

TERESA ZYCH\*, WOJCIECH KRASODOMSKI\*

## POLYOLEFIN FIBRES USED IN CEMENTITIOUS COMPOSITES – MANUFACTURING, PROPERTIES AND APPLICATION

### WŁÓKNA POLIOLEFINOWE STOSOWANE W KOMPOZYTACH CEMENTOWYCH – METODY WYTWARZANIA, WŁAŚCIWOŚCI I ZASTOSOWANIE

#### Abstract

This paper presents the manufacturing and properties of three types of polyolefin fibres: monofilament and fibrillated polypropylene microfibrils and macro-synthetic (PP/PE) fibres – today, besides steel and glass fibres, these are the most widely used fibrous reinforcement of cement composites. Different types of fibres result from various methods of improving the low modulus of elasticity and poor adhesion of PP fibres (chemically inert) to the cement matrix. These methods are also described in the paper.

*Keywords: polypropylene fibres, polyolefin fibres, macro-synthetic fibres, fibre reinforced cementitious composites, fibre-matrix bond strength*

#### Streszczenie

W artykule przedstawiono metody wytwarzania i właściwości trzech rodzajów włókien poliolefinowych: mikrowłókien polipropylenowych elementarnych (przędzy) i fibrylowanych oraz makrowłókien syntetycznych (PP/PE), stosowanych obecnie najczęściej (obok włókien stalowych i szklanych) jako zbrojenie włókniste kompozytów cementowych. Występowanie kilku typów włókien wynika z różnych metod poprawiania niskiego modułu sprężystości i słabej przyczepności włókien polipropylenowych (chemicznie obojętnych) do matrycy cementowej. Metody te także opisano w artykule.

*Słowa kluczowe: włókna polipropylenowe, włókna poliolefinowe, makrowłókna syntetyczne, fibrokompozyty cementowe, wytrzymałość połączenia włókno-matryca*

\* Ph.D. Eng. Teresa Zych, Institute of Building Materials and Structures, Faculty of Civil Engineering, Cracow University of Technology.

\*\*Ph.D. Wojciech Krasodomski, Department of Additives and New Chemical Technologies, Oil and Gas Institute – National Research Institute.

## 1. Introduction

Polyolefin fibres, like steel and glass fibres, are commonly used today to reinforce cementitious materials. Fibres made from **polyolefins**: polypropylene and polyethylene (Fig. 1) are the most popular polymer (synthetic) fibres for concrete. Polyolefins, along with other polymers from which fibres are produced, such as 'polyester, nylon, PVA, polyacrylic, aramids and blends of them', are listed in the standard EN 14889-2 'Fibres for concrete – Part 2: Polymer fibres' [35].

At present, there are three types of polyolefin fibres (polypropylene-based fibres) available:

- two types made from **polypropylene**, different in shape: **monofilament microfibrils** (monofilaments) – individual extruded fibres, cut from a yarn (bundles of several fibres) and **fibrillated** (net-shaped) **microfibrils** – cut from an extruded sheet (tape), both covered with a special surface finish,
- one type made from **polypropylene** and **polyethylene**: **macro-synthetic fibres** (bi-component macrofibrils) (individual extruded fibres).

Hence, polyolefin fibres represent all classes of fibres specified in the standard EN 14889-2 for polymer fibres [35]:

- class Ia fibres – microfibrils having a diameter less than 0.3 mm, mono-filamented;
- class Ib fibres – microfibrils having a diameter less than 0.3 mm, fibrillated;
- class II fibres – macrofibrils having a diameter larger than 0.3 mm.

Class II fibres are distinguished as structural fibres, which affects the load-bearing capacity of the fibre reinforced concrete element – 'class II fibres are generally used where an increase in residual flexural strength is required' [35].

These three types of polyolefin fibres offered today have been obtained through the reduction of typical drawbacks of the first produced monofilament polypropylene fibres – specifically, the **low modulus of elasticity** of the fibres and **poor bonding** of the fibres with the cement matrix. Monofilament polypropylene fibres, first used as the fibrous reinforcement of cementitious composites by Goldfein a few decades ago (in the 1960s) [12], have been further improved. The changes in the **material**, surface (**texture**) and **shape** of fibres, introduced over the years to provide better mechanical properties and durability of polypropylene fibre reinforced cement composites (PFRC), are described in this paper. The experimental studies concerning PFRC are still carried out by research centres and universities. The paper contains up-to-date information on polypropylene microfibrils and high-performance macro-synthetic fibres (their manufacturing, properties and the range of application).

## 2. Polypropylene-based fibres versus other types of polymer fibres

Polypropylene-based fibres: polypropylene microfibrils (monofilaments and fibrillated fibres) and polyolefin macrofibrils (also known as macro-synthetic fibres or bi-component macrofibrils), used today as the reinforcement of cementitious composites, are characterised by Young's modulus of 2–10 GPa. Microfibrils, having a modulus of elasticity in the range of 2–5 GPa, belong to the group of low-modulus polypropylene fibres whereas macrofibrils are

high-modulus polypropylene fibres (5–10 GPa). However, Young's modulus for both types of polypropylene fibres is still not higher than that for the cement matrix (10–40 GPa) [4, 10]. The tensile strength is in the range 150–500 MPa for polypropylene microfibrils and 470–690 MPa for polyolefin macrofibrils. These mechanical parameters are lower than for other types of polymer fibres (Table 1).

Table 1

**Properties of fibres [3, 4, 6, 7, 10, 11, 18, 40–56, 59–62]**

Type	Density (specific gravity) [kg/dm <sup>3</sup> ]	Diameter or thickness [μm]	Length [mm]	Modulus of elasticity [GPa]	Tensile strength [MPa]	Failure strain [%]
Monofilament polypropylene microfibrils	0.90–0.91	15–50	6–20	2–4	150–400	–
Fibrillated (chopped film) polypropylene microfibrils		30–100	6–51	~5	300–500	10
Polyolefin (polypropylene/polyethylene) macrofibrils	0.91–0.97	~800–1100	30–65	5–10 (embossed fibres: 8–10)	470–690 (embossed fibres: 550–690)	15–25
Polyethylene HD filament	0.96	900	3–5	5	200	–
Polyethylene HD high-modulus	0.96	20–50	continuous	10–30	>400	>4
Polyacrylonitrile (PAN)	1.16	13–100	6	17–20	900–1000	8–11
Polyvinyl alcohol (PVA)	1.3	3–15	2–12	12–40	700–1500	2–6
Aramid (aromatic polyamide)	1.20–1.45	10–15	5-continuous	70–130	2900–3500	1.8–5.0
Steel	7.85	100–1000	30–60	210	500–2000	0.5–3.5
Carbon	1.16–1.95	7–18	3-continuous	30–390	600–2700	0.5–2.4
Basalt	2.6–2.8	9–24	5–50	85–90	1700–4800	2.5–3.1
Glass AR (alkali resistant)	2.6–2.7	12–20	10–50	70–80	600–2500	1.5–4.5
Asbestos	2.6	0.02–30	5–40	160	200–3500	2–3
Cement paste	2.0–2.2	–	–	10–40	3–6	–

**Aramid** (aromatic polyamide) fibres, the strongest polymer fibres, are characterised by the modulus of elasticity of 70–130 GPa and the tensile strength of ~3000 MPa. Other polymer fibres have the following mechanical properties (Young's modulus and tensile strength, respectively): 12–40 GPa and 700–1500 MPa for **polyvinyl alcohol** (PVA) fibres; 17–20 GPa and 900–1000 MPa for **polyacrylonitrile** (PAN) fibres; 4–8 GPa and 300–900 MPa for **nylon** (polyamide) fibres; 1–5 GPa and 400–1100 MPa for **polyester** fibres; 10–30 GPa and above 400 MPa for **high-modulus HD** (high density) **polyethylene** fibres; and 5 GPa and 200 MPa for HD **polyethylene** fibres (by comparison, the values of Young's modulus and the tensile strength for **steel** fibres are as follows: 210 GPa and 500–2000 MPa, respectively) [6, 10, 18, 53, 55].

Such large differences in the modulus of elasticity and the tensile strength between polymer fibres result from both the variety of material (polymer) and the varied methods used to manufacture the fibres.

Polymer fibres are produced through the process of extrusion and spinning [10, 18, 21]. At the beginning, the raw polymer is transformed from solid to liquid. Depending on the type of polymer, this transformation is achieved either by dissolving or melting. Synthetic polymers (**aramid**, **vinyl** and **acrylic** polymers) are dissolved in a suitable solvent whereas **polyolefin** (polyethylene, polypropylene), **nylon** and **polyester** polymers are transformed into molten liquid. A spinneret consisting of many holes is used to extend the liquid polymer, which then solidifies into continuous filaments (Fig. 1). After spinning, the filaments undergo further extension in the longitudinal axis (drawing process) increasing the level of orientation of molecular chains within the filament structure. By aligning (orienting along one direction) the molecular chains, high-strength and high-modulus fibres can be produced. In the manufacturing process, the technological factors (the speed of attenuation, the melting point, cooling time and many other factors) are strictly controlled since small deviations lead to significant changes in the basic properties of the fibres, and thus, in their performance characteristics.

The method of spinning (gel, wet, dry and melt spinning) and the type of drawing (hot and cold drawing) depends on the type of fibres [18, 21].

For solute polymers, three types of spinning are used. These are gel, wet and dry spinning. **Aramid** and **PVA** fibres are manufactured by gel spinning whereas **acrylic** fibres are produced by both wet and dry spinning. Melt spinning is used to obtain **polyolefin**, **nylon** and **polyester** fibres.

In **gel spinning**, the polymer chains (in the polymer solution) are not completely separated into a totally liquid state but are bound together locally to form so-called 'liquid crystals' – this results in strong inter-chain forces in the extruded filaments. During the extrusion process the liquid crystals are aligned along the fibre axis (by the shear forces). The high degree of orientation of polymer chains is achieved through this method, which allows the obtaining of stiff and strong fibres. Gel spinning is also described as dry-wet spinning since the filaments first pass through the air and are then cooled in a liquid bath [18]. This method of spinning is also used to manufacture **high-modulus polyethylene** fibres (in this case, a precisely heated gel of polymer is extruded through a spinneret).

In the case of **wet spinning**, the polymer solution is forced (by a spinning pump) through the spinneret, which is submerged in a chemical bath and the polymer precipitates in the

chemical bath (the polymer solution is converted to a gelatinous state and finally to a solid state) due to the action of diffusion processes. Regarding **dry spinning**, instead of precipitating the polymer by chemical reactions, the solidification of filaments is achieved by evaporating the solvent in a stream of air or inert gas.

In **melt spinning**, a spinning pump forces the molten polymer (not the polymer solution as in wet spinning) through the spinneret to form the filaments which are then solidified by air-cooling (see Fig. 1 and Sections 3.1, 4.1, 5.1).

The filaments are then subjected to the process of drawing, which is very important for improving their mechanical properties. Depending on the surrounding temperature during the process, there are two types of drawing. These are hot and cold drawing. High performance fibres require a high temperature during drawing, for example over 400°C for aramid fibres (**hot drawing**), whereas polypropylene fibres, nylon fibres, etc. are drawn without applying external heat or at a temperature no greater than about 70°C (**cold drawing**) [10, 21, 40].

As the result of the advanced processes described above, fibres that can provide effective reinforcement for cementitious composites are obtained. Nevertheless, due to expensive manufacturing methods (such as gel spinning and heat drawing), the **price** of high performance fibres (aramid fibres, PVA fibres, PAN fibres) with **aligned chain microstructures** is currently too high for their common use in cement composites [10]. All high performance fibres have been investigated for use in fibre reinforced composites but only PVA fibres are applied at present. Aramid fibres are used as the efficient reinforcement of FRP (fibre reinforced polymers [plastics]). Polyacrylonitrile (PAN) is a raw material used in the production of carbon fibres, the most popular reinforcement of fibre reinforced polymers. However, despite their high price, **polyvinyl alcohol** (PVA) fibres are used as the reinforcement of cement composites (e.g. bendable concrete, known also as Engineered Cementitious Composite [ECC]), because in addition to their relatively high modulus of elasticity and tensile strength (12–40 GPa, 700–1500 MPa, respectively), they are characterised by their strong chemical bond with the surrounding cement matrix due to their hydrophilic nature [10, 24].

As regards the application of other polymer fibres as the reinforcement of cementitious composites, only polypropylene-based fibres are commonly used.

**Acrylic** and **polyester** fibres are not stable in the high pH environment of most cement-based matrices and are thus unsuitable for cementitious materials.

The mechanical properties of **nylon** fibres are comparable to those of polypropylene fibres (see Table 1). There is some interest in using nylon fibres as a replacement for polypropylene fibres but its commercial use is not widespread [53, 55].

**Polypropylene** fibres have a number of advantages and also some weak points. Comparing their non-mechanical properties with **steel** fibres (the most popular non-polymer fibrous reinforcement of concrete), they are cheaper and lighter (density of about 0.9 kg/dm<sup>3</sup> for polypropylene fibres compared with 7.85 kg/dm<sup>3</sup> for steel fibres) (Table 1). Since polypropylene fibres are **chemically inert**, their durability in corrosive environments is excellent. Polypropylene fibres are **non-rusting**, unlike steel fibres which may corrode in cracked concrete. They are unaffected by both alkalis found in cementitious composites and acids and salts [4, 10, 41, 42, 51]. Polypropylene fibres are **not metallic** – this property is vital in, for example, hospital rooms with specialized devices that require non-metallic environments in which to function [41, 51, 61].

Despite the benefits mentioned above, polypropylene fibres also have some disadvantages. Apart from the low modulus of elasticity (stiffness) and the tensile strength, they are susceptible to **degradation by ultraviolet (UV) radiation** (sunlight), but the concrete matrix efficiently protects them [15]. The **melting point** of polypropylene fibres is around 165°C, which is relatively low compared with other fibre types (e.g. 220°C for PVA and nylon fibres, 260°C for polyester fibres, ~1500°C for steel fibres [18]). This may be a limitation in certain processes such as autoclaving. Polypropylene fibres are **hydrophobic**, thus, the bond with the cement matrix needs to be improved. Polypropylene fibres are **prone to creep** (have a tendency towards time-dependent deformation under constant load) as they are non-crosslinked thermoplastic polymer fibres [3, 10, 31].

Three types of polypropylene-based fibres which are different in composition, size and geometry are presented below. These are monofilament polypropylene microfibrils, fibrillated polypropylene microfibrils and macro-synthetic fibres. The manufacturing process, structure, properties and fields of application of these fibres are described in Chapters 3, 4 and 5.

### 3. Monofilament polypropylene microfibrils

Monofilament polypropylene fibres have been applied as concrete reinforcement since the 1960s [12]. In the 1970s, large research programmes were started to test the properties of cementitious composites with polypropylene fibres (used as the replacement of asbestos fibres) (Zonsveld J.J., 1975; Walton P.L. & Majumdar A.J., 1975; Hannant D.J., 1980 [4]). Monofilaments have been one of the popular fibrous reinforcements of concrete for more than 40 years.

#### 3.1. Manufacturing of monofilament polypropylene microfibrils

Monofilament polypropylene fibres are manufactured from 100% virgin, isotactic polypropylene (homopolymer). A **monofilament** is any single filament (known also as fibril or elementary fibre) which is spun individually. A **multifilament** is a yarn consisting of a group of monofilaments [6]. Monofilaments (fibrils) are produced through **melt spinning** (Fig. 1) [4, 10, 21]. This is an **extrusion process**, used for polypropylene and other thermoplastic polymers that can be melted (e.g. nylon, polyester).

The process of manufacturing consists of many stages (Fig. 1). At the beginning, polypropylene is converted into a liquid state and extruded through the orifices of a spinneret to form continuous filaments. The filaments are then solidified by cooling (e.g. in a blast of cold air). After the application of a special finish, the filaments are drawn in-line to several times their original length in order to improve the stress-strain characteristics of the fibres. By orientation of the molecular structure of the polymer in one direction (the alignment of the long polymer chains along the longitudinal axis of the fibre), high-strength and high-modulus organic fibres can be produced [10]. The degree of the alignment of the polymer molecules affects the properties of the fibres. The closer the molecules are packed together, the greater the strength properties of the fibre [21]. The fibre modulus of elasticity can

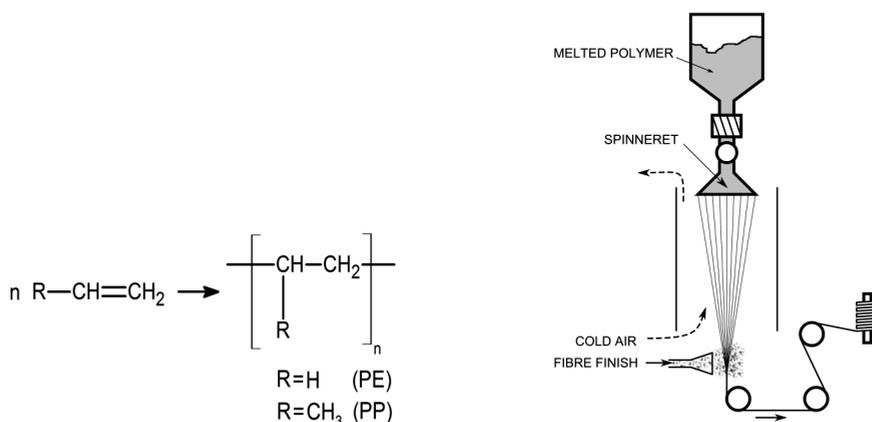


Fig. 1. Polyolefins (polyethylene – PE, polypropylene – PP); Melt spinning process [21, 59]

change in this process from around 2 GPa to 5 GPa or more [10]. The final stage is cutting the bundles (collected filaments) to the desired length.

The special fibre finish (coating), applied on the surface of the fibres, increases the wettability of fibres, enlarges the surface of fibres to improve the interfacial fibre–cement matrix bond and facilitates the dispersion of fibres in the cement paste [39].

### 3.2. Properties of monofilament polypropylene microfibres

The filaments (which are called staples after cutting) have different **lengths**. Monofilament fibres are available in the lengths of 3, 6, 12, 13, 18, 19 and 20 mm [40, 43, 47, 53, 55] (6 mm and 12 mm – long fibres are the most commonly used [42, 46, 51, 54, 61]) (Table 1). They are usually round in cross-section, ranging in **diameter** from 15  $\mu\text{m}$  to 50  $\mu\text{m}$  (usually 18, 32 and 38  $\mu\text{m}$  [43, 47, 51, 54, 61]) (Fig. 2).

Due to their finefilament nature, hair-like monofilaments are virtually undetectable on the surface finish of concrete [53]. They are widely used in aesthetically demanding concrete elements.

They are characterised by the **tensile strength** of 150–300 MPa (300–400 MPa for fibres providing the fire resistance of concrete [43, 47]) and **Young's modulus** of  $\sim$ 2–4 GPa [43] (Table 1).

Monofilament polypropylene microfibres are recommended as the secondary reinforcement to reduce **plastic shrinkage cracking in early-age concrete** [4, 6, 7, 10, 41–43, 47, 51, 53, 55, 61]. In young concrete, when its strength and stiffness are developed (the compressive strength of concrete is of the order of 3 MPa, the tensile strength is only 0.3 MPa and the modulus of elasticity is less than 5 GPa), the fibres, having higher Young's modulus than the base material (cement matrix), may reinforce concrete [17]. Monofilaments do not provide improvements to the properties of hardened concrete (e.g. in a concrete pavement), due to the low modulus of elasticity (2–4 GPa) when compared with concrete (30 GPa) and steel fibres (210 GPa) (tensile strength: 150–400 MPa for polypropylene fibres, 700–2000 MPa for steel fibres). They can be applied as the replacement for steel mesh.

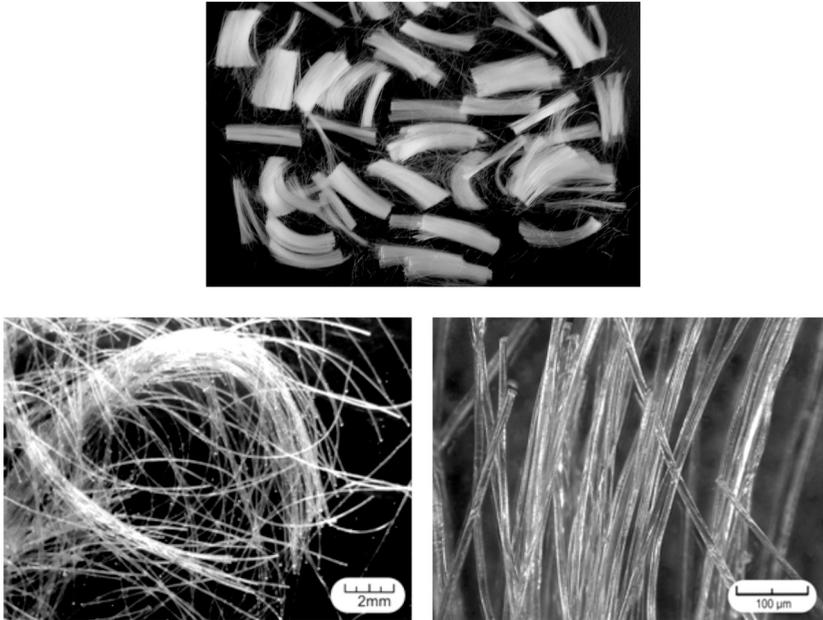


Fig. 2. Monofilament polypropylene fibres (10x, 200x) [51, 61]

Monofilament polypropylene fibres are added into concrete to increase its **fire resistance** (e.g. in tunnels) [4, 6, 10, 16]. The fibres protect concrete against **explosive spalling** (a rapid break-away of concrete fragments at very high temperatures, leading to the unveiling of the steel reinforcement and consequently, the loss of load-bearing capacity of the reinforced concrete element). High-performance concretes especially have a tendency to exhibit explosive behaviour under fire conditions. Spalling results from the high pressure of steam in the pores of concrete and, therefore, thermal stresses. At fire temperatures, the transformation of water (contained in damp concrete) into steam occurs. Steam which cannot escape causes high levels of internal pressure in concrete. A network of open pores (channels), formed after the melting of polypropylene fibres at a temperature of around 165°C, allows water vapour to escape so that the pressure of steam decreases and the internal stresses do not exceed the value at which the explosive destruction of concrete appears [4, 42, 45]. Fibres that are effective in reducing explosive spalling are very fine monofilament polypropylene fibres (18µm in diameter, 6mm long [43, 44, 46, 47]), used at the dosage of 1–3 kg/m<sup>3</sup> (with a modulus of elasticity of 2.3–3.9 GPa and the tensile strength of 300–400 MPa). Due to their dimensions and the extremely high number of fibres per cubic meter (more than 700 million per kg and typically also per cubic meter) [41, 43, 45, 47, 51], the fibres significantly increase the concrete durability in instances of fire. They are usually used in sprayed and precast concrete, e.g. in the lining of tunnels [45].

The **hybrid systems** of monofilament polypropylene microfibres and steel fibres (or fibrillated polypropylene fibres and steel fibres, or two different types of polypropylene fibres) are offered by manufacturers [51, 53, 61]. Blends of polypropylene and steel fibres

are used in order to combine the following benefits of both products: resistance to explosive spalling, improvements regarding plastic shrinkage provided by polymer fibres and structural improvements provided by steel fibres [6].

### 3.3. Application of monofilament polypropylene microfibres

Monofilaments are applied at the amount of 0.9–2 kg/m<sup>3</sup> [47] (usually 0.9 kg/m<sup>3</sup> (0.1% by volume) [47, 51, 54, 61] or 1 kg/m<sup>3</sup> [43]). The lower dosage (0.6 kg/m<sup>3</sup>) is also recommended [42, 43, 46, 47, 53]. The minimum amount of 2 kg/m<sup>3</sup> [46] is used in the case of very fine monofilament fibres providing resistance to explosive spalling in the case of fire.

Polypropylene monofilaments are used as the reinforcement (non-structural) of the following concrete elements/structures:

- stucco, screeds and other aesthetically demanding concrete elements (fine multifilament fibres provide strong cracking resistance with a smooth surface);
- thin-walled façade elements (panels, etc.);
- elements of ‘small architecture’;
- layers of repair reinforced concrete (shotcrete method);
- overlays, toppings;
- sidewalks, pedestrian paths, curbs, etc.;
- floors;
- tunnel linings;
- water retaining structures, sewer pipes, etc.;
- sea coast protection elements [4, 6, 10, 40, 43, 45–47, 51–53, 55, 61].

Fine polypropylene fibres are also applied as the components of various repair materials, which are produced on the basis of cement binder.

Since the 1990s, monofilament polypropylene fibres have been used to increase the **fire resistance** of concrete, e.g. in tunnel linings [10, 16, 41, 43–47] (see Section 3.2).

## 4. Fibrillated polypropylene microfibres

The modification of the shape of monofilaments (straight, individual fibres) in the 1980s and 1990s [12, 37] allowed for the formation of net-shaped fibres (fibrillated fibres). This has resulted in higher bond strength between fibres and the cement matrix and thus, better mechanical properties of fibre reinforced cement composites for the fibrillated fibres compared to the monofilaments.

### 4.1. Manufacturing of fibrillated polypropylene microfibres

Fibrillated (chopped-film) polypropylene fibres are manufactured from 100% virgin, isotactic polypropylene in an **extrusion process** of molten polymer using a rectangular die. The product of the extrusion is a polypropylene film (**sheet**), which is slit longitudinally into **tapes** after the application of a special finish (Fig. 1, 3). The tapes are then uniaxially stretched over specially designed roller pin systems [64]. The process of drawing out the

tapes results in an increase in the level of molecular orientation of the polymer and hence in the improvement of the mechanical properties of the fibres, however, this process leaves the tapes weak in the lateral direction. The final stages are splitting polypropylene tapes to achieve the main- and cross-fibril networks (Fig. 3) and cutting the bundles of slit tapes to the desired length. Fibrillated fibres, contrary to monofilaments, prevent balling because the bundles, separated into individual fibres during mixing, are evenly distributed throughout the cement matrix. High-precision fibrillation is crucial to ensure the uniform dispersion of fibres. The fibres also reduce the segregation of components of the concrete mixture.

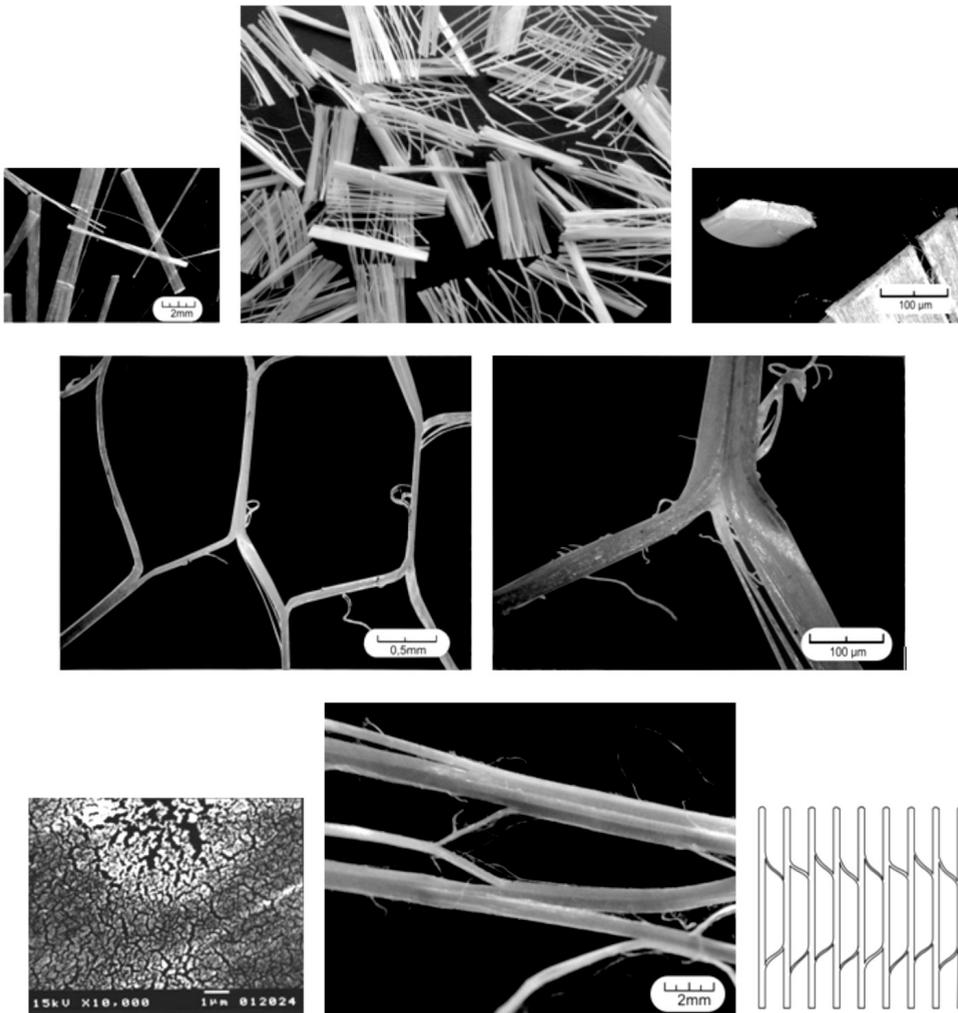


Fig. 3. Fibrillated (net-shaped) polypropylene microfibres (10x, 20x, 200x); surface of fibrillated polypropylene microfibres coated with a special substance (1000x) [37, 45, 51, 61]

A **net-like** physical structure of fibrillated fibres and the special fibre finish (coating) applied on the surface of fibres (as in the case of monofilament fibres; see Section 3.1) provide a good mechanical bond between the fibres and the cement matrix [39].

A very good mechanical anchorage has been obtained in the patented high tenacity polypropylene fibres (with an average cross-section of 30  $\mu\text{m}$  by 200  $\mu\text{m}$ ), having mechanical properties which are significantly better than in the case of fibrillated fibres (with a tensile strength above 500 MPa and a modulus of elasticity above 7 GPa) [4]. High performance polypropylene fibres are manufactured from the extruded tapes, which are split mechanically into single rectangular fibres in such a way that the edges of the fibres become uneven and frayed to induce a good mechanical bond with the cement matrix. The process of splitting has been highly controlled to change the size of the cross-section of the fibres and the degree of fraying. The width may vary considerably both from fibre to fibre and also along the individual fibre.

Fibrillated fibres made from 100% recycled polypropylene are also available on the market [53].

#### 4.2. Properties of fibrillated polypropylene microfibrils

The **geometry** of fibrillated polypropylene fibres (with a rectangular cross-section) is described by the thickness of the film (tape), ranging from  $\sim 30$   $\mu\text{m}$  to 100  $\mu\text{m}$  (35, 50, 80  $\mu\text{m}$  are the most common) and the width of individual filaments (fibrils), ranging from  $\sim 200$   $\mu\text{m}$  to 600  $\mu\text{m}$  (usually 330  $\mu\text{m}$ , 500  $\mu\text{m}$ ) [4, 10, 45, 47, 54]. The bundles consist of several filaments (fibrils) cross-linked together (Fig. 3) (as presented in Patent [37]).

Fibrillated polypropylene fibres are available in **lengths** from 6 to 51 mm (19, 38 mm are the most common) [10, 40, 45, 47, 51, 53–56, 61, 62].

An increase in fibre length may result in a higher bond [64]; however, longer fibres and a higher amount (dosage) of fibres provide a greater reduction in the consistency of the concrete mixture and thus workability of the concrete mixture decreases.

A network of fibrillated fibres eliminates bleeding, because the collated, bundled filaments (fibrils), **cross-linked** together, are uniformly distributed in the cement matrix during mixing with the other components of concrete [4, 6, 55, 56].

Fibrillated polypropylene microfibrils, as with other type of polyolefin fibres, provide strong adhesion when used in shotcrete; therefore, the **rebound** is lower than that in concrete without fibres and the application of thicker layers in one pass is possible [51, 56]. Moreover, they provide the resistance to fire-induced **explosive spalling** [45, 56].

Fibrillated polypropylene fibres are characterised by the **tensile strength** of 300–500 MPa (most often 300, 400, 500 MPa) and a **Young's modulus** of around 5 GPa (Table 1) [10, 45, 47, 51, 55]. They reduce the formation of cracks caused by **plastic** and **drying shrinkage** and **plastic settlement**. Therefore, they are applied as the secondary reinforcement of concrete. Polymer fibres cannot replace structural steel reinforcement, i.e. they cannot be used as the primary reinforcement providing post-peak strength and toughness [4, 10, 14, 47, 51, 53, 56, 61, 62, 64]. The fibres may be applied as an alternative to a welded wire mesh, e.g. in ground-floor slabs.

Lower amounts of fibres (less than around 1 percent of the volume fraction; see Section 4.3) are used to control shrinkage cracking in slabs, pavements, etc. which have large exposed surfaces that are highly susceptible to shrinkage cracking. The application of higher amounts of fibres may improve other properties of concrete such as **impact**, **abrasion** and **fatigue resistance**, etc. [40, 45, 51, 53–56]. For elements subjected to impact loading, the protection against initial cracking providing by the fibres is particularly important [6].

#### 4.3. Application of fibrillated polypropylene microfibres

Fibrillated polypropylene microfibres are usually used at the **dosage** of 0.1–0.2% by volume (0.9–1.8 kg/m<sup>3</sup>), most frequently in the amount of 0.9 kg/m<sup>3</sup> or 1 kg/m<sup>3</sup> [10, 45, 51, 53, 54, 62]. The maximum amount of 6 kg/m<sup>3</sup> for shotcrete is also given by the manufacturer [45].

The application areas of fibrillated polypropylene fibres are similar to that of monofilament polypropylene fibres [40–41, 45, 47, 51, 53–56, 61, 62] (see Section 3.3), since the properties of two types of polypropylene microfibres do not differ considerably. However, fibrillated fibres are recommended as the cracking reinforcement of, for example, ground-floor slabs and many prefabricated concrete elements [45, 51, 53, 61].

### 5. Macro-synthetic fibres

The weakpoints of polypropylene microfibres – their low modulus of elasticity: 2–5 GPa (by comparison, for steel fibres it is 210 GPa [10]) and their tensile strength of 150–500 MPa (for steel fibres this is 700–2000 MPa [10]) as well as the poor bonding of fibres (without the special fibre finish) with the cement matrix are improved in **macro-synthetic fibres**, also known as **monofilament polyolefin macrofibres**, **bi-component fibres** or **high performance macrofibres**. The modification of polypropylene microfibres, made in the **materials** that form a fibre and the **fibre morphology** allows the formation of macro-synthetic fibres. Macrofibres, first used as the concrete reinforcement in the mid-1980s [33], have been developed over recent years.

#### 5.1. Composition, manufacturing and structure of macro-synthetic fibres

Regarding the **materials** that form a fibre, macro-synthetic fibres are not mono-component fibres made of polypropylene (contrary to polypropylene microfibres), but they are made from modified polyolefins (usually polypropylene and polyethylene; 100% virgin resins). Macrofibres are mainly **bi-component fibres** [1, 45, 48, 62].

Macrofibres are produced by **melt spinning** in the process of extrusion of individual fibres (as with monofilament polypropylene microfibres; see Section 3.1).

The popular structure of macro-synthetic fibres is the **sheath-core** structure with one of the fibre components (core) surrounded by another component (sheath, also known as shell) (Fig. 4, 6) [18, 39].

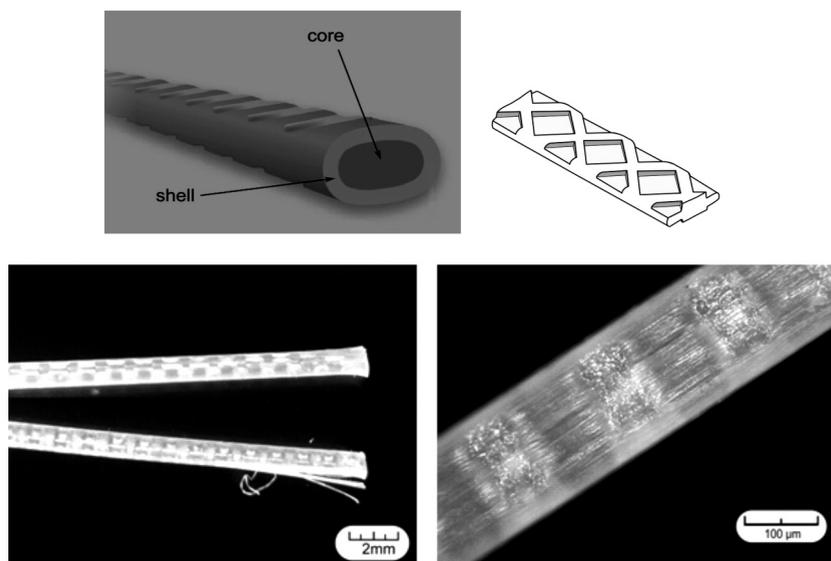


Fig. 4. Macro-synthetic fibres: bi-component, sheath-core (shell-core), embossed [45, 48]

Sheath-core fibres, described in Patent [39] (published in 2002), are monofilament bi-component fibres spun from two different types of polymers which are extruded side-by-side through a set of the holes [21]. As presented in Patent [39], sheath-core fibres may be fabricated with a ratio of sheath to core from 25:75 to 40:60 by weight. Moreover, a core should preferably be covered with a sheath on at least 90% of its surface; however, the percentage of a cover may be lower. Other structures of fibres, suggested in Patent [39] are **side-by-side**, **islands-in-the-sea**, **citrus type (segmented pie)**, depending on the arrangement of the polymer streams in the process of extrusion.

The material that forms an inner component (**core**) is a high strength and high E-modulus polymer or copolymer (also modified). The core provides the mechanical properties of the fibre. According to Patent [39], a core may be polypropylene or other polyolefins (linear high-density polyethylene, heterogeneously-branched linear low-density polyethylene, etc.), nylon, polyester or copolymers. The material used as a core should be compatible with sheath components. **Compatible** means that there is sufficient adhesion of the core to the sheath. The core, proposed in Patent [38] (published in 2015), is a polymer blend of polypropylene grafted with maleic anhydride as the first constituent (maleic anhydride ensures a very good chemical bond between the core and the sheath) and polypropylene or polyethylene as the second constituent.

The outer component (**sheath**) determines the strength of the bond of the fibre with the cement matrix. The sheath is made from materials that provide a strong **chemical** bond. As proposed in Patent [38], ethylene-vinyl alcohol (EVOH) may be used as the sheath. According to Patent [39], a strong bond may be achieved by the application of a fusing-fraying polymer as the sheath. The examples of sheath composition are as follows: 80%

polyethylene (low density of 0.913 g/cm<sup>3</sup>) and other constituents – 10% component A+10% component B or 10% component A+10% component C or 10% component B+10% component C; where component A refers to polyethylene grafted with maleic anhydride, component B refers to ethylene-styrene and component C refers to ethylene acrylic acid. Maleic anhydride and other additives provide very good chemical bonds between the sheath and the core as well as between the sheath and the cement matrix.

When macrofibres are made from only polypropylene (as **mono-component** fibres), specific **chemical compounds** should be incorporated into the base polypropylene resin before extrusion, as described in [2]. As polypropylene is chemically inert (polypropylene does not include functional groups that can chemically interact with the cement matrix), the added compounds provide a chemical bond between polypropylene fibres and the cement matrix through participation in the cement hydration reactions.

Experimental studies on the materials offering a good chemical bond have been carried out by many research centres and universities [2, 4, 6, 7, 10].

In the case of **mono-component** polypropylene macrofibres, not only the modification of a chemical bond by the addition of chemical compounds into polypropylene but also the increase in **wettability** (physical adhesion) of fibres by the application of a **special finish (coating)** on the surface of macrofibres (polypropylene is hydrophobic) may enhance the bond with the cement matrix, as in the case of microfibres (see Section 3.1) [10].

The materials that form a fibre have an influence on **chemical** and **physical adhesion**. Two types of adhesion together with the mechanical bonds, **mechanical anchorage** and **frictional bond**, determine the interfacial bond between the fibres and the cement matrix [19, 25, 64]. The mechanical bonds depend on the morphology of macrofibres – their shapes and textures.

## 5.2. Morphology of macro-synthetic fibres

The **fibre shape** and the **fibre texture** strongly affect the mechanical bond of fibres with the cement matrix and subsequently, the mechanical properties of fibre reinforced cementitious composites.

Regarding the **mechanical anchorage** of macrofibres with the concrete matrix, the bond may be achieved through **fibrillation**, **fraying** and the use of various geometric fibre **shapes**.

As described by Trottier et al. [28], **self-fibrillating** macrofibres can be made (Fig. 5) when two polymers applied as the core and the sheath of bi-component fibres are incompatible (typically, they should be compatible; compatibility of the components with each other and with the cement matrix provides strong chemical bonds – see Section 5.1). The monofilament, formed through the process of extrusion of a blend of two polymers (77% polypropylene and 23% high-density polyethylene) may fray when mixed with other components of the concrete mixture. The fibrillation occurs due to the immiscibility of the two polymers, which are separated from each other during mixing. Self-fibrillating fibres are characterised by a strong mechanical bond with the cement matrix [28].

The mechanical bond may also be obtained through **fraying** (partial fibrillation of the fibre). A fusing-fraying polymer, proposed in Patent [39] as a sheath, should have a lower melting point than a core polymer. This affects the behaviour of the core and sheath polymers

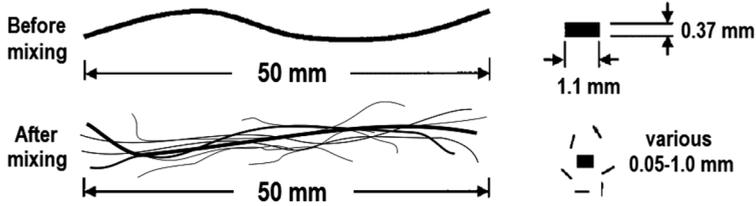


Fig. 5. 'Self-fibrillating' monofilament – fibre fibrillation and the change in dimensions before and after mixing [28]

during drawing. When the filament (fibre) is drawn, the two polymers extend to different degrees. During mixing with other constituents of the concrete mixture, the filaments fray at the ends into distinct fibrils. When fraying is too extensive, toughness of the fibre reinforced concrete can decrease. The controlled fraying overcomes the problem of inadequate bonding of large diameter fibres by giving them greater surface area to anchor to the cement matrix at the ends (Fig. 4, 6) [41, 45, 46, 48, 49]. Moreover, a lower melting temperature of the sheath compared to the core allows for melting of the sheath as the first and the fusing of filaments without substantially affecting the core polymer and thus without the changes in mechanical properties of fibre reinforced cement composites.

The mechanical anchorage strongly depends on the shape of fibres [20, 30]. The results of the investigations on the effect of the **geometry** of macro-synthetic fibres on the **interfacial bond strength** (known also as **interfacial shear strength** or **pullout strength**), conducted by Won et al. [30], in accordance with JCI SF-8 (Japan Concrete Institute) standard [36] are presented in Table 2.

Table 2

**Interfacial bond strength of macro-synthetic fibres with various types of mechanical anchorage [30]**

Fibre geometry ( $l = 50$ mm)	Mechanical anchorage type	Cross-section $b \times h$ [mm]	Interfacial bond strength $\tau_b$ [MPa]	$\tau_b / \tau_{b, \text{straight}}$
	Straight	$1.4 \times 0.7$	0.28	1.00
	Crimped	$1.4 \times 0.7$	1.82	6.50
	Twisted	$2.0 \times 0.7$	0.56	2.00
	Enlarged ends	Diameters: 1.0; 3.0	0.71	2.54
	Sinusoidal ends	$1.4 \times 0.7$	0.72	2.57
	Hooked	$1.4 \times 0.7$	0.40	1.43
	Double duoform	$1.4 \times 0.7$ ; $2.0 \times 0.7$	1.10	3.93

Interfacial bond strength, the parameter describing the mechanical anchorage of the fibres [13], has been calculated according to the formula given in standard [36]:

$$\tau_b = \frac{P_{\max}}{\pi d_{eq} l_e} \quad (1)$$

where:

- $\tau_b$  – interfacial bond strength (maximum) [MPa],
- $P_{\max}$  – maximum pullout load [N],
- $d_{eq}$  – equivalent diameter of fibre [mm],
- $l_e$  – embedded length of fibre [mm].

For all types of deformed fibres tested (crimped, twisted, enlarged ends, sinusoidal ends, hooked and double duoform), the interfacial bond strength is greater than for straight fibres (Table 2). The highest bond strength (1.82 MPa) was obtained for **crimped** fibres, this was more than 6 times higher than for straight fibres (0.28 MPa). High bond strength was also observed in cases of fibres with sinusoidal ends, fibres with enlarged ends and fibres with twisted forms; fibres with hooked ends are less effective. Pullout failure was noticed for fibres with sinusoidal ends and hooked fibres [30].

A comparative analysis of the bond strength of macro-synthetic fibres and steel fibres was carried out by Richardson et al. [22]. In the pullout test, performed according to the procedure described in the paper, the bond strength observed in the case of macro-synthetic fibres (40 mm × 1.67 mm × 0.095 mm, composed of 90% polypropylene and 10% polyethylene, characterised by a tensile strength of 620 MPa and a modulus of elasticity of 9.5 GPa) is 0.47 MPa whereas for steel fibres (50 mm long and 1 mm in diameter, cold drawn, hooked-end, with a tensile strength of 1100 MPa), a bond strength of 4.12 MPa was obtained.

Not only crimping, but also denting is recommended in Patent [38] (published in 2015) as a very useful method of increasing the bond of fibres with cementitious materials. Currently, the produced macro-synthetic fibres are deformed fibres: **embossed** fibres (more popular) with various textures (Fig. 4) [25, 41, 45, 47, 48, 51, 55, 61] and **crimped** fibres (Fig. 6) [41, 42].

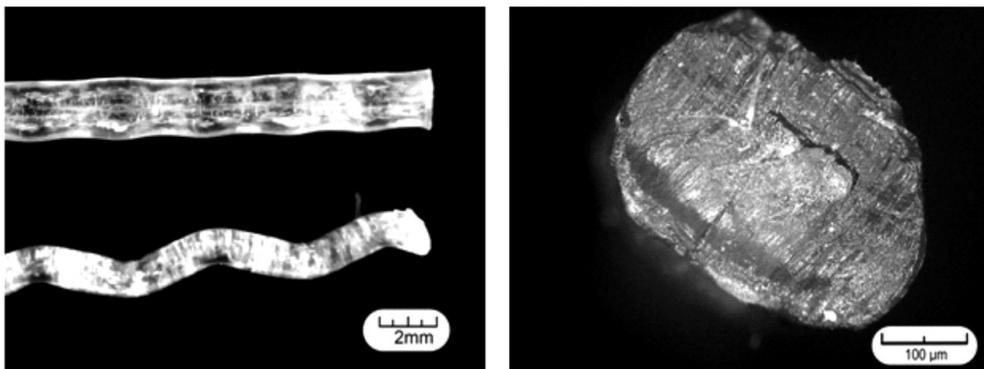


Fig. 6. Macro-synthetic fibres: crimped (10x, 200x) [41]

The use of embossed fibres, having a large lateral surface area, also results in a high **frictional bond** [25, 41, 47, 48]. Embossed fibres, which provide a strong interfacial fibre-cement matrix bond, are more effective than other types of macro-synthetic fibres.

The improvement in the frictional bond by the depositing of silica nanoparticles on the surface of polypropylene fibres (by sol-gel synthesis using ammonia as the basic catalyst) was proposed by Di Maida et al. [9].

Methods for the enhancement of the interfacial bond are constantly being developed.

### 5.3. Properties of macro-synthetic fibres

Macro-synthetic fibres differ from polypropylene microfibrils in their **dimensions**. They are larger than polypropylene microfibrils, with a diameter of ~0.8–1.1 mm (~0.8 mm or 1mm) and typically they are 50 mm long. Their diameters and lengths are similar to those of the steel fibres. Macro-synthetic fibres are available in lengths from 30mm to 65mm (the most common being 50 mm) [40–52, 54–56, 60–62].

The mechanical properties of macro-synthetic fibres are a **Young's modulus** from around 5 GPa to 10 GPa (crimped fibres – about 5 GPa; embossed fibres – 8–10 GPa) and a **tensile strength** of between 470 MPa and 690 MPa (crimped fibres – around 500 MPa; embossed fibres – usually 550 MPa) (see Table 1), which depend on the used polymers and the manufacture method; they are better in comparison with the properties of microfibrils [1, 4, 22, 40–52, 54–56, 60–62]. However, their Young's modulus (5–10 GPa) is not larger than that of cement concrete (about 30 GPa). Since 'reinforcing fibres are fibres that have Young's modulus higher than a base material' (according to the definition given in [4, 17]), macro-synthetic fibres should not be used as 'structural' fibres – the primary reinforcement of concrete, i.e. they should not replace steel structural reinforcement (steel rebars and/or steel fibres) (by comparison, the values of Young's modulus and the tensile strength for steel fibres are 210 GPa and 500–2000 MPa, respectively) [4, 10, 17, 43, 51, 52, 57, 58, 61].

As fibrillated polypropylene fibres, macro-synthetic fibres protect concrete against **cracking** occurring in the fresh and hardening concrete caused by plastic and drying shrinkage, plastic settlement, etc. [10, 17, 20, 49–52, 55, 56, 61, 62].

Regarding the behaviour of hardened concrete with macrofibres at **bending**, 'macro synthetic fibres provide some post-cracking or residual moment capacity but with significantly lower performance than steel fibres' – 'The Design Code for Concrete Industrial Ground Floor Slabs – TR34', by the Concrete Society; cited in [1]. The **post-cracking zone** in macro-synthetic fibre reinforced concrete depends on the **dosage** (see Section 4.4) and the types of fibres (materials, geometry, etc.) [20, 26, 41, 49, 50–52, 55, 56, 61, 62]. The example of the post-peak behaviour during the bending of 28-day concrete containing 2 kg/m<sup>3</sup> of 50 mm-long, bi-component (polypropylene-polyethylene) macro-synthetic fibres (characterised by a Young's modulus of 10 GPa and a tensile strength of 618 MPa) is presented in Fig. 7 [32, 45]. Comparing the load-deflection curves for concrete with steel and macro-synthetic fibres, steel fibres strongly enhance concrete after the peak load whereas macrofibres slightly improve fracture toughness of the brittle concrete matrix. Thus, macro-synthetic fibres can be recommended as a secondary reinforcement for crack control, but not for the structural load-bearing application.

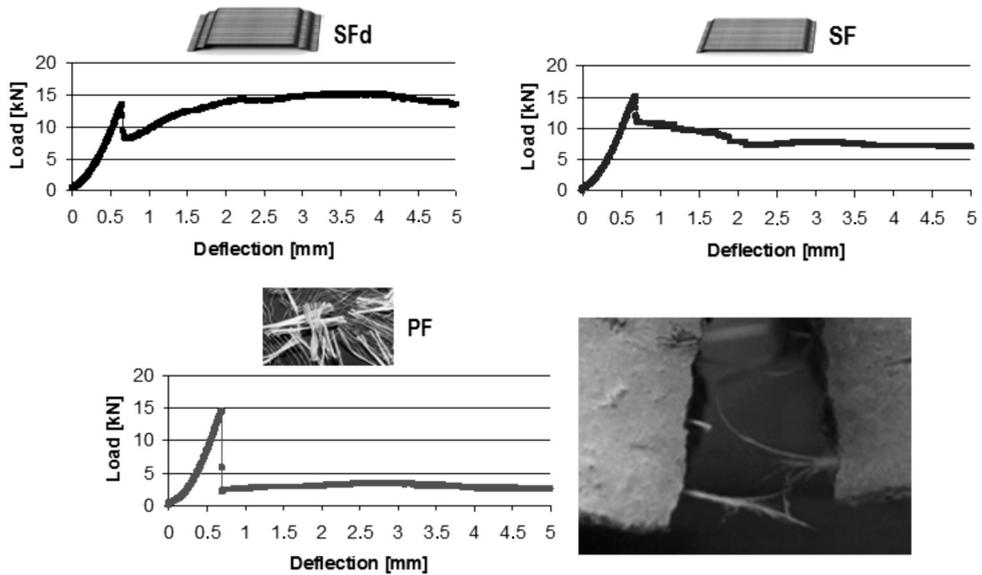


Fig. 7. Load-deflection curves recorded for 28-day concretes with bi-component (polypropylene-polyethylene) macro-synthetic fibres (PF),  $l = 50$  mm,  $E = 10$  GPa, tensile strength = 618 MPa,  $2 \text{ kg/m}^3$ ; steel fibres with single hooks (SF),  $l = 60$  mm,  $E = 210$  GPa, tensile strength = 1225 MPa; steel fibres with double hooks (SFd),  $l = 60$  mm,  $E = 210$  GPa, tensile strength = 2300 MPa; SF or SFd –  $30 \text{ kg/m}^3$ ; macro-synthetic fibres broken during the destruction of the beam [32]

As reported in [14, 26, 41–42, 46–52, 56, 61, 62, 64], macro-synthetic fibres improve not only flexural strength, but also **impact**, **fatigue** and **abrasion** resistance. The influence of the addition of macrofibres on the 28-day **compressive strength** of concrete is insignificant [10, 26, 32]. Increases in these mechanical properties of fibre reinforced concrete depend on the dosage of fibres (see Section 5.4) and their geometry [46–48]. However, macro-synthetic fibres are **prone to creep** (see Chapter 2).

In shotcrete applications, the fibres increase the compaction of concrete, reduce rebound and permit thicker layers per pass [49, 51, 55, 61].

Macro-synthetic fibres can reduce **spalling** of concrete at high temperatures [23, 48]. But, on the other hand, since macrofibres are **prone to heat damage**, they start to lose their mechanical properties as soon as the temperature reaches  $50^\circ\text{C}$ , by contrast steel fibres keep their mechanical performance up to a temperature of  $350\text{--}400^\circ\text{C}$  [43]. Synthetic fibres melt at around  $165^\circ\text{C}$  (the melting point ranges from  $159^\circ\text{C}$  to  $179^\circ\text{C}$ ). The ignition point is higher than  $450^\circ\text{C}$  (maximum  $590^\circ\text{C}$ ), depending on the type of fibres [48, 62]).

Macro-synthetic fibres are **non-magnetic**; therefore, they are widely used as concrete reinforcement in places where non-metallic materials are required, e.g. in hospital rooms equipped with specialist equipment [41, 51, 61].

Moreover, polypropylene-based macrofibres are chemically inert and provide excellent **corrosion resistance** – this allows their broad range of applications (see Section 5.4).

#### 5.4. Applications of macro-synthetic fibres

Macro-synthetic fibres are applied at a significantly higher **dosage** (2–10 kg/m<sup>3</sup>, depending on their application, this is frequently 5–7 kg/m<sup>3</sup>) than polypropylene microfibres (usually 1 kg/m<sup>3</sup>). The number of fibres, depending on the dosage, is 33000–62500 per kg [1, 4, 22, 45–48, 50, 55]. Macrofibres can be used as an alternative to welded steel wire mesh reinforcement which is used as anti-shrinkage reinforcement [41–43, 46–52, 55, 61, 62].

The advantageous properties of concrete reinforced with macro-synthetic fibres result in the application of these fibres in various concrete products, from architectural elements to structures exploited in harsh environmental conditions – they are also used when protection against spalling is required. Macrofibres are recommended as the reinforcement of concrete in the following concrete elements/structures [17, 23, 41–43, 46–49, 50–52, 55, 56, 61, 62]:

- precast or sprayed architectural elements such as cladding panels, elements of ‘small architecture’ and when complicated geometrical shapes are required;
- precast elements with fibres used as handling and transportation reinforcement;
- pathways, sidewalks, driveways, etc.;
- whitetoppings, pavements;
- external hardstandings, e.g. car parking areas, storage areas;
- floor slabs;
- sprayed concrete used for slope stabilisation, repair works, etc.;
- tunnel linings (e.g. mining, road tunnels);
- precast pipes, etc.;
- water tanks, etc.;
- tanks in sewage treatment plants, sewage tunnels, etc.;
- elements of marine structures.

Macro-synthetic fibres have been used as the non-structural (secondary) and structural (primary) reinforcement of concrete. The application of macro-synthetic fibres (e.g. in tunnel linings, slabs-on-ground [1, 8, 10, 23, 26, 29, 48]) as the only structural reinforcement of concrete (instead of steel rebars or steel fibres) is the subject of the wide discussion. There are many debates regarding the benefits that macro-synthetic fibres can offer and the fields of their application [5, 17, 22, 57, 58].

For structural applications of macro-synthetic fibres, the low E-modulus of these fibres (5–10 GPa compared to 210 GPa for steel fibres) is of great concern. Since the lower the Young’s modulus, the higher the deformation ( $\sigma = E\epsilon$ ), macro-synthetic fibres are characterised by large elongation which is much higher than for steel fibres [17]. Moreover, polymer fibres are prone to creep – they have a tendency to time-dependent deformation under constant load.

Therefore, the required tests for macro-synthetic fibre reinforcement concrete refer not only to determining load-bearing capacity, but also to the time-dependent properties of concrete, specifically, **creep behaviour** and crack width [17]. The reinforcing effect of fibres, observed, for example, in the standard beam test does not represent the long-term behaviour of concrete with macro-synthetic fibres, which are prone to creep. The real residual load-bearing capacity of bending elements can be significantly lower than the design value based on short-term strength assessment (15-minute test).

The experimental investigations conducted by Zerbino et al. on the time-dependent behaviour of pre-cracked macro-synthetic fibre reinforced concrete (PFRC) subjected to flexural loading [31] revealed significant creep of cracked concrete with polymer fibres. Moreover, the research has also shown that the application of loading-unloading cycles does not imply significant changes in the creep rate when compared to permanent loads of a similar magnitude.

Significant creep, and thus considerable crack widening over time, has also been observed for PFRC under uni-axial tensile sustained loading (Babafemi et al. [3]). The experimental studies have indicated that the fibre creep and the time-dependent fibre pull-out are the major sources of creep behaviour. Furthermore, the time-dependent crack widening has not been stabilized for 8 months, even at loads as low as 30% of the post-peak resistance [3].

Creep of macro-synthetic fibres leads to various crack widths thereby adversely affecting the serviceability and durability of concrete. It may cause failure of concrete at service loads [3, 17, 31].

However, the research conducted by Winterberg et al. [29] has shown that macro-synthetic fibres used in combination with conventional reinforcing bars are very effective in reducing crack widths generated in reinforced concrete elements as a result of flexural loading. Macrofibres are capable of bridging large cracks – they control crack widths to achieve the value below a permissible value of crack width for various environments (e.g. the tested macro-synthetic fibre reinforced concretes have reached the crack widths lower than 0.10–0.15 mm [29]). Thus, in reinforced concrete, flexural elements subjected to aggressive environmental conditions, macro-synthetic fibres, instead of steel fibres, are recommended to be used to reduce crack widths.

The study of creep behaviour of macro-synthetic fibre reinforced concrete in the cracked state is one of the main subjects of interest nowadays. Many research groups in the world are working on this matter. The development of test methods and the definition of parameters for its characterisation have become crucial points [3, 31].

## 6. Summary

Polypropylene-based fibres, the most popular polymer fibres used nowadays for the reinforcement of cementitious composites, are presented in this paper.

Various types of these fibres, polypropylene microfibres (monofilaments and fibrillated fibres) and macro-synthetic fibres (made from polypropylene and polyethylene), are the result of years of research in the petrochemical and textile industries and experience in the field.

The changes related to the material, the morphology and the surface of fibres, achieved by the selection of appropriate raw materials and the modification of the sophisticated production process allows the production of new generations of polypropylene fibres.

Individual, straight polypropylene microfibres (monofilaments), cut from a yarn (bundles of several fibres), have been modified by the application of the special fibre finish coating on their surface – this increases the wettability of fibres and enlarges the surface area of the fibres, thus improving the bond between the fibres and the cement matrix. Nowadays,

a fibre finish designed to obtain a rough surface of the fibres is commonly used for all types of polypropylene fibres. The precise fibrillation, achieved by the application of the patented methods, has changed the fibre shape. The fibrillated (net-shaped) fibres, formed during this process, achieve stronger mechanical anchorage to the cement matrix than monofilaments. Macro-synthetic fibres, the last generation of polypropylene fibres, are similar in their dimensions and shape to steel fibres. Currently, macro-synthetic fibres have been produced using two kinds of polyolefins (polypropylene and polyethylene) and various manufacturing methods to improve the mechanical bond of the fibres with the cement matrix (the frictional bond and the mechanical anchorage) and their chemical and physical adhesion. The structures of the macro-synthetic fibres, formed in the process of production, are sheath-core (popular) with one of the fibre components (core) (polypropylene) surrounded by another component (sheath) (polyethylene); side-by-side; islands-in-the-sea; citrus type (segmented pie). The mechanical anchorage of macro-synthetic fibres is achieved not only by fibrillation and self-fibrillation but also by fraying and the complicated shapes of fibres. Among the macrofibres of different shapes (straight, embossed, crimped, twisted, enlarged ends, sinusoidal ends, hooked and double duoforn), embossed and crimped fibres are those with the best interfacial bond strength. A strong chemical bond with the cement matrix is provided by the outer material (sheath) of bi-component macrofibres or by chemical compounds, incorporated into the base polypropylene resin in one-component fibres.

The details concerning the manufacturing processes, the properties and the application areas of all types of polypropylene fibres, as well as the other polymer fibres for the purpose of comparison, are provided in this paper. Moreover, the influence of the production process of the polypropylene-based fibres on their properties (modulus of elasticity, tensile strength, bonding with the cement matrix, etc.) and then on the long-term mechanical behaviour of both fresh and hardened concrete reinforced with the fibres (the formation of cracks caused by plastic and drying shrinkage, plastic settlement, service loading; the creep behaviour; etc.) is widely analysed.

This paper also presents the debates, reported in the literature, regarding the benefits that macro-synthetic fibres can offer and the fields in which they can be applied. The use of macro-synthetic fibres as a structural reinforcement of concrete has been the subject of intense debates.

These discussions highlight the need for further experimental studies on polypropylene-based fibres as the reinforcement of cementitious materials since these fibres, which are relatively cheap and have been in use for more than 40 years, are also 'fibres of tomorrow'.

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