Chapter 6

Polyolefin Fibres for the Reinforcement of Concrete

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Additional information is available at the end of the chapter

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Abstract

Given that concrete has limited tensile strength, it has been necessary to combine its properties with the use of steel bars. This resulted in the arrival of reinforced concrete which was the main solution used in structures in the last century. Partial or even full substitution of steel bars for fibres would not only allow the cost of a structure to be reduced but also provide certain improved properties. Modern fibre-reinforced concrete (FRC) now permits reduction or substitution of steel bars that has given rise to the commonly named structural FRC. Advances in the plastic industry during the last three decades have allowed the production of macro-polymer fibres as an alternative to steel fibres due to their chemical stability and lower weights for analogous residual strengths. After 30 years of research and practice, polyolefin-based macro-fibres have offered additional advantages such as safe handling, low pump wear and reduction in weight when transported and stored. This chapter provides an overview of the properties and structural capacities of polyolefin fibre-reinforced concrete (PFRC). Furthermore, the respective codes and test methods are examined. Moreover, the results obtained for structural design and the mechanical properties, found both in the literature and in practice, are supplied and discussed.

Keywords: self-compacting concrete, fibre-reinforced concrete, polyolefin fibres, steel fibres, fracture behaviour

1. Why polyolefin fibres?

The recent advances made in polymer science, chemical composition and engineering have increased the importance of polyolefins in day-to-day applications. Polyethylene and polypropylene are widespread polyolefins and the fastest growing polymer family due to the lower cost of production compared with the plastics and materials they replace [1]. Polyolefin fibres encompass a spectrum of uses in modern societies. The associated low costs, good resistance to chemicals, and high strength and toughness have encouraged the use. Their commercial advantages and disadvantages are listed in **Table 1**, although it should be noted that not all are applicable to the case of reinforcing concrete. In general, polyolefin fibres have good tensile properties, good abrasion resistance and excellent resistance to chemicals.

Regarding their use in concrete, the development of polyolefin-based synthetic macro-fibres with improved mechanical properties has extended the use of such plastic fibres beyond a conventional use in shrinkage-cracking control. Such synthetic macro-fibres have become an alternative to the traditional use of steel fibres in fibre-reinforced concrete (FRC) [3], forming what has been termed steel fibre-reinforced concrete (SFRC). The addition of randomly distributed steel fibres to concrete improves its low tensile strength and its brittleness enabling its use in industrial pavements or tunnels [4–6] among others. Based on the existing codes and standards [7–9], the contribution of the steel fibres has been considered in the structural design in recent years [10–12]. However, the recent concern of society regarding the environmental cost of materials, building processes and infrastructure refurbishment and rehabilitation has given rise to certain structures having a lifespan of up to 100 years. Therefore, the durability of materials has emerged as a key factor in the choice of materials. In such a sense, the potentially corrodible nature of steel fibres has aroused an interest in fibres that are not only chemically stable but also increase the mechanical performance of concrete. In addition, steel fibres are expensive for both purchase and in terms of storing and handling. Plastic industry in recent years has solved the aforementioned disadvantages allowing the production of a new generation of polyolefin-based synthetic macro-fibres that are inert in an alkaline environment and provide concrete with structural capacities to substitute steel reinforcement. Therefore, polyolefin fibres, which have good tensile properties, abrasion resistance, excellent

Advantages	Disadvantages
Low density (0.90–0.96 g/cm^3)	Low melting point (120–125°C for PE;
Good tensile properties	160–165°C for PP)
Good abrasion resistance	Prone to photolytic degradation
Excellent resistance to chemicals	Inferior shrink resistance above
Excellent resistance to mildew,	100°C
Micro-organisms and insects	Poor dyeability
Almost negligible moisture regain	High flammability
Good wicking action	Inferior resilience
High insulation	Significant degree of creep
Avoidance of dermatological problems	

Table 1. Commercial advantages and disadvantages associated with the use of polyolefin fibres [2].

resistance to chemical attack, and a reduced moisture regain, have emerged as an alternative to corrosive steel solutions that use steel-reinforcing mesh or steel fibres.

In order to consider these newly developed applications, in 2006 the European Committee for Standardization (CEN) approved the European Standard 14889 [13] which classifies the types of fibres that can be added to concrete. Such a recommendation divides the fibres into two groups: the first one deals with steel fibres and the second one polymer fibres. However, not all the characteristics that may be relevant in examining the performance of FRC were addressed. The recommendation defines the possible geometrical shapes and physical parameters of the fibres and establishes the procedures for the measurement of the fibre mechanical properties such as tensile strength or modulus of elasticity. In the case of polymer fibres, they are divided into two groups: non-structural micro-fibres and structural macro-fibres. The criterion used is their equivalent diameter, with it being classified into two types depending on whether its diameter is greater or smaller than 0.30 mm. **Figure 1** shows the classification of the fibres made by such a reference [13]. Polyolefin fibres with surface bulges and grooves along the fibre surface are produced from homo-polymeric resin into a mono-filament form [14] and, according to EN-14889, are classified as Class II macro-fibres.

Among the synthetic macro-fibres that can be employed in concrete, those made of high-density polyethylene (HDPE) boast a density of 0.95 g/cm^3 and a reduced tensile strength between

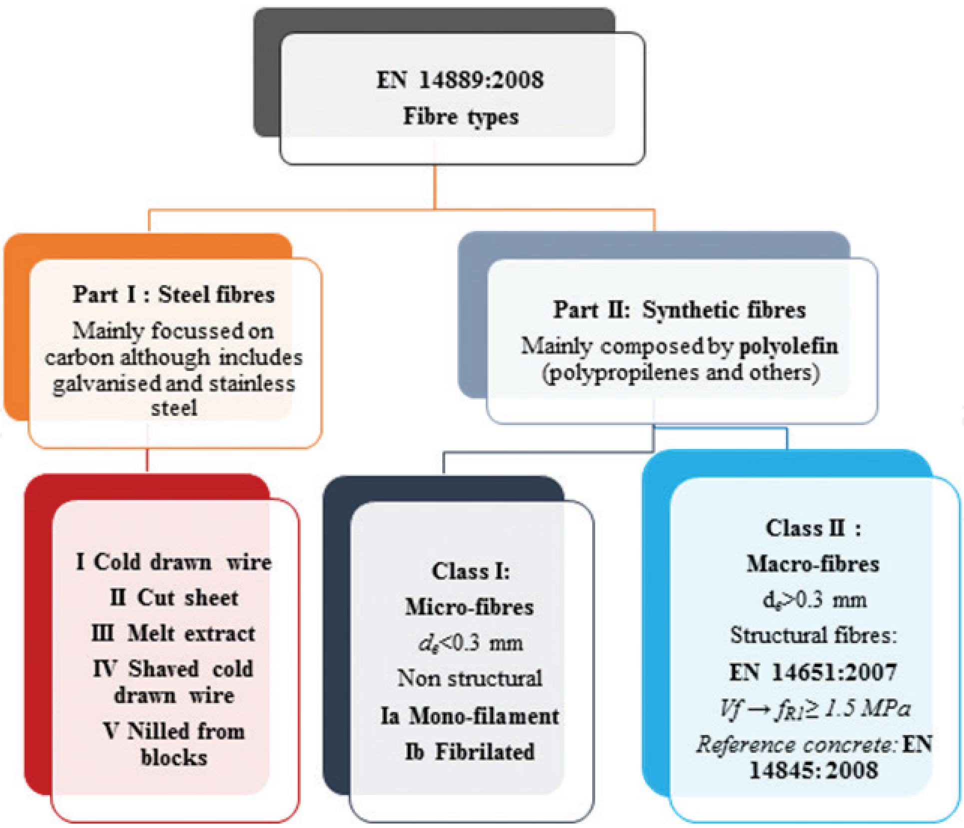

Figure 1. Fibre classification following EN-14889 [13].

25 and 40 MPa. These reduced mechanical properties hamper their use as a way to improve concrete mechanical properties. Nevertheless, other types that have been recently employed, which are manufactured with polyethylene terephthalate (PET), boast remarkable mechanical properties. Their tensile strength above 400 MPa might enable a successful use in concrete reinforcement but there are several issues reported [15]. Some that have been thoroughly studied are the difficulties found in their manufacturing process as well as their reduced resistance to alkaline environments [16, 17]. These two difficulties prevent their widespread use as a concrete reinforcement. Other types of macro-fibres that deserve being cited are those obtained from virgin and recycled polypropylene (PP). PP fibres have been widely used in the concrete industry, due to its ease of production, high alkaline resistance [18], and high tensile strength and Young's modulus [19].

Polyolefin fibres, which are among those considered PP fibres, enjoy an outstanding mechanical behaviour, their modulus of elasticity being of great relevance. The common value of such modulus is 9 GPa or even up to 15–20 GPa, which is much higher than certain other plastics that offer around 2–3 GPa. In addition, polyolefin fibres boast a tensile strength above 400 MPa. These remarkable properties have been obtained by using a bi-component fabrication strategy that combines two polymers: a core of high modulus and a sheath of low modulus [20, 21].

Another reason behind the remarkable performance of polyolefin fibres is the notable bond generated between the fibres and the concrete matrix due to their rough surface. This is provided for both the shape of the fibres and the mechanical interaction that takes place when the fibres are loaded. In such a sense, the interface fibre-matrix becomes rougher due to the damage of the fibre surface produced during the mixing process. Such roughening forms a mechanical interlock opposite to the relative movement of fibres after the cracks are initiated [22–24]. Concerning the fibre shape, the optimum macro-synthetic fibre geometry has also been sought. This involved exploiting the matrix anchorage fully without fracturing the fibres, and reaching the maximum pull-out resistance. In terms of bond, the crimped ones were the best among several deformed synthetic structural fibres [25, 26].

2. Fibre pull-out response of polyolefin fibres when added to concrete

Regardless of the type of fibre used, reinforcement is effective in concrete when the tensile strength of the fibre is significantly higher than that of concrete (two or three times), when the fibre-matrix bond strength is in the same order of magnitude of the tensile strength of the matrix, and the fibre modulus of elasticity in tension is significantly higher than that of the concrete [27, 28]. **Figure 2** shows the failure mechanisms of the fibres in PFRC.

At the optimum situation, the crack opening is controlled by 'fibre bridging' which has a portion of fibre on each side of the crack with enough embedded length and allows fibres to work at 100% without any slipping (number 3 in **Figure 2**). In such a situation, if the crack-growing process continues it is possible to make full use of the potential of the fibre up to its failure. On the contrary, if fibres slip during the opening processes, the debonding process may occur and the fibre may be pulled out. If one fibre is mobilized by friction shear stresses, it is possible that such stresses cause matrix cracking.

In order to determine which of the cases shown in **Figure 2** might emerge, the critical length (l_c) of the fibres used requires examination. Such a critical length has been defined as the length that allows the tensile strength of the fibre to be used without pulling it out of the matrix. In an ideal situation, when the fibre is being pulled out from the concrete matrix, two types of forces are applied to the fibre, preventing it from being extracted: the chemical adhesion in the inner part of the fibre and the frictional bond in the part of the fibre closer to the crack. A sketch of this can be seen in **Figure 3**.

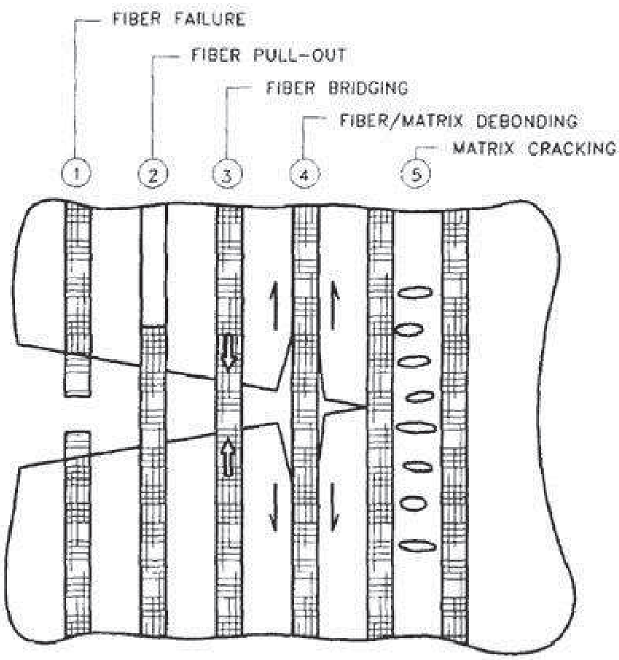

Figure 2. Energy absorbing the fibre matrix mechanisms [29].

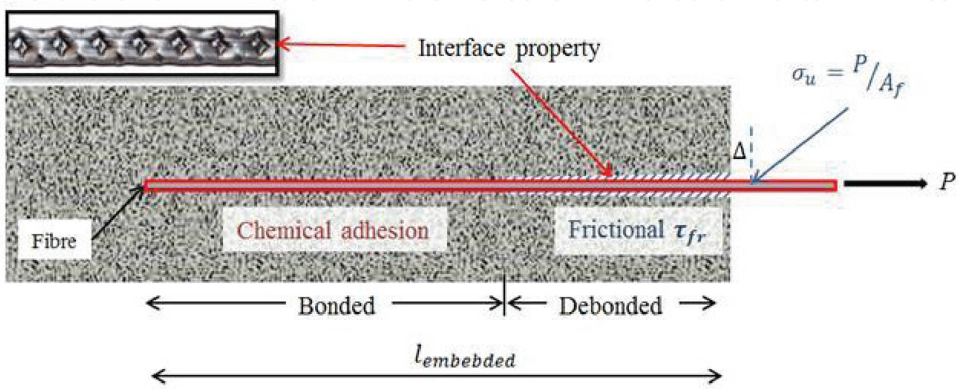

Figure 3. Pull-out mechanisms [8, 28].

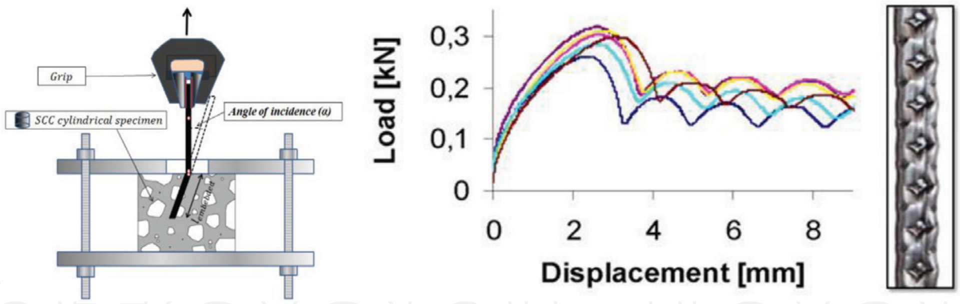

Figure 4. Set-up of pull-out test of a polyolefin-based macro-fibre made by [8] (left); pull-out test result (centre), typical embossed surface of a polyolefin fibre (right) [28, 30].

In the case of a certain type of polyolefin fibre, the test setup and the pull-out response obtained in the test can be seen in **Figure 4**. The results obtained depend on two variables: the embedded length and the angle formed between the fibre and the free surface of the sample. The amount of energy absorbed while pulling out of the fibre increases as the embedded length does. However, the effect of the angle between the free surface and the fibre has a minor effect in the total response of the system [8]. Apart from these two factors, the test results showed that the geometry of the embossed surface of the fibre has a major impact on the results. **Figure 4** shows how the load-displacement curves swing at a certain load level as a result of the fibre surface geometry.

The results obtained in the pull-out tests show that polyolefin fibres are apt for concrete reinforcement. How these micro-mechanisms are transferred into the macro-scale material behaviour will be explained in the next sections. Similarly, both the influence that the fibres have on the manufacturing process and the fresh state of the material will be shown in too.

3. Manufacturing of polyolefin fibre-reinforced concrete

Macro-fibre volumes currently used in FRC range from 0.3 to 1.5%. With such volume fractions, the procedure for mix proportioning can be essentially the same as that used for plain concrete [31]. While the addition of fibres does not affect the nature of the components of the mix, it does affect the mix workability. There are no limitations as regards the types of cement employed, although the most common one is a Portland cement without additions. Regarding the type of aggregates chosen, those rounded and crushed have been successfully used without encountering any disadvantage caused by interaction of the fibres and the aggregates [28]. The reduction of the concrete workability can be compensated with slight variations of the aggregate distribution, increasing the amount of fine fractions or even by adding or increasing the amount of admixtures. In any case, it is advisable to prepare trial mixes to achieve the final proportions. FRC can be manufactured, in general, with the same equipment and similar procedures merely by carefully studying the best mixing sequence to ensure that a good uniform dispersion of each type of fibres avoids segregations and balling of the fibres.

The cement content and the water/cement ratio are as decisive as in plain concrete. However, and in contrast to the cement content for SFRC, there is no general recommendation to increase the amount of cement weight used [32]. Such a difference is based on the bendable nature of polyolefin fibre in contrast to the stiffness of the steel fibres that result in a remarkable reduction of the concrete workability.

Regarding the fine/total aggregates relation, although there are no general recommendations it would be advisable to increase such a relation and limit the maximum aggregate size. For SFRC, it is usually accepted that the maximum aggregate size should not surpass 2/3 of the fibre length (the use of fibres two to five times longer than the maximum aggregate size is frequent) [33, 34]. Such guidelines should be followed and can be considered a valuable rule of thumb given that they enhance workability without affecting the hardened state properties. Moreover, if PFRC is placed by pumping it is recommended (as in the case of SFRC) that the amount of coarse aggregates employed be reduced by 10% [34]. While in the case of a steel fibre addition the possible effects between the proportion of fine aggregates and the fibre content for a given aspect ratio (l/d) have been clearly reported, in the case of polyolefin fibre such relations have not yet been clearly established due to the flexible nature of the fibres [35]. However, the use of between 40 and 60% of fine aggregates seems to be a fair option in obtaining satisfactory results. Above all, it should be noted that these recommendations are considered for fibre volumetric fractions below 2%. Above such values, in all probability the number of fibres added would severely change the fresh-state properties and obtain a heterogeneous distribution of fibres that would lead to a reduction of the properties of the concrete obtained. These precautions should not give the impression of a great modification of the fresh-concrete properties or even of a limited applicability of polyolefin fibres to high-performance concretes, such as high-strength concrete or self-compacting concrete (SCC) [36].

In the case of combining an SCC with an addition of polyolefin fibres, certain changes should be added to the proportions of the concrete constituents. Some design criteria [28, 37] focus on targeting a slump-flow diameter of 600 mm, with a recommended reference mixture being about 700 mm of diameter of the patty without fibres. Such rheology characteristics can be obtained by increasing the amount of cement and/or the proportion of fine aggregates by adding a fine material such as lime powder and using superplasticizer proportions of over 1% of the cement weight. In any case, due to the difficulty of obtaining an SCC, the aforementioned changes should be tested in laboratory preliminary mixes before in situ production. As may be easily understood, such changes in the concrete formulation have a remarkable impact on the final cost of the material. Similar to what happens in the case of a conventional concrete, the slump flow of SCC decreases with the addition of fibres depending on the type of fibre and its geometry. The addition of fibres in all cases alters the results of the fresh-state tests. If an excessive amount of fibres is added, obstruction of the flow and clustering of the fibres and/or aggregates may occur.

The mixing sequence employed for a vibrated conventional concrete (VCC) PFRC starts by carrying out a homogenization of the aggregates. The cement and the other fine components, if used, are then added to the mixer. Later, water and additives are added to the mix. In such a sense, some of the most common additives are superplasticizer and viscosity modifiers. Once the plain concrete is prepared, fibres are added to the mix and a thorough mixing is carried out in order to obtain a homogeneous distribution of fibres within the fresh concrete. This sequence has been altered on some occasions by adding the fibres directly after the aggregate homogenization with satisfactory results being obtained.

In the case of SCC with an addition of polyolefin fibres, due to the difficulty of obtaining such a type of concrete some changes should be made in the aforementioned procedure for obtaining satisfactory results. It is advised that fibres be added gradually during the mixing process. A third of the fibres should be added after the aggregate homogenization, another after adding the cement and lime powder, and the last one after pouring the water with the additives. It should be noted that the influence that the fibres have on the fresh properties of concrete might require supporting a final addition of superplasticizer to obtain the desired results in the fresh-state tests. Lastly, enough time should be left for the chemical additive to act which would mean that on some occasions the mix should rest for a few minutes in the mixer before emptying. **Figure 5** shows the procedure.

Regarding the placing method, if the mix is properly designed PFRC can be placed by external vibration, pumped or projected to pass through obstacles and with a good performance in hardened state. It is true that compacting FRC might be more difficult to achieve with high fibre contents if at least a descent of 9 cm in the slump test is recommended [28]. On another note, the placing conditions and the formwork geometries clearly affect the final properties of the hardened FRC because they influence the final positioning of the fibres [9]. Therefore, it is important to highlight that VCC and SCC moulds are not usually filled with FRC in the same manner. In such a sense, at the placing stage SCC improves the positioning of fibres in the pouring direction. Conversely, external vibration tends to align the fibres perpendicularly to the direction of vibration. Several test recommendations [38, 39] have fixed the procedure for casting the specimens and filling the moulds. Additionally, the standards establish that in the case of self-compacting concrete the mould should be filled in a single pour and levelled

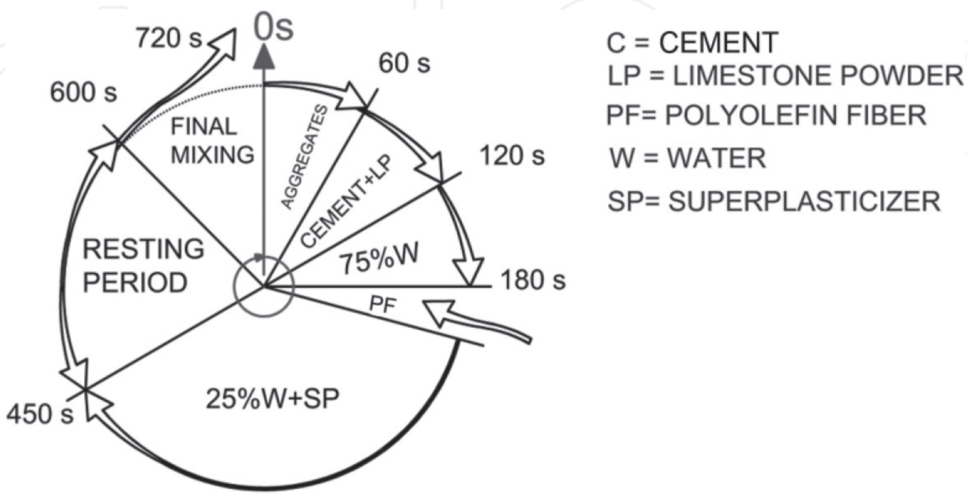

Figure 5. Mixing sequence of a polyolefin fibre-reinforced concrete.

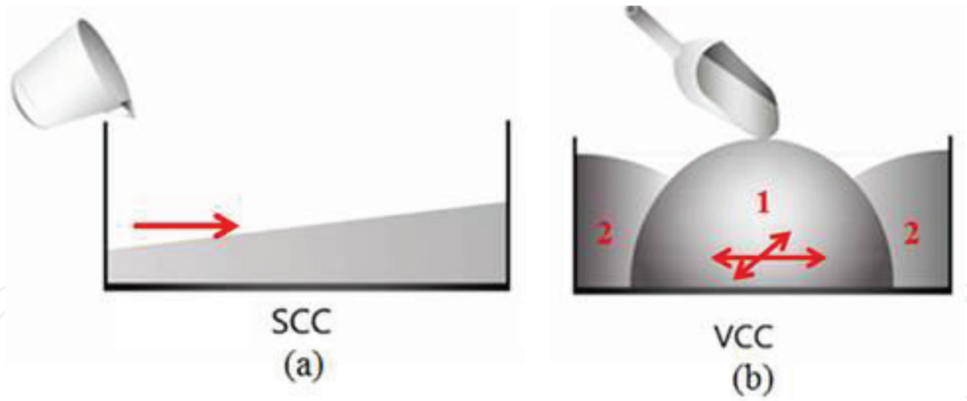

Figure 6. Filling methods for FRC: (a) flow method for SCC; (b) RILEM and EN-14651 Vibrated Concrete [38].

off without any compaction. The capacity of SCC to level itself enables the mould to be filled from one end to the other [30, 40]. **Figure 6** shows the procedures.

Once demoulded, as in the case of a conventional concrete, elements should be properly cured. In the case of laboratory specimens, they should be cured at 20°C and with a relative humidity above 95% until the age of testing.

4. Fresh and hardened concrete properties of polyolefin fibre-reinforced concrete

In the case of a VCC, the fresh-state properties are usually assessed by means of the slump test. It is clear that the presence of fibres hampers a normal behaviour of the material. Although it is true that as the amount of fibres grows, the viscosity of the PFRC increases it cannot be overlooked that the influence of the fibres is reduced when compared with that of steel fibres. In such a sense, it has been found that with an increment of around 15% of the superplasticizer added to the mix, it is possible to maintain at similar values the slump even when adding 10 kg/m^3 of polyolefin fibres [41, 28].

Similar to the case of a vibrated conventional concrete, the presence of fibres harms the self-compatibility that SCC has. However, the flexible nature of the polyolefin fibres significantly reduces such a decrease. In the case of an SCC, the fresh-state properties of the concrete are frequently determined by using tests such as the slump-flow test, the L-box test and the V-funnel tests. **Figure 7** shows the influence of the presence of fibres even if an SCC is limited, in both the slump test and the V-funnel test. This phenomenon underlines the versatile nature of polyolefin fibre if compared with rigid steel fibres of any kind. In addition, even in the case of a 10-kg/m^3 addition of fibres, no hint of balling was noticed. Moreover, there is evidence that concrete discharged from using polyolefin fibres in ready-mix trucks maintains a regular distribution of fibre along the concrete mass [7].

Compressive and tensile strengths of fibre-reinforced concrete have been thoroughly studied in the last decades with regard to steel and synthetic fibres [42, 43]. Fibres typically enhance

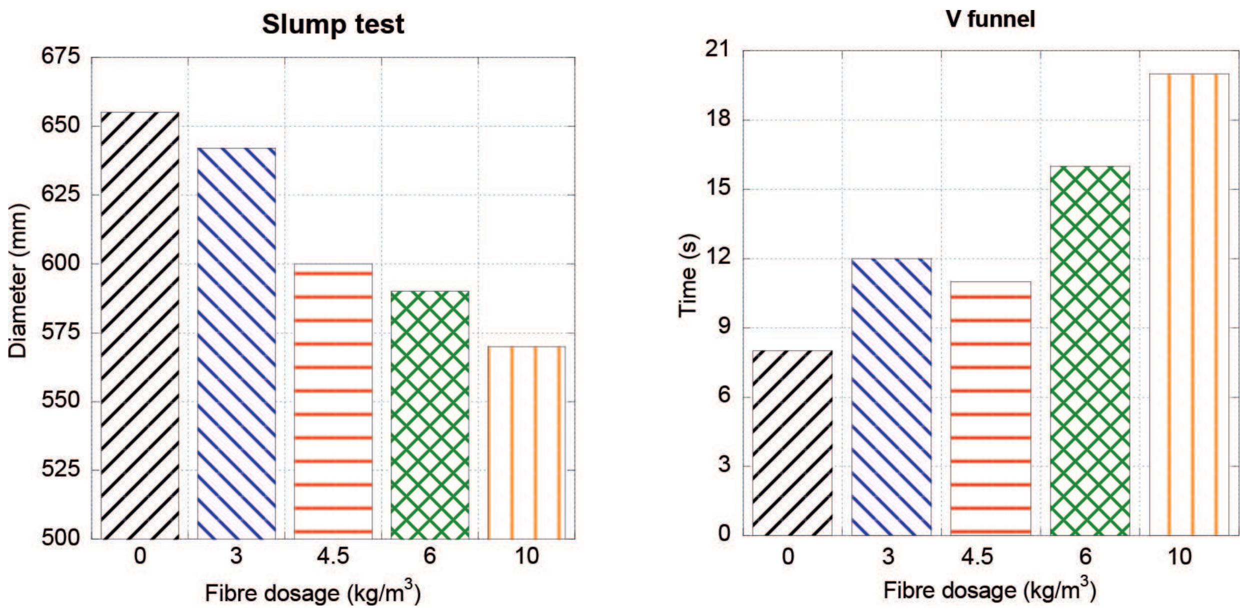

Figure 7. Slump test in an SCC PFRC [28].

the tensile properties of the plain concrete. However, their influence on other mechanical properties is varied depending on the type and shapes of the fibres.

Compressive strength, which is the most representative parameter to characterize concrete, provides essential information. The test is performed in a similar way to that of plain concrete [44]. In a conventional concrete, strength is not significantly affected when regular amounts of fibres are added. Nevertheless, the failure is usually less brittle due to the enhancement of the ductility and toughness provided by the fibres. Even a reduced amount of fibres produces remarkable changes in the failure mode, with it losing scarcely any mass (as **Figure 8** shows).

Nonetheless, it should be pointed out that there seems to be a threshold of volume fraction from which compressive strength is reduced even below values typical of plain concrete. This might have taken place due to a worsening of workability and compaction that causes heterogeneities in the concrete bulk and reduces its mechanical properties.

The mechanical explanation of this change in the failure mode is based on the reduction of lateral deformations above stress values 75% of its compressive strength. Such a change prevents the typical shear bands of plain concrete failure mode from appearing, avoiding the explosive failure of the material without fibres.

In order to assess tensile strength (as is accepted for plain concrete assessments), the indirect tensile-splitting tests—also named Brazilian tests—can be carried out. It should be clarified that in this subsection, tensile properties refer to initial tensile strength assessed by tensile-splitting tests. The residual post-cracking tensile strength is the keystone of the use of structural fibres and deserves a specific subsection focussed on fracture behaviour in tension or under tensile-flexural tests.

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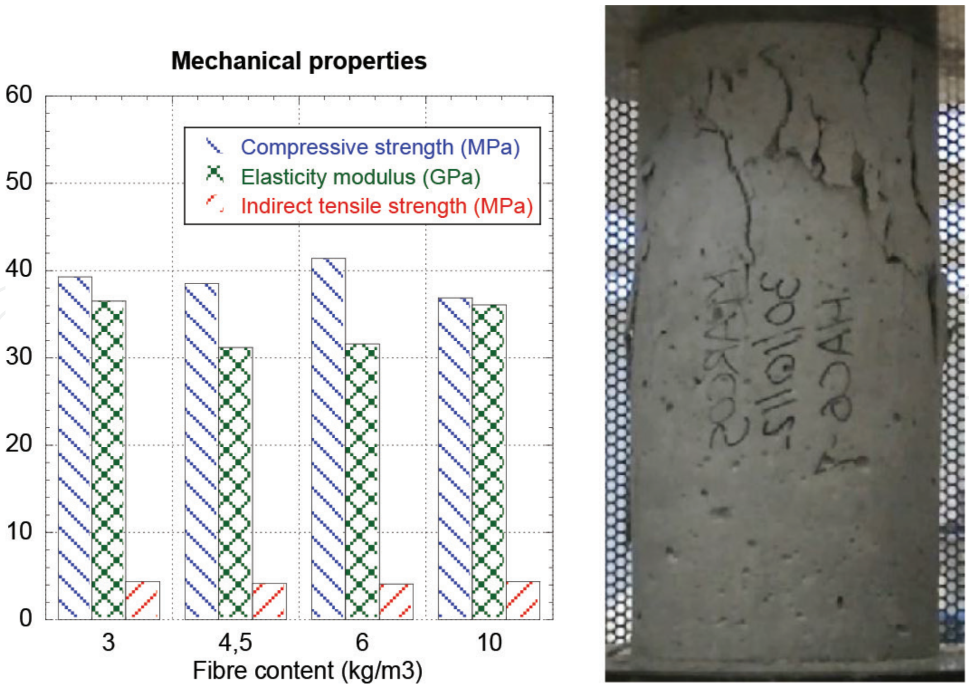


Figure 8. Mechanical properties and compressive strength sample after testing.

The tests and procedures are easy to perform. In the test, a concrete cylinder similar to the type used for compression tests is placed with its axis horizontal and between the platens of a testing machine. When the load is evenly applied along a generatrix, a near-constant tensile stress occurs in the central part of the vertical diameter [45]. The indirect tensile strength is related with the load at the first crack corresponding to peak load for plain concrete with brittle behaviour. However, this type of test is not suitable for assessing the residual strength of the materials provided by the fibres due to second-order effects that add bending stresses to the sample. Even though such second-order effects do not enable accurate residual strength values to be obtained, these indirect tests provide interesting values for the initial tensile strength. As regards the influence of the fibre content in the indirect tensile strength, as in the case of the compressive strength it could be considered that the influence of the fibre volume is negligible if the amount of fibres remains within the regular ranges (as **Figure 8** shows).

Regarding the modulus of elasticity (E) of the composite material, although theoretically its value should be related with the proportions of concrete and fibres, some other parameters have to be considered such as the fibre orientation and fibre length. Even in that case, the influence of the fibres in the modulus of elasticity is not clear as can be seen in **Figure 8**. In some cases, even when adding fibres with higher elasticity modulus than the matrix, a lower value of the composite material has been obtained.

All the features that were mentioned for the case of conventional vibrated concrete are also valid without performing major changes in the case of an SCC.

Another point that is worth considering is the durability of the PFRC when placed in potentially hazardous environments. The capacity of the PFRC to maintain its properties even in

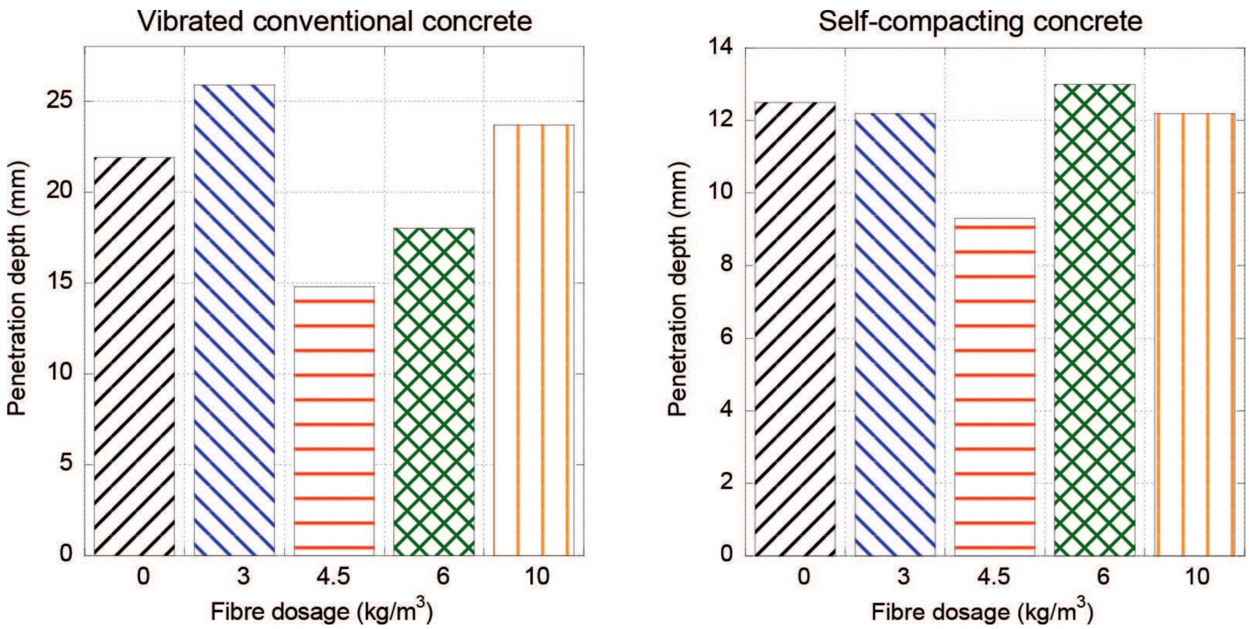


Figure 9. Permeability under pressure of water of VCC and SCC PFRC.

such environments depends on the action of the chemical compounds that ingress in the concrete bulk through the connected network of pores. In that sense, it should be underlined that the presence of fibres might offer preferential ways for such ingress. As can be seen in **Figure 9**, the permeability of the material under pressure of water is uninfluenced by the presence of fibres as there is no dependency of the penetration depth and the fibre content. Therefore, as happens with plain concretes, permeability is related to parameters such as the paste aggregate ratio and the size distribution of the aggregates used. If the type of aggregates and their proportion in the concrete mix are adequate, PFRC may be a material that bears the most hazardous of environments considered in some recommendations [12] such as those in direct contact with marine water, erosive materials, freeze-thaw conditions or even chemical industries.

5. Fracture behaviour and residual load-bearing capacity of polyolefin fibre-reinforced concrete

As previously mentioned, the main reason for adding fibres to a concrete formulation lies in the improvement of the flexural and tensile behaviour of plain concrete. The description of the fracture behaviour of plain concrete has significant differences due to the fibre-reinforcement nature, first and foremost, as regards the post-peak behaviour of the material. The response of concrete-reinforced with polyolefin fibres is conventionally characterized by testing specimens in the mesoscale under direct or flexural tensile stresses.

The uniaxial tension test, as described in several recommendations [30], can be used to determine the tensile strength and the softening parameters and define the stress-crack-opening curve in FRC. The test uses a notched cylindrical specimen with both ends fixed with respect to rotation. It is conducted under controlled tensile displacements. The test setup, as shown in

Figure 10, is rather complex and demands highly trained and experienced personnel. Therefore, as it is somewhat expensive and time-consuming, it is not considered an appropriate method for practical material testing (only being suitable for research purposes in specialized laboratories).

The most economical and practical tests available to determine the post-crack behaviour and assess the influence of conditions such as fibre types and dosage are bending tests. The three-point bending (TPB) test uses beams with a cross section of 150 × 150 mm and a span of 500 mm loaded in the middle of the upper face. A transverse notch of standard dimensions is made in the middle of the lower specimen face, in the same cross section where the load is applied. This setup, as shown in **Figure 11**, ensures that the crack is formed in this predefined position, making crack control simpler than in un-notched beams [30, 39].

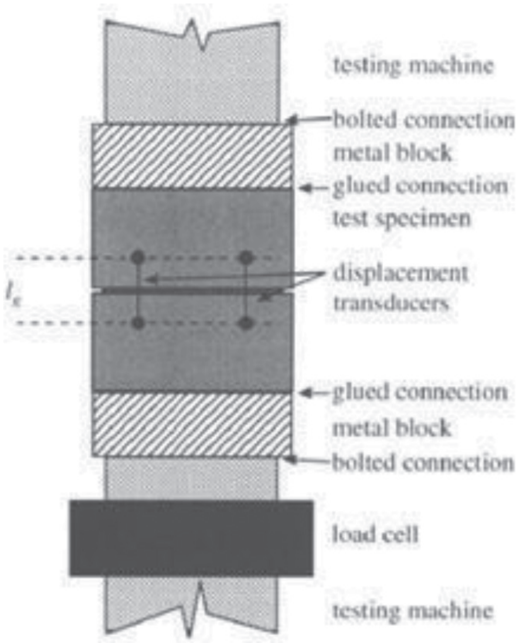


Figure 10. Uni-axial tension testing for concrete [30].

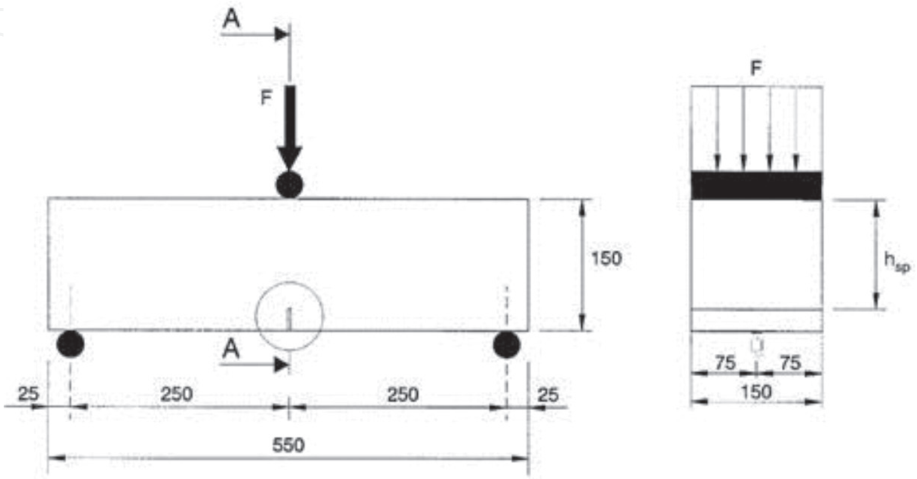


Figure 11. Test set-up in [38]. Measures in mm.

Four-point bending tests have also been adopted by some country national recommendations. The cross section of 150 × 150 mm has two equal loads applied in both sides of the middle third of the span [41, 45]. A typical setup is shown in **Figure 12**. The advantage of the four-point un-notched test is that the first crack will appear at the weakest section, therefore providing for the effect of a variation of material strength. The disadvantage is that the measuring of the crack opening is harder because the crack position cannot be predicted. Therefore, obtaining a complete characterization of the material is not always possible.

Regardless of the testing method employed, the curves obtained show the enhancement of the mechanical properties provided by the fibres. Furthermore, the behaviour or the composite material could be examined by taking into account the main effects regarding the plain concrete behaviour added to the contribution of the fibre reinforcement. Such a contribution depends on the crack opening and appears in the form of fibre bridging, fibre debonding and even fibre tensile failure. A theoretical scheme can be seen in **Figure 13**.

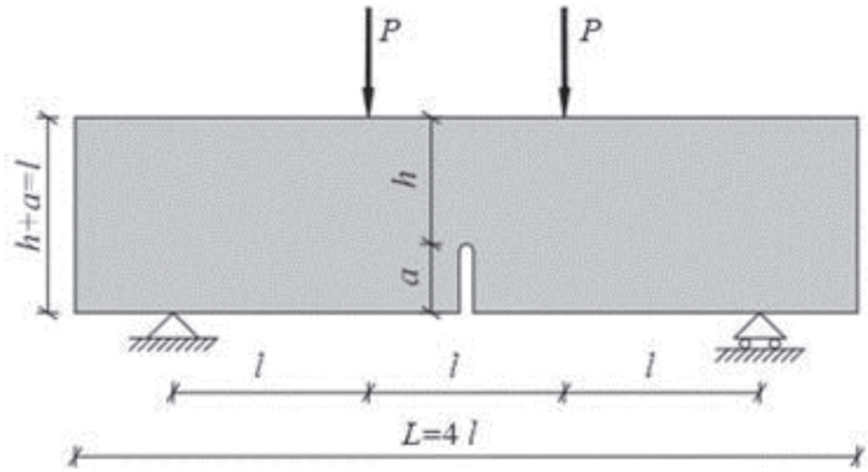


Figure 12. Four-point bending test [38, 46].

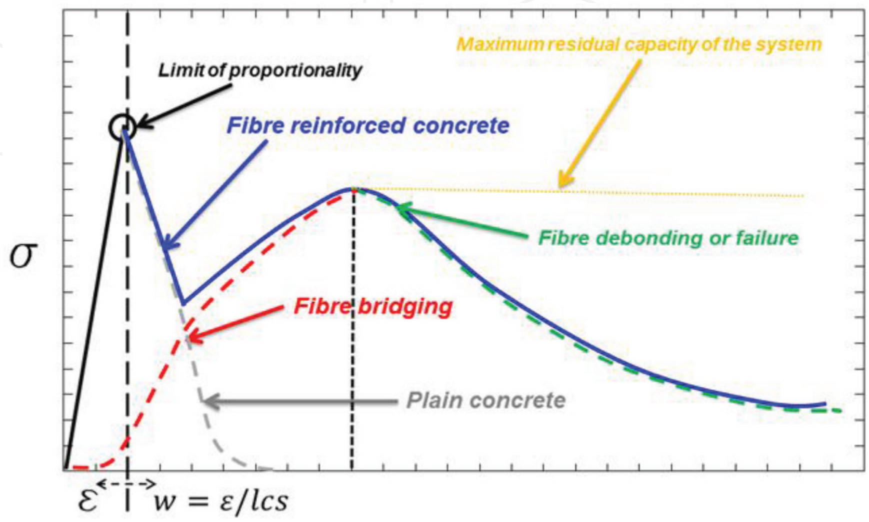


Figure 13. Conceptual bases of the discrete entities contribution to FRC constitutive relation [28].

Evidently, there are certain characteristics of the curves shown in **Figure 13** that depend not only on the amount of fibres used but also on the geometrical and mechanical properties of the fibres, the orientation and distribution of the fibres within the concrete element, the fresh properties of the concrete, the pouring process and, among others, the consolidation method. It is worth noting that predictive models and tools to consider such differences can be consulted in detail in references [28] and [47]. In any case, the main factor is the amount of fibres added. **Figure 14** shows how the amount of fibres changes the post-peak mechanical behaviour of PFRC.

The curves depicted in **Figure 14** have several common characteristics that should be mentioned. The behaviour of each curve is defined by the presence of three turning points. The first turning point took place when the loading process reached the maximum value and only a few inelastic processes were apparent (the behaviour of concrete is mostly linear if compared with subsequent stages). The turning point where the load reaches the maximum is commonly known as the load at the limit of proportionality (L_{LOP}), with it being the overall maximum load in plain concrete. A softening behaviour may also be

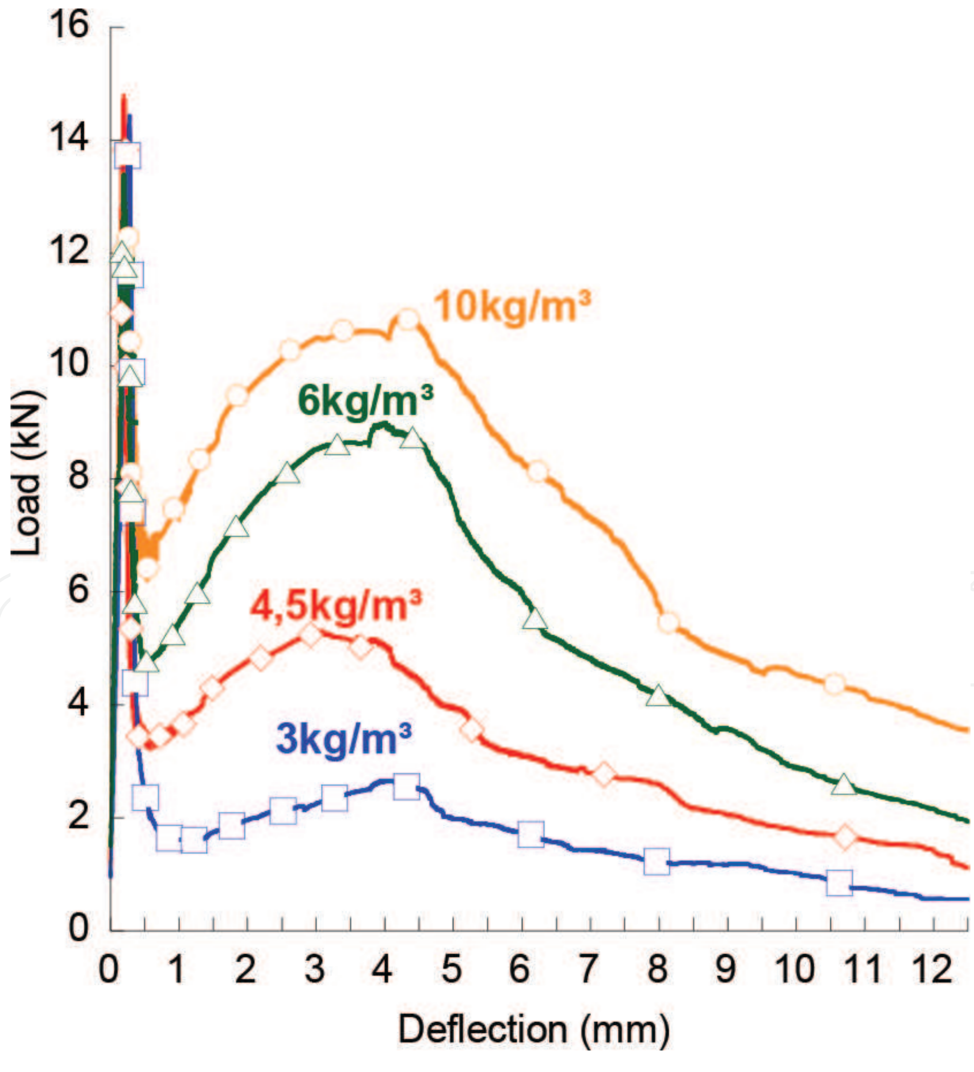


Figure 14. Fracture behaviour of PFRC with several amounts of fibres.

identified that governs the branch after L_{LOP}, as reported in many FRC types and especially for PFRC [3]. The softening behaviour is a distinctive characteristic in plain concrete fracture and, in such a case a steep unloading process leads to the specimen failure and collapse. Nonetheless, the polyolefin fibres are able to absorb the energy released by the concrete in the fracture processes by the so-called fibre bridging and change the loading tendency. At such a point, the curve reaches the minimum post-cracking load (L_{MIN}) while another uploading process starts again. The end of the load-increasing ramp is the third remarkable point of the curve. The descending slope drawn after L_{REM} continues until the end of the test. It should be noted that even at great deformation states, PFRC does not fail or collapse and that it shows remarkable improvements in ductility and toughness with respect to plain concrete.

Based on the previous description, it is easier to perceive the influence that the changes have on the behaviour that can appear when varying the amounts of polyolefin fibres added. The amount of fibres has a negligible influence on the peak load recorded in the fracture tests, and therefore L_{LOP} does not change with fibre dosage. The value of L_{LOP} is mainly determined by the tensile strength of the plain concrete. After reaching the peak load, the unloading part of the curve appears and such a part ends at L_{MIN} that is related with the amount of fibres added. The higher volumetric fraction of fibres the greater is the value of L_{MIN} obtained. It should be highlighted that, in contrast with the behaviour of an SFRC, even with volumetric fractions around 1% the value of L_{MIN} greatly differs from L_{LOP}. The slope of the curve between L_{MIN} and L_{REM} is greater as the amount of fibres added increases. In this case, it is important to note that the deflection value where L_{MIN} takes place does not depend remarkably on the dosage of fibres. Nevertheless, the maximum post-peak value L_{REM} is greatly modified by the amount of fibres added.

The number of fibres present in the fracture surface generated during the tests greatly influences the values of L_{MIN} and L_{REM} alike. However, not all the fibres that appear in the fracture surface influence the value of L_{MIN}. Due to the limited deformation state that the sample is bearing when L_{MIN} occurs, which is commonly used for service limit state (SLS) design, the contribution of fibres placed in the tensioned part of the section is more important than the rest of fibres. This corresponds to the lower third of the fracture surface generated. For high deformations, almost the whole cross section is in tension and, due to the quasi-brittle nature of the material, would already be almost fully cracked. Therefore, the total number of fibres would bear the final load obtained in the tests. These advanced deformations would correspond to ultimate limit state design (ULS). The situations that take place in the case of SLS and ULS are shown in **Figure 15**.

In order to relate the presence and distribution of fibres to the mechanical behaviour of the material, the values of L_{MIN} and L_{REM} versus the amount of fibres in the lower third of the fracture surface and the total amount of fibres in the fracture surface are plotted in **Figure 16**. This figure shows that there is a linear relation between the presence of fibres both in the lower third and the complete fracture surface with the values of L_{MIN} and L_{REM} in both conventional and self-compacting PFRC. It is also worth noting that the presence of fibres in the fracture surfaces does not correspond directly to the amount of fibres added. In such a sense, it should be noted that in not all cases higher dosages of fibres result in a greater number of

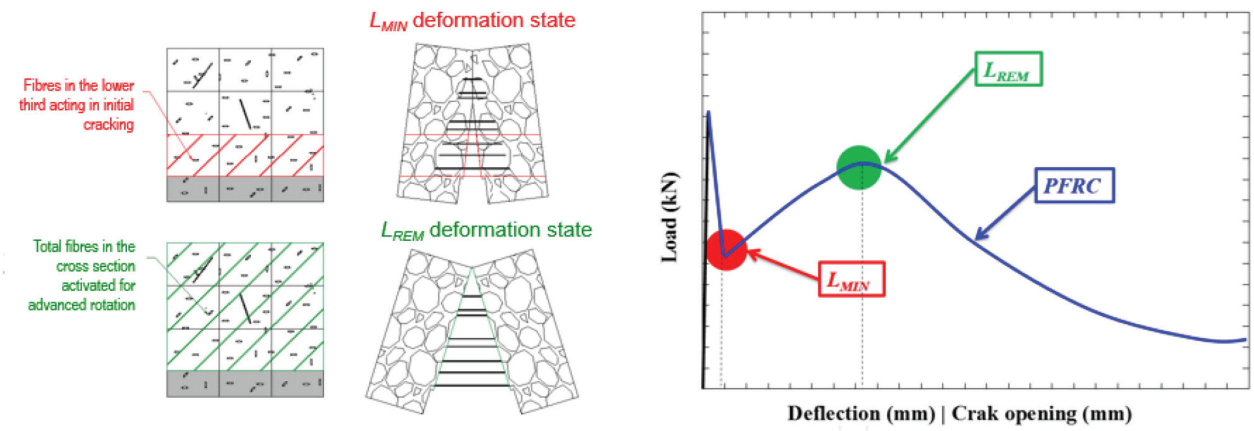


Figure 15. Deformation states of SLS or ULS.

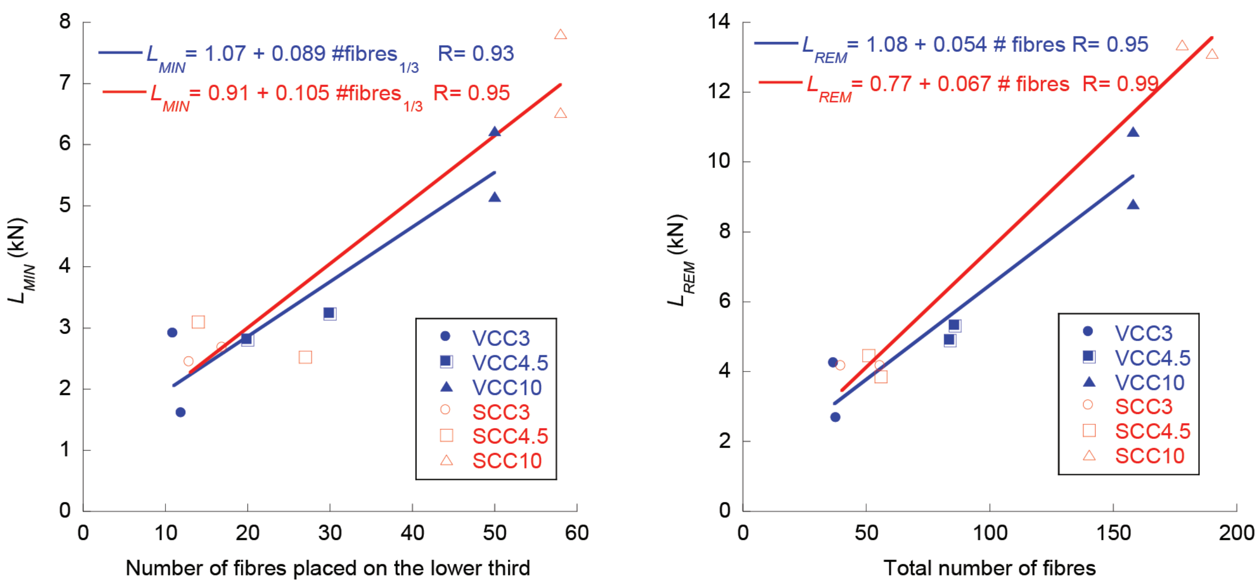


Figure 16. Relation between the number of fibres present in the fracture surfaces and the residual loads L_{MIN} and L_{REM} for vibrated conventional PFRC (VCC) and self-compacting PFRC (SCC). Tests performed following EN-14651 in reference [5].

fibres present in the fracture surfaces. Therefore, there are certain variations in the mechanical properties of the material that rely on other parameters unrelated with the amount of fibres added, such as the material rheology, pouring method and, among others, size of the element manufactured.

6. PFRC properties and their relation with the standards and recommendations

In previous sections, the improvement of properties provided by the fibres in PFRC has been shown. In order to take advantage of these benefits in the structural design of concrete elements, the mechanical properties of PFRC should fulfil certain requirements established in several standards and recommendations. Conventionally, as the most widespread structural fibres have been steel fibres almost all regulations have considered some of the requirements and borne in mind the properties of SFRC. However, if the fracture behaviours of SFRC and PFRC are compared, it can be noted that there are certain differences that should be underlined. If the fracture behaviours of a certain SFRC and PFRC are sketched as they are in **Figure 17**, such differences are perceived. As regards the peak load, there are no remarkable differences because this value both in SFRC and in PFRC is directly related with the properties of the bulk concrete due to the low volume fractions of fibres used. Nevertheless, once the unloading process that takes place after reaching the peak load starts, the first differences appear. Where SFRC is concerned, the decrement of the load-bearing capacity of the material is more reduced than in the case of the PFRC. This phenomenon appears even in the case of using high dosages of polyolefin fibres, which might be related, with the comparatively lower modulus of elasticity of these fibres if compared with steel fibres. Another difference that can be perceived is that the maximum post-peak load in the case of a PFRC takes place at higher deformation states than in the case of SFRC. Moreover, when L_{REM} is reached, the final unloading branch of SFRC will have been progressing for a while. Taking into account the aforementioned characteristics, it can be stated that for limited deformation states, such as those that correspond to SLS, SFRC might be more suitable than PFRC. On the contrary, if ULS is considered, then the most suitable option would be PFRC.

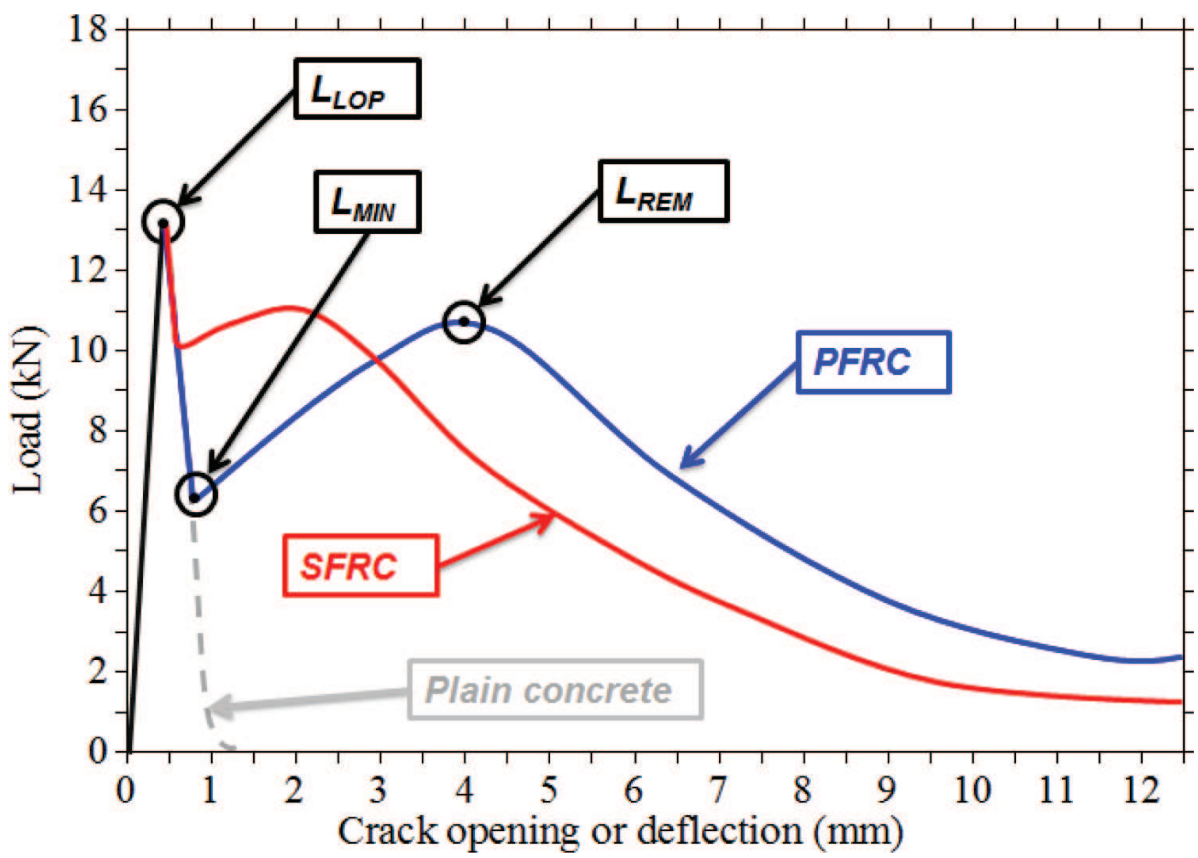


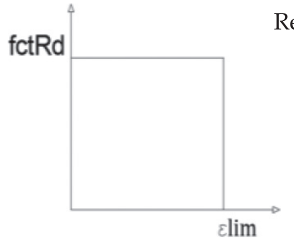
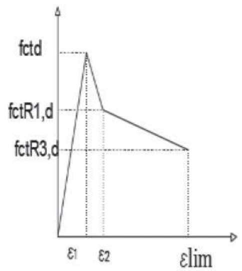
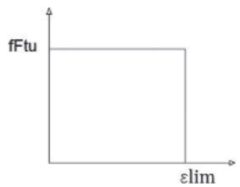
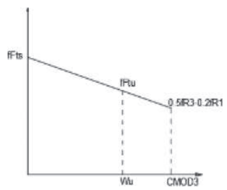
Figure 17. Schematic shape of the typical load-deflection curve obtained in a fracture test of PFRC compared with SFRC.

In any case and in order to supply structural requirements to design engineers, some national codes have offered several tests and guidelines. In 1992, the German Code [40, 45] proposed a σ-ε relationship for the structural design of tunnel linings that use steel fibres in concrete. In the last 15 years, many European countries, as well as Japan and the United States, have published codes and guidelines that allow the practical design of structures by considering fracture mechanics concepts aimed at taking into account the post-cracking residual strength under tension stress. Responding to their own internal demands, Germany [46], Italy [41] and Spain [12] have produced and even revised their codes and design guidelines. A complete review of the European codes can be seen in [11, 48, 49]. A summary of the types of tests and requirements can be seen in **Table 2**. At the time of writing, CEB-FIB Model Code 2010, MC2010 [50] is considered as a reference for newer revisions of Eurocode 2 and the guidelines of various European nation-states. Model Code 2010 establishes a material classification based on the results obtained by the earlier mentioned three-point bending tests as per EN 14651 [38] or [39, 51]. Model Code considers that the contribution of the fibres can be considered in the structural design if the following conditions are met. The value of the load at a crack mouth-opening displacement (CMOD) of 0.5 mm should be greater than 40% of the peak load, and when a CMOD reaches 2.5 mm the value of the load should be at least 20% of the peak load. Those values in terms of strength are known as f_{R1} and f_{R3} at 0.5 and 2.5 mm of CMOD, as can be better understood by consulting **Figure 18**. The first requirement is set for avoiding brittle failures of the structure and the second one seeks to set a minimum contribution of the fibres to the ultimate failure of the concrete element.

Although in some cases the requirements set by the standards are based on load values, in some others it is necessary to transform the load obtained from the fracture tests performed into residual strength values. This task can be accomplished in accordance with EHE-08 [12] and the Model Code [50] by Eq. (1) that transforms load values into strength, with L being the distance between the supporting cylinders, f_j the force registered by the load cell, b the width of the sample and h_{sp} the length of the ligament, is as follows:

$$f_{ct,j} = \frac{3}{2}\frac{f_j L}{b\ h_{sp}} \qquad (1)$$

When comparing **Figure 18** with **Figures 14** and **17**, the shapes of the curves are remarkably different. The fracture curves obtained in the PFRC of material after reaching the minimum post-peak load value (L_{MIN}) are capable of sustaining higher loads and reaching a maximum post-peak value (L_{REM}). As previously mentioned, structural requirements are related to the most representative residual strengths f_{R1} and f_{R3} at crack openings of 0.5 and 2.5 mm. Consequently, the brittleness limitation stated by the strength value at f_{R1}might be of relative significance when these regulations are used to assess the performance of PFRC. However, the analysis of **Table 3** reveals that an SCC and a VCC with 10 kg/m^3 of fibres (VCC10 and SCC10) met the aforementioned requirements. By contrast, when a VCC or an SCC with 6 or 4.5 kg/m^3 (VCC6, SCC6, VCC4.5 and SCC4.5) was studied, although it is clear that these mixes did not fulfil the requirements, such mixes were able to avoid brittleness. The latter is shown by the increment of the load that takes place in all mixes, after reaching L_{MIN}. Regarding a PFRC with 3 kg/m^3 of fibres (VCC4.5 and SCC3), although brittleness is avoided due to the

Test	Standard	Parameters	Constitutive models for structural design		
Three point bending	EHE	f_{R1}, f_{R3}, f_L		Rectangular	$f_{ctR,d}$= 0.33 $f_{R3,d}$ ε_{lim}=20% (flexural) ε_{lim}=10‰ (tensile)
				Trilineal	$f_{ct,d} = 0.6\, f_{ct,fl,d}$ $f_{ctR1,d} = 0.45\, f_{R,1,d}$ $f_{ctR3,d} = k\,(0.5\, f_{R,3,d} – 0.2\, f_{R,1,d})$, *con k=1(flexural) ò k=07(tensile)* $\varepsilon_1 = 0{,}1 + 1000^* f_{ct,d}/E_{c,0}$ $\varepsilon_2 = 2{,}5/l_{cs}$ ε_{lim} = 20% *(flexural) ò* 10% *(tensile)*
	FIB model code	f_{R1}, f_{R3}, f_{Ftu}, f_{Fts}		Rigid-Plástic	$f_{Ftu} = \frac{f_{R3}}{3}$ ε1=ε_{lim} =10%hardening; 20% softening
				Lineal	f_{Fts}=0.45 f_{R1} $f_{Ftu} = f_{Fts} – \frac{wu}{CMOD3}(f_{Fts} – 0.5 f_{R3} + 0.2 f_{R1})$ ε_{ELS} = CMOD1/l_{cs}; ε_{SLU}=Wu/l_{cs} = min(ε_{Fu}, 2.5/l_{cs}, 2.5/y); ε_{Fu}=10‰ end; 20‰ ablan
	UNE 14889				f_{R1}, f_{R4} $f_{R1\,(CMOD=0.5)} \geq 1.5$ MPa $f_{R4\,(CMOD=3.5\,mm)} \geq 1$ MPa

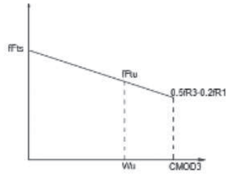
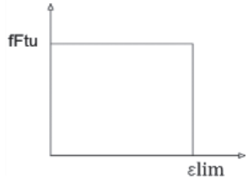
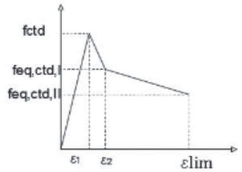
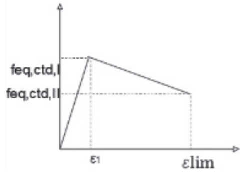
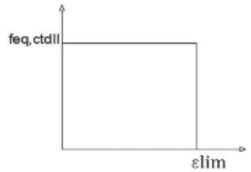
Test	Standard	Parameters	Constitutive models for structural design		
Four point bending	CNR-DT204	$f_{Fts}, f_{Ftu}, f_{eq1}, f_{eq2}$		Lineal-Elástic	$f_{Fts} = 0{,}45\cdot f_{eq1}$ $f_{Ftu}=k[f_{Fts} - \frac{Wu}{Wi2}\,(f\mathrm{Fts}-0{,}5f_{eq2}+0{,}2f_{eq1})$ k=1(flexural) ò k=0.7(tensile) $\varepsilon_2=\varepsilon_u$ (20% softening; 10‰ hardening)
				Rigid-PLASTIC	$f_{Ftu} = \frac{f_{eq2}}{3}$ $\varepsilon 1=\varepsilon_{lim}$ =10% hardening; 20% softening
	DBV	$f_{ctk,fl}, f_{eq,ctk,I}, f_{eq,ctk,II}$		Trilineal	$\sigma_1 = f^f_{ctd} = \alpha^f_c \cdot f_{ctk,fl}/\gamma^f_{ct}$ $\sigma_2 = f_{eq,ctd,I} \cdot \alpha^f_c \cdot \alpha_{sys}/\gamma^f_{ct}$ $\sigma_3 = f_{eq,ctd,II} \cdot \alpha^f_c \cdot \alpha_{sys}/\gamma^f_{ct} \le f_{eq,ctd,I}$ $\varepsilon 1 = \sigma_1/E_{HRF};\ \varepsilon 2 = \varepsilon 1 + 0.1‰;\ \varepsilon 3 = \varepsilon u = 25\%$
				Bilineal	$\sigma_1 = f_{eq,ctk,I} \cdot \alpha^f_c \cdot \alpha_{sys}/\gamma^f_{ct}$ $\sigma_2 = f_{eq,ctd,II} \cdot \alpha^f_c \cdot \alpha_{sys}/\gamma^f_{ct} \le f_{eq,ctd,I}$ $\varepsilon u = \varepsilon 2 = 10\%$
				Rectangular	$\sigma_1 = f_{eq,ctd,II} = f_{eq,ctk,II} \cdot \alpha^f_c \cdot \alpha_{sys}/\gamma^f_{ct} \le f_{eq,ctd,I}$ $\varepsilon 1 = \varepsilon u = 10\%$

Table 2. Comparison of some of the recommendations and standards.

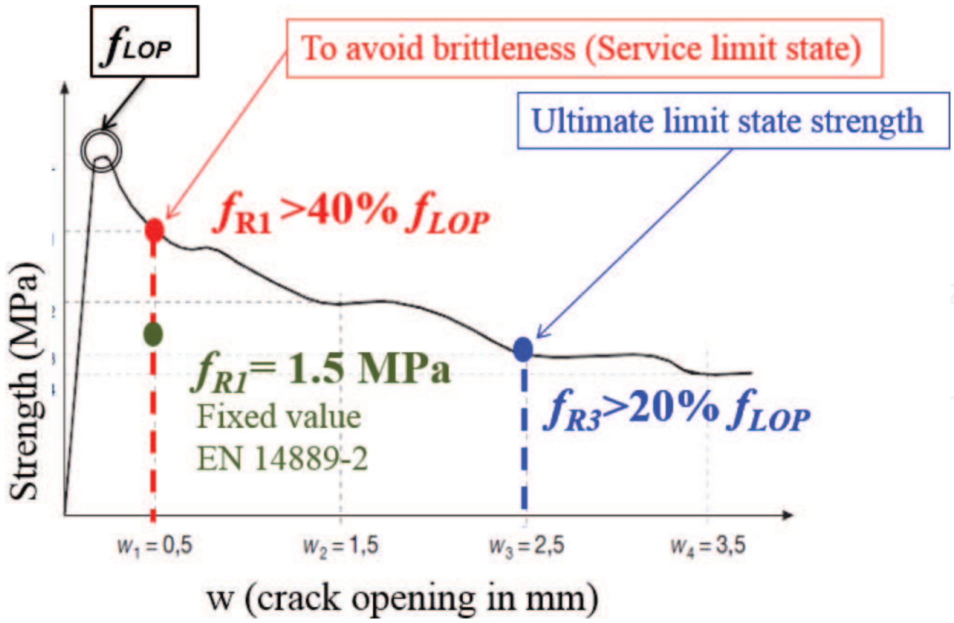


Figure 18. Load-CMOD curve of a FRC as stated in [12] with structural requirements.

	f_{LOP} (MPa)	f_{R1}(MPa)	% f_{LOP}	f_{R3} (MPa)	% f_{LOP}
VCC3	4.81	0.93	19%	0.96	20%
SCC3	5.21	0.93	19%	1.15	22%
VCC4.5	4.74	1.06	22%	1.40	29%
SCC4.5	5.23	0.95	18%	1.25	24%
VCC6	4.41	1.57	36%	2.38	54%
SCC6	5.09	1.39	27%	2.03	40%
VCC10	4.21	1.98	47%	2.87	68%
SCC10	5.22	2.41	46%	3.87	74%

Table 3. Residual strength of concrete.

increment of load that the material can bear at f_{R3}, there is only a 10% improvement of the strength between f_{R1} and f_{R3}. A wider view and detailed results with additional tools to consider fibre positioning as a function of the influencing parameters can be seen in Ref. [28].

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