Fibre reinforced concrete - a sustainable material in the context of building industry and environmental challenges

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Abstract. The sustainability of concrete technology can be attained by finding alternatives for the depleting raw materials of the concrete, reducing the energy consumption implied in the cement processing or maintaining and even improving the concrete properties even when non conventional and lower cost materials are used. If it is taken into discussion the improvement of the concrete properties and especially the improvement of its most important disadvantage, tensile strength, a traditional solution is to use the steel reinforcement of the concrete. Besides this, another method is the use of various fibres as dispersed reinforcement in concrete compositions. Fibres lead to the improvement of some concrete characteristics like post-peak behaviour, tensile strength, ductility and energy-dissipation ability. The most popular type of fibres used nowadays as disperse reinforcement in concrete are steel fibres. The aim of this paper is to present the advantages and disadvantages of this type of fibres and some of sustainable alternatives for steel fibre reinforced concrete.

Key Words: steel fibres, plastic fibres, polyoplefin, PP fibres.

Introduction. Over the last decades, in the whole world, the interest in finding ways to ensure the sustainability of concrete technology, in different forms, developed more and more. This sustainability can be attained by finding alternatives for the depleting raw materials of the concrete, reducing the energy consumption implied in the cement processing or maintaining and even improving the concrete properties even when non conventional and lower cost materials are used. All these directions imply the use of different kind of waste materials or by-products of different industries: supplementary cementitious materials for a partial replacement of the cement, alternative aggregates instead of the mineral ones, alternative fuels for cement processing, or addition of different types of waste which can improve the concrete properties. It is a well known fact that concrete is very strong in compression but very weak in tension. To ensure the improvement of this disadvantage, a traditional solution is to use the steel reinforcement of the concrete. Besides this, another method is the use of various fibres as dispersed reinforcement in concrete compositions. In last decades, the research and the developments in the fiber reinforced concrete (FRC) were very intensive (Rosidawania et al 2015).

The aim of this paper is to present the advantages and disadvantages of the most popular type of fibres used nowadays as disperse reinforcement in concrete, steel fibres, and some of sustainable alternatives for steel fibre reinforced concrete.

The main benefits of the dispersed fibre reinforcement in concrete. The fibre role in the cementitious matrix is to prevent the propagation of a crack and, in this way, water and contaminants penetration into the concrete is diminished. Fibres form a disperse reinforcement in which every individual fibre has a small contribution to an overall cumulative effect of controlling the crack growth (Yin et al 2015; Deng et al 2016; Islam & Gupta 2016), preventing plastic and dry shrinkage cracks, keeping the concrete integrity, reducing the brittleness of the concrete matrix and improving its ductility (Yin et al 2015).

Fibres lead to the improvement of some concrete characteristics like post-peak behaviour, tensile strength, ductility and energy-dissipation ability. The ductile behaviour is a very important property in the case of the structures located in high seismic regions (Rosidawania et al 2015). They improve compressive strength also, but in a smaller rate than the ductility and tensile strength (Siddique et al 2012).

The addition of fibres in small quantities lead to significant increase of the concrete strength and they are efficient in decreasing the crack's width and spacing. This crack control has implications on the penetration of water and chemicals into the concrete, so the resistance to corrosion is increased and a longer-term serviceability of the concrete is obtained (Saidani et al 2016).

FRC is used in nonstructural elements usually, but there exist exceptions permitted in some codes (Rosidawania et al 2015).

The pros and cons of using steel fibres in concrete composition. Mainly four types of fibres can be used in concrete composition: steel fibres, glass fibres, natural fibres, and synthetic fibres. Glass fibres ensure a very good strengthening effect but they have poor alkali resistance. Natural fibres, like wood, palm, coconut and vegetal fibres have the advantage to be cheap and easy renewable and available, but their durability is low (Yin et al 2015). Due to their very good mechanical properties, steel fibres represent the most popular material for concrete reinforcing (Deng et al 2016).

Steel fibres reinforced concrete (SFRC) is the subject of research for more than 40 years and its main applications are airport pavements and footpathways (Achilleos et al 2011). Steel fibres have the density 7.8 g cm^{-3} (Deng et al 2016). They have the ability to absorb energy and to control cracks. They have a major disadvantage represented by their corrosion which can deteriorate very quickly the concrete structures (Yin et al 2015).

Discrete steel fiber addition in concrete improves the compressive strength and strain at peak stress. An increased volume of steel fibres into the concrete leads to a flatter post-peak softening branch of the curve (Rosidawania et al 2015). SFRC slump decreases with fibre content increasing (Sengul 2016). In high quantities, steel fibers lead to a hard evenly dispersion in concrete (Deng et al 2016). In the concrete mixtures with higher fibre dosage, the durability on chloride ions penetration is improved and the concrete mechanical properties were mantained after the exposure to various chloride ions solutions (Abbas et al 2015).

In compression, stress-strain curve of SFRC increases in strain at peak stress and register a higher toughness. The toughness represent the energy absorption capacity of a material during the deformation (Rosidawania et al 2015). Steel fibers double the tensile strength of the concrete in the case of 4% addition, for example. In general, they can overcome the brittle behaviour of the concrete (Saidani et al 2016). In the case of ultra high performance concrete, short steel fibre addition lead to higher flexural tensile strength compared to the case with longer steel fibres (Abbas et al 2015).

Steels fibres addition have a positive effect on the impact resistance of concrete, so the resulted material is suitable for structures subjected to impact loads. SFRC pavement eliminates spring load restrictions and ensures fuel saving for heavy vehicles versus asphalt. From life cycle point of view, SFRC pavements have a twice longer life than asphalt road (Achilleos et al 2011) .

In the case of underground constructions, SFRC is subjected to a very high risk to develop steel corrosion, so a very careful maintenance is needed (Deng et al 2016). Recently, the fibre addition in concrete has been considered for using in structural elements as substitution of steel-bar reinforcement. In the codes and design standards are specified the mechanical requirements of the fibres for structural use, these being macro-steel fibres with specific shapes such as crimped or hooked-ended (Alberti et al 2016). Structural applications for SFRC are very limited (Rosidawania et al 2015).

Sustainable alternatives for steel fibre reinforced concrete

Recycled steel fibres – an environmental friendly solution to commercial steel fibres. Industrial steel fibres are made of steel, an alloy with a major content of iron which is a natural depleting resource; moreover, the virgin steel fibres have a high cost which may not justify their use, even if the life cycle costs are smaller due to reduced maintenance needs. To ensure the sustainability principles with a reduced cost level, the recycled steel fibres represent a more environmently correct approach (Achilleos et al 2011).

The use of recycled steel fibres in concrete has environmental benefits for tire recycling over landfilling, and economical ones (Achilleos et al 2011).

Studies on the concrete with recovered steel fibres from scrap tires are very limited (Sengul 2016). Recycled steel fibres recovered from scrap fires seems to get similar results as those of commercial ones. Sengul (2016) analyzed the compresive strength, splitting and flexural tensile strength, load-deflection curve and fracture energy of steel FRC made of virgin (commercial) fibres and of recycled steel fibres recovered from scrap tires. The author of the study obtained similar results, no matter the steel fibres type. A plus for the recycled version of steel fibres is also the price smaller than the commercial ones.

Achilleos et al (2011) studied the possibility to be used recycled steel fibres in the SFRC pavement and they found out that this type of fibres represents a well sustainable alternative to commercial ones. A disadvantage of recycled steel fibres is their uneven geometrical properties, so the properties of the SFRC may also vary (Sengul 2016).

Virgin steel fibres production is an expensive process because is energy intensive, so the recycled steel fibres can be an alternative to ensure the sustainability of concrete industry, if there are taken measures to ensure the same properties for the fibres by cathegorizing them by size ranges, for example, and if are well established their effects on concrete properties, to know their application posibilities (Sengul 2016).

Synthetic fibres – a more durable solution instead of steel fibres. In order to obtain a very reliable reinforcement in concrete, the used fibres must have a high tensile strength and Young's modulus. Besides the steel fibres, the synthetic ones have these properties. A very large category of synthetic fibres is represented by the plastic fibres; they can be found in two forms: micro plastic fibres and macro plastic fibres. Micro plastic fibres have the diameter between 5 to 100 μm and 5-30 mm length. They are efficient in controlling the plastic shrinkage cracking of the fresh concrete; in the hardened concrete, their effect is minimum (Yin et al 2015). Macro plastic fibres have the cross section between 0.6-1 mm^2 and 30-60 mm in length. They are used also to control the plastic shrinkage of the fresh concrete and the drying shrinkage of hardened concrete in the case of large flat areas like slabs in hot and dry environments (Yin et al 2016). A major advantage of macro plastic fibres is the increasing of post-cracking ductility of the concrete due to their capacity of crack arresting: large single cracks from plain concrete are transformed into dense micro-cracks in the reinforced concrete with macro plastic fibres (Yin et al 2015).

Macro synthetic fibres have the ability to improve concrete ductility and strength and, due to these characteristics, in the case of concrete columns from a structure, the required reinforcement can be reduced. The macro synthetic fibres improve the strength and ductility of the confinement of the high strength concrete (Rosidawania et al 2015). Virgin macro plastic fibres have a tensile strength of 300-600 Mpa and a Young's modulus of 4-10 Gpa. Macro plastic fibres are very used in concrete footpaths, precast elements and shotcrete mine tunels (Yin et al 2016).

Macro plastic fibres became an alternative to steel mesh and fibres used in concrete footpaths, non-structural precast elements and tunnel linings (Yin et al 2016).

The major types of macro plastic fibres are high density polyethilene (HDPE), polyethilene terephthalate (PET) fibres, polypropylene (PP), polyolefin (Yin et al 2015).

HDPE fibres have some disadvantages such as low tensile strength, higher hydrophilic character than PP fibres and their density it's not much higher than PP fibres (0.95 g cm^{-3}) (Yin et al 2015).

PET fibres have a density of 1.38g/cm^3 and a wetting tension of 40 mN m^{-1}, properties which ensure an easier mixing with concrete than PP and HDPE fibres. Their high tensile strength and Young's modulus recommend them for post-crack controlling use in concrete (Yin et al 2015). PET fibres produced by waste PET melting, roll-type sheets forming and thin strands cutting have a tensile strength higher than 400 Mpa and a Young's modulus of 10 Gpa. By simply cut the waste PET bottles, there are obtained fibres with limited strength (Yin et al 2016). As disadvantages, PET fibres present higher processing cost than PP or HDPE and a questionable alkaline resistance (Yin et al 2015). While, the reycled PET fibres started lately to be a research subject, for recycled PP fibres use in concrete there is very limited research (Yin et al 2016).

From using tendency point of view, PP fibres are the most commercialized ones, PET fibres are the object of extensive research, and HDPE are less used both in practice and in research (Yin et al 2015).

PP fibres have high alkaline resistance, high tensile strength and Young's modulus and they are easily produced. A disadvantage is their low density (0.9 g cm^{-3}) which make their incorporation into the concrete matrix to be more difficult due to the "float up" effect. Another disadvantage is represented by their low wetting tension of around 35 mN m^{-1} which decrease the fresh concrete workability and the bond with cement paste (Yin et al 2015).

The volume of the added PP fibres into the concrete are in inverse relationship with the concrete density. These type of fibres affects the concrete workability (Saidani et al 2016).

Macro PP fibres improve the tensile strength of the concrete by 1.5 times in the case of 4% addition in concrete. In general, they can overcome the brittle behaviour of the concrete (Saidani et al 2016). A percent of 0.1 of PP fibres addition into plain concrete leads to 2% decrease of compresive strength, but also to an increase of tensile strength of 39%. For a PP fibre content between 0.1% and 0.3%, plastic shrinckage cracks are reduced by 50-99% compared to plain concrete. PP fibre addition leads to the increase of water and gas permeability. Concrete with PP fibers is not indicated to be used in water retaining structures (Islam & Gupta 2016).

In concrete can be used virgin or recycled PP fibres. The recycled PP fibres have a very good post-cracking performance in concrete, very good alkali resistance, lower tensile strength, higher Young's modulus, ensure the same or slightly lower reinforcement compared to virgin PP fibres (Yin et al 2016). In an investigation made by the same authors, they concluded that recycled PP fibres had lower tensile strength but higher Young's modulus, and a better post-cracking performance, so they can be used instead of virgin PP fibres for concrete footpaths and precast panels manufacturing.

Regarding the plastic fibres durability, there are studies which demonstrated that virgin PP fibres maintain their strength up to 100 years in the cement matrix. The recycled PP fibres also are not degraded in the alkaline environment of the concrete (Yin et al 2016).

Synthetic fibres, such as polyolefin, acrylic, aramid or carbon fibres, are very useful in preventing the plastic shrinkage cracks in fresh concrete, in improving the post-cracking behavior of concrete and enhancing the energy-dissipation capacity of concrete elements under flexure, shear and axial load (Yin et al 2015).

Polyolefin-based synthetic macro-fibres are produced by plastic industry and represent an alternative solution to steel fibres. This type of fibres are stable in alkaline environment and cand replace the steel reinforcement of the structural concrete. The advantages of polyolefin fibres such as good tensile properties, abrasion and chemical attack resistance, and relatively low cost promote them as alternative to steel reinforcing meshes of steel fibres (Alberti et al 2016).

Macro polyolefin fibres are made by PP or HDPE. They have a 0.6*1.5 mm^2 in cross-section, 300-600 Mpa tensile strength and 4-10Gpa Young's modulus, these values varying according to manufacturing techniques. Their density is around of 0.9 g cm^{-3} (Deng et al 2016).

Macro polyolefin fibres improve flexural toughness, crack resistance and ductility of the plain concrete; they decrease the stress intensity at crack tip and the crack width, so cracks developing and propagation is reduced a lot. Also, water and contaminants permeability is slowed down and the corrosion risk of the steel reinforcement minimized (Deng et al 2016).

Alberti et al (2016) studied the fibre positioning and orientation in the elements made by polyolefin fibre reinforced concrete and their results showed that there was no tendency of fibres to float and the pouring point has a significant influence in fibre distribution. The authors concluded that the polyolefin fibres enhance the orientation factor for longer distances in the case of self-compacting concrete and suitable to be used in structural concrete.

Conclusions. The subject of fiber reinforced concrete was intensively studied in the past decades. The fibre role in the cementitious matrix is to prevent the propagation of a crack and, in this way, water and contaminants penetration into the concrete is diminished. Fibres lead to the improvement of some concrete characteristics like post-peak behaviour, tensile strength, ductility, and energy-dissipation ability. The most used fibres are virgin steel fibres but they have a major disadvantage represented by their corrosion which can be very distructive and also a high cost. A reduced cost level can be obtained by using the recycled steel fibres. Corossion disadvantage can be overcome by using synthetic fibres. A very large category of synthetic fibres is represented by the plastic fibres which can be found in two forms: micro plastic fibres and macro plastic fibres. Micro plastic are efficient in controlling the plastic shrinkage cracking of the fresh concrete; in the hardened concrete, their effect is minimum. Macro plastic fibres are used to control the plastic shrinkage of the fresh concrete and the drying shrinkage of hardened concrete. A major advantage of macro plastic fibres is the increasing of post-cracking ductility of the concrete. The major types of plastic fibres are HDPE, PET, PP and polyolefin fibres. From using tendency point of view, PP fibres are the most commercialized ones, PET fibres are the object of extensive research, and HDPE are less used both in practice and in research. PET fibres present higher processing cost than PP or HDPE and a questionable alkaline resistance. Virgin PP fibres maintain their strength up to 100 years in the cement matrix. The recycled PP fibres also are not degraded in the alkaline environment of the concrete. Polyolefin fibres are stable in alkaline environment and can replace the steel reinforcement of the structural concrete. Their advantages are good tensile properties, abrasion and chemical attack resistance, and relatively low cost.

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