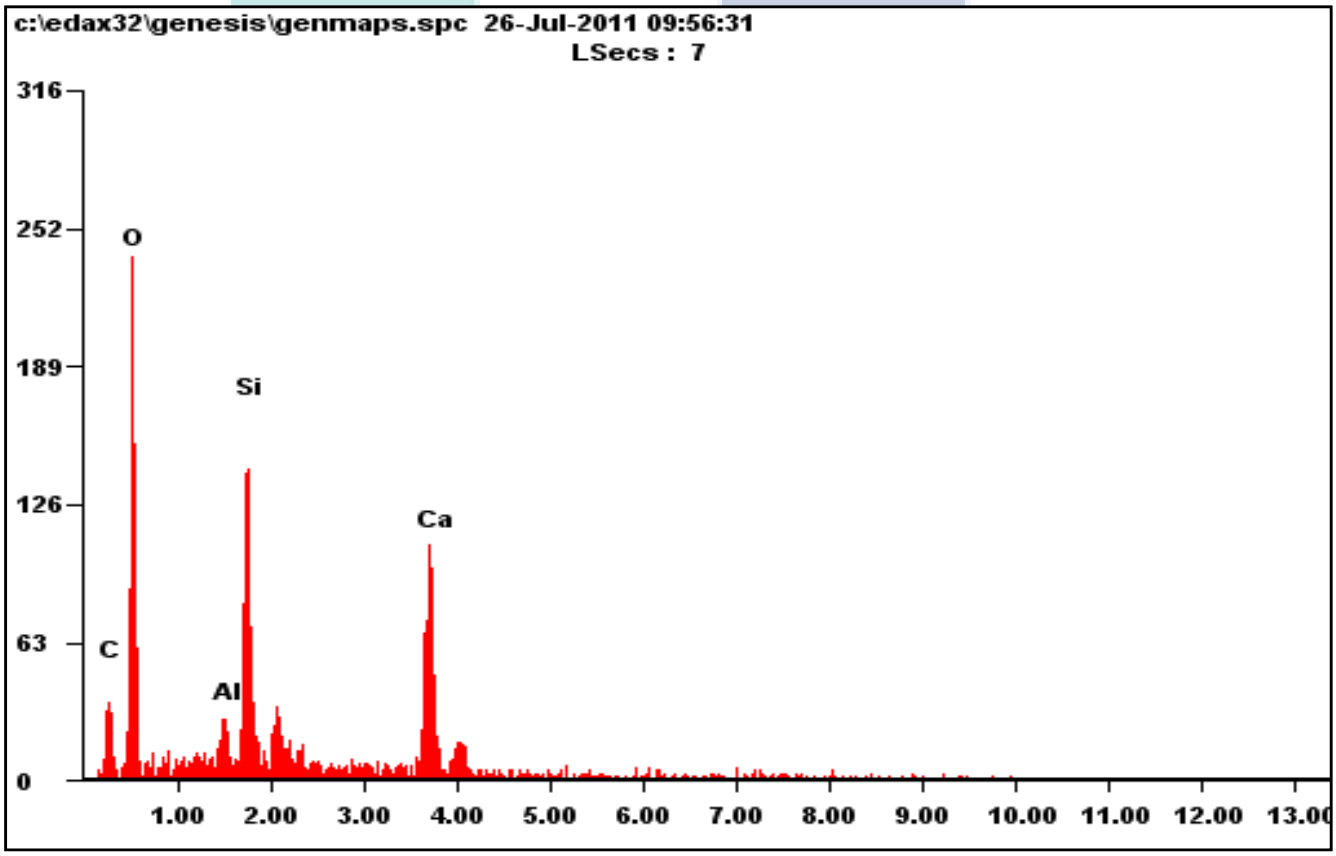


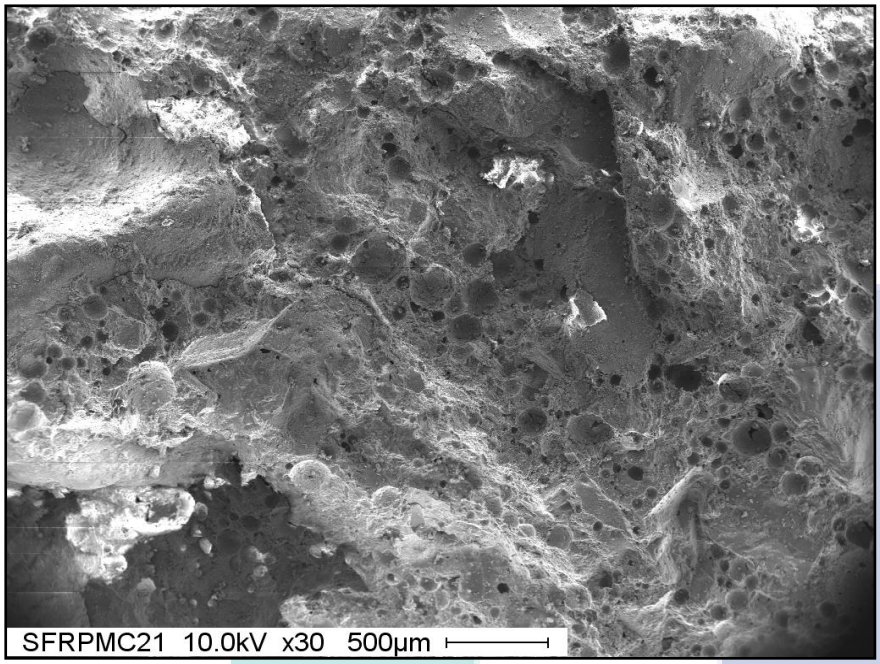
Element	Wt%	At%
C K	15.63	25.63
O K	39.50	48.63
NaK	00.42	00.36
AlK	01.29	00.94
SiK	15.37	10.78
CaK	27.79	13.66



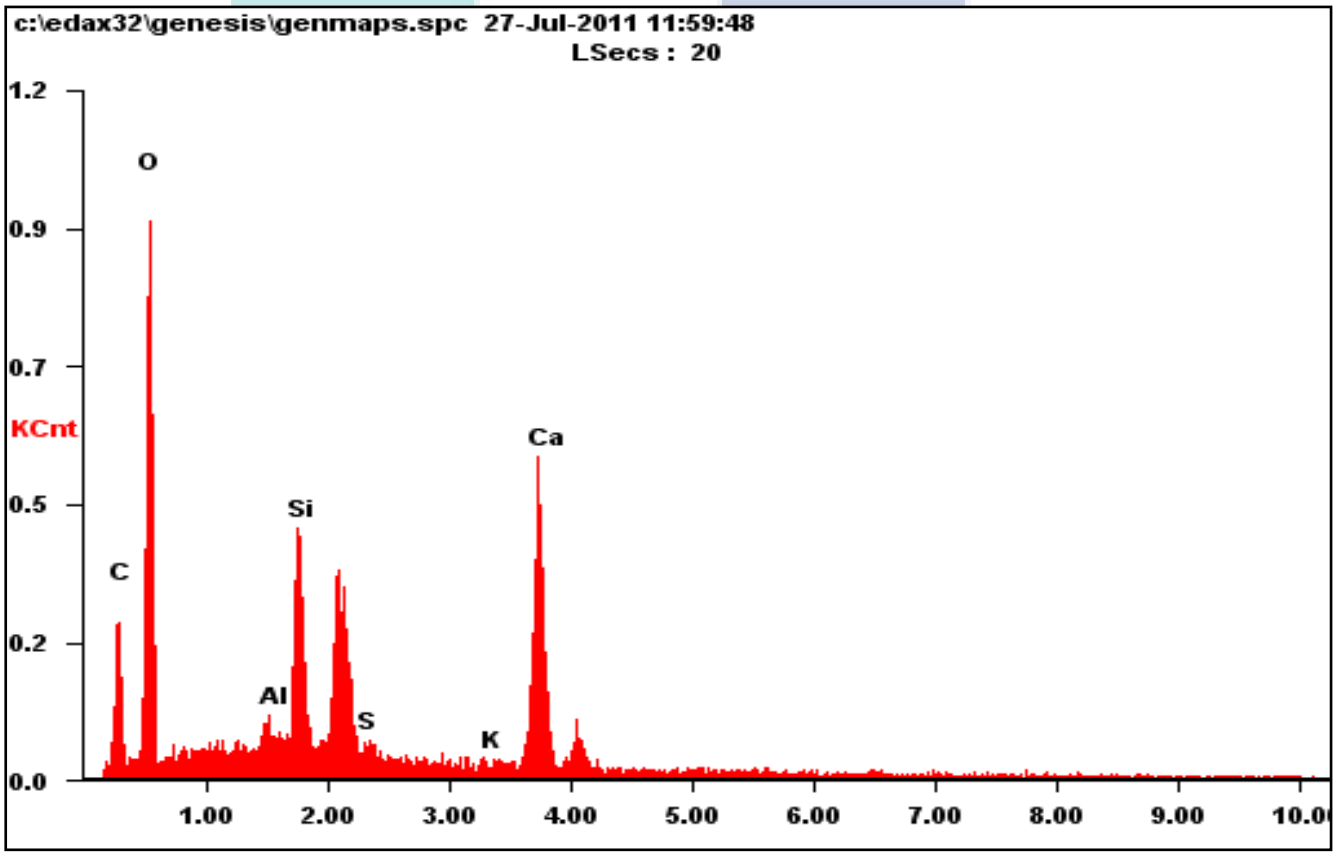


Element	Wt%	At%
C K	12.63	21.47
O K	38.83	49.54
AlK	02.49	01.88
SiK	16.82	12.22
CaK	29.24	14.89





Element	Wt%	At%
C K	09.96	17.90
O K	36.32	48.98
AlK	02.17	01.74
SiK	15.79	12.13
CaK	35.76	19.25



APPENDIX H

LIST OF PUBLICATIONS

Journal Publications

D.S. Hazimmah, S. Mohd and H.T. Cheng (2011). "**Mechanical Characterization of Steel Fibre Reinforced Acrylic Emulsion Polymer Modified Concrete**", *Journal of Engineering and Applied Science* 6 (3): 185-190, ISSN: 1816-949X © Medwell Journals.

D.S. Hazimmah, S. Mohd and H.T. Cheng (2011). "**Engineering Properties of Epoxy Polymer Cement Concrete Reinforced with Glass Fibers**", *Journal of Engineering and Applied Science* 6 (3): 191-199, ISSN: 1816-949X © Medwell Journals.

D.S. Hazimmah and S. Mohd. (2011). "**Mechanical Characterization of Acrylic-Emulsion Polymer-Modified Concrete Reinforced with Steel Fibre by Taguchi Application**" *Modeling, Simulation and Applied Optimization (ICMSAO) 2011, 4th International Conference* on 19 – 21 April 2011, Kuala Lumpur, *IEEE Electronic Library (IEL), ISBN: 978-1-4577-0003-3*.

D.S. Hazimmah, S. Mohd. and H.T. Cheng (2011). "**Mechanical properties of Acrylic Emulsion Polymer-Modified Concrete Containing Steel Fibre as Reinforcement**" *American Journal of Engineering and Applied Science*, 0051, 211-219.

Conference Publications

D.S. Hazimmah and S. Mohd. (2011). "**Mechanical Characterization of Acrylic-Emulsion Polymer-Modified Concrete Reinforced with Steel Fibre by Taguchi Application**" *Proceedings of the Fourth International Conference on Modeling, Simulation and Applied Optimization (ICMSAO'11)*, 19 – 21 April 2011, Kuala Lumpur, Malaysia.

D.S. Hazimmah, S. Mohd and P.R. Apte (2011). "**Optimization of Mix Proportion of Steel Fibre Reinforced of Acrylic Emulsion Polymer Modified Concrete**" *Proceedings of Asean Conference on Scientific and Social Science Research, Innovation and Challenges towards ASEAN Development Embracing Asean Diversity*, 22 – 23 June 2011, Penang, Malaysia.

Dayang Siti HAZIMMAH, Dato Dr Sabarudin MOHD, Prakash R.APTE (2011). "**Optimization of Mix Proportions of Steel Fibre, Acrylic Emulsion Polymer and Silica Fume for Improved Mechanical Properties of Modified Concrete using Taguchi Method**" *Proceedings of International Conference on Materials and Advance Technologies*, 26 June – 1 July 2011, Suntec, Singapore.

D.S. Hazimmah, S. Mohd. and H.T. Cheng (2011). "**Mechanical properties of Acrylic Emulsion Polymer-Modified Concrete Containing Steel Fibre as Reinforcement**" *1st International Conference and Exhibition of Women Engineer (ICEWE) 2011*, 21 – 22 November 2011, Gambang Resort, Kuantan, Pahang, Malaysia.

Accepted Journal

D.S. Hazimmah and S. Mohd. (2009). "**Engineering Properties of epoxy polymer concrete reinforced with glass fibers**" *National Postgraduate Conference on Engineering, Science and Technology (NPC2009)"*, 25 – 26 March 2009, Universiti Teknologi PETRONAS, Tronoh Perak, Malaysia.