Use of macro plastic fibres in concrete: A review

Shi Yin[1], Rabin Tuladhar[1*], Feng Shi[2], Mark Combe[3], Tony Collister[3], Nagaratnam Sivakugan[1]

[1] College of Science, Technology & Engineering, James Cook University, QLD 4811, Australia

[2] School of Materials Science and Engineering, Beijing Institute of Petrochemical Technology, Beijing, 100000, China

[3] Fibercon, QLD 4051, Australia

*Corresponding author: Rabin Tuladhar (rabin.tuladhar@jcu.edu.au)

Abstract

Use of macro plastic fibres to reinforce concrete has attracted widespread attention from both scientists and construction industry due to the multiple sustainability benefits they offer, compared to steel fibres and steel reinforcing mesh. This paper critically reviews the current state of knowledge and technology of using macro plastic fibres to reinforce concrete. Detailed review on the various preparation techniques and the resulting properties of macro plastic fibres are presented and the effects of macro plastic fibres on the fresh and hardened concrete properties are discussed in this paper. The effect of macro plastic fibres on workability, plastic shrinkage, compressive strength, splitting tensile strength, flexural strength, post-crack performance and dry shrinkage is discussed in this paper. Pull-out behaviour and degradation behaviour of the fibre in the concrete are also reviewed. Finally, some applications of the plastic fibre reinforced concrete are discussed.

Keywords: macro plastic fibre, concrete, fibre production, reinforcement, application

1. Introduction

Concrete is essentially a mixture of cement, aggregate and water. It is widely used in construction industry because all the raw materials required are widely available and are of low cost. 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 reinforcement, various fibres are also used to improve the properties of concrete, mainly for enhancing the tensile strength. There are mainly four types of fibres which can be used to reinforce concrete: steel fibre, glass fibre, natural fibre and synthetic fibre [1].

Steel fibres can greatly improve the tensile strength and the flexural strength of concrete due to their ability to absorb energy [2] and control cracks [3]. Their electric [4], magnetic [5] and heat [6] conductivity properties make them suitable for some special applications. However, corrosion of steel fibres can be detrimental and lead to rapid deterioration of concrete structures [7]. Glass fibre has an excellent strengthening effect [8] but poor alkali resistance [9]. Natural fibres, such as wood [10], sisal [11], coconut [12], sugarcane bagasse [13], palm [14], and vegetable fibres [15], are cheap and easily available, but they have poor durability. Synthetic fibres can be made of polyolefin [16], acrylic [17], aramid [18], and carbon [19]. They can prevent plastic shrinkage cracks in fresh concrete [20] and improve post-cracking behaviour of concrete [21].

The schematic diagram in Fig. 1 shows the different failure modes associated with the fibre reinforced concrete [22]. Fibre rupture (1), pull-out (2) and debonding of fibre from matrix (4) can effectively absorb and dissipate energy to stabilize crack propagation within concrete. Fibre bridging the cracks (3) reduces stress intensity at the crack tip. In addtion, 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, cracks will occur in other locations of the matrix (6). Although every individual fibre makes a small contribution, the overall effect of reinforcement is cumulative [22]. Therefore, the fibres can effectively control and arrest crack growth, hence preventing plastic and dry shrinkage cracks [23], retaining integrity of concrete [24], and altering the intrinsically brittle concrete matrix into a tougher material with enhanced crack resistance and ductility [25]. In order to achieve considerable reinforcement, the fibres should have high tensile strength and Young's modulus [26].

(Insert Fig. 1 here)

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 arrange from 5 to 100 μm and length are 10-20 mm [27]. These micro fibres can effectively control plastic shrinkage cracking, which is caused by shrinkage of fresh concrete during the first 24 hours after placement due to excessive evaporation of bleed water [28]. However, they do not have any effect on the properties of hardened concrete [29].

The macro plastic fibres normally have a length of 30-60 mm and cross section of 0.6-1 mm^2 [30]. The macro plastic fibres are not only used to control plastic shrinkage [31], but also mostly used for controlling drying shrinkage [32]. Drying shrinkage occurs due to the loss of water molecules from the hardened concrete [33]. This type of drying shrinkage can occur in large flat areas like slabs in hot and dry environments like in North Queensland, Australia. A steel reinforcing mesh is normally used to prevent the drying shrinkage cracks; but now it is gradually being replaced by the macro plastic fibres because of ease of construction, reduced labour and lower cost. Another significant benefit is the post-cracking behaviour provided by the macro plastic fibres [34]. Brittle plain concrete has no effective post-cracking ductility, but the macro plastic fibres can considerably improve the post-cracking response of concrete, because the plastic fibres act as a crack arrester, and alter the intrinsically brittle concrete matrix into a tough material with better crack resistance and ductility. Therefore, when concrete breaks, the common large single cracks can be substituted by dense micro-cracks due to the presence of fibre reinforcement [35]. The macro plastic fibres now have become increasingly popular in the construction of concrete footpaths [36], precast panels [37] and shotcrete mine tunnels [38].

The aim of this paper is to critically review the present state of knowledge and technology of macro plastic fibre reinforced concrete. After a detailed review of various preparation techniques and resulting properties of macro plastic fibres, attention is paid to effect of the fibres on performance of the fresh and hardened concrete. The effects of macro plastic fibres on workability, plastic shrinkage, compressive strength, splitting tensile strength, flexural strength, post-crack performance and dry shrinkage are discussed in this paper. The pull-out behaviour and degradation behaviour of the fibre in the concrete are then studied. Finally, some applications of the plastic fibre reinforced concrete are presented.

2. Preparation and properties of 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 alkaline resistance [39], and high tensile strength and Young’s modulus [26]. However, their low density (around 0.9 g/cm^3) may make the fibres 'float up' to the surface of concrete matrix [40]. 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 adhesion between the fibres and the concrete [41]. 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 [40]. 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 the PP or HDPE fibres. They also have high tensile strength and Young's modulus [41], which can effectively improve post-crack performance of concrete. However, PET granules must be dried for at least 6 hours before being processed into fibres. The PET granules also easily crystallised and stick on the inner wall of the extruder. Hence, it is more difficult and costly to process PET than PP or HDPE. Moreover, alkaline resistance of the PET fibres is questionable [42, 43]. Therefore, the PP fibres have become the most common commercial product as a 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 have are now investigating the use of recycled plastic fibres in concrete [44]. However, recycled plastics have uncertain processing and service history, impurities and varying degrees of degradation, leading to processing difficulties and unstable mechanical properties [45].

The physical and chemical characteristics of the macro plastic fibres vary widely depending upon the manufacturing techniques. A popular technique involves melt spinning plastic granules into filaments and then hot drawing monofilaments into fibres [46]. In the study conducted by Ochi et al. [41], PET granules were melted and extruded into monofilaments with a fineness of 60,000 dtex (dtex: grams per 10,000 meter length). Then the monofilaments were hot drawn into 5,000 dtex through a film orientation unit shown in Fig. 2. 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, inducing high crystallinity and thus significantly improving tensile strength and Young's modulus. Through this method, PET [46]and PP [30]fibre of tensile strength above 450 MPa can be obtained.

(Insert Fig. 2 here)

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) [47]. Kim et al. [48] used this technique to sucessfully 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 recylced plastic fibres just by mechanically cutting PET bottles. The remaining bottle necks and the bottoms are discarded. Foti [49] used this method to produce lamellar fibre and 'O'-shaped annular fibre. 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. Both de Oliveira and Castro-Gomes [50] and Foti [49] could only produce fibres of low tensile strength of around 150 MPa and low Young's modulus of about 3 GPa through this technique, which are much lower than those produced by the other two techniques.

3.1 Fresh concrete properties

3.1.1 Slump

Workability of fresh concrete can be determined through a slump test [51]. Table 1 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 [52]. Mazaheripour et al. [53] 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 % to 1% and (b) to add more water. However, addition of water will negatively affect concrete strength; hence plasticiser or water reducing admixtures are often used in fibre reinforced concrete to improve workability without increasing water content. [54].

(Insert Table 1 here)

3.1.2 Plastic shrinkage

Plastic shrinkage cracking is caused by moisture loss after casting [55]. Generally, if the moisture evaporation rate exceeds 0.5 kg/m^2/hr, it causes negative capillary pressure inside the concrete, resulting in internal strains [56]. Plastic shrinkage can cause cracks during the initial stages, when the concrete has not yet developed adequate strength [57]. Kim et al. [47] reported that although the macro plastic fibres do not affect the total moisture loss or moisture loss per hour, they still can effectively control the plastic shrinkage cracking through improvement of 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 [58] 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.

3.2 Hardened concrete properties

3.2.1 Compressive strength

As shown in Table 1 [54, 59], the macro plastic fibres have no significant effects on the compressive strength, which is also consistent with what was reported by Hsie et al. [60], Campione [61], Fraternali et al. [46], and de Oliveira and Castro-Gomes [50]. Ochi et al. [41] reported that although some variation exists, for different water-cement ratios, 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 suddenly with large single cracks at the peak load, while as reported by Brandt [35] the macro plastic fibre reinforced concrete cylinders failed with many minor cracks on the surface. Fig. 3 shows stress-strain curves of a compressive test on concrete cylinders conducted by Hasan et al. [54]. 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.

(Insert Fig. 3 here)

3.2.2 Splitting tensile strength

The split-cylinder test is an indirect test to obtain tensile strength of concrete [62]. As can be seen in Table 1 [54, 59], the macro plastic fibres improve the splitting tensile strength. When the tensile stress in concrete reaches tensile strength of concrete, the stress is transferred to the macro plastic fibres. The fibres can arrest the propagating macro cracks, thus improving the splitting tensile strength [60]. It was shown that plain concrete cylinders failed abruptly once the concrete cracks, whereas macro synthetic fibre reinforced concrete specimens could retain its shape even after concrete cracked. This shows that the macro synthetic fibre reinforced concrete has the ability to absorb energy in the post-cracking state [54].

3.2.3 Flexural strength

Flexural test is another indirect tensile test which measures the ability of concrete beam to resist failure in bending [63]. 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 [36]. However, in the four-point loading flexural test, maximum bending occurs on the moment span [27]. Research has found that the macro plastic fibres have no obvious effects on the flexural strength, which is dominated by the matrix properties [52]. The main benefit of using macro plastic fibres lies in improved ductility in the post-crack region and flexural toughness of concrete [50]. Brittle behaviour is always associated with plain concrete [64]. When the first crack is produced, the specimen cracks and collapses almost suddenly, with very small deformations and no prior warning. However, in plastic fibre reinforced concrete specimens, the failure progresses with bending, but without any sudden collapse as seen in plain concrete. When the conrete fails, the load is transmitted to the plastic fibres. The fibres prenvent the spread of cracks as shown in Fig. 1 and hence delay the collapse [49].
Hsie et al. [60] 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. 4, the plain concrete showed a brittle failure. The

flexural strength reached the maximum at a deflection of around 0.05 mm, and then decreases rapidly. 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 supported by the PP fibres, thus becoming stable around 1.5 MPa. Similar trends were also reported by de Oliveira and Castro-Gomes [50], Ochi, Okubo et al. [41], and Meddah and Bencheikh [65].

(Insert Fig. 4 here)

3.2.4 Post-crack 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 [46]. According to ASTM E1290 [66], 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-crack performance of fibre reinforced concrete [67]. According to BS EN 14651:2005+A1:2007 [68], CMOD test measures the opening of the crack at midspan 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. [46] performed CTOD tests on PP and recycled PET fibre reinforced concrete specimens. The PP fibre had 1.04 mm^2 of cross section, 47 mm of length, 29 % of ultimate strain and 250 MPa of tensile strength, while the recycled PET fibre had 1.54 mm^2 of cross section, 52 mm of length, 19 % of ultimate strain and 274 MPa of tensile strength. The results can be seen in Fig. 5. 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 has significantly improved in the PP and PET fibre reinforced specimens. This clearly exhibits the ability of macro plastic fibres to improve post-crack performance of concrete.

(Insert Fig. 5 here)

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-crack performance than concrete beams [69]. The panel-based performance assessment is desirable because panels fail through a combination of stress actions that reflect the behaviour of an fibre reinforced concrete more closely than other mechanical tests [70]. RDPT, based on ASTM C1550 [71], 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 [72].

Cengiz and Turanli [70] 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, and a Young's modulus of 3.5 GPa. The steel fibre had a length of 30 mm, a diameter of 0.6 mm, 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. 6, 0.45 % of steel fibre reinforced concrete showed 65 kN of peak load and 664 J of energy absorption at 25 mm, while 0.78 % of PP fibre reinforced concrete showed better post-crack performance with 70 kN of peak load and 716 J of energy absorption. Steel mesh showed very brilliant post-crack performance (1308 J in energy absorption).

(Insert Fig. 6 here)

3.2.5 Drying shrinkage

Drying shrinkage occurs in hardened concrete due to the loss of water from the hardened concrete [73]. The drying shrinkage can be quite significant in large flat areas like footpaths and slabs in hot, windy and dry environment [74]. Steel reinforcing mesh is typically being used to prevent the drying shrinkage cracks, but is now being gradually replaced by macro plastic fibres because of ease of construction, saving of labour and cost [70], and environmental benefits [75].

Soroushian et al. [52] tested the restrained drying shrinkage of plastic fibre reinforced concrete, according to ASTM C157 [76]. 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 [58] and Hsie et al. [60], the plain concrete can withstand only small drying shrinkage strains, 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.

3.2.6 Pull-out behaviour of 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 and matrix significantly affects capacity of the fibres to stabilise the crack propagation in concrete matrix [77]. Low mechanical bonding strength may not provide sufficient bridging force to control crack development. Moreover, the weak bonding strength also can cause internal micro-cracks in the interfacial area [41].

Oh et al. [78] explored optimum shape among the various plastic fibres as shown in Fig. 7. In their pull-out tests, the crimped-shape plastic fibres exhibited the highest energy absorption capacity. Kim et al. [47] 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 bond 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.

(Insert Fig. 7 here)

3.2.7 Degradation of plastic fibres in concrete

PP has a high resistance to chemical attack due to its non-polar nature [79]. For example, PP is resistant to alcohol, organic acids, esters and ketones, inorganic acids and alkalis. However, it swells when exposed to aliphatic and aromatic hydrocarbons and by halogenated hydrocarbons [80]. Brown et al. [81] 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 71 °C and -7 °C temperatures for six months, the tensile properties of the PP fibres remained unchanged. Elasto Plastic Concrete (EPC) company [43] did advanced alkalinity testing for their product olefin fibre. The fibres were subjected to an alkaline solution, which simulates a concrete environment. They reported that their olefin fibre could last up to 100 years in an alkaline environment without any decrease of strength

The olefin 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 [37]. The degradation tests of 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 [43]. However, Ochi et al. [41] and the ACI 544 [1] reported good alkaline resistance of PET fibres in mortars and concretes. Ochi et al. [41] immersed 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. Therefore, the PET fibre was considered to have sufficient alkali resistance as a concrete-reinforcing fibre in their study.

Silva et al. [42] 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) to simulate 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. Some alkaline terephthalates were found as precipitation of phases. Through Fourier Transform Infrared Spectroscopy (FTIR) tests, ions Ca^{2+}, Na^+, K^+, and OH^- were found to attack the C-O bonds of PET. The ions Ca^{2+}, Na^+, K^+ reacted with aromatic ring of the PET, while OH^- reacted with aliphatic ester of the PET. Consequently, the PET was split into Ca-, Na-, and/or K- terephthalates and ethylene glycol. The mechanical properties of the PET fibre reinforced concrete, such as compressive strength, tensile strength and flexural strength, were not influenced at the ages of 42, 104, and 164 days old. However, toughness of the PET fibre reinforced concrete decreased with the age due to the degradation of PET fibres inside the concrete.

3. Applications of plastic fibre reinforced concrete

Reinforcing steel in concrete 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 [82]. However, 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 [41].

Steel reinforcing mesh is conventionally used in the footpath applications to prevent drying shrinkage cracks [83]. 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, plastic fibres are now gradually replacing steel reinforcing mesh and steel fibres for such usage, because of ease of construction, and for saving labour and cost [70]. Table 2 lists some application of PET fibre in mines and pavements in Japan[41].

Macro plastic fibres are also appealing alternative to steel to reinforce precast concrete elements, such as pipes [84], sleepers [85] and pits [86]. Fuente et al. [87] 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 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.

(Insert Table 2 here)

4. Conclusion

Use of macro plastic fibres to reinforce concrete instead of steel mesh and steel fibres has become appealing to scientists and concrete industries due to its sustainability benefits. This paper has presented the current state of knowledge and technology of preparation techniques and properties of macro plastic fibres. It also reviewed the reinforcing effects of macro plastic fibres in concrete and applications of plastic fibres reinforced concrete. The major conclusions drawn from the study are:

1. PP, PET and HDPE are the three main raw materials used in the production of plastic fibres. PP fibres have become most common commercial products in fibre reinforced concrete, and PET fibres have attracted wide research, but HDPE fibres are still rare in both practice and research. Different production techniques result in different mechanical properties of the macro plastic fibres.
2. The macro plastic fibres decrease workability of fresh concrete, but effectively control plastic shrinkage cracking of fresh concrete.
3. 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-crack region and flexural toughness of concrete. The macro plastic fibres reinforced concretes show excellent post-crack performance and high energy absorption capacity. The macro plastic fibres also have good crack controlling capacity of dry shrinkage.
4. In order to improve bonding strength between the fibres and concrete, the plastic

fibres normally have various shapes and indents.

5. The olefin fibres, including PP and HDPE, show a high resistance to alkaline environment, further researcher is need to quantify durability of PET fibres in the Portland cement matrix.
6. The macro plastic fibres can be used in the construction of pavements, light precast elements and tunnel linings. The fibre reinforced concrete is easy to handle and has performed adequately in all the applications.

5. References

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6. Captions for Figures and Tables

Fig. 1 Failure mechanisms in fibre reinforced concrete. 1. Fibre failure; 2. Fibre pull-out; 3. Fibre bridging; 4. Fibre/matrix debonding; 5. Fibre Preventing crack propagation; 6. Matrix cracking [22]

Fig. 2 Apparatus for PET fibre extrusion [41]

Fig. 3 Average stress-strain curves for concretes with macro plastic fibres [54]

Fig. 4 Load-deflection curves of PP fibres reinforced concretes [60]

Fig. 5 Load-CTOD curves of recycled PET and PP fibres reinforced concretes [46]

Fig. 6 Comparison of RDPT results for concrete reinforced with steel mesh, steel fibre and PP fibre [70]

Fig. 7 Various types of plastic fibres for pull-out tests [78]

Table 1 Properties of macro plastic fibre reinforced concrete

Table 2 Example applications of the PET fibres reinforced concrete in Japan [41]

Table 1

Table 1 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 [55]	0.9mm 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 [54]	40mm x 1.4mm x 0.11mm	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

Table 2
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Table 2 Example applications of the PET fibres reinforced concrete in Japan [41]

Prefecture	Location	Concrete sprayed/ placed	Water/ Cement (%)	Fibre length (mm)	Volumetric content of fibres (%)	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

Figure 1
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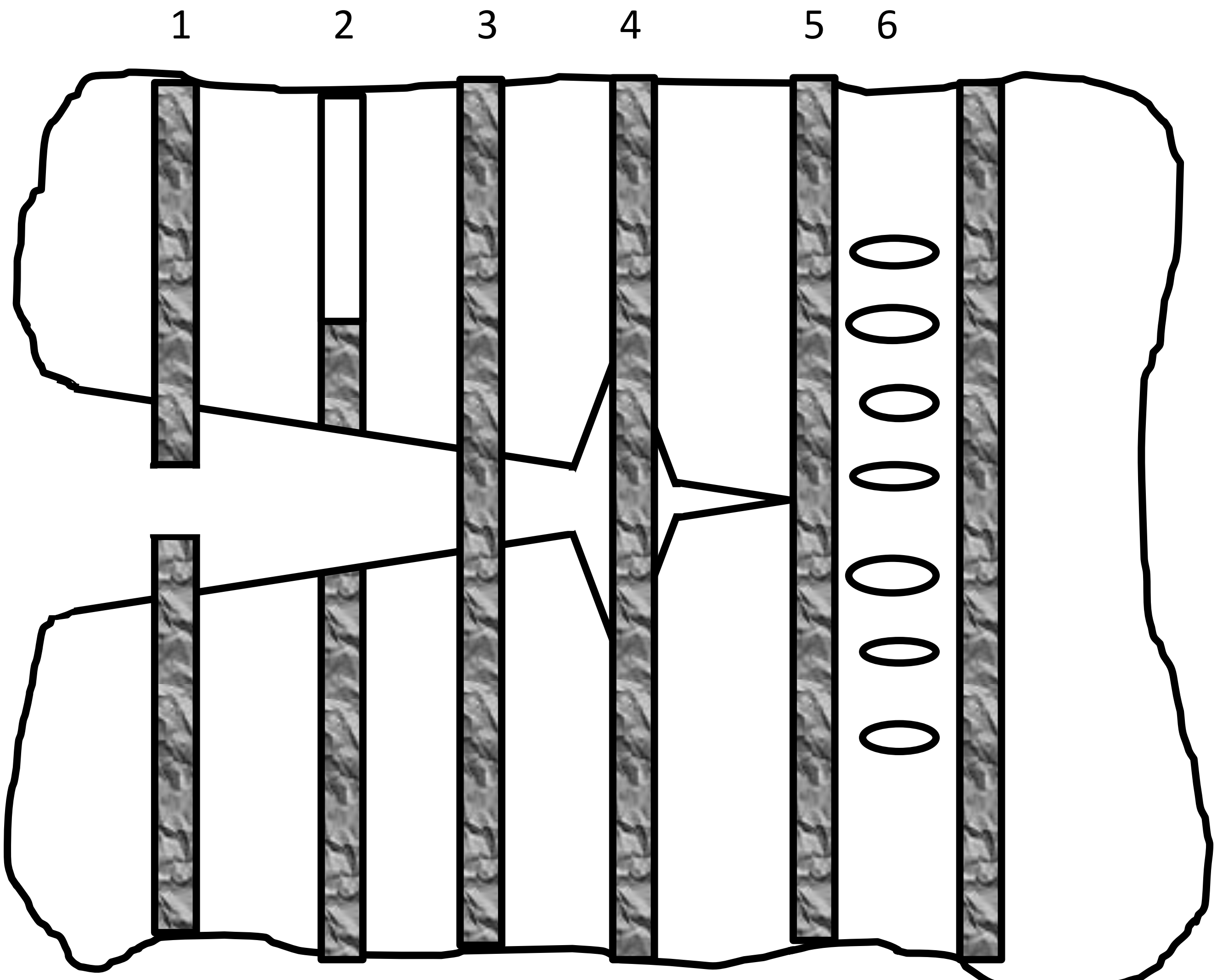

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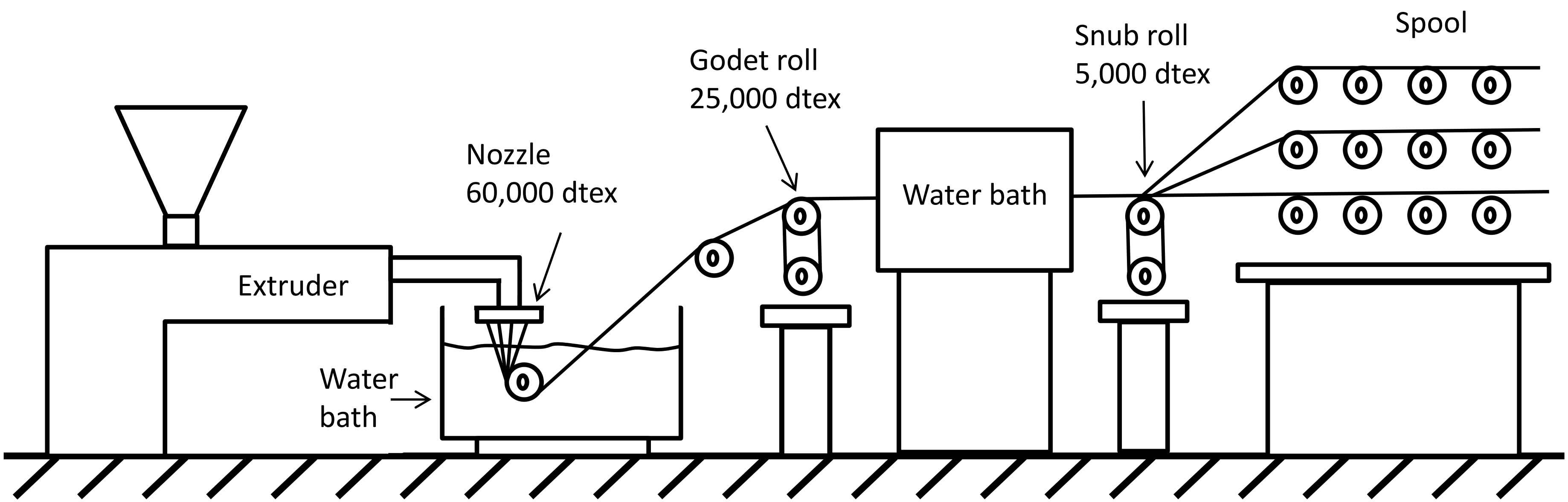

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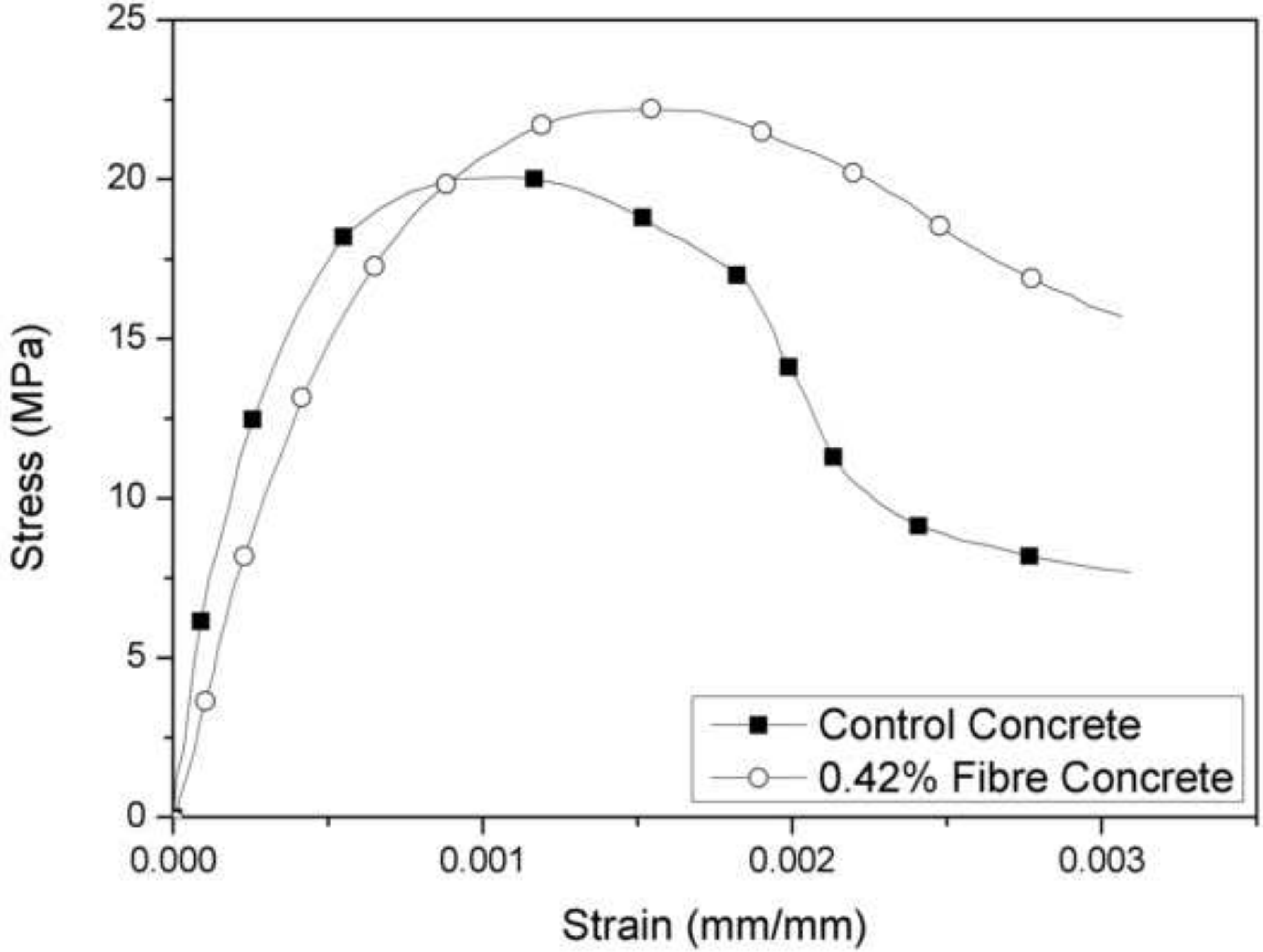

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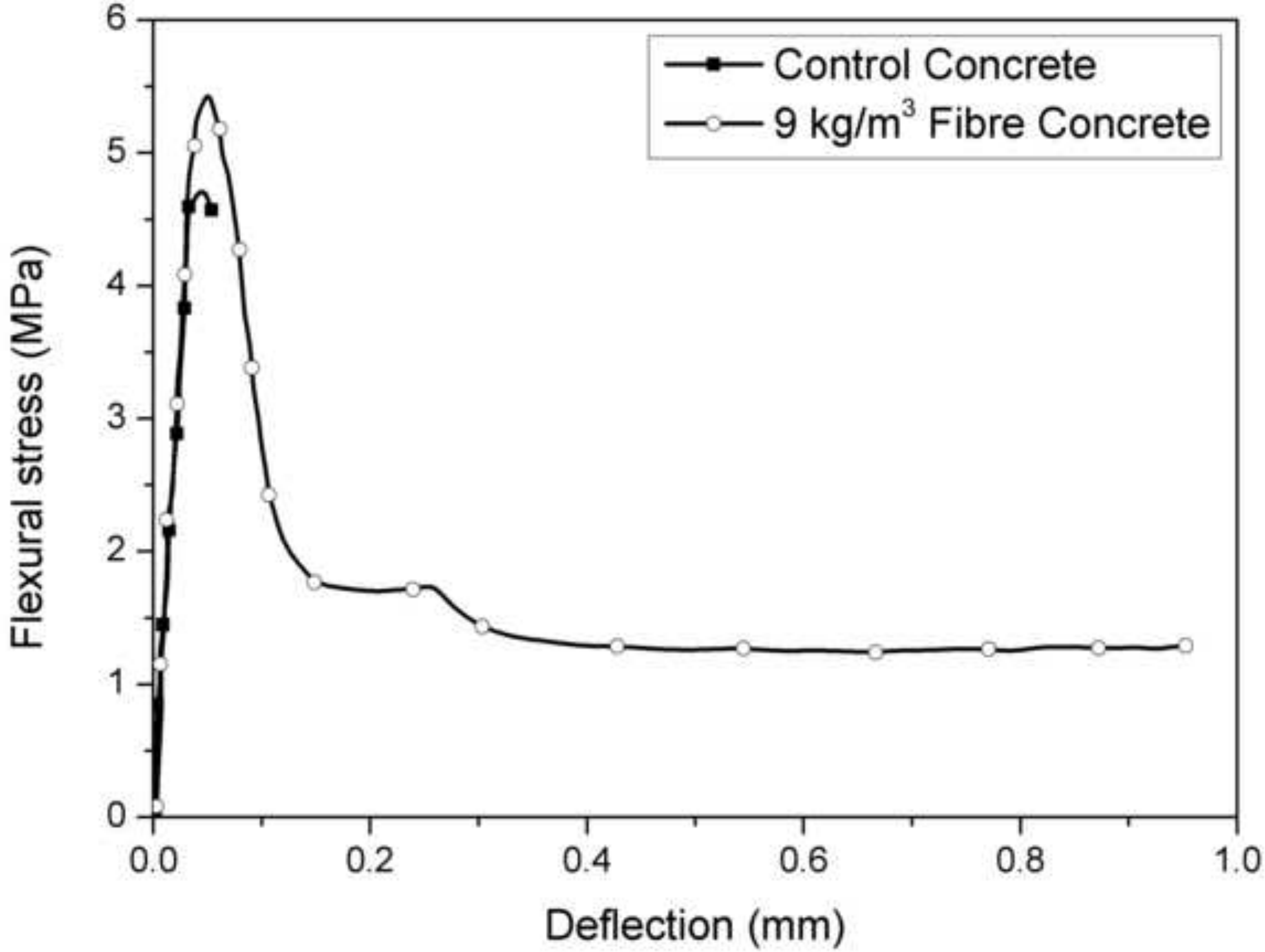

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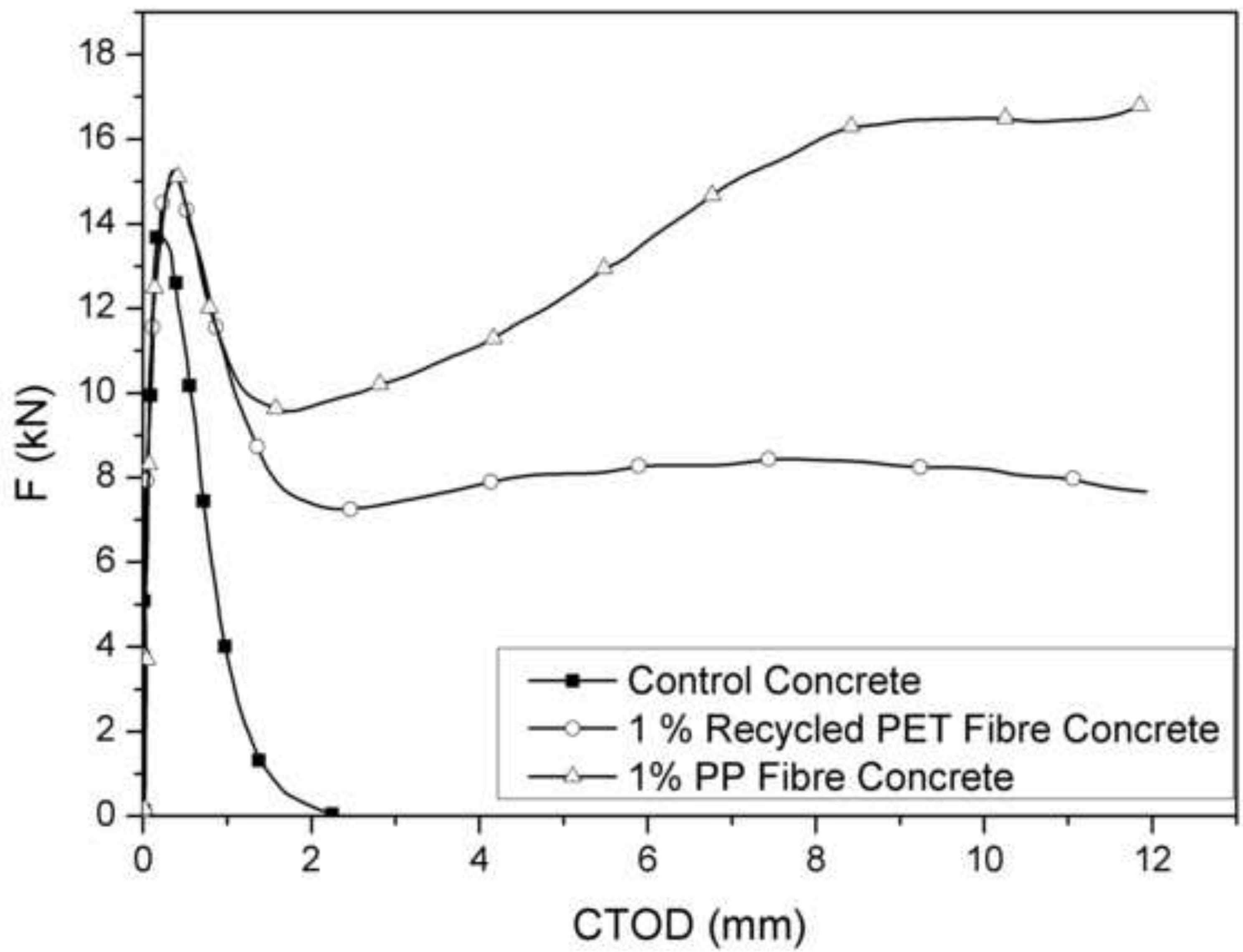

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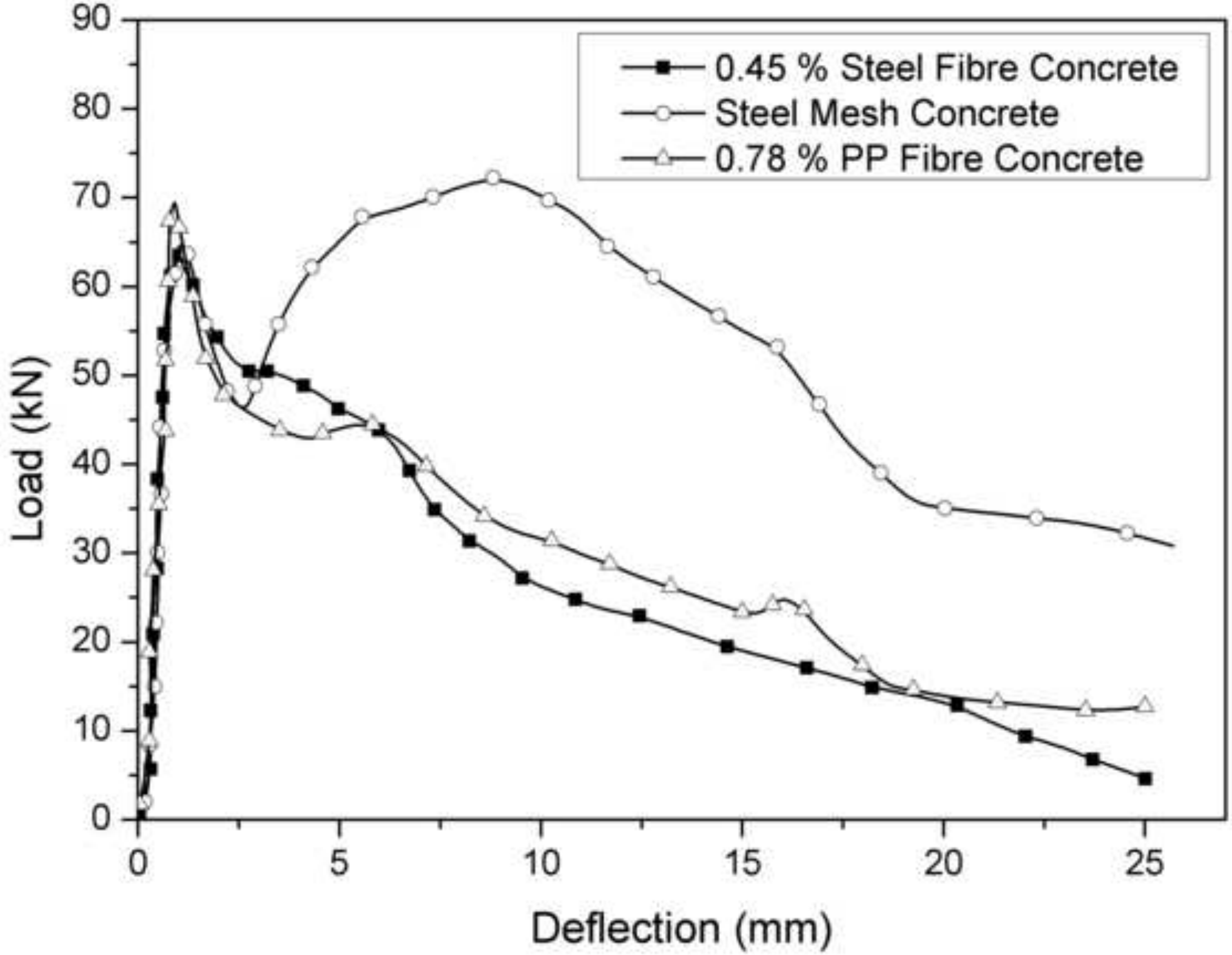

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