Chapter 2
Literature Review

2.1 Mechanical Reprocessing of Polypropylene Waste

Thermoplastic waste from disposable consumer packaging and products is increasing, elevating the environmental pollution and wasting useful resources. Polypropylene (PP) is one of major types of thermoplastics used throughout the world in a wide variety of applications, such as toys, containers, pipes, automotive parts, electrical components, etc. In Australia, 0.23 million tonnes of PP products were consumed in 2013, while the recycling rate was only 24% (i.e. 0.056 million tonnes) (A'Vard and Allan 2014). Legislations have been introduced around the world to limit disposal of the plastic wastes and to encourage more environmentally friendly options, to control plastic pollution (Achilias et al. 2008). Efficient recycling and recovery methods are therefore being researched and developed. According to Australian National Plastics Recycling Survey (A'Vard and Allan 2014), mechanical recycling is the most widely practiced of these methods in Australia, since it is relatively easy and economical. Technology and infrastructure required for collection and mechanical reprocessing of plastic waste is also widely available.

Mechanical recycling refers to reprocessing plastic waste into secondary raw materials and products by physical means. The mechanical recycling involves a series of treatments and preparation steps (Yin et al. 2015c). Generally, the first stage of recycling process includes collecting, sorting, shredding, milling, washing and drying the plastic waste into recycled plastic pellets, powder or flakes (Al-Salem et al. 2009). Extensive research has been carried out in this stage, especially in terms of collection and sorting techniques (Carvalho et al. 2012), such as flotation, optical sorting, density separation, electrical separation, etc. In the second stage the recycled plastic pellets, powder or flakes are molten and reprocessed into final products by resin moulding techniques (Demirel and Daver 2013), including extrusion moulding, injection moulding, blow moulding, vacuum moulding, inflation moulding, etc.

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Mechanically recycled products, however, often have mediocre mechanical properties in practice, which strongly limit their applicability and market demand (Khan et al. 2010). Two factors mainly lead to unsatisfactory performance of recycled plastic products. The first is degradation of the plastic waste (Sanchez et al. 2014). When plastics undergo high temperature or shearing during their processing stage, thermo-mechanical degradation occurs (Mbarek et al. 2006). Moreover, during the service life of plastic products, long exposure to the air, light, moisture, temperature and weathering gives rise to their natural aging. The second factor is heterogeneity of the plastic waste (Brems et al. 2012). Plastic waste is a mixture of various types and grades of polymers with distinct degrees of polymerisation and chemical structures, which are mutually incompatible. Furthermore, contaminants, such as paper scraps and adhesive additives deteriorate the mechanical properties of the recycled polymers and limit their applications. The more complex and contaminated the waste is, the more difficult it is to recycle mechanically. Thus, a full separation of individual components is rarely implemented (Brachet et al. 2008).

In order to improve quality of end products of recycled PP, various workable reprocessing techniques in the second stage of mechanical recycling have been developed and widely applied in the recycling industry (Kabamba and Rodrigue 2008). This chapter critically reviews the current reprocessing techniques of recycled PP. The degradation and crystallisation behaviour accompanying with the reprocessing processes is presented. This would help us compare different reprocessing methods and choose the most suitable one for the production of recycled PP fibre.

2.1.1 Degradation and Crystallisation Behaviours of Reprocessing PP Waste

Reprocessing recycled PP is always accompanied with degradation, crystallisation, and consequent processability problems, which result from molecular chain scission, branching and crosslinking. The degradation behaviour decreases tensile strength and impact strength, while the crystallisation behaviour increases Young's modulus and yield stress. Therefore, ultimate mechanical properties of the crystallisable plastics are determined by both degradation and crystallisation behaviours. In the recycling processes, the degradation behaviour is inevitable, but if the crystallisation behaviour can be taken full advantage of, the recycled plastic products still can maintain high quality and perform well (Andricic et al. 2008). Therefore, a good understanding of the degradation, crystallisation and processability is of scientific and technological importance for recycling PP wastes.

2.1.1.1 Degradation Behaviour

Since PP is an organic polymer, undesirable chemical reactions, mainly caused by photo-oxidation and oxidation, frequently occur during their manufacture processes and service life (da Costa et al. 2007). The chemical reactions result in irreversible changes in the polymer structure, thus affecting the polymer performance. There are four types of distinguished degradation: chemical, thermal, mechanical and biological (Al-Salem et al. 2009). These degradation processes are very complex, and usually several types of degradation occur simultaneously. The phenomena, such as discoloration, loss of volatile components or smoking, and loss of mechanical properties, are frequently observed (Bahlouli et al. 2006).

During the processing stage, PP is subjected to molecular chain damage, including crosslinking, chain scission and formation of double bonds. High shear forces, temperatures and presence of impurities and oxygen sever the polymer chains, producing highly reactive radicals at the end of chains. These radicals cannot recombine, but they can form peroxyl radicals and hydroperoxides with oxygen. Continuous degradation leads to serious molecular chain scission, branching and crosslinking, which may significantly change mechanical properties and processability of the recycled materials.

da Costa et al. (2005) studied PP degradation when it was submitted to multiple extrusion conditions. They found that under the condition of lower temperature (240 °C) and lower extrusion cycles (five cycles), the PP still remained with several entanglement points, and the mechanical chain breaking did not reach a level where extensive degradation occurred. When the PP was under the conditions of higher die zone temperature (270 °C) and higher processing cycles (nineteen cycles), chain scission massively happened, and the material behaved as a liquid-like material of low viscosity, which resulted from the considerable reduction of molar mass, long chains and entanglements. Their further research (da Costa et al. 2007) found that the degradation process considerably reduced the break properties of PP, such as break strain, break stress and energy to break, while the small strain properties, like yield stress and yield modulus, were just slightly affected.

In many operations, the recycled PP is pelletised first in plastic reprocessing plants. The extruded PP pellets are then delivered to plastic manufacturing plants for the production of end products. The double heating and reprocessing in the plastic reprocessing and manufacture plants cause more serious degradation. If this could be undertaken as only one heating cycle, the deterioration would be minimised. Residence time during extrusion or other heating processes would therefore be lowered and the plastics would be subjected to less overall heating. Cold processes, such as shredding and crumbing, are recommended to prevent the degradation from the hot processes, such as pelletisation.

2.1.1.2 Crystallisation Behaviour and Mechanical Properties

There is a potentially misleading idea that during the recycling processes there is a continuous deterioration on mechanical properties of the recycled plastics. However, after repetitive reprocessing for a low numbers of cycles, Young's modulus and yield stress of the recycled PP increase due to augmentation of crystallinity (da Costa et al. 2007). Ha and Kim (2012) successfully applied recycled PP as refrigerator plastics due to the comparable mechanical properties with virgin PP, and obtained about 50% cost-merit.

Aurrekoetxea et al. (2001) mimicked procedures of recycling PP through repetitively injection moulding for several cycles. With the increase of recycling cycles, the crystallinity increased from 44.5% (at the first cycle) to 48.5% (at the sixth cycle), and remained at 48.5% until the tenth cycle. When the recycling increased from one cycle to six cycles, the Young's modulus grew from 1700 to 2000 MPa, and the yield stress rose from 34.8 to 36.4 MPa, because of the increase of crystallinity. However, the elongation at break decreased from 66% to 45%, and fracture toughness decreased from 2.24 to 1.98 MPa $m^{1/2}$ due to the decrease of molar mass and tie-molecule density. They explained that the repetitively reprocessing breaks the molecular chain and allows the strained or entangled macromolecules to be released. The crystallisation is then developed by the rearrangement of these freed macromolecules segments. The crystalline structures hindered rotations of molecular segments, leading to the increase of stiffness.

2.1.2 Melt Blending

Melt blending is one of the most frequently-used ways of mechanically recycling plastic waste. It refers to blending recycled plastics with similar type of virgin plastics or different types of recycled plastics in the melt process. Blending recycled PP with virgin PP not only can reduce cost, but the new blended PP can maintain equal performance with the virgin plastic products (Yin et al. 2013). However, plastic waste collected from kerbside is a mixture of various types and qualities of polymers, thus extensive research has been carried out on reprocessing commingled plastic waste.

Blending recycled plastics with virgin plastics of similar components is often used for mechanically recycling industrial plastic waste, which is industrial plastic scrap off-cuts and off-specification items obtained from processing operations. The mechanical recycling of industrial plastic waste has been widely adopted due to ease of separation of different types of plastics, low level of impurities present, and their availability in large quantities. Meran et al. (2008) mixed recycled PP with its virgin material. As shown in Fig. 2.1, tensile strength of recycled PP can be effectively improved by mixing its virgin plastic. They believed that recycled PPs have the capacity of being as good as any engineering grade under optimised mixing rates and reprocessing conditions.

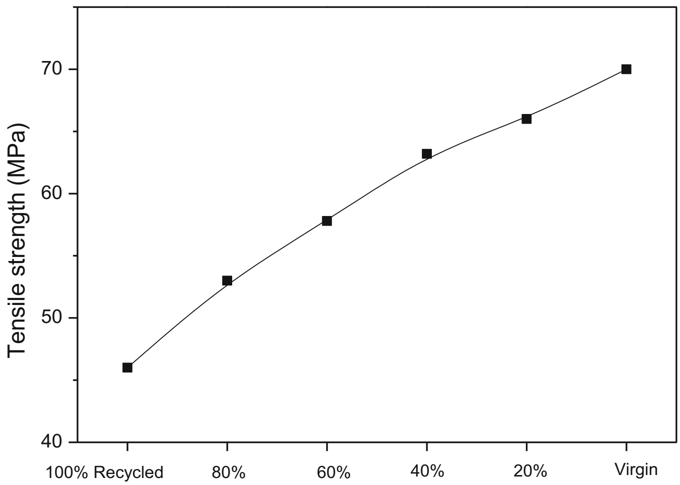


Fig. 2.1 Tensile strength of recycled PP blended with its virgin material (Meran et al. 2008)

Domestic plastic waste, consisting mostly of packaging materials from kerbside recycling collections, contains various types of polymers. A segregation of the plastic waste before recycling is time- and cost-consuming, and never fully separated. Therefore, the study on reprocessing the commingled plastic waste from roughly sorted waste is very practical. Table 2.1 shows mechanical properties when recycled PP is blended with recycled low-density polyethylene (LDPE) and HDPE (Hasanah et al. 2014; Strapasson et al. 2005). The mechanical properties show similar trends when the recycled PP is mixed with recycled LDPE and recycled HDPE. With the decrease of PP rate, the yield strength and Young's modulus of the

Table 2.1 Mechanical properties of the recycled PP–LDPE and PP–HDPE composites

	Blending rate	Yield strength (MPa)	Young's modulus (MPa)	Elongation at break (%)
PP–LDPE composites (Strapasson et al. 2005)	100:0	25.1	1304	600–700
	75:25	22.8	1149	100
	50:50	13.8	845	3.7
	25:75	11.4	435	400–529
	0:100	7.6	157	111
PP–HDPE composites (Hasanah et al. 2014)	100:0	45	2340	14
	80:20	34	1690	8
	60:40	29	1290	7
	50:50	29	1250	6
	40:60	27	1200	15
	20:80	26	920	25
	0:100	25	900	25

materials are decreasing, thus the materials are becoming more ductile. Elongation at break dramatically decreases when 50% of PP is mixed with 50% HDPE or LDPE, due to incompatibility of the different blends.

2.1.3 Filler Reinforcement

Filler reinforcement can effectively reduce cost, and enhance mechanical and thermal properties of the recycled plastics. A variety of fillers, such as natural fillers, inorganic fillers and elastomers, have been successfully applied to reinforce recycled plastics.

Natural fillers have substantial inherent advantages, such as low density, low abrasion of processing equipment, relatively good specific mechanical properties, biodegradability and low cost. The natural fillers, including wood, bagasse, phormium tenax and wheat straw have been widely used. The natural filler-based recycled polyolefins now have been used in construction applications, such as decking and furniture, and automotive ones, including door panels and seat frames. However, incompatibility, processability and thermal degradation are main problems which limit applications of the natural fillers in the recycled polyolefins (Mengeloglu and Karakus 2008). Extensive research has been carried out to solve these problems and improve mechanical properties of the composites.

The addition of inorganic fillers to plastics results in remarkable improvements in morphological, mechanical, rheological and thermal properties. Unlike the natural fillers, the properties can be significantly improved even upon using small amount of inorganic fillers. Various inorganic fibres have been developed and widely used in the plastic reprocessing industry. They are calcium carbonate, mica, glass beads, glass fibre, talc, silver, zinc oxide, titanium dioxide, cement, fly ash, and clays. The properties of inorganic filler reinforced recycled polyolefins strongly depend on size, shape, and distribution of the fillers in the plastic matrix, and also to the extent of interfacial adhesion between the fillers and the matrix.

Elastomer fillers can effectively improve toughness and impact resistance, but have side effects of decreasing tensile strength and Young's modulus (Clemons 2010). Elastomers, such as poly(ethylene-co-propylene) rubber (EPR), poly (ethylene-co-octene) rubber (EOR), and poly(ethylene-co-propylene-co-diene monomer) (EPDM) are often used to improve the toughness and elongation at break of recycled materials, but the yield strength, tensile strength and Young's modulus would decrease (Liu et al. 2010). Therefore, sometimes inorganic fillers are used as well to compensate the side effect of the elastomers.

2.1.4 Mechanochemistry

Due to the degradation and immiscibility of the plastic waste, high content of stabilisers, compatibilizers, and fillers have to be used, which is not economically feasible for the recycling industry. Mechanochemistry is a good alternative method, where reactive blending occurs in the mechanical pulverization of polymers without using any additives (Streletskii et al. 2015). The mechanochemistry denotes the chemical and physicochemical transformation of substances during the agglomeration caused by the mechanical energy. The technique includes a variety of reactions, such as fast decomposition and synthesis, graft modification, and polymorphic transformation. The advantages include simple process, ecological safety and possibility of obtaining a product in the metastable state. This technology has thus attracted wide focus (Guo et al. 2010).

Mechanical milling, typically ball milling, refers to the process that utilises high-energy ball milling technology to co-pulverize shredded recycled plastic, resulting in a considerable decrease in the polymer size (Kaupp 2009). The mechanical effects generated in the process, such as impact, compression, fracture, extension and shearing, can induce chain scission and hydrogen abstraction within the material particles, thus producing a large number of free radicals. The free radicals from different molecular chain species react with each other to induce chemical crosslinking and coupling (Liu et al. 2013).

Solid-state shear pulverization (S^3P) is a novel, continuous and one-step cryogenic extrusion process to recycle plastic waste (Akchurin and Zakalyukin 2013). The normally incompatible plastic waste is subjected to high shearing forces to shred the carbon-chain backbone of plastic, thus generating a large amount of free radicals, which can form graft copolymers. The pulverised particles are then used to prepare high-quality products through the injection moulding, rotational moulding, powder coatings, or blending with virgin plastics (Guo et al. 2010). Lebovitz et al. (2003) prepared recycled PPs through the S^3P process. The mechanical properties can be seen in Table 2.2.

The mechanochemical process only requires simple devices, and is a time-saving, cost-saving and eco-friendly process. The technology will contribute

Table 2.2 Properties of blends of postconsumer plastics (Lebovitz et al. 2003)

Feedstock	S^3P	Tensile properties		Izod impact (J/m)	Flexural properties	
		Ultimate (MPa)	Elongation (%)		Modulus (MPa)	Strength (MPa)
Recycled PP	Yes		375	32	1710	64.3
Recycled PP	No		330	37	1900	59.3
Virgin PP		28.2	38	21	1430	48
HDPE–recycled PP 70:30	Yes	19.6	8	11	960	27
LLDPE–recycled PP 70:30	Yes	12.9	8	32	510	19

considerably to economy, industry and environment in the future. But presently, the technology is just in the experimental stage, and still needs investigations for commercialization.

2.2 Use of Macro Plastic Fibres in Concrete

Concrete is very strong in compression, however, it has a very low tensile strength. To improve its tensile strength, reinforcing steel is often used in the concrete. Apart from traditional steel mesh and bars, various fibres, such as steel fibre, glass fibre, natural fibre and synthetic fibre, have also been used to improve the properties of concrete.

Steel fibres can greatly improve the tensile strength and the flexural strength of concrete due to their ability to absorb energy (Beglarigale and Yazici 2015) and control cracks (Buratti et al. 2013). Their electric (Dai et al. 2013), magnetic (Al-Mattarneh 2014) and heat (Sukontasukkul et al. 2010) conductivity properties make them suitable for some special applications, such as shielding electromagnetic interference. However, corrosion of steel fibres can be detrimental and lead to rapid deterioration of concrete structures (Soylev and Ozturan 2014). Glass fibres have excellent strengthening effect (Tassew and Lubell 2014) but poor alkali resistance (Sayyar et al. 2013). Natural fibres, such as wood (Torkaman et al. 2014), sisal (Silva et al. 2010), coconut (Ali and Chouw 2013), sugarcane bagasse (Alavez-Ramirez et al. 2012), palm (Abd Aziz et al. 2014), and vegetable fibres (Pacheco-Torgal and Jalali 2011), are cheap and easily available, but they have poor durability. Synthetic fibres can be made of polyolefins (Alberti et al. 2014), acrylic (Pereira-De-Oliveira et al. 2012), aramid (Vincent and Ozbakkaloglu 2013), and carbon (Chaves and Cunha 2014). They can prevent plastic shrinkage cracks in fresh concrete (Cao et al. 2014) and improve post-cracking behaviour of concrete (Pujadas et al. 2014b).

The schematic diagram in Fig. 2.2 shows the different failure modes associated with the fibre reinforced concrete (Zollo 1997). Fibre rupture (1), pull-out (2) and debonding of fibre from matrix (4) can effectively absorb and dissipate energy to stabilise crack propagation within concrete. Fibre bridging the cracks (3) reduces stress intensity at the crack tip. In addition, the fibre bridging can decrease crack width, which prevents water and contaminants from entering the concrete matrix to corrode reinforcing steel and degrade concrete. Fibre in the matrix (5) prevents the propagation of a crack tip. Consequently, minor cracks will be distributed in other locations of the matrix (6). Although every individual fibre makes a small contribution, the overall effect of three-dimensional reinforcement is cumulative (Zollo 1997). Therefore, the fibres can effectively control and arrest crack growth, hence preventing plastic and dry shrinkage cracks (Yoo et al. 2013), retaining integrity of concrete (Yoo et al. 2014), and altering the intrinsically brittle concrete matrix into a tougher material with enhanced crack resistance and ductility (Park 2011). In

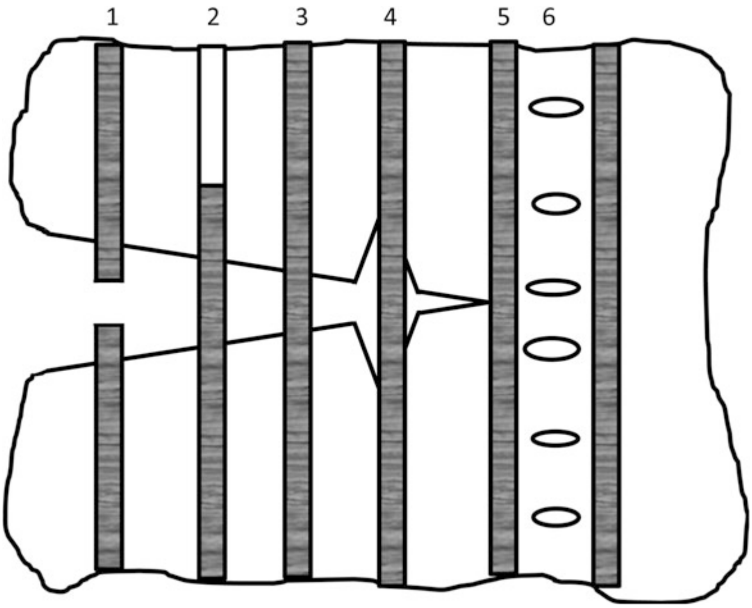


Fig. 2.2 Failure mechanisms in fibre reinforced concrete. *1* Fibre rupture; *2* Fibre pull-out; *3* Fibre bridging; *4* Fibre/matrix debonding; *5* Fibre preventing crack propagation; *6* Matrix cracking (Zollo 1997)

order to achieve considerable reinforcement, the fibres should have high tensile strength and Young's modulus (Yin et al. 2013).

Plastic fibres are synthetic fibres, which can be in the form of micro plastic fibres or macro plastic fibres. The micro plastic fibres refer to the plastic fibres whose diameter ranges from 5 to 100 μm and length is 5–30 mm (Nili and Afroughsabet 2010). These micro fibres can effectively control plastic shrinkage cracking (Soutsos et al. 2012), which is caused by shrinkage of fresh concrete during the first 24 h after placement due to excessive evaporation of bleed water (Guneyisi et al. 2014). However, they normally do not have obvious effects on the properties of hardened concrete, as reported by Pelisser et al. (2010) and Habib et al. (2013). It is noteworthy that some micro plastic fibres, such as nylon fibres and Polyvinyl Alcohol (PVA) fibres, can provide good thermal energy storage to concrete (Ozger et al. 2013), effectively controlling shrinkage of concrete (Song et al. 2005), and also significantly improving tensile strength and toughness of concrete (Spadea et al. 2015).

The macro plastic fibres normally have a length of 30–60 mm and cross section of 0.6–1 mm^2 (Yin et al. 2015b). The macro plastic fibres are not only used to control plastic shrinkage cracks (Chavooshi and Madhoushi 2013), but also mostly used for controlling drying shrinkage cracks (Pujadas et al. 2014a). Another significant benefit is the post-cracking performance provided by the macro plastic fibres (Buratti et al. 2011). The macro plastic fibres now have become increasingly popular in the construction of concrete footpaths (Alani and Beckett 2013), precast elements (Peyvandi et al. 2013) and shotcrete mine tunnels (Kaufmann et al. 2013).

2.2.1 Preparation and Properties of Macro Plastic Fibres

The macro plastic fibres can be virgin and recycled polypropylene (PP), high-density polyethylene (HDPE) or polyethylene terephthalate (PET) fibres. PP fibres have been widely used in the concrete industry, due to its ease of production, high alkali resistance (Santos et al. 2005), and high tensile strength and Young's modulus (Yin et al. 2013). However, their low density (around 0.9 g/cm^3) may make the fibres 'float up' to the surface of concrete matrix (Auchey 1998). Low hydrophilic nature of PP fibres, which can be reflected by low wetting tension of about 35 mN/m, also significantly deteriorates workability of fresh concrete and bonding between the fibres and concrete (Ochi et al. 2007). HDPE fibres have slightly higher density (around 0.95 g/cm^3) and are more hydrophilic than PP fibres. However, HDPE fibres have low tensile strength (ranging from 26 to 45 MPa), which significantly limits their applications (Auchey 1998). PET fibres have much higher density at 1.38 g/cm^3 and better wetting tension of 40 mN/m than PP fibres, so they are easier to be mixed with concrete than either of PP or HDPE fibres. They also have high tensile strength and Young's modulus (Ochi et al. 2007), which can effectively improve post-cracking performance of concrete. However, PET granules must be dried for at least 6 h before being processed into fibres. The PET granules are easily crystallised and stick on the inner wall of extruder. Hence, it is more difficult and costly to process PET than either of PP or HDPE. Moreover, alkali resistance of the PET fibres is questionable (EPC 2012; Silva et al. 2005). Therefore, the PP fibres have become the most common commercial concrete fibre, and PET fibres have attracted extensive research, but HDPE fibres are still rare in practice with very little research being reported in the literature. From the environmental and cost-saving perspective, researchers are now also investigating the use of recycled plastic fibres in concrete (Siddique et al. 2008). However, recycled plastics have uncertain processing and service history, impurities and varying degrees of degradation, leading to processing difficulties and unstable mechanical properties (Wang et al. 1994).

The physical and chemical characteristics of macro plastic fibres vary widely depending upon the manufacturing techniques. A popular technique involves melt spinning plastic granules into filaments and then hot drawing the monofilaments into fibres (Fraternali et al. 2011). In the study conducted by Ochi et al. (2007), PET granules were melted and extruded into monofilaments with a fineness of 60,000 dtex (dtex: grams per 10,000 m length). Then the monofilaments were hot drawn into 5000 dtex through a film orientation unit shown in Fig. 2.3 (Ochi et al. 2007). The resulting monofilaments were then indented and cut into fibres of 30–40 mm long. This melt spinning and hot drawing process highly oriented the molecular chains of the PET fibres, inducing high crystallinity and thus

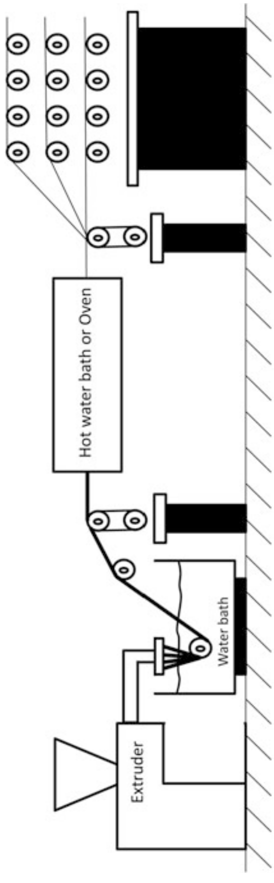


Fig. 2.3 Apparatus for PET fibre extrusion (Ochi et al. 2007)

significantly improving tensile strength and Young's modulus. Through this method, PET (Fraternali et al. 2011) and PP (Yin et al. 2015b) fibre of tensile strength above 450 MPa can be obtained.

Another popular processing technique is extruding PET, PP or HDPE granules through a rectangular die to form film sheets (0.2–0.5 mm thick). The resulting film sheets are then slit longitudinally into equal width tapes (1.0–1.3 mm wide) by a slitting machine. The tapes are then mechanically deformed using a patterned pin wheel, such as crimped and embossed. In some cases, the fibrillated tapes are also twisted before cutting to desired lengths (40–50 mm) (Kim et al. 2008). Kim et al. (2010) used this technique to successfully prepare recycled PET fibre with 420 MPa tensile strength and 10 GPa Young's modulus.

In order to reduce manufacturing costs, researchers have explored the potential of producing recycled plastic fibres just by mechanically cutting PET bottles, as reported by Fraternali et al. (2013), de Oliveira and Castro-Gomes (2011) and Foti (2011). Foti (2011) produced lamellar fibre and 'O'-shaped annular fibre by this method. The special shape of the 'O'-fibre can assist to bind the concrete on each side of a cracked section, thus improving ductility of the concrete. This technique though economical in smaller scale, cannot be used for a large-scale production. Firstly, the bottles should be washed before or after cutting which makes this process labour-intensive. Secondly, waste bottles have different history and degradation, which results in variable and poorer mechanical properties of the fibres. Moreover, the fibres produced through this technique only has a tensile strength of around 160 MPa and low Young's modulus of about 3 GPa (Foti 2013), which are much lower than those of the fibres produced by the other two techniques.

2.2.2 *Macro Plastic Fibre Reinforced Concrete*

2.2.2.1 Fresh Concrete Properties

Slump

Workability of fresh concrete can be determined through a slump test (AS1012.3.9 1993). Table 2.3 shows slump test results of macro plastic fibre reinforced concrete. The results indicate addition of macro plastic fibres decreases slump, thus decreasing workability of fresh concrete. This is due to the fact that the addition of fibres can form a network structure in the concrete matrix, thus restraining mixture from segregation and flow. Moreover, due to high content and large surface area of the fibres, the fibres can easily absorb cement paste to wrap around, hence increasing viscosity of the concrete mixture (Soroushian et al. 2003). Mazaheripour et al. (2011) made following two suggestions to improve the workability of fibre reinforced concrete: (a) to limit the volumetric content of macro plastic fibres to a range of 0.1–1% and (b) to add more water. However, addition of water will

Table 2.3 Properties of macro plastic fibre reinforced concrete

Macro plastic fibre	Fibre dimension	Fibre volumetric content (%)	Slump (mm)	Compressive strength (MPa)	Splitting tensile strength (MPa)
Macro PP fibre, wavelength shape (Choi and Yuan 2005)	0.9 mm in diameter, 50 mm in length	0	102	35.0	2.2
		1	38	35.4	3.2
		1.5	6.5	30.7	3.2
PP fibre, 620 MPa tensile strength and 9.5 GPa Young's modulus (Hasan et al. 2011)	40 × 1.4 × 0.11 mm	0	N/A	38.9	3.6
		0.33	N/A	40.5	3.9
		0.42	N/A	41.4	4.1
		0.51	N/A	41.6	4.1

negatively affect concrete strength; hence plasticiser or water reducing admixtures are often used in fibre reinforced concrete to improve workability without increasing water content (Hasan et al. 2011).

Plastic Shrinkage

Plastic shrinkage cracking is caused by moisture loss after casting (Banthia and Gupta 2006). Generally, if the moisture evaporation rate exceeds 0.5 kg/m^2/hr, it causes negative capillary pressure inside the concrete, resulting in internal strain (Uno 1998). Plastic shrinkage can cause cracks during the initial stages, when the concrete has not yet developed adequate strength (Sanjuan and Moragues 1997). Kim et al. (2008) reported that although the macro plastic fibres do not affect the total moisture loss or rate of moisture loss, they still can effectively control the plastic shrinkage cracking by improving integrity of the fresh concrete. They also found that once the fraction of fibre volume exceeds 0.5%, a sufficient number of fibres are involved in controlling plastic shrinkage cracking, so the fibre geometry had no further effect. Najm and Balaguru (2002) studied the effects of fibre aspect ratio on the plastic shrinkage crack areas. They found that longer fibres (aspect ratio with length/width = 167) were extremely efficient and provided a crack-free surface at a fibre dosage of 9 kg/m^3, while shorter fibre (aspect ratio with length/width = 67) could eliminate 94% cracking at a dosage of 18 kg/m^3.

2.2.2.2 Hardened Concrete Properties

Compressive Strength

As shown in Table 2.3 (Choi and Yuan 2005; Hasan et al. 2011), the macro plastic fibres have no significant effects on the compressive strength, which is consistent

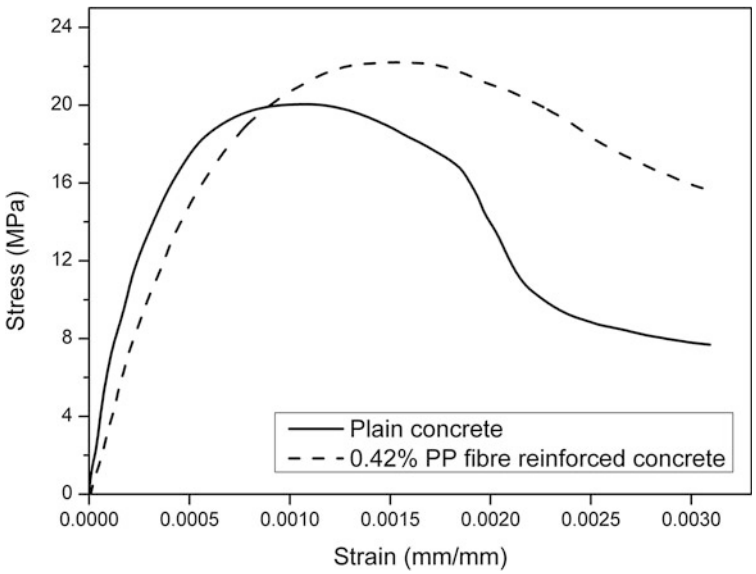


Fig. 2.4 Average stress-strain curves for concretes with macro plastic fibres (Hasan et al. 2011)

with what was reported by Hsie et al. (2008), Campione (2006), Fraternali et al. (2011), and de Oliveira and Castro-Gomes (2011). Ochi et al. (2007) reported that there is no significant variation in the values of compressive strength associated with varying PET fibre contents. Moreover, during the compression tests, the plain concrete failed catastrophically, while as reported by Brandt (2008) the macro plastic fibre reinforced concrete cylinders failed with many minor cracks on the surface. The plastic fibres still held the concrete together at the failure load. Figure 2.4 shows stress-strain curves of a compressive test on concrete cylinders conducted by Hasan et al. (2011). The samples with fibres showed a more ductile mode of failure and a post failure structural performance. This is attributed to ability of the fibres to distribute stresses and slow down the crack propagation process.

Splitting Tensile Strength

The split-cylinder test is an indirect test to obtain tensile strength of concrete (AS1012.10 2000). As can be seen in Table 2.3 (Choi and Yuan 2005; Hasan et al. 2011), the macro plastic fibres improve the splitting tensile strength of concrete. In the split-cylinder test, when the stress in concrete reaches tensile strength of concrete, the stress is transferred to the macro plastic fibres. The fibres can arrest the propagation of macro cracks, thus improving the splitting tensile strength (Hsie et al. 2008). The plain concrete cylinders failed abruptly once the concrete cracked, whereas the macro plastic fibre reinforced concrete could retain its shape even after concrete cracked. This shows that the macro plastic fibre reinforced concrete has the ability to absorb energy in the post-cracking state (Hasan et al. 2011).

Flexural Strength

Flexural test is another indirect tensile test which measures the ability of concrete beam to resist failure in bending (AS1012.11 2000). Three-point loading and four-point loading are normally used in the flexural tests. For the three-point loading flexural test, results are more sensitive to specimens, because the loading stress is concentrated under the centre loading point (Alani and Beckett 2013). However, in the four-point loading flexural test, maximum bending occurs on the moment span (Soutsos et al. 2012). Research has found that the macro plastic fibres have no obvious effects on the flexural strength, which is dominated by the matrix properties (Soroushian et al. 2003). The main benefit of using macro plastic fibres lies in improved ductility in the post-cracking region and flexural toughness of concrete (de Oliveira and Castro-Gomes 2011). Brittle behaviour is always associated with plain concrete (Berndt 2009). When the first crack is produced, the specimen cracks and collapses almost suddenly, with very small deformations and no prior warning. However, in the macro plastic fibre reinforced concrete specimens, the failure progresses with bending, but without any sudden collapse as seen in plain concrete. When flexural tensile cracks occur, the load is transmitted to the plastic fibres. The fibres prevent the spread of cracks as shown in Fig. 2.2 and hence delay the collapse (Foti 2011).

Hsie et al. (2008) tested the flexural strength of macro PP fibre reinforced concrete. The PP fibre had diameter of 1 mm, length of 60 mm, tensile strength of 320 MPa and Young's modulus of 5.88 GPa. As can be seen in Fig. 2.5, the plain concrete showed a brittle failure. The flexural strength reached the maximum at a deflection of around 0.05 mm without any post-cracking performance. The PP fibre slightly increased the maximum flexural strength to 5.5 MPa at the same deflection point as the plain concrete. However, after the maximum flexural strength, the load is transferred to the PP fibres, thus becoming stable around 1.5 MPa. Similar trends were reported by de Oliveira and Castro-Gomes (2011), Ochi et al. (2007), Meddah and Bencheikh (2009), and Koo et al. (2014).

Post-cracking Performance

Crack Tip Opening Displacement (CTOD) and Crack Mouth Opening Displacement (CMOD) tests are normally used to study the effect of fibres on the post-cracking behaviour of concrete (Fraternali et al. 2011). According to ASTM E1290 (ASTM 2008b), CTOD is the displacement of the crack surfaces normal to the original (unloaded) crack plane at the tip of the fatigue pre-crack. However, due to inherent difficulties in the direct determination of CTOD, CMOD test is a preferred test to assess post-cracking performance of fibre reinforced concrete (Zhijun and Farhad 2005). According to BS EN 14651:2005+A1:2007 (BSI 2007), CMOD test measures the opening of the crack at mid-span using a displacement transducer mounted along the longitudinal axis. Both tests can clearly display the ability of fibres to redistribute stresses and bridge the cracks formed.

Fraternali et al. (2011) performed CTOD tests on the PP and recycled PET fibre reinforced concrete specimens. The PP fibre had 1.04 mm^2 of cross section, 47 mm

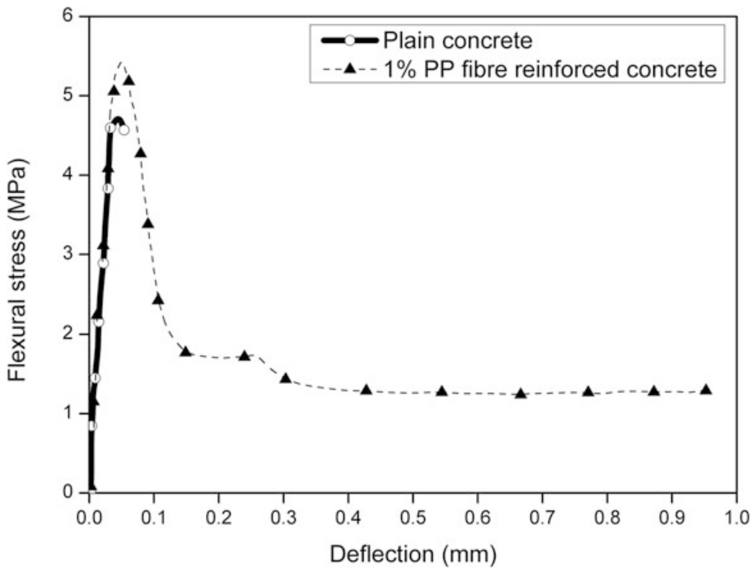


Fig. 2.5 Load-deflection curves of PP fibres reinforced concretes (Hsie et al. 2008)

of length, 250 MPa of tensile strength, 1.1 GPa of Young's modulus, and 29% of ultimate strain, while the recycled PET fibre had 1.54 mm^2 of cross section, 52 mm of length, 274 MPa of tensile strength, 1.4 GPa of Young's modulus, and 19% of ultimate strain. The results can be seen in Fig. 2.6 (Fraternali et al. 2011). The peak load was reached at a corresponding CTOD of less than 0.6 mm for all the specimens. However, compared to the plain concrete, ductility of the specimens after the peak load was significantly improved in the PP and PET fibre reinforced specimens. This clearly exhibits the ability of macro plastic fibres to improve post-cracking performance of concrete.

Round Determinate Panel Test (RDPT) is considered to better represent the relative behaviour of different fibre reinforced concretes. This test has a significantly lower variation in post-cracking performance than that of either CMOD or CTOD test (Bernard 2002). The panel-based performance assessment is desirable because panels fail through a combination of stress actions that reflects the behaviour of a fibre reinforced concrete more closely than other mechanical tests (Cengiz and Turanli 2004). RDPT, based on ASTM C1550 (ASTM 2012), involves bi-axial bending in response to a central point load, and shows a mode of failure related to the in situ behaviour of structures such as concrete slabs-on-grade and sprayed tunnel lining construction (Parmentier et al. 2008).

Cengiz and Turanli (2004) compared the shotcrete panels reinforced by macro PP fibre, steel mesh and steel fibre. The PP fibre had a length of 30 mm, a diameter of 0.9 mm, a tensile strength of 400 MPa, a Young's modulus of 3.5 GPa, and ultimate strain of 11%. The steel fibre had a length of 30 mm, a diameter of

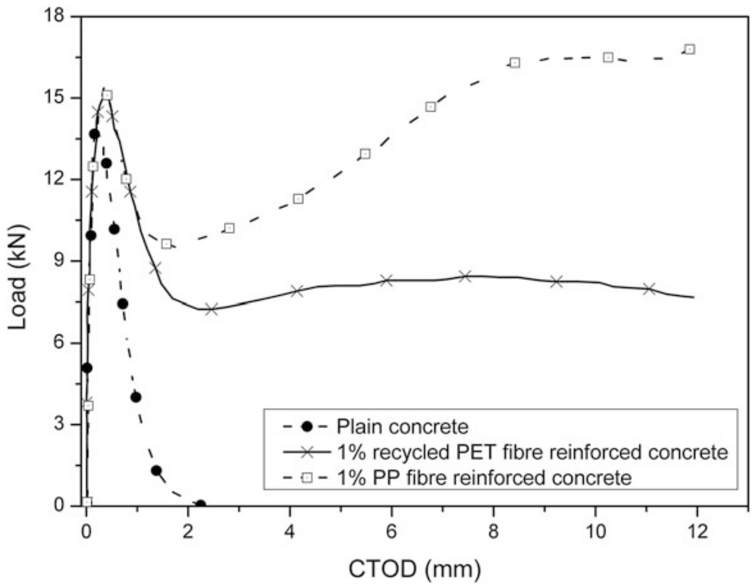


Fig. 2.6 Load-CTOD curves of recycled PET and PP fibres reinforced concrete (Fraternali et al. 2011)

0.6 mm, a tensile strength of 1.2 GPa, a Young's modulus of 200 GPa, ultimate strain of 0.6%, and flattened ends with a round shaft. The steel mesh had a diameter of 8 mm and intervals of 150 mm. As can be seen from Fig. 2.7, 0.45% of steel fibre reinforced concrete showed 65 kN of peak load and 664 J of energy absorption until 25 mm deflection, while 0.78% of PP fibre reinforced concrete showed better post-cracking performance with 70 kN of peak load and 716 J of energy absorption. Steel mesh showed much more brilliant post-cracking performance (1308 J in energy absorption) than either of steel or PP fibres. However, until deflection of 2.5 mm, the PP fibre reinforced concrete exhibited comparable load with that reinforced with steel mesh.

Drying Shrinkage

Soroushian et al. (2003) tested the restrained drying shrinkage of macro plastic fibre reinforced concrete, according to ASTM C157 (ASTM 2008a). They found that the average maximum crack width of plain concrete was 0.3 mm at the 90th day, while 0.19% of PP fibre effectively restrained the crack width to 0.15 mm, and delayed the initiation of cracking. As reported by Najm and Balaguru (2002) and Hsie et al. (2008), the plain concrete can withstand only small drying shrinkage strain, which is usually neglected. However, the addition of plastic fibres significantly increases the strain capacity of concrete, thus contributing to a reduction in crack widths and a delayed crack occurrence time.

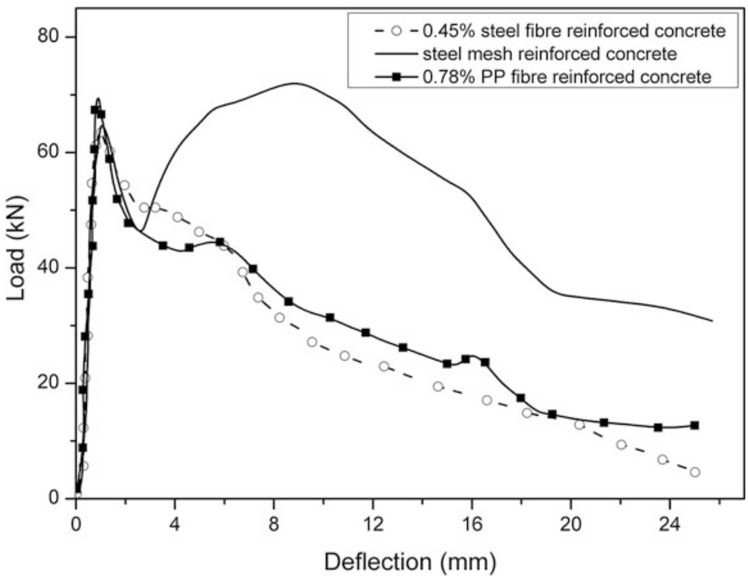


Fig. 2.7 Comparison of RDPT results for concrete reinforced with steel mesh, steel fibre and PP fibre (Cengiz and Turanli 2004)

Pull-Out Behaviour of Macro Plastic Fibres

Fibre debonding and pull-out (sliding) at the interface have a substantial impact on total energy absorption during the crack propagation. Therefore, the bond of fibre with matrix significantly affects capacity of the fibres to stabilise the crack propagation in concrete matrix (Singh et al. 2004). Low mechanical bonding strength may not provide sufficient bridging force to control crack development. Moreover, the weak bonding strength can cause internal micro-cracks in the interfacial areas (Ochi et al. 2007).

Oh et al. (2007) explored optimum shape among the various plastic fibres as shown in Fig. 2.8. In their pull-out tests, the crimped-shape fibres exhibited the highest energy absorption capacity. Kim et al. (2008) reported that the embossed fibre had high bonding strength at 5 MPa due to its high surface energy and friction resistance. The crimped fibre also had high bonding strength at 3.9 MPa, but its crimped part was stretched fully during the pull-out tests, thus leading to a rapid increase in displacement and low initial stiffness. The straight fibre had lowest bond strength at 1.7 MPa.

Degradation of Plastic Fibres in Concrete

PP has a high resistance to chemical attack due to its non-polar nature (Ha and Kim 2012). For example, PP is resistant to alcohol, organic acids, esters and ketones,

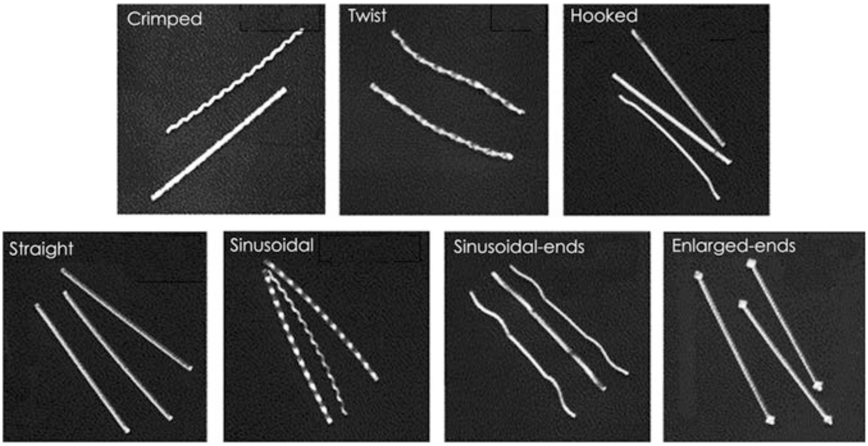


Fig. 2.8 Various types of plastic fibres for pull-out tests (Oh et al. 2007)

inorganic acids and alkalis. However, it swells when exposed to aliphatic and aromatic hydrocarbons and by halogenated hydrocarbons (da Costa et al. 2007).

Brown et al. (2002) studied long-term properties of virgin PP fibres in the concrete under a reactive environment. When PP fibres were exposed to an ionic environment of sodium and chloride ions created by salt water at different temperatures of 71 °C and −7 °C for six months, the tensile properties of the PP fibres remained unchanged. Roque et al. (2009) immersed PP fibre reinforced concrete in simulated saltwater conditions for 33 months, and found that rate of stiffness reduction was only 2.34%, which was much lower than those of steel fibre (14.0%) and polyvinyl alcohol (PVA) (59.9%) reinforced concrete. It was concluded that PP has the best durability for non-structural applications in the saltwater environment. Elasto Plastic Concrete (EPC) company (EPC 2012) did advanced alkalinity testing for their product polyolefin fibre. The fibres were subjected to an alkaline solution, which simulates a concrete environment. They reported that their polyolefin fibre could last up to 100 years in an alkaline environment without any decrease of strength.

The polyolefin fibres, including PP and HDPE, show high resistance to alkaline environment, while there is no agreement about the durability of PET fibres in Portland cement matrix. The PET fibres belong to the polyester group, and polyester fibres degrade when embedded in Portland cement matrix (Alani and Beckett 2013; Won et al. 2010). The degradation tests from EPC company showed that the PET fibre only could perform well for 10 years in the concrete, after that the strength of fibre decreased significantly (EPC 2012). However, Ochi et al. (2007) and the ACI 544 (Daniel et al. 2002) reported good alkali resistance of PET fibres in mortar and concrete. Moreover, Won et al. (2010) reported recycled PET fibres and recycled PET fibre reinforced concrete are highly resistant to salt, $CaCl_2$, and sodium sulphate, and have no significant difference in chloride permeability and repeated freeze-thaw tests compared to plain concrete.

Ochi et al. (2007) immersed recycled PET fibre into an alkaline solution, which was prepared by dissolving 10 g of sodium hydroxide in 1 dm^3 of distilled water, for 120 h at 60 °C. The results showed that the tensile strength of PET fibre after immersion was 99% of that before immersion, showing minimal deterioration. Fraternali et al. (2013) did the same test on the recycled PET fibre obtained by mechanically cutting post-consumer bottles, and found that the tensile strength of the PET after alkali attack was 87% of that before attack. Therefore, the recycled PET fibre was considered to have sufficient alkali resistance in both their studies.

Silva et al. (2005) immersed recycled PET fibres in a Lawrence solution (0.48 g/l $Ca(OH)_2$ + 3.45 g/l KOH + 0.88 g/l NaOH, pH = 12.9), which simulates a fully hydrated cement paste. Through micrographs they found that surface of the recycled PET fibres became rough after being immersed for 150 days at 50 °C. Toughness of the PET fibre reinforced concrete decreased with the age due to the degradation of PET fibres inside the concrete. Fraternali et al. (2014) submerged recycled PET fibre reinforced concrete in the Italian Salerno harbour seawater for a period of 12 months. Through the CTOD tests, the energy absorption in the heavily cracked regime (CTOD 0.6–3 mm) was found significantly decreased by 52.1%.

2.2.3 *Cost and Environmental Benefits of Using Macro Plastic Fibres*

In recent years, macro plastic fibres have become an attractive alternative to traditional steel reinforcement in construction industry due to multiple reasons. Firstly, plastic fibres have significantly low cost compared to steel. For instance, based on our previous study (Yin et al. 2015a), 100 m^2 of concrete footpath (100 mm thick) typically requires seven sheets of SL82 steel mesh (364 kg of total weight). Whereas, 40 kg of plastic fibre (4 kg/m^3) can achieve the same degree of reinforcement in concrete footpath of same area. As of current price in Australia, the cost of 40 kg PP fibre is AU$600 (Fibercon 2015), while seven sheets of SL82 steel mesh cost AU$800 (OneSteel 2015). This shows the clear saving of price when using macro plastic fibres. Furthermore, preparation required when using steel mesh such as laying, cutting and tying requires considerable labour time and cost compared to the use of plastic fibres, which can be directly added to the agitator of an agitator truck and combined with the ready-mixed concrete. Ochi et al. (2007) reported that the process of using traditional steel reinforcement in a footpath of size 100 m^2 and thickness of 150 mm includes steel mesh preparation, and concrete placing and finishing, which requires 20 worker-hours (i.e. 0.2 man-h/m^2). However, the PP fibres can be directly mixed with concrete, eliminating the need of preparation of steel, which significantly reduces worker-hours to 10 h, (i.e. 0.1 man-h/m^2).

Thirdly, steel is highly corrosive in nature; corrosion of steel reinforcement in concrete structures can lead to their deterioration and failure. However, plastic fibres, especially PP fibres, as we discussed before, are highly resistant to corrosion, thus having a long-term durability. Moreover, handling plastic fibres are much safer and lighter than using steel.

Last but not least, the production of plastic fibres can significantly reduce carbon footprint compared to that of producing steel. For instance, producing 40 kg of PP fibre can emit 140 kg carbon dioxide equivalents (Shen et al. 2010), while the production of 364 kg of steel has a 1250 kg of carbon emissions (Strezov and Herbertson 2006).

2.2.4 Applications of Macro Plastic Fibre Reinforced Concrete

Reinforcing steel is expensive and its placement in concrete is labour and time intensive, often requiring placement in difficult and dangerous locations. Moreover, steel is highly corrosive in nature, which commonly deteriorates concrete. Therefore, macro plastic fibres are increasingly used in concrete and shotcrete industries for construction of footpaths, non-structural precast elements (pipes, culverts, cable pits and other small components), tunnels and underground structures, to partially or totally substitute steel reinforcement.

At mines, some locations, such as bedrock, are very difficult to support and are susceptible to collapse. In these cases, there is a long-standing demand to increase the support by increasing the fiber content. In the case of steel fiber reinforced concrete, difficulty of mixing and formation of fiber balls have prevented the use of higher fiber contents (Yang et al. 2012). However, macro plastic fiber reinforced concrete can be produced with fibre dosage more than 1% within the normal mixing time without any fibre ball formation and pipe clogging issues (Ochi et al. 2007).

Steel reinforcing mesh is conventionally used in the footpath applications to prevent drying shrinkage cracks (Abas et al. 2013). However, some roads, such as passages in tunnels under construction, passages through underground structures, urban alleyways, and bush roads, are commonly narrow, winding, and steep. It is desirable to apply fibre reinforced concrete to the pavement of such narrow sections of road. Unfortunately, traditional steel fibre can puncture tires, corrode and also can reduce workability of concrete. Therefore, macro plastic fibres are now gradually replacing steel reinforcing mesh for such usage, because of ease of construction, and for saving labour and cost (Cengiz and Turanli 2004). Table 2.4 lists some applications of PET fibre in mines and pavements in Japan (Ochi et al. 2007).

Macro plastic fibres are also an appealing alternative to steel for reinforcing precast concrete elements, such as pipes (Haktanir et al. 2007), sleepers (Ramezanianpour et al. 2013) and pits (Snelson and Kinuthia 2010). Fuente et al. (2013) produced fibre reinforced concrete pipes with internal diameter of 1000 mm, thickness of 80 mm and length of 1500 mm. PP fibre with continuously embossed indents (54 mm in length, 0.9 mm in diameter, 10 GPa Young's modulus and

Table 2.4 Example applications of the PET fibres reinforced concrete in Japan (Ochi et al. 2007)

Prefecture	Location	Concrete sprayed/placed	Water/cement (%)	Fibre length (mm)	Fibre content (%)	Remark
Kagoshima	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	Bush road	Placed	64	40	0.75	Replacement of wire mesh. Considerable laboursaving
Ibaragi	Bush road	Placed	64	40	1	Applied successfully to road with 10% gradient
Ehime	Slope	Sprayed	50	30	0.3	Replacement of steel fibre on the sea front
Fukuoka	Tunnel	Placed	52	40	0.3	Applied to tunnel support for the first time
Tottori	Tunnel	Placed	52	40	0.3	A new fibre content analyser was developed and used
Kanagawa	Bridge pier	Placed	50	30	0.3	Crack extension was substantially decreased
Shiga	Tunnel	Placed	52	40	0.3	A new fibre injector was developed and used

640 MPa tensile strength) was used at 5.5 kg/m^3 dosage to reinforce the pipes. Through a crush test, they found that the peak strength of 50 kPa was achieved at the deflection of 1 mm, with the strength dropping to 30 kPa at the deflection of 2 mm, which kept constant until 10 mm. They reported that the traditional pipe production systems can be adapted while using PP fibre reinforced concrete, and the pipes can meet required strength classes without resorting to conventional rebar reinforcement.

2.3 Characterisation of Toughness and Post-cracking Behaviour of Fibre Reinforced Concrete

The macro plastic fibres do not have obvious effects on the compressive strength of concrete (de Oliveira and Castro-Gomes 2011), but they can effectively improve the toughness and post-cracking performance of concrete (Fraternali et al. 2011). Therefore, a good characterisation of the toughness and post-cracking behaviour is of scientific and technological importance for the macro plastic fibre reinforced concrete.

The toughness of fibre reinforced concrete materials can be considered as their energy absorption capacity. It is conventionally characterised by the area under the load-deflection curve obtained experimentally. Various testing methods, such as tensile, compressive and flexural tests, have been developed to study the energy absorption and toughness of the fibre reinforced concrete. The most straightforward way to characterise a material regarding its post-cracking behaviour in tension is by performing uniaxial tension tests under closed-loop displacement control (de Montaignac et al. 2012). However, such test procedure is complicated to carry out as compared to bending tests, and requires equipment that is not generally available. Using the flexural tests to characterise the toughness has been widely adopted and become the most popular, since the tests are easy to be operated and can simulate most of engineering situations. Therefore, various kinds of flexural toughness tests have been developed, and are of common use in different parts of the world.

No Australian standards exist at present to determine toughness and post-cracking performance of fibre reinforced concrete. Most of the available European and American standards and guidelines recommend the use of unnotched beam specimens subjected to four-point loading, such as ACI Committee 544 (544 1988), ASTM C1018 (ASTM 1997), ASTM C1399 (ASTM 2011a), and ASTM C1609 (ASTM 2011b). Load versus mid-span deflection curves are used in these standards to study the toughness of fibre reinforced concrete. Load-crack opening diagrams are recommend by some standards, including ASTM E1290 (ASTM 2008b) and BS EN 14651 (BSI 2007), through a three-point bending test on a notched specimen. ASTM C1550 (ASTM 2012) suggests testing the toughness on a concrete round panel instead of a beam. Other standards, such as JSCE-G551 (JSCE 2005a), JSCE-G552 (JSCE 2005b), and RILEM TC162-TDF (RILEM 2002) are also used to evaluate the toughness of fibre reinforced concrete. Facing with such a large amount of standards and guidelines, it is important to choose appropriate testing methods to characterise the toughness and post-cracking behaviour of macro plastic fibre reinforced concrete.

2.3.1 Four-Point Flexural Tests on the Unnotched Beams

2.3.1.1 ASTM C1018

For many years ASTM C1018 (ASTM 1997) was the most common testing method for evaluating the toughness of fibre reinforced concrete. As shown in Fig. 2.9, a four-point loading is carried on an unnotched beam of 350 × 100 × 100 mm. The specimen net mid-span deflection is used to control the rate of increase of deflection using a closed-loop, servo-controlled testing system. The deflection of specimen at the mid-span increases at a constant rate within the range of 0.05–0.10 mm/min.

The toughness indexes were defined in terms of the ratio of the area under the load versus deflection curve out to some specified deflection to the area under the curve out to the point of first crack. As shown in Fig. 2.10, the toughness index I_5, I_{10}, and I_{30} are the numbers obtained by dividing the area up to a deflection of 3, 5.5 and 15.5 times the first-crack deflection (δ_f) respectively by the area up to first crack.

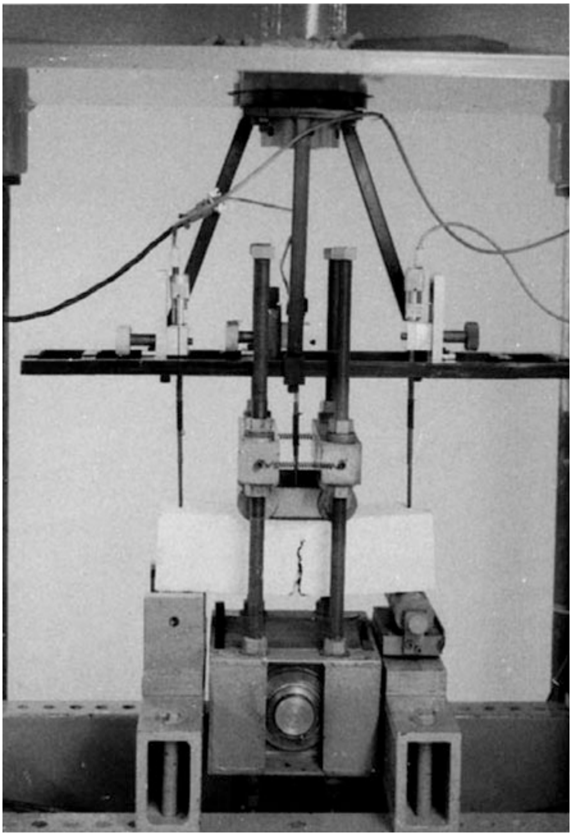


Fig. 2.9 Typical four-point flexural tests based on ASTM C1018 (ASTM 1997)

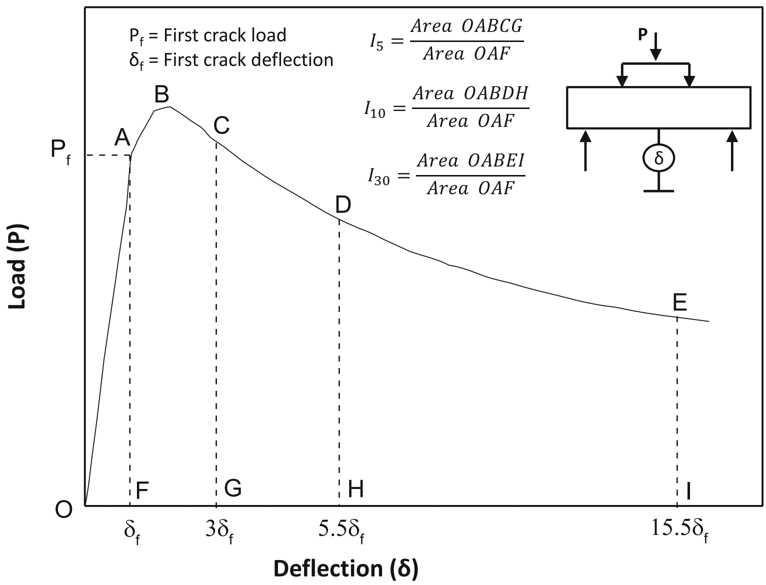


Fig. 2.10 Definition of ASTM C1018 toughness parameters (Gopalaratnam et al. 1991)

The first crack point is defined as 'the point of the load-deflection curve at which the form of the curve first becomes non-linear'. When using first crack deflection as part of a method for characterising toughness, an objective, accurate, and practical definition for the first crack point is important. However, the location of this point in practice is ambiguous and depends upon the resolution of the recording device and the judgement of the operator. Thus, errors can be introduced due to the difficulty of accurate definitions of the first crack point (Mindess et al. 1994). Moreover, these errors can be propagated and magnified when this deflection is multiplied by several numerical factors to calculate the toughness indexes. Equally important is an exact determination of the beam deflections both before and after the first crack. However, this is often difficult, due to various extraneous deflections that may occur due to machine deformations and seating of the specimen on the supports (El-Ashkar and Kurtis 2006). Other limitations include: the wide range of parameters that have been used to interpret test results (Banthia and Trottier 1995), the greater variation in the recorded deflections in four-point bending tests compared with three-point bending tests (Taylor et al. 1997), and the influence of size effects on the test results (Gopalaratnam et al. 1991). As a result of these problems, ASTM C1018 was withdrawn in 2006.

2.3.1.2 ASTM C1399

ASTM C1399 (ASTM 2011a) is a very useful method of assessing the toughness of fibre reinforced concrete, especially for the concrete reinforced by relatively low fibre volumes (Banthia and Dubey 1999). This test is an open-loop test, so the testing machine does not need a displacement control. It was found by Banthia and Dubey (1999, 2000) that the load versus deflection curves obtained in this way were very similar to those obtained using a closed-loop testing machine with proper displacement control.

As shown in Fig. 2.11, a four-point loading is carried on a beam of 350 × 100 × 100 mm, which is the same size with the beam in ASTM C1018. Different with the ASTM C1018, a steel plate is used under the beam before concrete cracks. After the beam is cracked, the steel plate is removed and the cracked beam is reloaded to obtain data to plot a reloading load-deflection curve. An open-loop testing system is used with the rate of displacement of loading head at 0.65 mm/min.

ASTM C1018 uses relative toughness value descriptions, which normalise the energy absorbed up to a specified deflection by the energy absorbed up to the first crack, while the ASTM C1399 describes absolute toughness values, which involve the average energy absorption [i.e. average residual strength (ARS)]. The ARS is calculated using the loads determined at reloading curve (Fig. 2.12) deflections of 0.50, 0.75, 1.00, and 1.25 mm as follows:

$$\mathrm{ARS} = \frac{P_A + P_B + P_C + P_D}{4} \times \frac{L}{bd^2} \tag{1}$$

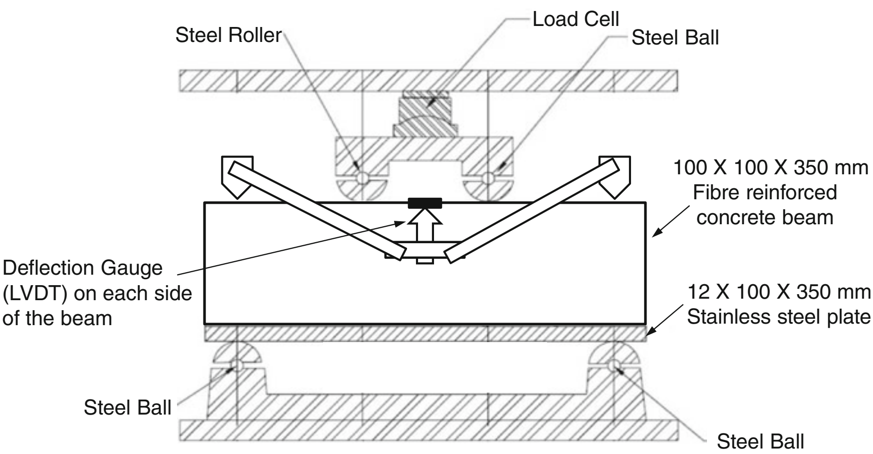
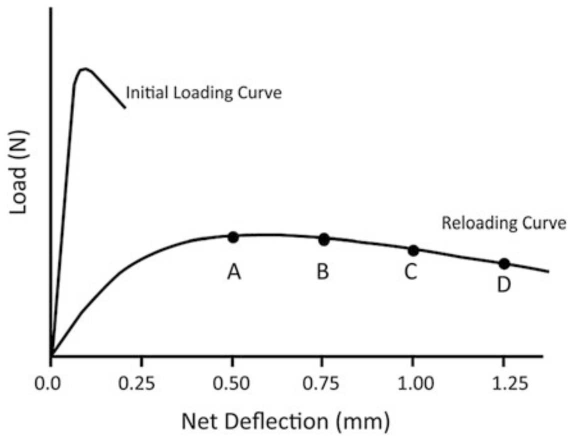


Fig. 2.11 Schematic of ASTM C1399 (ASTM 2011a)

Fig. 2.12 Load-deflection curves (ASTM 2011a)



where

ARS	average residual strength, MPa,
$P_A + P_B + P_C + P_D$	sum of recorded loads at deflections of 0.50, 0.75, 1.00, and 1.25 mm, N,
L	span length, mm,
b	average width of beam, mm, and
d	average depth of beam, mm.

This standard, however, has some disadvantages (Banthia and Mindess 2004). Firstly, since the test procedure is divided into two parts, the effect of the fibres on the behaviour just after first cracking is lost. Another concern is that in an uncontrolled open-loop test, during initial loading, the deflection is very hard to control and the net deflection requirements are seldom met. This is of particular concern for very high strength matrices. Doubts are often raised as to the capacity of the pre-cracking procedure (with steel plate) to effectively replace proper re-loading test setup. Moreover, the length of the pre-crack obtained is unknown, and is variable for different fibre reinforced concrete systems. This makes comparison between different fibre reinforced concrete beams difficult.

2.3.1.3 ASTM C1609

Due to the drawbacks of ASTM C1018, this standard has been replaced by ASTM C1609 (ASTM 2011b) since 2005. The ASTM C1609 has similar procedures with ASTM C1018 for obtaining the load versus deflection curve, but the resulting curve is analysed in a totally different way. Therefore, the faults in the ASTM C1018 were excluded.

Based on the ASTM C1609, toughness tests are carried out on concrete beams with size of 350 × 100 × 100 mm and 500 × 150 × 150 mm. A closed-loop, servo-controlled testing system and roller supports are used in this test. Flexural

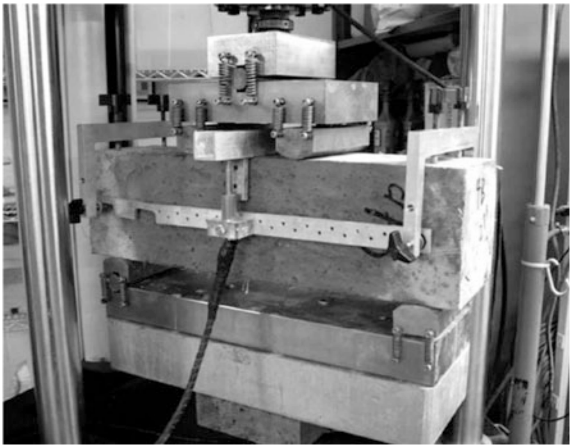


Fig. 2.13 Test apparatus of ASTM C1609 (ASTM 2011b)

load is applied under constant rate of displacement (not exceeding 0.05 mm/min) at one-third of test specimen spans. As shown in Fig. 2.13, a frame (referred to as a 'yoke') is mounted to the beam specimens, which allows direct measurement of the net central deflection of the beams. The use of the 'yoke' eliminates extraneous deflections arising from support settlements and results in load-deflection curves which are considerably different from those obtained by using the cross-head displacement of the testing machine.

Different to ASTM C1018, this standard calculates residual strength (f^{D}_{600} and f^{D}_{150}) at net deflection of L/600 and L/150, respectively. Absolute toughness (T^{D}_{150}) and equivalent flexural strength ratio ($T^{D}_{T,\ 150}$) are also presented. As shown in Fig. 2.14, this test uses first-peak instead of first-crack, which is more accurate and objective. The equivalent flexural strength ratio, which is based on the first-peak strength, is more accurate. However, some difficulties still arise when this standard is applied to ultra-high performance fibre reinforced concrete containing very high volume fraction of fibres and exhibiting deflection-hardening behaviour (Wille et al. 2014). The peak load in ASTM C1609 is defined as the first point on the load-deflection curve where the slope is zero. Clearly, deflection-softening fibre reinforced concrete exhibits such a response. However, a deflection-hardening fibre reinforced concrete may have a stable deflection-hardening response without a sudden load drop after peak load, so there is no point with a zero slope (Yehia 2009).

2.3.2 Three-Point Flexural Tests on the Notched Beams

The stress-strain relation from the four-point flexural test on the unnotched beams is considered to be the most desirable since it can be directly used in engineering calculations. However, it does not represent the actual post-cracking behaviour of fibre reinforced concrete and cannot be retrieved directly from a characterisation

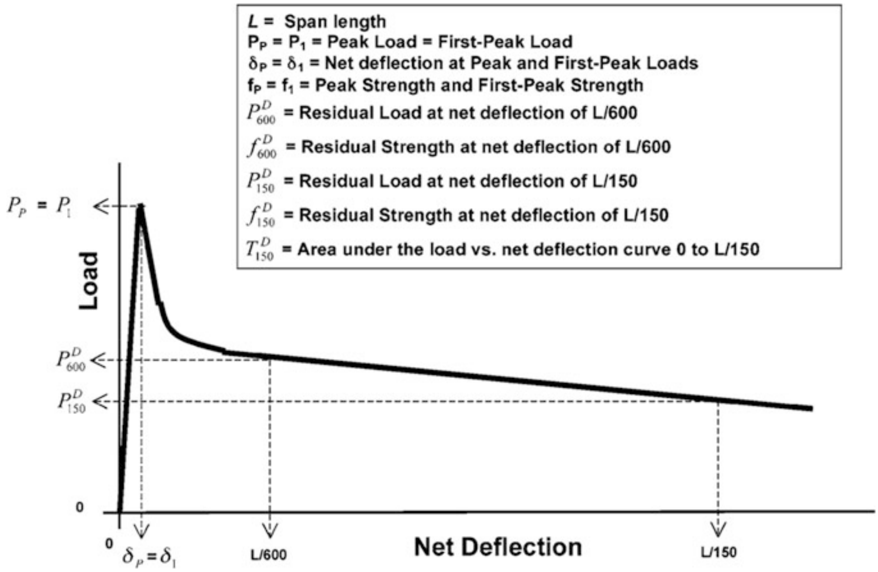


Fig. 2.14 Load-deflection curve of ASTM C1609 (ASTM 2011b)

test. Moreover, during the test, there is a momentary loss of stability when the concrete matrix cracks, even under displacement control, and while using relatively stiff conventional testing machines (Barr et al. 1996). Therefore, the unnotched beams through a four-point flexural test normally have a great variation in the recorded deflections.

Notched beam tests offer a promising alternative to characterise toughness of fibre reinforced concrete. The tests avoid many of the problems associated with the four-point test on the unnotched beams, and thus guarantee stability throughout the tests even for unreinforced and high-strength low fibre-content concretes (Shaheen and Shrive 2007). A mid-point loading configuration is obviously more appropriate for notched beam specimens than the four-point loading (Ding 2011).

For the notched mid-point loaded specimen, crack initiates at the notch-tip and propagates along the notch plane and hence, deformation is always localised at the notch-plane and the rest of the beam does not undergo significant inelastic deformations (Mahmud et al. 2013). This minimises the energy dissipated over the entire volume of the specimen and, therefore, all the energy absorbed can be directly attributed to fracture along the notch plane. Consequently, the energy dissipated in these tests can be directly correlated to material response (i.e. fibre reinforcement) (Stynoski et al. 2015). Moreover, the stress-crack opening relation from the tests naturally expresses the real post-cracking behaviour of fibre reinforced concrete. The stress-crack opening properties are also independent of the structural member size (de Montaignac et al. 2012). Therefore, three-point flexural test on the notched beams are considered as the best way of studying toughness, crack propagation and the associated fibre reinforcement.

Crack Tip Opening Displacement (CTOD) and Crack Mouth Opening Displacement (CMOD) tests are common three-point flexural tests on the notched beams. According to ASTM E1290 (ASTM 2008b), CTOD is the displacement of the crack surfaces normal to the original (unloaded) crack plane at the tip of the fatigue precrack. However, due to inherent difficulties in the direct determination of CTOD, CMOD test is a preferred test to assess post-cracking performance of fibre reinforced concrete (Zhijun and Farhad 2005). According to BS EN 14651:2005 +A1:2007 (BSI 2007), CMOD test measures the opening of the crack at mid-span using a displacement transducer mounted along the longitudinal axis.

During the last ten years many laboratories have been using closed-loop servo-hydraulic machines to test concrete specimens in the fracture tests. In such machines the opening of crack mouth is used to control the tests. In such tests, the CMOD can be used directly as a measure of the response of the beam, thus eliminating the need to monitor the actual central deflection of the test specimens via a 'yoke' arrangement (Aslani and Bastami 2015). The load-CMOD curves directly represent the deformation of the critical section. Though this requires more sophisticated testing equipment than that required for load-displacement curves, such testing equipment results in stable post-peak response and avoids the effects of energy dissipation outside the cracking zone (Bordelon et al. 2009). Therefore, in our research CMOD tests were carried out to study the reinforcing effects of the recycled plastic fibres in concrete, rather than using the four-point flexural tests on the unnotched beams.

Figure 2.15 shows the test set-up and the schematic of the controls. A CMOD transducer monitors the crack opening displacement and supplies the feed-back signal to the servo-controller, as shown in Fig. 2.15(a). A Japanese yoke is mounted around the specimen to record the net deflections so that the extraneous deflections resulting from settlement of supports, crushing at load points, and load-fixture deformation are automatically eliminated. Averaged data from two LVDTs placed on either side of the specimen are used to record the net deflection of the beam at the mid-span (de Montaignac et al. 2012), as shown in Fig. 2.15(b). A load-CMOD relationship can be obtained from the test. Using this type of relationship, the load at the limit of proportionality and the residual flexural tensile strength parameters can be obtained.

2.3.3 Flexural Tests on the Round Panel

Round determinate panel test (RDPT), according to ASTM C1550, involves a centre point loading of a large circular plate (800 mm in diameter and 75 mm in thickness) supported on three points. The specimen toughness is assessed in terms of the energy absorbed in loading the plate to some selected values of central deflection. This test has become popular for fibre reinforced shotcrete due to its high precision in post-cracking performance evaluation (Wang et al. 2004), and is often used in the mining industry (Decker et al. 2012). Its panel-based performance assessment is desirable because panels fail through a combination of stress actions

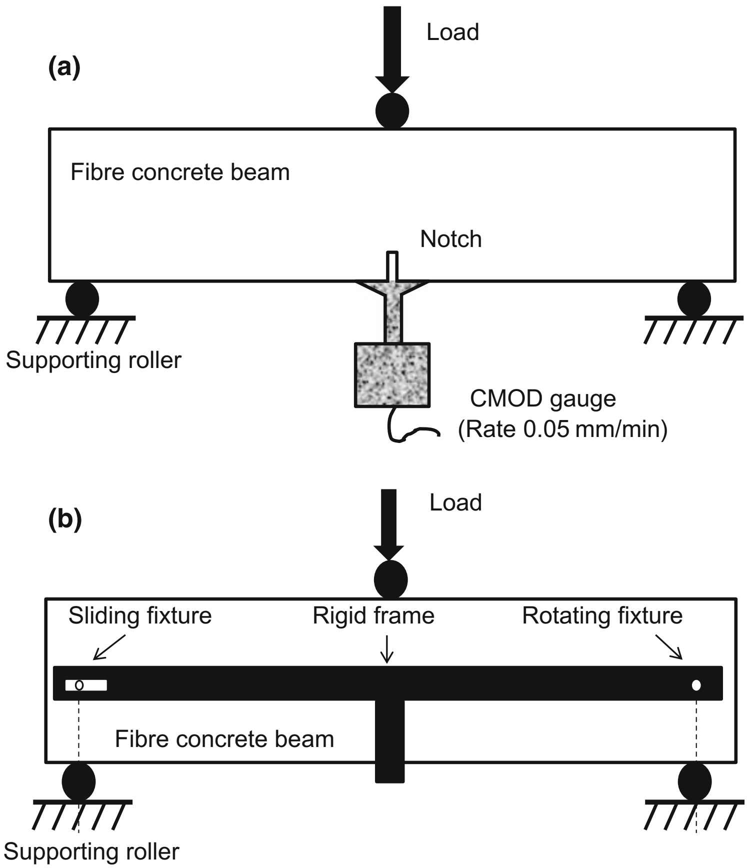


Fig. 2.15 Schematic of BS EN 14651

that reflect an in situ behaviour of concrete footpaths more closely than other mechanical tests in the laboratory (Parmentier et al. 2008). This test has a significantly lower variability in post-cracking performance than other tests, and therefore energy absorption in the round determinate panel is considered the most reliable test method of post-cracking performance assessments (Zi et al. 2014). Therefore, in our research the RDPT is another method chosen to assess the reinforcement of recycled plastic fibres in concrete.

As shown in Fig. 2.16, a load is applied to the centre of the panel by a hemispherical-ended steel piston. The load is controlled by a programmable logic controller to maintain a constant deflection rate of 4.0 ± 1.0 mm/min. The panel rests on three pivots, evenly spaced around its circumference, and deflection is carried out until a central displacement of at least 40 mm is achieved. The energy absorbed is recorded at deflections of 10, 20, 30, and 40 mm (de Montaignac et al. 2012).

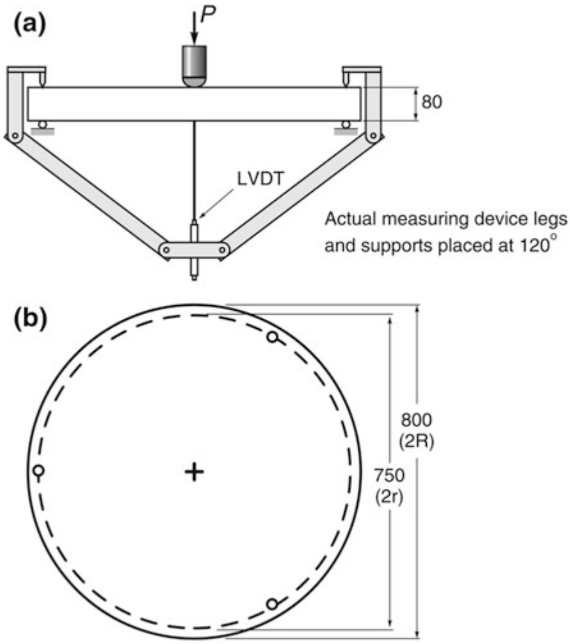


Fig. 2.16 Side view **a** and top view **b** of the RDPT apparatus setup according to ASTM C1550

2.4 Life Cycle Assessment

In order to help decision makers correctly consider the comparative environmental impacts of virgin PP fibre, recycled PP fibres and steel reinforcing mesh in concrete footpaths, it is very important to carry out environmental impact assessment (EIA). The environmental impact assessment is a formal process used to predict the positive or negative environmental consequences of a project prior to making decisions (Achilleos et al. 2011; Carvalho et al. 2014). There are a variety of general and industry specific assessment methods, such as GMP-RAM (Jesus et al. 2006), INOVA Systems (Jesus-Hitzschky 2007), fuzzy logic EIA method (Afrinaldi and Zhang 2014; Peche and Rodriguez 2009). However, life cycle assessment (LCA) (Sandin et al. 2014) is the most comprehensive among the available tools and widely adopted and used in a wide variety of applications. For example, the LCA is widely used in building assessment (Gabel et al. 2004; Ingrao et al. 2014; Iribarren et al. 2015; Silvestre et al. 2014) and its implementation must adhere to standards ISO14040: 2006 (ISO14040 2006) and ISO14044: 2006 (ISO14044 2006).

Life cycle assessment is commonly used to identify and measure the impacts associated with all the stages of a product's life from-cradle-to-grave (i.e., from raw material extraction and raw materials processing, to product manufacture, distribution, use, repair and maintenance, and ending with disposal or recycling). It considers all stages to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy consumed, materials used and waste released to the environment (Sandin et al. 2014). The LCA methodology is generally considered the best environmental management tool for quantifying and comparing alternative eco-performances of products, as well as recycling and disposal systems (Lasvaux et al. 2014). The structure of LCA consists of four distinct phases: goal and scope definition, inventory analysis, impact assessment and interpretation (Dodbiba et al. 2007).

The goal of an LCA states the intended application, the reasons for carrying out the study, the intended audience, and where the results are going to be used. The scope should be sufficiently well defined to ensure that the breadth, depth and details of the study are compatible and sufficient to address the stated goal. It includes the following items: the product system to be studied; the functional unit; the system boundary; allocation procedures; impact categories and methodology of impact assessment, and subsequent interpretation to be used; data requirements; assumptions; limitations; initial data quality requirements; and format of the report required for the study.

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. Data for each unit process within the systems boundary can be classified under major headings, including energy inputs, raw material inputs, ancillary inputs, other physical inputs; products, co-products and waste; emissions to air, discharges to water and soil, and other environmental aspects. Following the data collection, calculation procedures, including validation of data collected, the relating of data to unit processes, and the relating of data to the reference flow of the functional unit, are needed to generate the results of the inventory of the defined system for each unit process and for the defined functional unit of the product system that is to be modelled.

The impact assessment phase of LCA aims at evaluating the significance of potential environmental impacts using the life cycle impact (LCI) results. In general, this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts. Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together. The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations (Viksne et al. 2004).

Perugini et al. (2005) studied the LCA for recycling of Italian household plastic packaging waste. Their study quantified the overall environmental performances of mechanical recycling of plastic containers in Italy and compared them with conventional options of landfilling or incineration, as well as comparing with other innovative processes of feedstock recycling (low-temperature fluidised bed pyrolysis, and high-pressure hydrogenation). Their results confirmed that recycling scenarios were always preferable to those of non-recycling. Arena et al. (2003) also studied the Italian system of collecting and mechanically recycling the post-consumer polyethylene (PE) and polyethylene terephthalate (PET) liquid containers. They found that the production of recycled PET can save between 29 and 45% of energy compared to virgin PET production, depending on whether the process wastes (mainly coming from sorting and reprocessing activities) were used for energy recovery. Moreover, 39–50% reductions in energy use were observed in the production of recycled PE compared to virgin PE.

Shen et al. (2010) assessed the environmental impact of PET bottle-to-fibre recycling. Four recycling cases, including mechanical recycling, semi-mechanical recycling, back-to-oligomer recycling and back-to-monomer recycling were analysed. The LCA results showed that recycled PET fibres offered important environmental benefits over virgin PET fibre, including energy use savings of 40–85%.

2.5 Conclusions

1. In order to decrease the plastic pollution and conserve non-renewable fossil fuel, efficient technology for recycling plastic waste has become increasingly important. Mechanical recycling is relatively easy and economic, and infrastructure for collection and reprocessing has been well established. In order to improve quality of end products of recycled plastics, various workable reprocessing techniques in the second stage of mechanical recycling have been developed and widely applied in the recycling industry. Reprocessing recycled polypropylene is always accompanied with degradation, crystallisation, and consequent processability problems, which result from molecular chain scission, branching and crosslinking. The degradation behaviour decreases tensile strength and impact strength, while the crystallisation behaviour increases Young modulus and yield stress. This chapter critically reviews the current reprocessing techniques of recycled polypropylene, including melt blending, filler reinforcement and mechanochemistry. Each method has inherent context, application and specific recycling advantages. However, reprocessing recycled polypropylene into fibre has limited research. The degradation and crystallisation behaviour in the reprocessing of fibre production is unknown.
2. This chapter then presents the current state of knowledge and technology of preparation techniques and properties of macro plastic fibres. It also reviews the reinforcing effects of macro plastic fibres in concrete and applications of plastic fibres reinforced concrete. The macro plastic fibres decrease workability of fresh concrete, but effectively control plastic shrinkage cracking of fresh concrete. The macro plastic fibres have no obvious effects on compressive and flexural strength, which are dominated by the concrete matrix properties. The main benefit of using macro plastic fibres lies in improved ductility in the post-cracking region and flexural toughness of concrete. The macro plastic fibres reinforced concrete shows excellent post-cracking performance and high energy absorption capacity. The macro plastic fibres also have good crack controlling capacity of dry shrinkage. The macro plastic fibres offer significant cost and environmental benefits over traditional steel reinforcement, thus have been widely used in the construction of pavements, precast elements and tunnel

linings. However, there is a very limited study on the performance of recycled PP fibres in concrete.

3. The macro plastic fibres do not have obvious effects on the compressive strength of concrete, but they can effectively improve the toughness and post-cracking performance of concrete. This chapter critically compares various testing methods of characterisation of the toughness and post-cracking behaviour, including four-point flexural tests on the unnotched beams (ASTM C1018, ASTM C1399 and ASTM C1609), three-point flexural tests on the notched beams (ASTM E1290 and BS EN 14651) and flexural tests on the round panel (ASTM C1550). After comparing different standards and guidelines, the crack mouth opening displacement test based on BS EN 14651 and round determinate panel test based on ASTM C1550 were considered as appropriate testing methods of ascertaining the ability of recycled PP fibres to enhance the post-cracking performance of concrete.
4. The environmental impact assessment is a formal process used to predict the positive or negative environmental consequences of a project prior to making decisions. There are a variety of general and industry specific assessment methods, such as GMP-RAM, INOVA Systems, fuzzy logic EIA method. Life cycle assessment is the most comprehensive among the available tools and widely adopted and used in a wide variety of applications. The literature on LCA of recycling plastic waste are very limited, and are strongly influenced by final product types, plastic sources, and by local characteristics of procedures for collecting and reprocessing plastic waste. Hence, these studies cannot be extrapolated to Australian conditions, where there is limited information on comparative LCA of recycling plastic wastes. In order to help decision makers correctly consider the comparative environmental impacts of virgin PP fibre, recycled PP fibres and SRM in concrete footpaths, it is very important to carry out life cycle assessment.

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