FLEXURAL BEHAVIOUR OF FIBRE REINFORCED CONCRETE BEAMS CONTAINING POLYETHYLENE TEREPHTHALATE (PET) WASTES

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A thesis submitted in
fulfillment of the requirement for the award of the
Degree of Master of Civil Engineering

Faculty of Civil and Environmental Engineering
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JULY 2014

ABSTRACT

Concrete is a brittle material that can be improved by introducing an additive such as fiber. Studies have proven that the flexural behavior of concrete, such as deflection and cracking, improved when incorporated with fiber. Recently, fibres, such as steel, glass, synthetic, or natural fibres, have been used concrete in concrete to improve the weakness. Recycled polyethylene terephthalate (PET) from bottle wastes, which belongs to the synthetic fiber group, has been used for such purpose. The use of recycled PET bottle wastes can be an alternative solution to PET disposal treatment, which is beneficial to the environment. Therefore, this study collected irregular PET bottle wastes from the Universiti Tun Hussein Onn Malaysia (UTHM) and a recycling collector in Muar for use as fiber in concrete. The bottle wastes were ground to produce PET fibres with an irregular size that ranges from 5 mm to 10 mm. Based on previous studies, three volume fractions of PET fiber (0.5%, 1%, and 1.5%) were incorporated in concrete. This study investigated the material properties and flexural behavior of irregular PET FRC. Density, moisture content, and workability tests were performed for physical properties, whereas compressive strength, tensile strength, and modulus elasticity were tested for mechanical properties. In flexural behavior properties, RC was tested under four-point loading to investigate its beam, deflection, and cracking behavior. The results for material and flexural behavior properties were compared with the control. Both results presented irregular PET FRC in line with the control. At the end of this study, a modified maximum crack spacing ($S_{max,PET}$) model was proposed based on the Gilbert model. Regression analysis and validation work showed that the modified model can be used to predict the maximum crack spacing for irregular PET fiber RC beam.

ABSTRAK

Kelemahan konkrit seperti rapuh boleh diperbaiki dengan menggunakan bahan tambah seperti serat. Kebanyakkan kajian membuktikan bahawa penggunaan serat sebagai bahan tambah ke dalam konkrit telah menambahbaik sifat lenturan konkrit tersebut seperti pesongan dan keretakan. Mutahir ini, kajian konkrit tetulang dengan serat sebagai bahan tambah seperti keluli, kaca, sintetik atau serat daripada sumber semulajadi telah dijalankan bagi tujuan memperbaiki kelemahan konkrit. Polyethylene Terephthalate (PET) daripada sumber botol terpakai yang merupakan serat di dalam kategori sintetik telah digunakan bagi tujuan tersebut. Disamping dapat memperbaiki kelemahan konkrit normal, ia juga boleh menjadi salah satu penyelesaian alternatif kepada pelupusan bahan tersebut yang boleh mencemarkan alam sekitar. Oleh yang demikian, kajian ini telah menggunakan serat daripada sumber botol terpakai dalam bentuk tidak malar. Serat tersebut telah dikumpul daripada dua sumber iaitu sekitar UTHM dan pusat pengumpulan bahan terpakai di Muar. Untuk menghasilkan serat dalam bentuk tidak malar dengan ukuran lima ke sepuluh mm, botol terpakai yang dikumpulkan menjalani proses pengisaran. Berdasarkan kajian lepas, serat akan dimasukkan ke dalam konkrit dalam peratus isipadu 0.5%, 1% dan 1.5%. Kajian ini dijalankan bertujuan mengkaji sifat bahan dan lenturan konkrit dengan tambahan serat PET tidak malar. Ujian ketumpatan, kandungan lembapan dan kebolehkerjaan dijalankan untuk mengkaji sifat fizikal konkrit tersebut manakala ujian kekuatan mampatan, kekuatan tegangan dan modulus keanjalan dijalankan untuk mengkaji sifat mekanikal konkrit. Di dalam ujikaji lenturan, konkrit bertetulang atau rasuk dijalankan dengan menggunakan ujikaji "*four point loading*" untuk mengkaji sifat lenturan rasuk tersebut. Hasil kajian bagi sifat bahan dan lenturan tersebut telah dibandingkan dengan specimen yang dikawal. Hasil kajian tersebut menunjukkan konkrit dengan bahan serat PET tidak malar selari dengan specimen yang dikawal. Di hujung kajian ini, pengubahsuaian model untuk mencari jarak maksimum retakan untuk rasuk telah dihasilkan berdasarkan model daripada Gilbert. Analisis regresi dan kerja-kerja pengesahan dibuat menunjukkan model tersebut diterima dan boleh digunakan untuk menganggarkan jarak maksimum retakan bagi konkrit dengan serat PET tidak malar.

CONTENTS

CHAPTER I

INTRODUCTION

1.1 Background

Plastics are polymers with large molecules that consist of long repeating chains of smaller molecules known as monomers. Two major raw materials, namely, oil and natural gas, are used to produce plastics. Each plastic has distinct characteristics; however, most plastics are resistant to chemicals, possess thermal and electrical insulation properties, lightweight, possess varying degrees of strength, and can be processed easily in various ways (Siddique et al., 2007).

Plastic consumption has become an integral part of our lives nowadays. Thus, the amount of plastics consumed annually has been increasing steadily. Several characteristics of plastic contribute to the rapid growth of plastic consumption, such as low density, easy fabrication capabilities, long life, lightweight, and low production cost (Siddique et al., 2007). Plastics are used widely in packaging, automotive and industrial applications, medical delivery systems, artificial implants, healthcare applications, land/soil conservation, water desalination, flood prevention, food preservation and distribution, housing, communication materials, security systems, and other uses. Wide applications of plastics in all parts of our daily activities increase the volume of plastic wastes. Table 1.1 shows the predicted amount of municipal solid wastes (MSW) in Kuala Lumpur (KL), Malaysia (Saeed et al., 2009)

Table 1.1: Prediction of MSW in Kuala Lumpur (Saeed et al., 2009)

Year	**Population of KL city (millions)**	**MSW (kg/each person/day)**	**MSW (millions kg/day)**	**MSW (millions kg/year)**
2008	2.34	1.62	3.79	1383.35
2010	2.53	1.69	4.28	1562.20
2012	2.74	1.76	4.82	1759.30
2014	2.96	1.83	5.42	1978.30
2016	3.20	1.90	6.08	2219.20
2018	3.46	1.98	6.85	2500.25
2020	3.75	2.06	7.73	2821.45
2022	4.05	2.14	8.67	3164.55
2024	4.38	2.23	9.77	3566.05

The trend of population growth in comparison to the growth of MSW in Table 1.1 indicates a serious issue. From 2008 to 2024, the population of KL is expected to increase by 87% from 2008 to 2024; however, the MSW growth is predicted to increase by 157.8%, which indicates that the percentage of MSW growth is greater than the population growth. The contradiction percentage between the population and MSW growth shows that the MSW problem would worsen if proper treatment is ignored. According to Manaf et al., (2009), MSW comes from food, mixed paper, plastics, textiles, rubbers, glass, and organic wastes. Table 1.2 classifies the percentage of each type of waste in MSW, whereas Table 1.3 shows the plastic use in several industries. The plastics commonly used in the packaging industry for food and beverage (PET) constitute about nine to ten percent of MSW.

Table 1.2: Solid wastes composition of selected locations in Kuala Lumpur, Malaysia (Agamuthu & Faizura, 2005)

Wastes consumption	**Percentage (%)**
Garbage	45.7
Plastic	9.0
Glass	3.9
Paper or cardboard	29.9
Metals	5.1
Fabric	2.1
Miscellaneous	4.3
TOTAL	**100**

Table 1.3: Consumption of plastics according to industrial sectors by MPMA

Sectors	**Plastic consumption (%)**
Domestic	19
Agriculture	3
Electrical and electronics	39
Automotive	26
Packaging (Food and beverage)	10
Building and construction	3

The prediction in Table 1.1 shows that plastic consumption would be approximately 356.6 million kg by the year 2020. The worst scenario is that most of the plastics used nowadays are thrown away after one use. The problem is further complicated because plastic wastes are non-biodegradable and may cause environmental hazards. Treatment methods for plastic wastes, specifically incineration, produce toxic gas such as dioxin, which is dangerous to human health. Several methods are available for disposing plastic wastes; however, most of these treatments are not feasible if plastic waste generation is too high. Therefore, one of the potential solutions to the problem is to recycle PET for use in the construction industry.

1.2 Problem statement

Most PET bottle wastes are thrown away by consumers after one use because plastic is inexpensive and consumers lack environmental awareness (Welle, 2011). Normally, most consumers throw PET bottle wastes in dustbins, which are then sent to the landfill. This improper treatment would decrease landfill capacity and contribute to environmental issues in the long term. According to Zhang and Wen, (2013), PET bottles can be recycled for use in the agriculture, manufacturing, and construction industries. In the construction industry, PET bottle wastes can be recycled as fine aggregates or fibress (Frigione, 2010) (Kim et al., 2010). Therefore, a proper recycling method of PET bottle wastes for use as fibress for concrete in the construction industry must be determined in line with previous studies.

Various methods have been studied to add PET bottle wastes as fibres in concrete to improve the compressive strength of normal concrete, as summarized in Table 1.4. Four different studies in terms of different shapes, percentage of PET volume fractions, water cement ratios, and concrete compressive strengths, have been reported. Fraternalli et al. (2011) studied PET with different tensile strengths. In the study by Foti (2011), PET from bottle wastes was used with different shapes and strips. Kim et al. (2010) and Ochi et al. (2007) studied PET in strips from the manufacturing process.

Table 1.4: Summary of previous research

Research	**Volume fraction of PET fibre [%]**	**Shape of PET fibre**	**W/C ratio**	**Compressive strength**
Kim (2010)	0.50, 0.75, 1.00	Strip	0.41	Decrease
Fraternalli (2011)	1.00	Strip	0.53	Increase
Foti (2011)	0.26	Strip & circular	0.70	Decrease
Ochi (2007)	0.50, 1.00, 1.50	Strip	0.55, 0.60, 0.65	Increase

**W/C = Water over cement*

Fraternalli et al. (2011) investigated PET properties and obtained different concrete compressive strengths. They proved that using high tensile strength PET as fibres contributes to the high compressive strength, which improved by 35% compared with normal concrete. The same trend in compressive strength was obtained by Ochi et al. (2007), where the compressive strength of concrete increased by 1.1% to 13.8%. Other studies by Kim et al. (2010) and Foti (2011) indicated different compressive strength results and found that the compressive strength of concrete decreased by 1% to 9% and 31.9% to 37.5%, respectively, compared with normal concrete. Based on the concrete properties mentioned above, variations in concrete strength may be attributed to the PET tensile strength, shape, and added volume.

Fibress can improve the flexural strength of an RC beam. Ding et al. (2009) showed that the flexural toughness of concrete increases by 30% with the addition of fibres in plain concrete. In terms of cracking behavior, fibres improves cracks by bridging the two surfaces to prevent cracks from propagating (Yang et al., 2011; Mindness et al., 2003; Ahmed et al., 2007). Deflection and ductility behavior can also be improved by introducing fibres in the RC structure. According to Kim and Shin (2011) and Kim et al. (2010), the use of fibres can improve the ductility and ultimate strength of concrete. As a result, the deflection number and ductility of the structure increases compared with the plain concrete structure. Evidence indicates the role of fibres in improving the flexural behavior in RC structure.

Inconsistent results from the principle test (concrete strength) of PET triggered the need for further study, especially to verify the properties of PET and the mix proportion of concrete to produce the best mix properties of PET as fibres in concrete that could be applied in large-scale experimental work. Fibres significantly affects the flexural behavior of the RC structure; hence, a study on flexural behavior must be carried out. Based on previous studies, the irregular shape of PET fibres is yet to be studied. Therefore, a study on material and flexural behavior of irregular PET fibres is needed. With regard to the flexural behavior capacity of RC beam, the results of the study on the crack behavior of concrete is expected fill the research gap and contribute to fundamental knowledge.

1.3 Objectives of study

The objectives of the study are:

1. To investigate the effect of irregular PET fibres on concrete physical properties (workability, moisture content, density) and mechanical properties (compressive and tensile strength and modulus of elasticity (MOE)).
2. To investigate the influence of irregular PET fibres in reinforced concrete beams for mid span, mode of failure, deflection and cracking behaviour.
3. To propose the maximum crack spacing model for irregular PET fibre reinforced concrete beam.

1.4 Scope of study

This study consists of field activities, laboratory works, and mathematical and statistical analyses. Field activities involve collecting drinking bottle wastes from a recycling collector in Muar and around Universiti Tun Hussein Onn Malaysia (UTHM). The drinking bottle wastes are limited to mineral water and carbonated drink bottles. The collected PET bottle wastes are then cleaned and dried to remove impurities. Afterward, the waste bottles are ground by using a granulator machine and sieved in 5 mm to 10 mm. Based on previous studies, 0.5%, 1.0%, and 1.5% volume fractions of PET fibres are used in this study.

The laboratory works include two parts, namely, material properties and flexural behavior tests. SCC is used as concrete medium. Two tests are performed for the material properties investigation, namely, physical and mechanical property tests. Workability, density, and moisture content are investigated for the physical characteristic tests. Compressive and tensile strengths and MOE are performed for the mechanical property tests. A four-point loading test for RC beams is performed for flexural behavior properties after the beams have been casted for 28 days. In flexural behavior testing, mid-span section, mode of failure, and deflection and cracking behavior are investigated.

Three models are used in the maximum crack spacing discussion, namely, Gilbert model, EC 2 1997, and CEB-FIP 1990. Based on the comparison for each model, the significant model is selected and modified to produce maximum crack spacing model for PET fibres-reinforced concrete (FRC) beam. The modified model is validated in two different ways: validation through statistical analysis by using SPSS and validation through a new flexural test on PET fibres concrete beam.

1.5 Significant of study

Manaf et al. (2009) and Kathirvale et al. (2003) showed that the average amount of MSW generated in Malaysia is 0.5–0.8 kg to 1.7 kg per person in a day. The trend shows that the generated MSW increases rapidly by more than 50%. According to Saeed et al. (2009), the quantity of MSW that is generated is estimated to increase to 282.1 million kg by the year 2020, which is an increase of more than 50% from 2012. PET bottle wastes in food and beverage constitute 10% of the total MSW consumption according to MPMA; PET bottle waste consumption by 2020 would approximately be 282.1 million kg. The large numbers of PET bottle wastes decrease the landfill capacity if recycling behavior is low. Therefore, the recycling method in the construction industry could contribute to solving this problem.

The addition of fibres to concrete significantly improves the brittle properties of concrete into a ductile material (Ding et al., 2009). Ding et al. (2009) showed that the flexural toughness of concrete increased by about 30% compared with plain concrete. The improvement in flexural toughness significantly affects the flexural cracking of the structure. Dong et al. (2012) found that the maximum crack width decreased when fibres is introduced into the structure. In addition, the fibres improved to the point where a deflection-hardening response in bending accompanied by multiple cracks after initial cracking is exhibited.

Previous studies have proven that the addition of fibres to a concrete structure is beneficial for the flexural behavior of the latter, such as toughness and crack resistance. In addition, this process provides an alternative solution to wastage disposal of PET wastes because it can be recycled into fibress and applied in the concrete structure. In this research, PET from raw bottle wastes is used in irregular shapes to assess the flexural behavior when added to concrete. The PET fibress used in this study were obtained from the collected PET drinking bottle wastes. The PET fibress were ground into irregular shapes. Using raw PET fibress from recycled PET bottle wastes would reduce the cost of producing the fibress. This type of PET has not been explored previously. Thus, the results from this study would provide fundamental knowledge on the flexural behavior of the beam structure when irregular PET bottle wastes are applied as fibres.

1.6 Structure of the thesis

The structure of this thesis is shown as follow:

i. Chapter 2: Describes the literature on the subject of this thesis.

ii. Chapter 3: Describes the experimental work for material and flexural behaviour test setup.

iii. Chapter 4: Describes the results and discussion for material properties; physical and mechanical properties.

iv. Chapter 5: Describes the results and discussion for RC beams specimens test. In this chapter, the beam behaviour, mid span section, cracking behaviour and deflection are discussed.

v. Chapter 6: Presents the discussion on the crack maximum spacing models. A modification and validation of maximum crack spacing model for PET fibre reinforced concrete beam is presented in this chapter.

vi. Chapter 7: Presents the concluding remarks on all test results. The research contribution is presented in chapter along with the recommendations for further works

1.7 Concluding remarks

This study is important and timely to provide the basic knowledge and understandings on the material properties and flexural behaviour of irregular PET fibre for reinforced concrete beam. The maximum crack spacing model modified for PET fibre reinforced concrete beam provides benefit to future research to predict the maximum crack spacing at initial stage.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

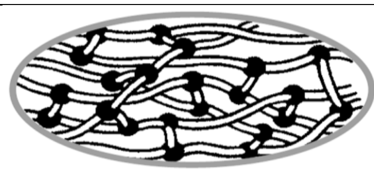
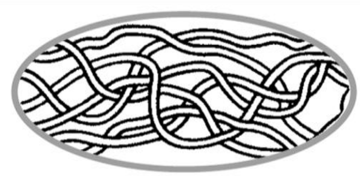
Several studies on FRC have been conducted. The most commonly used fibress are steel, polypropylene, glass, and PET. Fibres influences the RC by increasing the energy absorption capacity and toughness of the material, which is defined as a function of the area under the load over deflection curve (Mindness et al., 2003). In addition, fibres increases the tensile and flexural strength of concrete. Moreover, fibres acts as a bridge across the cracks that developed through post-cracking ductility (Mindness et al., 2003). If the fibress are sufficiently strong and bonded to the material, the fibres can bear significant stresses over a relatively large strain capacity in the post-cracking stage (Mindness et al., 2003). PET fibres in the concrete mixture is expected to enhance the resistance of traditional RC to cracking, deflection, and other serviceability conditions because of the characteristics of the materials used in fibres concrete (Mindness et al., 2003).

2.2 Polyethylene Terephthalate

The characteristic of plastic consists of thermosets and thermoplastics are discussed in Table 2.1. Each plastic has it characteristics, but commonly most plastics have the following general attributes as stated in Malaysia Plastic Forum (2007):

1. Plastics can be very resistant to chemicals
2. Plastics can be both thermal and electrical insulators
3. Plastics are very light in weight with varying degrees of strength
4. Plastics can be processed in various ways to produce thin fibres or vey intricate parts

Table 2.1: Characteristic of plastics by Malaysian Plastic Forum (2007)

Thermosets	**Thermoplastics**
	
Permanent once moulded; they do not deform under heat	Melt under heat and can be reformed repeatedly
Valued for its durability and strength and are used primarily in automotive and construction industry	Offer versatility and wide range of applications. It is widely used for packaging because it can be rapidly and economically formed into any shape required to full-fill the packaging function
Example of product: toys, coating, ski boots, furniture, etc	Example of product: mineral water bottles, automotive bumpers, microwave containers, sheeting, credit cards, etc

Based on Table 2.1, Polyethylene terephthalate (PET) bound in thermoplastic group. According to International Life Sciences Institute (ILSI, 2000) report on Packaging Materials 1 entitled “Polyethylene Terephthalate (PET) for Food Packaging Applications”, PET is a type of long-chain polymer which is belonging to the generic family of polyesters. It is a plastic material which has found highly demand within the packaging field. PET is an intermediate formation of terephthalic acid (TPA) and ethylene glycol (EG), which are both extracted from oil feedstock (ILSI, 2000). All polyesters are formed by the general polymerisation reaction between an acid and an alcohol, but the intermediates that differentiate the type of polyesters produced. In its most genuine form, PET is an amorphous glass-like material. It develops crystallinity under the influence of direct modifying additives (ILSI, 2000). It consists of polymerized units of the monomer ethylene terephthalate, with repeating ($C_{10}H_8O_4$) units. Figure 2.1 below shows the chemical structure of PET.

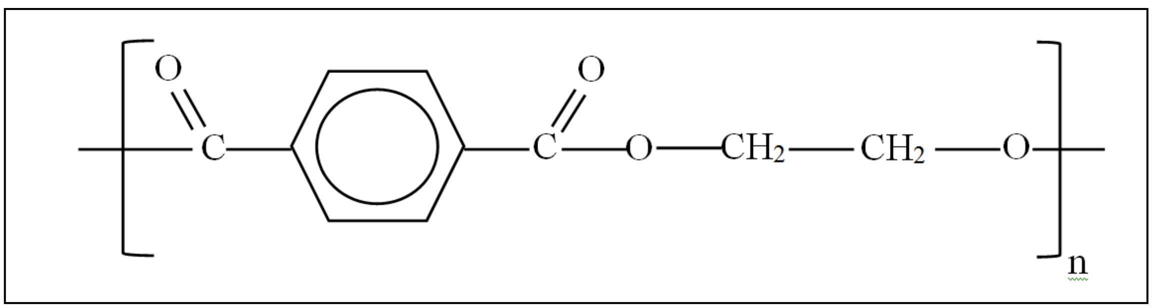


Figure 2.1 Chemical structure of PET (ILSI, 2000)

2.2.1 Formation of Polyethylene Terephthalate

According to ILSI, (2000), polyesters are formed by the reaction of bifunctional acids and alcohols, in the presence of a metal catalyst. In the polymerisation reaction, the condensation reaction is very important in which the molecules react and release water. Then, a second polymerisation reaction takes place in the solid phase. The process of

PET involves when the pure terephthalic acid (PTA) and ethylene glycol (EG) are heated together, the first product is a monomer (BHET – bis-hydroxyethyl-terephthalate) mixed with low molecular weight polymers (oligomers). When the mixture reacts further, it then distils out excess ethylene glycol and forms the PET. PET formed at this stage is a viscous molten liquid. It is extruded and water quenched to form a glass-like amorphous material, which is in its purest form (ILSI, 2000).

For the second polymerisation reaction, a high molecular weight PET is manufactured at this stage at lower temperature which efficiently removes all the volatile impurities, such as acetaldehyde, free glycols and water. The produced high molecular weight is significant for good mechanical properties providing stiffness, toughness and creep resistance meanwhile, at the same time, giving sufficient flexibility to resist bursting and breaking under pressure (ILSI, 2000). The complete chemistry process of PET formation is shown in Figure 2.2.

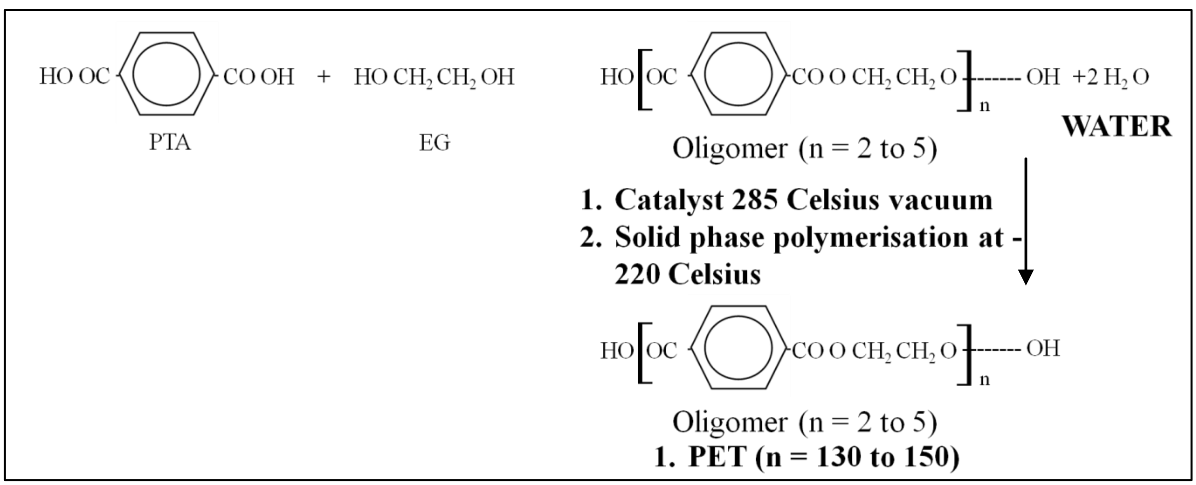


Figure 2.2 Chemistry formation of PET (ILSI, 2000)

2.2.2 Properties of Polyethylene Terephthalate

According to ILSI, (2000), semi-crystalline polymer when heated above 72^{o}C, it changes from a rigid glass-like state into a rubbery elastic form. In this state, the polymer molecular chains can be stretched and aligned in one direction or two directions to form fibres and bottles respectively. When the polymer melts, it is still held in stretched state and is cooled quickly, and then the chains are frozen with their orientation remaining unbroken. Thus, the material is exceptionally tough and confers the properties in a typical PET bottle.

On the other hand, crystalline PET (CPET) is detained in stretched form at temperature above 72^{o}C, slowly crystallises and the material starts to become opaque (non-transparent), more rigid and less flexible. This CPET is capable of enduring higher temperatures, for example trays and containers which have the capability to withstand the moderate oven temperatures. Usage of 'heat setting' technique also promotes the crease and washes resistance properties of polyester textiles. There are numerous products can be generated using the same basic chemical formula of PET with careful manipulation between each of these forms.

PET is becoming popular in the food packaging application because of its physical properties of glass-like transparency together with adequate gas barrier properties for retention and carbonation (ILSI, 2000). Other than that, it exhibits a high toughness/weight property ratio which permits lightweight, large capacity safe unbreakable containers. In additional, PET has the characteristics of clear, tough, has good gas, and moisture barrier in which make PET an ideal for drinking bottle applications or other food containers (MPMA, 2007).

2.3 Fibre Reinforced Concrete

According to Mindness et al., (2003), plain concrete has characteristics such a brittle material, low tensile strength and strain capacities. To overcome these disadvantages, extensive of research have been conducted on fibre reinforced concrete (FRC). FRC can be defined as concrete incorporating with short, discrete, discontinuous fibres. The additional of fibres in concrete purposely not to increase the concrete strength, though modest increases in strength may occur but the principal role of fibres is to control the cracking of the fibre reinforced concrete and to modify (Mehta & Monteiro, 2006), (Kim et al., 2010). In Table 2.2 and 2.3, it indicates the conventional fibres use in concrete by Mindness et al., (2003). According to Table 2.2, the fibres have tensile strength and elongation break range between 0.08 to 4 GPa and 0.5 to 80%.

Table 2.2: Typical properties of common fibres used (Mindness et al., 2003)

Fibre		**D, (μm)**	**MOE (GPa)**	**Tensile Strength (GPa)**	**Elongation at Break (%)**
Steel		5-500	200	0.5-2.0	0.5-3.5
Glass		9-15	70-80	2-4	2.0-3.5
Asbestos	Crocidolite	0.02-0.4	196	3.5	2.0-3.0
	Chrysotile	0.02-0.2	164	3.1	2.0-3.0
Synthetic	PP	6-200	5-77	0.15-0.75	15
	PET	25-1000	0.3	0.08-0.6	3-80
Cellulose		-	10	0.3-0.5	-

Table 2.3: Description of common fibre used based on (Mindness et al., 2003)

Fibre	Description
Steel	Produced by cutting wire, shearing sheets, or from a hot-melt extract. First generation of steel fibre were smooth and found in not sufficient bond with the concrete element. Modern steel fibre improved by deformed along their lengths or ends.
Glass	Produced by a process of molten glass is drawn in form of filaments through heated. Commonly available in chopped strand and continuous roving. Used primarily in thin sheet components such as architectural panels.
Synthetic (PP, PET)	Commonly known as low-modulus synthetic fibres (<0.5%) of fibres produce effectiveness in reducing the amount of plastic shrinkage cracking, provide some toughening and impact resistance.
Carbon	High-modulus synthetic fibres and tensile strength, though its very effectiveness fibres in FRC. Due to high cost, the application has limited.
Organic	High-modulus and tensile strength fibres compare to other synthetic fibre. Commonly use as a replacement for asbestos fibres Need special processing before it can be used in FRC.

2.3.1 Mechanics of Fibre Reinforcement

As stated earlier in Mindness et al., (2003) and (Mehta & Monteiro, 2006), the principal role of fibres is to bridge across the cracks when the strain of the composite has exceeded the ultimate strain capacity of the brittle. Figure 2.3 represent the load-deflection curve for fibre reinforced concrete in flexure.

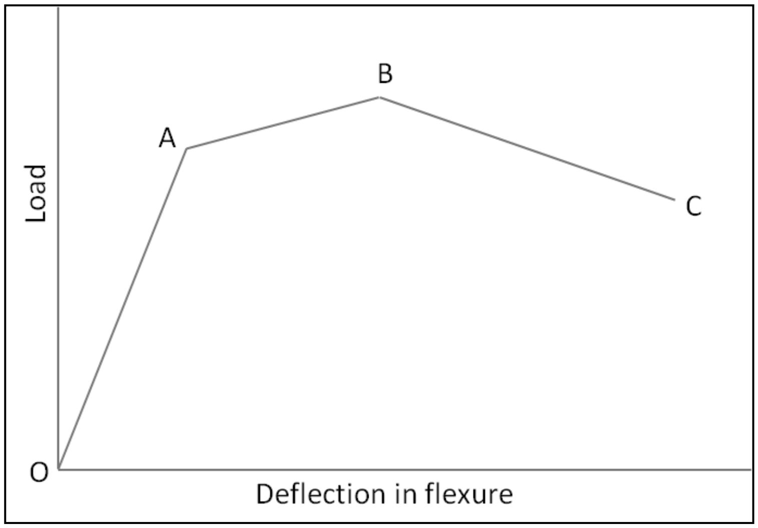


Figure 2.3: Load-deflection curve for fibre reinforced concrete in flexure (Mindness et al., 2003)

Point A represents the point in which the concrete started to crack. The OA segment is essentially the same for both plain and fibre reinforced concrete. At the AB line, the line indicates at yielding stage. At this stage, the concrete structure is completely varied on the reinforcement placed. The additional of fibre may little influence on the strength of fibre reinforced concrete while the post-peak toughness and load bearing capacity greatly increased. The fibre transferred the load across the cracks in post-cracking zone. Point B indicates the ultimate strength that the concrete can achieve and the concrete is measured as failure along BC line. The schematic diagram of fibres bridging across a crack is represented in Figure 2.4.

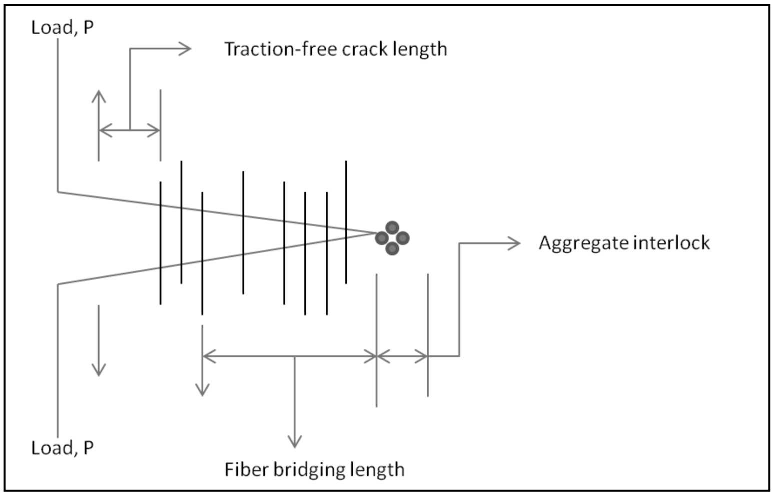


Figure 2.4: Fibre bridging across the crack (Mindness et al., 2003)

2.3.2 Fabrication of Fibre Reinforced Concrete

Fibre reinforced concrete production is to be the same with the plain concrete as stated in Mindness et al., (2003). One of the major aspect need to be stressed is how the fibres are uniformly dispersed throughout the concrete by avoiding segregation or balling of fibres. These problems become more severe as the aspect ratio, the fibre volume, or the maximum size of coarse aggregate increase. Figure 2.5 represents the fibres composites in concrete mix.

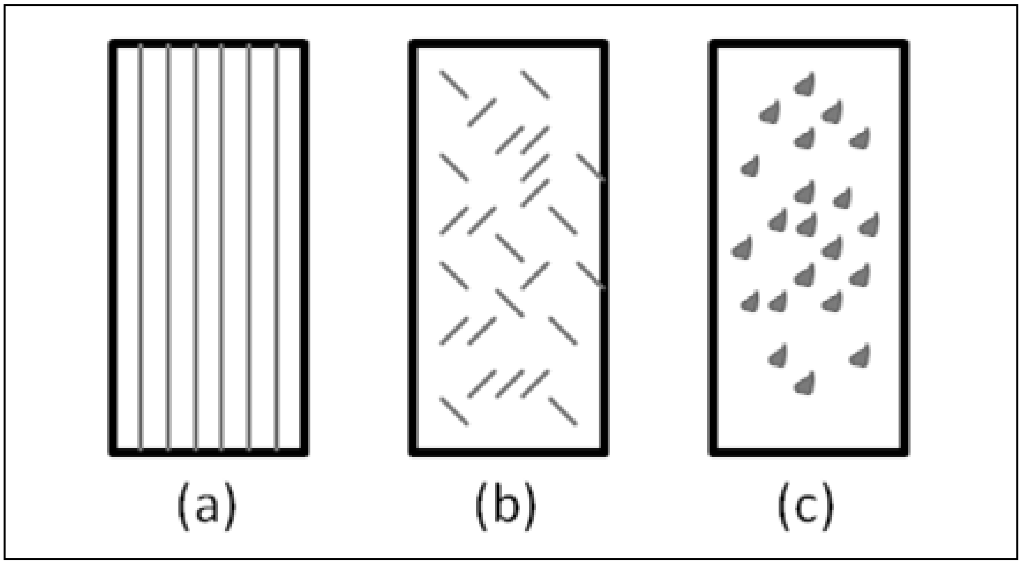


Figure 2.5 Schematic of microscopic composites: (a) aligned fibres, (b) random strip fibres, and (c) random particles size fibres by Mindness et al., (2003)

The common problem occurs in steel fibre application as mentioned in Mindness et al., (2003) is where the steel fibres are eased to clumping (balling), thus the fibres should be added to the mix in a clump-free state. Alternatively, the fibres can be added to the aggregates on a conveyor belt during the addition of aggregates to the mix. Commonly, collated steel fibres are used in which the fibres are held together by a water-soluble sizing that dissolves during the mixing process in order to abolish the clumping problem.

The other type of conventional fibre mentioned in Mindness et al., (2003) is synthetic fibres. Synthetic fibres are to be known as low water absorption in mixing of concrete. Thus, it is difficult to add more than about 0.2% of fibrillated polypropylene fibres to a normal concrete mix because of the workability problems. However, as mentioned in previous research by Kim et al., (2010), the monofilament synthetic fibres can be added relatively easily up to at least 0.5% by volume. On the other hand, for glass fibres, a “spray-up” procedure is commonly used to produce thin sheets. Special pump and spray gun need to used as to chop and combined the fibres with cement slurry before it was sprayed onto a mold. Therefore, as stated in Mindness et al., (2003), the similar method can be copied for carbon and synthetic fibres where the fibre volume can achieve up to 10% to 15%.

2.3.3 Application of Fibre Reinforced Concrete

Previous application of PET fibres mentioned in Ochi et al., (2007) such as slope spraying, tunnel support, and application to a bridge pier are summarized in Table 2.4. In all cases, the PET fibre reinforced concrete has shown few advantages namely, easy handling, labour saving, alternative replacement of steel fibre and improve the crack properties. In that research, it stated that the PET volume ratio used is in the range of 0.3 to 1.0 (Ochi et al., 2007) and the length of PET fibre of 30 and 40 mm. In all cases, it stated that the water-cement ratio used is 50% to64%.

Table 2.4: Example of PET fibre reinforced concrete applications by Ochi et al., (2007)

Study	**Application of PET**	**Method applied**	**W/C ratio (%)**	**Fibre length (mm)**	**Volume of PET (%)**	**Remarks**
Kagoshima (2004)	Mine gateway	Sprayed	50	30	0.3	Replacement of steel fibre. First trial to use PET fibre in Japan. Found to be very easy to handle
Kanagawa (2004)	Bush road	Placed	64	40	0.75	Replacement of wire mesh. Considerable laboursaving
Ibaragi (2004)	Bush road	Placed	64	40	1.0	Applied successfully to road with 10% gradient

Ehime (2004)	Slope	Sprayed	50	30	0.3	Replacement of steel fibre on the sea front
Fukuoka (2004)	Tunnel	Placed	52	40	0.3	Applied to tunnel support for the first time
Tottori (2005)	Tunnel	Placed	52	40	0.3	A new fibre content analyzer was developed and used
Kanagawa (2005)	Bridge pier	Placed	50	30	0.3	Crack extension was substantially decreased
Shiga (2005)	Tunnel	Placed	52	40	0.3	A new fibre injector was developed and used

Based on discussion before, the use of PET fibres can contribute high potential in improving the concrete especially in flexural behaviour such as crack and deflection.

2.4 Flexural Capacity of Fibre Reinforced Concrete Beam

Considering any reinforced concrete beam, the flexural capacity can be explained as the maximum capacity of the beam absorbing an external load. Once the flexural capacity reaches the maximum limit, at least one of the sections of the beam or both of its material has stretched to their maximum strain or strength. According to Park & Paulay., (1975), Eurocode 2 and Carino & Clifton, (1995), to assess the flexural capacity of a beam, some assumptions need to be made in the following:

i. Plain sections remain plain under bending forces or straining

ii. Reinforcement stress-strain relationship is known

iii. Tensile strength of concrete is negligible

iv. Concrete stress-strain in compression is known

With the hypotheses mentioned above, the flexural capacity can be evaluated by cracked section analysis in Figure 2.6 as long the bond behaviour between the concrete and reinforcement is adequate. According to the Figure 2.6 by Eurocode 2, the strains and stress in cracked section analysis are explained as follows:

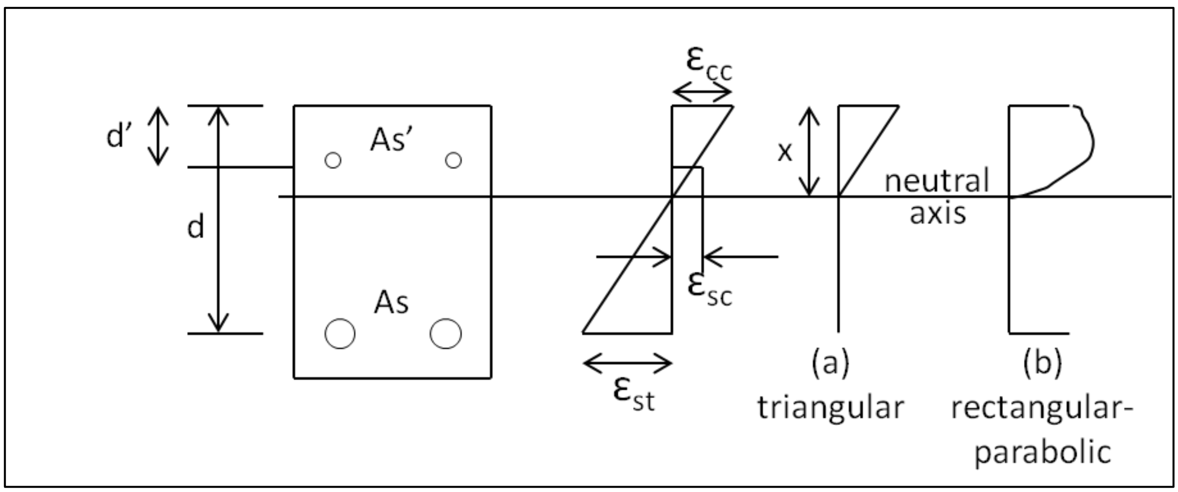


Figure 2.6 Strains and stresses in cracked section analysis

i. Triangular stress distribution applies when the stresses are nearly proportional to the strains which normally occur at the serviceability limit state.

ii. Rectangular-parabolic in cracked section analysis indicates as distribution at failure when the compressive strains within the plastic range and follow with the design for ultimate limit state.

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