Plastic waste utilization as macro fiber in concrete

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การนำกากของเสียประเภทพลาสติกกลับมาใช้ใหม่แบบเส้นใยขนาดใหญ่ในคอนกรีต

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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การใช้พลาสติกมีการเติบโตอย่างต่อเนื่องตลอดระยะเวลาหลายปีที่ผ่านมา ผลที่ตามมาย่อมก่อให้เกิดขยะพลาสติกในปริมาณที่มหาศาล และเกิดการสะสมในสิ่งแวดล้อม เนื่องจากคุณสมบัติของพลาสติกที่ย่อยสลายไม่ได้และทนทานในสภาวะแวดล้อม ดังนั้น กระบวนการนำกลับมาใช้ใหม่จึงกลายเป็นหนึ่งในทางเลือกของการแก้ไขปัญหาขยะพลาสติกที่ยั่งยืน และช่วยลดการเสื่อมโทรมของสภาพแวดล้อม ขยะพลาสติกที่นำมาใช้ในการศึกษาครั้งนี้ ประกอบด้วย พลาสติกโพลีเอทิลีนที่มีค่าความหนาแน่นสูง (HDPE) พลาสติกโพลีเอทิลีนที่มีค่าความหนาแน่นต่ำ (LDPE) พลาสติกโพลีโพรพีลีน (PP) และโพลีเอทิลีน เทเรฟทาเลต (PET) ที่รวบรวมมาจากโรงงานอุตสาหกรรมพลาสติกและนำมาผ่านกระบวนการเพื่อกลายเป็นเส้นใยพลาสติกขนาดใหญ่และนำมาใช้เป็นส่วนประกอบในมอร์ตาร์ การศึกษาครั้งนี้คาดว่าเส้นใยพลาสติกดังกล่าวจะช่วยปรับปรุงคุณสมบัติมอร์ตาร์ให้ดีกว่าคุณสมบัติของมอร์ตาร์ทั่วไป เบื้องต้นการศึกษาครั้งนี้ได้ทำการทดสอบหาความเข้มข้นที่เหมาะสมของสารลดแรงตึงผิวแบบไม่มีประจุ (LS-12) เพื่อนำมาใช้เพิ่มการเคลือบของน้ำบนผิวของพลาสติก ผลจากการศึกษา พบว่า ที่ความเข้มข้น 10 เท่าของค่าความเข้มข้นของสารลดแรงตึงผิวรวมตัวกันเป็นไมเซลล์ (CMC) ทำให้ค่าแรงตึงผิว (interfacial tension) และค่ามุมสัมผัส (contact angle) ของน้ำลดลงมาที่ 31-32 มิลลินิวตัน/เมตร และ 65-68 องศา ถือว่าเหมาะสมต่อการนำมาใช้ในงานวิจัยต่อไป วัตถุประสงค์หลักของการศึกษา คือ การเปรียบเทียบคุณสมบัติของมอร์ตาร์ที่มีส่วนผสมของเส้นใยพลาสติกขนาดใหญ่กับคุณสมบัติของมอร์ตาร์ทั่วไป ผลการศึกษา พบว่า ค่าความพรุนของคอนกรีตมีค่าเพิ่มขึ้น ((-8%)-44%) แต่ค่าความสามารถเทได้ ((-91%)-52%) ค่าความหนาแน่นรวม ((-14.7%)-(-0.3%)) ค่าการนำความร้อน ((-31%)-(-2%)) ค่าความทนแรงดึง ((-77%)-7%) และค่าความทนแรงกด ((-79%)-(-6%)) มีค่าลดลง เมื่อเพิ่มสัดส่วนเส้นใยพลาสติกในมอร์ตาร์ ค่าการนำความร้อนที่ต่ำที่สุด (-31%) ของมอร์ตาร์ที่ผสมกับเส้นใยพลาสติก คือ ร้อยละ 30 โดยปริมาตรของ LDPE และ HDPE PP และ PET ตามลำดับ นอกจากนี้ ผลการศึกษาการสลายตัวของเส้นใยพลาสติกในของเหลวที่สภาวะด่าง (7-180 วัน) ไม่ได้ทำให้ค่าแรงดึงของพลาสติกลดลงอย่างมีนัยสำคัญ แต่การฉายรังสี UV-A สามารถลดค่าแรงดึงของพลาสติกเมื่อเพิ่มระยะเวลาสัมผัส กล่าวโดยสรุป ข้อเสนอแนะของการศึกษาวิจัยครั้งนี้ได้แนะนำปริมาณการใช้เส้นใยพลาสติกขนาดใหญ่ของ HDPE และ LDPE ร้อยละ 5 PP ร้อยละ 10 และ PET ร้อยละ 50 ในมอร์ตาร์ ซึ่งจะทำให้ค่ากำลังอัดของมอร์ตาร์ผสมเส้นใยพลาสติกขนาดใหญ่ดังกล่าวเป็นไปตามค่ามาตรฐานของแผ่นผนังคอนกรีตสำเร็จรูป

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The use of plastics has increased over the years, thus resulting in a large volume of plastic waste being generated and accumulated in the environment. Due to its non-biodegradability and persistence, recycling processes have become one of the sustainable solutions for preventing environmental deterioration. Plastic wastes, including high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), and polyethylene terephthalate (PET), were collected from industrial sector and used as additional ingredients (macro fiber) to improve mortar properties. Prior to mortar processing, an increase in wettability of plastic fibers using nonionic surfactant, Dehydol LS-12, was investigated. At the optimal concentration of 10 times of the critical micelle concentration (CMC), an interfacial tension and a contact angle were reduced to 31–32 mN/m and 65–68 degree, respectively. Properties of synthetic fiber reinforced mortar were determined and compared to those of the conventional mortar samples. Porosity was found to increase ((-8%)-44%) with higher volume fraction of plastic fibers, whereas decreases in workability ((-91%)-52%), bulk density ((-14.7%)-(-0.3%)), thermal conductivity ((-31%)-(-2%)), splitting tensile strength ((-77%)-7%), and compressive strength ((-79%)-(-6%)) were encountered. The lowest thermal conductivity (-31%) was recorded for mortar samples prepared with 30% by volume of LDPE fibers, and the rest in descending order were HDPE, PP, and PET, respectively. The degradations of plastic fibers immersed in alkaline solution (7-180 days) did not reduce their tensile strength significantly while UV-A radiation could decrease their tensile strength with increase time exposure. Furthermore, the maximal inclusions of plastic fibers were 5% for HDPE and LDPE, 10% for PP, and 50% for PET so as to satisfy the precast concrete wall requirements.

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CHAPTER 1 INTRODUCTION

1.1 Background

At present, plastic industry which is one of the Thai economic foundations plays an important role in various consumer products; for example, automobile industry, electronic appliance industry, construction industry, packaging industry and so on. The rate of plastic production is continuously rising. It is due to the fact that plastic is used as raw material in many industries such as consumer products like plastic bags, clothes, furniture, mobile phone cases, and automobile parts. Annual plastic consumption during 2012-2016 ranges from 4.6 to 5.4 million tons as shown in **Figure 1.1** [1]. According to Petroleum Institute of Thailand (PTIT) 2017, the percentage of plastic consumption classified by types includes Polyethylene (PE) 33%, Polypropylene (PP) 25%, Polyethylene terephthalate (PET) 22%, Polyvinyl chloride (PVC) 11%, Polystyrene (PS) 4%, Acrylonitrile butadiene styrene (ABS)/Styrene acrylonitrile (SAN) 4% and Expandable polystyrene (EPS) 1% [1] as shown in **Figure 1.2**.

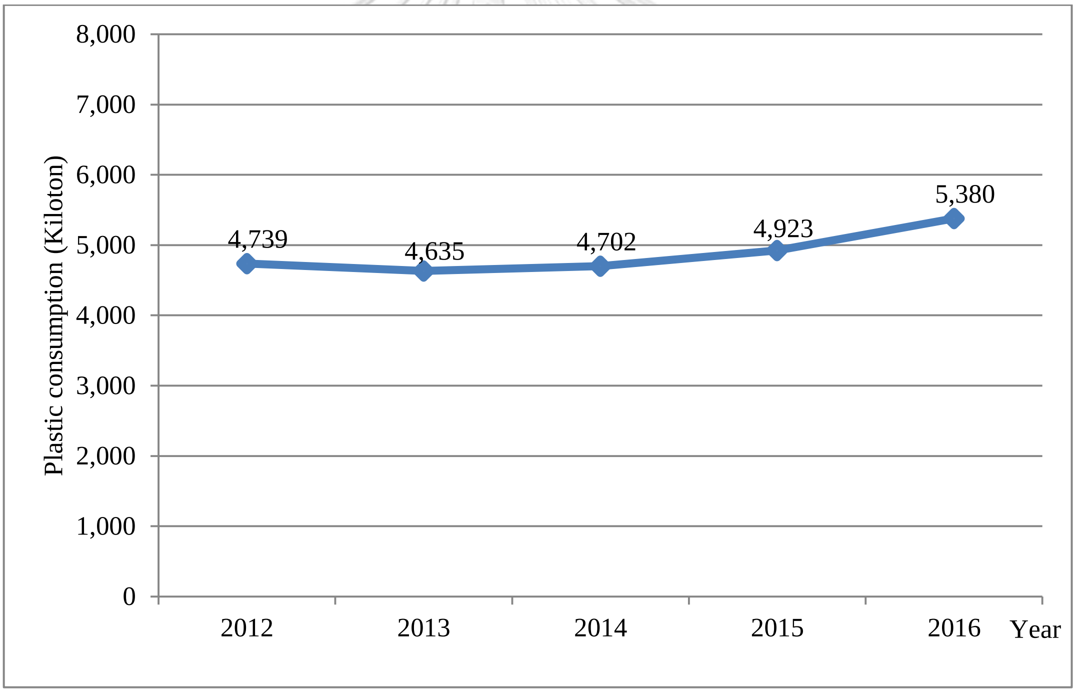

Figure 1.1 Annual plastic consumption in the period of 2012 to 2016 [1]

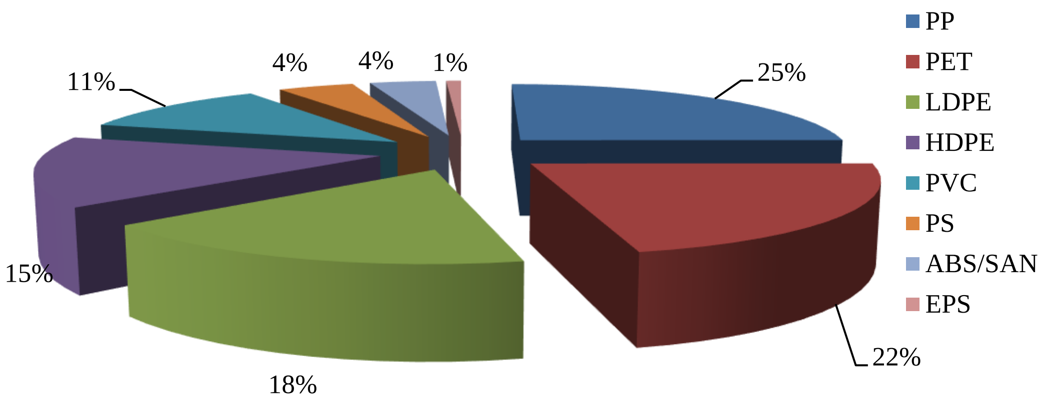

Figure 1.2 Plastic consumption classified by types in 2016 [1]

1.2 Statement of the Problem

After consumption, those plastics ended up as plastic waste. Plastic waste in Thailand is generated from various sources such as industrial and domestic sectors. Pollution Control Department of Thailand reported that plastic waste generation and plastic waste recycling in domestic sector have increased steadily. Besides, private sector, for examples from 2012-2016, information gathered from the Office of Industrial Economics, Research and Development Center for Thai Rubber Industry, Thai Rubber Research Institute, Thai Pulp and Paper Industries Association, Iron and Steel Institute of Thailand, and Federation of Thai Industries, with additional data provided by Pollution Control Department reported the amount of plastic waste recycling around 35-87%, the plastic waste left unmanaged was around 13-65% [2], as shown in **Figure 1.3** (PCD, 2014). Evidently, it is very important to find an appropriate waste management option to handle these residues.

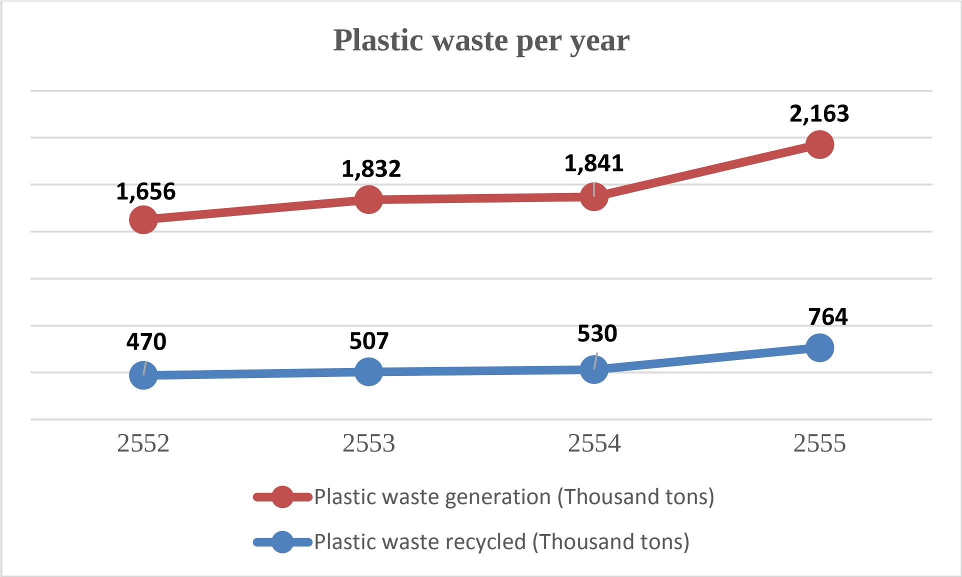

Figure 1.3 The amount of plastic waste generation and recycled plastic waste from 2009 to 2012 [2]

There are two types of plastic; namely, thermosetting plastic, which is not amenable to recycling and thermoplastic. Nowadays, waste management in Thailand comprises four options: improper municipal solid waste disposal site nationwide (2,480 sites) and proper ones (330 sites) consisting of landfill disposal (92 sites), controlled dumps (<50 tons/day) (202 sites), incinerators (19 sites), and integrated system (17 sites) [2]. Even though there are 2,810 waste treatment stations in total, the capability is still insufficient to handle the huge amount of waste generated each year as it is obvious that around 43-62% of community waste during 2008-2016 had not been managed properly. The unmanaged plastic waste then becomes pollution that subsequently produces adverse effects to human health and the environment. It can be a source of carriers for diseases, clog sewer systems, produce harmful air pollution after burning, i.e. volatile organic compounds, carbon monoxide, and greenhouse gases. There are several studies on plastic waste utilization in concrete work for example used as aggregate, polymer concrete and macro fiber. With its continuous generation and its persistence in environment, this research will focus on reusing or recycling plastic waste as macro fiber in concrete work. In addition, this should help to reduce the plastic waste and to develop the new source of concrete materials. Basically, this research also aims to develop new materials to replace natural resources like macro synthetic fibers and moreover this study tries to describe the physic-chemical effect due to characteristics of recycled plastic waste as macro fiber in concrete work.

1.3 Research objectives

1. To study the basic requirements for concrete containing plastic waste according to the American Society for Testing and Materials (ASTM) standards in order to find the best recycled plastic type applied to concrete work.
2. To study the appropriateness of material characteristics emphasis on its volume of recycled plastic used as macro fiber in concrete work safely and according to international concrete standards.

1.4 Scope of study

The substantial activities in this research are described in bullets below;

- Recycled plastics (HDPE, LDPE, PP and PET) are re-sized in new shape as macro fiber and characteristics appropriate to concrete work.
- Fresh and Hardened concretes will be tested according to ASTM standards (such as ASTM 29, ASTM 33, ASTM 39, and so on) in academic laboratory. The parameters to be mentioned include density, slump test, compressive strength, tensile strength, modulus of elasticity, surface analysis, alkalinity resistance, UV radiation effect and thermal conductivity.

1.5 Research hypotheses

1. Different types of recycled plastic applied in concrete work can affect the basic properties of fresh and hardened concrete (e.g. density, slump, compressive strength, tensile strength and modulus of elasticity).
2. UV radiation can deteriorate the strength of synthetic fiber reinforced concrete.
3. Thermal conductivity value of synthetic fiber reinforced concrete is lower than that of ordinary mortar.
4. Surfactant can help reducing interfacial tension between macro synthetic fiber and concrete matrix and can reduce its void inside, thus indirectly enhancing compressive strength.
5. Surfactant can improve the bond characteristic between concrete microstructures and recycled plastic.

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CHAPTER 2 LITERATURE REVIEW

2.1 Plastic

2.1.1 General Plastic Property

There are 2 major types of plastic including thermoplastic and thermosetting plastic;

2.1.1.1 Thermosetting Plastic

The general definition of thermosetting plastic is a complex compound or "polymeric material" that is able to be molded by heat and pressure, but the result is permanent chemical reactions that cannot be reformed by heat and pressure for further application [3]. The thermosetting plastic is normally applied in insulation, laminating process, electrical circuit, etc.; for example, Phenolic resin, Epoxy resin, Melamine resin, Urea-formaldehyde foam, etc.

2.1.1.2 Thermoplastic

General characteristics of thermoplastic are the polymer resins that can be liquidized when heated and solidified when cooled down. In case of frozen, it turns glass-like and tends to fracture. As its characteristics above, this material can be reversible that is able to be reheated, reshaped and chilled repeatedly. So, thermoplastic waste can be recyclable again.

There are several kinds of thermoplastics that can be classified in crystalline organization and density. Some types commonly produced today are polypropylene (PP), polyethylene (PE), polyethylene theraphthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), and polycarbonate (PC).

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2.1.2 Thermoplastic Types

2.1.2.1 Polyethylene (PE)

The characteristics of Polyethylene (PE) are toughness, very little moisture absorption, outstanding chemical resistance, acid-base resistance at room temperature, superior electrical insulating properties, low coefficient of friction, and easy production. PE can be classified by density including low-density polyethylene (LDPE) (0.910-0.925 g/cm^3), medium-density polyethylene (MDPE) (0.926-0.940 g/cm^3) and high-density polyethylene (HDPE) (0.941-0.965 g/cm^3) [4]. The major properties of three types are different; for example, hardness, heat resistance, chemical resistance, and load bearing. In case of high density, it can increase hardness, heat resistance, stiffness, and permeable resistance. While, low density can raise tensile strength and impact strength. PE can be applied for house wares, pipe, heater ducts, toys, automobile interior side panels, containers, wire and cable insulation, bottles, and packaging products.

• HDPE can be used for bearing light loads in short term. Even though HDPE can bear 11,000 psi at very low temperature around -40 ^{o}C, at high temperature it does not perform as well as other thermoplastics; for example, 3,700 psi (260.14 kg/cm^2) at 23 ^{o}C and 1,100 psi (77.34 kg/cm^2) at 93 ^{o}C.

• LDPE can resist operating temperature around 60-79 ^{o}C; even though, its grade can tolerate up to 93 ^{o}C. When compared to other, this material is easily bent and its stiffness modulus is about 13,000-30,000 psi (913.99-2,109.21 kg/cm^2). It has high impact strength but relatively low heat resistance.

2.1.2.2 Polypropylene (PP)

The properties of polypropylene (PP) are flexural modulus (150,000-240,000 psi (10,546.04-16,873.67 kg/cm^2)), heat resistance (66 psi at 93-121 ^{o}C), chemical resistance, less water absorption, dielectric property and easy production. Isotactic index, which is the repeated units in molecular chain of PP, increases; consequently, hardness, stiffness and tensile strength will highly increase. On the contrary, isotactic index decreases, elongation and impact strength will increase. PP can bear light load for long period and over wide temperature range. PP does not have excellent long-term creep resistance whilst fatigue tolerance limit is superior. The limitation of PP is brittle at low temperature at -20 ^{o}C. Now PP copolymer, however, can enhance the ability of brittleness of PP at -29 ^{o}C. PP can resist to water, solvent, acid, alkalis, and salt solutions. Anyway, more than 79 ^{o}C, PP can dissolve in aromatic substances i.e. toluene xylene, and chlorinated hydrocarbons (trichlorethylene). Normal application consist of radio and television cabinets, pipe and fittings, automotive interior parts, housewares, bottles, pump impellers, fibers, luggage, electrical connectors, and packaging.

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2.1.2.3 Polyethylene terephthalate (PET)

Polyethylene terephthalate (PET) is a synthetic resin made by copolymerizing ethylene glycol and terephthalic acid, widely used to make polyester fibers [5]. This is one kind of thermoplastic polymer resins of polyester family, which can be used as raw material in cloth fiber, container (drinking water bottle, medical goods, and food), etc. The characteristics of PET are highly crystal-like, melting point near 224 ^{o}C, hardness, and very toughness. Besides, PET can resist to abrasive force, be low coefficient of friction, chemical resistance, good dielectric properties, and low moisture absorption. This polyester can be extruded from plastic extruder and be injected and blown in mold [4].

2.2 Concrete

2.2.1 Cement Characteristic

Cement is ground into fine powder to react with water and produce setting and hardening, “hydration reaction”. This results in concrete strength development. Cement property is one of the major factors on mortar and concrete, so the understanding in chemical and physical properties of cement will help to prove the concrete test correctly.

Portland cement is mainly composed of Tricalciumsilicate (C_3S), Dicalciumsilicate (C_2S), Tricalciumaluminate (C_3A) and Tetracalciumaluminoferite (C_4AF). Moreover, it includes the trace compounds; for example, Gypsum, Free lime, Magnesium oxide and Alkaline oxide.

2.2.1.1 Chemical Compositions of Portland Cement

Chemical properties of Portland cement which consist of various oxides shown in **Table 2.1** including

1) Major chemicals

The major chemicals in cement include CaO, SiO_2, Al_2O_3 and Fe_2O_3, which can be estimated about 90% wt of cement.

2) Minor chemicals

The minor chemicals in cement include MgO, Na_2O, K_2O, TiO_2, P_2O_5 and gypsum.

Table 2.1 Chemical Properties in Portland Cement

Oxides	% wt
Major chemicals	
CaO	60.0-67.0
SiO_2	17.0-25.0
Al_2O_3	3.0-8.0
Fe_2O_3	0.5-6.0
Minor chemicals	
MgO	0.1-5.5
$Na_2O + K_2O$	0.5-1.3
TiO_2	0.1-0.4
P_2O_5	0.1-0.2
SO_3	1.0-3.0

Source: [6]

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All major oxides which will be mixed during clinker process can generate new four main compounds including Tricalcium Silicate (C_3S), Dicalcium Silicate (C_2S), Tricalcium Aluminate (C_3A) and Tetracalcium Aluminoferrite (C_4AF) as shown in **Table 2.2**.

Table 2.2 Main chemical compounds in Portland cement

Chemical compounds	Chemical compositions	Abbreviation
Tricalcium Silicate	$3CaO + SiO_2$	C_3S
Dicalcium Silicate	$2CaO + SiO_2$	C_2S
Tricalcium Aluminate	$3CaO + Al_2O_3$	C_3A
Tetracalcium Aluminoferrite	$4CaO + Al_2O_3 + Fe_2O_3$	C_4AF

Source: [6]

2.2.1.2 Setting and Hardening

Cement can set and harden via hydration reaction; consequently, its properties can bear load or force. Cement mixed by water will be cement paste which is plastic and workable paste in such time period. This period is called "Dormant period". Afterwards, cement will be stiff and unworkable paste which is called as "Initial set". Until this point, this period is named as "Initial setting time". Cement paste is continuously setting until it is rigid solid which is "Final set" and this time period is called as "Final setting time". The cement paste hardening still moves on until it can bear load. All process calls "Setting and Hardening" as shown in **Figure 2.1**.

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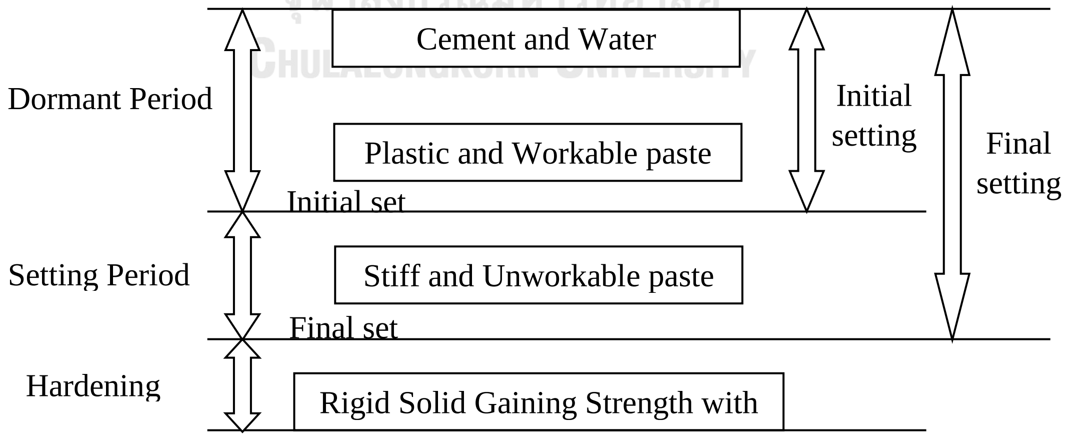

Figure 2.1 Cement paste: setting and hardening step [6]

2.2.1.3 Hydration Reaction

Setting and hardening of cement are brought forth by hydration reaction. Hydration reaction can form in 2 ways;

a. Solution phase; Cement will solute in water and generate various ions in solution. These ions will agglomerate and become new compounds.

b. Solid phase; Hydration reaction occurs on the solid surface without solution. This reaction is called as "Solid State Reaction"

Normally, hydration reaction in cement paste can be in both solution and solid phases. In early hydration reaction in cement paste depends on solution. Next time, solid state reaction becomes major reaction.

Influencing factors to hydration reaction rate which affects to hardening property of cement paste include;

- Age of cement paste

  Except for dormant period, hydration reaction rate is the highest in early period. And then it will gradually decrease until reaction is complete.

- Cement composition

  The early period is only dependent on major compounds (C_3S and C_3A) in cement. If they are compound of high proportion in cement, cement paste will react very fast. In the final period, hydration reaction of each major compound will not differ significantly.

- Cement fineness

  The fineness of cement increases; consequently, cement surface reacted with water is also more. This can increase hydration reaction rate in early period, but it does not affect significantly to hydration reaction rate in final period.

- Water cement ratio

  In early period, water cement ratio will not significantly affect to hydration reaction rate. However, in final period, if water cement ratio is less, hydration reaction rate will decrease.

- Temperature

  In early period, if temperature increases, cement paste will have high hydration reaction rate.

- Additives

  There are two types of additives, including 1) delayed hydration reaction i.e. sweet substances, Lignosulfonic acid and Sodium lignosulfonate 2) urgent hydration reaction i.e. $CaCl_2$.

2.2.1.4 Heat of Hydration

Heat of hydration is generated from hydration reaction which is reaction between cement and water. The heat value of hydration reaction is mainly affected by chemical composition of cement including C_3A and C_3S. Besides, other factors to heat values include water cement ratio, cement fineness, curing temperature, etc. (**Figure 2.2**)

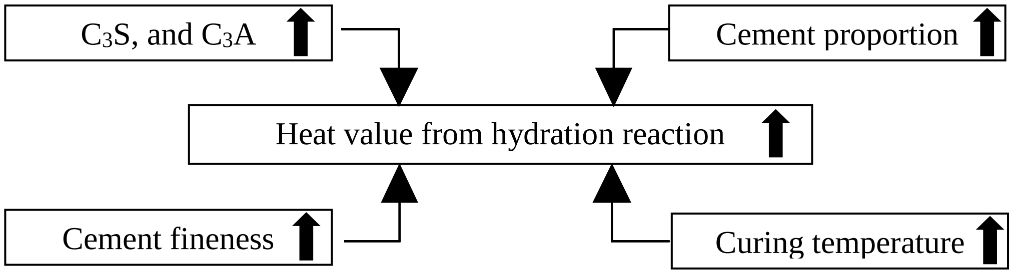

Figure 2.2 Factors to heat of hydration reaction [6]

Normally, heat of hydration reaction creates high temperature at 3 days after concrete mix and then temperature will decrease continuously.

Hydration reaction of main chemical compounds in Portland cement;

1) Calcium silicate (C_3S and C_2S)

Calcium silicate will react with water to form calcium hydroxide ($Ca(OH)_2$) 10-15% and Calcium silicate hydrate (CSH). Heat values of hydration reaction of C_3S and C_2S are approximately 500 and 250 Joule/gram.

2) Tricalciumaluminate (C_3A)

C_3A will suddenly react with water and readily form cement paste in solid phase. Generally, cement factory adds gypsum while milling clinker in order that it can delay hydration reaction of C_3A by forming Ettringite layer on C_3A. Heat value of hydration reaction of C_3A is approximately 850 Joule/gram.

3) Tetracalciumaluminoferrite (C_4AF)

C_4AF will early react with gypsum and $Ca(OH)_2$ that can form Sulphoaluminate and Sulphoferrite. C_4AF similar to C_3A can be flash set in minute. Heat value of hydration reaction of C_4AF is approximately 420 Joule/gram.

2.2.2 Concrete Characteristic

2.2.2.1 General Concrete Property

Concrete is widely used in many constructions for example building, house, road, bridge, etc. because of its property that makes it possible to be molded into various shapes. Additional properties are its durability, non-flammability, and inexpensive cost when comparing to steel. Typically concrete consists of 2 major parts; cement paste (including cement, water and additives) and aggregates (including fine aggregate (or sand) and coarse aggregate (or rock)). When all is mixed, at early period it remains plastic and can be poured in mold called as “Fresh concrete”. After that concrete will be changed with time to be hardened solid. Its strength will be increased as age until its property meets requirement that can bear load or force called as "hardened concrete".

2.2.2.2 Fresh Concrete

Fresh concrete is concrete which is just mixed and still be liquid phase a while. Afterwards, it will be proper viscosity state and be applied in mold. Good fresh concrete can be defined as following;

- Concrete uniformity

Concrete mixture including cement, sand, rock, water and some additives is well mixed and the concrete can be uniformity throughout. Concrete uniformity can affect to the strength of material after concrete hardening.

- Workability

Workability is overall energy that can overcome friction force of concrete mixture. In real concrete practice, the energy must include the friction of mold and rebar and concrete vibration, so workability is hard to measure according to definition above. Besides, workability of concrete depends on types of building; for example, high workability of concrete for foundation is not enough for reinforced concrete or thin structure. Workability test has various standards such as BS EN 12350-3, BS EN 12350-4, BS EN 12350-5, BS EN 12350-2 and ASTM C143. This study, however, will use ASTM C143 standard.

- Segregation

Segregation of concrete is less cohesion of concrete mixture that can affect to workability, concrete compact, hardening and concrete lifetime. There are 2 types of concrete segregation;

1) Coarse aggregate is separated from concrete mixture because it is heavier than other and submerges in concrete.
2) Cement paste and water is divided from concrete mixture because concrete mixture is too fluid to be molded in concrete work.

The segregation level can be observed by slump test (ASTM C143).

- Bleeding

Fresh concrete releases water while concrete setting because it is lighter than other mixtures that is called as "Bleeding". Bleeding will stop when cement paste is hardening enough for bearing heavier mixtures. Bleeding can affect to concrete as following;

1) Hardening concrete surface is easy to be loose as a flaky sheet or dust and not beautiful.
2) Capillary pores can be formed under coarse aggregates and rebar, which causes weak cohesion force between mortar and aggregates or rebar. Besides, rebar can be oxidized by oxygen.
3) Concrete cracking such as plastic shrinkage crack and plastic settlement crack.

- Setting time

Setting time is important to concrete work and framework that can be divided in 3 stages;

1) Stiffening time

After concrete mixing, this stage can be observed when concrete starts agglomerating or when mortar can resist penetration 5 kg/cm^2.

2) Initial setting time

After compacting, concrete begins hardening or when mortar can resist penetration 35 kg/cm^2.

3) Final setting time

Concrete is completely hardening and develops strength or when mortar can resist penetration 276 kg/cm^2.

2.2.2.3 Hardened Concrete

Normally, concrete can be taken off from concrete mold after 24 hours. Afterwards, concrete will be cured by water. However, the hydration reaction of 4 major compounds continues developing in concrete. 80% of hydration reaction of C_3S, C_2S, C_3A and C_4AF spends 10, 100, 6 and 50 days.

Concrete curing is to assist hydration reaction of concrete completely, which help strength and durability of concrete. Besides, curing process can reduce concrete crack by cooling and reduce water evaporation. Theoretically, concrete curing in water 28 days is found to have the highest strength at 90 days concrete age. In real practice, curing time of Portland cement type 1 is generally assigned at least 1 week.

2.2.3 Plastic Fiber in Concrete

Plastic waste is very attractive to reusing in building and construction sectors to reduce the bulky waste to landfills. Both micro synthetic fiber and macro synthetic fiber are applied in concrete because they can benefit both environmental aspect and new alternative material aspect [7, 8]. Now, fibers applied in concrete technology include 4 types i.e. steel fiber, glass fiber, natural fiber and synthetic fiber. Steel fiber is proved that it can greatly enhance tensile strength and flexural strength of concrete [9, 10]. Nevertheless, steel fiber can be corroded by oxidation reaction that can cause to deterioration of concrete strength. Glass fiber in concrete can increase compressive strength and control shrinkage cracking and improve the flexural and tensile strengths [11, 12] but glass fiber is easily deteriorated by concrete alkalinity [13]. Natural fibers i.e. wood, coconut, palm and vegetable fiber are cheap and widely available but they are very poor durability in environment. Synthetic fibers such as polyolefin, polypropylene, acrylic, etc. can tolerate in environment and reduce plastic shrinkage cracks in fresh concrete [14] and improve post-cracking behavior of concrete [15].

2.2.3.1 Plastic Shrinkage Cracking

Plastic shrinkage cracking is generally found in poor curing of Portland concrete. Shrinkage cracking behavior causes from capillary water loss due to high rate of evaporation and high ambient temperature and restraint of concrete composite. When tensile stress is more than tensile strength of concrete, concrete crack can be happened. This may affect on the service life of concrete application. Fibers can be used to reduce brittleness and shrinkage of concrete [14]. Synthetic fibers help making bond connection between cracks and reduce its propagation. Either volume fraction of fiber or fiber geometry can affect plastic shrinkage cracking in concrete [16].

2.2.3.2 Post-cracking Behavior of Concrete

After ordinary concrete is cracked, it cannot bear any load at all. While fiber reinforced concrete can reduce crack propagation and bear some load. Synthetic fiber in concrete can enhance cross-linkage among composite material in hardened concrete. This cross-linkage can absorb energy, control crack, reduce the opening of cracks and resist its propagation [15].

2.2.4 Nonionic Surfactant

The general characteristic of surface active agents or surfactants is called as schizophrenic molecules including hydrophilic side and hydrophobic side. As **Figure 2.3**, the head of surfactant structure is hydrophilic section and the tail generally represents hydrocarbon chain. Surfactant is able to form colloid-sized aggregates called as micelles at a sufficient surfactant concentration. The lowest concentration of surfactant which can form micelle is normally called the critical micelle concentration (CMC). Besides, surfactant is able to form in other shapes such as admicelle and hemimicelle on material surface.

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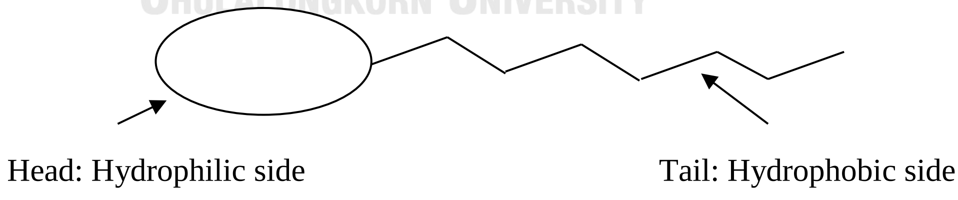

Figure 2.3 Surfactant Structure

There are 4 types of surfactants which are classified by charge on hydrophilic side;

1) Anionic surfactants contain negative charge on their head; for example, $RCOO_3^-Na^+$ (soap), $RC_6H_4SO_3^-Na^+$ (alkylbenzene sulfonate).
2) Cationic surfactants contain positive charge on their head; for example, $RNH_3^+Cl^-$ (salt of a long-chain amine), $RN(CH_3)_3^+Cl^-$ (quaternary ammonium chloride).

3) Zwitterionic surfactants contain both positive and negative charges on their head; for example, $RN^{+}H_2CH_2COO^{-}$ (long-chain amino acid), $RN^{+}(CH_3)_2CH_2CH_2SO_3^{-}$ (sulfobetaine).
4) Nonionic surfactants contain no charge on their head; for example, $RCOOCH_2CHOHCH_2OH$ (monoglyceride of long-chain fatty acid), Laureth-12 (12 ethylene oxides and 12-14 fatty acids).

Normally, strength of concrete matrix develops from hydration reaction of various oxides in Portland cement so no charges on surfactant which avoid obstructing concrete ionic reaction are advantage to the strength of concrete matrix. This study selects nonionic surfactant of which trade name is Laureth-12. Laureth-12 consists of 12 ethylene oxide molecules and fatty alcohol 12-14 molecules. Its physical properties are white solid in ambient temperature, odorless, 0.986-0.990 g/cm^3 at 70 ^{o}C, pH-value 6.0-7.5 and cloud point 79.0-83.0 ^{o}C. Ethylene oxide is miscible to water so Laureth-12 is tendency to be hydrophilic-like which is able to solute in water during concrete work.

One of major plastic properties is low surface energy; consequently, the mechanical bond strength between plastic and cement composites is very weak [17]. Poor adhesion force cannot control crack development of concrete matrix effectively. Besides, this poor mechanical bond strength can raise micro voids on the interfacial area between synthetic fiber and concrete matrix which causes inside micro cracks [18]. This study aims to reduce the surface energy between synthetic fiber and concrete matrix by using surfactant, especially Laureth-12 which is one kind of nonionic surfactants.

2.2.4.1 Interfacial tension

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Interfacial tension is the property between two substances such as liquid-liquid, air-liquid, and solid-liquid. In case of liquid, van der Waals and dispersion forces are two main forces between liquid molecules. Normally, difference of both forces will be close to zero in order to maintain the stability of water molecules. However, attraction force which is unbalanced on the surface of water is able to induce hemisphere water droplet on the solid surface especially hydrophobic materials. Normally, interfacial tension of water is about 72-73 mN/m (at room temperature) [19] while hydrocarbon's interfacial tensions are likely to be lower than the water for example interfacial tensions of HDPE LDPE PP and PET were about 30, 30, 30 and 42 mN/m respectively [20]. Plastic surface is considered as lower interfacial tension than water so water is likely to bead on plastic surface. Besides, according to high temperature can decrease interfacial so this is one of the limitation of surfactant use [19]. High Interfacial tension between liquid and solid can reduce contact angle and increase wettability on plastic surface.

2.2.4.2 Contact Angle

Contact angle is the angle between liquid droplet and solid surface which can illustrate the wettability of materials. The lower contact angle can increase wetting on the solid surface. Normally, there are two types of contact angle including receding and advancing contact angles as shown in **Figure 2.4**. Normally, the advancing contact angle is higher than receding contact angle. However, average contact angle is normally used for interpreting wetting of liquid on the solid surface. In case of less than 90° contact angle between liquid solution and solid surface as shown in **Figure 2.5**, it indicates that liquid can wet on solid surface while more than 90° contact angle is reversed [21]. The lower contact angle can increase wetting on solid surface so in case of high contact angle between liquid solution and solid surface, surfactant can improve its wettability.

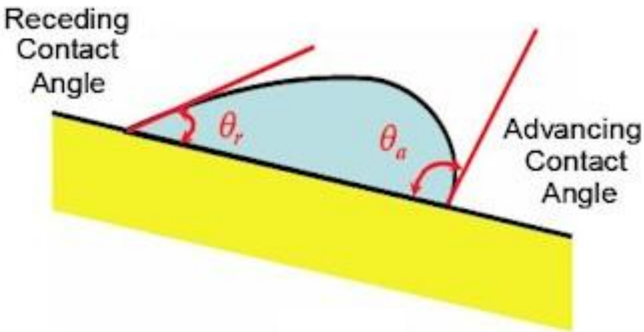

Figure 2.4 Contact angle between liquid droplet and solid surface [22]

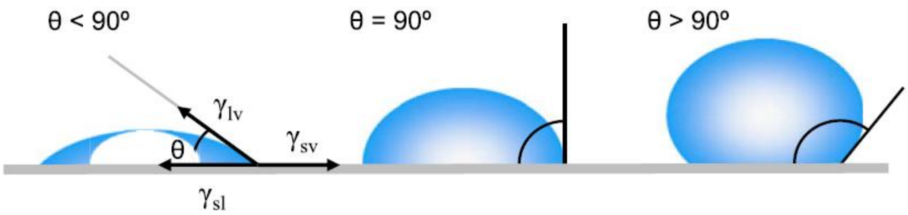

Figure 2.5 contact angle between liquid solution and the solid surface

2.3 Material Testing Standard

2.3.1 Sand analysis: Fineness Modulus (F.M.)

Gradation of sand is the average size distribution of sand. Fineness Modulus is one of the main factors to either robust or durability of concrete. F.M. value is no unit and used for elaborating sand's roughness or fineness. Low F.M. value normally can result in less amount of cement proportion which is used for concrete mixing. The suggestion range of F.M. is proposed about 2.3-3.2 [23]. This appropriate

F.M. value is directly related to concrete quality; for example, more than 15% and 5% sand particle sizes at sieve no.50 and no.100 respectively with less than 5% of sand particle size at sieve no.200 which are recommended in concrete can enhance well concrete agglomeration. The sand size at sieve no.200 is limited because it consists of mainly clay which needs to increase water proportion in concrete mixing. Besides, in case of more sand size at sieve no.200, it can cause shrinkage cracking on concrete surface. F.M. value affects on concrete properties as detailed below;

- Cement amount: the proper F.M. value results in filling up gap between roughness and fineness aggregates completely; consequently, cement proportion mixed in concrete is used less.
- Workability: appropriate F.M. value can reduce void in concrete so the residue of cement acts as lubricants and low friction force resulting in good workability.

Segregation: there are 2 types of segregation including overvibration and bleeding. Overvibration results in mortar separation from aggregate, while bleeding causes from concrete composition which cannot retain water in concrete matrix.

2.3.2 Recycled synthetic fiber

2.3.2.1 Tensile strength

Tensile strength is the capability of materials to resist elongation force. Max tensile strength is the highest elongation force (Newton) per unit area (m^2). Plastic material is normally higher in tensile strength than ordinary concrete because it is more elastic than concrete [7]. Previous study found that synthetic fiber in concrete helped to increase tensile property of concrete [24-28].

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2.3.2.2 Young's modulus

Modulus of young is the relationship between stress and strain of materials either compression or extension forces, which can be calculated by slope of the graph. Normally, material which is compressed or extended by some force can be reversible to its original shape after unloading. Higher Young's modulus value of material means stiffer than the lower value. Actually, plastic is more flexible than concrete material as it has lower Young's modulus value than those of concrete materials. Lower Young's modulus of plastic mixed in concrete can reduce the overall Young's modulus of concrete, resulting in a more flexible composite material. Some previous studies said that plastic fiber mixed in concrete could help reducing plastic shrinkage cracking and post-cracking behavior of concrete [14, 15].

2.3.2.3 Elongation

Elongation of plastic material is the highest extending deformation property of material. Material can be stretched by force until its detachment calling max force. Elongation or strain is expressed by the extension ratio between final and initial lengths of material, so it is no unit. Plastic is considered to be more extendable than concrete material because of its more flexible property. More elongation value means more extendable of material. This property in composite material can enhance the tensile capacity; consequently, concrete which is low tensile strength but high compressive strength reduce cracking due to tensile force.

2.3.2.4 Bulk density

Bulk density of material is considered as the weight of material in finite volume. High bulk density value of material means high mass amount at the same dimension so material which has high bulk density value can be heavier than the lower one. Bulk density of material consists of three phases including gas, liquid and solid phases. The bulk density of material was calculated by ratio of weigh and volume. Low bulk density of material like plastic fiber mixed in concrete can help decreasing weight of concrete material which is higher bulk density; consequently, reducing load to main structure such as concrete pillar or beam. Besides, low bulk density of material including the number of voids can insulate heat transfer from side to side [29, 30].

2.3.3 Concrete

2.3.3.1 Workability

Workability of concrete is to sum of energy which overcomes friction force between molecules in fresh concrete; consequently complete compression of concrete [6]. The strength of concrete is directly affected by void appearing in hardened concrete so it is recommended to increase concrete density by good workability of fresh concrete into mold. 5% porosity due to low workability can cause low compressive strength of concrete up to 30% [6]. Concrete workability depends on many factors such as aggregate composition, concrete composition, water cement ratio, duration of fresh concrete, ambient temperature, and so on.

2.3.3.2 Unit weight

Unit weight is material weight per its finite volume including air void inside of material. This value is useful for converting volume of the material to be mass for either concrete preparation or material's density comparison. Normal concrete weight is approximately 2,400 kg/m^3 (2,200-2,600 kg/m^3) recommended for main structures such as house, building, road, and so on. Unit weight of concrete is used for defining lightweight or heavyweight concretes. Unit weight of lightweight concrete is suggested between 300 to 1,850 kg/m^3 for non load bearing structure such as precast concrete wall panel, heat insulation, and so on. Lightweight concrete can help reducing load for main structure of building. Unit weight of heavyweight concrete is about 3,200 kg/m^3 used for designing radiation protective structure. Factors to unit weight include air void, aggregate types, aggregate proportion, and water cement ratio [6].

2.3.3.3 Air content

Air content proportion is the ratio between air and concrete volumes. Air content in concrete is useful for concrete floor at freeze storage room especially 3-5% air voids in concrete in order to enhance the frozen water expansion in capillary pores. In case of no void, the water volume in void will expand; consequently, concrete will be cracked. There are 2 types of air voids in concrete including entrapped air voids and entrained air voids. Factors affecting to air void in concrete consist of materials in concrete, concrete composition, and concrete vibration. Besides, plastic materials mixed in concrete which are hydrophobic material result in air void inside so bulk density of synthetic fiber reinforced concrete is decreased [31].

2.3.3.4 Compressive Strength

According to ASTM C39, this test covers concrete cylinder shape which is molded at construction area, laboratory or drilled core from structure. However, the density of concrete tested according to this standard must be more than 800 kg/m^3. Compressive strength is one of the general parameters of concrete test which can be used for building design and concrete quality analysis. Normally, high compressive strength concrete is more durable than low compressive strength concrete. Besides, this test can explain the quality of mix design, framework concrete pour, tamping and vibrating concrete, etc. The test method in brief can be explained; 1) prepare cylinder shape concrete (15 cm diameter and 30 cm length) as desired concrete age 2) put hardened concrete in vertical alignment of compressed machine (as shown in **Figure 2.6**) 3) press hardened concrete until collapse and 4) result analysis [32].

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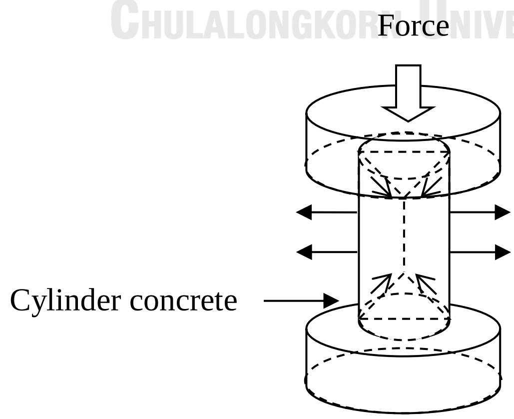

Figure 2.6 Compressive strength test

2.3.3.5 Splitting Tensile Strength

According to ASTM C496, this test covers concrete cylinder shape which is molded at construction area, laboratory or drilled core from structure. Splitting tensile test is considered as an indirect test to obtain tensile strength of concrete because direct tensile strength of concrete is hard to measure and spends a lot of time. Besides, the result of splitting tensile test is low uncertainty. It is noted that the result of splitting tensile strength is usually more than real tensile strength of concrete approximately 15% [32]. The test method in brief can be explained; 1) prepare cylinder shape concrete (15 cm diameter and 30 cm length) as desired concrete age 2) put hardened concrete in horizontal alignment of compressed machine born by 3 mm thickness, 300 mm length and 25 mm width of plywood (as shown in **Figure 2.7**) 3) press hardened concrete until collapse and 4) result analysis [32].

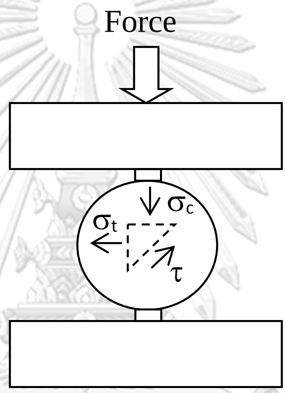

Figure 2.7 Splitting tensile test [32]

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2.3.3.6 Stress-strain Curve

The stress-strain curve of either tensile or compressive strength of cylinder concrete shows the relationship between stress (force per area) and strain (the proportion of deformation of concrete) (as shown in **Figure 2.8**). The stress can be calculated from the ratio of perpendicular force (N) and cross sectional area (m^2) of cylinder concrete. Sometimes, it can be called tensile stress due to the fact that every part of material is assumed to be done by tension. The unit of stress is the Newton (N) per square meter (m^2) or the Pascal (Pa). The strain can be calculated from the ratio of deformation (ΔL) and length of material (L), so the strain will not have unit. The slope of this curve reveals the modulus of elasticity of material (E).

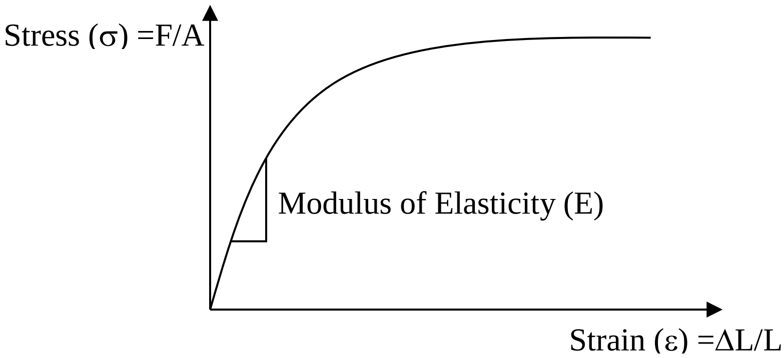

Figure 2.8 Stress-strain curve of concrete

2.4 UV Radiation Effect on Plastic Fiber Reinforced Concrete

Sunlight includes various the electromagnetic radiations from the Sun. The spectrums of solar radiation consist of infrared, visible and ultraviolet (UV) light. UV can be classified in three wave length including UVA (100 to 280 nm), UVB (280 to 315 nm), and UVC (315 to 400 nm). So, synthetic fiber reinforced concrete applied in non-load bearing structure can be affected by UV radiation from sunlight. According to [33], when UV radiation irradiate to plastic materials, they can be oxidized to be hydroperoxides resulting from dissociation of polymer chain. Besides, according to [34], they found that the compressive strength of 0.75 kg/m^3 of Isotactic polypropylene (PPi) reinforced concrete irradiated with ultraviolet radiation was roughly 10% lower than no irradiated specimen. According to [35], tensile strength of LLDPE with Fe-stearate was reduced when intensity of exposure of UV irradiation increased. This study aims to find out the effect of UV on durability of synthetic fiber reinforced concrete.

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2.5 Thermal properties on Plastic Fiber Reinforced Concrete

Thermal conductivity is the material characteristic which is able to transfer heat from higher to lower temperature sides of material. Normally, low thermal conductivity materials are low rate of heat transfer such as air void, plastic material, and so on which is different from high thermal conductivity materials (such as steel, copper, and so on). Low thermal conductivity can call high thermal resistance or high thermal insulation. Thermal insulation is one of the favor properties in construction in order that the building will need less energy consumption. Influencing factors of thermal conductivities include temperature, chemical phase, electrical conductivity, gaseous phase, and so on. Normally, thermal conductivities of ordinary concretes (medium and dense types) are about 0.9-1.7 W/(m K) [36]. Similar to [37], the thermal conductivities of mortar and ordinary concrete are 2.0-2.3 W/(m K). When comparing to other insulation materials, there are several materials which are used for thermal insulation; for example, Fiberglass, Mineral wool, Cellulose, Polyurethane foam, and Polystyrene (EPS). Their thermal conductivities are about 0.04, 0.04, 0.23, 0.03, and 0.03 W/(m K) at 25 °C [38]. The thermal conductivity value of concrete is found to have higher than others, so this is the reason why thermal insulation is necessarily applied in building. However, some of insulation materials especially Fiberglass and Mineral wool are unsafe for human health which can cause damage to the eyes, lungs, and even skin if direct contact. According to [39], thermal conductivities of HDPE, LDPE and PP are found to be about 0.43, 0.35 and 0.23 W/(m K) at 25 °C as shown in **Figure 2.9** and thermal conductivity of PET is about 0.15-0.40 W/(m K) at 23 °C [40] which are found to be lower than mortar and ordinary concrete even higher than general insulation materials. However, HDPE, LDPE and PP are seemed to be safer to human health than general insulation materials and besides are one of the new alternative materials which can also solve environmental problem. The plastic fibers mixed in concrete of this study are expected to help reducing the thermal conductivity of ordinary concrete. This study will also investigate the thermal conductivity of plastic fiber reinforced concrete made by HDPE, LDPE, PP and PET.

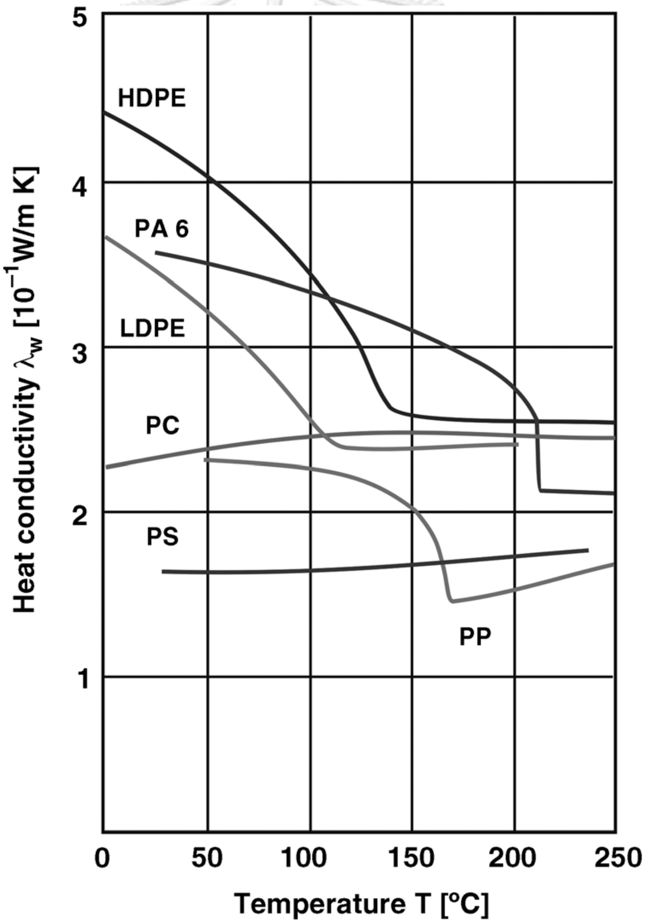

Figure 2.9 Heat conductivity for semicrystalline thermoplastics (HDPE, LDPE and PP), [39]

2.6 Alkalinity Resistance of Plastic Fiber in Concrete Matrix

When synthetic fiber is applied in concrete work, there are some questions on the durability of fiber reinforced concrete especially alkalinity resistance. Concrete matrix is found to be strongly alkaline condition (pH 10 to 12) due to hydration reaction of calcium silicates and aluminates resulting in calcium hydroxide ($Ca(OH)_2$) [41], so alkalinity resistance of synthetic fiber directly relating to life time of fiber reinforced concrete constructions should be considered. According to [42], the virgin PP fibers reinforced concrete was immersed in salt water at different temperatures between -7 to 70 ^{o}C for six months. They found that its tensile property was not changed. Besides, another study by [43], PP fiber reinforced concrete was immersed in salt water for 33 months. It is found that stiffness reduction was about 2.34% which was better than steel fiber (14.0% reduction) and PVA (59.9% reduction). In case of PET, most of studies [41] [44] [27] [45] [46] found that the surface of PET fiber was be degraded in alkaline solution but performance (tensile strength) of PET fiber was reduced about 1-13%. It meant that PET was good alkaline resistance in mortar and concrete. However, most of studies used pellet recycled plastic or plastic waste to reproduce synthetic fiber. This study will use 4 types of plastic waste i.e. HDPE, LDPE, PET and PP and aims to make plastic waste to be macro fiber directly by cutting. Alkalinity solution is prepared at the same pH value as concrete matrix (pH 10-12).

2.7 Cost of synthetic fiber reinforced concrete production

This systematic tool is used for analyzing strengths and weaknesses of alternative ways to determine the best option especially in both renewable resources and inexpensive materials. The cost analysis will help investment decision by providing basic information for comparing among alternative ways. This research aims to reuse plastic waste as macro synthetic fibers comparing to virgin plastic in terms of operation cost.

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CHAPTER 3 RESEARCH METHODOLOGY

Overall framework of this study was to find the best synthetic fiber reinforced concrete made by recycled plastic waste which was cut as macro fiber shown in **Figure 3.1**. At the beginning, plastic waste samples were taken from a plastic bag manufacturer and a PET sheet manufacturer. After taking plastic waste samples (HDPE, LDPE, PP and PET), they were sorted and cleaned in each types of the plastics. All plastics were cut off in 3 mm wide x 50 mm long. Some of them were coated by surfactants and mixed with mortar. After making synthetic fiber reinforced concrete, some of them were irradiated by UV radiation. Finally, all plastic-made concretes were examined compressive strength, splitting tensile and thermal conductivity according to ASTM standards. Some of plastic fibers (HDPE, LDPE, PP and PET) were immersed in alkalinity solution ($CaOH_2$, pH 12.3) to test alkalinity resistance. Moreover, some were irradiated by UV-A lamp in definite periods. Afterwards they were tested tensile strength test followed to ASTM standards. Besides, surface analysis of all processed plastics were examined by SEM.

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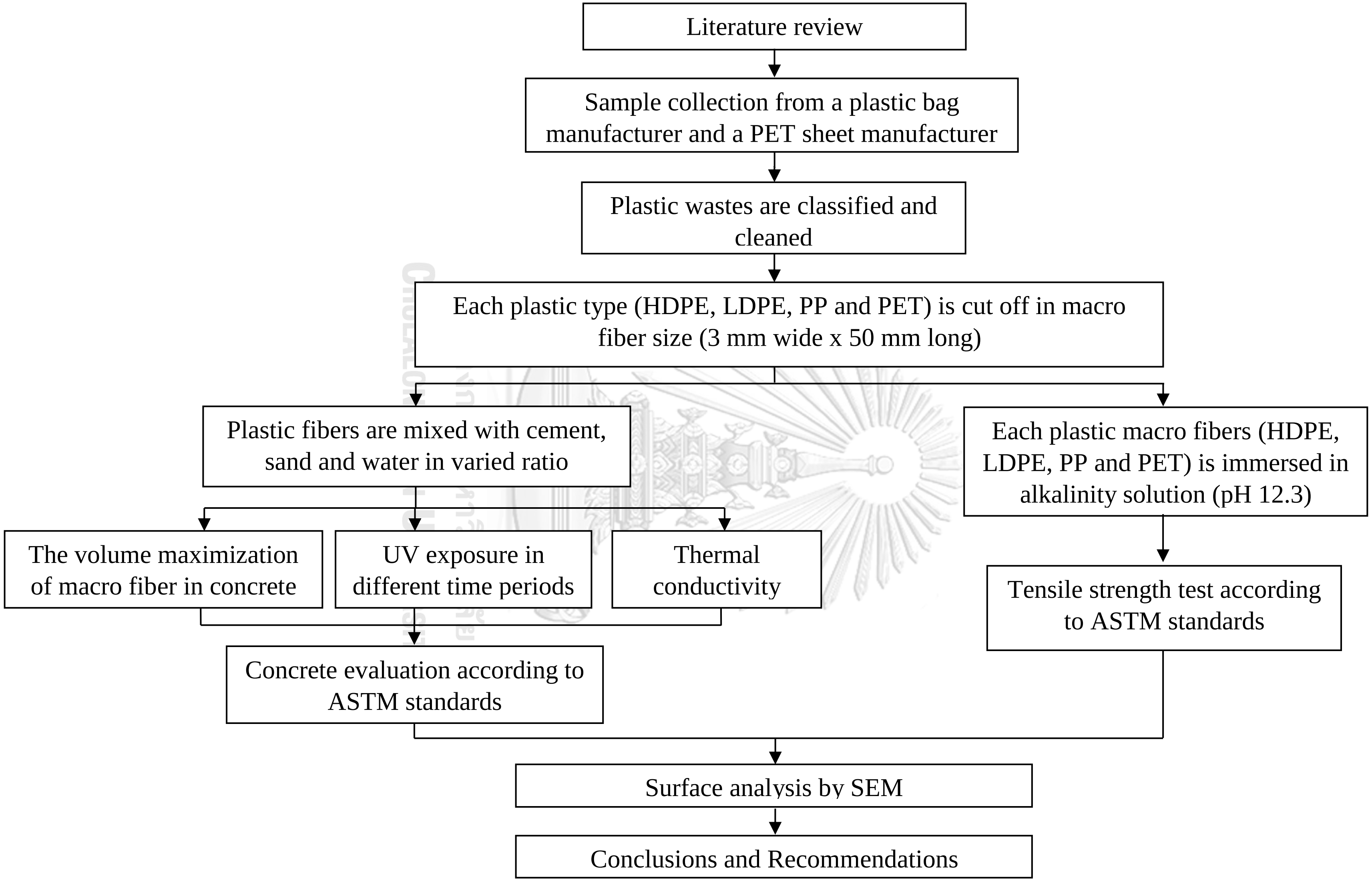

Figure 3.1 Overall framework of methodology

3.1 Synthetic fiber preparation made of plastic wastes

Four types of plastic wastes, including high density polyethylene (HDPE), low density polyethylene (LDPE), and polypropylene (PP) collected from a plastic bag manufacturer (T.VIJITPLASTICS, Bangkok, Thailand), as well as polyethylene terephthalate (PET) collected from a PET sheet manufacturer (ROYCE UNIVERSAL Co., Ltd., Nakornpathom, Thailand), were utilized as part of ingredients for concrete production in this study. Then, all are classified, cleaned and cut in macro fiber size (3 mm wide and 50 mm long) as shown in Figure 3.2.

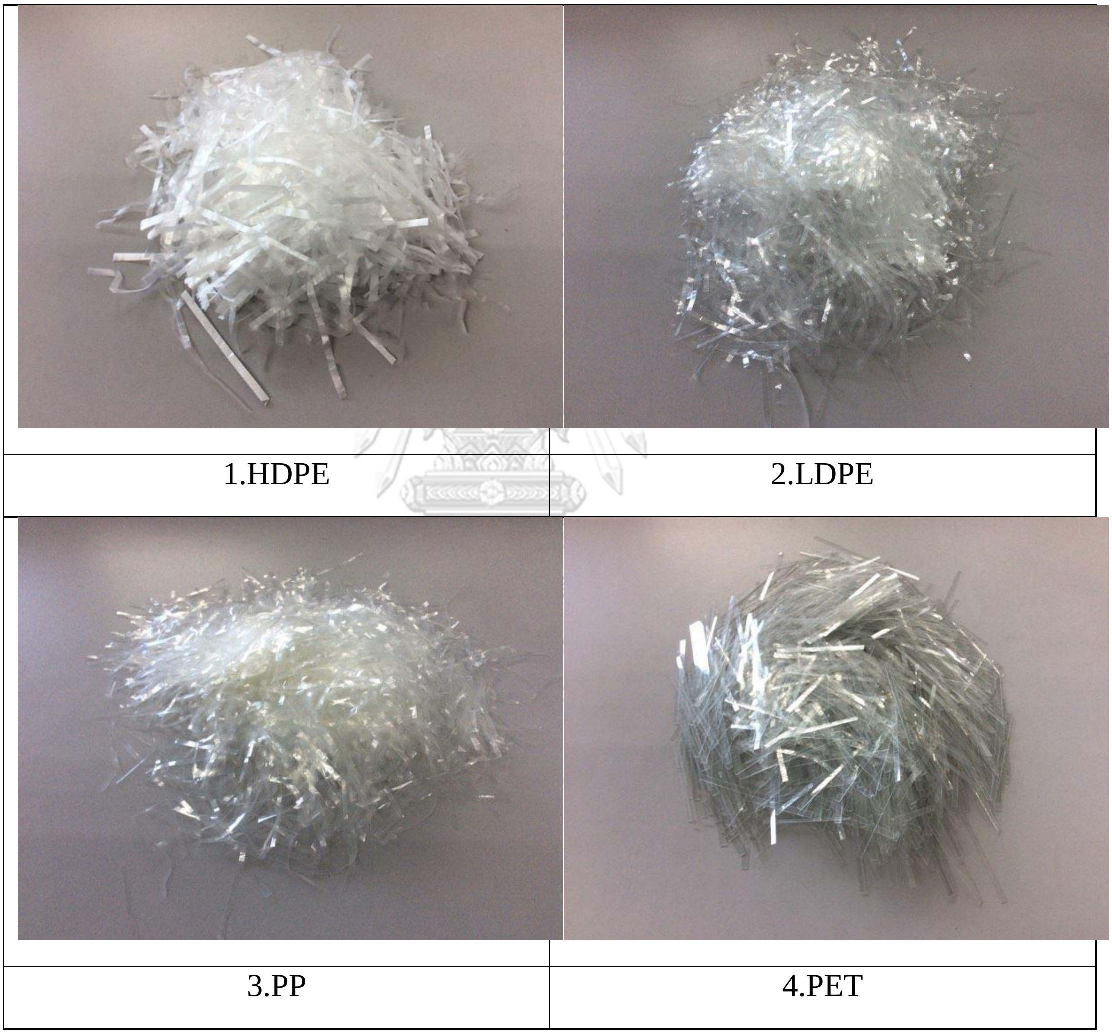

Figure 3.2 Photographs of types of macro synthetic fibers made of industrial plastic waste

3.1.1 Sample preparation

1) Equipment
- Plastic tray
- Cutter
- Ruler
- Scissor
- Container
- Tamping rod
- Balance

2) Chemical
- Synthetic fiber (3 mm wide and 50 mm long) made by plastic wastes (HDPE, LDPE, PP and PET)

3.1.2 Analysis method

1) Bulk unit weight

The bulk unit weight measured at ambient temperature is used to convert from plastic volume to plastic weight during plastic preparation. Bulk unit weight is investigated according to ASTM C29 [47] as shown in **Figure 3.3**. The ASTM C29 method is starting from weighing blank container and recording in note. Afterwards, material is filled up container and material-filled container is weighed on balance and recorded in note. Bulk unit weight is calculated by material weight which is different between before and after filling up material in container divided by container volume. Low bulk unit weight means lower weight than high bulk unit weight value at the same volume so plastic fiber including air void is likely to decrease the bulk unit weight value.

2) Interfacial tension and contact angle

According to plastic property, it has low surface energy so water is hard to be coated on plastic surface. When mixing between synthetic fiber and concrete, it may cause air bubble inside and less adhesion which can directly affect to the strength of synthetic fiber reinforced concrete. Surface active agent or surfactant especially non-ionic surfactant (Dehydol LS-12 TH) which can reduce the interfacial tension between plastic surface and water is assumed to enhance water coating on the surface of plastic and help hydration reaction of concrete matrix throughout. Prior to the concrete processing, wettabilities of plastic fibers were determined to optimize the nonionic surfactant amount. Two parameters; namely, interfacial tension (IT) and contact angle (θc) were used to measure the wettability according to DIN 53914 standard. Brief procedure includes preparing the plastic fibers of HDPE, LDPE, PP, and PET in a 1 cm x 2 cm size, and measuring the interfacial tension and contact angle at various LS-12 solution concentrations from 1 to 100 times of its critical micelle concentration (CMC) at 25 °C by DCAT 11 (IP-HSM laboratory at Chulalongkorn University, Bangkok, Thailand) or Dynamic contact angle and tension meter as shown in **Figure 3.4**. This

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study will mix fresh synthetic fiber reinforced concrete with Dehydol LS-12 TH at optimal Critical Micelle Concentration (CMC) and prepare cylinder-shaped concrete.

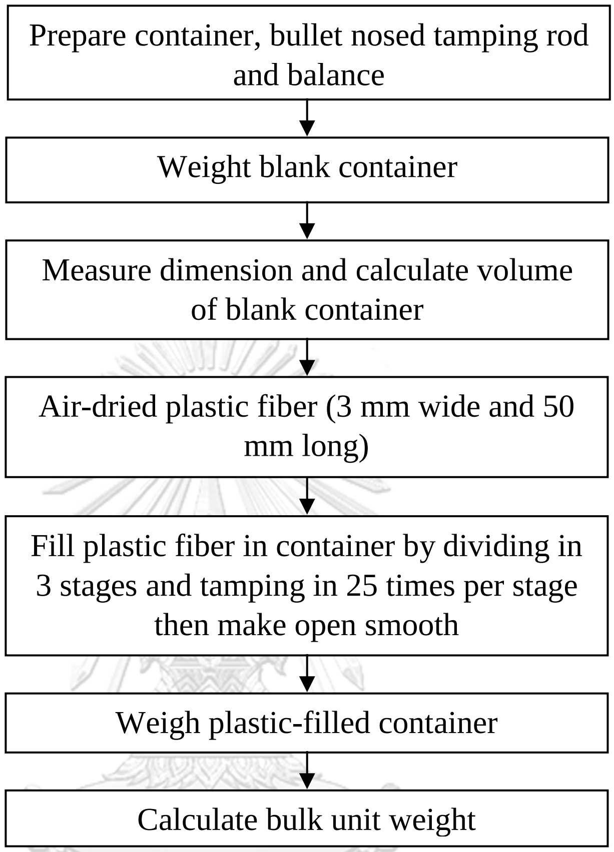

Figure 3.3 Bulk unit weight method according to ASTM C 29 [47]

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(a)	(b)

Figure 3.4 Photographs of wettability experiment (a) Interfacial tension and contact angle measurement using a DCAT 11 with cooler, and (b) Plastic samples in a 1 cm × 2 cm size.

3) Alkalinity resistance

Alkalinity resistance study as shown in **Figure 3.5** prepares lime-saturated water ($Ca(OH)_2$) at ambient temperature (30 °C) by dissolving 1.56 g $Ca(OH)_2$ which pluses 10% mass in 1 liter water (pH = 12.3). All types of plastic fibers (3 mm wide and 50 mm long) are immersed into lime-saturated water (as shown in **Figure 3.6**) in 7, 14, 28, 90 and 180 days comparing to blank sample which is plastic fibers immersed in distilled water. All of them will be analyzed by physical property especially tensile strength, Young's modulus and surface characteristic. Tensile strength and Young's modulus are tested by Universal Testing Machine (UTM). Surface characteristic is analyzed by Scanning Electron Microscope (SEM).

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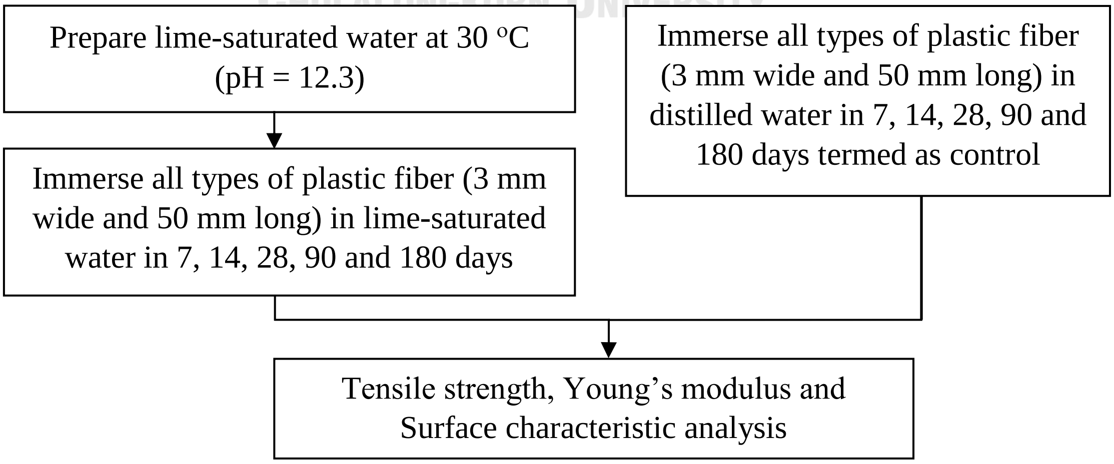
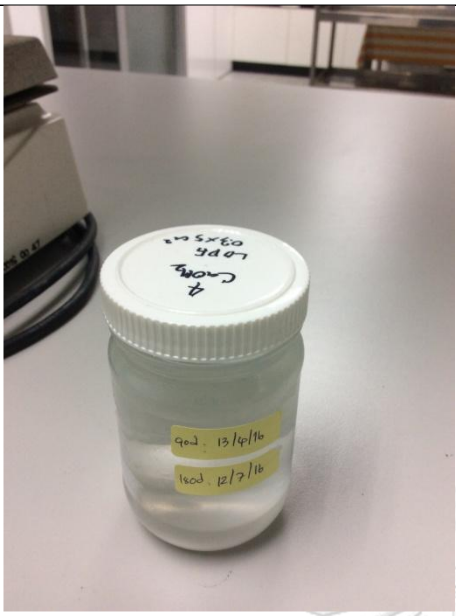


Figure 3.5 Alkalinity resistance study



(a)

(b)

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(c)

Figure 3.6 Photographs of alkalinity experiment (a) Lime-saturated water in container with plastic fibers, (b) Tensile strength test by 10kN UTM, and (c) Surface analysis by SEM

3.2 Fresh concrete

3.2.1 Sample preparation

1) Equipment
- Concrete mixer
- Cylinder-shaped mould (Inside diameter = 15 cm and Height = 30 cm)
- Square-shaped mould (30x30x7.5 cm^3 and (15x15x15 cm^3)
- Tray
- Trowel
- Scoop
- Spade
- Container
- Slump mould (Inside diameter = 10 cm at top and 20 cm at bottom and Height = 30 cm)
- Balance (Readability at 0.05 kg)
- Bullet nosed tamping rod (Diameter = 16mm and Length = 600 mm)
- Square tamping rod (Cross-section area = 1 $inch^2$ and Length = 300 mm)
- Metal bucket (Diameter = 15 cm and Height = 16 cm)
- Thermometer

2) Chemical
- Portland type 1 cement
- Sand (Fine aggregate)
- Synthetic fiber (3 mm wide and 50 mm long) made by plastic wastes (HDPE, LDPE, PP and PET)
- Surfactant (Dehydol LS-12 TH)
- Potable water
- Lubricant oil

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3.2.2 Analysis method

1) Sieve analysis: Fineness Modulus (F.M.)

Sand gradation of this study will be analyzed according to ASTM C136 [48]. Sand will be cleaned and dried at 105-115 °C until its weight is stable. Dried sand will be weighed approximately 300 gram and poured in the top of sieve mesh tower of which the highest sieve mesh is descending from top to bottom as shown in **Figure 3.7**. Close the top by steel lid and shake by shaker in 10 minutes. Weigh sand in each sieve mesh rack and record in note. If the total weight loss between before and after shaking is less than 0.3%, this sand gradation result is reliable. Fineness Modulus (F.M.) representative as sand gradation is calculated from sum accrual sand weight in each sieve mesh rack and divided by 100. F.M. value is recommended about 2.30-3.20.

(a)	(b)

Figure 3.7 Photographs of sieve analysis (a) Dried sand and (b) Various steel sieve meshes

2) Mix design

Fresh concrete of this study will be prepared by mixing Portland type 1 cement, sand, synthetic fibers (5-50%) and water in varied ratios as shown in **Table 3.1**. Although water is considered as one of the concrete strength factors, concrete includes high excess water which may cause bleeding, segregation, low compressive strength, shrinkage and high porosity which affects to concrete life. Theoretically, the optimal water cement ratio which can make the highest concrete strength is about 0.28±0.01 [49]. Water cement ratio, however, which is proper to fresh concrete flowing to mould is required more than 0.35. As previous preliminary experiment, w/c ratio was used in synthetic fiber concrete (10% and 30% volume of LDPE) about 0.5; it found that slump test results were very low about 8.50 and 0.25 cm respectively. Synthetic fiber used in this study will be mixed in concrete in various volume proportions including 5-50% so w/c ratios are various in 0.5-0.6 due to increase in fresh concrete flow and decrease in concrete segregation. Besides, preliminary experiment results were found that the compressive strength of synthetic fiber reinforced concrete about 10% LDPE fiber volume in mortar met precast concrete standard (16 N/mm^2) whereas the compressive strength of 30% LDPE fiber volume is not met one. So, this study plans to mix synthetic fiber in mortar in 0% (termed as blank), 5%, 10%, 15%, and 20% volume of cement. However, the maximization of plastic fiber volume of 4 types of plastic waste in concrete is investigated in this study so some plastic fiber types might be increased until their compressive strengths still meet desirable standard. Water cement ratio is varied at 0.5-0.6. Cement and sand in mass proportion is 1:2. Sand will be measured the bulk unit weight according to ASTM C 29 [47] as shown in **Figure 3.3**. The bulk unit weight measured at ambient temperature is used to convert from volume to weight during material preparation.

Concrete mixing procedure

a) Prepare all ingredients such as cement, sand, water, nonionic surfactant, and macro synthetic fiber in desired volume proportion.
b) Convert ingredient volume to be mass by using their bulk unit weight.
c) Weigh all ingredients in calculated mass.
d) Dissolve weighed nonionic surfactant in desired water in basin.
e) Put plastic fiber in nonionic surfactant solution in basin in 10 minutes.
f) Wash concrete mixer by portable water and switch on it in 2 minutes and then pour it out concrete mixer.
g) Put weighed sand in concrete mixer and then switch on concrete mixer in 2 minutes.
h) Put weighed plastic fibers soaked by nonionic surfactant solution into concrete mixer and cover by lid then switch on it in 2 minutes.
i) Put weighed cement in concrete mixer and cover by lid then switch on concrete mixer in 2 minutes.
j) Put weighed nonionic surfactant solution (d) into concrete mixer and then switch on it in 10 minutes or until all mixed well.

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Table 3.1 Mix proportions of concrete processing from various plastic wastes

Experimental conditions	Water-to-cement (W/C) ratio	Cement (kg)	Sand (kg)	Water (kg)	Nonionic surfactant (kg)	Plastic waste fiber * (kg)
(1) Mortar	0.50	33.00	66.00	16.50	6.93	-
	(2) 5% volume fraction					
- HDPE	0.50	30.12	60.24	15.06	6.33	0.14
- LDPE	0.50	30.12	60.24	15.06	6.33	0.22
- PP	0.50	30.12	60.24	15.06	6.33	0.18
- PET	0.50	30.12	60.24	15.06	6.33	0.24
	(3) 10% volume fraction					
- HDPE	0.50	30.12	60.24	15.06	6.33	0.28
- LDPE	0.50	30.12	60.24	15.06	6.33	0.44
- PP	0.50	30.12	60.24	15.06	6.33	0.36
- PET	0.50	30.12	60.24	15.06	6.33	0.48
	(4) 15% volume fraction					
- HDPE	0.55	30.12	60.24	16.57	6.96	0.42
- LDPE	0.55	30.12	60.24	16.57	6.96	0.66
- PP	0.55	30.12	60.24	16.57	6.96	0.54
- PET	0.55	30.12	60.24	16.57	6.96	0.72
	(5) 20% volume fraction					
- HDPE	0.60	30.12	60.24	18.07	7.59	0.56
- LDPE	0.55	30.12	60.24	16.57	6.96	0.88
- PP	0.55	30.12	60.24	16.57	6.96	0.72
- PET	0.55	30.12	60.24	16.57	6.96	0.96
	(6) 30% volume fraction					
- HDPE	0.60	30.12	60.24	18.07	7.59	0.84
- LDPE	0.55	30.12	60.24	16.57	6.96	1.32

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Experimental conditions	Water-to-cement (W/C) ratio	Cement (kg)	Sand (kg)	Water (kg)	Nonionic surfactant (kg)	Plastic waste fiber * (kg)
- PP	0.55	30.12	60.24	16.57	6.96	1.08
- PET	0.55	30.12	60.24	16.57	6.96	1.44
	(7) 40% volume fraction					
- HDPE	-	-	-	-		-
- LDPE	-	-	-	-		-
- PP	-	-	-	-		-
- PET	0.55	30.12	60.24	16.57	6.96	1.92
	(8) 50% volume fraction					
- HDPE	-	-	-	-		-
- LDPE	-	-	-	-		-
- PP	-	-	-	-		-
- PET	0.55	30.12	60.24	16.57	6.96	2.40

Remark: * The mass of plastic fibers were calculated by their bulk unit weight. Plastic's bulk unit weight was shown in Table 4.1 (plastic fibers) while cement (Portland cement type 1) and sand were approximately 1,506 [50] and 1,560.74±12.34 kg/m^3 respectively.

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3) Workability

There are several workability methods such as slump test, compacting factor test, Kelly ball test, etc. so this study will select only one method that is ASTM C 143 [51]. According to ASTM C 143 as shown in **Figure 3.8**, after ready mixed concrete, it will be taken from concrete mixer and poured in wet slump mould. Concrete is divided and poured in three stages while each stage is tamped in 25 times. Until it is full, the top of mould is cut the concrete to smooth by trowel. After that slump mould is pulled out in vertical alignment and put aside concrete. The subsidence value or slump value is measured and recorded in report as shown in **Figure 3.9**.

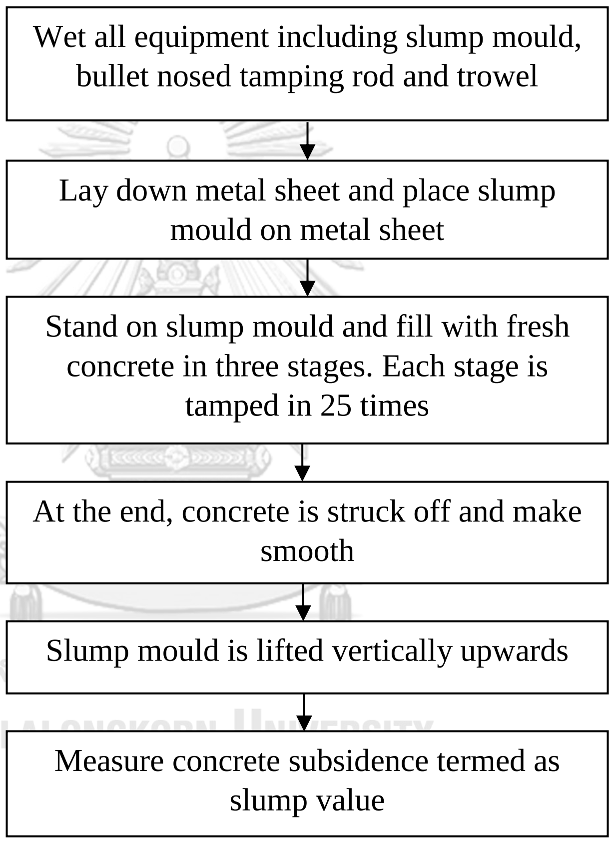

Figure 3.8 Slump test method according to ASTM C 143 [51]

(a)

(b)

(c)

Figure 3.9 Photographs of workability test according to ASTM C29 during concrete processing: (a) Complex network of 20 vol.% HDPE fibers in concrete, (b) Segregation of 30 vol.% PP fibers in concrete, and (c) Mortar (control sample without plastic fibers).

4) Cylinder-shaped concrete

According to ASTM C 192 [52] as shown in **Figure 3.10**, it requires to prepare cylinder-shaped mould (Inside diameter = 15 cm and Height = 30 cm) as shown in **Figure 3.11**. While casting concrete, cylinder-shaped mould will be coated by lubricant oil and poured by concrete in three stages. At the same time, every stage is tamped by tamping rod in 25 times. Until it is full, the top of mould is cut the concrete to smooth by trowel. Mould with fresh concrete is left in 24 hours. After 24 hours, all cylinder concrete will be taken off from mould and cured by immersing in lime-saturated water in pond in 28 days.

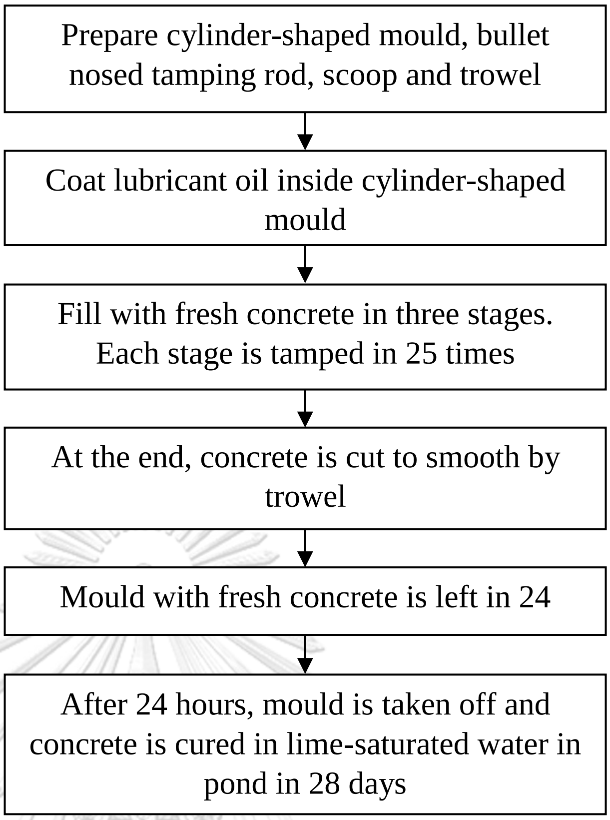

Figure 3.10 Cylinder-shaped concrete method according to ASTM C 192 [52]

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(a) (b)

Figure 3.11 Photographs of cylinder concrete (a) Cylinder concrete (Diameter 15 cm and Height = 30 cm) and (b) Curing cylinder concrete in 28 days by lime-saturated water pond

5) Square-shaped concrete

According to UV effect study, the square-shaped concrete samples as shown in **Figure 3.12** will be prepared in 15x15x15 cm^3 according to BS 1881: Part 3 as shown in **Figure 3.13**. While casting concrete, fresh concrete is divided in 3 stages and each stage is tamped by square tamping rod in 35 times. Afterwards, the top of mould is cut the concrete to smooth by trowel. Mould with fresh concrete is left in 24 hours. After 24 hours, all square-shaped concrete will be taken off from mould and cured by immersing in lime-saturated water in pond in 28 days.

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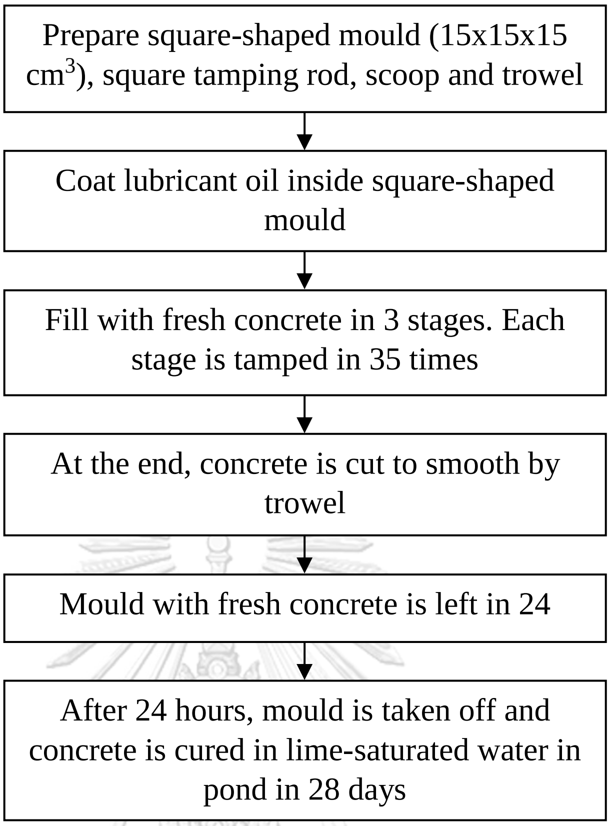

Figure 3.12 Square-shaped concrete according to BS 1881 Part: 3

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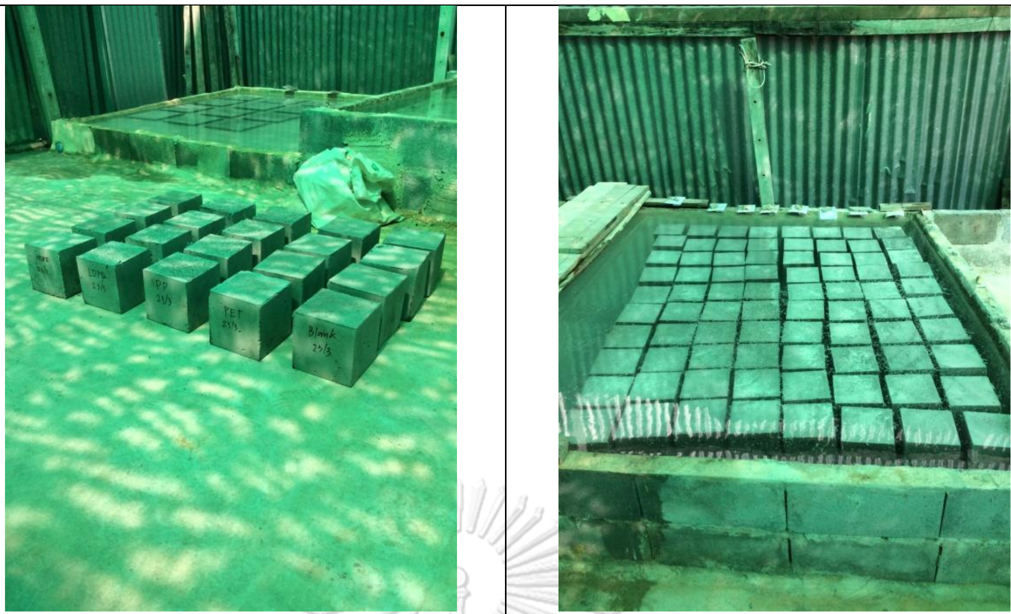

(a)	(b)

Figure 3.13 Photographs of cube concrete (a) Cube concrete (15x15x15 cm^3) and (b) Cube concrete in lime-saturated water pond

According to thermal conductivity study, heat flow meter (NETZSCH HFM 436) followed to ASTM C 518 [53] requires square-shaped concrete samples in 30x30x7.5 cm^3 as shown in **Figure 3.14** and **Figure 3.15**. While casting concrete, fresh concrete is divided in 2 stages and each stage is tamped by square tamping rod in 35 times. Afterwards, the top of mould is cut the concrete to smooth by trowel. Mould with fresh concrete is left in 24 hours. After 24 hours, all square-shaped concrete will be taken off from mould and cured by immersing in lime-saturated water in pond in 28 days.

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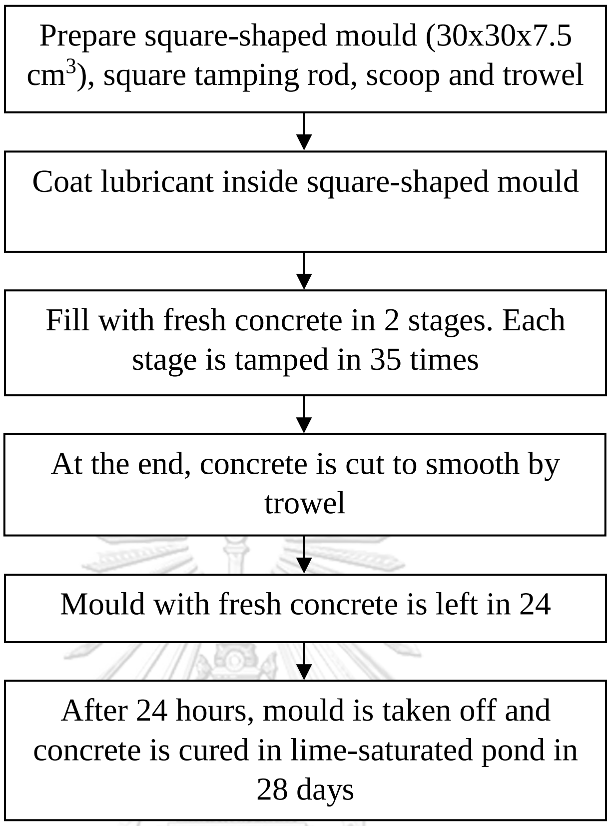

Figure 3.14 Square-shaped concrete for thermal conductivity test

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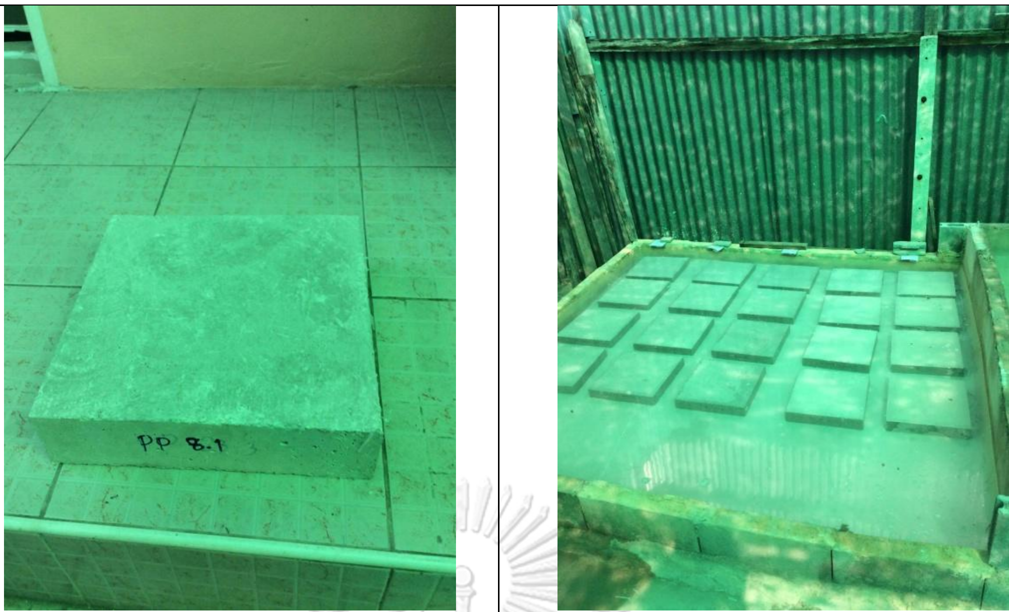

(a) (b)

Figure 3.15 Photographs of cube concrete (a) Cube concrete (30x30x7.5 cm^3) and (b) Cube concrete in lime-saturated water pond 28 days

3.3 Hardened concrete

Hardened concrete is already set concrete which is caused by major calcium silicate hydrate reaction. Normally hardened concrete of this study is cured in 28 days before testing.

3.3.1 Sample preparation

1) Equipment
   - Balance (Readability at 0.05 kg)
   - Ruler (Readability at 0.1 cm)
   - Scanning Electron Microscope (SEM)
   - Universal testing machine (UTM)
   - Linear Variable Differential Transformer (LVDT) and data logger
   - Load cell (200 ton) with calibration curve
   - Heat flow meter (NETZSCH HFM 436)
2) Chemical
   - Lime-saturated water ($Ca(OH)_2$) at 30 °C (pH = 12.3)
   - Distilled water

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3.3.2 Analysis method

1) Bulk density

After 28 days curing period, all cured concrete will be taken out from curing pond and then dried up in the air in 24 hours. All are weighed and measured dimension to calculate the volume. Afterwards, concrete density is calculated from the proportional relation between mass and volume.

2) Bond characteristics

This study will prepare synthetic fiber reinforced concrete in cylinder shape with Dehydol LS-12 TH at optimal Critical Micelle Concentration (CMC) as **Figure 3.4**. The adhesion characteristic between concrete matrix and plastic fiber with and without surfactant is investigated by SEM.

3) Permeable void

Permeable void or air content in hardened concrete is tested according to ASTM 642 [54]. The hardened concrete was evaluated for the porosity. The testing procedure as shown in **Figure 3.16** was as follows; (1) measure the dry weight of produced concrete (as seen in **Figure 3.17**) after heating at 100–110 °C in an oven and cooling down to 20–25 °C in a desiccator, (2) immerse the concrete in the water at 21 °C for 48 hours, and then measure the weight, (3) boil the concrete for five hours, and then measure the weight after cooling down, and (4) suspend the concrete in the water, and measure the immersed apparent mass [54]. Permeable void can be calculated by **Equation 1**.

$$\text{Permeable void} = \frac{(C-A)\ x\ 100}{(C-D)} \qquad \textbf{Equation 1}$$

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Where;

A	=	Mass weight of oven-dried sample in air (g)
C	=	Mass of surface-dry sample in air after immersion and boiling (g)
D	=	Apparent mass of sample in water after immersion and boiling (g)

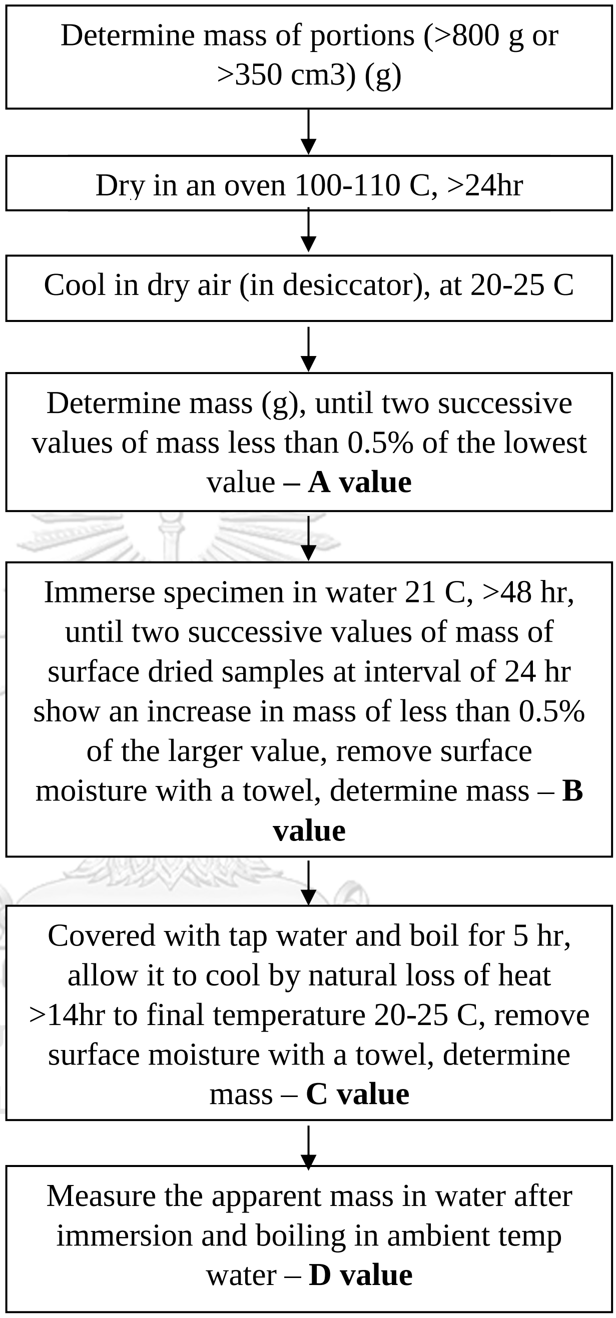

Figure 3.16 ASTM C 642 standard method

(a)

(b)

(c)

(d)

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Figure 3.17 Photographs of cube concrete for permeable void test (a) Cube concrete (5x5x5 cm^3), (b) Stove: 105-115 °C, (c) cube concrete immersed in water, and (d) Balance

4) Compressive strength

All synthetic fiber reinforced concrete will be molded in cylinder shape to measure compressive strength according to ASTM C 192 [52]. After 28 days curing period, it will be taken out from curing pond and then dried up in the air in 24 hours. All are weighed and measured dimension. Compressive strength is measured by UTM as shown in **Figure 3.18**. The maximum compressive strength (fc') is calculated from the proportion between maximum force (N) and cross-sectional area of cylinder concrete (mm^2) by **Equation 2**.

$$f_{c'} = \frac{F}{A}$$ **Equation 2**

Where; $f_{c'}$ = Compressive strength (N/mm^2)

P = Maximum force (N)

A = Cross-sectional area of cylinder concrete (mm^2)

(a)

(b)

(c)

(d)

Figure 3.18 Photographs of compressive strength test (a) Compression testing machine 300 ton, (b) Cube concrete: compressive strength test, (c) Cylinder concrete: splitting tensile strength test, and (d) Cylinder concrete: compressive strength test with LDVT and 200 ton load cell.

5) Splitting tensile strength

According to [49], direct tensile strength is hard to measure because center-point mass is not in active alignment. So, splitting tensile strength which is indirect value is applied and followed to ASTM C 496 [55] as shown in **Figure 3.18 (c)**. Normally, splitting tensile strength is found to have higher value than direct tensile strength about 15% because compression zone includes both ends of cylinder concrete too [49]. All samples will be molded in cylinder shape and cured in lime-saturated water in pond in 28 days. When testing splitting tensile strength, cylinder-shaped concrete is placed in horizontal alignment on UTM. Splitting tensile strength can be calculated by **Equation 3**.

$$f_s = \frac{2P}{\pi \times d \times L}$$ **Equation 3**

Where; f_s = Splitting tensile strength (N/mm^2)

P = Maximum force (N)

d = Diameter of cylinder concrete (mm)

L = Height of cylinder concrete (mm)

6) Modulus of elasticity

Modulus of elasticity or Young's modulus is the slope value of stress-strain curve. Both stress and strain values are measured by UTM and LVDT respectively during compressive strength measurement. Stress is the proportional relation between force and cross-sectional area of cylinder concrete (N/mm^2). Strain is the proportional relation between changed length (ΔL) and original length (L_0). Stress and strain are plotted in plot graph X and Y axes respectively so Young's modulus value is able to be calculated from its slope by **Equation 4**.

$$\text{Young's modulus} = \frac{F/A}{\Delta L/L}$$ **Equation 4**

Where; Young's modulus = Elastic modulus value (N/mm^2)

F = Force (N)

A = Cross-sectional area of cylinder concrete (mm^2)

ΔL = Changed length (mm)

L = Original length (mm)

7) Ultraviolet (UV) effect

Synthetic fiber reinforced concrete is molded in cube shape (15x15x15 cm^3) at 10% fiber volume as shown in **Figure 3.13**. This study will set closed room which includes UV-A lamp inside, so some cube concretes are put inside the closed room and some are placed outside covered by canvas termed as blank as shown in **Figure 3.19** and **Figure 3.20**. According to Thai Meteorological Department (TMD) 2009-2010, UV monitoring data including max UV-A and UV-B in Bangkok are about 1,318.04 and 43.53 kJ/d/m^2. UV-A is seemed to have much more value than UV-B about 30 times, so this study will select UV-A as major representative from sunlight. This study will set UV-A contacting time to synthetic fiber reinforced concrete about 250, 500, 750 and 1,000 hours. The distance between UV-A lamp and synthetic fiber reinforced concrete surface was set at 1 cm so UV mini meter used to measure UV-A intensity at 1 cm on top of concrete found the amount of 365 mJ/s/cm^2 (3,650 J/s/m^2) on average. This study will set UV-A contacting time to synthetic fibers and synthetic fiber reinforced concrete about 250, 500, 750, and 1000 hours. Based on the amount of UV-A from sunlight by TMD (23 J/s/m^2), the contacting times of 250, 500, 750 and 1,000 hours of UV-A exposure in chamber are able to be counted 7, 14, 20 and 27 years in environment respectively. Besides, the synthetic fiber reinforced concretes irradiated by UV are analyzed physical properties including compressive strength by UTM and surface characteristics by SEM.

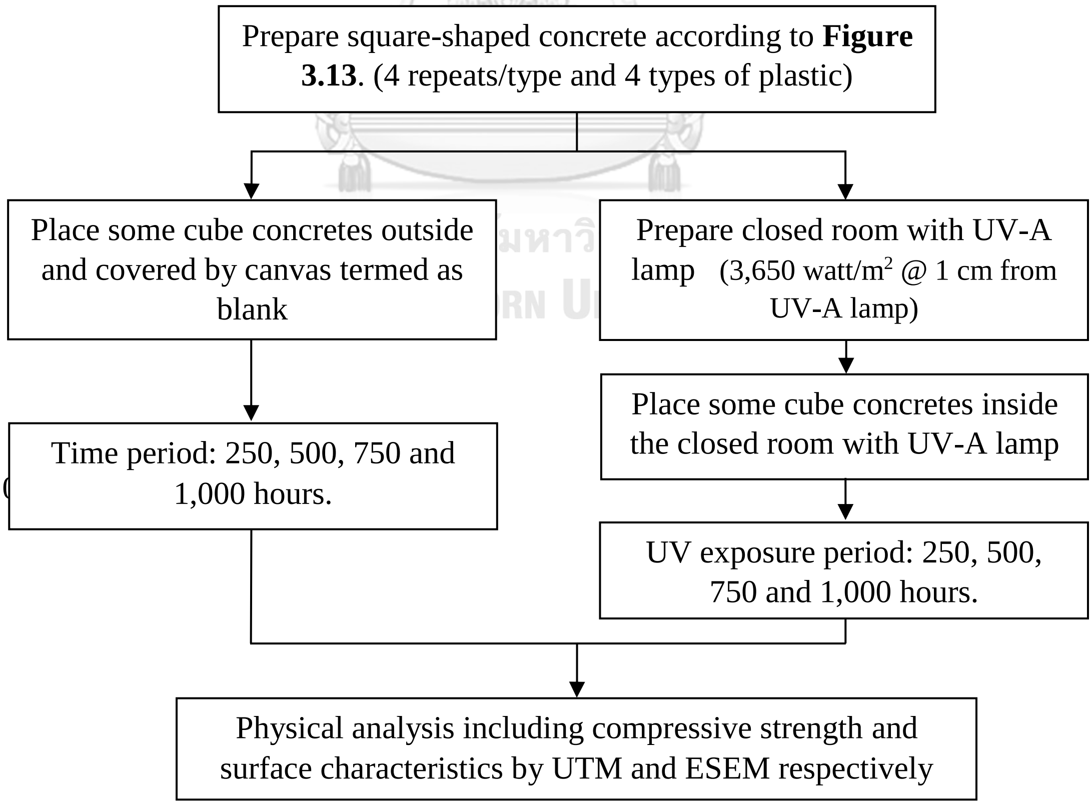
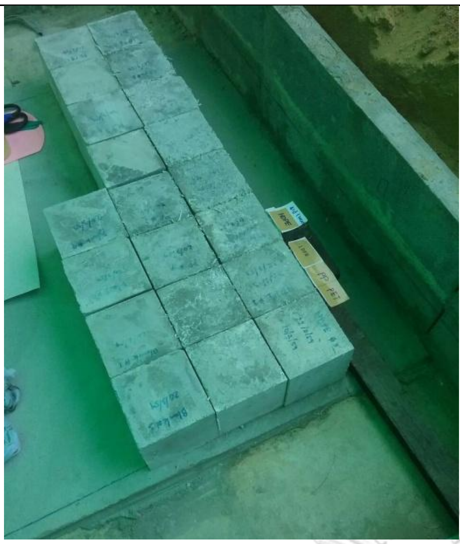


Figure 3.19 Ultraviolet (UV) effect study



(a)

(b)

(c)

(d)

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(e)

Figure 3.20 Photographs of UV effect study; (a) Cube concrete after curing 28 days, (b) Plastic fibers exposed by UV-A directly, (c) 1 cm between concrete surface and UV-A lamp, (d) UV-A chamber with UV-A lamp, and (e) Canvas covering on UV-A chamber

8) Thermal conductivity

Thermal conductivity of HDPE, LDPE and PP are about 0.43, 0.35 and 0.23 W/(m K) at 25 °C [39] and thermal conductivity of PET is about 0.15-0.40 W/(m K) at 23 °C [40], which seem to be lower than ordinary mortar (about 0.9-2.3 W/(m K) [36] [37]), so synthetic fiber reinforced concrete is assumed to help resist heat transfer than ordinary mortar. The samples of synthetic fiber reinforced concrete are cast in square shape (30x30x7.5 cm^3) as shown in **Figure 3.15**. Thermal conductivity is analyzed by Heat flow meter (NETZSCH HFM 436) as **Figure 3.21** according to ASTM C 518 [53]. Thermal conductivity (K-value) can be calculated by **Equation 5**.

Thermal conductivity (K-value) $= \frac{Q \times L}{A \times \Delta T}$ **Equation 5**

Where; Thermal conductivity (W/m-K) = A material property to conduct heat

Q = Heat transfer (W)

L = Thickness of sample (m)

A = Heat area (m^2)

ΔT = Temperature difference between hot and cold sides

Figure 3.21 Photographs of heat flow meter: NETZSCH HFM 436 equipment

3.4 Quality Assurance and Quality Control

Quality Assurance and Quality Control of concrete work are very important to reduce man-made error and uncertainty from inappropriate equipment use. This study aims to reduce these errors by following to ASTM or other international standards. Quality Control of concrete work of this study is as following;

- Raw materials (cement, sand, water, admixture and so on) are prepared, collected, cleaned and used according to ASTM standards.
- Mixing design of concrete is based on ASTM standard and other research work.
- All equipment such as balance, measuring container, concrete mixer and so on is calibrated according to ASTM standards.
- Preliminary experiment of concrete work is required to check some parameters such as slump test and compressive strength.
- Record form is designed to collect all necessary data of each parameter; for example, analysis date, temperature, concrete dimension, concrete failure characteristics etc.
- All analysis results are analyzed by statistical tools such as mean value, standard deviation etc.
- Result analysis and discussion are followed ASTM standards.
- Monitor and correction are required in all steps.

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CHAPTER 4 EXPERIMENT RESULTS

4.1 Plastic fiber test

4.1.1 Bulk unit weight

Four types of plastic wastes, including high density polyethylene (HDPE), low density polyethylene (LDPE), and polypropylene (PP) collected from a plastic bag manufacturer (T.VIJITPLASTICS, Bangkok, Thailand), as well as polyethylene terephthalate (PET) collected from a PET sheet manufacturer (ROYCE UNIVERSAL Co.,Ltd., Nakornpathom, Thailand), were utilized as part of ingredients for concrete production in this study. The plastic wastes were cleaned and cut into 3 mm wide and 50 mm long plastic fibers. Thicknesses of the plastic fibers were approximately 0.05 mm for HDPE and LDPE, 0.1 mm for PP and 0.2 mm for PET, respectively.

The four plastic fibers were fit as macro synthetic fibers in which their lengths were 12–65 mm [56] and equivalent diameters (thickness) were <0.3 mm [57]. Bulk unit weight of these fibers was investigated in order to convert the volume of plastic fibers into mass during concrete preparation. Bulk unit weight calculated by **Equation 6** was proportion between mass of plastic fibers and volume of container.

$$\text{Bulk unit weight} = \frac{(W_2 - W_1)}{V} \qquad \textbf{Equation 6}$$

Where; W_1 = Weight of empty container
W_2 = Weight of container with plastic fiber
V = Volume of container

The average bulk unit weight of plastic fibers was measured [47] as shown in **Table 4.1**; the values were 142 ± 12 kg/m^3 for HDPE, 221 ± 22 kg/m^3 for LDPE, 179 ± 12 kg/m^3 for PP, and 242 ± 5 kg/m^3 for PET. The results showed that low bulk density of plastic fibers resulted in high volume at the same weight. According to the bulk unit weight results, HDPE fiber was found to be the lowest value so its volume was the highest when comparing to the others. Lower bulk unit weight of plastic fiber mixing in concrete was likely to decrease bulk density of composite material (concrete). Besides, this bulk unit weight was used for preparing amount of fiber in concrete by converting to weight so the amount of plastic fiber used in the concrete mixing was calculated according to the different cement volume proportions (5%, 10%, 15%, 20%, 30%, 40% and 50%).

Table 4.1 Bulk unit weight of plastic fibers

Plastic types	Empty container weight (kg)	Container + fiber weight (kg)	Fiber weight (kg)	Volume of Container (m^3)	Bulk unit weight (kg/m^3)
1.HDPE	1.1	1.54	0.44	0.003	150.6
		1.56	0.46	0.003	157.4
		1.49	0.39	0.003	133.5
		1.52	0.42	0.003	143.8
		1.47	0.37	0.003	126.6
Average					142.4±12.5
2.LDPE	1.1	1.77	0.67	0.003	229.3
		1.70	0.60	0.003	205.4
		1.85	0.75	0.003	256.7
		1.70	0.60	0.003	205.4
		1.71	0.61	0.003	208.8
Average					221.1±22.3
3.PP	1.1	1.61	0.51	0.003	174.6
		1.58	0.48	0.003	164.3
		1.62	0.52	0.003	178.0
		1.62	0.52	0.003	178.0
		1.68	0.58	0.003	198.5
Average					178.7±12.4
4.PET	1.1	1.81	0.71	0.003	243.0
		1.79	0.69	0.003	236.2
		1.81	0.71	0.003	243.0
		1.83	0.73	0.003	249.9
		1.80	0.70	0.003	239.6
Average					242.3±5.1

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4.1.2 Nonionic surfactant

1) Interfacial tension

Interfacial tension calculated by **Equation 7** was proportion between force (mN) and wetted length of plastic sheet (m). According to **Figure 4.1**, the cosθ was the angle between liquid and the plate or plastic sheet. This study prepared the plastic sheets (HDPE LDPE PP and PET) as shown in **Figure 4.2** in order that they would be tested by tensiometer (DCAT 11) at HSM's laboratory.

Solution was prepared by varying nonionic surfactant (LS-12) in 0 (portable water), 1, 10, 30, 50, 70, and 100 times of critical micelle concentration (CMC). According to Thai Ethoxylate Company Limited, CMC of LS-12 at 25 °C was about 42 ppm or mg/l so the LS-12 concentrations used in experiment were varied about 0, 42, 420, 1260, 2100, 2940, and 4200 ppm or mg/l respectively.

$$\text{Interfacial tension (mN/m)} = \frac{F}{(L \; x \; cos\theta)} \qquad \textbf{Equation 7}$$

Where;

Where;	F	=	Force of compression (mN)
	L	=	Wetted length of material (m)
	cosθ	=	Angle between liquid and solid surface

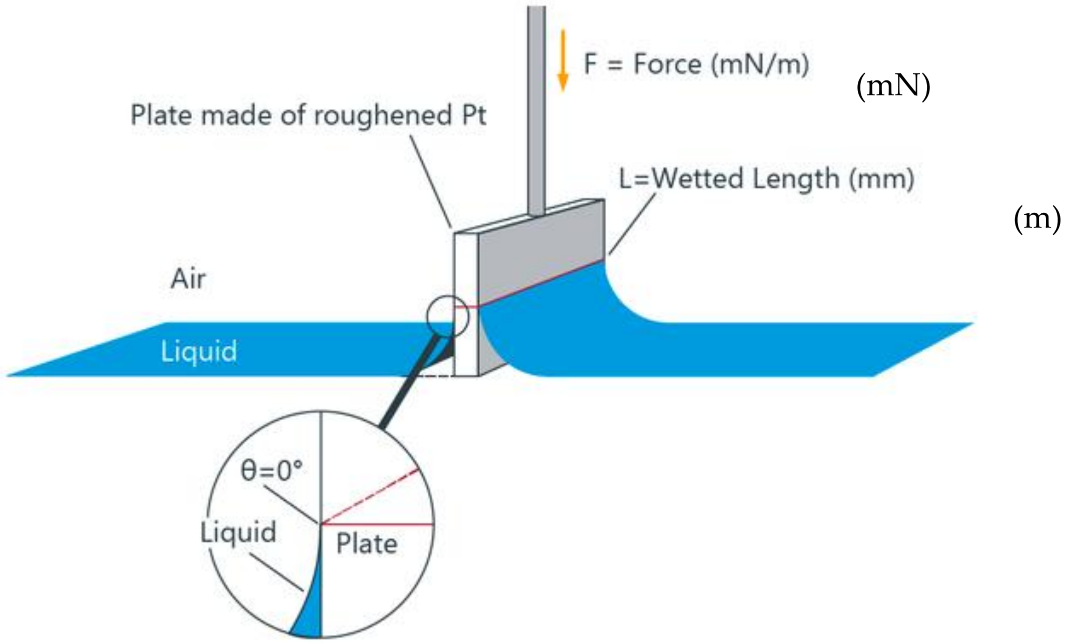

Figure 4.1 The Interfacial tension measurement of Wilhelmy plate method [58]

(a) (b)

Figure 4.2 Plastic sheet preparation for Interfacial tension and contact angle measurement (a) Interfacial tension and contact angle measurement using a DCAT 11 with cooler, and (b) Plastic samples in a 1 cm × 2 cm size

This study found that average values of Interfacial tension between portable water and HDPE LDPE PP and PET surface were about 49.6±8.4, 36.3±4.1, 27.9±3.8, and 37.9±4.5 mN/m respectively as shown in **Table 4.2** and **Figure 4.3**. The low Interfacial tension could enhance the wettability of solution on plastic surface so the lowest Interfacial tension values between all plastic types and LS-12 solution was found to be at 30 x CMC of LS-12 which were 26.8±0.3, 26.4±0.8, 25.5±0.3, and 25.4±0.5 mN/m on average respectively.

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Table 4.2 Interfacial tension between plastic fiber and LS-12 solution

Unit: mN/m

Sample number	HDPE	LDPE	PP	PET
Portable water				
1	53.5	29.7	26.6	42.9
2	38.1	35.5	28.3	39.7
3	60.2	40.0	24.2	40.5
4	45.1	37.9	26.1	32.4
5	51.1	38.7	34.1	33.9
Average	49.6±8.4	36.3±4.1	27.9±3.8	37.9±4.5
1 x CMC (42 mg/l)				
1	42.8	32.5	29.0	38.9
2	38.8	32.5	32.8	38.1
3	47.2	36.5	30.5	38.8
4	47.1	35.8	31.4	35.8
5	49.3	37.8	34.8	35.7
Average	45.1±4.2	35.0±2.4	31.7±2.2	37.4±1.6
10 x CMC (420 mg/l)				
1	31.0	31.9	31.4	31.8
2	33.2	32.9	31.2	31.4
3	32.3	32.5	30.8	31.3
4	31.7	32.2	31.4	31.0
5	31.6	32.6	31.4	31.5
Average	32.0±0.8	32.4±0.4	31.2±0.3	31.4±0.3
30 x CMC (1260 mg/l)				
1	27.3	27.3	25.6	26.2
2	26.7	27.1	25.4	25.1
3	26.6	26.5	25.8	25.4

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Sample number	HDPE	LDPE	PP	PET
4	26.6	25.6	25.9	25.0
5	26.6	25.8	25.1	25.4
Average	26.8±0.3	26.4±0.8	25.5±0.3	25.4±0.5
50 x CMC (2100 mg/l)				
1	29.0	28.5	28.9	28.5
2	28.8	29.5	28.8	28.4
3	29.2	24.9	29.0	28.7
4	29.0	28.7	28.9	28.8
5	29.1	29.0	28.8	29.2
Average	29.0±0.1	28.1±1.8	28.9±0.1	28.7±0.3
70 x CMC (2940 mg/l)				
1	27.4	26.9	26.9	27.0
2	29.2	27.8	26.7	27.0
3	33.3	27.0	29.0	37.2
4	27.2	26.7	27.0	26.6
5	27.2	26.9	26.8	32.6
Average	28.8±2.6	27.1±0.4	27.3±1.0	30.1±4.7
100 x CMC (4200 mg/l)				
1	31.8	31.4	31.4	31.7
2	31.6	31.7	31.1	31.5
3	34.7	31.4	34.0	31.4
4	31.3	31.1	31.4	31.2
5	31.5	31.4	31.2	37.1
Average	32.2±1.4	31.4±0.2	31.8±1.2	32.6±2.6

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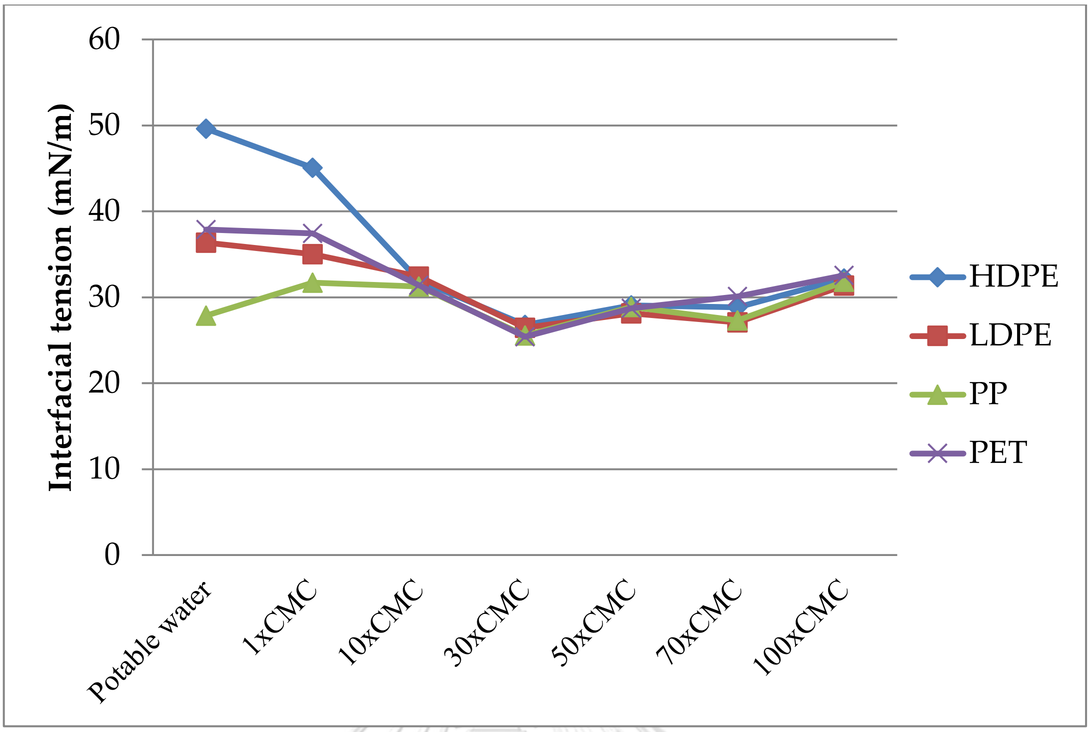

Figure 4.3 Average value of Interfacial tension

2) Contact angle

Lower contact angle as shown in **Figure 4.4** could increase water coating on plastic surface [58] so LS-12 as nonionic surfactant was used for reducing the contact angle between water droplet and plastic surface in order to increase wettability of solution on plastic surface. This might help enhancing adhesiveness and indirectly decreasing air void between concrete matrix and plastic surface during concrete mixing. Contact angle calculated by **Equation 8** was the relationship of interfacial tension between liquid and solid phases.

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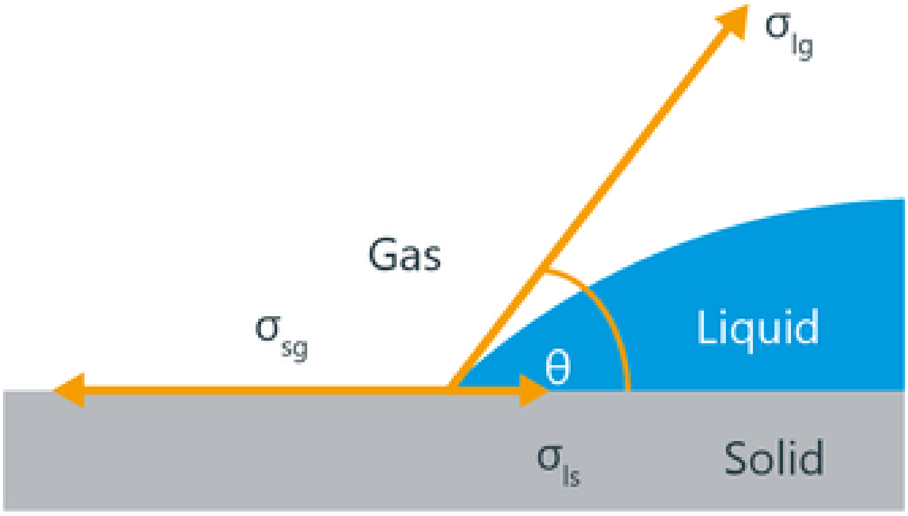

Figure 4.4 Contact angle measurement of Wilhelmy plate method [58]

$$\sigma_s = \sigma sl + (\sigma l \; x \; cos\theta) \qquad \textbf{Equation 8}$$

Where; σ_s = Surface free energy of solid (mN/m)

σ_{sl} = Interfacial tension between liquid and solid (mN/m)

σ_l = Interfacial tension of liquid (mN/m)

θ = Contact angle

The contact angle results of this study shown in **Table 4.3** and **Figure 4.5** were found that average contact angle between portable water and plastic surface were about 72.4±1.5, 73.7±1.5, 69.9±1.6, and 67.4±3.6 degree respectively. The lowest contact angles between LDPE PP and PET sheet and LS-12 solution were about 67.3±0.8, 66.2±1.0, and 64.2±0.7 degree at 100 x CMC of LS-12 while HDPE's was 65.2±4.0 degree at 1 x CMC.

Table 4.3 Contact angle results between various LS-12 concentrations and plastics

Unit: Degree

Sample number	HDPE	LDPE	PP	PET
Portable water				
1	73.7	75.0	69.9	66.9
2	70.2	71.1	71.9	61.5
3	73.9	73.7	70.7	71.2
4	71.8	73.9	67.7	68.1
5	72.4	74.6	69.1	69.1
Average	72.4±1.5	73.7±1.5	69.9±1.6	67.4±3.6
1 x CMC				
1	67.1	68.3	67.3	67.8
2	66.5	67.7	65.4	65.5
3	67.2	68.1	68.1	67.6
4	58.0	69.1	67.4	67.2
5	67.2	68.4	66.7	66.8
Average	65.2±4.0	68.3±0.5	67.0±1.0	67.0±0.9
10 x CMC				
1	67.7	68.1	67.3	66.7
2	66.6	68.0	65.7	65.1
3	67.1	67.4	68.1	64.8
4	66.7	68.3	67.5	64.9
5	67.0	66.8	66.1	65.7
Average	67.0±0.4	67.7±0.6	66.9±1.0	65.4±0.8
30 x CMC				
1	67.5	67.7	67.0	65.7
2	65.9	67.4	65.4	64.2
3	66.8	67.1	67.1	63.7

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Sample number	HDPE	LDPE	PP	PET
4	67.1	67.9	66.8	64.8
5	66.9	67.1	65.9	65.6
Average	66.8±0.6	67.4±0.4	66.4±0.8	64.8±0.9
50 x CMC				
1	67.3	68.0	66.9	66.3
2	66.3	67.5	66.7	65.6
3	66.5	66.9	67.6	65.6
4	67.6	68.7	66.5	65.7
5	68.6	68.2	66.4	65.2
Average	67.3±0.9	67.9±0.7	66.8±0.5	65.7±0.4
70 x CMC				
1	68.1	68.6	67.8	66.5
2	64.6	67.5	67.0	67.0
3	63.5	67.6	68.7	65.8
4	68.0	69.4	68.1	66.8
5	67.5	67.2	66.4	63.9
Average	66.3±2.1	68.0±0.9	67.6±0.9	66.0±1.3
100 x CMC				
1	66.6	67.0	66.9	65.4
2	65.3	67.2	65.6	64.2
3	67.4	66.5	67.3	63.6
4	66.5	68.1	66.5	63.8
5	66.4	67.5	64.7	63.8
Average	66.4±0.8	67.3±0.6	66.2±1.0	64.2±0.7

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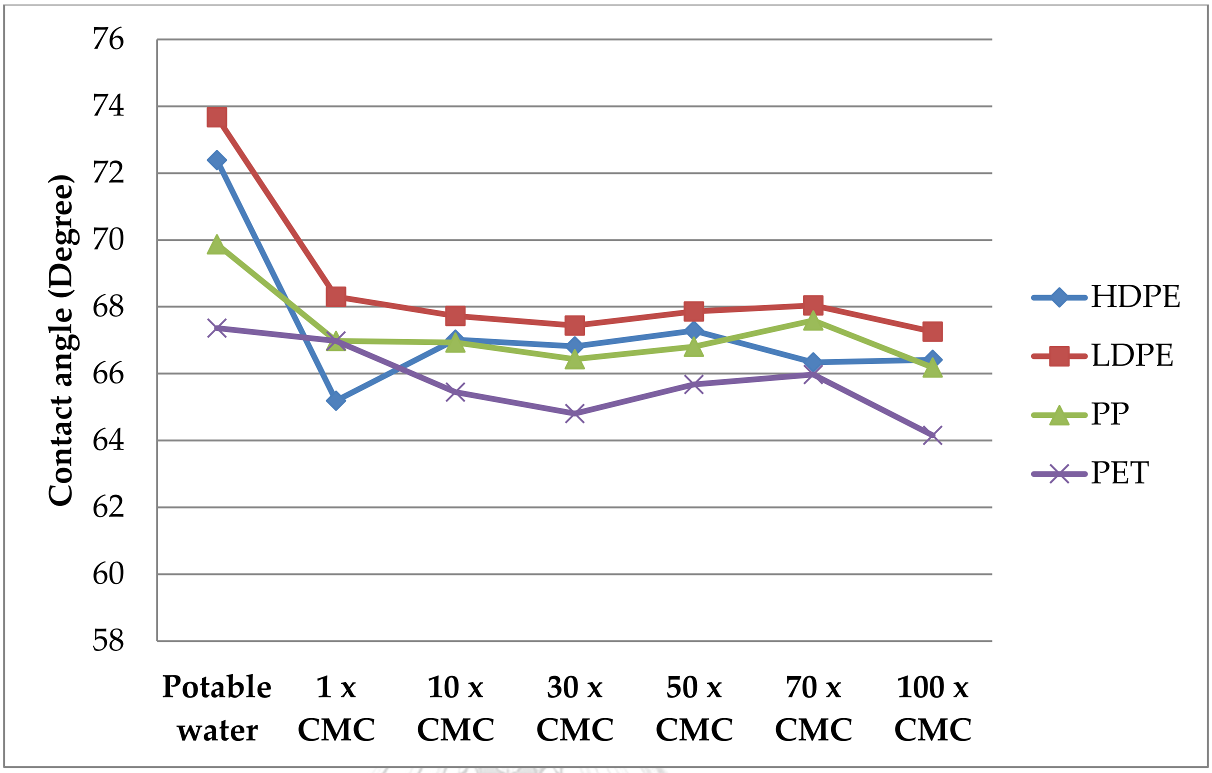

Figure 4.5 Average value of contact angle

According to **Figure 4.3** and **Figure 4.5**, the Interfacial tension and contact angle values of 1-100 times of CMC were not significantly different so 1 x CMC of LS-12 was found to be enough for enhancing wettability of liquid on plastic surface. However, 10 x CMC of LS-12 should be recommended to use in further concrete experiment because 10 times was safety factor to make sure that surfactant was working in concrete matrix properly.

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4.1.3 Degradation

1) Alkalinity resistance

1.1) Tensile strength

Tensile strength or stress was the material property which could resist forcing to material's elongation. Tensile strength equation was calculated in **Equation 9**.

$$\sigma = \frac{F}{A} \qquad \textbf{Equation 9}$$

Where; σ = Tensile strength (N/mm^2)
F = Elongation force (N)
A = Area of cross section of materials (mm^2)

- Plain plastic fibers

Tensile strengths of macro synthetic fibers (HDPE, LDPE, PP and PET) of this study tested as ASTM D882 [59] in 5 repeats were about 155.5±12.8 N/mm^2 (1,585.66±130.52 kg/cm^2), 75.4±5.9 N/mm^2 (768.87±60.16 kg/cm^2), 40.5±1.3 N/mm^2 (412.99±13.26 kg/cm^2) and 104.0±16.1 N/mm^2 (1,060.50±164.17 kg/cm^2) at ambient temperature (25 °C) respectively as shown in **Table 4.4** and **Figure 4.6** which were lower than ASTM D7508 standard for polyolefin chopped strands requirement (344.4 N/mm^2) [56]. According to previous study, tensile strengths of recycled macro PP and PET fibers were found to be about 250.0-550.0 and 263.7-550.0 N/mm^2 respectively [27, 44, 60, 61]. Recycled macro HDPE LDPE and PP fibers of this study are made of waste of plastic bag-producing company and recycled macro PET fiber is made of waste of PET sheet-producing company. Comparing to other studies above, their tensile strengths seemed to be lower than others. The major causes could be described; 1) difference of additive chemicals or recycled plastic added in plastic waste and 2) the age of recycled plastics exposed by environment; consequently, they may result in their tensile strengths lower than those. In this study results, it could be concluded that tensile strength of HDPE was found to be the highest value while PP was found to be the lowest one.

- Plastic fibers immersed in water

Plastic fibers immersed in water were used for comparing to ones soaked in alkaline solution. Time periods of this study were varied at 7, 14, 28, 90 and 180 days. The first fourth was considered as short term periods of degradation while 180 days was assumed as representative of long term period. Tensile strengths of HDPE LDPE PP and PET fibers were found about 41.3-57.4 N/mm^2 (421.14-585.32 kg/cm^2), 68.3-84.6 N/mm^2 (696.47-862.68 kg/cm^2), 39.0-43.0 N/mm^2 (397.69-438.48 kg/cm^2) and 116.6-131.2 N/mm^2 (1,188.99-1,337.87 kg/cm^2) respectively as shown in **Table 4.4** and **Figure 4.6**. These results could be informed that percentage of tensile strengths of LDPE PP and PET comparing to plain plastic fibers were differed about (-9)-12%, (-4)-6% and 12-26% respectively, which were not significantly different. Conversely, percentage of HDPE's tensile strength comparing to plain plastic fibers was dramatically declined by water about (-73)-(-63)%. According to Ho and others [62], they found that temperature and humidity were able to increase the rate of degradation of plastic. Moreover, Ragaert and others [63] and Dahlbo and others [64] informed that humidity exposure is one of the degradation factors of plastic age. So, this study results were found that tensile strength and break extension of HDPE made from waste immersed in water from 7-180 days at 25 °C could be reduced by water exposure. However, HDPE's, LDPE's, PP's, and PET's results would need more information such as swelling effect, water absorption, and so on in order to confirm their negative effects.

- Plastic fibers immersed in $Ca(OH)_2$

Concrete is likely to be an alkaline material so alkalinity resistance of recycled plastic wastes as macro fiber used in concrete in this study is proved. Calcium hydroxide ($Ca(OH)_2$) (pH 12.3) is considered as a major representative of alkali in hardened concrete due to hydration reaction so this study used saturated calcium hydroxide solution as alkaline solution. All plastic fibers were immersed in base solution varying in time periods (7, 14, 28, 90 and 180 days). Tensile strength loss was indicated for degree of degradation of recycled plastic fiber in alkaline environment. Tensile strengths of plastic fibers (HDPE LDPE PP and PET) were found to be about 43.9-99.7 N/mm^2 (447.66-1,016.66 kg/cm^2), 43.9-74.3 N/mm^2 (447.66-757.65 kg/cm^2), 35.8-42.2 N/mm^2 (365.06-430.32 kg/cm^2) and 116.5-132.9 N/mm^2 (1,187.97-1,355.20 kg/cm^2) respectively as shown in **Table 4.4** and **Figure 4.6**. When comparing to tensile strength of plain synthetic fibers, their percentage differences were (-72)-(-36)%, (-42)-(-2)%, (-12)-4% and 12-28% respectively. It was found that HDPE's and LDPE's tensile strength immersed in alkaline solution was declined while PP's and PET's tensile strengths were not significantly different from plain samples and water-immersed samples. It was some argument in HDPE and PET performance in concrete matrix. According to EPC company report [7, 65], they proved that olefin polymers especially HDPE and PP were able to resist alkaline condition in 100 year without decreasing in their strength. While, Elasto Plastic Concrete (EPC) company [65] found that PET was able to perform only 10 years in concrete matrix. Moreover, Silva et al. [44] using alkaline solution (Lawlence solution including 0.48 g/l Ca(OH)2, 3.45 g/l KOH and 0.88 g/l NaOH, pH=12.9) to test PET durability in alkaline condition found that PET toughness was decreased with immersion time.

However, Ochi et al. (2007) [27] and Fraternali et al. [46] found that tensile strengths of PP and PET fibers immersed in strong alkaline solution (10 g/L NaOH) at 60 °C for 5 days were durable in such environment, which was found a bit lower than control about 1-13% and 14% respectively. Comparison between previous study and this study made of waste, PP's tensile strength of this study was able to tolerate alkaline environment same as those. HDPE's tensile strength was decreased by water and alkaline solution since 7 day exposure while LDPE's was not clearly decreased by water and alkaline solution. Moreover, PET's tensile strength was not deteriorated by base solution which was same as Ochi et al. (2007) [27] and Fraternali et al. [46] results.

Table 4.4 Physical property of recycled plastic fibers

Plastics	Tensile strength (N/mm²)	Break extension (%)	Modulus of elasticity (N/mm²)
Control (plain plastic)			
HDPE	155.5±12.8	300.0±54.7	52.7±7.1
LDPE	75.4±5.9	724.0±52.5	10.4±0.7
PP	40.5±1.3	21.6±6.1	198.2±50.8
PET	104.0±16.1	7.8±1.5	1361.0±186.4
Soaked by Water			
HDPE	41.3±7.3 to 57.4±7.4	18.1±7.8 to 30.9±33.5	284.4±151.8 to 449.9±390.4
LDPE	68.3±18.5 to 84.6±4.8	649.6±61.9 to 726.4±56.3	10.5±0.5 to 11.7±0.7
PP	39.0±1.8 to 43.0±4.1	13.5±3.5 to 26.8±13.1	170.1±22.2 to 324.8±109.9
PET	116.6±7.8 to 131.2±1.6	7.8±0.2 to 9.1±1.6	1442.0±129.9 to 1574.1±93.3
Soaked by Alkalinity ($CaOH_2$)			
HDPE	43.9±13.6 to 99.7±18.6	132.7±31.9 to 262.0±92.2	32.0±11.6 to 71.7±51.9
LDPE	43.9±19.9 to 74.3±14.3	391.0±269.9 to 656.0±83.4	10.0±0.9 to 15.1±5.3
PP	35.8±4.3 to 42.2±6.3	18.6±2.0 to 32.0±19.8	141.9±91.8 to 219.0±26.4
PET	116.5±1.6 to 132.9±1.7	7.4±0.5 to 9.5±3.3	1314.8±339.5 to 1742.0±104.5

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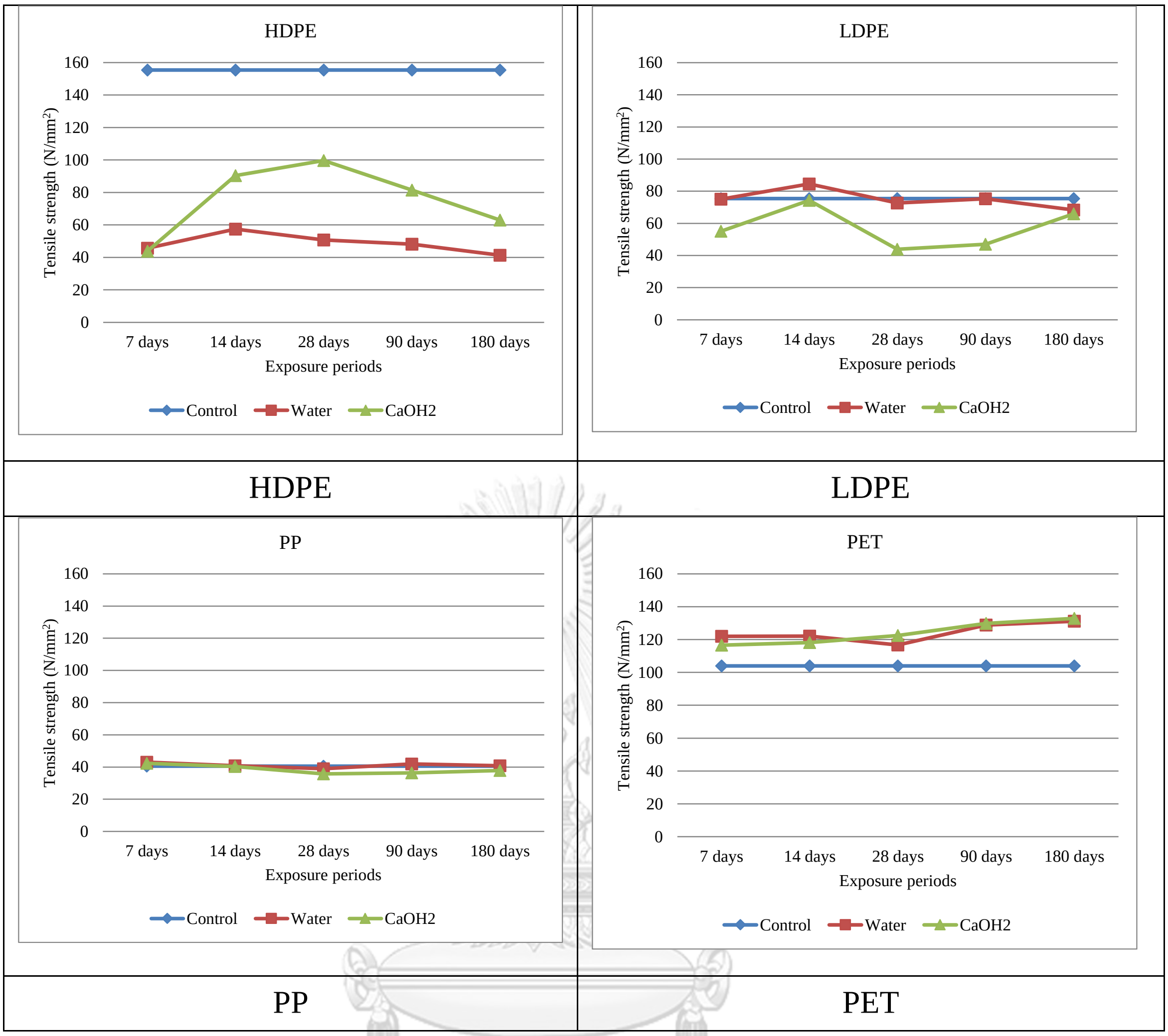

Figure 4.6 Tensile strength of synthetic fibers (HDPE, LDPE, PP and PET)

1.2) Break extension

Break extension or strain calculated by **Equation 10** was the proportion between difference stretching lengths and original length of material. Normally, this value is unitless.

$$\varepsilon = \frac{(L_2 - L_1)}{L_1} \qquad \textbf{Equation 10}$$

Where; ε = Strain (no unit)

L_1 = Length of material before stretching (m)

L_2 = Length of material after stretching (m)

- Plain plastic fibers

Break extension of recycled plastic fiber implies to the extension of material after stretching. Plastic property is normally found to have higher elongation than other rigid materials which are usually hardness but brittleness. Break extension results (HDPE, LDPE, PP and PET) of this study were about 300.0±54.7%, 724.0±52.5%, 21.6±6.1% and 7.8±1.5% respectively as shown in **Table 4.4** and **Figure 4.7**. In this study, LDPE's break extension was found to have the highest value while PET's was the lowest one.

- Plastic fibers immersed in water

Break extension results of HDPE, LDPE, PP and PET fibers after immersed in water were about 18.1-30.9%, 649.6-726.4%, 13.5-26.8% and 7.8-9.1% respectively as shown in **Table 4.4** and **Figure 4.7**. These results proved that break extensions of LDPE PP and PET fibers comparing to plain plastic fiber were varied about (-10)-0%, (-37)-24% and 0-17% respectively, which was slightly different from plain plastic fibers so it meant that their break extensions were not notably affected by water. While, HDPE's break extension was clearly reduced about (-94)-(-90)% from plain synthetic fiber.

- Plastic fibers immersed in $Ca(OH)_2$

Break extension results (HDPE, LDPE, PP and PET) after immersed in alkaline solution were about 132.7-262.0%, 391.0-656.0%, 18.6-32.0% and 7.4-9.5% respectively as shown in **Table 4.4** and **Figure 4.7**. When comparing to break extension of plain synthetic fibers, their percentage differences were (-56)-(-13)%, (-46)-(-9)%, (-14)-48% and (-4)-22% respectively. HDPE's and LDPE's break extension seemed to be affected by $Ca(OH)_2$ while PP and PET demonstrated that alkaline solution did not significantly affect to their break extensions.

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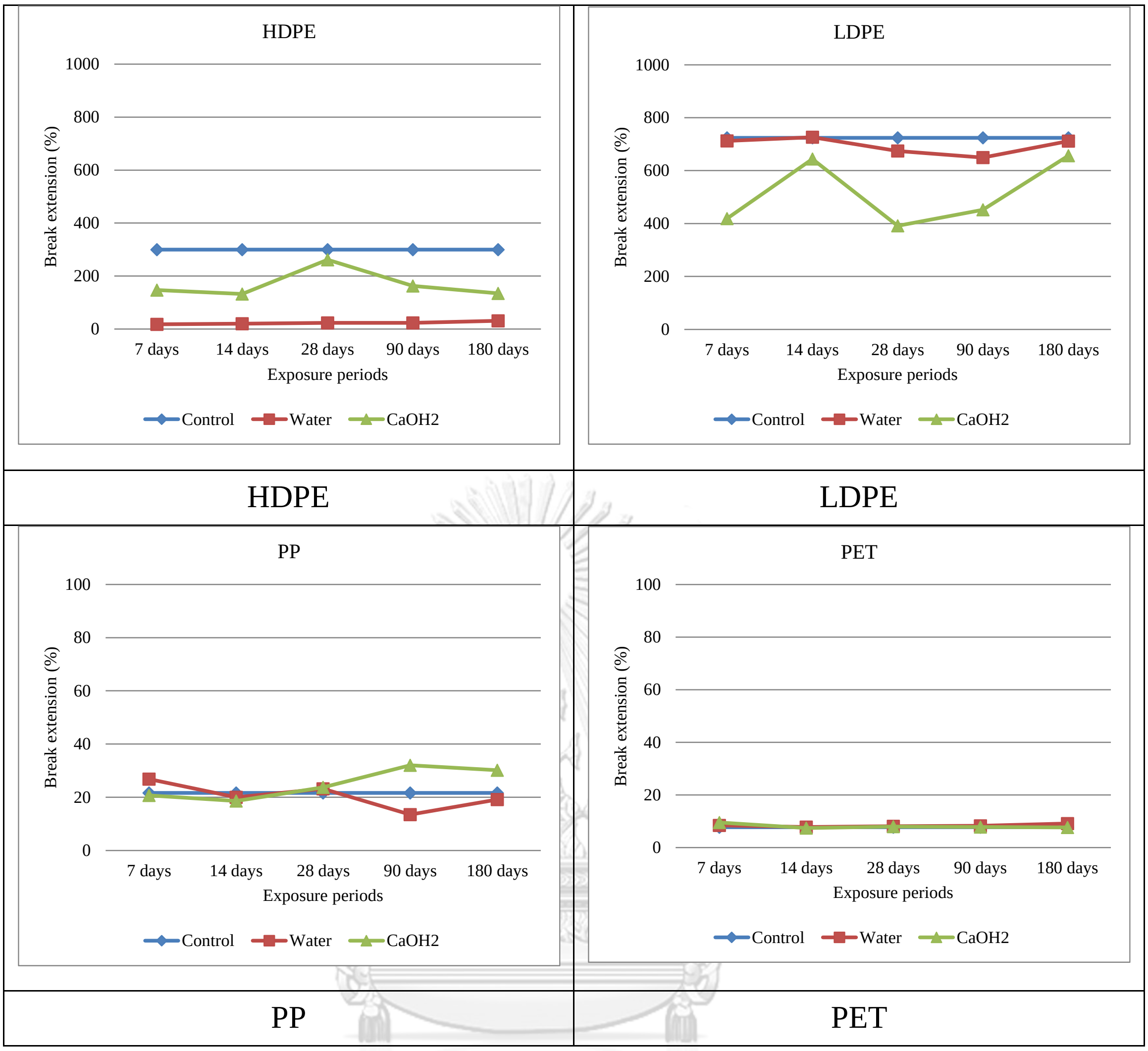

Figure 4.7 Break extensions of synthetic fibers (HDPE, LDPE, PP and PET)

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1.3) Modulus of elasticity

Modulus of elasticity was the proportion between stress and strain or slope of stress-strain curve. The higher modulus of elasticity value meant material stiffer than the lower one. Modulus of elasticity could be calculated by **Equation 4**.

- Plain plastic fibers

Modulus of elasticity was the proportion between stress which was force per area and strain which was deformation ratio of materials. The low modulus of elasticity value of materials was likely to be elastic materials while high value was likely to be stiff materials. The results of this study showed that modulus of elasticity values of HDPE, LDPE, PP, and PET were about 52.7±7.1 N/mm^2 (537.39±72.40 kg/cm^2), 10.4±0.7 N/mm^2 (106.05±7.14 kg/cm^2), 198.2±50.8 N/mm^2 (2,021.08±518.02 kg/cm^2), and 1361.0±186.4 N/mm^2 (13,878.34±1,900.75 kg/cm^2) respectively as shown in

Table 4.4 and **Figure 4.8**. As the results, HDPE and LDPE were more elastic than PP and PET and PET was found to be the stiffest when comparing to others.

- Plastic fibers immersed in water

The results of modulus of elasticity of plastic fibers (HDPE, LDPE, PP and PET) immersed in water were about 284.4-449.9 N/mm^2 (2,900.07-4,587.70 kg/cm^2), 10.5-11.7 N/mm^2 (107.07- 119.31 kg/cm^2), 170.1-324.8 N/mm^2 (1,734.5-3,312.04 kg/cm^2), and 1442.0-1574.1 N/mm^2 (14,704.31-16,051.35 kg/cm^2) respectively as shown in **Table 4.4** and **Figure 4.8**. When comparing to plain plastic fibers, modulus of elasticity values of LDPE, PP, and PET were slightly increased (about 1-12%, (-14)-16%, and 6-16%) but HDPE's was highly raised (439-753%).

- Plastic fibers immersed in $Ca(OH)_2$

The results of modulus of elasticity of plastic fibers (HDPE, LDPE, PP and PET) immersed in alkaline solution (saturated $CaOH_2$ at pH = 12.3) were about 32.0-71.7 N/mm^2 (326.31-731.14 kg/cm^2), 10.0-15.1 N/mm^2 (101.97-153.98 kg/cm^2), 141.9-219.0 N/mm^2 (1,446.98-2,233.18 kg/cm^2), and 1314.8-1742.0 N/mm^2 (13,407.23-17,763.46 kg/cm^2) respectively as shown in **Table 4.4** and **Figure 4.8**. When comparing to plain plastic fibers, modulus of elasticity values of HDPE, LDPE, PP, and PET were about (-39)-36, (-4)-45%, (-28)-11%, and (-3)-28% respectively which were not significantly affected by alkaline solution.

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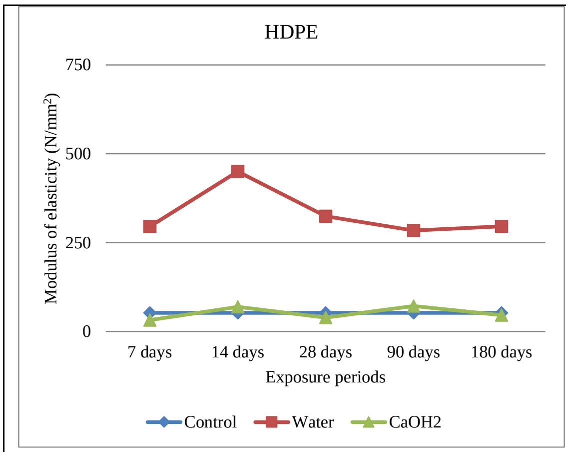
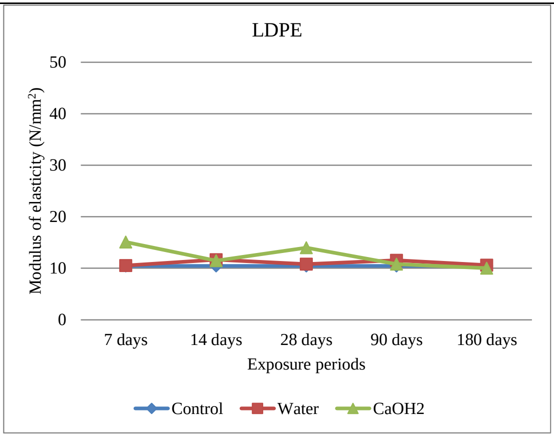
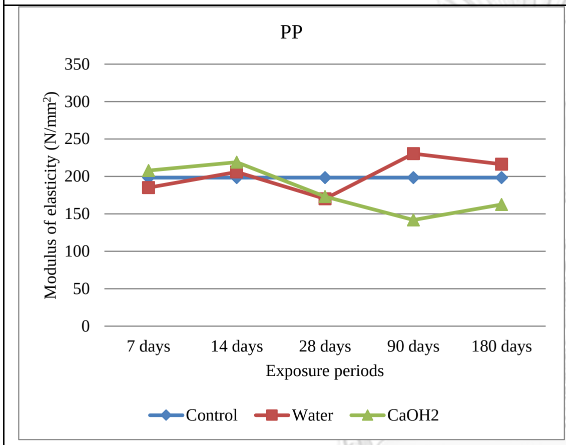


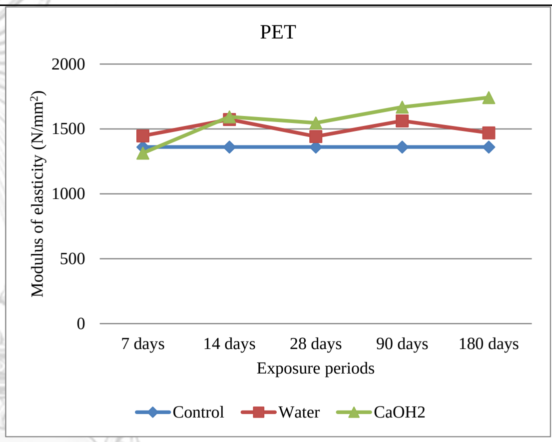
HDPE



LDPE



PP



PET

Figure 4.8 Modulus of elasticity of synthetic fibers (HDPE, LDPE, PP and PET)

1.4) Surface analysis

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- Plain plastic fibers

Surface analysis figures or micrograph of HDPE LDPE PP and PET surfaces were analyzed by Scanning Electron Microscope (SEM) at accelerating beam voltage of 20 kV and magnification of 10000x. Plastic surfaces were very sensitive to destroy by electron beam of SEM so gold-coated plastic samples were prepared before testing in order to protect plastic surface deterioration during surface scanning by SEM. According to surface analysis results as shown in **Figure 4.9**, HDPE surface was found to be corrugated and flaky and PP surface was rough and scratch whereas LDPE and PET surfaces were plain and smooth.

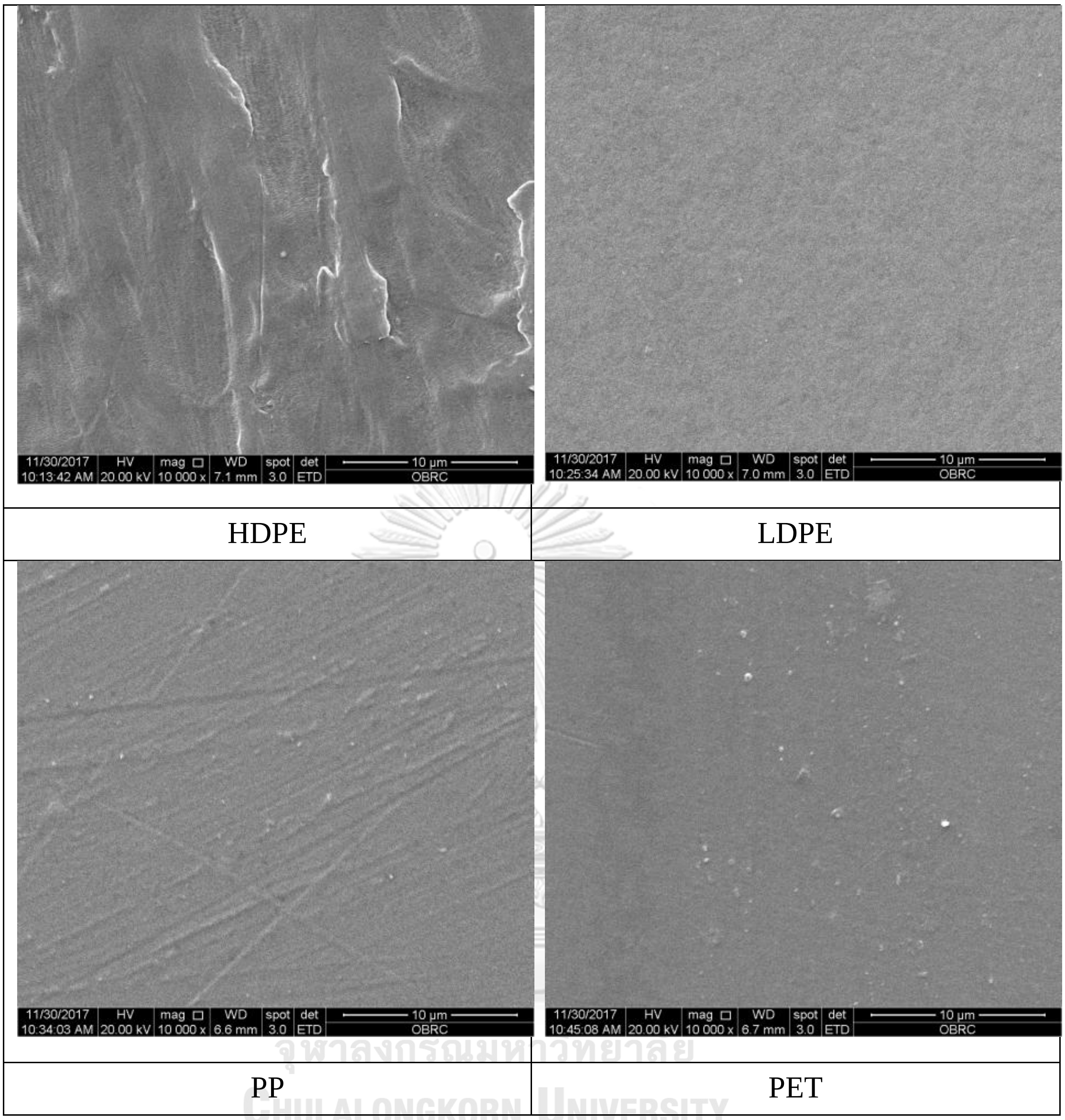

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Figure 4.9 Micrograph of plain HDPE, LDPE, PP and PET fibers
(Beam voltage: 20kV and magnification: 10000x)

- Plastic fibers immersed in water

This study soaked 4 plastic fibers in water in order to compare alkaline solution as control samples in 7, 14, 28, 90, and 180 days. Micrographs of HDPE LDPE PP and PET soaked by water at 7-180 days were not different so micrograph of 180 days was selected as representative of plastic fibers in water. Their surfaces as shown in **Figure 4.10** were not obviously different from surfaces of plain plastic fibers as shown in **Figure 4.9**.

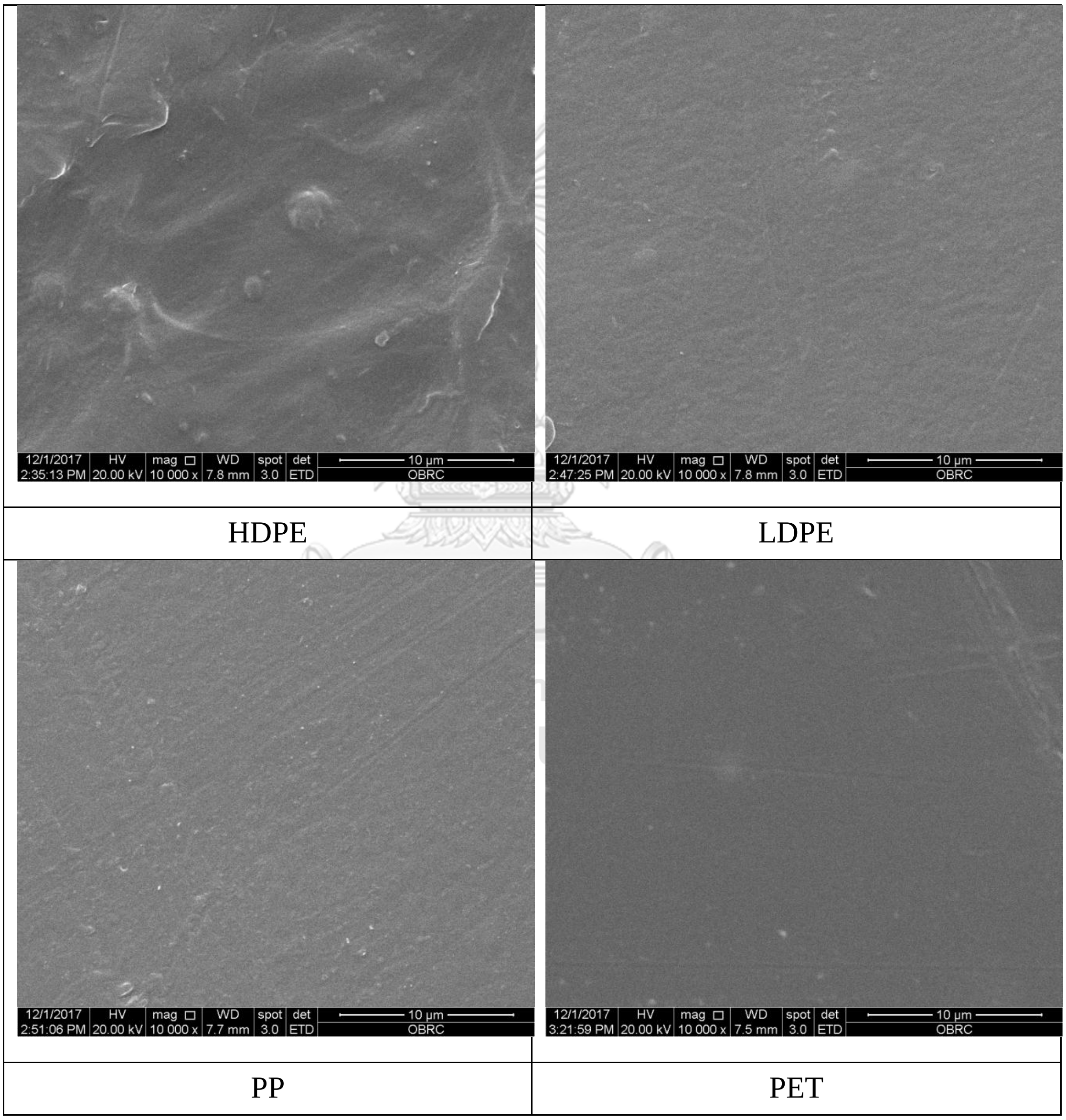

Figure 4.10 Micrograph of HDPE, LDPE, PP and PET fibers immersed in water 180 days (Beam voltage: 20kV and magnification: 10000x)

- Plastic fibers immersed in $Ca(OH)_2$

After plastic fibers immersed in alkaline solution varying in 7, 14, 28, 90 and 180 days, surface analysis of synthetic fibers (HDPE, LDPE, PP and PET) was investigated by Scanning Electron Microscope (SEM). Micrographs of HDPE LDPE and PP surfaces at 7, 14, 28, 90 and 180 days were found to be same as plain synthetic fibers as shown in **Figure 4.11**. While PET surfaces at 7 and 14 days were same as plain plastic fiber but 28, 90 and 180 days were found to have some spikes or some small hole on their surface. Although some PET surface results were found to have some flaws, their tensile strengths were not significantly reduced.

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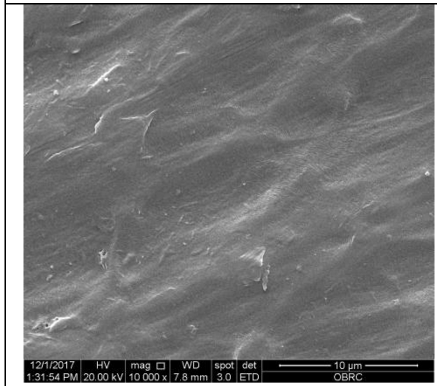
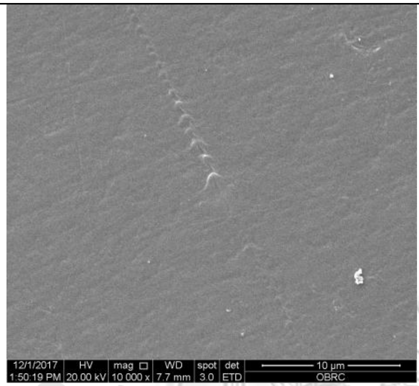
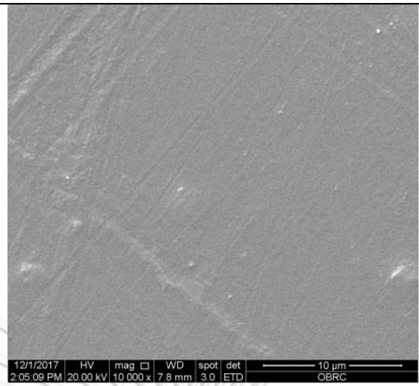
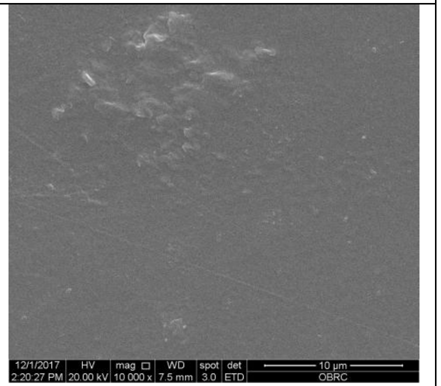
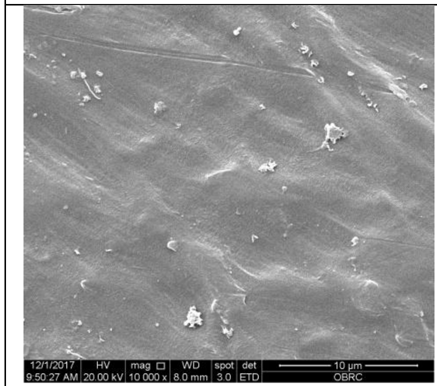
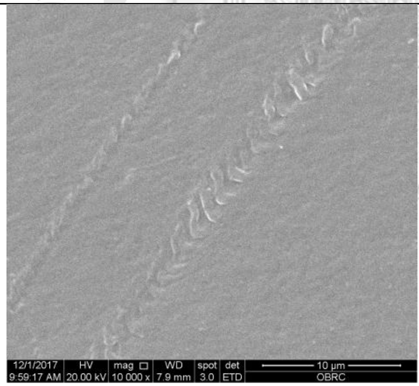
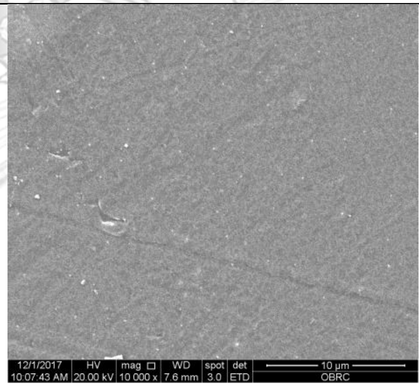
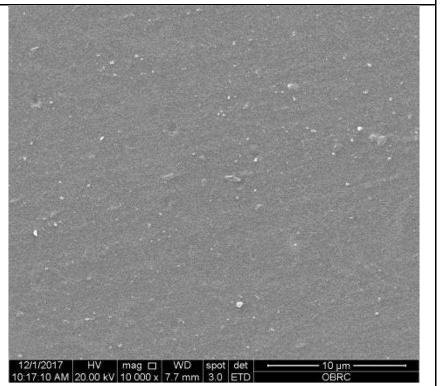
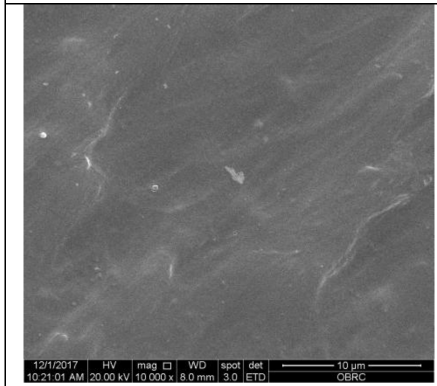
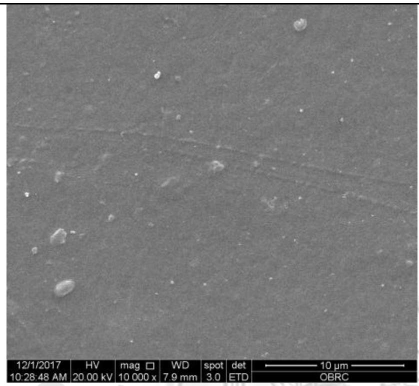
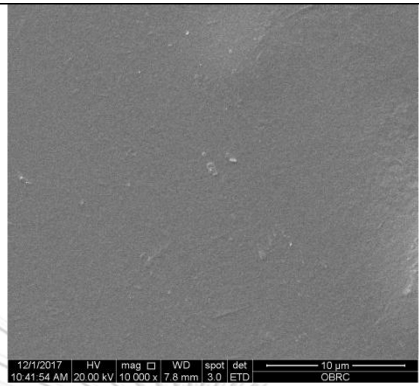
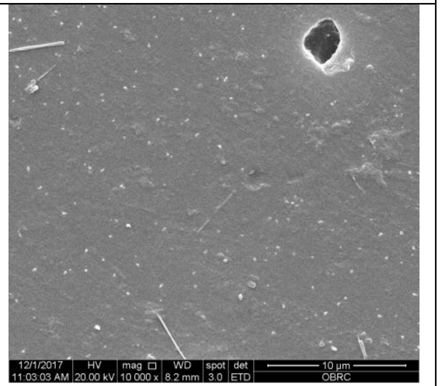
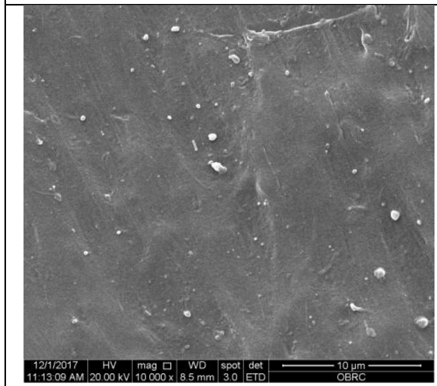
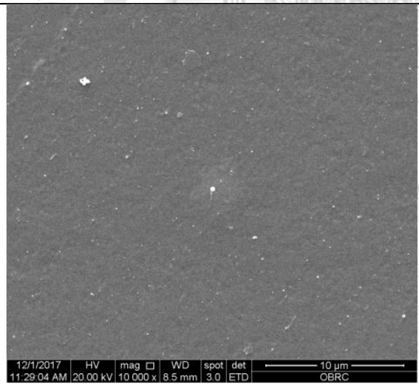
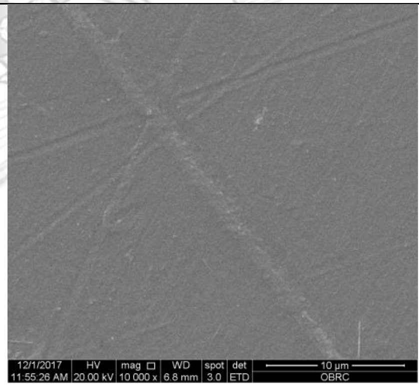
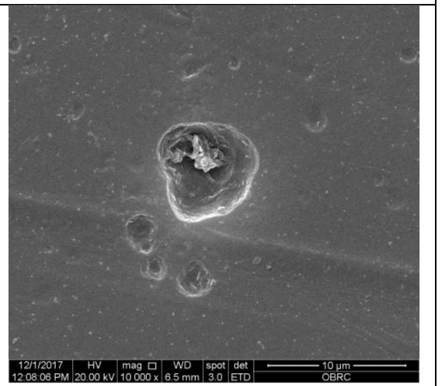
HDPE	LDPE	PP	PET
			
Alkaline solution: 7 days			
			
Alkaline solution: 14 days			

HDPE	LDPE	PP	PET
			
Alkaline solution: 28 days			
			
Alkaline solution: 90 days			

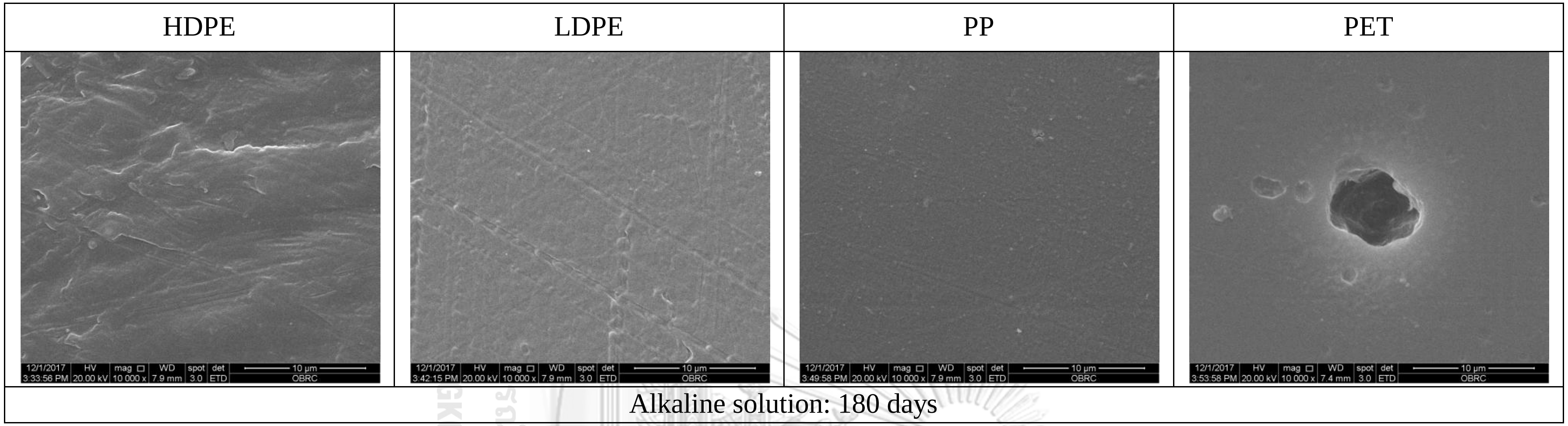


Figure 4.11 Surface of plastic fibers immersed in alkaline solution analyzed by SEM (Beam voltage: 20kV and magnification: 10000x)

2) UV resistance

2.1) Tensile strength

- Plastic fibers directly exposed by UV-A radiation

Synthetic fibers (HDPE, LDPE, PP, and PET) were directly exposed by UV-A at 250, 500, 750, and 1000 hours. Their tensile strengths tested by Instron Universal Testing Machine (UTM) showed that tensile strengths of synthetic fibers were about 58.2-86.0 N/mm^2 (593.47- 876.96 kg/cm^2), 13.2-25.7 N/mm^2 (134.60- 262.07 kg/cm^2), 0-42.8 N/mm^2 (0-436.44 kg/cm^2), and 97.2-130.3 N/mm^2 (991.16-1,328.69 kg/cm^2) respectively as shown in **Table 4.5** and **Figure 4.12**. When comparing to tensile strengths of plain synthetic fibers, their percentage differences were about (-63)-(-45)%, (-83)-(-66)%, 5%, and (-6)-25% respectively. HDPE's, LDPE's, and PP's tensile strengths were clearly declined or destroyed when increasing with exposure periods of UV-A radiation while PET's was not notably reduced by UV-A radiation.

Table 4.5 Tensile strength and Break extension of synthetic fibers

Plastic samples	Plain	250 hours	500 hours	750 hours	1,000 hours
Tensile strength (N/mm^2)					
1.HDPE	155.5±12.8	58.2±11.2	67.0±10.1	86.0±0	68.4±6.9
2.LDPE	75.4±5.9	25.7±2.8	23.0±4.2	13.2±3.1	20.2±1.7
3.PP	40.5±1.3	42.8±9.0	- *	- *	- *
4.PET	104.0±16.1	130.3±6.1	123.5±7.1	116.6±8.8	97.2±28.2
Break extension (%)					
1.HDPE	300.0±54.7	9.0±0.9	12.4±4.3	6.7±0	5.0±0
2.LDPE	724.0±52.5	77.7±5.9	29.9±18.1	3.1±0	15.4±6.7
3.PP	21.6±6.1	12.3±0.5	- *	- *	- *
4.PET	7.8±1.5	9.0±0.4	8.2±1.0	8.3±0.8	5.8±1.8
Modulus of elasticity (N/mm^2)					
1.HDPE	52.7±7.1	565.0±61.0	509.1±89.2	1287.4±0	1375.3±137.7
2.LDPE	10.4±0.7	32.8±2.4	106.8±72.0	426.9±100.3	151.6±62.4
3.PP	198.2±50.8	381.7±49.1	- *	- *	- *
4.PET	1361.0±186.4	1453.8±101.8	1524.6±209.1	1410.9±167.3	1711.9±187.0

Remark: * PP samples exposed by UV-A since 500 hours were broken to become dust.

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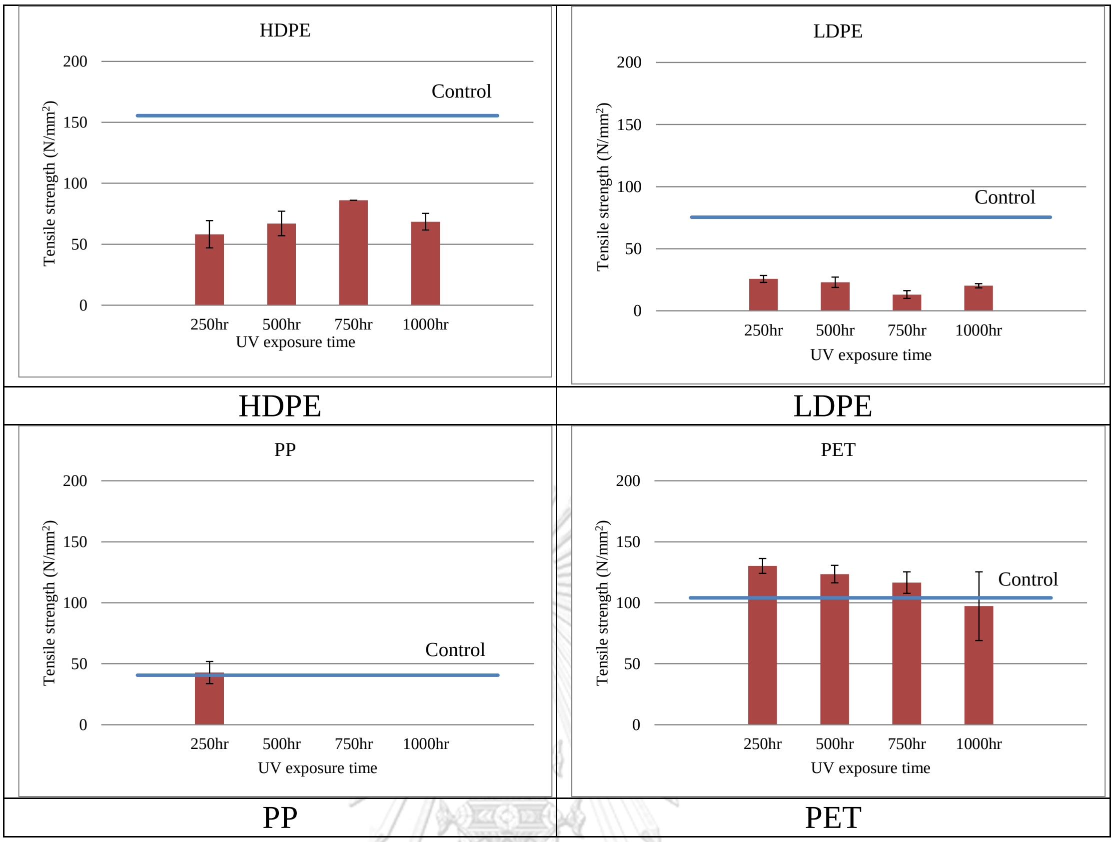

Figure 4.12 Tensile strength results after plastic fibers directly irradiated by UV-A

2.2) Break extension

- Plastic fibers directly exposed by UV-A radiation

After synthetic fibers (HDPE, LDPE, PP and PET) were exposed by UV-A in 250 to 1,000 hours, Break extensions were about 5.0-12.4%, 3.1-77.7%, 0-12.3%, and 5.8-9.0% respectively as shown in **Table 4.5** and **Figure 4.13**. When comparing to plain synthetic fibers, their percentage differences were about (-98)-(-96)%, (-100)-(-89)%, -43%, and (-26)-16% respectively. Break extensions of HDPE, LDPE, and PP fibers seemed to be declined or destroyed when increasing with exposure periods of UV-A radiation while PET's was not significantly decreased by UV-A radiation.

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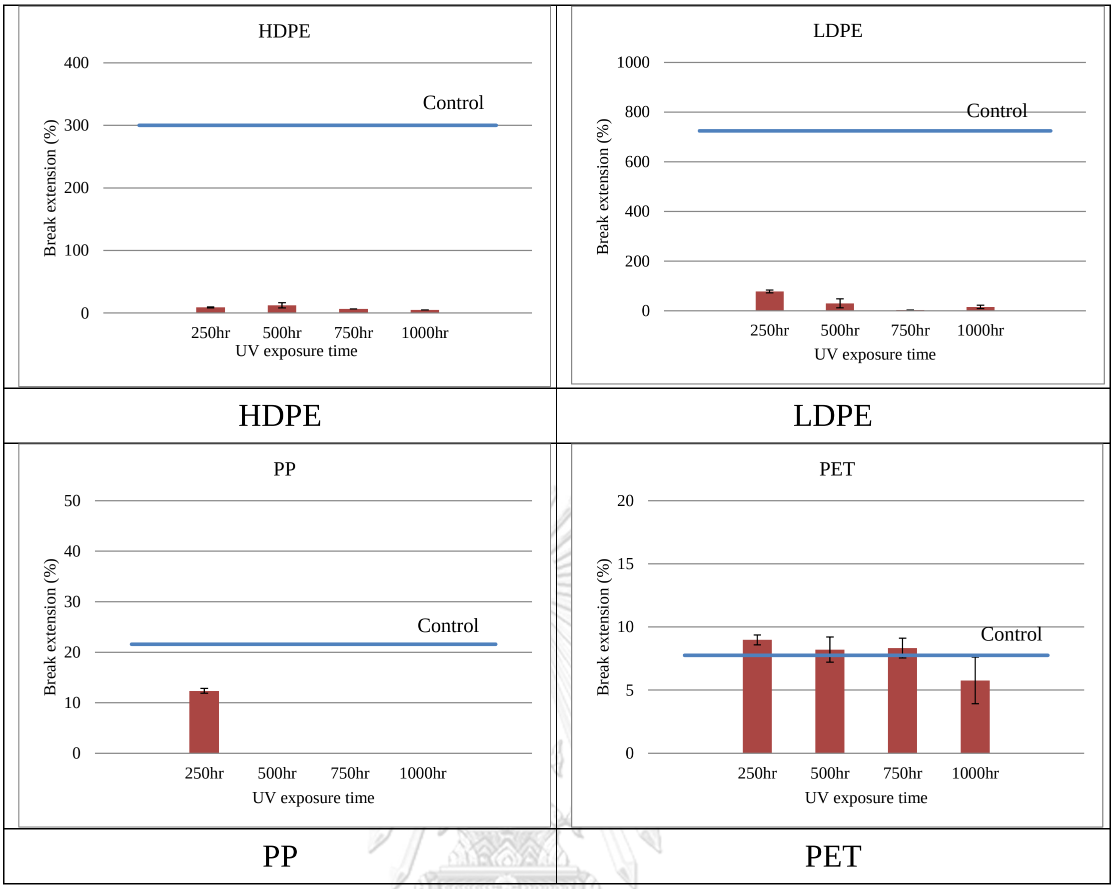

Figure 4.13 Break extension results after plastic fibers directly irradiated by UV-A

2.3) Modulus of elasticity

- Plastic fibers directly exposed by UV-A radiation

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Modulus of elasticity was shown the elastic property of material. In case of this study, all synthetic fibers (HDPE, LDPE, PP, and PET) were irradiated by UV-A radiation with different periods including 250, 500, 750, and 1000 hours. According to analysis results as shown in **Table 4.5** and **Figure 4.14**, modulus of elasticity values were about 509.1-1375.3, 32.8-426.9, 0-381.7, and 1410.9-1711.9 N/mm^2 respectively. When comparing to plain synthetic fibers, their percentage differences were about 866-2508%, 214-3991%, 93%, and 4-26% respectively. Modulus of elasticity of HDPE and LDPE fibers seemed to be increased when more exposure time of UV-A radiation while PET's was not significantly increased by UV-A radiation.

It was concluded that UV-A radiation could affect to tensile strength, break extension, and modulus of elasticity of HDPE, LDPE, and PP fibers clearly while PET fiber's physical properties was not significantly reduced by UV-A radiation during exposure periods varied 250-1000 hours.

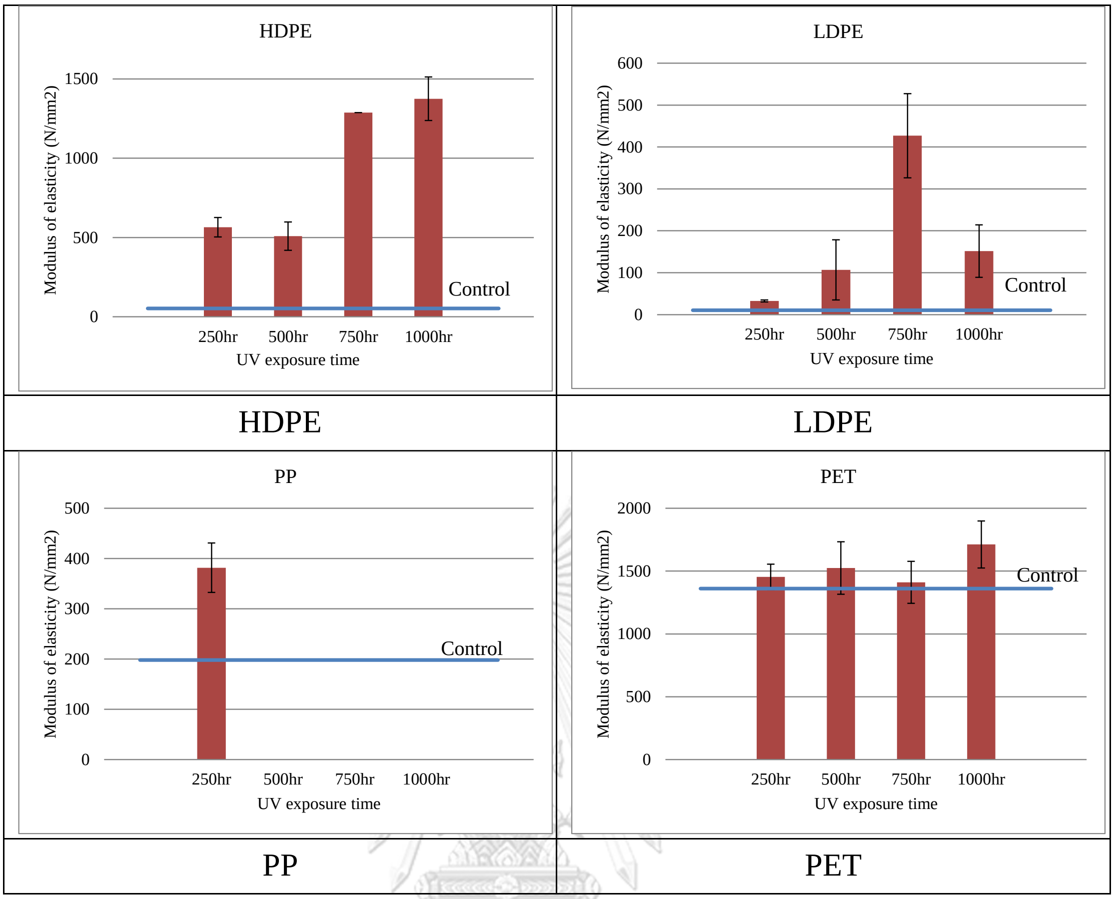

Figure 4.14 Modulus of elasticity of plastic fibers irradiated by UV-A with various periods

2.4) Surface analysis

- Plastic fibers directly exposed by UV-A radiation

Surface of plastic fibers after irradiated by UV-A radiation is analyzed by Scanning Electron Microscope (SEM) as shown in **Figure 4.15** in order to compare their effects to plain synthetic fibers which are no UV-A exposure. It was same as 1) Alkalinity resistance, plastic fiber samples were coated by gold before testing in order to prevent destroying plastic surface during surface scanning by SEM. HDPE surfaces after irradiated by UV-A radiation in 250, 500, 750, and 1000 hours were found no deterioration significantly on their surfaces. While, LDPE surface exposed by UV-A radiation in 250 hours was found flaky and LDPE surfaces in 500-1000 hours were found flaky with some small holes. PP surfaces irradiated by UV-A radiation in 250-1000 hours were found some small rods on their surface. PET surface irradiated by UV-A radiation in 250 hours was found to have some small holes and PET surfaces in 500-1000 hours were found some small rods on their surfaces. This results could be concluded that LDPE PP and PET surfaces were destroyed by UV-A radiation found to have some fouling after directly exposed by UV-A radiation in 250-1000 hours while

HDPE surfaces after irradiating by UV-A radiation during 250-1000 hrs were still the same as plain sample.

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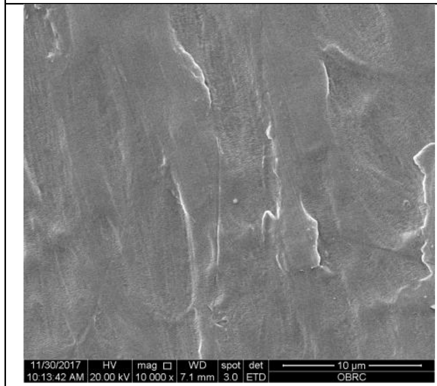
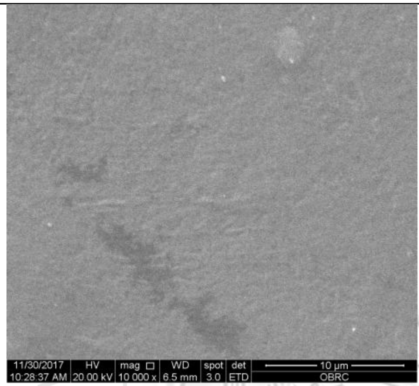
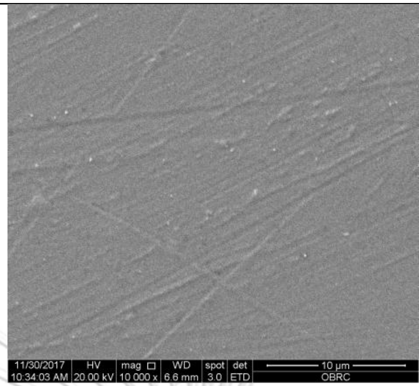
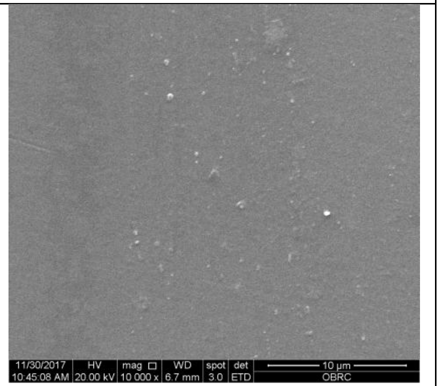
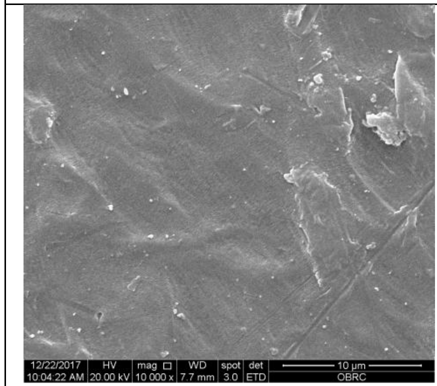
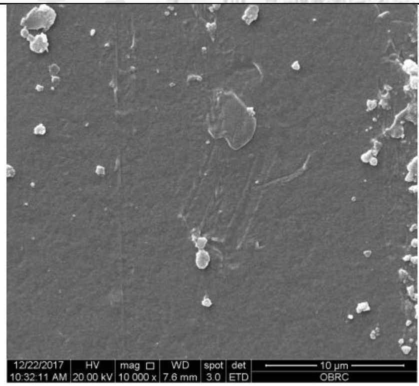
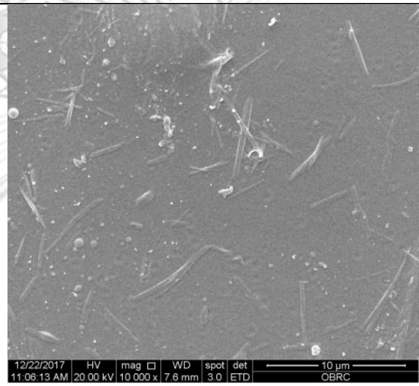
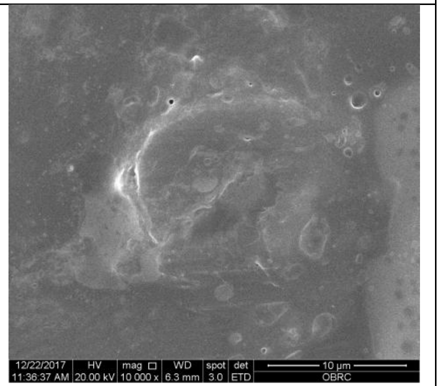
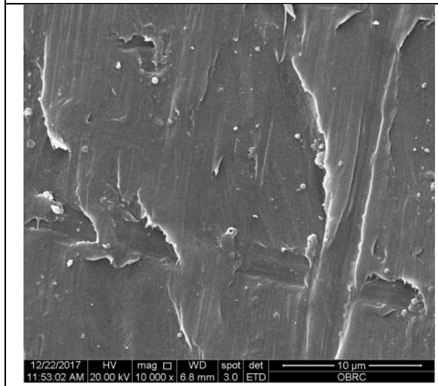
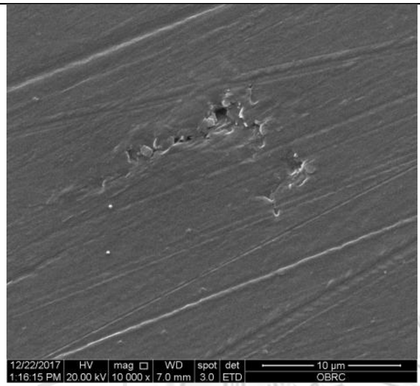
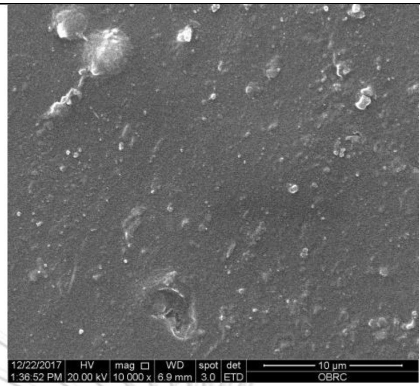
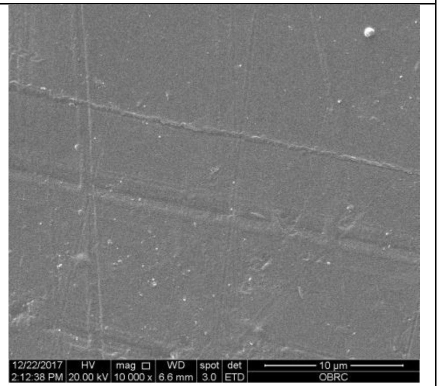
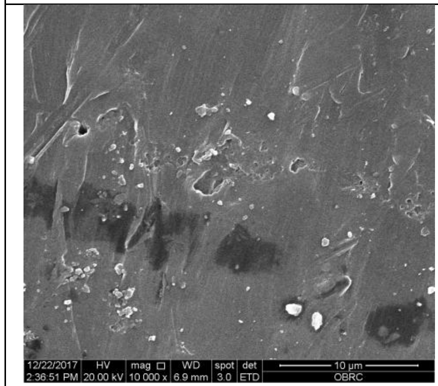
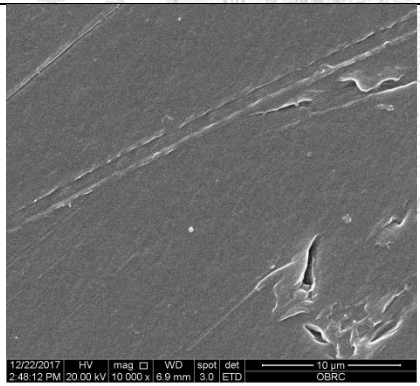
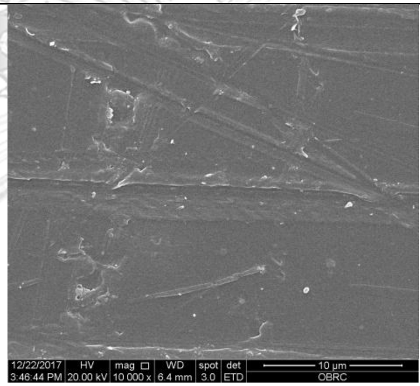
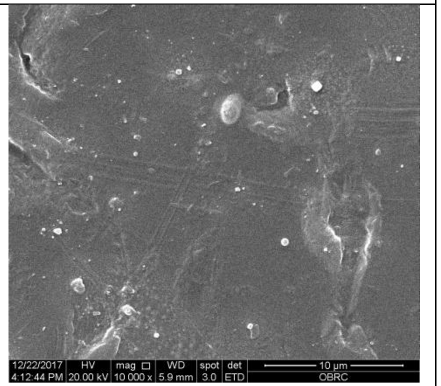
HDPE	LDPE	PP	PET
			
Plain synthetic fibers and no UV-A exposure			
			
UV-A exposure: 250 hours			

HDPE	LDPE	PP	PET
			
UV-A exposure: 500 hours			
			
UV-A exposure: 750 hours			

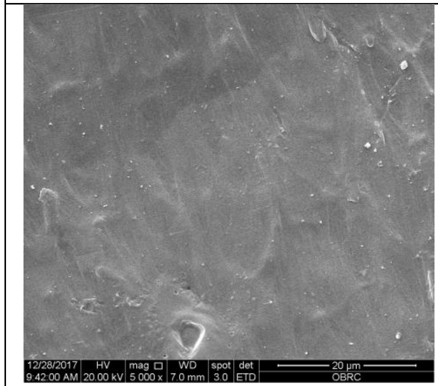
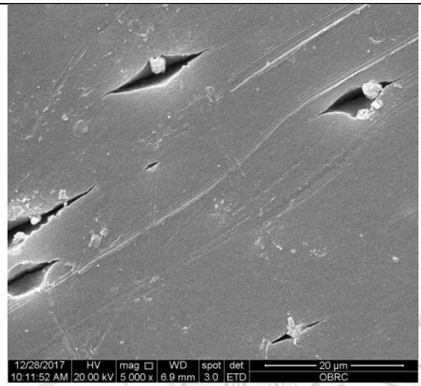
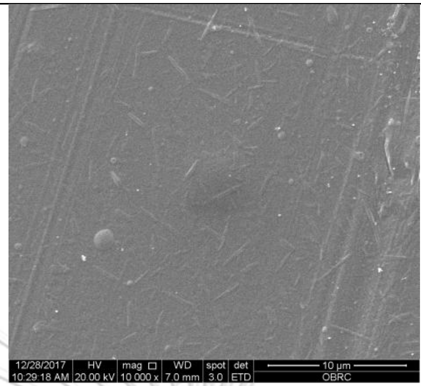
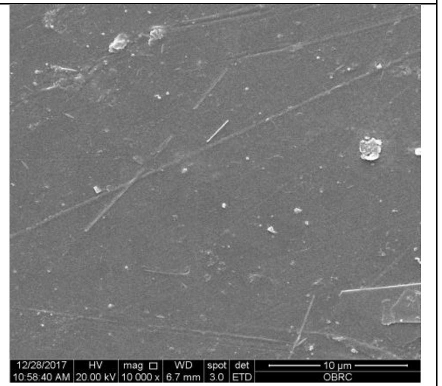
HDPE	LDPE	PP	PET
			
UV-A exposure: 1,000 hours			

Figure 4.15 Surface of plastic fibers directly exposed by UV-A analyzed by SEM
(Beam voltage: 20kV and magnification: 10000x)

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4.2 Concrete test

4.2.1 Fresh concrete

1) Concrete mix design

Concrete mix design of this study was preparing 4 types of plastic fibers as shown in **Figure 3.2** made from industrial wastes (including HDPE LDPE PP and PET) mixed with cement sand water and nonionic surfactant. The proportions of plastic fibers in concrete were assigned according to the volume fraction of cement so the amount of fibers were specified in 5% 10% 15% 20% 30% 40% and 50% vol. as shown in **Table 3.1**. The weight of plastic fibers were calculated by the bulk unit weight from 4.1.1 in order that amount of plastic fibers during preparation would be more accuracy than measuring them by container volume.

Water cement ratio was increased according to the more amount volume fraction of plastic fibers in concrete because the complex structure of plastic fiber in fresh concrete as shown in **Figure 4.16** decreased in workability and induced fiber ball of fresh concrete which directly caused to more segregation and porosity in concrete. These causes could reduce the strength of synthetic fiber reinforced concrete lower than the acceptable level such as compressive strength of precast concrete wall panel standard. There were two general solutions which could solve these problems including 1) adding water reducing agent (chemical) and 2) adding the amount of water. It was due to the fact that this study used nonionic surfactant as low surface energy chemical in order to decrease surface energy and also reduce contact angle between water and surface of plastic fiber so it was to avoid chemical interaction in composite material. Finally, water addition in concrete was chosen in this study.

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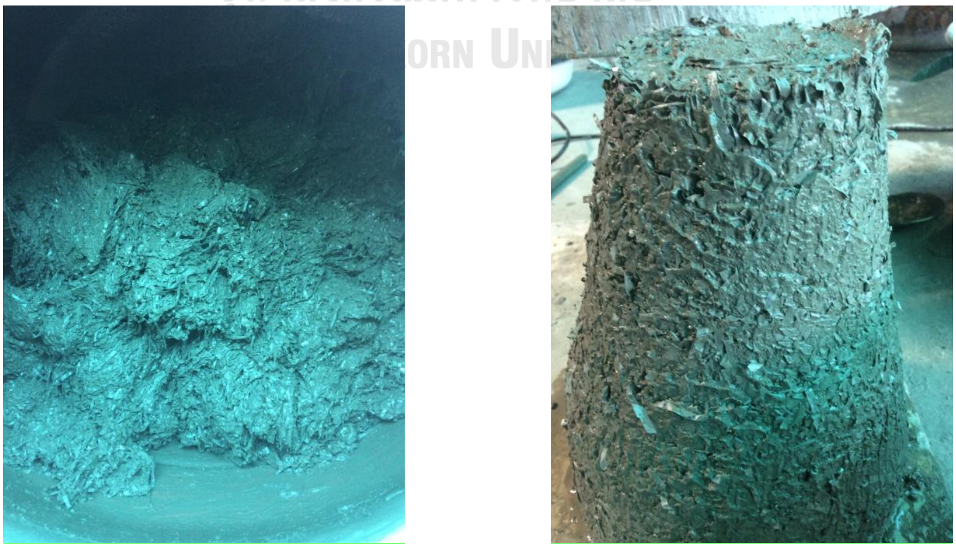

Figure 4.16 Complex structure of plastic fiber in fresh concrete

2) Sand sieve analysis (Fineness Modulus (F.M.))

The sand sieve would be analyzed according to ASTM C136 [48] to find out the distribution of fine aggregate size. Sand samples were prepared at least 300 gram in dry condition and then dried in oven at 110±5 °C until their weights were stable. Sieve cloth was mounted and sorted by the larger sieve size at the top and lesser one to bottom and then placed dried sand on the top sieve cloth. After shaking sieve cloth about 10 minutes by shaker, each sieve tray would be weighed in order to calculate the Fineness Modulus (F.M.) of sand as **Equation 11**.

$$F.M. = \frac{(X_1+X_2+X_3+X_4+X_5+X_6)}{100}$$ **Equation 11**

Where; X_1 to X_6 = The cumulative percentage retained on each sieve No.4, No.8, No.16, No.30, No.50, and No.100

F.M. should be in the range of 2.3-3.2 in order that sand would be fine particle enough for concrete mixing. The sand analysis result of this study was found that F.M. average value was about 2.75 ± 0.1 as **Table 4.6** that is in the suggested range.

F.M. average = (2.76+2.68+2.81+2.79+2.72) / 5

= 2.75 ± 0.1

Table 4.6 Sand sieve analysis results

Sieve no.	**Sand weight (g)**	**% restrained sand**	**Cumulative percentage**
Sample no.1			
No.4	1.92	0.64	0.64
No.8	24.22	8.06	8.70
No.16	58.42	19.45	28.15
No.30	82.78	27.56	55.71
No.50	90.77	30.22	85.93
No.100	33.64	11.20	97.13
No.200	5.21	1.73	
Pan	3.41	1.14	
Sum	300.37	100.00	276.27
F.M.			2.76

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Sieve no.	Sand weight (g)	% restrained sand	Cumulative percentage
Sample no.2			
No.4	1.17	0.39	0.39
No.8	20.92	6.97	7.36
No.16	56.81	18.92	26.27
No.30	79.89	26.60	52.87
No.50	94.1	31.33	84.20
No.100	37.48	12.48	96.68
No.200	6.31	2.10	
Pan	3.65	1.22	
Sum	300.33	100.00	267.78
F.M.			2.68
Sample no.3			
No.4	2.45	0.81	0.81
No.8	26.45	8.79	9.61
No.16	61.99	20.61	30.21
No.30	82.13	27.30	57.52
No.50	86.01	28.59	86.11
No.100	32.92	10.94	97.05
No.200	6.11	2.03	
Pan	2.76	0.92	
Sum	300.82	100.00	281.31
F.M.			2.81
Sample no.4			
No.4	1.76	0.59	0.59
No.8	25.71	8.57	9.15
No.16	63.13	21.04	30.19
No.30	78.84	26.27	56.46
No.50	87.41	29.13	85.59
No.100	33.75	11.25	96.84
No.200	6.07	2.02	

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Sieve no.	Sand weight (g)	% restrained sand	Cumulative percentage
Pan	3.42	1.14	
Sum	300.09	100.00	278.82
F.M.			2.79
Sample no.5			
No.4	1.17	0.39	0.39
No.8	21.56	7.17	7.56
No.16	57.63	19.16	26.71
No.30	84.59	28.12	54.83
No.50	91.82	30.52	85.35
No.100	35	11.63	96.98
No.200	6.25	2.08	
Pan	2.84	0.94	
Sum	300.86	100.00	271.80
F.M.			2.72

3) Workability (Slump test)

Workability of fresh concrete using HDPE, LDPE, PP, and PET fibers was represented by subsidence values, and the results were shown in **Figure 4.17**. From **Figure 4.17** and **Table 4.7**, the HDPE and PP fibers at various volume fractions provided lowered subsidence values in comparison with that of the mortar (**Figure 4.18c**). In the meantime, the LDPE and PET fibers offered lower subsidence values than that of the mortar, when the volume fraction was 20% and 30%. Relatively low subsidence values of 1–6 cm were obtained when the HDPE fiber was utilized in the concrete.

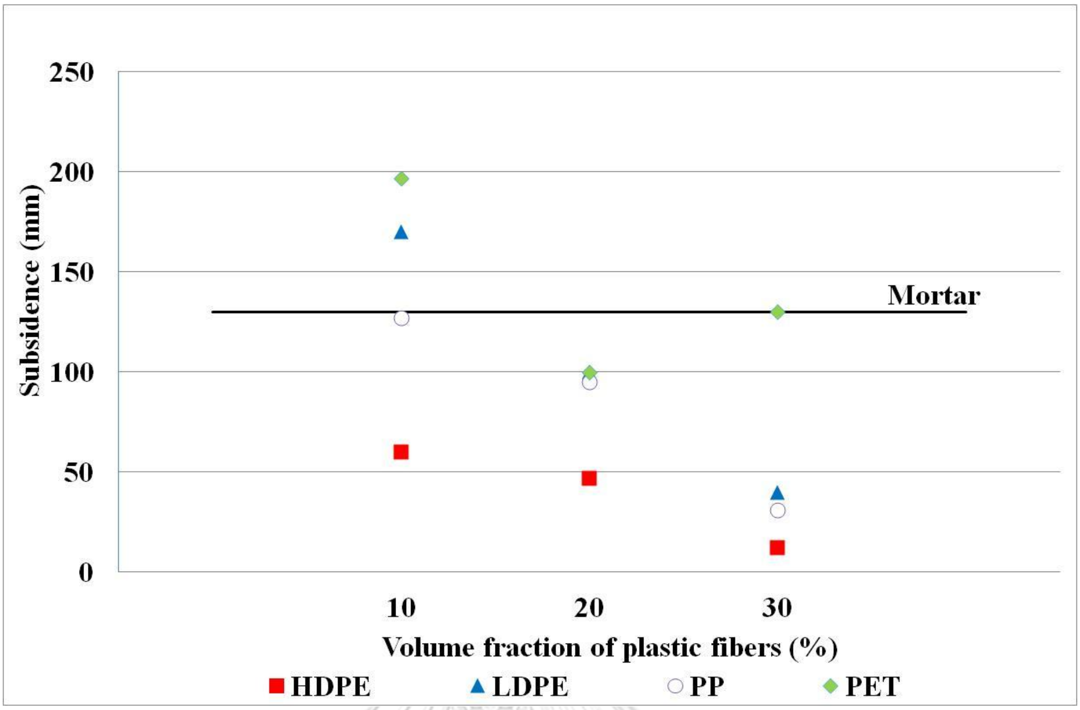

Figure 4.17 Workability of fresh concrete. The subsidence of mortar (control sample) is in the solid line

The subsidence values of this study were found to have decreased with increasing volume fraction of plastic fibers same as [7, 25, 66]. Movement of fresh concrete/mortar, which is primarily the cause of workability or slump, is restricted by the presence of recycled plastic fibers. The occurrence of complex network structure during the concrete processing is presented in **Figure 4.18a**. In addition, increasing the surface area of plastic fibers at high volume fractions can improve the cement paste absorption and the viscosity of fiber reinforced concrete [7, 26, 67, 68]. The low subsidence value refers to the low workability of fresh concrete, which can cause segregation in building structures. Fresh concrete dissociation brings about fracture on hardened concrete, and consequently losing concrete strength. To prevent segregation of plastic fibers (see **Figure 4.18b**) in the reinforced concrete composites, two recommendations were proposed [7, 25, 66]: 1) Increasing the amount of water used in the mix and 2) adding water reducing agents. Increasing water to cement (w/c) ratio was appropriate for this study in order not to cause chemical interaction with the non-ionic surfactant. That w/c ratio was gradually increased from 15% volume fraction so as to help reduce honeycomb concrete [69].

According to these results, PET was observed to be more rigid than other plastics, so addition of PET fibers to the concrete was likely to agglomerate and form fiber balls [70]. PET fiber balls (even though they are hydrophobic) can adsorb water within voids during concrete processing. When produced concrete was put into the slump cone and tamped, water retained in PET balls could be released. Finally, increasing the amount of water in the mixture would increase subsidence value.

Table 4.7 Slump test results

Concrete sample	Subsidence value (mm)
Mortar	130
HDPE	
10%	60
20%	47
30%	12
LDPE	
10%	170
20%	100
30%	40
PP	
10%	127
20%	95
30%	31
PET	
10%	197
20%	100
30%	130

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(**a**)

(**b**)

(c)

Figure 4.18 Photographs of workability test during concrete processing: (a) Complex network of 20 vol.% HDPE fibers in concrete, (b) Segregation of 30 vol.% PP fibers in concrete, and (c) Mortar (control sample without plastic fibers).

4.2.2 Hardened concrete

1) Bulk density

In this study, bulk density of the produced concrete was also affected by the increase in volume fraction of plastic fibers. The use of plastic fibers as the additional ingredient resulted in lower bulk density of produced concrete than that of the mortar [71-73]. This is because the complex network structure from plastic fibers resulted in honeycombs [8, 28, 69]. According to ASTM C642, bulk density of synthetic fiber reinforced concrete could be calculated by **Equation 12**

$$\text{Bulk density} = \frac{A \, x \, \rho}{(C-D)} \qquad \textbf{Equation 12}$$

Where;
A = Mass weight of oven-dried sample in air (gram)
C = Mass of surface-dry sample in air after immersion and boiling (gram)
D = Apparent mass of sample in water after immersion and boiling (gram)
ρ = Density of water = 1 g/cm3

The lowest bulk density of approximately 1677±19 kg/m^3 on average was obtained in the produced concrete from HDPE fiber, and the bulk densities of the produced concrete with LDPE, PP and PET were about 1853±9, 1892±3, and 1960±12 kg/m^3 on average, respectively as shown in **Figure 4.19a** and **Table 4.8**.

Table 4.8 Bulk density of hardened fiber reinforced concrete

Sample	Plastic volume fraction (%)			
	0%	10%	20%	30%
Mortar				
#1	1960	-	-	-
#2	1968	-	-	-
#3	1961	-	-	-
#4	1970	-	-	-
Average	1965	-	-	-
SD	5	-	-	-
HDPE				
#1	-	1767	1809	1681
#2	-	1758	1804	1677
#3	-	1735	1796	1652
#4	-	1743	1820	1699
Average	-	1751	1807	1677
SD	-	14	10	19
LDPE				
#1	-	1894	1867	1916
#2	-	1901	1850	1870
#3	-	1894	1847	1935
#4	-	1899	1849	1922
Average	-	1897	1853	1911
SD	-	4	9	28
PP				
#1	-	1952	1890	1937
#2	-	1947	1894	1909
#3	-	1933	1889	1914
#4	-	1962	1895	1910
Average	-	1949	1892	1917
SD		12	3	13
PET				
#1	-	1987	2008	1948
#2	-	1993	2016	-
#3	-	-	-	1961
#4	-	1992	2000	1972
Average	-	1991	2008	1960
SD	-	3	8	12

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2) Permeable void

Permeable void was calculated by **Equation 1** in ASTM C642. The synthetic fiber reinforced concrete sample would be prepared at least 800 gram and weighed in various conditions as detailed below.

According to **Table 4.9**, permeable void results of Mortar, HDPE, LDPE, PP, and PET were 19.8±0.6, 24.4±0.4 to 28.6±0.6, 22.2±0.1 to 24.2±0.3, 21.1±0.3 to 22.5±0.1, and 18.3±0.8 to 21.6±1.9 % respectively. Permeable void or porosity of the produced concrete was also likely to be increased by adding in volume fraction of plastic fibers. It was due to the fact that plastic was considered as hydrophobic material so it induced air void in concrete as well as the complex network structure from plastic fibers resulting in honeycombs [8, 28, 69]. Moreover, the interfacial tension between plastic and water of HDPE was found to be higher than other plastics, and consequently inducing air void generation.

The permeable void (porosity) was negatively correlated to the bulk density as shown in **Figure 4.19a** so the lower bulk density of produced concrete than the mortar was observed, especially the produced concrete from HDPE fiber. Therefore, the produced concrete in this study could be further developed to be lightweight concrete with high insulation.

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Table 4.9 Permeable void of synthetic fiber reinforced concrete

Sample	Plastic volume fraction (%)			
	0%	10%	20%	30%
Mortar				
#1	20.5	-	-	-
#2	19.6	-	-	-
#3	19.9	-	-	-
#4	19.0	-	-	-
Average	19.8±0.6	-	-	-
HDPE				
#1	-	23.8	24.4	28.0
#2	-	24.4	25.0	29.3
#3	-	24.6	25.2	28.8
#4	-	24.7	24.6	28.3
Average	-	24.4±0.4	24.8±0.4	28.6±0.6
LDPE				
#1	-	22.1	23.7	22.0
#2	-	22.2	24.4	24.0
#3	-	22.2	24.5	21.1
#4	-	22.4	24.2	22.2
Average	-	22.2±0.1	24.2±0.3	22.3±1.2
PP				
#1	-	21.2	22.6	21.3
#2	-	20.8	22.6	22.0
#3	-	21.4	22.3	22.0
#4	-	20.9	22.3	21.9
Average	-	21.1±0.3	22.5±0.1	21.8±0.4
PET				
#1	-	19.0	18.6	21.1
#2	-	17.5	18.7	24.4
#3	-	-	-	20.5
#4	-	18.4	18.8	20.5
Average	-	18.3±0.8	18.7±0.1	21.6±1.9

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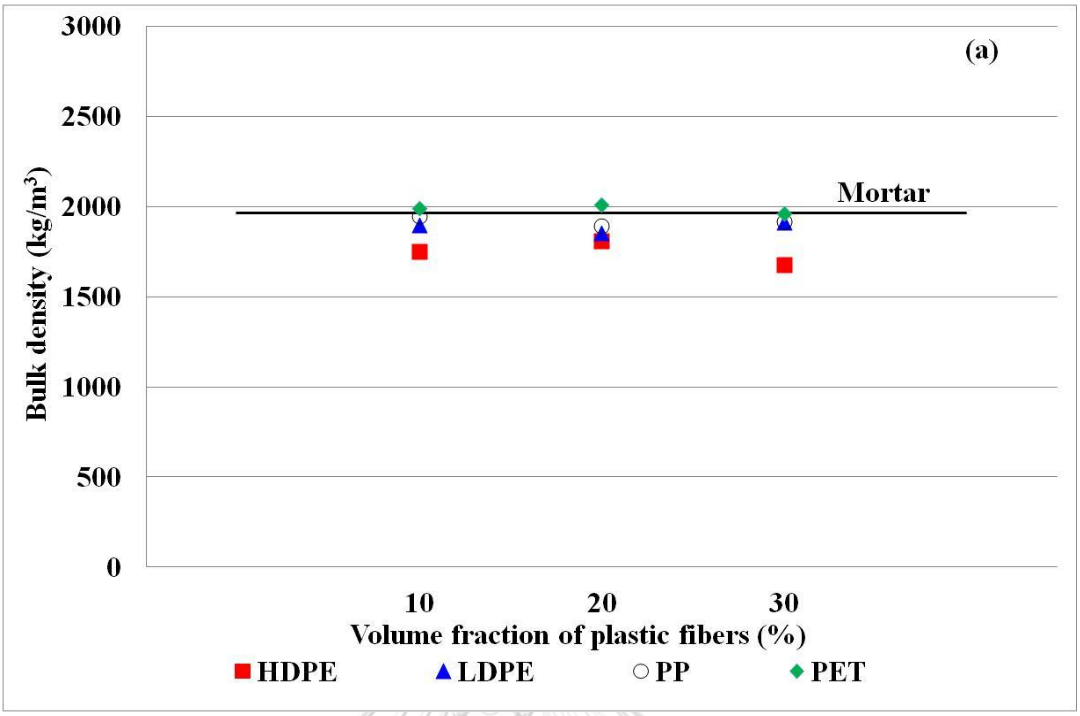
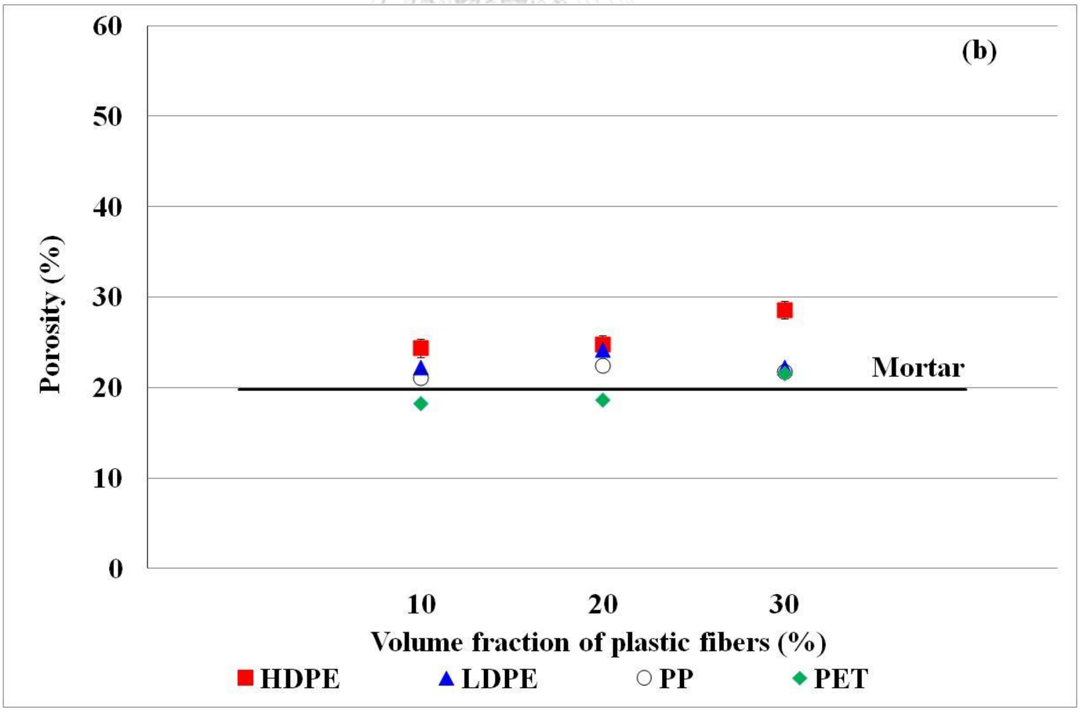


(a) Bulk density



(b) Porosity

Figure 4.19 Relationship between volume fraction of plastic fibers and (a) bulk density and (b) porosity of produced concrete. The bulk density and porosity of mortar (control sample) are in the solid line.

3) Plastic volume maximization in concrete

3.1) Compressive strength

Concrete is commonly known for its high compressive strength with a rather low tensile strength, typically about one-tenth of its compressive strength. Compressive strength was usually calculated by **Equation 2**.

3.1.1) Synthetic fiber reinforced concrete with nonionic surfactant

Table 4.10 and **Figure 4.20** showed the compressive strength of concrete produced with the addition of HDPE, LDPE, PP, and PET recycled plastic fibers. The volume fraction of fibers used in this study varies from 5 to 50%. It was found that the compressive strength values of all the mixings, regardless of the fiber type and fiber volume fraction, were likely to be declined with increase in plastic contents. The compressive strength results of HDPE, LDPE, and PP at 5-20% vol. were found about 5.4-16.4, 8.7-23.7, and 10.2-19.8 N/mm^2 respectively. PET's compressive strength results at 5-50% vol. were about 16.0-22.0 N/mm^2. With a 5% fiber volume fraction, mixing with HDPE, LDPE, and PP recycled fibers showed a strength reduction of −36%, −8%, and −23%, respectively, when compared to mortar. The strength reduction escalated to −79%, −66%, and −60% when fiber volume fraction increased to 20%. However, concrete with PET recycled plastics showed a better performance with lesser strength reduction, ranging from only −38% to −17% when the fiber volume fraction increased from 10% to 50%.

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Table 4.10 Compressive strength results of synthetic fiber reinforced concrete

Unit: N/mm²

Volume fraction	HDPE		LDPE		PP		PET	
	W/SF	W/O SF	W/SF	W/O SF	W/SF	W/O SF	W/SF	W/O SF
Mortar	25.7±3.1	24.9±1.9	25.7±3.1	24.9±1.9	25.7±3.1	24.9±1.9	25.7±3.1	24.9±1.9
5%	16.4±3.0	18.4±2.3	23.7±3.0	21.3±2.5	19.8±2.1	21.0±3.8	21.1±3.8	23.5±6.2
10%	11.6±1.8	13.9±1.3	14.2±1.5	16.9±2.3	16.8±1.3	16.2±2.1	20.2±4.6	23.1±3.0
15%	9.2±0.9	8.1±1.1	12.9±0.5	15.1±1.4	11.4±1.4	13.2±2.1	22.0±1.5	22.1±2.2
20%	5.4±0.5	7.7±0.5	8.7±1.6	11.2±1.2	10.2±0.9	10.7±1.3	21.2±0.3	21.7±2.1
25%	-	-	-	-	-	-	20.0±0.3	17.6±2.0
30%	-	-	-	-	-	-	19.2±3.5	20.8±1.6
35%	-	-	-	-	-	-	18.9±1.3	19.3±1.2
40%	-	-	-	-	-	-	19.3±2.7	18.1±1.4
50%	-	-	-	-	-	-	16.0±2.1	16.7±0.1
Standard *	16.0							

Remark: W/SF = With surfactant
W/O SF = Without surfactant
* Precast concrete wall panel standard

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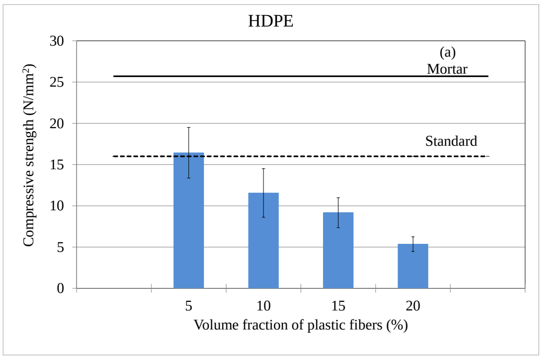
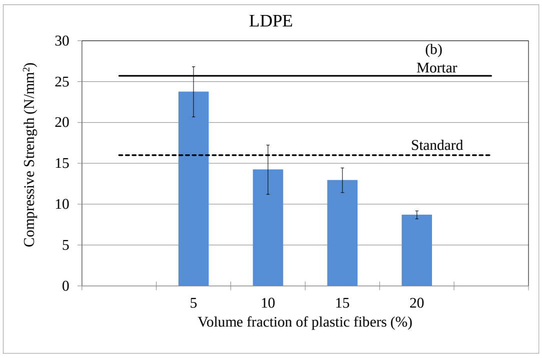
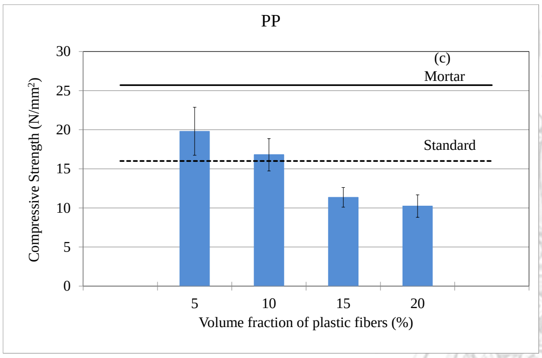


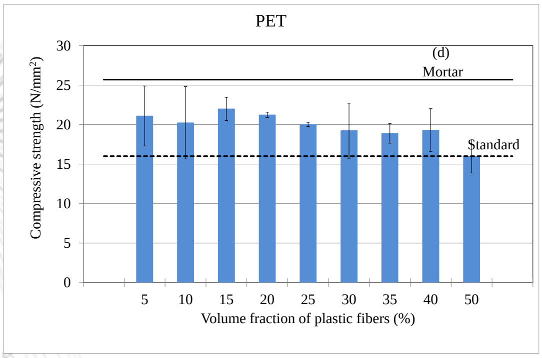
(a) HDPE



(b) LDPE



(c) PP

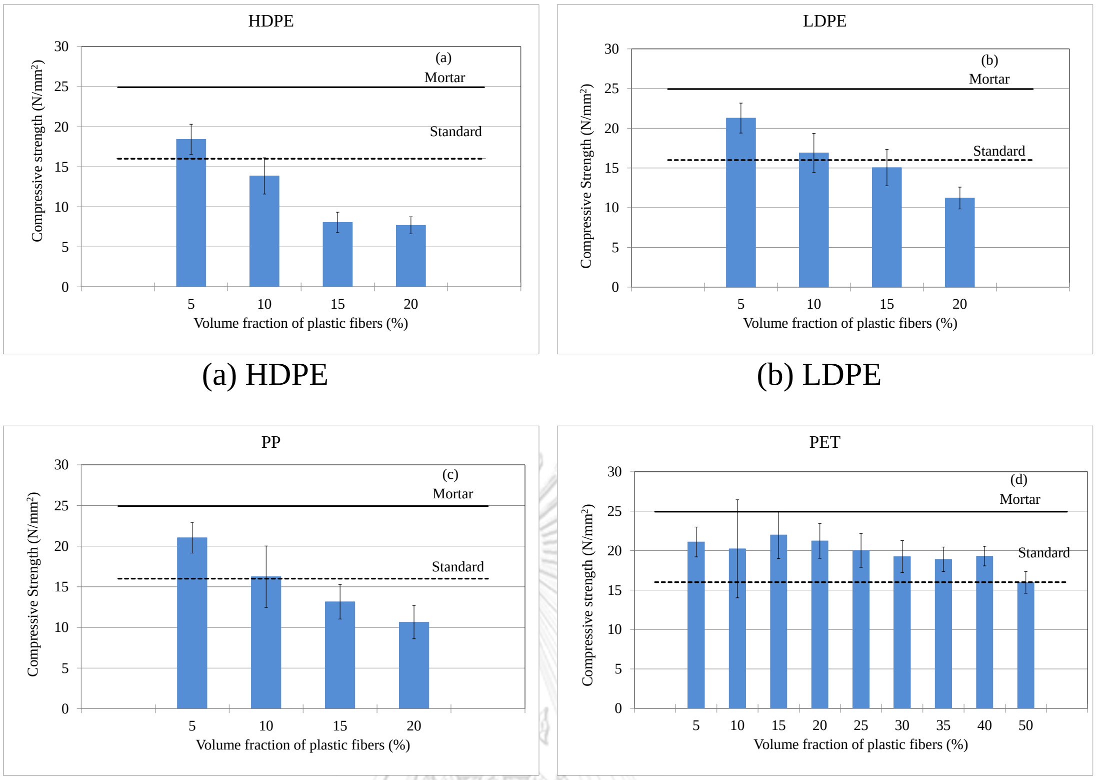


(d) PET

Figure 4.20 Compressive strengths of produced concrete with nonionic surfactant; (a) HDPE, (b) LDPE, (c) PP, and (d) PET fibers. The compressive strength of mortar (control sample) and the standard of compressive strength for precast concrete wall panel are denoted with solid lines and dash lines, respectively.

3.1.2) Synthetic fiber reinforced concrete without nonionic surfactant

Table 4.11 and **Figure 4.21** showed the compressive strength of concrete produced the addition of HDPE, LDPE, PP, and PET recycled plastic fibers and no nonionic surfactant. It was same as 3.1.1) that the compressive strength values of all the mixings, regardless of the fiber type and fiber volume fraction, were likely to be declined with increase in plastic contents. The compressive strength results of HDPE, LDPE, and PP at 5-20% vol. were found about 7.7-18.4, 11.2-21.3, and 10.7-21.0 N/mm^2 respectively. PET's compressive strength results at 5-50% vol. were about 16.7-23.5 N/mm^2. With a 5% fiber volume fraction, mixing with HDPE, LDPE, and PP recycled fibers showed a strength reduction of −26%, −15%, and −16%, respectively, when compared to regular mortar. The strength reduction escalated to −69%, −55%, and −57% when fiber volume fraction increased to 20%. However, concrete with PET recycled plastics showed a better performance with lesser strength reduction, ranging from only −33% to −6% when the fiber volume fraction increased from 10% to 50%.



(a) HDPE (b) LDPE

(c) PP (d) PET

Figure 4.21 Compressive strengths of produced concrete without nonionic surfactant; (a) HDPE, (b) LDPE, (c) PP, and (d) PET fibers. The compressive strength of mortar (control sample) and the standard of compressive strength for precast concrete wall panel are denoted with solid lines and dash lines, respectively.

Similar results of strength reduction of both were also reported by other investigators [67, 71, 74] when percentage of fiber volume fractions used in the concrete was increased. The addition of low fiber volume content (typically less than 1% for plastic fibers such as PP) into concrete often does not affect the compressive strength of concrete [24, 25, 60, 75, 76]. In some circumstances, the presence of fibers can enhance some property of concrete composites [24-28, 60], for instance, tensile strength, micro crack reduction, crack opening reduction, and so on. However, the large volume fraction of fibers often lowers the compressive strength of concrete as the hydrophobic property of plastics is likely to increase air void [28, 69, 77] in the cementitious composites.

Typical compressive strength of concrete used in the USA construction industry varies from 17 N/mm^2 for residential buildings to 28 N/mm^2 for commercial buildings [78]. As stated, one of the objectives of this study was to investigate the potential utilization of recycled plastics of materials for concrete wall panel, which must adhere to the TIS 2226-2548 Standard for precast concrete wall panel. It is required that all concrete used for precast wall panels (non-structural load carrying) must have a minimum compressive strength of 16 N/mm^2 [79]. In this study, only concrete mixing with HDPE and LDPE recycled plastics with 5% fiber volume fraction and PP with

10% fiber volume fraction produced sufficient compressive strength to be used for precast wall panel application. As for PET recycled plastic, all mixings (with 10% to 50% fiber volume fraction) tested in this study met the minimum compressive strength requirement for precast wall panel application. Clearly, this study shows that recycled plastics, when used in fiber-reinforced concrete, have a good potential to be used as construction materials for many non-structural load carrying members in the building system, thus paving the way for a new type of environmental friendly renewable construction materials [73, 80].

3.2) Splitting tensile strength

Concrete is commonly known for its low tensile strength with a rather high compressive strength, typically about one-tenth of its compressive strength. Direct tensile strength was hardly investigated so splitting tensile strength used as representative of tensile strength of was concrete calculated by **Equation 3**.

3.2.1) Synthetic fiber reinforced concrete with nonionic surfactant

Table 4.11 and **Figure 4.22** showed the splitting tensile strength of concrete produced with the addition of HDPE, LDPE, PP, and PET recycled plastic fibers. The volume fraction of fibers used in this study varied from 5 to 50%. It was found that the splitting tensile strength values of all the mixings, regardless of the fiber type and fiber volume fraction, were likely to be declined with increase in plastic contents which was same as compressive strength. The splitting tensile strength results of HDPE, LDPE, and PP at 5-20% vol. were about 0.7-1.8, 1.1-1.9, and 1.5-2.6 N/mm^2 respectively. PET's splitting tensile strength results at 5-50% vol. were about 2.1-2.9 N/mm^2. With a 5% fiber volume fraction, mixing with HDPE, LDPE, and PP recycled fibers showed a strength reduction of −45%, −45%, and −16%, respectively, when compared to mortar. The strength reduction escalated to −77%, −65%, and −45% when fiber volume fraction increased to 20%. However, concrete with PET recycled plastics showed a better performance with lesser strength reduction, ranging from only −32% to −7% when the fiber volume fraction increased from 10% to 50%.

Table 4.11 Splitting tensile strength results of synthetic fiber reinforced concrete

Unit: N/mm²

Volume fraction	HDPE		LDPE		PP		PET	
	W/SF	W/O SF	W/SF	W/O SF	W/SF	W/O SF	W/SF	W/O SF
Mortar	3.1±3.1	3.0±3.0	3.1±3.1	3.0±3.0	3.1±3.1	3.0±3.0	3.1±3.1	3.0±3.0
5%	1.7±0.2	1.9±0.3	1.7±0.6	2.2±0.3	2.6±0.4	3.2±0.5	2.8±0.6	2.9±0.6
10%	1.8±0.2	1.9±0.3	1.9±0.2	2.1±0.4	2.2±0.4	2.5±0.1	2.1±0.2	2.9±0.3
15%	1.3±0.1	1.8±0.2	1.9±0.3	2.3±0.2	1.5±0.3	1.7±0.1	2.7±0.3	2.7±0.3
20%	0.7±0.1	1.1±0.2	1.1±0.2	1.4±0.2	1.7±0.2	1.7±0.3	2.7±0.1	2.5±0.5
25%	-	-	-	-	-	-	2.8±0.2	2.0±0.3
30%	-	-	-	-	-	-	2.9±0.2	2.6±0.1
35%	-	-	-	-	-	-	2.5±0.2	2.3±0.7
40%	-	-	-	-	-	-	2.5±0.2	2.6±0.1
50%	-	-	-	-	-	-	2.1±0.3	2.3±0.6

Remark: W/SF = With surfactant
W/O SF = Without surfactant

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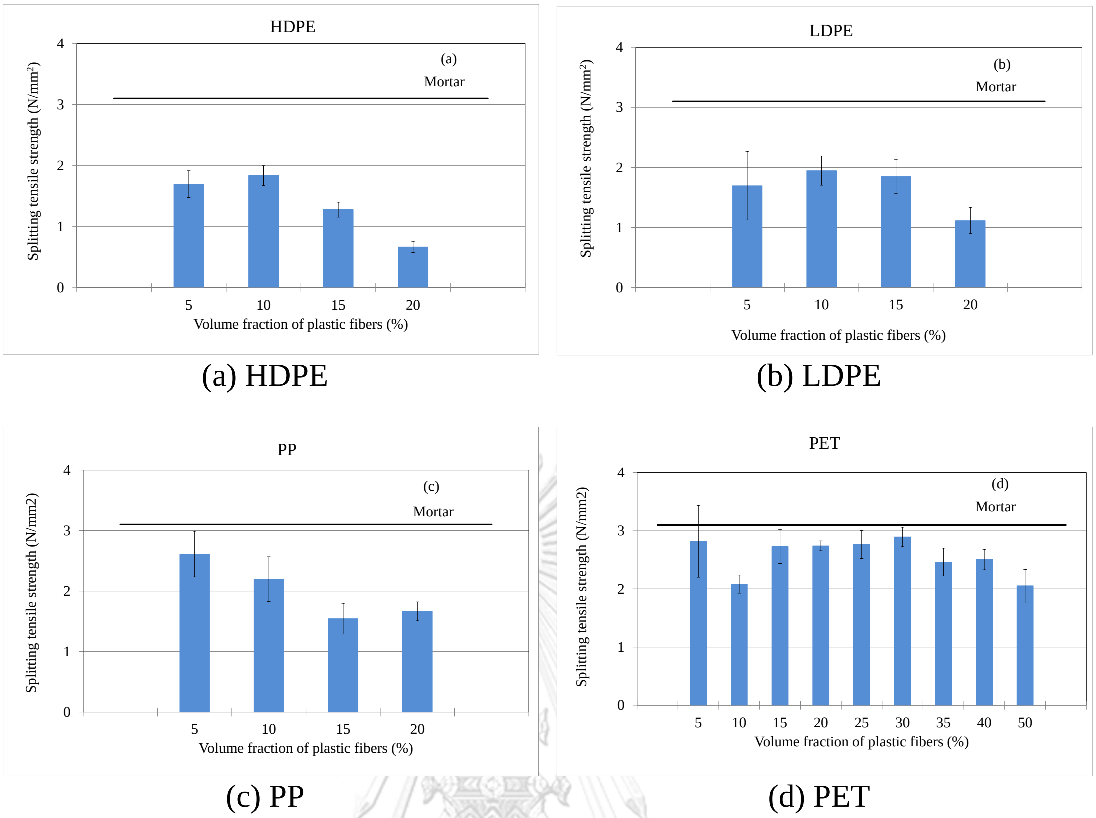
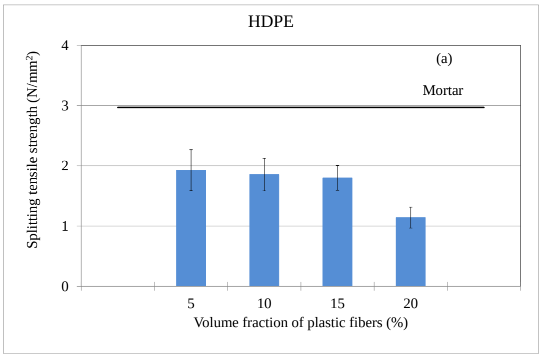


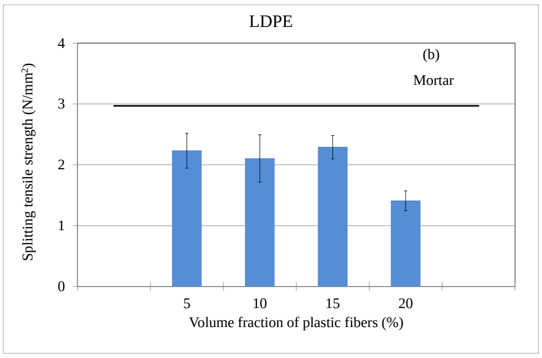
Figure 4.22 Splitting tensile strengths of produced concrete with nonionic surfactant; (a) HDPE, (b) LDPE, (c) PP, and (d) PET fibers. The splitting tensile strength of mortar (control sample) is denoted with solid lines.

3.2.2) Synthetic fiber reinforced concrete without nonionic surfactant

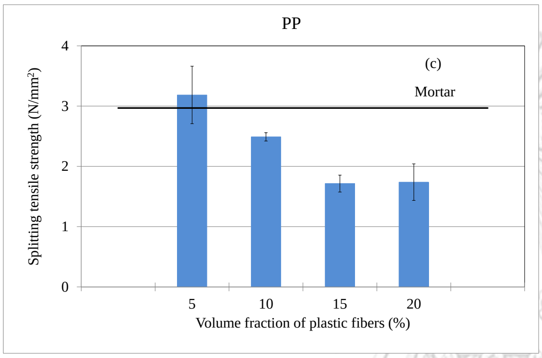
Table 4.12 and **Figure 4.23** showed the splitting tensile strength of concrete produced the addition of HDPE, LDPE, PP, and PET recycled plastic fibers and no nonionic surfactant. It was same as 3.2.1) that the splitting tensile strength values of all the mixings, regardless of the fiber type and fiber volume fraction, were likely to be declined with increase in plastic contents. The splitting tensile strength results of HDPE, LDPE, and PP at 5-20% vol. were found about 1.1-1.9, 1.4-2.2, and 1.7-3.2 N/mm^2 respectively. PET's splitting tensile strength results at 5-50% vol. were about 2.0-2.9 N/mm^2. With a 5% fiber volume fraction, mixing with HDPE and LDPE recycled fibers showed a strength reduction of −37% and −27% respectively while PP fiber increased about 7%, when compared to regular mortar. The strength reduction escalated to −63%, −53%, and −43% when fiber volume fraction increased to 20%. However, concrete with PET recycled plastics showed a better performance with lesser strength reduction, ranging from only −33% to −3% when the fiber volume fraction increased from 10% to 50%.



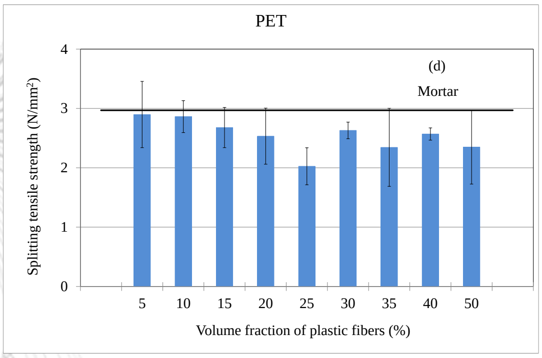
(a) HDPE



(b) LDPE



(c) PP



(d) PET

Figure 4.23 Splitting tensile strengths of produced concrete without nonionic surfactant; (a) HDPE, (b) LDPE, (c) PP and (d) PET fibers. The splitting tensile strength of mortar (control sample) is denoted with solid lines.

Normally, tensile strength of concrete is low when compared with its compressive strength, as a result, high tensile strength materials, such as, steel, plastic, etc., are introduced into the mixture to improve the brittle property of the cementitious composites. According to Hasan et al. [25], adding 0.33–0.51% by volume of macro PP synthetic fibers in concrete could enhance about 10–15% of the splitting tensile strength. Other investigators had also found similar results [24, 26-28]. Choi and Yuan [24] reported that adding 1–1.5% by volume of PP fibers in concrete increased the splitting tensile strength of concrete by 50%, and Hsie, Tu, and Song [26] increased the splitting tensile strength (9–13%) of concrete by mixing 3.6–9.6 kg/m^3 of PP hybrid fibers with concrete.

Ductile fibers, when added into cementitious composites, can enhance its tensile strength depending on several factors such as fiber toughness, fiber volume fraction, alignment, and bonding between the fibers and the cementitious matrix. In this study, the optimum volume fractions of recycled HDPE, LDPE, and PET plastic to achieve the highest splitting tensile strength of the fiber-reinforced concrete composites with nonionic surfactant were found to be 10%, 15%, and 30% respectively while ones without nonionic surfactant were about 10%, 15%, and 10% respectively. Lower and higher volume fraction than these optimum amounts resulted a lower splitting tensile strength. For the case of PP recycled plastic with and without nonionic surfactants, optimum splitting tensile strength of the composites was found to be at 5% volume fraction, thereafter, at higher volume fractions the tensile strengths of the composites reduced as shown in **Figure 4.22** and **Figure 4.23**. In general, all the mixings in this study with different fiber volume fractions showed lower splitting tensile strengths than that of plain mortar (about 3.0-3.1 N/mm^2). The strength reduction varied from 3 to 77% depending on type of fiber and volume fraction.

Similar findings were reported by several investigators [24, 28, 69, 71-73] that increasing fiber volume fraction could cause weak bonding between plastic fiber and cementitious matrix, thus reducing its effectiveness in strengthening the concrete composites. Besides, the splitting tensile strength reduction (when mixed with 25–75% fiber volume fraction) was reported to be lower by 41% when compared with the tensile strength of normal concrete [24]. As mentioned earlier, the lower strength might be attributed to the high volume fractions of plastic fibers used in this study. Larger volume fraction often leads to clumping or balling of fibers [70], making them less effective in strengthening the concrete composites. It should be noted that one of the objectives of this study is to explore the potential utilization of recycled plastics in concrete as alternative to typical disposal in landfill. The use of large quantity of recycled plastic fibers is therefore a goal of this investigation, if the final fiber-reinforced cementitious composites can be used as construction materials, such as wall panel, etc.

4.2.3 Modulus of elasticity

The modulus of elasticity of synthetic fiber reinforce concrete **Equation 4** was the slope of stress (F/A) and strain (ΔL/L) curve as shown in **Figure 4.24**.

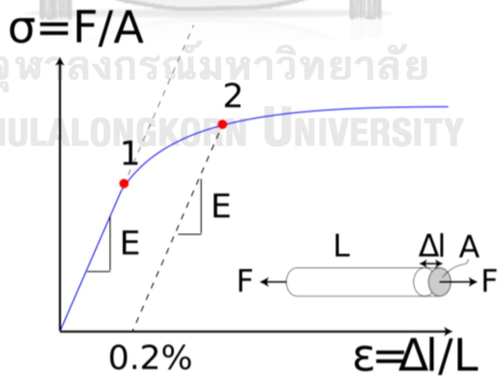


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Figure 4.24 Stress-strain curve [81]

The modulus of elasticity of this study was analyzed by Amsler 400 ton set up with LDVT. The stress of concrete was calculated in proportion between force (N) and cross-sectional area (mm^2). The strain of concrete was the proportion between changed length and original length. The results of modulus of elasticity (**Table 4.12** and **Figure 4.25**) of mortar were about 36.9±7.1 (with surfactant) and 27.7±2.2 (no surfactant). At 5% of HDPE and LDPE in concrete with surfactant and 10% in concrete without surfactant were likely to be increased after that they were dramatically declined until 20% volume fraction. Modulus of elasticity of PP fiber in concrete was likely to be declined with increase plastic volume while at 5% of PP in concrete without surfactant was the peak and then slightly decrease with adding plastic in concrete. Both PET fibers with and without surfactant at 0-40% were likely to be the same until 50% of PET was sharply decreased.

Table 4.12 Modulus of elasticity of synthetic fibers in concrete

Volume fraction of synthetic fibers	**Modulus of elasticity (x1,000 N/mm^2)**	
	With surfactant	**Without surfactant**
Mortar	36.9±7.1	27.7±2.2
5% HDPE	40.3±7.8	35.3±7.0
5% LDPE	39.6±7.9	31.1±0.7
5% PP	32.6±4.6	36.7±6.9
5% PET	31.5±5.5	32.1±3.3
10% HDPE	25.7±1.3	36.6±5.5
10% LDPE	26.7±0.3	30.0±2.6
10% PP	25.2±1.3	31.0±1.5
10% PET	29.9±4.4	29.7±2.9
15% HDPE	16.0±2.3	27.0±5.8
15% LDPE	22.7±0.3	24.4±3.5
15% PP	20.8±4.5	28.3±4.1
15% PET	29.3±3.4	35.7±4.6
20% HDPE	10.9±4.9	23.2±3.8
20% LDPE	18.4±3.2	25.4±4.7
20% PP	20.9±5.4	25.4±6.5
20% PET	27.1±4.5	29.2±5.7
25% PET	23.2±3.1	28.2±3.0
30% PET	30.6±4.2	29.6±5.5
35% PET	30.0±0.9	30.9±4.3
40% PET	27.2±1.3	30.8±2.5
50% PET	0.3±0.1	0.3±0.0

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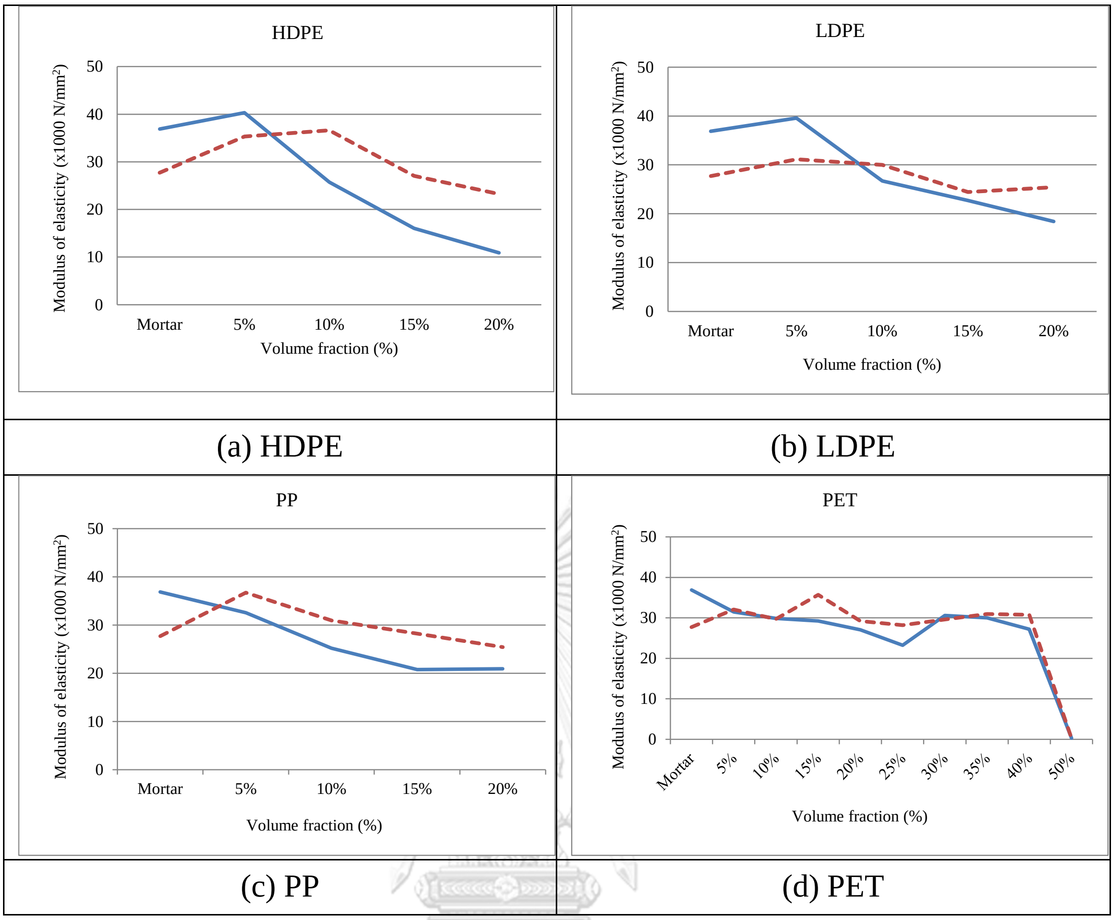

Figure 4.25 The graph of modulus of elasticity of synthetic fibers in various ratios mixed in concrete (a) HDPE, (b) LDPE, (c) PP and (d) PET. The solid line is concrete with surfactant while dash line is concrete without surfactant.

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4.2.4 UV irradiation effect

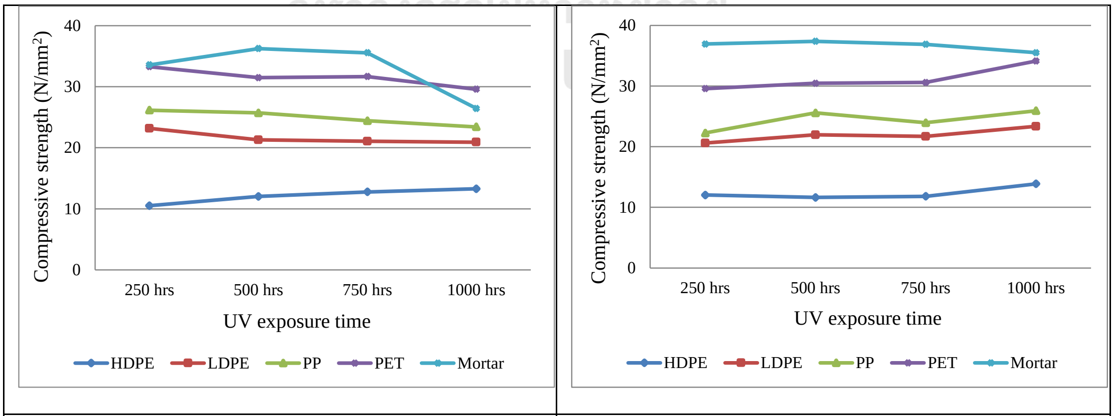
1) Compressive strength

Cube shapes of synthetic fiber reinforced concrete (10% vol. of HDPE, LDPE, PP and PET) prepared according to BS 1881: Part 3 were irradiated by UV-A chamber in 250, 500, 750, and 1,000 hours. Afterwards, their compressive strengths tested according to BS 1881: Part 4 were 10.5-13.3, 20.9-23.2, 23.4-26.2, and 29.6-33.3 N/mm^2 respectively while compressive strengths of ordinary mortar were 26.4-36.3 N/mm^2 as shown in **Table 4.13** and **Figure 4.26**. In case of synthetic fiber reinforced concrete exposed by UV-A in varied time periods (250, 500, 750, and 1,000 hours), the compressive strengths of LDPE, PP and PET fibers in concrete were likely to be a bit declined with increase time exposure while compressive strength of HDPE fiber concrete was a bit increased. Besides, compressive strength of mortar was a bit raised at 250-750 hours and then at 1000 hours was sharply reduced. Cube concretes with no UV-A exposure from 250 to 1000 hours used as control samples were found to have compressive strength about 11.6-13.9, 20.6-23.4, 22.3-25.9, and 29.6-34.1 N/mm^2

respectively while compressive strengths of ordinary mortar were 35.5-37.4 N/mm^2 as shown in **Table 4.13** and **Figure 4.26**. All types of synthetic fiber reinforced concretes were likely a little raised up with time while mortars (from 250 to 1000 hours) were found to be the same.

Table 4.13 Compressive strength of synthetic fibers reinforced concrete in UV-A chamber

UV-A exposure periods	Ordinary mortar (N/mm^2)	Synthetic fiber reinforced concrete (N/mm^2)			
		HDPE	LDPE	PP	PET
UV-A exposure					
250 hours	33.6±2.8	10.5±0.5	23.2±1.3	26.2±1.1	33.3±1.8
500 hours	36.3±1.6	12.0±0.5	21.3±0.9	25.7±2.0	31.5±0.8
750 hours	35.6±3.0	12.8±1.2	21.1±1.4	24.4±0.6	31.7±2.4
1000 hours	26.4±2.4	13.3±1.9	20.9±1.6	23.4±3.4	29.6±2.2
no UV-A exposure					
250 hours	36.9±2.3	12.0±1.2	20.6±1.3	22.3±1.6	29.6±2.4
500 hours	37.4±2.8	11.6±0.5	22.0±1.9	25.6±1.2	30.5±2.8
750 hours	36.9±1.0	11.8±1.4	21.7±2.8	24.0±2.1	30.6±2.5
1000 hours	35.5±1.7	13.9±0.6	23.4±1.0	25.9±0.7	34.1±4.2
Standard *	21				



UV-A exposure	No UV-A exposure

Figure 4.26 Compressive strength (N/mm^2) of synthetic fiber reinforced concrete: UV-A exposure and No UV-A exposure

Compressive strengths of most of synthetic fibers (LDPE, PP and PET) reinforced concretes exposed to UV-A were likely to decline except HDPE because of heat accumulation in concrete affecting to increase temperature in materials. Temperature was one of the main factors of strength in concrete because high temperature can affect fast hydration reaction resulting in incomplete structure and more porosity inside concrete [82]. Moreover, Burg (1996) [83] found that high curing temperature in chamber after 7 days of curing age affected to compressive strength lower than lower curing temperature specimen.

In case of HDPE's results, HDPE's porosity was found to have the highest porosity as shown in **Figure 4.19** so HDPE's bulk density result was the lowest. According to Singh, Shukla, & Brown (2004) [17], one of the major plastic properties was low surface energy; consequently, the mechanical bond strength between plastic and cement composites was very weak. Besides, this poor mechanical bond strength could raise micro voids on the interfacial area between synthetic fiber and concrete matrix which caused inside micro cracks [18]. This study results confirmed that the more air void percentages inside MSFRC can decrease compressive strength so HDPE's compressive strength was the lowest one.

2) Surface analysis

- Plastic fibers in concrete exposed by UV-A radiation

When these synthetic fibers are applied as non-load bearing structure (i.e. precast concrete wall), it is likely to be exposed by UV from sunlight. Besides, concrete is considered as alkaline material because of lime composition which is byproduct of hydration reaction. So, this study aims to find out degradation on synthetic fiber surface comparing synthetic fiber reinforced concrete samples between UV and no UV exposures in 250, 500, 750, and 1,000 hours by SEM.

Comparison micrographs (**Figure 4.27**) between plain synthetic fiber and synthetic fiber in mortar which is no UV-A exposure in 1,000 hours, HDPE surface was more flaky and LDPE, PP, and PET surfaces in concrete was rougher than plain ones. This means that surface of synthetic fibers in mortar can be changed to become more flaky and rougher. Besides, surfaces of synthetic fibers inside concrete irradiated by UV-A were likely to be deteriorated rapidly when comparing to ones which were not irradiated by UV-A. Synthetic fibers in concrete were irradiated by UV-A in 250 hours; HDPE and LDPE were found to be rougher while PP and PET surfaces was found to be rougher and have some small fibers on their surfaces. While comparison between synthetic fibers in top and bottom of concrete irradiated by UV-A in 1,000 hours, they were found to be the same effect although surfaces of synthetic fibers in bottom of concrete were not irradiated by UV-A. It could be assumed that UV-A was not directly affected to surface of plastic fibers in concrete but heat accumulation in concrete during UV-A irradiation under alkalinity condition could expedite their surface deterioration. Like Ho and others [62, 84], they found temperature and humidity could accelerate plastic deterioration when longer time exposure.

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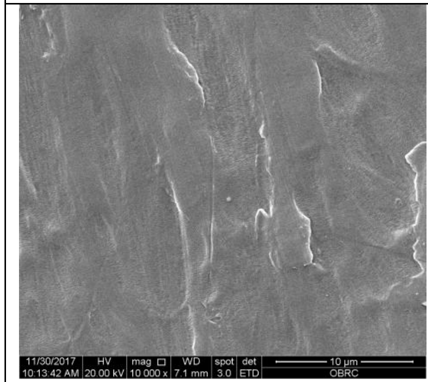
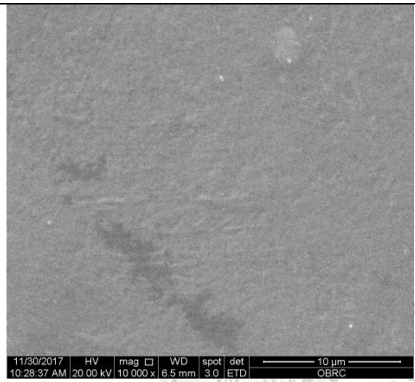
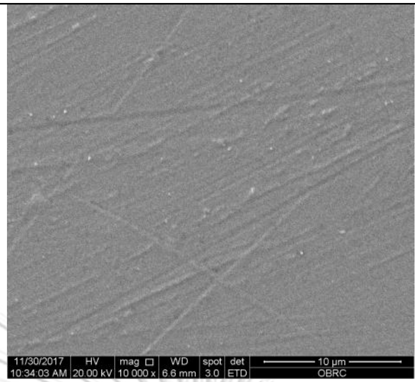
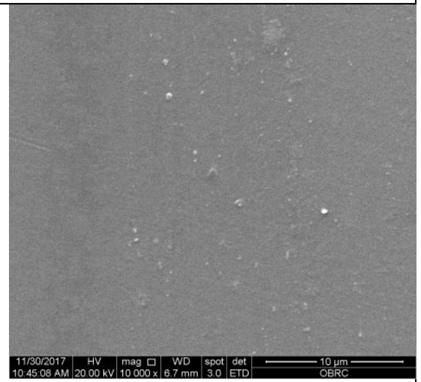
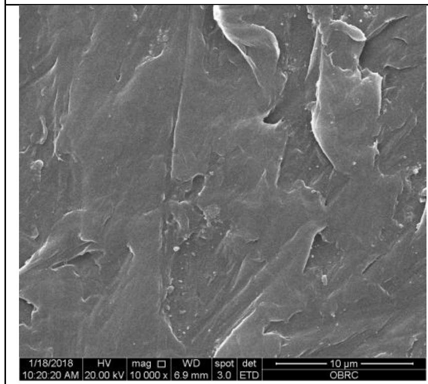
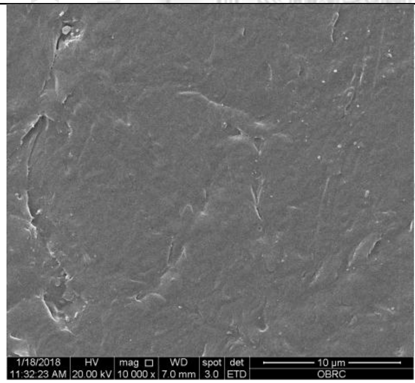
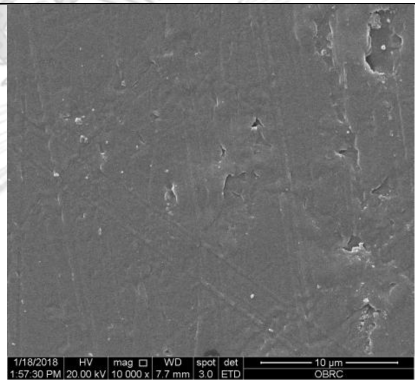
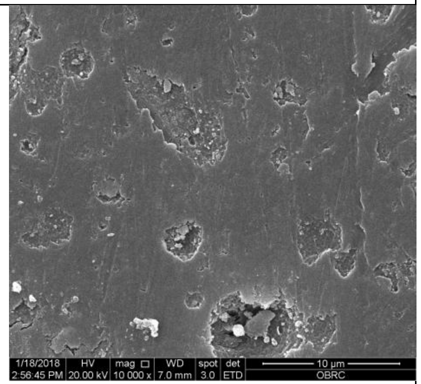
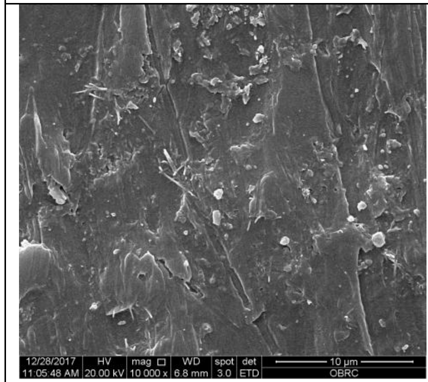
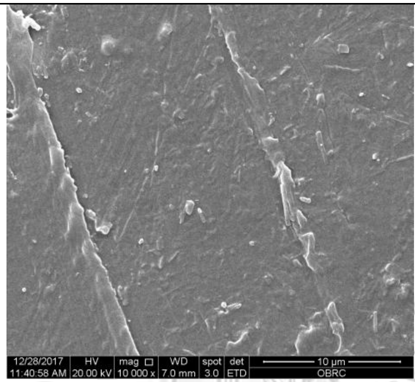
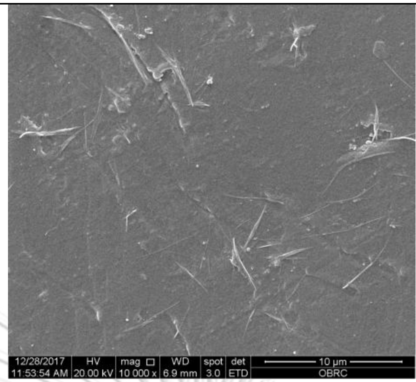
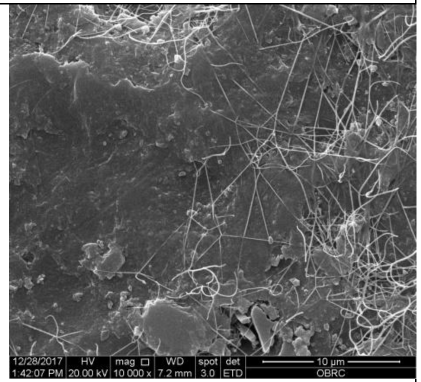
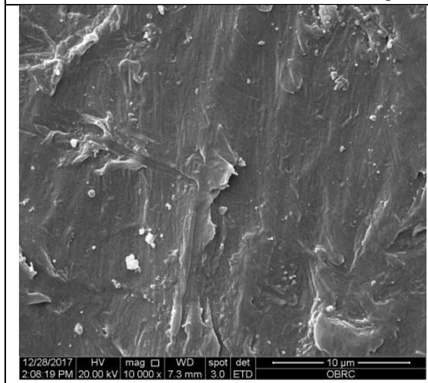
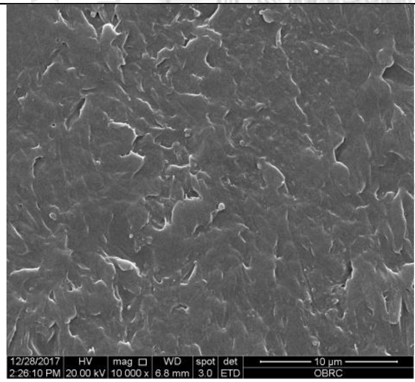
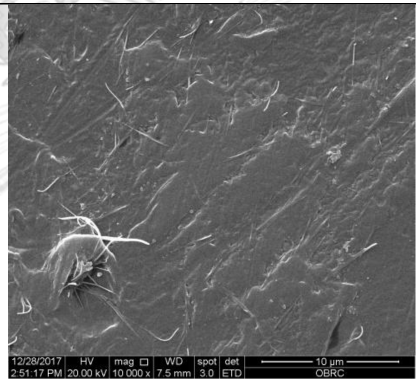
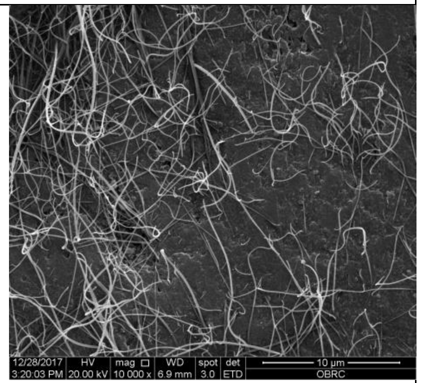
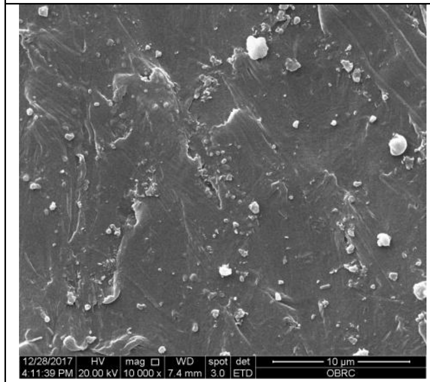
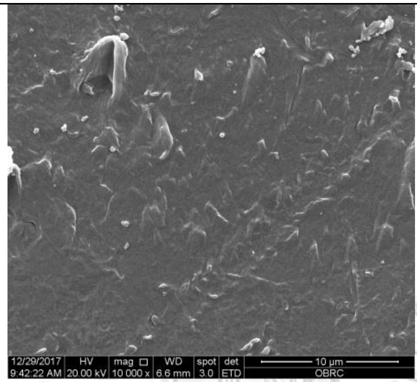
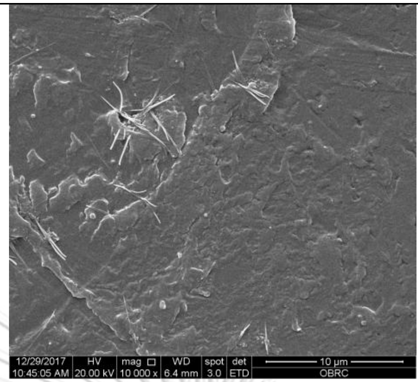
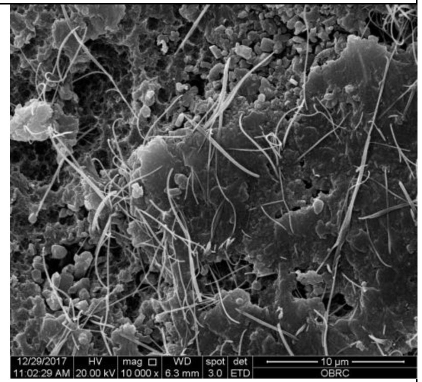
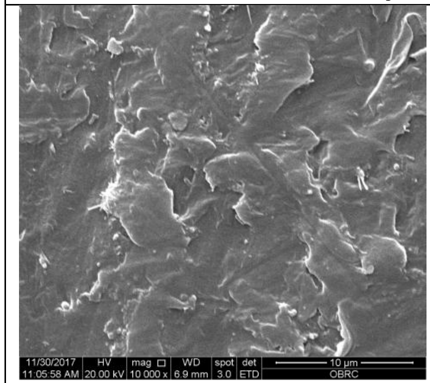
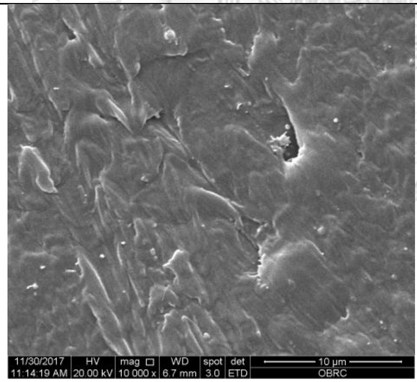
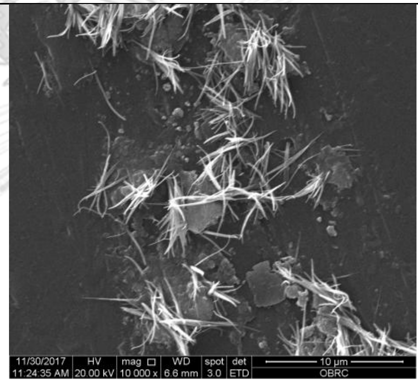
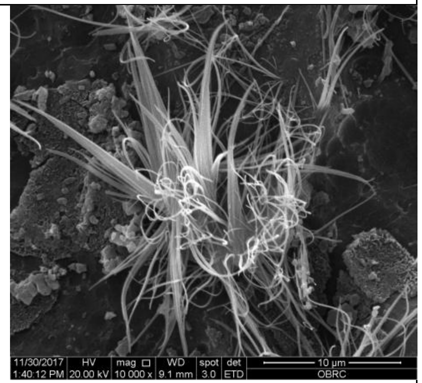
HDPE	LDPE	PP	PET
			
Plain synthetic fibers and no UV-A exposure			
			
Synthetic fibers in concrete and no UV-A exposure: 1,000 hours			

HDPE	LDPE	PP	PET
			
Synthetic fibers in concrete and UV-A exposure at top of concrete: 250 hours			
			
Synthetic fibers in concrete and UV-A exposure at top of concrete: 500 hours			

HDPE	LDPE	PP	PET
			
Synthetic fibers in concrete and UV-A exposure at top of concrete: 750 hours			
			
Synthetic fibers in concrete and UV-A exposure at top of concrete: 1,000 hours			

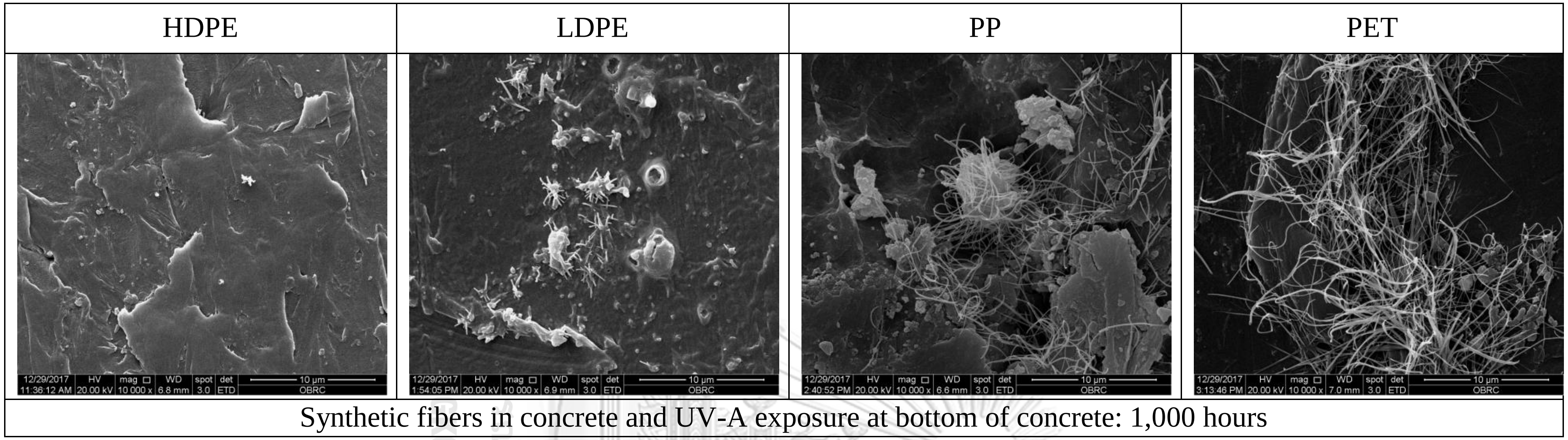


Figure 4.27 Surface of synthetic fibers taken from MSFRC analyzed by SEM (Beam voltage: 20kV and magnification: 10000x)

4.2.5 Thermal conductivity and Thermal resistance

The thermal conductivity (k) of the produced concrete was calculated from the experiments by **Equation 5** whereas the thermal resistance (R) of fiber reinforced concrete was in **Equation 14**

$$\text{Thermal resistance } (m^2\cdot K/W) = \frac{L}{K} \qquad \textbf{Equation 13}$$

Where; L = Thickness of sample (m)

K = Thermal conductivity (W/m-K)

The thermal conductivities of concrete mixed with recycled HDPE, LDPE, PP, and PET shown in **Table 4.14** and **Figure 4.28** were about 0.74–0.96, 0.72–0.86, 0.84–0.94, 0.95–1.02 W/(m·K) on average at 25 °C, respectively, whereas the thermal resistances of fiber reinforced concrete were found to be about 0.08–0.11, 0.09–0.11, 0.08–0.09, and 0.07–0.08 $m^2\cdot K/W$, respectively. Apparently, the thermal conductivity values of produced concrete from all plastic fibers decreased with increasing volume fractions of plastic fibers which was different from thermal resistance, and their thermal conductivities were lower than that of the mortar by about 2–31%.

Thermal conductivity is inversely proportional to thermal resistance. Thermal conductivity depends on the material property, surface area, thickness, and temperature gradient in steady state heat transfer condition [85]. According to Fourier's law equation [86], thermal conductivity is the term for material characteristic which can transfer heat from higher to lower temperature sides. According to Klein [39], thermal conductivities of HDPE, LDPE, and PP were found to be about 0.43, 0.35, and 0.23 W/(m·K) at 25 °C, while thermal conductivities of ordinary concretes with various aggregates were normally about 1.34–2.92 W/(m·K), three to thirteen times higher [36]. Similarly, Tae Sup Yun et al [37] found that the thermal conductivities of mortar and concrete were about 2.0 W/(m·K). Plastic fibers are expected to help reducing thermal conductivities of concrete due to its property. This is concordant with the work of Fraternali et al [60] who studied recycled PET fiber and virgin PP at 1% in concrete and the thermal conductivities were found to have reduced when comparing to the thermal conductivities in plain concrete. Not only is synthetic fiber property affecting the thermal conductivity of fiber-reinforced concrete but small permeable void [32,55] can also restrain heat transfer as well. According to **Figure 4.19**, the more volume fractions of synthetic fibers are mixed in concrete, the more permeable voids of fiber-reinforced concrete were found [16,56]. The results demonstrated that the plastic fibers of HDPE, LDPE, PP, and PET can decrease the thermal inducing property or heat transfer of produced concrete. The lowest thermal conductivity of 0.7–0.9 W/(m·K) was found in the produced concrete from LDPE fiber, which had higher porosity than the control. The thermal property improvement of produced concrete was in the following order; LDPE > HDPE > PP > PET. Furthermore, the thermal resistance values (R) of produced concrete were calculated, the maximal value of 0.1 $m^2\cdot K/W$ was recorded in the produced concrete at 30% volume fraction of LDPE fiber, which was verified to be a good thermal insulator. Therefore, the produced concrete from LDPE fiber has an energy-saving potential when it is applied as a green building material. In fact, one of the green building requirements promoted in Thailand is low energy consumption, therefore if this composite material is used in concrete precast wall or non-load-bearing structure, it can insulate heat transfer from side to side better than the ordinary mortar and help to reduce energy consumption from room temperature adjustment.

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Table 4.14 Thermal conductivity and Thermal resistance of synthetic fiber reinforced concretes

Sample	Thermal conductivity (W/m-K)			Thickness (m)	Thermal resistance (m^2-K/W)		
	10%	20%	30%		10%	20%	30%
Mortar		1.04±0.02		0.08		0.073±0.001	
HDPE	0.96±0.04	0.77±0.01	0.74±0.10	0.08	0.080±0.003	0.101±0.002	0.108±0.017
LDPE	0.86±0.12	0.86±0.09	0.72±0.08	0.07-0.08	0.090±0.012	0.089±0.009	0.109±0.013
PP	0.91±0.12	0.94±0.08	0.84±0.07	0.08	0.085±0.011	0.081±0.007	0.092±0.008
PET	0.95±0.10	1.02±0.02	0.98±0.01	0.08	0.081±0.009	0.075±0.001	0.078±0.001

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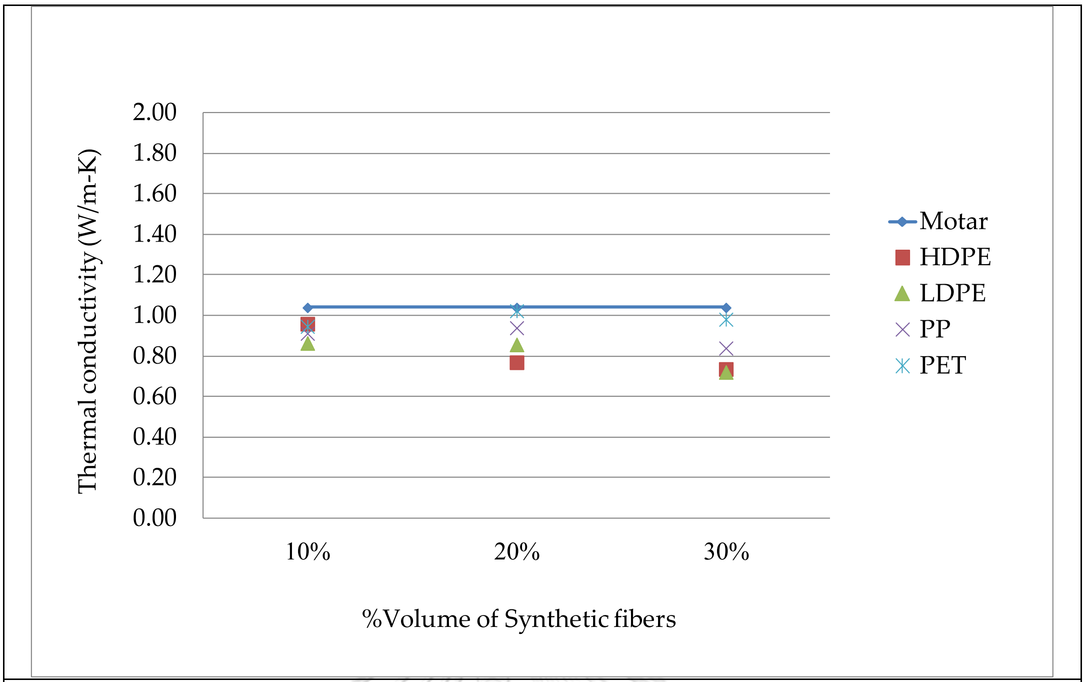
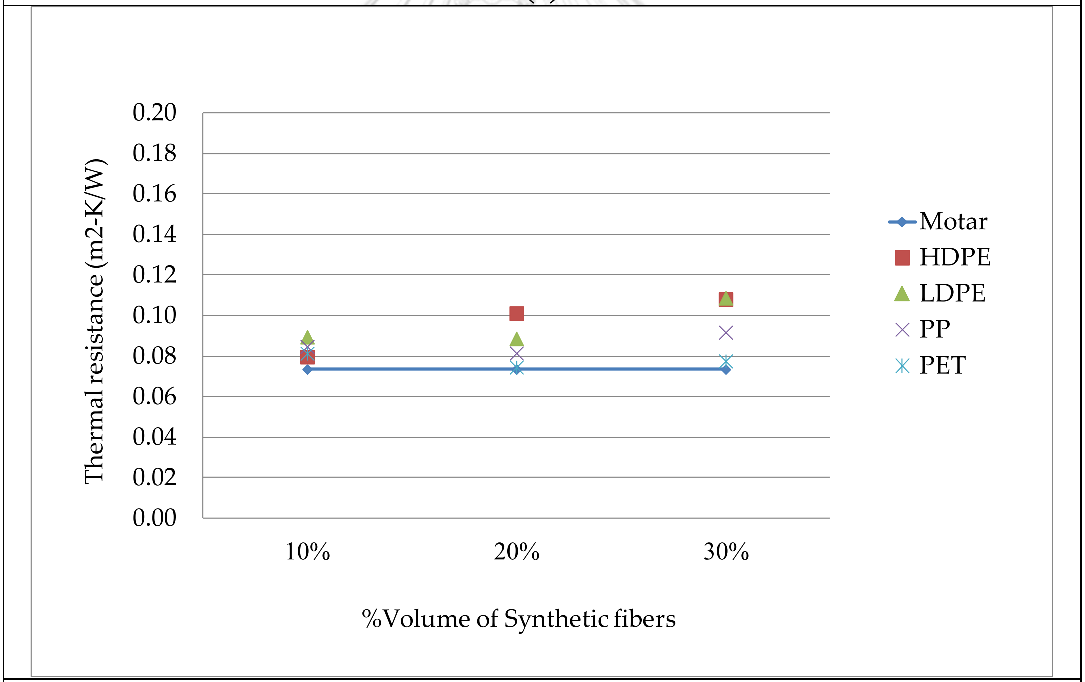


(a)



(b)

Figure 4.28 (a) Thermal conductivity and (b) Thermal resistance of produced concrete. The mortars (as control sample) are in the solid line.

4.3 Cost of synthetic fiber reinforced concrete production

This study aims to reuse industrial plastic waste as macro synthetic fibers in order to indirectly reduce using virgin plastic bead. The cost of this study likes to focus on plastic fiber production cost (or operation cost) by comparing between recycled plastic waste and new plastic bead (especially HDPE, LDPE, PP, and PET). The raw materials of new plastic beads are normally produced from petroleum, so the cost of plastic fiber production made of new plastic bead consists of new plastic, plastic sheet production, and cutting process. While recycled plastic waste costs are relevant to collection cost, separation cost, sorting cost, cleaning cost, and cutting cost.

According to Thai Plastic Industries Association, virgin plastic beads of HDPE, LDPE, PP and PET were about 45.0-52.0, 47.0-54.5, 40.5-48.5, and 33.5-50.5 Baht/kg respectively [87] as shown in **Table 4.15**. In case of using new plastic bead, making plastic sheets spends production cost about 10 Baht/kg while cutting cost is about 330 Baht/kg (1 man-day). The total plastic fiber (HDPE, LDPE, PP, and PET) production costs are about 385.0-392.0, 387.0-394.5, 380.5-388.5, and 373.5-390.5 Baht/kg respectively.

According to plastic waste cost estimation mostly taking into account from Wongpanit recycling company in Thailand (4 February 2019) [88], the prices of HDPE, LDPE, PP, and PET waste collection, separation, sorting, and cleaning were about 1.0, 1.3, 4.0, and 7.2 Baht/kg while cutting cost is about 330 Baht/kg (1 man-day). The total cost of plastic fiber made of plastic waste were about 331.0, 331.3, 334.0, and 337.2 Baht/kg. The production cost of plastic fiber comparison between virgin plastic and recycled plastic waste found that the cost of recycled plastic waste was lesser than virgin plastic bead about 10.8-19.2%.

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Table 4.15 Cost of plastic fiber production made of virgin bead and plastic waste

Activity	Production cost (Baht per kg)	
	Plastic fiber made of virgin bead	Plastic fiber made of plastic waste
1.Collection, Separation, Sorting, and Cleaning [88]	-	1.0-7.2
2.Cutting	330 (1 man-day)	330 (1 man-day)
3.New plastic bead [87]	HDPE (45.0-52.0) LDPE (47.0-54.5) PP (40.5-48.5) PET (33.5-50.5)	-
4.Production cost	10	-
Total cost	373.5-394.5	331.0-337.2

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

Plastic waste is now one of the global issues which needs to be solved urgently so this research aims to find out the way to reduce it scattering in the environment and also to utilize it as new alternative renewable materials (i.e. heat-insulating material, lightweight material, etc.) for concrete technology. According to ASTM standard, macro synthetic fiber is now capable to be applied in concrete [89] which can help increasing tensile strength, after cracking reduction, and shrinkage cracking reduction [7]. Making synthetic fiber from plastic waste should be low cost, easy process and massive use so this research study selected to make macro synthetic fiber. Plastic wastes (HDPE, LDPE, PP and PET) processed by cutting into 3 mm wide and 50 mm long classified as macro synthetic fiber according to ASTM D7508m [56] were mixed with mortar.

According to bulk unit weights, Portland cement type 1 and sand were much higher than plastic waste fibers (HDPE, LDPE, PP, and PET). As results, it was found that HDPE was the lowest bulk unit weight, but PET was found the highest one. When they are mixed, bulk densities of them at 30% volume fraction were lower than the ordinary mortar (about (-15) to (-0.3) %) so plastic materials could reduce overall concrete weight. Lightweight concrete using as non-load bearing structure would be good to reduce load for main concrete structure, indirectly minimizing cost of construction.

Slump test results of HDPE and PP concretes were found to be under ordinary mortar while LDPE and PET at low volume fraction (10% vol.) were above control one but lower at higher volume fraction (20% and 30% vol.). Slump test results were reduced when increasing plastic fiber volumes because plastic fibers could result in complex structure and were high surface area which was likely to be agglomeration. Actually, plastic waste was considered as hydrophobic material while cement and sand were hydrophilic one. This is the reason why LS-12, non-ionic surfactant, was used to increase wettability on plastic surface which might reduce micro void between plastic surface and concrete matrix, and indirectly enhance compressive strength and tensile strength of new composite material. As experiment results, although contact angles between plastic surfaces and non-ionic solution were sharply decreased at 1xCMC, 10xCMC was used to apply in this research as safety factor value. The experiment results of LS-12 at 10xCMC mixed in concrete were found such that increasing plastic fiber fraction in concrete resulted in more voids inside hardened concrete and decreasing compressive strengths and tensile strengths. Compressive strengths and tensile strengths of concrete with LS-12 were not increased significantly when comparing to those without surfactant in spite of decreasing in contact angle results between plastic surface and LS-12 solution. These results implied that LS-12 at 10xCMC could not help bonding between synthetic fiber and concrete matrix and its void as well as not enhance strengths of concrete when increase in volume fraction of synthetic fibers.

Alkalinity resistance results of plastic fiber in lime rich environment were found such that LDPE, PP, and PET were not clearly negative effect on their tensile strength while HDPE's tensile strength was obviously reduced by water and alkaline solution. The results could be concluded that HDPE's concrete is not proper to moisture environment. Moreover, tensile strengths of plastic fibers (HDPE, LDPE, PP, and PET) directly exposed by UV-A were declined and destroyed while LDPE, PP, and PET surfaces at 1,000 hours could be observed some small holes and some spikes on their surfaces. In case of plastic fiber in concrete exposed by UV-A, their compressive strengths decreased with time exposure while compressive strengths of no UV-A exposure samples were slightly increased with time. The major cause was assumed that heat accumulation in concrete by UV-A irradiation is the major effect on strength of concrete. Besides, plastic surface deteriorations were clearly observed with time exposure especially, LDPE, PP, and PET surfaces at 1,000 hours observed some spikes and some small fibers on their surfaces. In short, UV-A irradiation could negatively affect to synthetic fiber in concrete both strength and deterioration so this composite materials should be avoid irradiating UV-A from sunlight and heat accumulation when used in construction building.

All thermal conductivity values of synthetic fibers (HDPE, LDPE, PP, and PET) in concrete were found to be lower when increasing plastic fiber volume fraction. Moreover, their thermal conductivities of 10-30% vol. plastic fibers were found to be lower than ordinary mortar. From all experiments and characterization, HDPE, LDPE, and PP have the potential to be used as additional ingredients to hinder concrete's thermal conductivity and can be used for manufacturing of high insulation material. However, the property was found to be more effective in the produced concrete from LDPE fiber, and to a lesser degree from HDPE and PP fibers. Though PET fiber was found unsuitable for thermal resistance property in concrete because of its inability to show clear improvement over regular mortar, PET fiber compressive strength and splitting tensile strength were higher than other fibers, which was the advantage for utilizing PET waste in green building.

Recommendations for further study

- Swelling effect and water absorption of plastic fiber or plastic waste in order to confirm their physical property during wet condition.
- Cationic and anionic surfactant should be applied in synthetic fiber reinforced concrete to decrease surface energy between water and plastic fiber surfaces.
- Water reducing agent is very interesting to be used to reduce the water and increase concrete's strength.
- Different plastic length or plastic dimension should be investigated to find out the effect on physical property of synthetic fiber reinforced concrete.
- UV-A irradiation experiment is recommended to extend time exposure (6-12 months) and UV-intensity in further study.

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