

**MECHANICAL BEHAVIORS OF HIGH-DENSITY  
POLYETHYLENE (HDPE) FIBER REINFORCED CEMENT  
MORTAR**

**TRITHOS KAMSUWAN**

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT  
OF THE REQUIREMENTS FOR  
THE DEGREE OF DOCTOR OF PHILOSOPHY  
(MATERIAL SCIENCE AND ENGINEERING)  
FACULTY OF GRADUATE STUDIES  
MAHIDOL UNIVERSITY  
2016**

**COPY RIGHT OF MAHIDOL UNIVERSITY**

Thesis  
entitled

**MECHANICAL BEHAVIORS OF HIGH-DENSITY  
POLYETHYLENE (HDPE) FIBER REINFORCED CEMENT  
MORTAR**

*Trithos K.*

.....  
Mr. Trithos Kamsuwan  
Candidate

*Toemsak Srikhirin*

.....  
Asst. Prof. Toemsak Srikhirin,  
Ph.D. (Polymer Science)  
Major advisor

*T. Amornsakchai*

.....  
Assoc. Prof. Taweechai Amornsakchai,  
Ph.D. (Polymer Physics)  
Co-advisor

*T. Osotchan*

.....  
Asst. Prof. Tanakorn Osotchan,  
Ph.D. (Physics)  
Co-advisor

*Patcharee Lertrit*

.....  
Prof. Patcharee Lertrit,  
M.D., Ph.D.(Biochemistry)  
Dean  
Faculty of Graduate Studies  
Mahidol University

*Teerakiat K.*

.....  
Asst. Prof. Teerakiat Kerdcharoen,  
Ph.D. (Physical Chemistry)  
Program Director  
Doctor of Science Program in  
Materials Science and Engineering  
Faculty of Science  
Mahidol University

Thesis  
entitled  
**MECHANICAL BEHAVIORS OF HIGH-DENSITY  
POLYETHYLENE (HDPE) FIBER REINFORCED CEMENT  
MORTAR**

was submitted to the Faculty of Graduate Studies, Mahidol University  
for the degree of Doctor of Philosophy (Materials Science and Engineering)  
on  
November 24, 2016



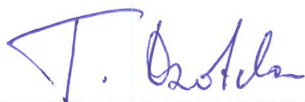
.....  
Mr. Trithos Kamsuwan  
Candidate



.....  
Assoc. Prof. Smith Songpiriyakij,  
Ph.D. (Civil Engineering)  
Chair



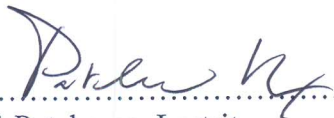
.....  
Asst. Prof. Toemsak Srihirin,  
Ph.D. (Polymer Science)  
Member



.....  
Asst. Prof. Tanakorn Osotchan,  
Ph.D. (Physics)  
Member



.....  
Assoc. Prof. Taweechai Amornsakchai,  
Ph.D. (Polymer Physics)  
Member



.....  
Prof. Patcharee Lertrit,  
M.D., Ph.D. (Biochemistry)  
Dean  
Faculty of Graduate Studies  
Mahidol University



.....  
Assoc. Prof. Sittiwat Lertsiri,  
Ph.D. (Agriculture Science)  
Dean  
Faculty of Science  
Mahidol University

## ACKNOWLEDGEMENTS

There are many people whom I'd like to thank for their moral support, their ingenuity, and for helping me with materials procurement and testing equipment.

First, it gives me immense pleasure to express my deep sense of gratitude to my advisor Assis. Prof. Dr. Toamsak Srihirin for his invaluable guidance, motivation, constant inspiration and above all for his ever co-operating attitude that enabled me in bringing up this thesis in the present form.

I am extremely thankful to Assos. Prof. Dr. Tavechai Amorsakchai coordinate adviser for their help and advice during the course of this work.

I would like to thank my committee Assis. Prof. Dr. Tanakorn Osotchan for his guidance, support and tremendous help.

I express my sincere gratitude to Department of Civil Engineering Faculty of Engineering for providing the necessary facilities in the department.

I would like to acknowledge and thank the Faculty of Science, Mahidol University for providing technical and financial support and materials for this project. Very special thanks to the Department of Material Science and Engineering personnel Pantisa Ruenpakdan, and Thapanee Wongpreedee for their help with the entire process of fabricating fibers samples and guidance throughout the project. Sincere thank go to Saijai Pengoun and Suthiwan Udomrat for their help.

Also I am greatly thankful to all the staff members of the Material Science and Engineering Department and all my well wishers, class mates and friends for their inspiration and help.

Finally, I would like to express my gratitude to my family and friends for their encouragement without which it would have been difficult to achieve my goals.

Trithos Kamsuwan

**MECHANICAL BEHAVIORS OF HIGH-DENSITY POLYETHYLENE (HDPE) FIBER REINFORCED CEMENT MORTAR****TRITHOS KAMSUWAN            5137663 SCME/D****Ph.D. (MATERIALS SCIENCE AND ENGINEERING)****THESIS ADVISORY COMMITTEE : TOEMSAK SRIKHIRIN, Ph.D.,  
TAWEECHAI AMORNSAKCHAI, Ph.D., TANAKORN OSOTCHAN, Ph.D.****ABSTRACT**

In material science, advanced composites and the fundamental understanding of mechanical behavior is a rapidly expanding branch within the field of science and engineering materials. Fiber-reinforced cement composites have played a dominant role for a long time in a variety of applications for their high specific strength and modulus. Fiber reinforced cement composites has so far been successfully used in many applications such as slabs on grade, shotcrete, architectural panels, precast products, offshore structures, structures in seismic regions, thin and thick repairs, crash barriers, footings, hydraulic structures. Polyethylene has very high potential for producing high modulus and high strength fibers. Polyethylene fiber produced by melt spinning is commercially available and has been around for quite some time. To produce stronger fibers, polyethylene needs to be drawn to very high draw ratio exceeding that used in conventional fiber production. This research evaluates the effect of melt spinning ultra-draw HDPE fiber using as the reinforced material in cement mortar. A whole set of experimental data were created reference to the efficiency of using HDPE fiber reinforced on the tensile, flexural and toughness properties of cement mortar with different high drawn ratio of HDPE fibers. The fiber with the different drawn ratio 10x (d10 with E xx), 25x (d25 with E xx), and 35x (d35 with E xx) fiber volume fraction (0.5%, 1.0%, 1.5%) and fiber length (5 mm., 10 mm., 15 mm., 20 mm.) were used and the stress – strain displacement relationship behavior of HDPE short fiber reinforced cement mortar were investigated. It was found that the high drawn ratio of HDPE fiber show more improvement in tensile strength and toughness than the low drawn ratio of HDPE fiber when reinforced in cement mortar. In this research, consideration the efficiency HDPE fiber reinforced cement mortar, HDPE fiber D25 is suitable for fiber volume fraction v1.5% and fiber length 20 mm. The HDPE fiber D35 is suitable for fiber volume fraction v1.0% and fiber length 15 mm.

**KEY WORDS: BEHAVIORS / MECHANICAL / FIBER / REINFORCED / CEMENT MORTAR**

พฤติกรรมด้านกำลังของซีเมนต์มอร์ต้าที่เสริมแรงด้วยเส้นใยโพลีเอทิลีนความหนาแน่นสูง  
MECHANICAL BEHAVIORS OF HIGH-DENSITY POLYETHYLENE (HDPE) FIBER REINFORCED  
CEMENT MORTAR

ไทรทศ ขำสุวรรณ 5137663 SCME/D

ปร.ด. (วิทยาศาสตร์และวิศวกรรมวัสดุ)

คณะกรรมการที่ปรึกษาวิทยานิพนธ์ : เดิมศักดิ์ ศรีศิริพันธ์, Ph.D. (POLYMER SCIENCE), ทวีชัย อมรศักดิ์ชัย,  
Ph.D. (POLYMER PHYSICS), ธนกร โอสดจันท์, Ph.D. (PHYSICS)

บทคัดย่อ

ในความก้าวหน้าทางวิทยาศาสตร์ของวัสดุเชิงประกอบ และพื้นฐานในความเข้าใจของพฤติกรรมทางกลสมบัติของวัสดุ ได้ถูกพัฒนาขยายตัวในด้านวิทยาศาสตร์ และวิศวกรรมทางวัสดุอย่างต่อเนื่อง ปัจจัยด้านความกำลังแรงดึงและโมดูลัสยืดหยุ่นที่สูง มีความโดดเด่นต่อการประยุกต์ใช้เส้นใยเสริมแรงในวัสดุซีเมนต์ผสม ในหลายลักษณะ ได้แก่ งานพื้นทางลาด, ชิ้นส่วนงานสถาปัตยกรรม, ชิ้นส่วนอัดแรง, โครงสร้างส่วนแผ่นดินไหว, งานซ่อมที่มีความหนาบาง, แผ่นกันกันกระแทก, งานฐานราก และโครงสร้างชลประทาน เป็นต้น ด้วยศักยภาพที่ดีของพอลิเมอร์โพลีเอทิลีนที่สามารถเพิ่มโมดูลัสและแรงดึงสูงในการทำเส้นใย จากกรรมวิธีการหลอมเม็ดพลาสติกและปั่นด้ายเส้นจากเม็ดพอลิเมอร์โพลีเอทิลีน โดยเพิ่มความเร็วยกเว้นจากการดึงเส้นใย เพื่อให้ได้กำลังของเส้นใยที่สูงเพิ่มขึ้น การวิจัยนี้เป็นการศึกษาและประเมินประสิทธิภาพของการใช้เทคนิคการดึงผลิตเส้นใย HDPE ด้วยอัตรารอบแรงดึงที่สูงต่างกัน เพื่อใช้เป็นเส้นใยเสริมแรงในวัสดุซีเมนต์มอร์ต้า โดยตัวอย่างการทดลองและการทดสอบทั้งหมดอ้างอิงในด้านประสิทธิภาพการเสริมรับแรงดึง, แรงดัด, และค่าคุณสมบัติความเหนียว ในวัสดุเชิงประกอบเส้นใยเสริมซีเมนต์มอร์ต้า ด้วยอัตรารอบแรงดึงในตัวเส้นใย HDPE ที่ต่างกัน สำหรับความแตกต่างในอัตรารอบแรงดึง 10 เท่า ใช้สัญลักษณ์แทน d10, อัตรารอบแรงดึง 25 เท่า ใช้สัญลักษณ์แทน d25, และอัตรารอบแรงดึง 35 เท่า ใช้สัญลักษณ์แทน d35 สำหรับค่าปริมาณสัดส่วนผสมเพิ่มของเส้นใยที่อัตราส่วน 0.5%, 1.0%, 1.5% สำหรับค่าความยาวของเส้นใยที่ขนาด 5 มม., 10 มม., 15 มม., 20 มม., ซึ่งศึกษาพฤติกรรมการรับแรงของเส้นใย HDPE เสริมแรง โดยอาศัยเส้นความสัมพันธ์ระหว่าง ค่าความเค้นกับความเครียดหรือการเปลี่ยนรูป ในการศึกษาวิจัยนี้พบว่า การใช้เส้นใย HDPE ที่มีอัตรารอบแรงดึงในเส้นใยสูง จะสามารถเพิ่มประสิทธิภาพของคุณสมบัติการรับแรงดึง และค่าคุณสมบัติความเหนียวของการเสริมแรงใช้วัสดุซีเมนต์มอร์ต้าได้ดีกว่า เส้นใย HDPE ที่มีอัตรารอบแรงดึงที่ต่ำกว่าที่เป็นเส้นใยที่ใช้โดยทั่วไปในปัจจุบัน ในการศึกษาวิจัยนี้ ประสิทธิภาพของการใช้เส้นใย HDPE เสริมแรงในซีเมนต์มอร์ต้า พบว่า เส้นใย HDPE ชนิด D25 เหมาะสมกับปริมาณสัดส่วนผสมที่ 1.5% ขนาดความยาวเส้นใย 20 มม. และเส้นใย HDPE ชนิด D35 เหมาะสมกับปริมาณสัดส่วนผสมที่ 1.0% ขนาดความยาวเส้นใย 15 มม.

## CONTENTS

		<b>Page</b>
<b>ACKNOWLEDGEMENTS</b>		<b>iii</b>
<b>ABSTRACT (ENGLISH)</b>		<b>iv</b>
<b>ABSTRACT (THAI)</b>		<b>v</b>
<b>LIST OF TABLES</b>		<b>ix</b>
<b>LIST OF FIGURES</b>		<b>x</b>
<b>CHAPTER I</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Overview	1
	1.2 Background	2
	1.2.1 Fiber Reinforced Cement Composites	2
	1.2.2 Characterization of Cement	4
	1.2.3 The Addition of Fibers	5
	1.3 Objectives	6
	1.4 Scope of Research	6
<b>CHAPTER II</b>	<b>LITERATURE REVIEW</b>	<b>8</b>
	2.1 Definitions	8
	2.1.1 Fiber reinforced cement mortar (FRCM)	8
	2.1.2 Synthetic fibers	8
	2.1.3 Composite material	8
	2.1.4 High-density polyethylene (HDPE)	9
	2.2 Development of high strength polyethylene fiber	9
	2.3 Effects of fiber reinforcement	10
	2.4 Cementitious Matrices	11
	2.5 Reinforcement mechanisms	12
	2.6 Mechanisms of failure	14
	2.7 Fiber matrix reinforcing effectiveness	15

## CONTENTS (cont.)

		<b>Page</b>
	2.8 Effect of independent variables composite design	16
	2.9 Rules of fiber reinforced composites	18
<b>CHAPTER III</b>	<b>MATERIALS AND EXPERIMENTAL</b>	<b>20</b>
	3.1 Characterization of Constituent Materials	20
	3.2 Instruments	23
	3.3 Mix Proportions	23
	3.4 Mixing and Curing Procedure	24
	3.4.1 Mixing of cement mortar	24
	3.4.2 Flow determination	25
	3.4.3 Curing procedure	26
	3.5 Mechanical Properties Testing	26
	3.5.1 Compressive strength testing	26
	3.5.2 Splitting tensile testing	27
	3.5.3 Direct tensile testing	28
	3.5.4 Flexural performance testing	29
	3.5.5 Toughness determination	30
	3.6 Standard Test Method for Static Modulus of Elasticity	32
	3.7 Scanning Electron Microscope (SEM)	33
<b>CHAPTER IV</b>	<b>RESULTS AND DISCUSSIONS</b>	<b>34</b>
	4.1 Part I: Mechanical behaviors of HDPE	
	fiber reinforced cement mortar	34
	4.1.1 Workability	34
	4.1.2 Mortar density	35
	4.1.3 Compressive strength	37
	4.1.4 Tensile strength	38
	4.1.5 Flexural strength	39
	4.1.6 Toughness and Residual strength	42

**CONTENTS (cont.)**

	<b>Page</b>
4.2 Part II: The Efficiency of HDPE Fiber	
Reinforced Cement Mortar	43
4.2.1 Efficiency of fiber strength	46
4.2.2 Efficiency of volume fiber	48
4.2.3 Efficiency of fiber length	50
4.2.4 Efficiency of fiber direction	52
4.2.5 The behavior of HDPE fiber reinforced cement mortar	56
4.2.6 Microstructure HDPE fiber bonding	59
<b>CHAPTER V CONCLUSION AND RECOMMENDATION</b>	<b>62</b>
5.1 General Conclusion	62
5.2 Recommendation	63
<b>REFERENCES</b>	<b>64</b>

## LIST OF TABLES

<b>Table</b>	<b>Page</b>
2.1 Mechanical properties of drawn HDPE fiber	10
3.1 Chemical composition of the Portland cement	20
3.2 Aggregate gradation, fine aggregates	21
3.3 Properties of fibers used	22
3.4 Summarizes the mix design for FRCC	24
3.5 The minimum tensile strength values	28
4.1 Flow ability Test results	34
4.2 Density, Flow ability, and Compressive strength of HDPE fiber reinforced cement mortar.	36
4.3 Flexural indices and Residual strength factors	42
4.4 Properties of Ultra draw high ratio HDPE fiber	44
4.5 Summary properties of efficiency of HDPE ultra draw fiber reinforced cement mortar	53
4.6 The efficiency factor for the effect of fiber orientation and fiber length follow by the formula of the modified rule of mixtures	54
4.7 The efficiency factor for the effect of fiber orientation and fiber length follow by Curtis et al. modified the rule of mixtures	55

## LIST OF FIGURES

<b>Figure</b>		<b>Page</b>
1.1	Typical stress-elongation curves in tension of fiber reinforced cement composites: (a) Strain-softening behavior. (b) Strain-hardening behavior (HPFRCC)	3
2.1	Different types of polyethylene (a) high density polyethylene (b) low density polyethylene	9
2.2	Composite model considered as a fiber and matrix	12
2.3	Fiber Reinforcement Before and After the Creation of a Macro-Crack (Left) and Crack Bridging by Fibers (Right)	13
2.4	Stress-Strain Curves Showing Strain-Hardening at High Fiber Volume Fractions	14
2.5	Desirable fiber versus matrix properties	16
2.6	Independent variables, components, constraints and solutions in FRC design	18
2.7	Classification of Fiber reinforced composites	18
3.1	Schematic diagram of a Randcastle monofilament line employed in the study	22
3.2	Processing of HDPE fiber	22
3.3	Test setup for compressive strength	27
3.4	Test setup for splitting tensile test	27
3.5	Test setup for direct tensile test	29
3.6	Test setup for measuring flexural strength of FRCC	29
3.7	Load–deflection curve (ASTM C 1018)	32

## LIST OF FIGURES (cont.)

<b>Figure</b>		<b>Page</b>
4.1	Distribution of fiber reinforced mortar	35
4.2	Density of fiber reinforced mortar	36
4.3	Compressive strength of fiber reinforced mortar	37
4.4	Tensile strength of HDPE fiber reinforced cement mortar	38
4.5	Flexural strength of HDPE fiber reinforced cement mortar	39
4.6	stress-deformation relationship of volume fraction HDPE fibers reinforced mortar	40
4.7	Microstructure of bending fracture for different volume fraction fibers ratio	41
4.8	SEM photographs of highly oriented HDPE fibers with different draw ratios	45
4.9	Tensile stress-strain diagrams of fiber strength effective for tensile stress	46
4.10	Flexural stress-deformation diagrams of fiber strength effective for the toughness	47
4.11	Tensile stress-strain diagrams of volume fiber effective for tensile stress	48
4.12	Flexural stress-deformation diagrams of volume fiber effective for the toughness	49
4.13	Flexural stress-deformation diagrams of fiber length effective for the toughness	51
4.14	Tensile stress-strain diagrams of volume fiber effective for elastic modulus	52
4.15	Schematic stress-strain behavior of high modulus HDPE fiber reinforced cement mortar in tension	57
4.16	Strain softening behavior curve in tension of fiber reinforced cement composites	59

**LIST OF FIGURES (cont.)**

<b>Figure</b>		<b>Page</b>
4.17	SEM. Image HDPE D35 bonding with cement mortar	60
4.18	SEM. Image HDPE D25 bonding with cement mortar	60
4.19	SEM. Image HDPE D10 bonding with cement mortar	61

## LIST OF ABBREVIATIONS

HDPE	High density polyethylene
FRC.	Fiber reinforced cement
FRCM	Fiber reinforced cement mortar
DR	Draw ratio
V	Volume
L	Length
$\sigma_t$	Tensile Stresses
$\varepsilon$	Strain
E	Elastic modulus
$\delta$	Displace
$\tau$ .	Shear stress
R	Residual stresses
A	Area
MPa.	Mega Pascal
GPa.	Giga Pascal
N	Newton
ASTM	American Society for Testing and Materials
ACI	American Concrete institutions

# CHAPTER I

## INTRODUCTION

### 1.1 Overview

The last four decades have seen a large number of research studies on fiber reinforced cement materials, most of which devoted to the use of metallic (steel), synthetic (polymeric), ceramic (glass), or natural (organic) fibers. In contrast, few studies dealt with the design and development of the fibers themselves. Indeed most polymeric fibers on the market today have been conceived and introduced over thirty years ago. Addressing recent trends and future directions, Fiber Reinforced Cement Composites presents new opportunities for developing innovative and cost-effective materials and techniques in cement and concrete composites manufacturing, testing, and design.

Essentially, the fiber-reinforcement concept is about the increment of quality of a complex composite material (mortar cement and concrete) by improving certain properties of fresh and hardened material which are crucial for its practical application. The principal reason for incorporating fibers into a cement matrix is to increase the toughness and tensile strength, and improve the cracking deformation characteristics of the resultant composite. In order for fiber reinforced cement (FRC) composites to be a viable construction material, it must be able to compete economically with existing reinforcing systems.

Several types of fibers have been used to reinforce the cement-based matrices. Various types of fibers, both synthetic and natural, have been found suitable for the commercial applications. Currently, the commercial products are reinforced with steel, glass, polyester and polypropylene fibers. The selection of the type of fibers is guided by the properties of the fibers such as diameter, specific gravity, young's modulus, tensile strength etc. and the extent these fibers affect the properties of the cement matrix[1,2].

Polyethylene has very high potential for producing high modulus and high strength fiber [3]. Polyethylene fiber produced by melt spinning is commercially available and has been around for quite some time. This fiber has rather low modulus and strength in the region of 4-6 GPa and 400-500 MPa, respectively. To produce stronger fiber, polyethylene needs to be drawn to very high draw ratio exceeding that used in conventional fiber production [4].

To reduce the brittleness and increase the resistance to cracking, reinforcement with short randomly distributed fiber has been successfully used [5-6] and the resulting composite is known as fiber reinforced cement (FRC) composites. The performance of FRC composites depends on many factors such as fiber material properties, fiber geometry, fiber volume content, matrix properties and interface properties [7].

Therefore, the advantages of conventional FRC composites systems, there are other desirable features that could extent the application of these materials. Frist is the issue of economics, which is to increase the availability of lower cost materials, HDPE fiber. Second are technological issues, related to the development HDPE fiber by melt spinning at high draw ratio to produced high strength fibers. For these reasons, considerable interest has been generating in experimental evaluation of the flexural and tensile behaviour of FRC composites. Taking into account the mechanical behavior of the high-performance HDPE fiber reinforced cement mortar, the major objective of this work is to increase the energy absorption capacity and toughness of the material, but also increase tensile and flexural strength of cement mortar.

## **1.2 Background**

### **1.2.1. Fiber Reinforced Cement Composites**

Definition of fiber reinforced cement composites; for practical purposes and mechanical modeling, fiber reinforced cement (FRC) or concrete composites are generally defined as composites with two main components, the fiber and the matrix [8].

While the cementitious matrix may itself be considered a composite with several components, it is generally assumed to represent the first main component of

the FRC composite. The fiber represents the second main component. The fiber is assumed to be discontinuous and, unless otherwise stated, randomly oriented and distributed within the volume of the composite. Both the fiber and the matrix are assumed to work together, through bond, and provide the synergism needed to make an effective composite.

The fiber reinforced cement composites can be simply classified according to one distinguishing characteristic of their stress-strain response in tension. In the strain-softening case, localization occurs immediately after first cracking and, with increasing elongation; the stress after first cracking is smaller than that at first cracking. Figure 1.1a illustrates the response in tension (stress versus elongation) of a strain-softening composite. In the strain-hardening case, the stress after first cracking increases with strain, and multiple cracking occurs up to the maximum post-cracking stress (Figure. 1.1b). At that point, localization occurs, and the stress decreases with increasing elongation, similar to the case of a strain-softening material [9,10].

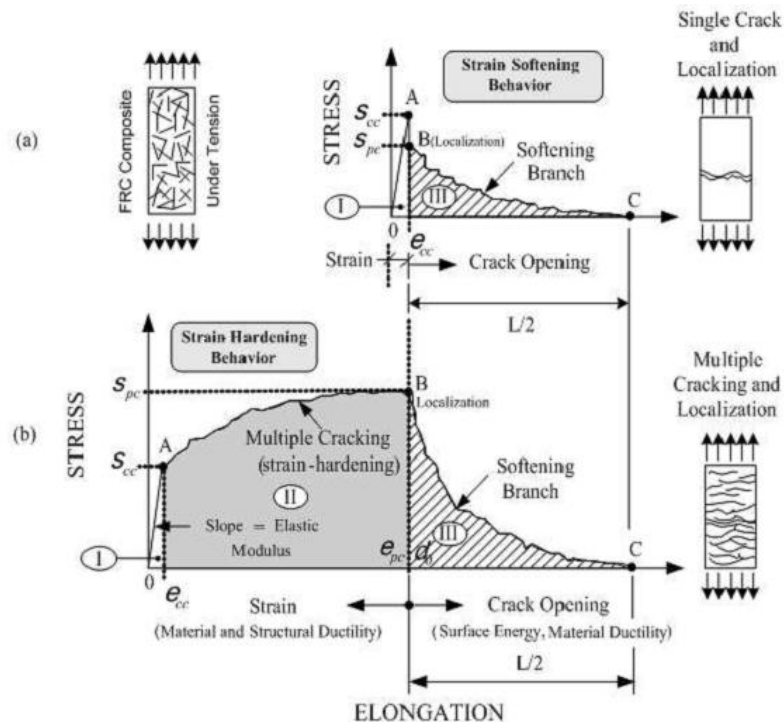


Figure 1.1 Typical stress-elongation curves in tension of fiber reinforced cement composites: (a) Strain-softening behavior. (b) Strain-hardening behavior (HPFRCC).

### 1.2.2. Characterization of Cement

Cement is an organic mineral product with hydraulic properties, i.e. it reacts with water, hardens and is no more soluble in water. In the fresh state, it is almost fluid and may be given any shape. Hardening occurs usually at ambient temperature, but may be accelerated by modest heating. During hardening, crystals grow and fill the space by solid matter. However, there are two important features involved: first, pores remain in the solid thus formed, and second, shrinkage occurs in that solid.

After hardening, the pore volume may be 10 to 40 percent of the apparent volume of the solid, with pore sizes ranging from a nanometer to a few micrometers. The very small pores (gel pores) are filled with physically bound water while the larger pores (capillary pores) are filled with water or empty depending on the ambient humidity. The capillary pores form the main medium for transporting fluid, ions and gas.

Generally, pores can be seen as defects in an amorphous matter the strength of which is due to secondary bonds between the crystals. For hardened cement based binders, the global tensile strength is small; the strain capacity is low and fracture energy amounts only to about  $100 \text{ Jm}^{-2}$ . Thus, hardened cement paste is characterized as a rather brittle material.

Shrinkage is caused by three phenomena, namely: chemical binding of water, evaporation of surplus water, and carbonation. Chemical shrinkage occurs during hydration in a state where displacements of crystals are possible. Drying shrinkage follows in the hardened state causing stresses due to differential moisture content. Carbonation shrinkage proceeds from the surface (where carbon dioxide is readily available) to inside the material. Since stiff inclusions within the material (such as aggregates), or imposed boundaries do not allow for free movements, shrinkage causes stresses due to imposed deformations. Cracks of various widths may result.

### **1.2.3. The Addition of Fibers**

The deficiencies of hardened cement as mentioned above – low strength, low strain capacity, low fracture energy, interior cracks, visible cracks – can be counteracted by materials, such as fibers, embedded in the cement matrix and having high tensile strength and ductility. A prerequisite for the beneficial effect is a reliable bond and/or anchorage between the two materials.

The fibers can act most effectively if they are aligned in the direction of the largest tensile stresses. This principle is applied in the reinforced and prestressed concrete. However, only in a few cases, the direction of maximum tensile stresses is known in advance, and production of aligned short fiber reinforcement is difficult.

Fibers are most beneficial when large strains occur in the cement matrix. Since the tensile strain capacity of the matrix is small, this is only possible if cracks develop. So, the aim of the addition of fibers should be to keep the crack widths as small as possible and to resist the tensile forces which are no longer taken by the cement matrix in its softening stage. Depending on the special aim, the fibers should act during both the early or mature age of the matrix.

The effectiveness of fiber reinforcement is dependent on the properties of the fibers, and cement matrix. Fiber properties which affect performance characteristics include: strength, stiffness, % volume, length, aspect ratio, and cross section area. Important cement matrix properties depend on compressive strength and type of aggregate used in the mix. The main variables for aggregate are the size of the particles and the volume.

Many of the disputes over fiber reinforced cement composite (FRC) stem from the wide range of results obtained during testing. A major contributor to this inconsistency is the non-uniformity of fibers in the cement matrix. The uniform distributor of fiber reinforcement is dependent upon the characteristic of the aggregate and fibers as mentioned previously. Large aggregate takes up more volume and limits the volume occupied by the fibers. The less volume available for fibers increase the concentration of fibers and leads to the problem of balling. “Balling” is the formation of a large mass of fibers sticking together.

### **1.3 Objectives**

In these research have two main objectives. The first objective is to study the mechanical behaviours of HDPE fiber reinforced in cement mortar. Physical and mechanical properties of high strength HDPE fibers reinforced render cement mortar are measured with special consideration about mortar toughness indices. An important aspect to emphasize in this study is that good properties high strength high density polyethylene (HDPE) fiber processing is performed only with the technique of melt spinning fiber. This process aims to develop the role of fiber reinforced cement. The fibers were produced with different draw ratio and therefore had different modulus and strength. The second objective is to understand the modelling of HDPE fiber reinforced in cement mortar. Basically, addition of fibers to cement composites its mechanical properties which significantly depend on the type and percentage of fiber. In addition, for effective using synthetic HDPE fiber reinforced cement, the modelling of fiber reinforced cement should have suitable condition in fiber reinforced system that was involve with many of parameters in theory of short fiber reinforced composites.

### **1.4 Scope of Research**

This research scope on an experimental study of the flexural-tensile behavior of synthetic HDPE fiber reinforced cement composites. In this research, types of high strength fiber from high draw ratio HDPE fibers (D10, D25, and D35) were tested in cement mortar to examine the effect of fiber reinforced cement mortar. The factors can effects the mechanical properties of cement mortar such as a mount of volume fraction, vary aspect ratio in order to investigate the effect of fiber reinforced cement mortar will be conducted to produce high quality of cement mortar. Laboratory test will be carried out to make sure that the engineering properties in cement mortar occur after HDPE fiber was added in the mortar mix. Fibers used in the FRC test specimens included high strength fiber (HDPE fiber produced by melt spinning at high draw ratio). The properties of these fibers are presented. The mechanical properties of FRC were studied by the compressive strength, direct tensile, spitting test and flexural test. Stress versus crack separation curves and fracture

energies of FRC are reported. Observations of fiber reinforcement effects on the workability of freshly mixed FRC are described. The mechanical behaviors have been studies and are reported elsewhere.

## **CHAPTER II**

### **LITERATURE REVIEW**

#### **2.1 Definitions**

**2.1.1 Fiber reinforced cement mortar (FRCM)** is cement mortar containing fibrous material which increases its structural integrity. 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 lend varying properties to the cement mortar.

**2.1.2 Synthetic fibers** are man-made fibers resulting from research and development in the petrochemical and textile industries. There are two different physical fiber forms: monofilament fibers and fibers produced from fibrillated tape. Currently there are two different synthetic fiber volumes used in application, namely low-volume percentage (0,1 to 0,3% by volume) and high-volume percentage (0,4 to 0,8% by volume). Most synthetic fiber applications are at the 0,1% by volume level[11]. At this level, the strength of the concrete is considered unaffected and crack control characteristics are sought. Fiber types that are used in portland cement concrete are: acrylic, aramid, carbon, nylon, polyester, polyethylene, and polypropylene.

**2.1.3 Composite material** are materials made from two or more constituent materials with significantly different physical or chemical properties, that when combined, produce a material with characteristics different from the individual components. The individual components remain separate and distinct within the finished structure. The majority of composite materials use two constituents: a binder or matrix and a reinforcement. The reinforcement is stronger and stiffer, forming a sort of backbone, while the matrix keeps the reinforcement in a set place.

**2.1.4 High-density polyethylene (HDPE)** is a polyethylene thermoplastic made from petroleum. HDPE is known for its large strength-to-density ratio. The density of HDPE can range from 0.93 to 0.97 g/cm<sup>3</sup>. Although the density of HDPE is only marginally higher than that of low-density polyethylene, HDPE has little branching, giving it stronger intermolecular forces and tensile strength than LDPE. The difference in strength exceeds the difference in density, giving HDPE a higher specific strength [12].

## 2.2 Development of high strength polyethylene fiber

Basically rule, polymer which is linear chain can be effectively oriented more than branch one. In this case, high density polyethylene (HDPE) that has linear chain nature, a broad molecular weight distribution, high molecular weight chains and their larger number of entanglements can be developed by orientation to become high crystallinity, modulus and strength fiber . There are two processes for producing the strength fiber such as melt-spinning and gel-spinning processes. Melt spinning process is suitable for formal polyethylene while ultra high molecular weight polyethylene used the latter process[13].

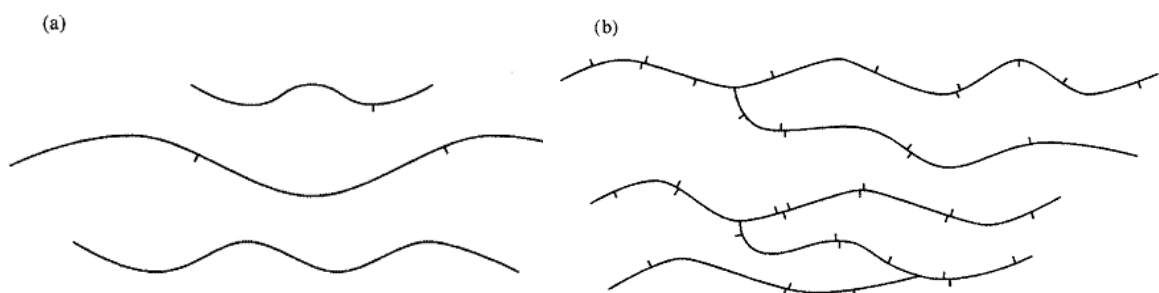


Figure 2.1 Different types of polyethylene (a) high density polyethylene (b) low density polyethylene [13].

Siriphan C. studied the mechanical properties of high density polyethylene (HDPE) fiber oriented by melt spinning. The mechanical properties of the drawn fiber related with draw ratio. The modulus and strength of drawn fibers increases with increasing draw ratio as shown in Table 2.1. Theirs properties were improved to better compare to that of general [14].

**Table 2.1** Mechanical properties of drawn HDPE fiber

<b>Draw ratio (DR)</b>	<b>Tensile strength (GPa.)</b>	<b>Modulus at 1% strain (GPa.)</b>
10	1.00 ± 0.02	18.06 ± 0.90
12	1.20 ± 0.06	27.40 ± 1.16
17	1.11 ± 0.09	38.74 ± 2.18
20	1.23 ± 0.04	41.36 ± 1.32
25	1.24 ± 0.14	41.85 ± 1.69

### 2.3 Effects of fiber reinforcement

The addition of fibers to cement matrix has shown improvement in flexural strength, toughness, enhanced ductility, impact resistance, fatigue strength and resistance to cracking. In addition composite deformation at peak stress is much greater than plain mortar. Fibers help to alter the behavior of cement matrix after cracking has begun. The crack bridging behavior of fibers is what improves the ductility of the matrix[15].

- **Factors Controlling Fiber Reinforced Cement Composite** [16]
  - Aspect ratio,  $l/d$
  - Volume fraction,  $v_f$
  - Fiber reinforcing index,  $RI=l/d \times v_f$
  - Critical length,  $l_{min}$
  - Balling of fibers
  - Good mix design: more matrix, small aggregate, workable
  - Type of fibers-size, shape, strength, modulus

## 2.4 Cementitious Matrices

Cement-based matrices have evolved enormously since the 1960 s in particular due to a better understanding of their microstructure and the influence of packing and porosity, as well as the development of mineral and chemical additives to achieve a number of particular properties. Typically, the matrix for fiber reinforced cement composites can be a cement paste, a mortar (that is, essentially a paste with sand), or a concrete (that is, essentially a mortar with coarse aggregates or gravel). The cement paste is made of cement and water, and may contain additives, which can be mineral (such as fly ash) or chemical such as air entraining admixtures. The paste itself can be made to have low viscosity, be stiff like clay, or to flow like a liquid; in the latter case, the term slurry or slurry paste is often used to describe the matrix.

The cement powder, which reacts with water to eventually leads to the binder and hardened matrix, may be blended, that is, containing supplementary cementitious materials, such as flash ash, ground furnace slag, micro-silica, and the like (Fig. 2.2). Indeed, mineral components such as silica fume and fly ash are now commonly used either as additives, to or as replacement of cement. They help provide a denser composite, reduce porosity, improve fresh properties, improve strength, corrosion resistance and durability, control the hydration reaction, etc. Chemical admixtures, such as water-reducing agents, superplasticizers, and viscosity agents, help control and improve a host of other properties in the fresh state to help in the fabrication and manufacturing phase. Today, self-consolidating and self-compacting cementitious mixtures allow us to rethink construction procedures for fiber reinforced cement composites. Such mixtures, for instance, allow us to use fiber reinforced concrete in congested areas of reinforced concrete structures such as in beam column connections, coupling beams and the like, without losing the penetrating and encapsulating function of the matrix [17, 18].

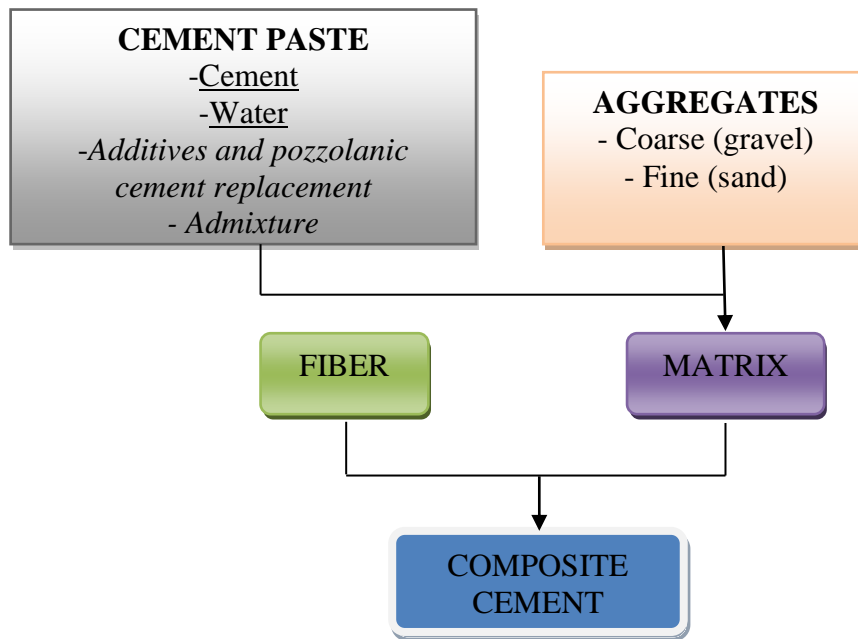


Figure 2.2 Composite model considered as a fiber and matrix.

## 2.5 Reinforcement mechanisms

Cement carries flaws and micro-cracks both in the material and at the interfaces even before an external load is applied. These defects and micro-cracks emanate from excess water, bleeding, plastic settlement, thermal and shrinkage strains and stress concentrations imposed by external restraints. Under an applied load, distributed micro-cracks propagate coalesce and align themselves to produce macro-cracks. When loads are further increased, conditions of critical crack growth are attained at the tips of the macro-cracks and unstable and catastrophic failure is precipitated. The micro and macro-fracturing processes described above, can be favourably modified by adding short, randomly distributed fibers of various suitable materials. Fibers not only suppress the formation of cracks, but also abate their propagation and growth.

After placement, evaporation of the mix water and the autogenously process of cement hydration create shrinkage strains in cement. If restrained, this contraction can cause stresses far in excess of those needed to cause cracking. In spite of every effort, plastic shrinkage cracking remains a serious concern, particularly in large surface area placements like slabs on grade, thin surface repairs,

patching and shot Crete linings. With large surface areas, fibers engage water in the mix and reduce bleeding and segregation. When combined with post-crack bridging capability of fibers, fibers reduce crack widths and cracks areas when cement is retrained [19].

In the hardened state, when fibers are properly bonded, they interact with the matrix at the level of micro-cracks and effectively bridge these cracks thereby providing stress transfer media that delays their coalescence and unstable growth (Figure 2.3). If the fiber volume fraction is sufficiently high, this may result in an increase in the tensile strength of the matrix [20]. Indeed, for some high volume fraction fiber composite, a notable increase in the tensile/flexural strength over and above the plain matrix has been reported (Figure 2.4). Once the tensile capacity of the composite is reached, and coalescence and conversion of micro-cracks to macro-cracks has occurred, fibers, depending on their length and bonding characteristics continue to restrain crack opening and crack growth by effectively bridging across macro-cracks. This post-peak macro-crack bridging is the primary reinforcement mechanism in the majority of commercial fiber reinforced concrete composites.

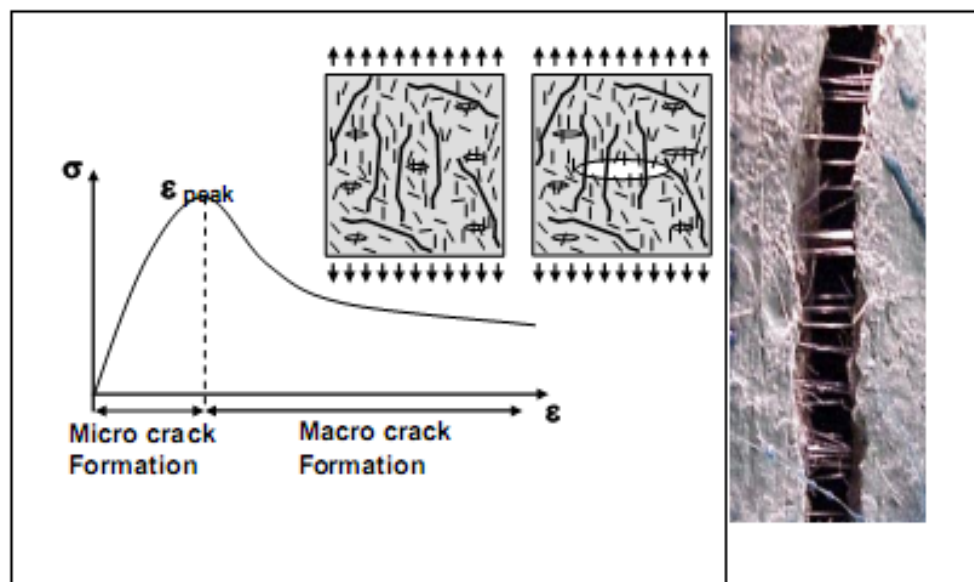


Figure 2.3 Fiber Reinforcement Before and After the Creation of a Macro-Crack (Left) and Crack Bridging by Fibers (Right).

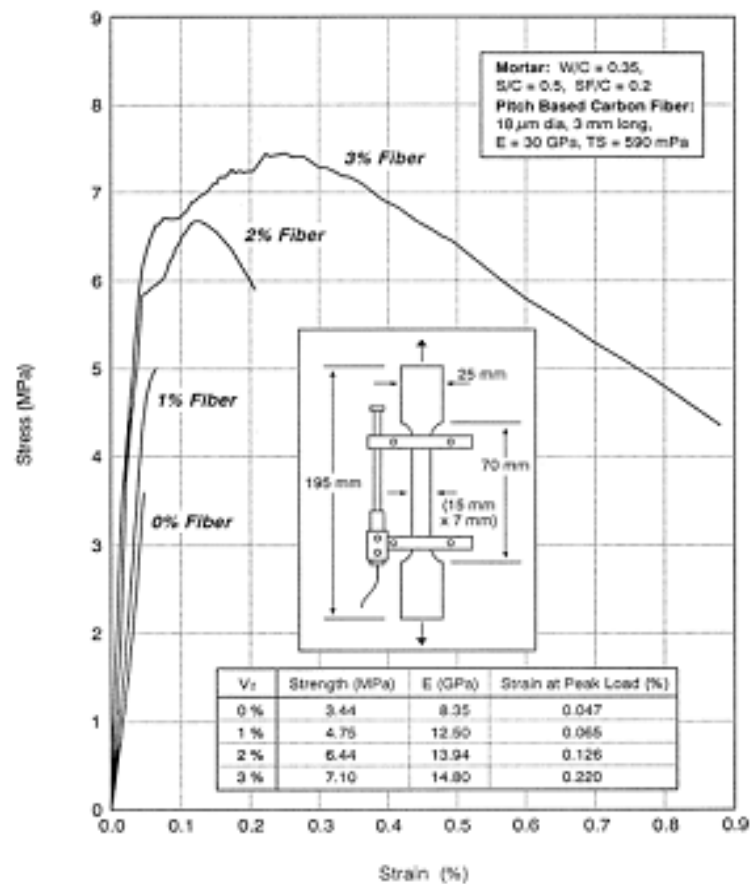


Figure 2.4 Stress-Strain Curves Showing Strain-Hardening at High Fiber Volume Fractions.

## 2.6 Mechanisms of failure

Concern in crack opening is inhibited by energy supplied to drive mechanisms of failure such as:

- 1) Fiber debonding
- 2) Fiber pull-out against interfacial friction
- 3) Deformation of fibers which lay at oblique angles to the crack face. <sup>[6]</sup>

Currently there are two theories for analyzing fiber debonding. First is the strength-based approach which is dependent upon the material interfacial strengths. The second theory is the fracture-base approach which is based on the strain energy required to break the interfacial bonds between fiber and matrix.

Interfacial friction during pull-out contributes to the ductility of the composite. Energy is transferred from driving cracks to fiber pull-out which also increase the composite strain at failure.

For fiber lying obliquely to a crack, the pull-out force has two components. One due to debonding and pull-out of the fiber and the other due to the bending of the fiber. As the crack opens the fiber is pulled as well as bent. Debonding and pull-out are a function of interfacial bonding and friction between the fiber and matrix. The bending component is a function of the fiber and matrix stiffness and strength. Bending of the fiber can result in fiber yielding or breakage as well as spalling of matrix near the fiber exit point.

## **2.7 Fiber matrix reinforcing effectiveness**

By its very definition a reinforcement (i.e., the fiber) is supposed to induce an increase in strength in the reinforced material (i.e., the matrix). Both analysis and experimental test results suggest that, in order to be effective in cement matrices, fibers must have the following properties (Figure 2.5): 1) a tensile strength significantly higher than that of cement matrix (two to three orders of magnitude); 2) a bond strength with the cement matrix preferably of the same order as or higher than the tensile strength of matrix; and 3) unless self-stressing is used through fiber reinforcement, an elastic modulus in tension significantly higher than that of the cement matrix. The Poisson's ratio and the coefficient of thermal expansion should preferably be of the same order for both the fiber and the matrix. Indeed if the Poisson's ratio of the fiber is significantly larger than that of the matrix, detrimental debonding will occur under tensile load. However, these drawbacks can be overcome by various methods such as inducing surface deformation to create mechanical anchorage.

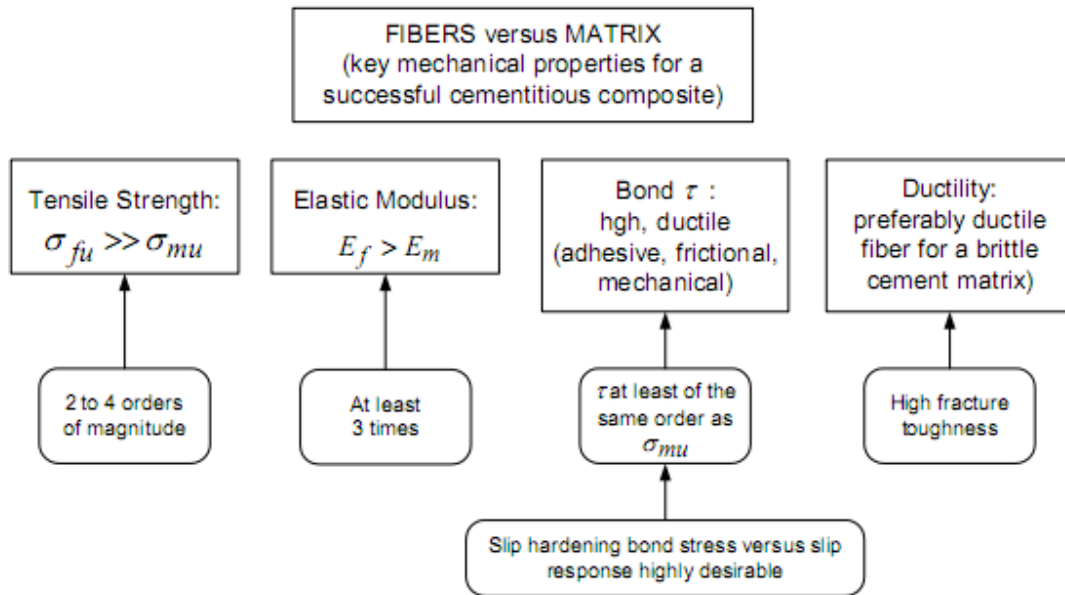


Figure 2.5 Desirable fiber versus matrix properties[21].

## 2.8 Effect of independent variables composite design

These variables or parameters are shown in Figure 2.6. Increasing one or a combination of independent variables  $V_f$  or  $\tau$  or  $L/d$  or  $\psi L/A$  should lead to an increase in the post-cracking strength of the composite. However there is a practical limit to how much each variable can be increased or controlled.

For instance, if normal fibers are to be premixed with a cement matrix, using more than about 2% fibers by volume becomes difficult from a practical viewpoint; it may lead to balling, segregation, harsh mix, etc. To further increase  $V_f$ , other processes are used such as in SIFCON or SIMCON where a fiber network of a fiber mat is preplaced in a mold and is infiltrated by a cement matrix. Note that increasing the volume fraction of fibers, invariably leads to a matrix made with only fine grain particles, that is, a cement matrix without coarse aggregate or even without normal sand, generally leading to a decrease in the elastic modulus of the composite.

Similarly, with rigid fibers such as steel fibers, increasing the aspect ratio beyond about 100, leads to increased segregation, balling and difficulty in mixing. Theoretically this correlates with the topography of a fiber network and how randomly

oriented and distributed rigid fibers fill a given volume. The aspect ratio limitation, can also be overcome by using other processes such as by shotcreting, or in SIFCON or SIMCON where the fibers do not need to be premixed.

The coefficient  $\Lambda$  in Figure 2.6 is the product of a number of other coefficients and depends on several statistics such as 1D, 2D, or 3D, little can be done to change the other coefficients. Thus  $\Lambda$  can only marginally be controlled.

The last and most difficult parameter to control composite performance is the bond strength,  $\tau$ , which is often assumed in composite design to be a constant. Increasing the average bond strength,  $\tau$ , leads to a direct increase in the post-cracking strength of the composite and other important properties as well such as toughness and energy absorption capacity. A comprehensive discussion of the various bond components listed in Figure 2.6 (adhesion, friction, mechanical, interlock) is given in Naaman (1999 and 2000b). It is argued that in order for bond to be truly effective, its value must be maintained over relatively large slips, leading to what is described as a ductile bond stress versus slip response. It should be noted that in the current state of the art, all four components of bond have been explored. Friction is considered an essential part of bond and is practically always counted on. Adding for instance latex or an epoxy resin to the cement matrix will increase the adhesive (or chemical) bond at the fiber matrix interface; however, prior tests have shown that because of the brittle nature of adhesion, the bond increase observed in a single fiber pull-out test, does not translate in an equal improvement at the composite level. Practically all fibers have their bond improved through mechanical deformations; examples include crimping or indenting the fibers along their length or adding hooks or buttons or paddles at their ends. Fiber-to-fiber interlock exists in SIFCON and SIMCON composites where the fibers are in contact with each other but cannot be generally counted on when fibers are premixed with the matrix.

In summary to Figure 2.6 and the above discussion, it seems at first that no additional improvement can be thought of to improve composite performance. However, as shown in the following section, bond offers some interesting and hidden opportunities that have been recently uncovered and have led to a new type fiber, here identified as high performance HDPE fiber, for use in composite applications.

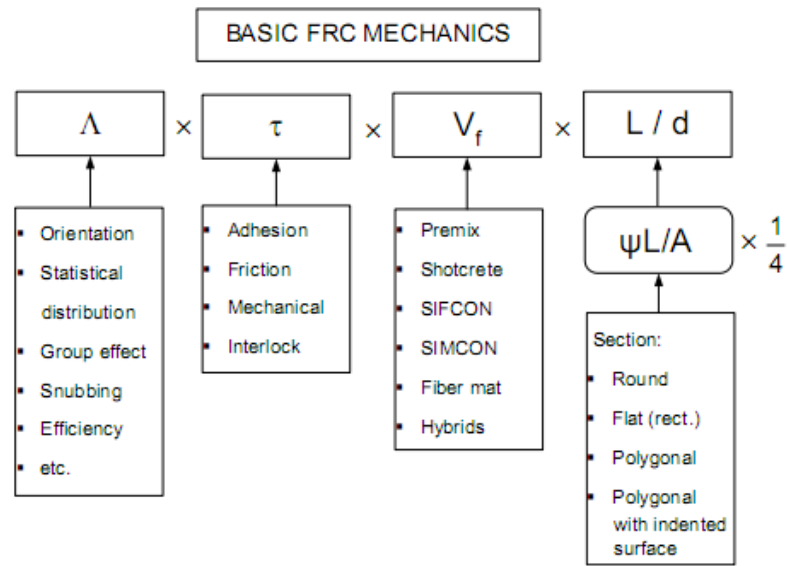


Figure 2.6 Independent variables, components, constraints and solutions in FRC design[22].

### 2.9 Rules of fiber reinforced composites

Synthetic fiber based composites incorporates synthetic fibers as reinforcement with cement matrix. Details of classification are given in figure 2.7

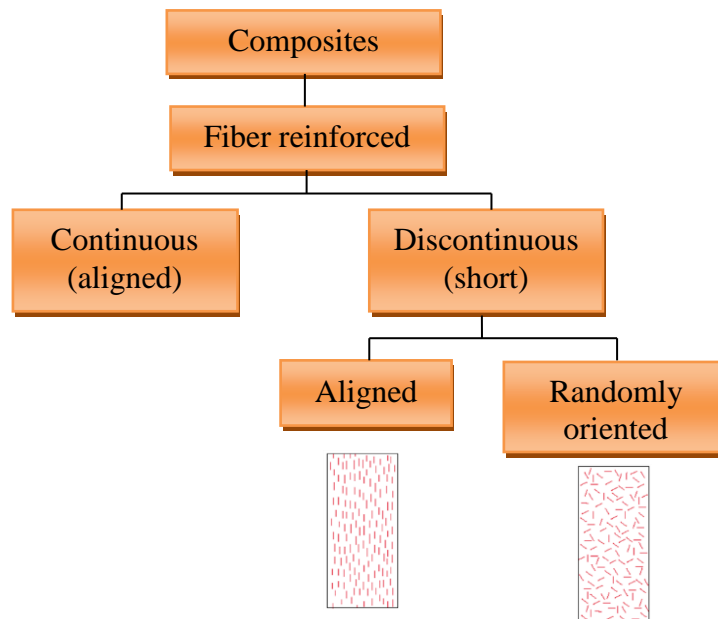


Figure 2.7 Classification of Fiber reinforced composites

The rules of mixtures are mathematical expressions which give some property of the composite in terms of the properties, quantity and arrangement of its constituents. These can apply to predict the tensile stress of the fiber reinforced cement composites.

The formula of the modified rule of mixtures

$$\sigma_c = K \sigma_f V_f + \sigma_m(1-V_f) \quad \text{by Blumentritt and Cooper}$$

Where

$\sigma_c$  – The strength of the composite

$K$  – The fiber efficiency factor for strength (Fiber orientation and Fiber length)

$V_f$  – The volume fraction of the fiber

$\sigma_f$  – The strength of the fiber

$\sigma_m$  – the matrix stress at the fracture strain of the composite

Curtis et al. modified the rule of mixtures into the following form:

□

$$\square \sigma_c = X_1 X_2 \sigma_f V_f + \sigma_m V_m \quad \text{by Curtis et al}$$

Where

$\sigma_c$  – the strength of the composite.

$X_1$  – the effect of fiber orientation.

$$= d/\Delta V_f \text{ (effect of fiber orientation)}$$

$X_2$  – the effect of fiber length or effective length of fiber that carries load

$$= 1 - s_c/2s ; \text{ (effect of fiber length) ; } s_c = \text{aspect ratio } (l_c/d) ; l_c = \sigma_f d / 2\tau_y$$

$\sigma_f$  – the strength of the fiber

$V_f$  – the fiber volume fraction

$\sigma_m$  – the matrix strength

## CHAPTER III

### MATERIALS AND EXPERIMENTAL

This Chapter is divided into six sections: characterization of constituent material; Instruments; mix proportions; mixing and curing procedures; mechanical properties testing of unreinforced and fiber reinforced cement mortar; and Scanning Electron Microscope (SEM).

#### 3.1 Characterization of Constituent Materials

##### a) Cement

An ordinary Portland cement was Portland Cement Type I (Elephant Brand) used throughout this research work was from The Siam Cement Public Company. The chemical composition of which is given in Table 3.1.

**Table 3.1** Chemical composition of the Portland cement

SiO <sub>2</sub> (%wt.)	Al <sub>2</sub> O <sub>3</sub> (%wt.)	Fe <sub>2</sub> O <sub>3</sub> (%wt.)	CaO (%wt.)	MgO (%wt.)	SO <sub>3</sub> (%wt.)	Na <sub>2</sub> O (%wt.)	K <sub>2</sub> O (%wt.)	Loss on ignition	Specific Gravity	Blaine Fineness (cm <sup>2</sup> /g)
21.10	4.93	3.05	66.04	0.84	2.37	0.08	0.56	1.03	3.15	3,200

##### b) Siliceous sand

The fineness modulus for the siliceous sand was 2.51. Following are the specific gravity values: 2.65. The absorption of the sand was 1.35. Gradation results for the sand, as obtained from tests undertaken in the Siam University laboratories according to ASTM C33[23], are given in Table 3.2.

**Table 3.2** Aggregate gradation, fine aggregates

Sieve size	Percentage Passing of sieve analysis (%)
9.50-mm (3/8")	100
4.75-mm (No.4)	97
2.36-mm (No.8)	91
1.18-mm (No.16)	67
0.60-mm (No.30)	41
0.30-mm (No.50)	19
0.15-mm (No.100)	7
Pan	0

c) High density polyethylene (HDPE)

High density polyethylene (HDPE) grade InnoPuls HD5000S was purchased from PTT Chemical Public Company Limited. It has a melt flow index and a density of 0.8 g/10 min.(230 °C/2.16 kg.) and 0.954 g/cm<sup>3</sup>., respectively.

d) Fibers

High density polyethylenes (HDPE) employed in the present study were 5000S. The fiber was prepared on a Randcastle monofilament line as schematically shown in Figure 3.1 and 3.2 Fiber was prepared by 2-step method. Extruder temperatures were set at 120, 180, 190 and 215°C for zone 1, 2, 3 and die, respectively. As-spun fiber was spun at a screw speed of 2.2 rpm, or otherwise stated. The fiber was allowed to cool in air. The as-spun fiber had a diameter of about 500 μm. The as-spun fiber was drawn to different draw ratios with two sets of rollers through a glycerol bath set at 115°C. Draw ratio was calculated from the ratio of the speed of the follower to leader roller. Tensile testing was carried out at room temperature with sample gauge length of 50 mm and a crosshead speed of 25 mm/min.

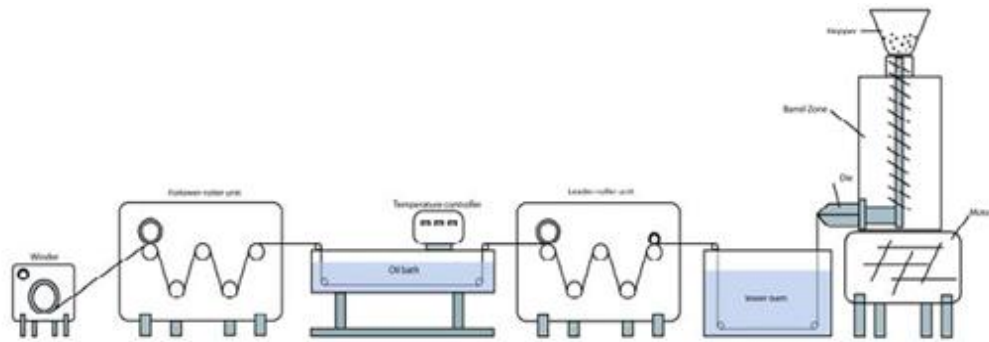


Figure 3.1 Schematic diagram of a Randcastle monofilament line employed in the study[24].

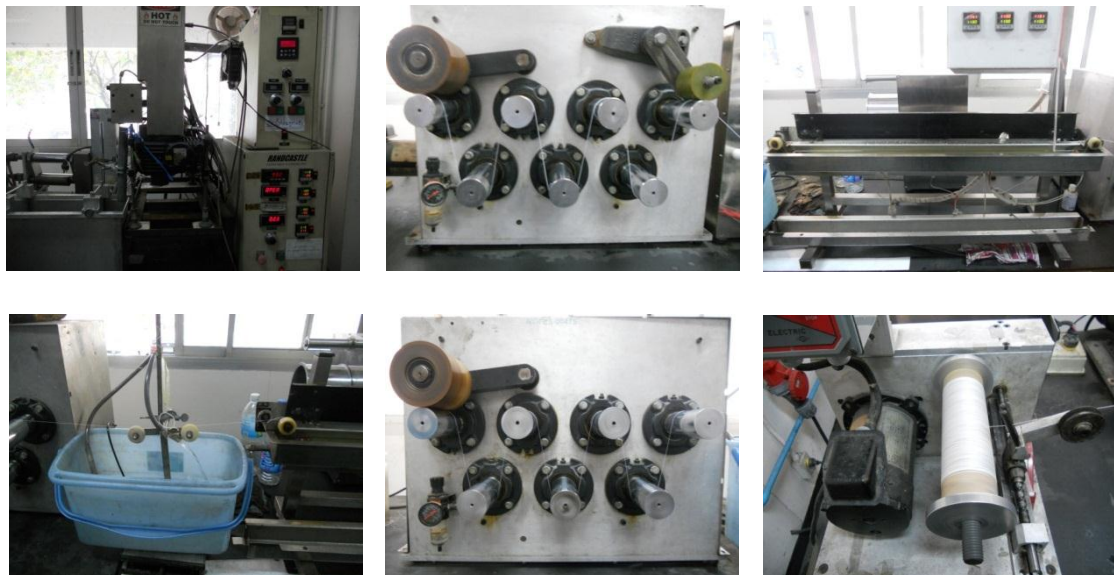


Figure 3.2 Processing of HDPE fiber

**Table 3.3** Properties of fibers used

	$\phi$ (mm.)	L/d	E (GPa)	$\sigma_B$ (GPa)	$\epsilon_B$ (%)
<b>HDPE-DR 10</b>	0.202	99	$6.9 \pm 1.06$	$0.50 \pm 0.06$	$20 \pm 0.95$
<b>HDPE-DR 25</b>	0.172	116	$24.9 \pm 1.80$	$0.86 \pm 0.08$	$5 \pm 0.58$
<b>HDPE-DR 35</b>	0.148	135	$34.5 \pm 2.67$	$1.05 \pm 0.10$	$4.5 \pm 0.60$

\*Fiber Length 20 mm

### 3.2 Instruments

Instruments, manufacturers and models for this research were listed as follow;

- Micro-Extruder (Randcastle models RCP-0626)
- Fiber Drawing Units (Randcastle)
- Lab Scale Internal Mixer (Hakke Rhecord 90)
- Hot Plate (model IKA® C-MAG HS 7)
- Temperature Controller (model IKA® ETS-D5)
- Tensile Testing Machine for fibers test (Instron models 5566)
- Automatic Flexural Tensile Tester (WYKEHAM FARRANCE ENGINEERING LTD. Model No.59605)
- Universal Testing Machines (UTM) Micro-computer (Hung Ta Instrument models HT-9502)
- Scanning Electron Microscope(SEM) (JEOLmodels JEM-5410LV)
- Mixer Mortar Machines (SYBO model B200 Power 1.1kW.)

### 3.3 Mix Proportions

The mix proportions used in this study were applicable to cement mortar (the standard mortar shall be one part of cement to 2.75 parts of graded standard sand by weight and water/cement ratio 0.7). After testing workability with non-fiber and fiber reinforced by flow-able test of cement mortar, water/cement ratio were suitable between 0.6-0.8. A series of 12 cement mortar mixes were prepared with and without fibers. As mentioned earlier, the fiber volume fractions for this study were 0%, 0.5%, 1.0%, and 1.5% by total volume respectively. Table 3.4 summarizes the mix design for FRCC

**Table 3.4** Summarizes the mix design for FRCC

Mix Types	Cement	Sand	Water	Fiber	Total (g.)
<b>Plain Mortar</b>	1000	2750	700	0	4450
<b>D10M0.5%</b>	1000	2750	700	10	4460
<b>D10M1.0%</b>	1000	2750	700	20	4470
<b>D10M1.5%</b>	1000	2750	700	30	4480
<b>D25M0.5%</b>	1000	2750	700	10	4460
<b>D25M1.0%</b>	1000	2750	700	20	4470
<b>D25M1.5%</b>	1000	2750	700	30	4480
<b>D35M0.5%</b>	1000	2750	700	10	4460
<b>D35M1.0%</b>	1000	2750	700	20	4470
<b>D35M1.5%</b>	1000	2750	700	30	4480

### 3.4 Mixing and Curing Procedure

#### 3.4.1 Mixing of cement mortar

- By Mechanical mixer

a) Fix the mixing bowl and paddle at mixing position and pour specified quantity of water.

b) Start the mixer with low speed (approximately  $140 \pm 5$  rpm) and put the specified amount of cement in 30 sec while rotating the paddle.

c) Put the specified amount of sand in the next 30 sec while continuing mixing. After subsequent mixing for 60 sec, pause for 20 sec. Scrape off the adhered mortar to the mixing bowl and paddle using a spoon while in the pause. Further mix the mortar by spoon in such a manner to scrape the mortar upwards from the bottom of the mixing bowl.

d) After completion of the pause, start mixer again and continue mixing for 2 min at medium speed (approximately  $285 \pm 10$  rpm). After the mixing has finished, remove the mixing bowl from the mixer.

- By Hand mixing

a) Put the specified quantities of cement and sand upon a smooth nonabsorbent surface and mix thoroughly with spoon or trowel for 2 min.

b) Form a crater in the center and pour the specified quantity of water in the crater. Use the trowel to turn the particles from the outside edge into the crater in 30 sec. Leave the sample to absorb the water for further 30 sec and mix thoroughly with spoon or trowel for another 3 min.

In this research, the following mixing procedure was used for all mixes specified in ASTM C109 [25] except for the procedure of addition of fibers. First, cement and sand were mixed for approximately 5 minute. Then 50% of the mixing water was added and the mixture was mixed for 1 minute to allow for water absorption. Next, the remaining water was added. The mixing continued for another 3 minutes. All component materials except for fibers were added to ensure proper and uniform mixing. Finally, fibers were added to the mix. Altogether, the additional mixing time took approximately 5 minutes to ensure a uniform fiber distribution and to minimize fiber segregation and balling effects. After completion of the batch, the mix was placed into the appropriate molds, which were then placed on a vibrating table. The vibrating process was continued for approximately 1-2 minutes.

### **3.4.2 Flow determination**

a) Carefully wipe the flow table top clean and dry. Pack the mortar, which has been mixed either mechanically or manually, in two layers (each layer is about 25 mm in thickness) into the flow cone which has been placed at the centre of the flow table.

b) Tamp each layer on all over its surface 20 times each, so that the end of the tamping rod can reach to the depth approximately 1/2 the depth of the layer.

c) Cut off the mortar to a plane surface, flush with the top of the mold by drawing the straight edge of a trowel with a sawing motion across the top of the mold.

d) Remove the cone correctly upwards, then impart 25 times 3 of falling motion in 15 sec. The flow is the resulting increase in average base diameter of the mortar mass, measured on at least four diameters at approximately equal spaced intervals, expressed as a percentage of the original base diameter.

e) The mortar used in the flow test shall not be used neither in the strength test nor in the next trial of the flow test[26].

### **3.4.3 Curing procedure**

Curing of all specimens was carried out in accordance with ASTM C192/C M-02 (2004)[27]: after placement, these specimens covered with a plastic sheet and kept in their plastic for 24 hours. The specimens were then removed from their molds and moved to water bath, which was maintained at 100 percent relative humidity until the time of testing. Continuous curing in fresh water was contained for 28 days.

## **3.5 Mechanical Properties Testing**

Unreinforced cement is a brittle material, but reinforcement of cement with fibers will create a material with higher compressive, tensile, flexural and shear strength properties. The random distribution of short fibers may contribute to the load transferring mechanism through shear stresses at the fiber-hardened cement part matrix interface. For a given mixture, the fiber volume fraction, fiber geometry, and fiber distributions have considerable effect on the mechanical properties of FRCC [28-30].

This section describes the mechanical properties of FRCC designed to evaluate effects of fiber and fiber type on mechanical properties of FRCC. Three different mechanical tests were performed to investigate the physical differences between unreinforced cement and FRCC: compression (ASTM C109), splitting tension (ASTM C496-01)[31], direct tensile (ASTM:CRD-C260-01)[32], and flexural performance of FRCC (ASTM C 1609)[33].

### **3.5.1 Compressive strength testing**

Compressive strength testing in accordance with ASTM C109 was performed after 28 days of curing time as show in Figure 3.3 The load was applied at stress rate until failure of the specimen. The ultimate compressive strength was calculated by dividing the maximum load by the average cross-sectional area as shown by the following equation:

$$f_c = 4P/(\pi.D^2)$$

Where

$f_c$  = ultimate compressive strength of cylinder, in ksc.

$P$  = ultimate compressive axial load applied to cylinder, in kg.

$D$  = diameter of cylinder specimen, in cm.

The average values of compressive strength from three cylinders were taken as the compressive strength of the concrete.



Figure 3.3 Test setup for compressive strength

### 3.5.2 Splitting tensile testing

Three standard cylindrical test specimens were prepared to determine the splitting strengths at 28 days. This was obtained directly from the load recorded by using a 50 ton capacity UTM testing machine. The setup for the splitting tensile test is shown in Figure 3.4.



Figure 3.4 Test setup for splitting tensile test

Before testing, the diameter and length of the each test specimen were determined to nearest 0.01 cm. by averaging three diameters measured near the ends and the middle of the specimen and two lengths of the specimen on the two ends. The splitting tensile testing was performed in accordance with the ASTM C 496-01. The load was applied continuously and without shock, at a constant rate until failure of the specimen. The maximum applied load indicated by the testing machine at failure was recorded. The splitting tensile strength was computed as follows:

$$f_{st} = \frac{2P}{\pi.L.D}$$

Where

$f_{st}$  = splitting tensile strength, in ksc.

P = maximum applied load applied to cylinder, in kg.

D = diameter of cylinder specimen, in cm.

L = length of cylinder specimen, in cm.

### 3.5.3 Direct tensile testing

The test method specified in ASTM:CRD-C260-01 determined the tensile strength of cement mortar with a certain mix proportion by the use of briquette specimens. This method allows for the determination of tensile strength of a hydraulic cement mortar by casting and testing briquet specimens. It is recommended that the tester be familiar with this method in order to obtain the best possible accuracy. The minimum tensile strength values which were stated limits in ASTM Specification : CRD-C260-01 for portland cement are shown in the following Table 3.5.

**Table 3.5** The minimum tensile strength values

Curing condition	Cement type	
	ASTM Type I	ASTM Type III
1 day in moist air, psi (ksc)	NA.	275 (19.4)
1 day in moist air, 2 days in water, psi (ksc)	150 (10.6)	375 (26.4)
1 day in moist air, 6 days in water, psi (ksc)	275 (19.4)	NA.
1 day in moist air, 27 days in water, psi (ksc)	350 (24.7)	NA

At the time of testing (age of 3, 7 and 28 days), wipe each sample to a surface-dry condition and remove any loose sand grains or incrustation from the

surface. Carefully center the briquet in the clips and apply the load continuously at the rate of  $270 \pm 10$  kg/min. The tensile strength can be calculated from the maximum load and the cross-sectional area at failure of the specimen



Figure 3.5 Test setup for direct tensile test

#### 3.5.4 Flexural performance testing

The test method specified in ASTM Specification : C 1609 evaluated the flexural performance of fiber reinforced cement using parameters derived from the load-deflection curve obtained by testing a simply supported beam under third-point loading as shown in Figure 3.6.



Figure 3.6 Test setup for measuring flexural strength of FRCC

The test specimens after environmental conditioning were turned on their side respect to the position as cast when placing on the support system. The load was applied at the rate of increase of net deflection within the range 0.05 to 0.1 mm/min until a net deflection of  $L/600$  was reached. After that, the rate of increase of net

deflection was within the range 0.05 to 0.2 mm/min until reaching net deflection of  $L/150$ . Test results were discarded when the crack initiated outside of the middle third of the span. The first peak load was the value of load corresponding to the first points on the load-deflection curve where the slope is zero was determined as well the corresponding deflection value at that point. The first peak strength ( $f_b$ ) using the first peak load ( $P_b$ ) was calculated by following formula for modulus of rupture

$$f_b = PL/(B.D^2)$$

Where

$f_b$  = Flexural strength, ksc.

$P$  = maximum applied load applied to specimen, kg.

$L$  = the span length, cm.

$B$  = the average width of the specimen, cm.

$D$  = the average depth of the specimen, cm.

### 3.5.5 Toughness determination

Within concrete materials characterization testing, toughness is a term that provides some indication of the concrete energy absorption capability. Usually, toughness is quantified in terms of the area under a load–deflection response curve.

Toughness values are specific to the testing procedure implemented. The ASTM C1018 test method presents one means of determining the toughness of fiber reinforced mortar. The test results are analyzed in terms of the area under the load–deflection curve up to specific deflection levels. The toughness results are then normalized by dividing the total area under the curve up to the specified deflection by the area under the curve up to the deflection at first cracking.

ASTM C1018 defines a set of toughness indices in terms of the behavior that might be expected from a material that exhibits an elastic–inelastic, flexural, load–deflection response. The points that limit the areas are defined as multiples of first cracking ( $\delta$ ) deflection, as shown in Figure 3.7.

The  $I_5$  index corresponds to the ratio between OACD area and OAB area, and the point D corresponds to a deflection equivalent to three times the first

deflection ( $\delta$ ). The  $I_{10}$  index corresponds to the ratio between OAEF area and OAB area, and the point F is equivalent to a  $5.5 \times \delta$ . Finally, the  $I_{30}$  index corresponds to the ratio between OAGH area and OAB area, and the point H corresponds to the deflection of  $15.5 \times \delta$ . ASTM C 1018 recommends that the end point of the deflection and its index are selected to reflect the level of cracking and deflection required in service.

Obtaining index values of toughness on the order of 5 to  $I_5$ , and 10 to  $I_{10}$ , and so on, indicate that the composite has perfect elasto-plastic behaviour. Values are dimensionless and provide a reference to the proximity of the material behavior in relation to an idealized elasto-plastic material. These indices have the advantage of presenting an evaluation of the behaviour of the fibre/matrix (composite). From the results obtained for the toughness indices ( $I_5$ ,  $I_{10}$ ,  $I_{20}$ ,  $I_{30}$ ) is possible to determine the relationship of toughness as shown by ASTM C1018, according to formular below.

The residual strength index represents approximately the ratio between the resistance capacity on the deflection range between the displacements of the index  $I_a$  and  $I_b$ , in relation to index corresponding to the first crack. For example, a perfect elasto-plastic material, always present a residual strength index about 100.

$$R_{a,b} = (100 / b-a) \times (I_b - I_a)$$

where

$R_{a,b}$  is the residual strength index between the reference indices “a” and “b” and  $I_a$  and  $I_b$  is the toughness indices with references “a” and “b”.

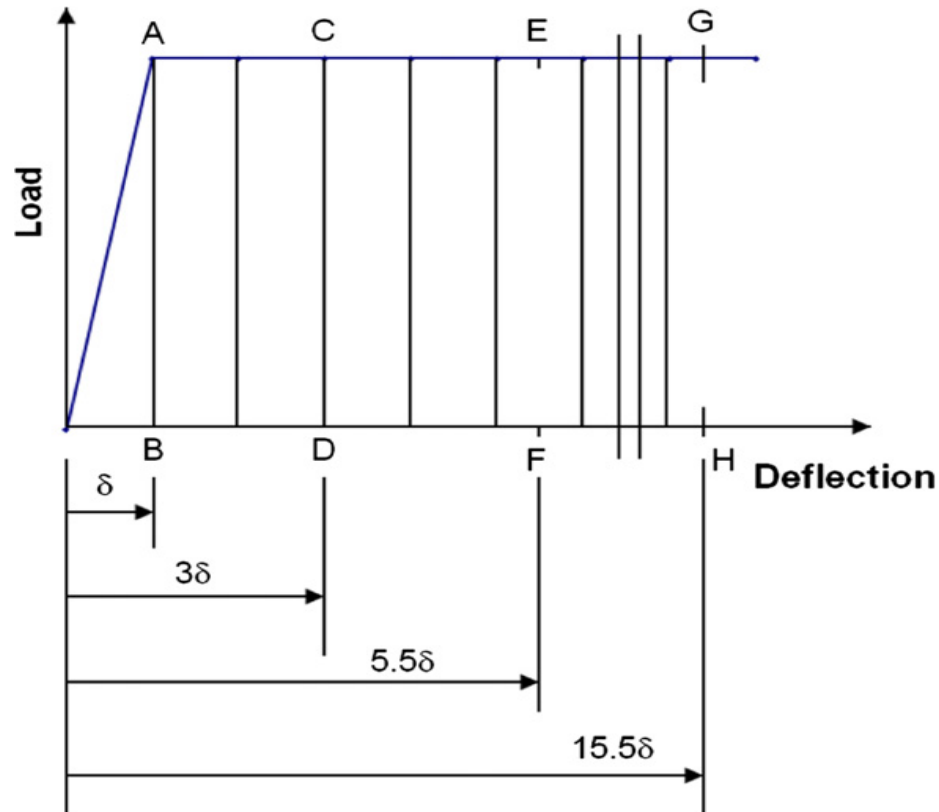


Figure 3.7 Load–deflection curve (ASTM C 1018)[34].

### 3.6 Standard Test Method for Static Modulus of Elasticity [35]

ASTM C 469, the “Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression,” describes modulus of elasticity as a stress to strain ratio value for hardened concrete at whatever age and curing condition that may be designated. This Standard also states that the modulus of elasticity is applicable with the customary working stress range of 0 to 40% of the ultimate concrete strength. the modulus was calculated from the following equation:

$$E=(S_2-S_1)/(\epsilon_2-0.000050)$$

Where : E=chord modulus of elasticity (in psi) S<sub>2</sub>=stress corresponding to 40% of the ultimate load of the concrete (in psi) S<sub>1</sub>=stress corresponding to a longitudinal strain of  $\epsilon_1$  at 50 millionths (in psi)  $\epsilon_2$ =longitudinal strain produced by S<sub>2</sub>

### 3.7 Scanning Electron Microscope (SEM)

**The Jeol JEM 5410 LV** Scanning Electron microscope, facilitates three-dimensional imaging of a specimen's surface with high resolution and impressive depth-of field.

**Imaging by SEM.** The scanning electron microscope generates an image of the sample surface by probing it with a high-energy beam of electrons. These 'primary' electrons hit the sample and eject secondary electrons. The SEM's primary imaging method is based on this secondary electron emission. These electrons are focused on a scintillation material which generates a flash of light whenever hit by an electron. The light flashes are then detected and amplified by a photomultiplier tube.

**Resolution and magnification.** The wavelength of light rays is the limiting factor in microscopy. A light microscope which uses wavelengths between 400 to 700 nm can distinguish between two adjacent objects separated by ~ 200 nm, and is limited to about 1000-fold magnifications. In contrast, the SEM which uses high energy electrons as its source of 'illumination' with wavelengths of about 0.01 nm is capable of up to 1 million-fold magnifications. Our 5410 SEM is usually used at magnifications between 20 and 35,000 X and can resolve two objects 3.5 nm apart, when operated at 35,000 kV.

**Sample Preparation.** Air molecules block and scatter the stream of electrons aimed at the sample. Samples are usually fixed at low temperatures in special fixatives, in order to preserve the morphology and structural integrity of the specimen. The preserved specimen is next sputter-coated with gold, in order to give it the electrical conductivity required for imaging by SEM.

## CHAPTER IV

### RESULTS AND DISCUSSIONS

This chapter describes and discuss test results of laboratory investigations of mechanical properties and the efficiency of HDPE fiber reinforced.

#### 4.1 Part I: Mechanical behaviors of HDPE fiber reinforced cement mortar

##### 4.1.1 Workability

The workability of the fresh mixtures was determined from the flow measurements. ASTM C 230/ C230M - 08, the standard test method for flow of hydraulic-cement mortar, determines how much a mortar sample flows when it is unconfined and consolidated. The flow table test result for workability is shown in Table 4.1. The water/cement ratio (w/c) refers to 0.7. The result was recommended that workability of samples were decreased according to percent volume of fiber added.

After hardening of the cement mortar, the specimen was cut cross the section area in order to observe the distribution of fibers in each mixture as showed in Figure 4.1. As expected, high strength HDPE fiber D10, D25, and D35 dispersed throughout the area of cement mortar follow on the percent volume of fiber 0.5, 1.0, and 1.5 respectively.

**Table 4.1** Flow ability Test results

Volume Fraction (%)	Flow able (%)		
	W/C(0.6)	W/C(0.7)	W/C(0.8)
<b>Normal mortar</b>			
<b>0%</b>	109	114	116
<b>Add. Fibers</b>	<b>D10</b>	<b>D25</b>	<b>D35</b>
<b>0.50%</b>	112	110	109
<b>1.00%</b>	109	108	107
<b>1.50%</b>	106	105	105

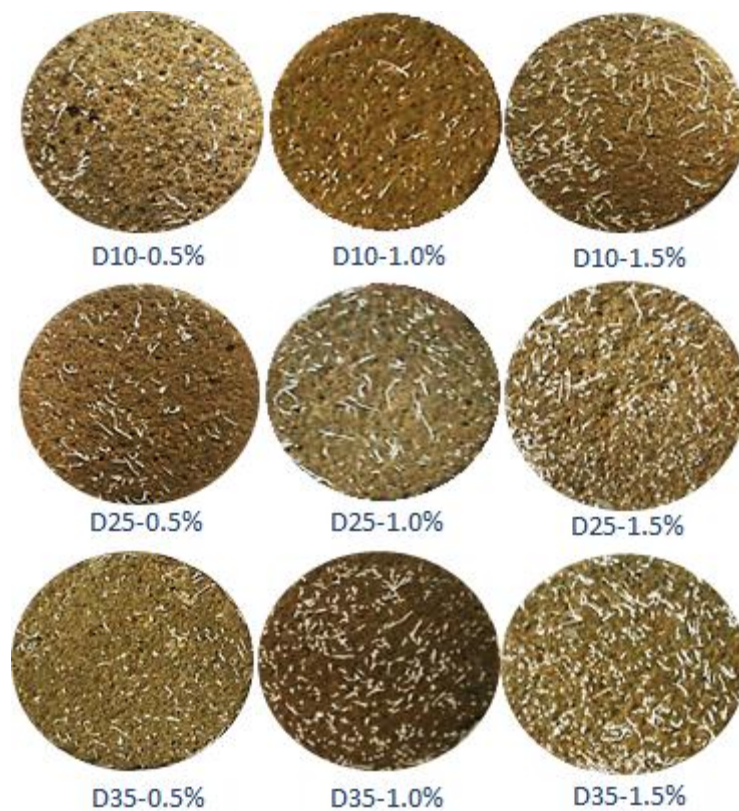


Figure 4.1 Distribution of fiber reinforced mortar

#### 4.1.2 Mortar density

The hardened mortars density results presented in Table 4.2, For the Figure 4.2 shows that the fibers addition causes a tiny decrease in density. Overall percentage difference in the reduction of the average density is very minimal. This is because the difference is only in the range of 0.5%-1.5% for fiber added specimens. Whereas the density of HDPE fiber reinforced mortars are around  $1.983\text{-}2.005\text{ g/m}^3$ . It can be concluded that the HDPE fibers incorporation, used in this study, do not affected the density of hardened mortar.

**Table 4.2.** Density, Flow ability, and Compressive strength of HDPE fiber reinforced cement mortar.

	Volume fraction	Plain mortar	SD	D10	SD	D25	SD	D35	SD
<b>Density (g/m<sup>3</sup>)</b>	v 0%	2.052	0.02						
	v 0.5%			1.983	0.016	1.992	0.003	2	0.006
	v 1.0%			1.987	0.030	1.999	0.011	1.999	0.007
	v 1.5%			1.992	0.006	2.004	0.009	2.005	0.008
<b>Compressive Strength (MPa.)</b>	v 0%	21.98	0.94						
	v 0.5%			21.24	0.27	21.6	0.31	21.39	0.3
	v 1.0%			21.77	0.38	22.2	0.51	21.93	0.6
	v 1.5%			22.37	0.33	22	0.27	21.67	0.38

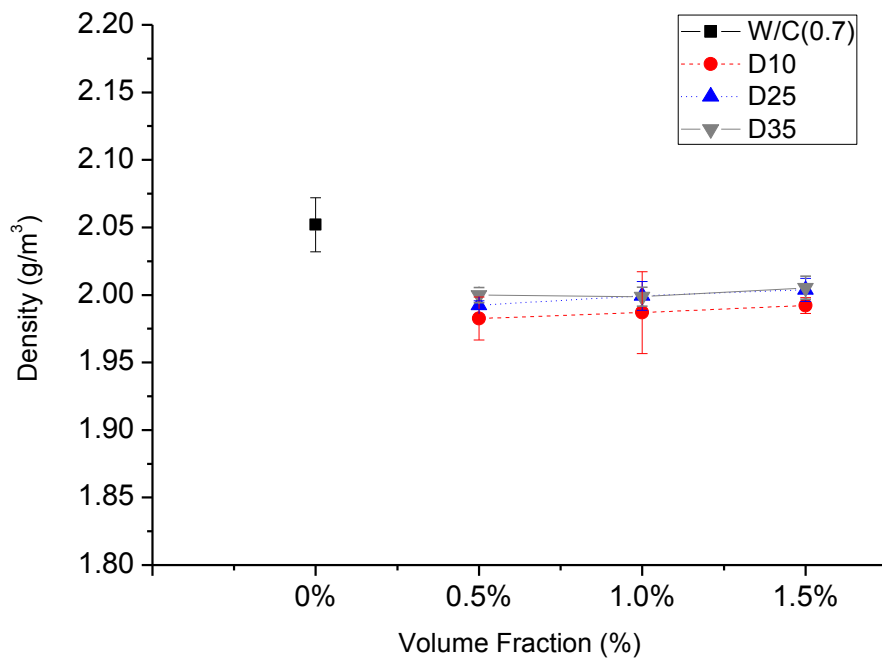


Figure 4.2 Density of fiber reinforced mortar

### 4.1.3 Compressive strength

The results of compressive strength indicate that the fibers incorporation does not effectively change the magnitude of the mortar compressive strength. The results for compression test are show in Table 4.2 and Figure 4.3. As expected, the compressive strength of the cement mortar without fibers was 21.98 MPa. at 28 days. Fibers in this experiment not assist too much in compressive strength. The strength is affected to a much lesser degree by the present of fibers. One of the objectives of adding fiber in mortar is to control cracking and the mode of failure by means of post cracking ductility. However, these cracks do not have much effect on the compressive strength.

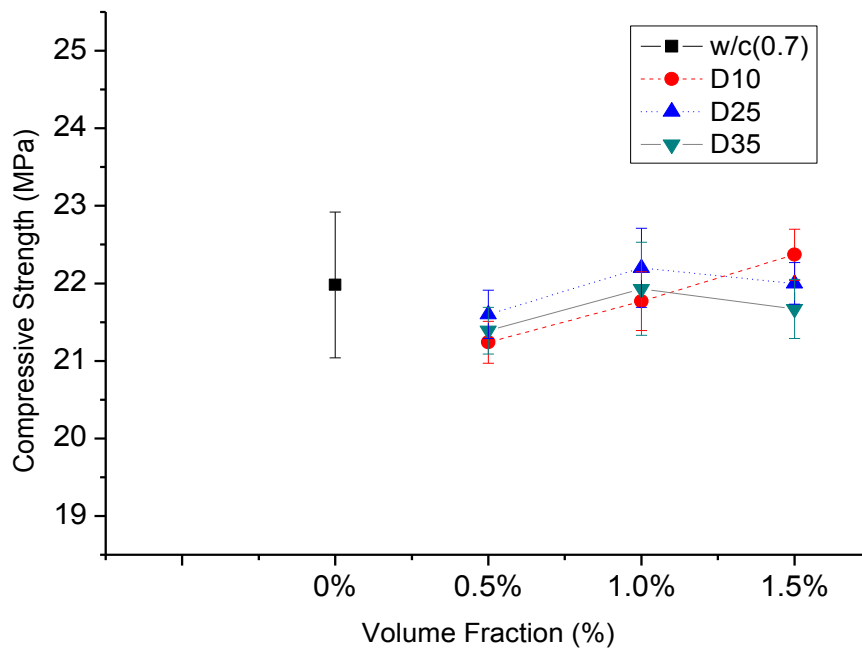


Figure 4.3 Compressive strength of fiber reinforced mortar

### 4.1.4 Tensile strength

The values both of the splitting tensile strength and direct tensile strength are presented in Figure 4.4. The addition of high strength HDPE fibers showed the improvement of tensile strength for all samples. The maximum values were obtained for cement mortar which contained 1.5% of HDPE fiber D25 by volume. In this case, the splitting tensile strength (3.29 MPa.) was about 1.5 times higher than the normal cement mortar: w/c=0.7(2.02 MPa.). Tensile strength is improved with the inclusion of discontinuous fibers in cement matrix. The improvement is due to the presence of fibers.

Although the direct tensile test results have a similar trend in comparison with the splitting tensile strength test results, the behaviours in reinforced of fiber compared to normal cement mortar was greater than for splitting tensile approach. The greatest values were obtained for cement mortar which contained 1.5% of HDPE fiber D25 by volume. In this case, the direct tensile strength (3.33 MPa.) was about 54 percent higher than the normal cement mortar: w/c=0.7(2.02 MPa.) Between different draw ratio HDPE fibers (D10, D25 and D35), the result show that mortar which is contain high draw ratio (D25 and D35) have higher strength compare with low draw ratio (D10). It is because elastic modulus of high draw ratio D25 and D35 HDPE is 24.9-34.5 GPa. higher than the fiber low draw ratio D10 HDPE (6.9 GPa.).

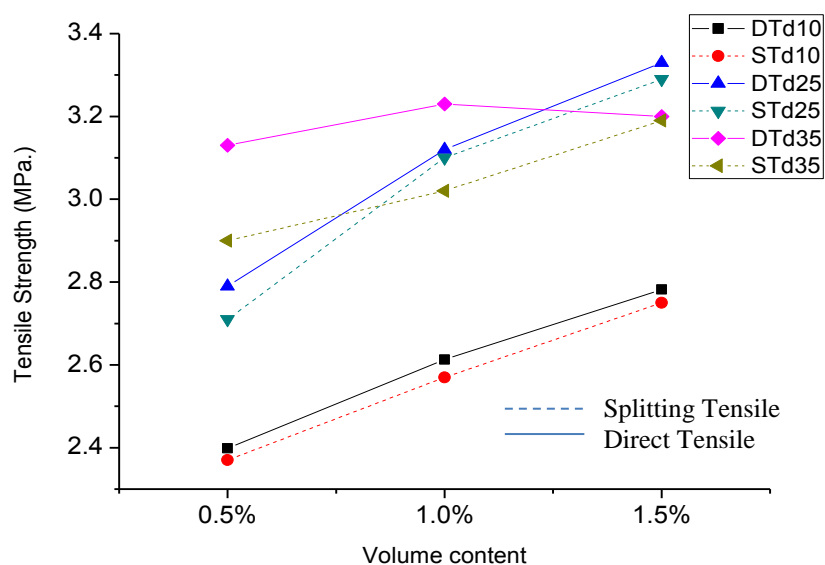


Figure 4.4 Tensile strength of HDPE fiber reinforced cement mortar

#### 4.1.5 Flexural strength

From the results, it can be concluded that flexural strength shown some different compared with plain mortar and samples with different draw ratio HDPE fibers (D10, D25 and D35). The flexural strength of fiber reinforced mortar is higher than the flexural strength of plain mortar due to the ability of the fibers to withstand stress after cracking and this fiber in samples act as reinforcement. When the contents of HDPE fiber increase from 0.5% to 1.5%, the flexural behavior is supposed to increase owing to the fact that a greater amount of fiber exists, which enables a greater capability of resisting the tensile stress, especially at the post-cracking stages. However, in the reality it depends on fiber random distribution in the tensile zone of the test samples.

According to above results, the highest flexural strength was observed in HDPE fiber D25 contained 1.5% volume fiber fraction. In Figure 4.5, the flexural strength of specimens contained 0.5% HDPE fiber does not show considerable increment. Nevertheless, in mixes contained 1% and 1.5% HDPE fibers, represent a relative increment in flexural strength. However, results of fiber reinforced specimens showed that the flexural strength in fiber reinforced mortars was slightly higher than in mortars without fibers.

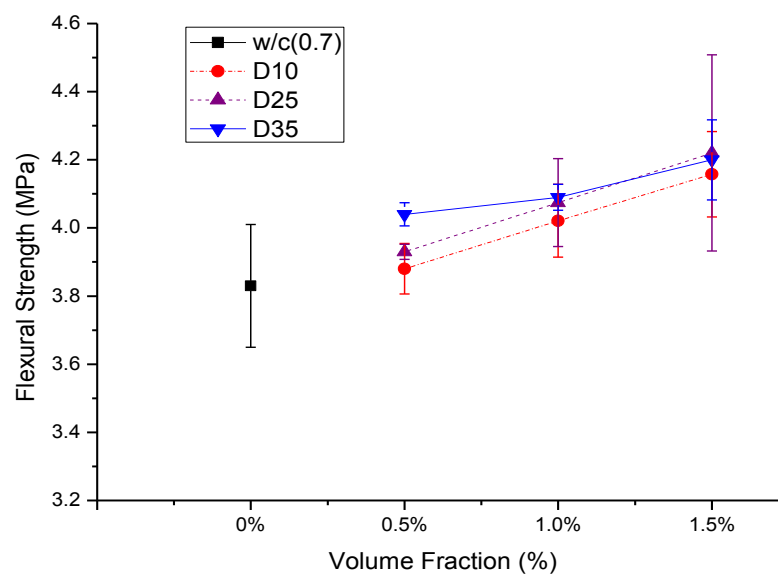


Figure 4.5 Flexural strength of HDPE fiber reinforced cement mortar

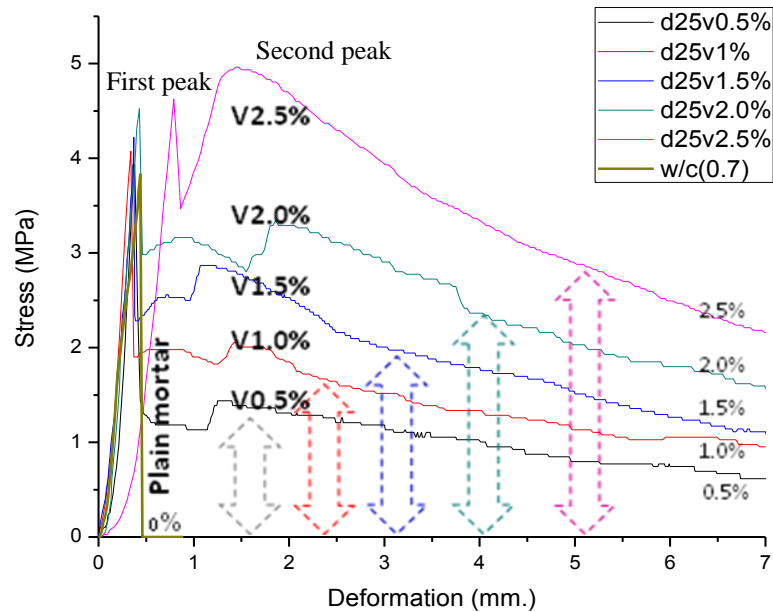


Figure 4.6 stress-deformation relationship of volume fraction HDPE fibers reinforced mortar

Figure 4.6 represents typical stress-deformation responses of plain mortar and mixtures contained 0.5%, 1%, 1.5%, 2.0% and 2.5% fibers. For plain mortar, the behaviour was in a brittle manner. When the strain energy was high enough to cause the crack to self-propagate, fracture occurred almost while the peak load was reached (this is due to the tremendous amount of energy being released). The high strength HDPE fibers contained 1.5% volume fiber bridging effect helped to control the rate of energy release significantly. Thus, fibers still can carry load even after the peak. With the effect of fibers bridging across the crack surface, fibers were able to maintain the load carrying ability even after the mortar had been cracked. Our laboratory results indicate that, by increasing the amount of fiber and increasing the high strength of HDPE fiber in matrix flexural toughness rise up.

With high draw ratio and high strength HDPE fibers like D10, D25, and D35, a noticeable drop in strength appeared after the first peak – even with a specimen with high fiber content. This was likely due to the properties of HDPE fibers which are highly flexible but having a low strength quality. Once cement matrix begins to start cracking, HDPE fibers require a large deformation to occur before the fibers are

stretched enough and begin to pick up the load. In the case of high strength HDPE fibers, the second peak response is also found in D10, D25, and D35 with 0.5%, 1% and 1.5% volume fraction fiber content. However, as the fiber content increased, the load can be increase after the first crack became small. This is because high draw ratio HDPE fibers were ultra draw ratio high strength quality, and able to carry load much higher than the low draw ratio fibers.

Normally, the second peak of load-deflection, response was used for characterizing fiber's ability to withstand load after crack. For all HDPE fibers reinforced cement mortar, the second peak load was found to increase as the fiber content increase. However, D35 at 1.5% fiber content seemed to perform better than the other fibers as seen by the higher post-peak load.

It should be noted that increasing the fibers in matrix causes low compressive strength, but it increases the flexural toughness substantially. In fact the ability for absorbing the energy rises up. In the experiment result indicated that when the amount of fiber and high strength fiber are develop in matrix, there are possible to increase the flexural toughness.

In Figure 4.7 explain the behaviour cracking in different volume fiber contained in cement mortar. The volume friction fibers have effect on the behavior mechanical cracking of cement mortar. The microstructure of cement mortar at the interface between the fiber and matrix is the most important region influencing the fibers effectiveness. They can improve the flexural toughness and tensile strength by increasing the amount of fiber in matrix of specimens.



Figure 4.7 Microstructure of bending fracture for different volume fraction fibers ratio

#### 4.1.6 Toughness and Residual strength

Toughness indices  $I_5$ ,  $I_{10}$ ,  $I_{20}$ , residual strength factors  $R_{5,10}$ ,  $R_{10,20}$  and first crack strength were obtained according to ASTM C1018 standard. Toughness indices and residual strength factor results from the three point loading tests calculation are detailed in Table 4.3. The test results showed that HDPE fibers had increased toughness indices and residual strength factors. The HDPE fibers held the cement mortar beam together under extreme deflection following the rupture plane being formed.

As expected, the behavior of fibers could increase area under curve between load and deflection while it depends on the amount of fibers and type of fibers. In critical, the fibers in the beam specimens held the cement mortar together under extreme deflection, due to the frictional bond between the matrix and the fiber in the rupture plane. It was generally accepted; the strength of the cement mortar had little effect on the failure load for the fibers, as this was attributable to the bond between the cement mortar and the fiber that broke first [Bentur et al, 1997]. The final post crack load was influenced by fiber direction, volume of fibers, fiber type and concrete type [Parviz and Lee, 1990].

These results are indicative of good performance of fiber obtained by high strength HDPE fiber and endorse the importance of further studies that may provide a performance comparison with other synthetic available fibers.

**Table 4.3** Flexural indices and Residual strength factors

Samples	Flexural indices			Residual strength factors	
	$I_5$	$I_{10}$	$I_{20}$	$R_{5,10}$	$R_{10,20}$
D10v0.5%	1.72	2.13	2.98	8.22	8.45
D10v1%	1.99	2.89	4.22	17.92	13.32
D10v1.5%	2.49	4.07	6.20	31.62	21.27
D25v0.5%	1.79	2.69	4.14	17.84	14.57
D25v1%	2.90	5.37	9.59	49.26	42.25
D25v1.5%	3.68	6.78	11.15	62.02	43.70
D35v0.5%	2.36	3.89	6.70	30.60	28.08
D35v1%	3.03	5.51	9.62	49.70	41.06
D35v1.5%	3.92	7.29	12.01	67.36	47.19

To summarize all results, the mechanical behavior in HDPE fiber reinforced in cement mortar by development high strength fiber using differently draw ratio melt splitting method can improved the mechanical properties of fibers and cement mortar. The detail results obtained in this study leads to the following primary conclusion:

- The workability determination designated by flow table test does effects the flow property by added amount of fibers
- The density of hardened mortar is not significantly altered by incorporation of HDPE fibers in the volumes and sizes here studied.
- The high strength HDPE fibers (amount volume fraction between 0.5-1.5%) do not significantly change the magnitude of the compressive strength.
- The direction and distribution of reinforce HDPE fibers are important to tensile strength behavior.
- The volume fraction fiber and high elasticity modulus of HDPE fiber can effect to flexural behavior of HDPE fiber reinforced cement mortar.
- For length 20 mm, the optimum for the best performance of the HDPE fiber reinforced cement mortar is the volume of HDPE fibers of 1.5% for D25.
- Increasing high strength and volume fractions of HDPE fibers have many valuable in toughness and residual strength behavior.

These findings are indicative of good mechanical behavior of the fibers and enable in part the HDPE fiber developing [36].

## **4.2 Part II: The Efficiency of HDPE Fiber Reinforced Cement Mortar**

In an experimental for the study of the efficiency of HDPE synthetic fiber reinforcement in cement mortar refer various factor that effect to the mechanical properties of fiber reinforced cement mortar. High density polyethylene (HDPE) grade InnePlus HD5000S from PTT chemical Public Company Limited was the fiber prepared by a Randcastle monofilament line. The properties of ultra draw high ratio HDPE fibers as show on Table 4.4.

**Table 4.4** Properties of Ultra draw high ratio HDPE fiber

HDPE	D10	D25	D35
Length(mm)	20	20	20
$\phi$ (mm)	0.202	0.172	0.148
Aspect ratio(l/d)	99	116	135
$\sigma$ (GPa)	$0.50 \pm 0.06$	$0.86 \pm 0.08$	$1.05 \pm 0.10$
$\varepsilon$ (%)	$20 \pm 0.95$	$5 \pm 0.58$	$4.5 \pm 0.60$
E (GPa)	$6.9 \pm 1.06$	$24.9 \pm 1.80$	$34.5 \pm 2.67$
Roughness, $R_a$ (nm)	$8.36 \pm 0.1$	$25.68 \pm 0.28$	$50.31 \pm 1.04$
$\tau$ (MPa)	$0.563 \pm 0.07$	$0.914 \pm 0.01$	$1.015 \pm 0.10$

In state of art report by ACI committee 544 and the other researches [37], we found that the factors influence on the stress and strain curve of the fiber reinforced cement (FRC) mortar comprising of the strength of fiber, volume fraction of the fiber, the length of fiber, and patterns of mixing the fibers. In this study, using cement mortars mixing cement/sand (1:2.75) and water/cement ratio 0.7 for plain mortar referenced.

For experimental design in this research, synthetic fibers, HDPE produced by the technique of pulling fiber high draw ratio to improve the tensile properties called high draw ratio melt spinning technique. Three majors parameters were investigated including (a) tensile strength and the elastic modulus of the fiber where the fiber with different draw ratio at 10 (d10), 25(d25) and 35(d35) will be tested (b) fiber content where percent volume fraction of the fibers will be varied from %0, 0.5 %, % 1.0, and % 1.5, and (c) the length of the fibers were varied 5, 10, 15, and 20mm. The FRC recipe will be referred to as  $d_{xx}v_{xx}l_{xx}$  where d follows by the fiber draw ratio, v follows by percent volume fraction and l follows by fiber length in millimeter, for example d25v0.5l15 is the system with fiber draw ratio 25 having a percent volume fraction of 0.5% and the fiber length of 15 mm. The effect of the fiber orientation will be investigated in order to between non-oriented and partially oriented system.

According to ASTM C 1609, the specimen samples bending tested have dimension 50x50x150 mm. The load was applied at the rate of increase of net deflection within the range 0.05 to 0.1 mm/min until a net deflection of  $L/600$  was reached. After that, the rate of increase of net deflection was within the range 0.05 to 0.2 mm/min until reaching net deflection of  $L/150$ . Test results were discarded when the crack initiated outside of the middle third of the span.

In addition, the test method specified in ASTM C260-01 determined the tensile strength of cement mortar with a certain mix proportion by the use of briquette specimens. This method allows for the determination of tensile strength of a hydraulic cement mortar by casting and testing briquet specimens. Carefully centre the briquet in the clips and apply the load continuously at the rate of  $270 \pm 10$  kg/min. The tensile strength can be calculated from the maximum load and the cross-sectional area at failure of the specimen.

The fiber used in this study is the ultra drawn HDPE which provide the tensile strength xx higher than the normal HDPE fiber. This superior mechanism was originated from the special process which the fiber was drawn at high drawn ratio. As a result, the polymeric molecule is highly oriented along the fiber direction and yields an improvement of the strength of the fiber [38]. The properties of the fiber used in this study are shown on table 4.4 and figure 4.8 presents SEM photographs of highly oriented HDPE fiber.

From experiments and tested results. The variable factors affecting the fiber reinforced cement mortar found that to compare with plain mortar, several variables can effected on the tensile stress and toughness of materials.

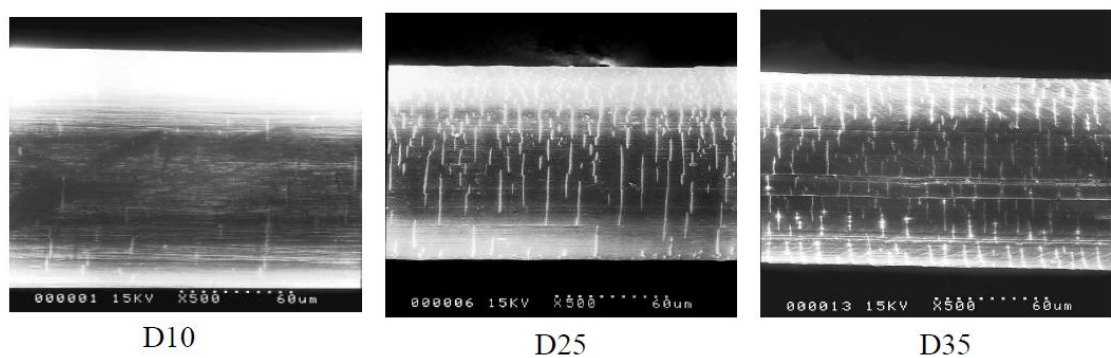


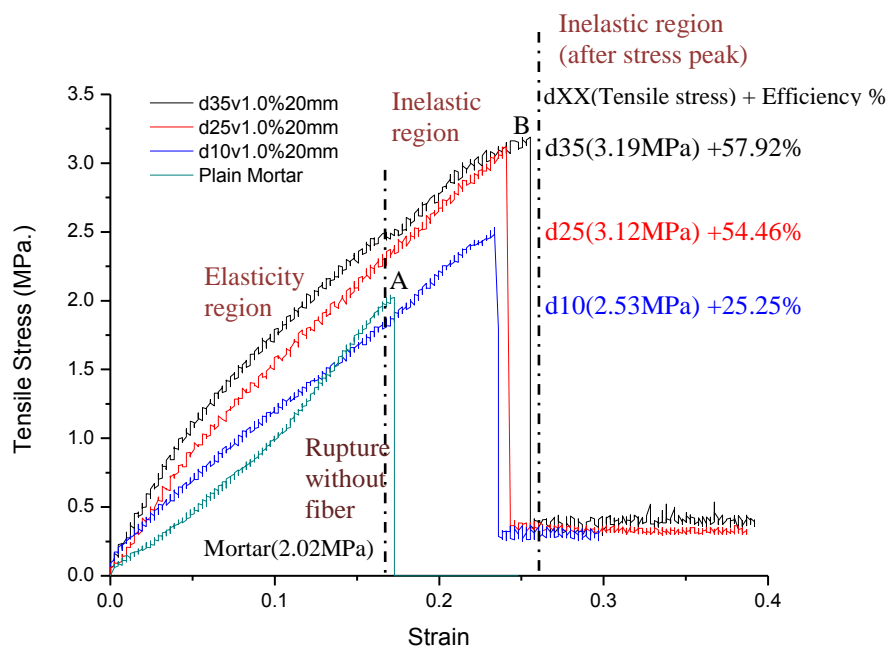
Figure 4.8 SEM photographs of highly oriented HDPE fibers with different draw ratios.

### 4.2.1 Efficiency of fiber strength

In order to investigate the effect of fiber draw ratio, all other parameters will be kept constant. The volume fraction fiber and fiber length were kept constant at 1% volume fraction and 20 mm. in length.

All cement based materials (without the fiber reinforced) contain pores and micro-cracks even in their virgin, unstressed state. Under applied tensile stresses, micro-cracks form at the mortar interfaces leading to the pre-peak nonlinear. The transition from linear to nonlinear response (point A figure 4.9) is primarily governed by the extent of available interfaces.

Basically, the fracture mechanics of cement mortar refer to the damage mechanics models. The interfacial micro-cracks first form between the mortar and the largest size aggregates. With a further increase in tensile stress, not only do the existing micro-crack propagate stably, but also more micro-cracks are progressively formed at interfaces between the mortar and aggregates of smaller size. As cement based materials usually contain a range of aggregate size, the process of stable micro-crack growth and formation of new micro-cracks continues under increasing tensile stress resulting the prepeak nonlinearity(stage AB in figure 4.9).



\* Efficiency calculate ( $\eta$ ) =  $[(E_{xx} - E_{mortar}) / E_{mortar}] \times 100\%$

Figure 4.9 Tensile stress-strain diagrams of fiber strength effective for tensile stress

The cement mortar reinforced with ultra draw HDPE fiber shows that the tensile strength fiber behavior can influence on the tensile strength properties of the cement mortar in term of the relationship between stress and strain as shown in figure 3. HDPE fiber d35(3.19 MPa.) shown maximum value of tensile stress reinforced in cement mortar that it's response to high strength of Ultra draw HDPE fiber on this research. According to HDPE fiber d25(3.12 MPa.) show value of tensile stress higher than HDPE fiber d10(2.53 MPa.). When compare with the plain mortar, the value of HDPE fiber can increase tensile stress follow on the high modulus properties of fiber d35(+57.92%), d25(+54.46%) and d10(+25.25%) respectively.

The result of post peak stress and the toughness and residual strength factors were show in figure 4.10. It found that high modulus in HDPE fiber can improve the post peak stress and the toughness of the materials. These behaviors refer to the theory of short fiber reinforced cement composite model. When the load is applied to the mortar, part of the load is transferred to the fiber along its surface. Because of the difference in stiffness between the fiber and the mortar, shear stress develops along the surface of the fiber. This shear stress helps to transfer some of the applied load to the fiber. If the fiber is stiffer than the cement mortar, the deformation at and around the fiber will be smaller. If the fiber modulus is less than the cement mortar modulus, then the deformation around the fiber will be higher.

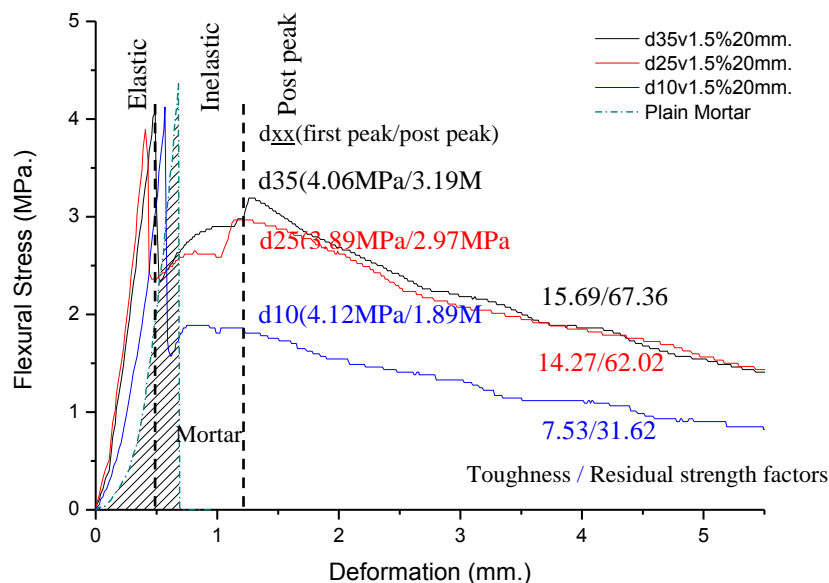


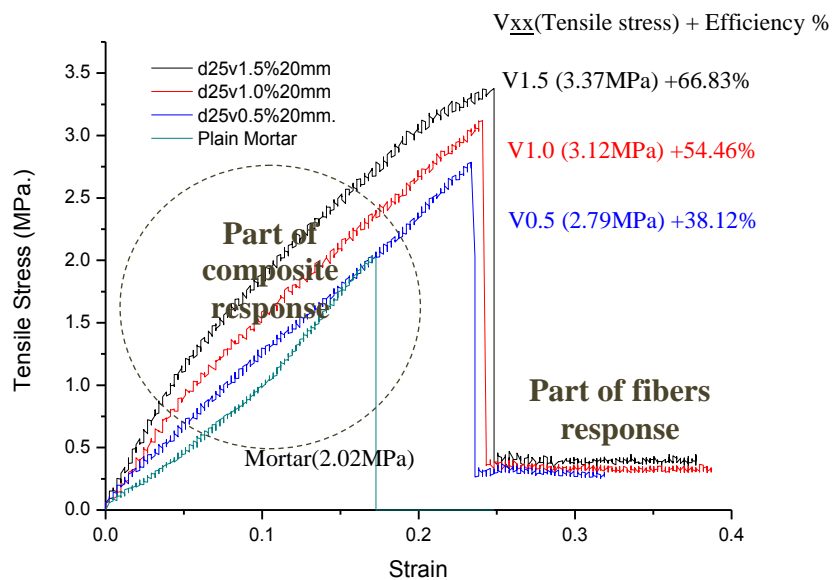
Figure 4.10 Flexural stress-deformation diagrams of fiber strength effective for the toughness

### 4.2.2 Efficiency of volume fiber

In order to investigate the effect of volume fiber fraction, all other parameters will be kept constant. The strength of fiber and fiber length were kept constant at D25 strength of fiber and 20 mm. in length.

Figure 4.11 shows the influence of the amount of fiber reinforcement in relationship between tension stress and strain. The variable of volume fibers reinforced cement mortar has tensile stress increasing depend on the volume fiber fraction. The 1.5% volume fiber of D25 HDPE fiber reinforced increase tensile stress 3.37 MPa. and improve the tensile efficiency to 66.83%. The 1.0% volume fiber increase tensile stress 3.12 MPa. and improve the tensile efficiency to 54.46%. The 0.5% volume fiber increase tensile stress 2.79 MPa. and improved the tensile efficiency to 38.12%. These results were compared with plain cement mortar has tensile stress 2.02 MPa.

For a given high modulus fiber a higher volume fraction provides more energy absorbing capacity or toughness as long as the fibers can be property mixed and the composite can be cast and compacted properly. This result should be expected because more fibres provide more resistance, especially in the tension zone.



\* Efficiency calculate ( $\eta$ ) =  $[(E_{xx} - E_{mortar}) / E_{mortar}] \times 100\%$

Figure 4.11 Tensile stress-strain diagrams of volume fiber effective for tensile stress

In figure 4.12 shows the efficiency of the volume fiber fraction in term of relationship between flexural stress and deformation. The effect of volume fiber can increase the post peak stress and improved the toughness and residual strength factors.

The relationship between flexural stress and deformation are clearly show post peak loads that increase in volume of fiber. Also the relationship of tensile stress and strain show tensile properties that increase in volume fraction of fiber reinforced is a substitution of the increasing of fiber area in the cross section of cement mortar which is decreasing. According to tensile properties of fiber reinforced materials, better compared to the tensile properties of the cement mortar was less by then. Thus the behavior both in the elastic and inelastic region of composites will improve the ductility and energy indices depend on the amount of fiber increasing.

Normally, for cement mortar, the threshold and ultimate strains were accurately measured by Kaplan[39] under several tensile loading combinations. He found that they depend on only the volume fraction of the large size of aggregate in mortar, but do not vary with other micro-structural parameters, such as the type and texture of aggregate or the water/cement ratio.

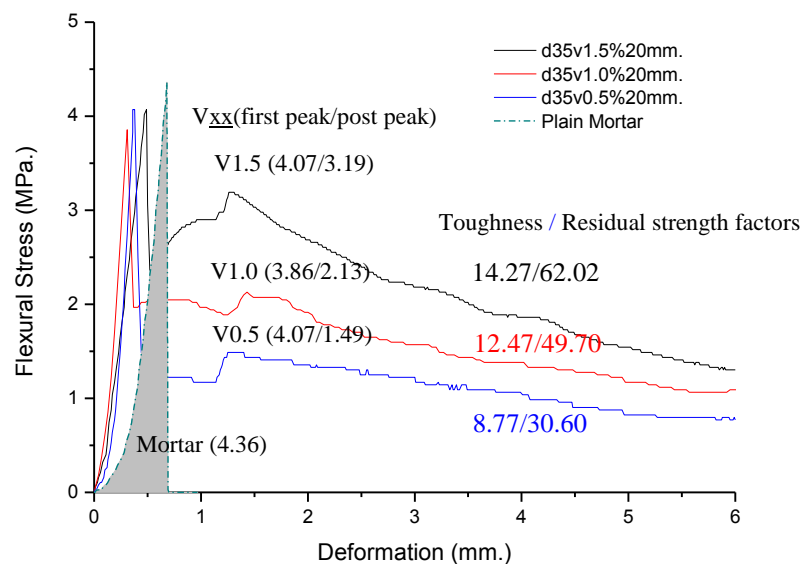


Figure 4.12 Flexural stress-deformation diagrams of volume fiber effective for the toughness

When the cement mortar composite containing the fibers is loaded in tension, at a certain stage the mortar cracks. Once the cement matrix cracks, the fiber carries the load across the crack, transmitting load from one side of the matrix to the other. In practice, several fibers will bridge the crack, transferring the load across the crack. If the fibers can transmit sufficient load across the crack, more crack will form along the length of the specimen. Amount of fiber will hold the specimen and reinforced in cement matrix.

However, in other research, the study found that the excessive fiber suitable proportions can decrease the tensile properties as well. This is probably caused by the acts of the cement less bonding with the surface.

#### **4.2.3 Efficiency of fiber length**

For investigation the effect of fiber length, all other parameters will be kept constant. The strength of fiber and volume fiber were kept constant at d35 strength of fiber and 1.0% of volume fiber. Fiber length 20, 15, 10, and 5 mm. were determined.

In figure 4.13, the relationship between flexural stress and deformation in the testing of different fiber length are distributed. The various fiber lengths in HDPE fiber reinforced cement mortar effect on the increasing of the post peak loads and deformation. The length effects of short fibers can be viewed in term of the parameter call critical length. Stress transfer from the matrix to fiber will result in shear forces at the interface between fibers and cement matrix. As the length of the fiber decrease, its efficiency in carrying loads decrease since the ends of the fiber are partially loads. The minimum length of the fiber required to achieve the full strength capacity of the fiber is referred to as the critical length.

Base on the theory of surface adhesion around the fiber throughout the length of fiber, the result show that the length of the fiber is greater than the critical length can transfer the force of adhesion in fiber reinforced cement mortar. Moreover, the experimental found that over length of fiber would effect on ball and group between the fibers and fibers during the mixing. The efficiency of the tensile stress transfer might be decreased, depending on the ball and group between the fibers

themselves while mixing. Because of the fiber surface adhesion around the axis area that is inefficient.

In this result show the efficiency of fiber length in term of the toughness and residual strength factor increasing. The fiber length 20mm. is a maximum improve in both toughness (12.47) and residual strength factor (49.70). The fiber length 15 mm. was increased both toughness (9.62) and residual strength factor (41.06) less than the fiber length 20 mm. The fiber length 10 mm. was increased both toughness (8.20) and residual strength factor (30.31). The fiber length 5 mm. is a minimum improve in both toughness (7.01) and residual strength factor (25.97).

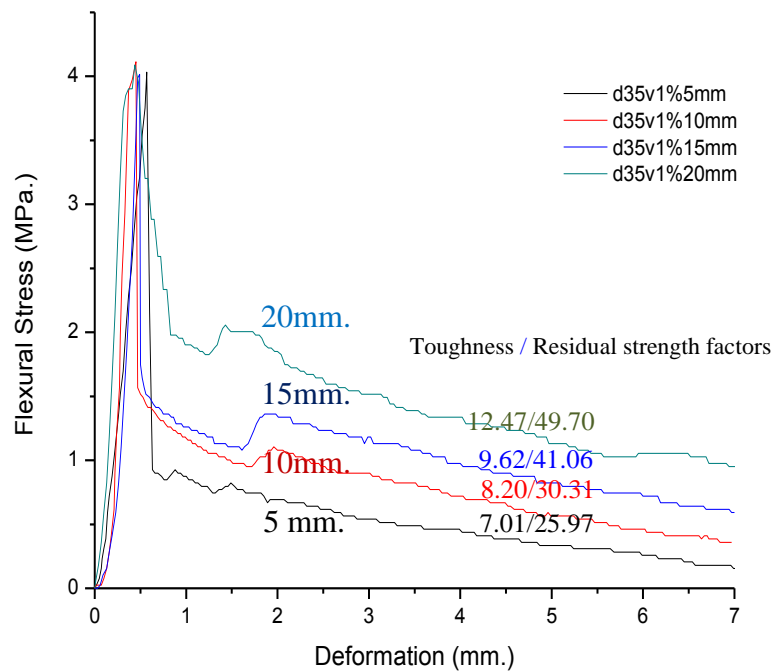
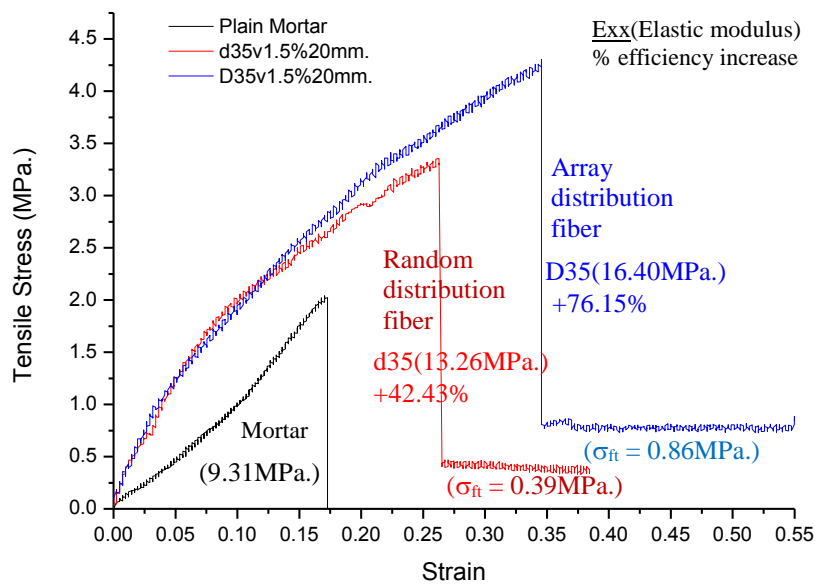


Figure 4.13 Flexural stress-deformation diagrams of fiber length effective for the toughness

#### 4.2.4 Efficiency of fiber direction

The curve relationship between tensile stress and strain in comparing of the efficiency of the array distribution fiber and random distribution are shown in figure 4.14. These results show that the pattern of fiber orientation parallel to the line of force could increase the tensile stress as well. The array direction of fiber can improve the elastic modulus (16.40 MPa.) more than the plain mortar (9.31 MPa.) 76.15%. The random distribution fiber increase the elastic modulus (13.26 MPa.) more than the plain mortar 42.43%.

In addition, the distribution of the fiber all over cross section composited could increase the properties of the force distribution and improve a lot of the tensile stress. Furthermore, the factor of the distribution fiber would depend on the amount of fiber during mixing. The use of the excessive amount of fiber would effect on the ball and group between the fibers themselves. Of course, the efficiency of the force would be decreased.



\* Efficiency calculate ( $\eta$ ) =  $[(E_{xx} - E_{mortar}) / E_{mortar}] \times 100\%$

Figure 4.14 Tensile stress-strain diagrams of volume fiber effective for elastic modulus

**Table 4.5** Summary properties of efficiency of HDPE ultra draw fiber reinforced cement mortar

	Tensile Stress (MPa.)	Elastic Modulus (GPa.)	Toughness	Residual strength factors
Stress fiber effective				
Plain mortar		9.31		
D35v1.5I20	3.19	15.96	15.69	67.36
D25v1.5I20	2.97	15.07	14.27	62.02
D10v1.5I20	1.86	9.89	7.53	31.62
Volume fiber effective				
V1.5d25I20	2.97	15.07	14.27	62.02
V1.0d25I20	1.95	14.12	12.47	49.70
V0.5d25I20	0.88	11.64	8.77	30.60
Length fiber effective				
L20v1.0d25	2.01	14.68	12.47	49.70
L15v1.0d25	1.36	14.14	9.62	41.06
L10v1.0d25	1.11	13.61	8.20	30.31
L5v1.0d25	0.82	11.71	7.01	25.97
Direction fiber effective		11.43		
DD35v1.5I20	0.86	16.40	N/A	N/A
DD35v1.0I20	0.79	14.51	N/A	N/A
DD35v0.5I20	0.67	12.19	N/A	N/A
d35v1.5I20	0.39	13.26	N/A	N/A
d35v1.0I20	0.30	13.13	N/A	N/A
d35v0.5I20	0.27	12.06	N/A	N/A

From Table 4.5, overview all of the experimental results in term of the variables that influence the performance of the ultra draw HDPE fiber reinforced cement mortar found that the efficiency of using these HDPE fiber reinforced in cement mortar can refer the relationship between stress and strain (or deformation) to the mechanical properties of tensile stress and elastic modulus and toughness index are increased in condition under tensile testing and flexural testing.

**Table 4.6** The efficiency factor for the effect of fiber orientation and fiber length follow by the formula of the modified rule of mixtures

	$\sigma_f$ (MPa.)	$V_f$ (%)	$S_f$ (MPa.)	$\sigma_m$ (MPa.)	$V_m$ (%)	$S_m$ (MPa.)	$S_c = KS_f + S_m$ (MPa.)	K
D10v0.5-0.5cm	500	0.5	2.5	2.02	99.5	2.0099	3.51	0.60
D10V0.5-1cm	500	0.5	2.5	2.02	99.5	2.0099	3.65	0.66
D10v0.5-1.5cm	500	0.5	2.5	2.02	99.5	2.0099	3.67	0.66
D10V0.5-2cm	500	0.5	2.5	2.02	99.5	2.0099	3.69	0.67
D25v0.5-0.5cm	860	0.5	4.3	2.02	99.5	2.0099	3.91	0.44
D25V0.5-1cm	860	0.5	4.3	2.02	99.5	2.0099	4.30	0.53
D25V0.5-2cm	860	0.5	4.3	2.02	99.5	2.0099	4.30	0.53
D35vf0.5-0.5cm	1050	0.5	5.25	2.02	99.5	2.0099	4.62	0.50
D35V0.5-1cm	1050	0.5	5.25	2.02	99.5	2.0099	4.81	0.53
D35V0.5-2cm	1050	0.5	5.25	2.02	99.5	2.0099	4.83	0.54
D10v1.0-2cm	500	1	5	2.02	99	1.9998	3.82	0.36
D25v1.0-2cm	860	1	8.6	2.02	99	1.9998	4.77	0.32
D35v1.0-2cm	1050	1	10.5	2.02	99	1.9998	4.91	0.28
D25v1.0-1.5cm	860	1	8.6	2.02	99	1.9998	5.09	0.36
D35v1.0-1.5cm	1050	1	10.5	2.02	99	1.9998	5.25	0.31
D25v1.0-1cm	860	1	8.6	2.02	99	1.9998	4.53	0.29
D35v1.0-1cm	1050	1	10.5	2.02	99	1.9998	5.16	0.30
D10v1.5-2cm	500	1.5	7.5	2.02	98.5	1.9897	4.25	0.30
D25v1.5-2cm	860	1.5	12.9	2.02	98.5	1.9897	5.46	0.27
D35v1.5-2cm	1050	1.5	15.75	2.02	98.5	1.9897	4.85	0.18
D25v1.5-1cm	860	1.5	12.9	2.02	98.5	1.9897	5.24	0.25
D35v1.5-1cm	1050	1.5	15.75	2.02	98.5	1.9897	5.29	0.21
D10v2.0-2cm	500	2	10	2.02	98	1.9796	4.33	0.24
D10v2.5-2cm	500	2.5	12.5	2.02	97.5	1.9695	4.44	0.20
D25v2.0-2cm	860	2	17.2	2.02	98	1.9796	5.70	0.22
D25v2.5-2cm	860	2.5	21.5	2.02	97.5	1.9695	5.80	0.18

From the table 4.6, the efficiency factor for the effect of fiber orientation and fiber length (K) have value decrease when the strength of the fiber increase and volume fraction increase and fiber length increase.

**Table 4.7** The efficiency factor for the effect of fiber orientation and fiber length follow by Curtis et al. modified the rule of mixtures

	$\sigma_f$	$V_f$	$S_f$	$V_m$	$S_m$	$S_c$	factor, $X_1$	factor, $X_2$	$S_c = X_1 X_2 V_f S_f + V_m S_m$
<b>D10v0.5-0.5cm</b>	500	0.5	2.5	99.5	2.95	3.51	0.34	0.80	3.62
<b>D10V0.5-1cm</b>	500	0.5	2.5	99.5	2.95	3.65	0.34	0.90	3.70
<b>D10v0.5-1.5cm</b>	500	0.5	2.5	99.5	2.95	3.67	0.34	0.93	3.73
<b>D10V0.5-2cm</b>	500	0.5	2.5	99.5	2.95	3.69	0.34	0.95	3.74
<b>D25v0.5-0.5cm</b>	860	0.5	4.3	99.5	2.95	3.91	0.29	0.93	4.09
<b>D25V0.5-1cm</b>	860	0.5	4.3	99.5	2.95	4.30	0.29	0.96	4.13
<b>D25V0.5-2cm</b>	860	0.5	4.3	99.5	2.95	4.30	0.29	0.98	4.16
<b>D35vf0.5-0.5cm</b>	1050	0.5	5.25	99.5	2.95	4.62	0.25	0.95	4.17
<b>D35V0.5-1cm</b>	1050	0.5	5.25	99.5	2.95	4.81	0.25	0.97	4.21
<b>D35V0.5-2cm</b>	1050	0.5	5.25	99.5	2.95	4.83	0.25	0.99	4.22
<b>D10v1.0-2cm</b>	500	1	5	99	2.93	3.82	0.22	0.95	4.00
<b>D25v1.0-2cm</b>	860	1	8.6	99	2.93	4.77	0.19	0.98	4.54
<b>D35v1.0-2cm</b>	1050	1	10.5	99	2.93	4.91	0.16	0.99	4.63
<b>D25v1.0-1.5cm</b>	860	1	8.6	99	2.93	5.09	0.19	0.98	4.53
<b>D35v1.0-1.5cm</b>	1050	1	10.5	99	2.93	5.25	0.16	0.98	4.63
<b>D25v1.0-1cm</b>	860	1	8.6	99	2.93	4.53	0.19	0.96	4.51
<b>D35v1.0-1cm</b>	1050	1	10.5	99	2.93	5.16	0.16	0.97	4.61
<b>D10v1.5-2cm</b>	500	1.5	7.5	98.5	2.92	4.25	0.22	0.95	4.51
<b>D25v1.5-2cm</b>	860	1.5	12.9	98.5	2.92	5.46	0.19	0.98	5.34
<b>D35v1.5-2cm</b>	1050	1.5	15.75	98.5	2.92	4.85	0.16	0.99	5.47
<b>D25v1.5-1cm</b>	860	1.5	12.9	98.5	2.92	5.24	0.19	0.96	5.29
<b>D35v1.5-1cm</b>	1050	1.5	15.75	98.5	2.92	5.29	0.16	0.97	5.44
<b>D10v2.0-2cm</b>	500	2	10	98	2.90	4.33	0.20	0.95	4.82
<b>D10v2.5-2cm</b>	500	2.5	12.5	97.5	2.89	4.44	0.16	0.95	4.80
<b>D25v2.0-2cm</b>	860	2	17.2	98	2.90	5.70	0.17	0.98	5.80
<b>D25v2.5-2cm</b>	860	2.5	21.5	97.5	2.89	5.80	0.14	0.98	5.79

When comparative with the factor  $X_1$  and  $X_2$  in Curtis et al. modified the rule of mixtures,  $X_1$  is 0.14 - 0.34 the value vary in term of the ultra draw ratio of

HDPE fiber, volume of fiber, and length of fiber.  $X_2$  is 0.8 - 0.99 depending on the factor effect changed.

However, these fibers efficiency of strength  $K$ ,  $X_1$ , and  $X_2$  form the both formula by Blumentritt and Cooper or by Curtis et al. are represented the efficiency of the strength of the composite that concern with the high tensile strength of fiber, volume fraction of fiber, length of fiber, distribution and direction of fiber, and the other factors.

Normally, the rule of mixtures of the fiber composite can describe to the continuous fiber length composite. In case of short fiber length composite, the formula rule of mixtures cannot explained the effect of behavior HDPE fiber reinforced cement mortar. Because theirs have many factor effect to the efficiency of strength composite. There for, in case of short fiber reinforced composite cannot use theory fiber reinforced composite (rule of mixture) to explain the  $K$  value constant.

#### **4.2.5 The behavior of HDPE fiber reinforced cement mortar**

The relative stress-strain curves in tension for a high modulus fiber and a plain cement mortar are shown in figure 4.15. In case of the basic synthetic fiber reinforced, the cement matrix will fracture long before the fiber reaches its tensile strength since the fracture strain for the cement matrix is very low compared to the fracture strain of fiber. Once the cement matrix cracks, further behavior of the composite could be following on this.

In case of conventional polymer synthetic fiber (as d10), after the cement matrix cracks, the load carrying capacity could drop but the composite could continue to resist loads that are lower than the peak load. When the cement matrix cracks, the load is transferred from the composite (matrix plus fibers) to the fibers at the crack interface. Hence, further load carrying comes from the fibers transferring the load across the crack. As the deformation increase, fibers pull out of the cement matrix, resulting in lower and lower load carrying capacity. This type of composite does not provide an increase in strength (over the matrix strength) but provides ductile behavior. The area under the stress-strain curve is an indication of the ductility or toughness of the composite.

In case of high modulus HDPE fiber reinforced, after the cement matrix cracks, the fiber will start carrying the increased loads. If there are sufficient fiber across the crack, after the load carrying capacity could drop by the cement fracture then these fibers will continue to resist higher loads than the normal polymer synthetic fiber. The stiffness of the stress-strain curve will drop because of the loss of matrix contribution. The slope of the post cracking response would depend on the high modulus of fiber, the high volume fraction of fiber and their length fibers bonding to the cement matrix. As the load increase, more cracks will form along the length of the specimen.

Moreover, the load carrying capacity could drop but the composite could continue to resist loads that are lower or higher than the peak load that depend on high modulus of fiber and high volume fraction of fiber. At the cement matrix cracks, the behavior of HDPE fiber reinforced cement mortar are similar to a normal synthetic polymer fibers but they are different in the load is transferred from the fiber is high modulus in load carrying comes from high shear stress around the roughness surface fibers transferring the load hold the crack. As the deformation more increase, fibers pull out of the cement matrix, resulting in high and higher load carrying capacity. This type of composite provides some increase in strength and provides ductile behavior. The area under the stress-strain curve is an indication of the ductility or toughness of the composite.

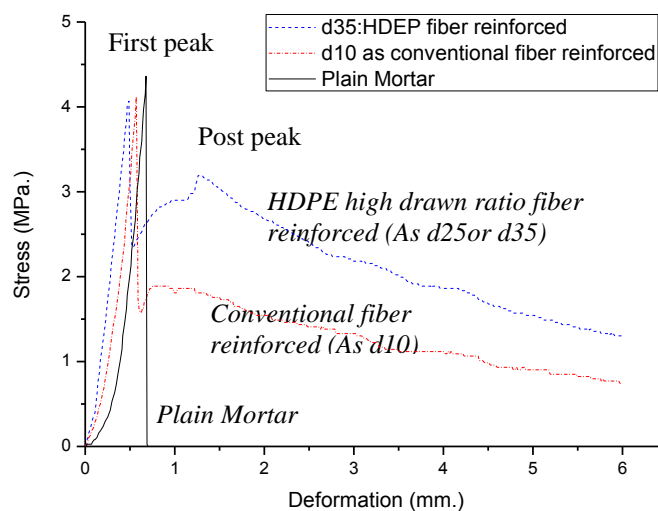


Figure 4.15 Schematic stress-strain behavior of high modulus HDPE fiber reinforced cement mortar in tension

For a given fiber direction array, longer fiber typically provide greater toughness. The effect is predominant in the case of straight smooth fibers. For a given fiber volume and length, deformed fibers provide better toughness.

According to figure 4.16, the deformation characteristics of cementitious matrices in tension are distinguished according to their postcracking deformation behavior. Plain mortar, lose their tensile load carrying capacity almost immediately after formation of the first matrix crack. The addition of fibers in conventional fiber reinforced cement can increase the toughness of cement mortar significantly, however, their tensile strength and especially strain capacity beyond first cracking are not enhanced. Therefore, the normal polymeric fiber reinforced cement is considered to be a quasi-brittle material with strain softening behavior (figure 4.16). High modulus HDPE fiber reinforced cement mortar are defined by high strength higher than the conventional polymeric fiber and the formation of multiple cracking during the inelastic deformation process (figure 4.16 (c)). In contrast to localized deformation in conventional polymeric fiber reinforced cement mortar, where the apparent cracking is single cracking (figure 4.16 (b)).

An observation of the relationship between stress and strain during condition inelasticity of each variable which influence to fiber reinforced found that high modulus of fiber reinforced and high volume fiber fiction can increase stress and strain higher, respectively. The length of the fiber can lengthen the deflection of structure is increased accordingly. The arrangement and orientation of fibers can increase tensile strength increased clearly.

Moreover, factors that influence to fiber reinforced cement mortar in each variable might effects on decreasing the capacity of fiber reinforced. In case of group and ball on each fiber which are caused by over length and over amount of fibers. Therefore, the method of mixing the synthetic fiber reinforced is a significant factor for solving these problems.

- Finally, the efficiency for using HDPE fiber reinforced cement mortar might consider with many factors (such as cost economic, time production, method for using and etc.) that influence to probability for realization. In this case, consideration of the efficiency HDPE fiber reinforced cement mortar, HDPE fiber d25 is suitable for fiber volume fraction v1.5% and fiber length 20 mm. The HDPE fiber d35 is suitable

for fiber volume fraction  $v_f 1.0\%$  and fiber length 15 mm. In case of the economic, when we consider for the factor of economic, The HDPE fiber d35 is using the amount of volume fiber less than HDPE fiber d25. In case of the production HDPE fibers, when we consider for the factor of production HDPE fibers, The HDPE fiber d25 is suitable for producing than HDPE fiber d35.

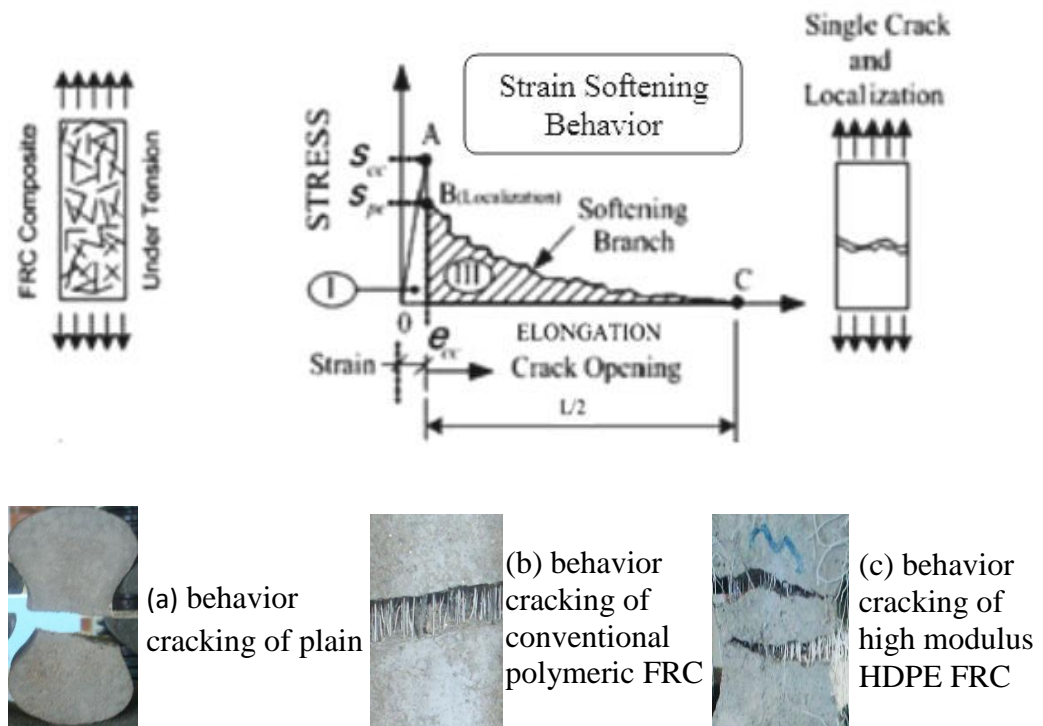


Figure 4.16 Strain softening behavior curve in tension of fiber reinforced cement composites

#### 4.2.6 Microstructure HDPE fiber bonding.

From the Figure 4.17-4.19, SEM image show bonding between the cement matrix and fibers surface each type HDPE fibers. Fiber D35 show that smaller diameter than the others and particle of cement matrix can hold around the surface. Fiber D25 show that the particle of cement matrix can hold around the surface less than the fiber D35. Fiber D10 has biggest diameter and show that the particle of cement can hold around the surface less than the others. Because of the processing of draw of the fiber change the draw ratio to high speed. The high speed draw ratio as D35 has the shape diameter smaller than the fiber D25 and D10 and the surface has

rough areas. These might be the reason to improve the strength of fiber reinforced cement mortar. These image results according with the morphology of HDPE fiber that shows rough surface depend on the high draw ratio.

The mechanism of interface failure between HDPE fibers and cement matrix was exhibited in the SEM images. The calcium silicate hydrate (CSH) was observed on the surface of fibers. The SEM micrographs of CSH show that their contact directly the surface of HDPE fiber. The adhesion between cement particle and surface fiber is a case of the interfacial failure.

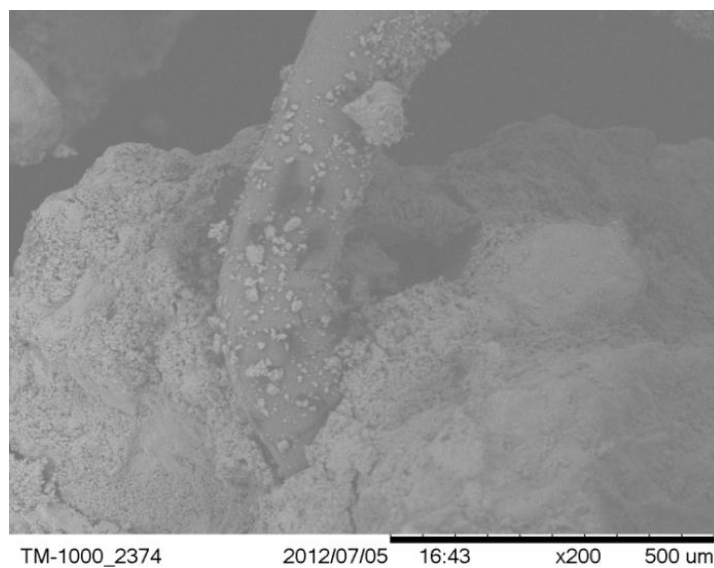


Figure 4.17 SEM. Image HDPE D35 bonding with cement mortar

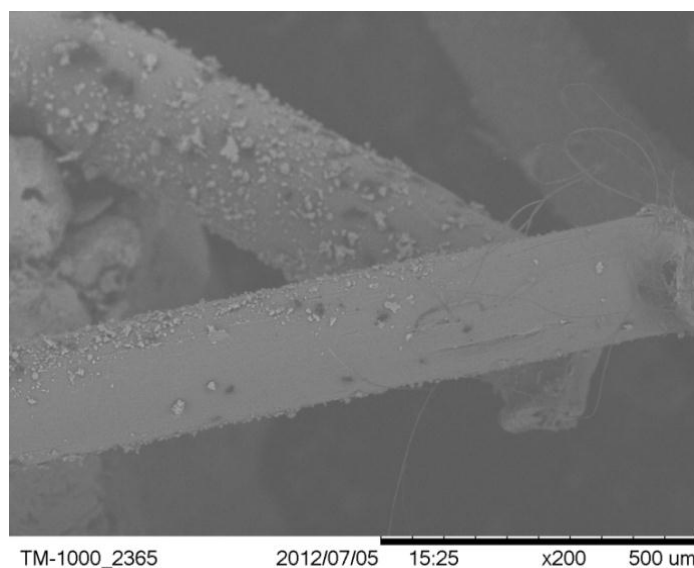


Figure 4.18 SEM. Image HDPE D25 bonding with cement mortar

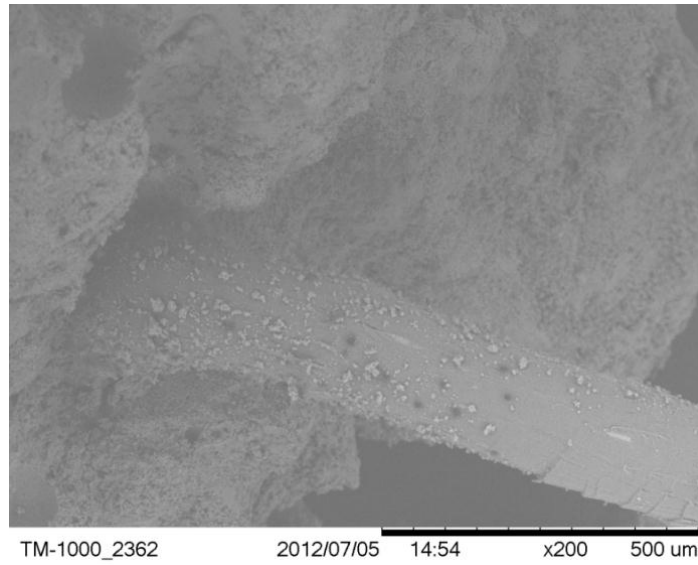


Figure 4.19 SEM. Image HDPE D10 bonding with cement mortar

## **CHAPTER V**

### **CONCLUSION AND RECOMMENDATION**

#### **5.1 General Conclusion**

The presented results undoubtedly exhibit great improvement in mechanical properties for composites type mortar made with the addition fiber-reinforcement (HDPE) in comparison to the reference cement mortar. The addition of HDPE fibers in the different types of HDPE fibers (D35, D25, D10), combined with the various volume fraction (0.5, 1.0, 1.5%), gave higher strength, both flexural and tensile. Base on the results of the part I and part II, it can be concluded that

- Mechanical properties of the cement mortar increased using HDPE fibers in all types.
- That the increase of the high strength of fiber and interface bond obtained from melt spinning process, was one of the important elements, can increases this effect in particular in tensile behavior case.

According to the objective, we developed a synthetic fiber HDPE to be used as reinforcing in cement mortar. The technique of melt spinning high draw ratio was used to process high tensile strength fiber. The efficiency of HDPE fiber reinforced cement mortar can summary:

- The development of HDPE fiber by technique melt spinning high draw ratio for using in cement mortar can improve more tensile strength and ductility. These tensile improvement are follow on high draw ratio. The fiber d35 have more maximum tensile strength than the fiber d25 and d10.
- The high tensile strength of HDPE fiber can improve the efficiency of HDPE fiber reinforced cement mortar. The HDPE fiber d35 can improve the efficiency for reinforcing in cement mortar 81.42% at volume fraction 1.0% and fiber length 15 mm. The HDPE fiber d25 can improve the efficiency for reinforcing in cement mortar 84.46% at volume fraction 1.5% and fiber length 20 mm. The HDPE

fiber d10 can improve the efficiency for reinforcing in cement mortar 44.59% at volume fraction 1.5% and fiber length 20 mm.

- The efficiency of volume fraction of HDPE fiber can increase the tensile stress and ductility. The volume fraction of HDPE fiber d35, d25, and d10 have efficiency for reinforcing in cement mortar at maximum 1.5% by weigh.
- The efficiency of HDPE fiber lengths bonding can addition the area of ductility. The fiber length 20 mm. have maximum efficiency for reinforcing in cement mortar for the HDPE fibers d25 and d10. The fiber length 15 mm. have maximum efficiency for reinforcing in cement mortar for the HDPE fibers d35.
- The efficiency of direction and distribution of HDPE fiber can reduce the problem of group and balls during the mixing and can control the forces direction to reach more tensile strength.

## 5.2 Recommendation

Recommendations can be inferred from this thesis as follow:

- In order to confirm the mechanical behaviours of HDPE fiber reinforced cement mortar, we should set up the laboratory for large scale.
- Monitoring the mechanical behaviours of HDPE fiber reinforced cement mortar, the response in tension (stress versus elongation) of a strain-softening composite always affect for using these fibers by adding more fibers.
- The processing of HDPE fibers by melt spinning technique must control the temperature and speed draw ratio during the process to get the quality of HDPE fibers.
- The scope testing of the mechanical behaviours of HDPE fiber reinforced cement mortar might be extent to unlimited volume fraction for finding the capacity of these fibers.
- The HDPE fibers for the ultra draw ratio processing d10, d25, and d35 can applied to the part of construction building such as ground floor, wall panel, and repair part for cracking reduce. These polymer fibers are better than the other polymer fiber in term of the high tensile strength.

## REFERENCES

1. J.I. Daniel, J.J. Roller and E.D. Anderson, Fiber Reinforced Concrete, Portland Cement Association, Chapter 5, 1998, pp. 22-26.
2. A. E.Naaman, Engineered Steel Fibers with Optimal Properties for Reinforcement of Cement Composites, *Journal of Advanced Concrete Technology 1*, 2003, pp. 241-252.
3. Dermnet.org.nz. Thermoforming HDPE
4. Typical Properties of Polyethylene (PE). Ides.com. Retrieved on 2011-12-30.
5. Compare Materials: HDPE and LDPE. Makeitfrom.com. Retrieved on 2011-12-30
6. Bentur, A., Mindness, S., "Fiber Reinforced Cementitious Composites", Elsevier Applied Science, 1990, pp.1-15.
7. Morton, J., Groves, G. W., "The cracking of composites consisting of discontinuous ductile fibers in a brittle matrix-effect of fiber orientation", *Journal of Materials Science*, vol.9, 1974, pp.1436
8. A. E. Naaman, Fiber Reinforced Concrete: State of Progress at the Edge of the New Millennium, *Proceedings of the ACI-KC Second International Conference*, 2007, pp.2
9. Naaman, A.E., Toughness, Ductility, Surface Energy and Deflection-Hardening FRC Composites, in Proceedings of the JCI Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC) Application and Evaluation, Japan Concrete Institute, Tokyo, Japan, October 2002, pp. 33-57.
10. Naaman, A.E., Strain Hardening and Deflection Hardening Fiber Reinforced Cement Composites, in High Performance Fiber Reinforced Cement Composites (HPFRCC-4), A.E. Naaman and H.W. Reinhardt, Editors, RILEM Publications, Pro.30, June 2003, pp. 95-113.
11. H. Rathore, Steel Fiber Reinforced Concrete: An Analysis, the Inquisitive Meridian, ISSN-2347-6257 Volume1, Dec.2013, pp.4

12. [https://en.wikipedia.org/wiki/HDPE#cite\\_note-3](https://en.wikipedia.org/wiki/HDPE#cite_note-3), Typical Properties of Polyethylene (PE). Ides.com. Retrieved on 2011, pp.12-30.
13. G. M. Barrera and R. Lo ´pez, Polym. Eng. Sci., 2005, 9,4-8
14. S. Chantrasakul and T. Amornsakchai, *High strength polyethylene fibers from high densityethylene/organoclay composites*, Polymer Engineering and Science, 04/2007, pp.943-950
15. Ramakrishnan, V., Naghabhushanam, M., Vondran, G.L., "Fatigue Strength of Polypropylene Fiber Reinforced Concretes," pp 533-543 in *Fiber Reinforced Cements and Concretes, Recent Developments.*, Edited by Swamy, R.N., Barr, B., September, 1989.
16. Reinhardt, H.W., and Naaman, A.E, "High Performance Fiber Reinforced Cement Composites: Workshop Summary, Evaluation and Recommendations", pp 551-558 in *High Performance Fiber Reinforced Cement Composites*, edited by Reinhardt, H.W., and Naaman, A.E, Proceedings of the International RILEMAC/ACI Workshop, published by E & FN SPON, June, 1991.
17. Naaman, A.E., Evaluation of steel fibers for applications in structural concrete, in *Fiber Reinforced Concretes BEFIB 2004*, Edited by M. di Prisco, R. Felicetti, and G.A. Plizzari, RILEM Proceedings PRO 39, Vol. 1, 2004, pp. 389-400.
18. Parra-Montesinos, G., High Performance Fiber Reinforced Cement Composites: an Alternative for Seismic Design of Structures, *ACI Structural Journal*, Vol. 102, No. 5, Sept.-Oct. 2005, pp. 668-675.
19. Banthia, N., Gupta R., and Mindess, S. Developing crack resistant FRC overlay materials for repair applications, *NSF Conference, Bergamo, Italy*; 2004.
20. Banthia N (2012), "FRC: Milestone in international Research and development", proceedings of FIBCON2012, ICI, Nagpur, India, February 13-14, pp 48.
21. Naaman, A.E., "Fiber Reinforcement for Concrete: Looking Back, Looking Ahead," in *Proceedings of Fifth RILEM Symposium on Fiber Reinforced Concretes (FRC), BEFIB' 2000*, Edited by P. Rossi and G. Chanvillard, September 2000, Rilem Publications, S.A.R.L., Cachan, France, pp. 65-86.
22. Naaman, A.E., "Engineered Steel Fibers with Optimal Properties for Reinforcement of Cement Composites" *Journal of Advanced Concrete Technology* Vol.1 No.3, 2003, pp.241-252.

23. American Society for Testing and Materials. *Standard Specification for Concrete Aggregates*, Active Standard ASTM C33 / C33M | Developed by Subcommittee: C09.20
- 24 T. Amornsakchai and grope. *Development of High Strength Polyethylene Fiber from Local Materials for Ballistic Applications*.
25. American Society for Testing and Materials. *Standard test method for compressive strength hydraulic cement mortars*. ASTM C 109/C109M-11a. Book of ASTM Standards. Parte 04.01. ASTM Philadelphia; 2003.
26. American Society for Testing and Materials. *Standard Specification for Flow Table for Use in Tests of Hydraulic Cement*. ASTM C230 / C230M - 08. Book of ASTM Standards. Parte 04.01. ASTM Philadelphia; 2003.
27. American Society for Testing and Materials. *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*. Active Standard ASTM C192 / C192M | Developed by Subcommittee: C09.61
28. Beaudoin, J.J. *Handbook of Fiber-Reinforced Concrete; Principles, Properties, Developments and Applications*, Noyes Publications, Inc., New jersey, 1990.
29. Bentur, A. & Mindess, S. *Fiber Reinforced Cementitious Composites*, Elsevier Applied Science, London and New York, 1990.
30. Bentur, A. and grope. *Bonding in Polypropylene Fibre Reinforced Concrete*, The International Journal of Cement Composite and Lightweight Concrete, Vol.11, No.3, 1989.
31. American Society for Testing and Materials. *Standard test method for splitting tensile strength of cylindrical concrete specimens*. ASTM C 496/C496M-02. Book of ASTM Standards. Parte 04.02. ASTM Philadelphia; 2000.
32. American Society for Testing and Materials. CRD-C 260-01 *Standard Test Method for Tensile Strength of Hydraulic Cement Mortars*. "Manual of Cement Testing," Annual Book of ASTM Standards, Vol 04.01.
33. American Society for Testing and Materials. *Standard test method for flexural performance fiber-reinforced concrete (using beam with third-point loading)*. ASTM C 1609/C1609M-10. Book of ASTM Standards. Parte 04.02. ASTM Philadelphia; 2000.

34. American Society for Testing and Materials. Standard test method for flexural strength toughness and first crack strength of fiber reinforced concrete. ASTM C 1018. Book of ASTM Standards. Parte 04.02. ASTM Philadelphia; 2000.
35. American Society for Testing and Materials. Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. Active Standard ASTM C469 / C469M, Book of Standards Volume: 04.02. Philadelphia; 2002.
36. TrithosK., TaweechaiA., and Toemsak S. (2013) *Mechanical Behaviors of HDPE Fiber Reinforced Cement Mortar*. Advanced Materials Research Vols. 671-674, pp 1893-1904.
37. ACI Committee 544, "Revision of State-of-the-Art Report (ACI 544 TR-73) on Fiber Reinforced Concrete," ACI JOURNAL, Proceedings, Nov. 1973, Vol. 70, No. 11, pp. 727-744.
38. Chaiyut N., Amornsakchai T., Thanawan S., Force volume imaging of defects in highly drawn high-density polyethylene. *Polymer testing* 2007; 26:396-401.
39. Kaplan, M.F. J. Am. Concr. Inst. 1963, 50, 853-880.