AN OVERVIEW INTO THE USE OF SINGLE AND HYBRID FIBRE REINFORCED CONCRETE

LABIB Wafa[1]

Abstract

Over the past few decades, advances in concrete technology have led to the development of fibre reinforced concrete material. The worldwide yearly consumption of fibres used in concrete is 300,000 tons. Even though, the available standards, guidelines and recommendations do not really recognise the contribution of various types of fibres in enhancing mechanical properties of concrete.

The aim of this paper is to investigate into the effect of using various types of fibres in enhancing the mechanical properties of concrete such as tensile strength, bending strength, shear strength, toughness, fire resistance and resistance to cracking. These types include steel, polypropylene, glass, carbon, polyolefin, polyvinyl and waste fibre. This paper also investigated into the use of a combination of two types of fibres, often called hybridization, which shows a great potential to optimise the properties of concrete material as well as improve the mechanical performance of reinforced concrete members. The reviewed literature showed that combining of fibres is limited to two types, a mix of steel and polypropylene fibres and a mix of steel fibres with different geometry, shape and size.

The paper concludes with a discussion into the future potential use of different combination of hybrid fibres to improve the mechanical properties of concrete with emphasise on their effects on the punching shear capacity of concrete.

Keyword: steel fibre, waste fibre, hybrid fibre, punching, concrete

1. Introduction

To date, advances in concrete technology have led to the development of fibre reinforced concrete (FRC) materials (Huang et al., 2015). The addition of fibres into cementitious composites enables considerable improvement in mechanical and dynamic properties of reinforced concrete members. FRC demonstrates excellent tensile strength, toughness, energy dissipation capacity (Brandt, 2008 & Di Prisco, 2009). It also increases significantly the shear (Aoude et al., 2012; Barros et al., 2014; Susetyo et al., 2013) the flexural (Barros et al., 2014; Caggiano et al., 2012; De Montaignac, 2012), the punching (Safeer et al., 2004; Ventura-Gouveia, 2011) resistance and the durability (Banthia et al., 2010; Granju et al., 2005; Kunieda et al., 2014) of concrete structures as well as superb resistance to cracking (Qian et al., 2000).

[1] S Labib Prince Sultan University-Riyadh-KSA 00966114948187 wlabib@psu.edu.sa

Those attractive properties allow the direct application of fibres in concrete. However, each fibre type could enhance specific concrete properties. Accordingly, the aim of this paper is to investigate into the potential of using various types of fibres which includes steel fibre, synthetic fibres such as polypropylene, glass, carbon, polyolefin and polyvinyl in enhancing the mechanical properties of concrete.

Recent researches showed that waste fibres can also be a valuable reinforcement system to decrease significantly the brittle behaviour of cement based materials, by improving their toughness and post-cracking resistance (Aiello, 2009). It also has beneficial environmental and economic impacts (Graeff et al., 2012; Neocleous et al., 2006). The effect of using waste fibre in enhancing concrete properties is further investigated in the below sections.

The use of two or more types of fibres in a suitable combination showed a great potential to optimise the properties of concrete material as well as improve the mechanical performance of reinforced concrete members. This combining of fibres, often called hybridization is currently used as the inclusion of single fibre in concrete cannot attain an optimal performance. The use of hybrid is commonly limited to two types. These are a mix of steel and polypropylene fibres as well as a mix of steel fibres with different geometry, shape and size. A further description on different fibre combinations is shown in the below sections.

2. Types of Fibres

Applications of FRC are very common in civil and structural engineering. All over the world considerable research efforts have been made contributing to theoretical and technological knowledge about properties and behaviour of FRC.

There are numerous fibre types, in various sizes and shapes, available for commercial and experimental use. The basic fibre types are steel fibre, synthetic fibres such as polypropylene, glass, carbon, polyolefin, polyvinyl and waste fibre materials. Using these fibres individually as well as on hybrid basis has an effect on the mechanical properties of FRC members. These mechanical properties depend on the type, geometry and content of fibres (Bentur, 1990; Buratti et al., 2011) as described below.

3. Effect of using single type of fibres on concrete mechanical properties

3.1 Steel Fibres

Steel fibre is becoming an important type of concrete reinforcement due to the numerous advantages that it offers for concrete. Therefore, many efforts have been made in recent years to optimise the shape of steel fibres in order to achieve improved fibre-matrix bond characteristics, and to enhance fibre dispersibility in the concrete mix (Pajak et al., 2013). The five most popular types of steel fibres are: traditional straight, hooked, crimped, with deformed ends and with deformed wire (Katzer et al., 2012). A statistical analysis of the assortment offered by the largest fibre producers allows claiming that around 67% of sold fibre consists of the hooked type. Other most popular fibre types are: straight fibre (around 9%), fibre with deformed wire (around 9%) and crimped fibre (around 8%) (Katzer, 2006).

Over the past three decades, the potential of using Steel Fibre Reinforced Concrete (SFRC) to improve the performance of structures has been investigated (Zamanzadeh et al., 2015).

The available literature on the subject shows that steel fibre reinforcement can increase significantly the shear, the flexural and the punching resistance, as well as the energy dissipation capacity and durability of concrete structures.

In studying the effect of steel fibres on the shear capacity of concrete, some investigations were carried out for evaluating the performance of beam–column sub assemblages. Susetyo et al., 2013 conducted experimental investigations on concrete panels under in-plane pure-shear monotonic loading conditions to evaluate the effectiveness of steel fibres in meeting minimum shear reinforcement requirements for concrete elements. The test results indicate that concrete elements exhibiting ductile behaviour, sufficient shear strength, and good crack control characteristics can be obtained with an adequate addition of steel fibres, meeting or exceeding the level of performance achievable using code prescribed minimum amounts of conventional shear reinforcement. The role of steel fibres in enhancing the shear strength of concrete was also confirmed by many researchers (Aoude et al., 2012; Barros et al., 2014; Lee, 2007).

Moreover, has noteworthy effect on the residual tensile strength and flexural strength. The flexural behaviour of concrete reinforced with straight and hooked end steel fibres was studied by Pajak et al., 2013. It was found that the increase of fibres volume ratio increases the flexural tensile strength. The fracture energy increases with the increase of fibre dosage and is higher for hooked end steel fibres than for straight ones. Steel fibres continue to carry stresses after matrix failure. This is also confirmed by many researchers (Barros et al., 2014; Caggiano et al., 2012; De Montaignac, 2012).

Labib 2008 conducted experimental investigations on concrete slab-column connections reinforced with hooked end steel fibres failing in punching, It was found that the inclusion of steel fibres significantly increases the load carrying capacity of tested specimens and is strongly dependent on the fibre dosage. Moreover, the crack opening restraint provided by the reinforcement mechanisms of steel fibres bridging the crack surfaces lead to significant increase in terms of load carrying capacity and energy absorption capability of concrete structures. This was also confirmed by (Safeer et al., 2004; Ventura-Gouveia, 2011).

The role of fibres in bridging the crack opening and enhancing the load capacity and post-peak behaviour leads to better concrete durability and structural integrity (Banthia et al., 2010; Granju et al., 2005; Kunieda et al., 2014). The was also confirmed by the experimental results of Stephen 2001 which showed that the introduction of steel fibres into the concrete can arrest the early spalling of the concrete cover and increase the load capacity as well as the ductility of the columns over that of comparable non-fibre reinforced specimens. Similar observations were reported more recently by Lee, 2007, Joao, 2010 and Röhm et al., 2012.

3.2 Synthetic Fibres

Synthetic fibres are man-made fibres resulting from research and development in the petrochemical and textile industries. Synthetic fibre reinforced concrete utilises fibres derived from organic polymers which are available in a variety of formulations (ACI Committee 544.1R, 1996). Synthetic, organic fibres have low modulus of elasticity and high elongation properties (Manolis et al, 1997). Therefore, they have the potential to provide concrete with significant ductility. As a result, when added to concrete these fibres are able to control cracking caused by thermal movements and long-term drying shrinkage

(Concrete Society, 2003) and improve the performance of concrete by negates its disadvantages such as low tensile strength, low ductility, and low energy absorption capacity (Lakshmi et al., 2010; Chanvillard et al., 1990; Mu et al., 2000; Bayasi, et al., 1997; Banthia et al., 1996).

Synthetic fibre types that have been tried in Portland cement concrete based matrices are: polypropylene, glass,carbon, polyolefin and polyvinyl. For many of these fibres there is little reported research or field experience, while others are found in commercial applications and have been the subject of extensive reporting (ACI Committee 544.1R, 1996). Among these materials, polypropylene fibres are one of the most widely used for construction applications such as blast resistant concrete and pavements (Mwangi, 2001).

3.2.1 Polypropylene Fibres

Polypropylene fibres are gaining in significance due to the low price of the raw polymer material and their high alkaline resistance (Keer, 1984; Maidl, 1995). They are available in two forms i.e.monofilament or fibrillated manufactured in a continuous process by extrusion of a polypropylene homopolymer resin (Keer, 1984; Knapton, 2003). Polypropylene fibres are used extensively in concrete for the purpose of reducing, plastic shrinkage cracking and plastic settlement cracking (Perry, 2003).

Mazaheripour et al., 2011, investigate the effect of polypropylene fibres inclusion on fresh and hardened properties of concrete. The results obtained have shown that the polypropylene fibres did not influence the compressive strength and elastic modulus, however applying these fibres at their maximum percentage volume increased the tensile strength and the flexural strength of concrete.

Fire still remains one of the most serious risks for tunnels, buildings and other concrete structures. Therefore, there is need for engineers to greatly take into consideration the risks associated with elevated temperatures when designing concrete structures, such as explosive spalling which has been observed by many researchers often resulting in serious deterioration of the concrete (Phan et al., 2002; Horiguchi et al., 2004).

It has been widely shown that polypropylene fibres are very effective in mitigating spalling in concrete exposed to elevated temperatures. Bangi et al., 2012 carried out an experimental and study which investigates the effect of fibre type and geometry on the amount of maximum pore pressures measured at different depths in fibre-reinforced high strength concrete exposed to elevated temperatures. Polypropylene, polyvinyl alcohol and steel fibres of varying lengths and diameters were used. Pore pressure measurements showed that addition of organic fibres regardless of the type significantly contributes to pore pressure reduction in heated concrete. Polypropylene fibres were more effective in mitigating maximum pore pressure development compared to polyvinyl alcohol fibres while steel fibres had a slightly low effect. This result has been proved by studies from different researchers. They found that the complex mechanism of porosity variations in concrete at elevated temperatures, enriched with polypropylene fibres (Khoury, 2008; Kalifa, 2001; Han et al., 2005; Zeimi et al., 2006; Muzzucco et al., 2015)

On the other hand, polypropylene fibres can improve not only mechanical properties of concrete but also its durability due to reduced crack width by fibre bridging effect. Therefore, it could be considered as solutions to extend of lifecycle in terms of improvement of durability (Kunieda et al., 2014).

3.2.2 Other Synthetic Fibres

As stated previously, while polypropylene is extensively used in concrete other synthetic fibres such as: glass, carbon, polyolefin and polyvinyl had little reported research or field experience.

Barhum et al., 2012 studied the influence of the addition of short, dispersed fibres made of alkali-resistant (AR) glass and carbon on the fracture behaviour of textile-reinforced concrete. A series of uniaxial, deformation-controlled tension tests was performed to study the strength, deformation, and fracture behaviour of the concrete specimens with and without the addition of short fibres. Pronounced enhancement of first-crack stress was achieved due to the addition of glass and carbon fibres. While more and finer cracks were observed on the specimens with short fibres added, a moderate improvement in tensile strength was recorded.

However, recent studies have showed that, when polyolefin based fibres employed to reinforce concrete, forming polyolefin fibre reinforced concrete, they are not only chemically stable (which avoids the corrosion problems that steel fibres suffer) but also lighter and with a final lower cost. They have been proved to be suitable for structural uses. Moreover, in some cases they have substituted steel fibres (Behfarnia et al., 2014; Pujadas et al., 2014; Alberti et al., 2015). On the other hand, polyvinyl alcohol organic fibres and nylon are also effective in mitigating spalling while others like polyethylene fibres are not so effective.

Investigations from Laura et al., 2014 indicated that the use of synthetic fibre reinforced concrete can enhance the ductility and energy dissipation capacity of concrete.

3.2.3 Waste fibres

The use of waste fibres plays an important role in sustainable solid waste management. It helps to save natural resources, decreases the pollution of the environment and save energy production processes. It has beneficial environmental and economic impacts therefore wastes and industrial by-products should be considered as potentially valuable resources merely awaiting appropriate treatment and application (Graeff et al., 201; Neocleous et al., 2006). Therefore, the addition of waste to concrete corresponds to a new perspective in research activities, integrating the areas of concrete technology and environmental technology.

Steel fibres originated from the industry of tyres and plastic wastes are among these wastes; their disposal has harmful effects on the environment due to their long biodegradation period, and therefore one of the logical methods for reduction of their negative effects is the application of these materials in other industries.
Recent research is showing that steel fibres originated from the industry of tyre recycling, can be a valuable reinforcement system to decrease significantly the brittle behaviour of cement based materials, by improving their toughness and post-cracking resistance. Recycled Steel Fibre Reinforced Concrete is therefore becoming a promising candidate for both structural and non-structural applications (Aiello et al., 2009). Zamanzadeh et al., 2015 compared the characterisation of the post cracking properties of recycled steel fibre reinforced concrete and industrial steel fibre reinforced Concrete, on its use as shear reinforcement. Although the results indicated that the fibre reinforcement mechanisms for relatively small crack width levels were not as effective in the recycled steel fibres as were

in the industrial steel fibres, but it was verified that both fibres have similar trend in the post-cracking behaviour.

Much research effort has focused on reusing waste materials from plastic industries in concrete. Different works, have analyzed the effect of addition of recycled polyethylene terephthalate (PET) to the properties of concrete (Choi et al. 2005, Jo et al., 2007; Robeiz, 1995). Foti, 2011 analyzed the reinforced concrete with PET bottles waste fibres and found that adding little amount of recycled fibres from PET bottle wastes can have a great influence on post-cracking performance of simple concrete elements. As well, these fibres improve the toughness of samples and increase the plasticity of concrete. De Oliveira et al., 2011 used fibres made from recycled PET bottles in reinforced mortar. Their results showed that using PET fibres makes a significant improvement on compressive strength of mortars, in addition to a noticeable effect on their flexural strength along with increase in their toughness. The work realised by Foti, 2013 is to explore the possibility of recycling PET fibres, obtained from waste bottles with different shapes. The tests showed that PET fibers in a concrete mixture are likely to increase the ductility of concrete.

At the end, as limited research has been carried out in this area, therefore, more studies could be carried out on the effect of using the previously mentioned wastes on the mechanical properties of concrete to prove the above results and to further examine different mechanical properties. In addition, the effect of using other types of wastes on the mechanical properties of concrete could be investigated.

3.3 Effect of using hybrid fibres

Although, the research mentioned above have convinced us that remarkable improvement in mechanic performance can be achieved by using single fibre type in concrete, it is worth noting that the failure in concrete is a gradual and multi-scale process, each type of fibre can only be effective in a limited range, an optimal performance cannot been attained when single FRC is used. Therefore, attempts have been made to use fibre combinations with different constitutive responses, dimensions and functions into cementitious composite. The use of hybrid combinations of steel and non-metallic fibres can offer potential advantages in improving concrete properties as well as reducing the overall cost of concrete production (Bentur and Mindess, 1990). When fibre fractions are increased, it results in a denser and more uniform distribution of fibres throughout the concrete, which reduces shrinkage cracks and improves post-crack strength of concrete. This combination of low and high modulus fibres can arrest the micro and macro cracks respectively which could be also achieved by using combination of long and short fibres as different lengths of fibres would control different scales of cracking.

A number of studies indicated the overall benefits of using combinations of steel fibres and polypropylene fibres (Xu et al., 2011; Sivakumar,2011; Chi, 2014; Ding et al., 2010; Sahoo et al., 2015). While limited research was carried out on the effect of using steel fibres and other types of fibres such as glass, polyethylene (Banthia et al., 2014), or using a mix of short and long steel fibres (Caggiano et al., 2012).

Xu et al., 2011 found that the tensile strength of steel-polypropylene hybrid fibre reinforced concrete. The results indicate that the tensile strength of conventional concrete can be dramatically improved by mixing with hybrid steel-polypropylene fibres. The enhancing effect of hybrid fibre is better than that of single fibre, and the volume fraction of steel fibre is observed to have a great impact on the tensile strength. The same results were found by Sivakumar,2011 who studied the flexural strength, toughness, and ductility of concrete specimens containing individual steel fibres and hybrid combinations of steel and non-metallic fibres such as glass, polyester and polypropylene. He found that the ability of non-metallic fibres of bridging smaller micro cracks, was suggested as the reasons for the enhancement in flexural properties compared to individual steel fibre.

The effect of inclusion hybrid steel-polypropylene fibre reinforced concrete on triaxial compression was developed by Chi, 2014. The results showed that the steel fibres mainly contribute to the composite's triaxial strength that was observed to improve significantly when both the volume fractions and aspect ratios of steel fibre were increased. On the other hand, the polypropylene fibres were found to have considerable effect on improving the tensile meridian rather than compressive meridian.

Ding et al. 2010 analysed the influence of various fibre types, including steel macro-fibre and hybrid fibre (macro-steel fibre and macro plastic fibre) on the shear strength and shear toughness of reinforced concrete beams. The results indicated that hybrid fibers can evidently enhance both the shear toughness and the ultimate shear bearing capacity.

Sahoo et al., 2015 studied the influence of using both high-modulus (steel) and low-modulus (polypropylene) fibres on the shear strength of reinforced concrete beams. A better post-peak residual strength response is noticed in case of all FRC beam specimens due to multiple cracking associated with the fibre bridging action. The main parameters investigated are shear strength, failure mechanism and displacement ductility. The FRC specimens with combined steel and polypropylene fibres showed that the shear resistance and deformability values are improved significantly multiple cracks of smaller crack width are noticed at the failure stage of the specimens indicating the better fibre bridging action of combined metallic and non-metallic fibres.

Banthia et al., 2014 used hybrid fibres by using two types of macro-steel fibres and a micro-cellulose fibre. Flexural and direct shear tests were performed and the results were analyzed to identify the degree of enhancement in the mechanical properties associated with various fibre combinations.

4. Conclusion and future research

This paper investigated into the potential of using various types of fibres in reinforced concrete to optimise the properties of concrete material as well as improve the mechanical performance of reinforced concrete members. The reviewed literature highlighted the role of fibres in enhancing the concrete tensile strength, bending strength; shear strength, toughness, energy dissipation capacity, resistance to cracking and fire resistance. The reviewed literature also indicated that, in most cases FRC contains individual type of fibres, which includes steel, polypropylene, glass, carbon, polyolefin and polyvinyl. Although of the extensive research conducted on the FRC, the reviewed literature showed a dearth of research conducted on waste fibre. The reviewed literature highlighted that the research conducted on the use of waste fibre in concrete is limited to the effect of waste fibre on toughness, flexural strength, compression strength and post-peak behaviour of concrete elements. The literature showed no studies conducted on effect of waste fibre on the shear and punching shear strength of concrete. This paper concluded with a recommendation into a future research on the effect of waste fibre on the punching shear capacity of concrete.

In addition, this paper reported on the use of two or more types of fibres in a suitable combination which has proved the potential to improve the mechanical properties of concrete. Numerous studies on hybrid fibre reinforced concrete have been performed The reviewed literature showed that combining of fibres is commonly limited to two types of mixes, a mix of steel and polypropylene fibres and a mix of steel fibres with different geometry, shape and size. This paper further recommended on future research to be carried out on the use of different hybrid fibres including, but not limited to, steel-recycled tyre hybrid and steel-plastic waste and investigates their effects on different mechanical properties of concrete.

Acknowledgements

The work presented herein was funded by Prince Sultan University, Riyadh, KSA. The financial support is gratefully acknowledged.

References

[1] ACI Committee 544.1R. *Fibre reinforced concrete*, 1996, American concrete institute, Michigan, USA.

[2] Aiello MA, Leuzzi F, Centonze G, Maffezzoli A. *Use of steel fibres recovered from waste tyres as reinforcement in concrete: pull-out behaviour, compressive and flexural strength*. Waste Manage 2009, 29(6), 1960–70.

[3] Alberti MG, Enfedaque A, Galvez JC. *On the mechanical properties and fracture behavior of polyolefin fiber*-reinforced *self-compacting concrete*. Constr Build Mater 2014, 55, 274–288.

[4] Aoude A, Belghiti M, Cook W, Mitchell D. *Response of steel fibre-reinforced concrete beams with and* without *stirrup*s. ACI Struct J 2012,109(3), 359–68.

[5] Bangi M, Horiguchi T, *Effect of fibre type and geometry on maximum pore pressures in fibre-reinforced high* strength *concrete at elevated temperatures*, Cement and Concrete Research 42 (2012) 459–466.

[6] Banthia N, Krstulovic N, Galiant M. *Report on the physical properties and durability of fiber-reinforced concrete*. ACI 544.5R-10, reported by ACI Committee 544; 2010.

[7] Banthia N, Majdzadeh F, Wu J, Bindiganavile V. *Fiber synergy in hybrid fiber reinforced concrete (HyFRC) in flexure and direct shear*. Cem Concr Compos 2014, 48, 91–97.

[8] Banthia N, Sheng J. *Fracture toughness of micro-fiber reinforced cement composites*. Cement Concrete Comp 1996, 18, 251–69.

[9] Barhum R, Mechtchenne /v, *Effect of short, dispersed glass and carbon fibres on the behaviour of textile-reinforced concrete under tensile loadin*g Engineering Fracture Mechanics, Volume 92, September 2012, Pages 56–71

[10] Barros JA, Lourenço LA, Soltanzadeh F, Taheri M. *Steel fibre reinforced concrete for elements failing in bending and in shear*. Eur J Environ Civil Eng 2014,18(1), 33–65

[11] Bayasi MZ, Zeng J. *Composite slab construction utilizing carbon fiber reinforced mortar*. ACI Struct J 1997, 94, 442–6.

[12] Behfarnia K, Behravan A. *Application of high performance polypropylene fibers in concrete lining of water tunnels*. Mater Des 2014, 55, 274–279.

[13] Bentur A, Mindess S. Fiber reinforced cementitious composites. New York: Elsevier Applied Science, 1990.

[14] Brandt A. Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering. Compos Struct 2008, 86, 3–9.

[15] Buratti N, Mazzotti C, Savoia M. Post-cracking behaviour of steel and macrosynthetic fibre-reinforced concretes. Constr Build Mater 2011, 25, 2713–2722.

[16] Caggiano A Cremona M, Faella C., Lima C, Martinelli E, *Fracture behavior of concrete beams* reinforced *with mixed long/short steel fibers*, construction and building materials journal, Volume 37, December 2012, Pages 832–840

[17] Chanvillard G, Aitcin P. *Thin bonded overlays of fiber-reinforced concrete as a method of rehabilitation of concrete roads*. Can J Civil Eng 1990, 17, 521–7.

[18] Chi Y, Xu LH, Mei GD, Hu N, Su J. *A unified failure envelop for hybrid fiber reinforced concrete subjected to true triaxial compression*. Compos Struct 2014, 109, 31–40.

[19] Chi Y, Xu LH, Zhang YY. *Experimental study on hybrid fiber-reinforced concrete subjected to uniaxial compression*. J Mater Civ Eng 2014, 26, 211–8.

[20] Choi Y-W, Moon D-J, Chung J-S, Cho S-K. *Effects of waste PET bottles aggregate on the* properties *of concrete*. Cement Concr Res 2005, 35, 776–781.

[21] Concrete Society, (2003) *Concrete industrial floors-A guide to their design and* construction,

[22] De Montaignac R, Massicotte B, Charron JP. *Design of SFRC structural elements: flexural behaviour prediction*. Mater Struct 2012, 45(4), 623–36.

[23] De Oliveira LAP, Castro-Gomes JP. *Physical and mechanical behaviour of recycled PET fibre* reinforced *mortar*. Constr Build Mater 2011, 25, 1712–1717.

[24] Di Prisco M, Plizzari G, Vandewalle L. *Fibre reinforced concrete: new design* perspectives. Mater Struct 2009,42(9),1261–81.

[25] Ding YN, You Z, Jalali S. *Hybrid fiber influence on strength and toughness of RC beams*. Compos Struct 2010, 92, 2083–2089.

[26] Foti D. Preliminary *analysis of concrete reinforced with waste bottles PET fibers*. Constr Build Mater 2011, 25, 1906–1915.

[27] Foti D. *Use of recycled waste pet bottles fibers for the reinforcement of concrete*. Comp Struct 2013, 96, 396–404.

[28] Graeff A, Pilakoutas K, Neocleous K, Peres MV. *Fatigue resistance and cracking mechanism of concrete* pavements *reinforced with recycled steel fibres recovered from post-consumer tyres*. Eng Struct 2012, 45, 385–95.

[29] Granju J, Balouch S. Corrosion *of steel fibre reinforced concrete from the* cracks. Cem Concr Res 2005, 35(3), 572–7.

[30] Han CG, Hawang YS, Yang SH, Gowripalan N. *Performance of spalling resistance of high performance concrete* with *polypropylene fiber contents and lateral confinement*. Cem Concr Res 2005, 35, 1747–1753.

[31] Horiguchi T, Sugawara T, Saeki N, *Fire resistance of hybrid fiber reinforced high strength concrete*, 39, RILEM Publications PRO, 2004, pp. 303–310.

[32] Huang L., Xu L., Chi Y. & Xu H., *Experimental investigation on the seismic performance of* steelpolypropylene *hybrid fiber reinforcedconcrete columns,* Construction and Building Materials, Volume 87, 15 July 2015, Pages 16-27

[33] Jo B-W, Tae G-H, Kim C-H. *Uniaxial creep behavior and prediction of recycled-PET polymer concrete*. Constr Build Mater 2007, 21, 1552–9.

[34] Joao P. *Behaviour of fiber reinforced concrete columns in fire*. Compos Struct 2010, 92, 1263–1268.

[35] Kalifa P, Chene G, Galle G., *High* temperature *behaviour of HPC with polypropylene fibres from spalling to microstructure,* Cem. Concr. Res. 31 (2001) 1487–1499.

[36] Katzer J, Domski J. Quality and mechanical properties of engineered steel fibres used as reinforcement for concrete. Constr Build Mater 2012, 34, 243–8.

[37] Katzer J. *Steel fibres and steel fibre reinforced concrete in civil engineering*. Pac J Sci Technol 2006,7(1),53–8.

[38] Keer, J., (1984) Fibre reinforced concrete, in *Concrete Technology and Design*, volume 2: New reinforced concretes, Ed. Swamy RN, Surry University Press, London.

[39] Khoury GA. Polypropylene fibres in heated concrete. Part 2: Pressure relief mechanisms and modelling criteria. Mag Concr Res 2008, 60(3), 189–204.

[40] Knapton, J., (2003) *Ground* bearing *concrete slabs*, Thomas Telford, London

[41] Kunieda M, Ueda N, Nakamura H. *Ability of recycling on fiber reinforced concrete*. Constr Build Mater 2014, 67, 315– 320.

[42] Labib W, 2008. an experimental study and finite element analysis of punching shear failure in steel fibre-reinforced concrete ground-suspended floor slabs, Liverpool John Moores University, Liverpool, UK.

[43] Lakshmi R, Nagan S. *Studies on concrete containing E plastic waste*. Int J Env Sci 2010, 1, 270–81.

[44] Laura I, Patrick P, Rami E, Jean P. Seismic behavior of synthetic fiber-reinforced circular columns. ACI Mater J 2014, 111, 189–200.

[45] Lee H. *Shear* strength *and behavior of steel fiber reinforced concrete columns under seismic loading*. Eng Struct 2007;29,1253–62.

[46] Lee S, Cho J, *Vecchio FJ. Diverse embedment model for fibre-reinforced concrete in tension: model development*. ACI Mater J 2011, 108(5), 516–525.

[47] Maidl B. *Steel* fibre *reinforced concrete*. 1995, Bernhard R. Maidl/ in co-operation with Jorg Dietrich, Ernst & Sohn, Berlin.

[48] Manolis, G, Gareis P, Tsonos A, Neal J. *Dynamic properties of polypropylene fibre-reinforced concrete slabs, Cement and Concrete Composites*, 1997, 19, pp. 341-349.

[49] Mazaheripour H, Ghanbarpour S, Mirmoradi S, Hosseinpour I. *The effect of polypropylene fibers on the properties of fresh and hardened lightweight selfcompacting concrete*. Constr Build Mater 2011, 25, 351 358.

[50] Mazzucco G, Majorana C, Salomoni V, *Numerical simulation of polypropylene fibres in concrete materials under fire conditions*, Computers and Structures 154 (2015) 17–28.

[51] Mu B, Li Z, Peng J. *Short fiber-reinforced cementitious extruded plates with high percentage of slag and different fibers*. Cement Concr Res 2000, 30, 1277–1282.

[52] Mwangi J. *Flexural behavior of sisal fiber reinforced concrete beams. Doctoral* dissertation, University of California, Davis; 2001.

[53] Neocleous K, Tlemat H, Pilakoutas K. *Design issues for concrete reinforced with steel fibres, including fibres recovered from used tyres*. Mater Civil Eng 2006,18(5), 677–85.

[54] Ozcan O, Binici B, Ozcebe G. *Improving seismic performance of deficient reinforced concrete columns using carbon fiber-reinforced polymers*. Eng Struct 2008,30,1632–46.

[55] Pajak M, Ponikiewski T, *Flexural behavior of self-compacting concrete reinforced with different types of steel fibers*, Construction and Building Materials 2013, 47, 397–408.

[56] Perry, B., (2003) *Reinforcing external* pavements *with both large and small synthetic fibres*, 37 (8), pp.46-47.

[57] Phan L, Carino N, *Effects of test conditions and mixture proportions on behaviour of high-strength concrete exposed to high* temperature, ACI Materials Journal (January-February 2002) 54–66.

[58] Pujadas P, Blanco A, Cavalaro SHP, Aguado A, Grunewald S, Blom K, et al. Plastic fibres as the only reinforcement for flat suspended slabs: parametric study and design considerations. Constr Build Mater 2014,70,88–96.

[59] Qian CX, Stroeven P. *Development of* hybrid *polypropylene–steel fiber reinforced concrete*. Ceme Concr Res 2000, 30, 63–9.

[60] Qian CX, Stroeven P. *Fracture* properties *of concrete reinforced with steel–polypropylene hybrid fibers*, Cem Concr Compos 2002, 22, 343–351.

[61] Rebeiz K. *Time-temperature properties of polymer concrete using recycled PET*. Cement Concr Comp 1995, 17, 119–24.

[62] Röhm C, Novák B, Sasmal S, Karusala R, Srinivas V. *Behaviour of fibre reinforced beam-column sub-assemblages under* reversed *cyclic loading*. Constr Build Mater 2012, 36, 319–329.

[63] Safeer H, Ahmed M, Moncef L. *Experimental study on settlement and pnching behaviour of full-scale RC and SFRC precast tunnel lining segments*. Eng Struct 2004, 72(1), 1–10.

[64] Sahoo D., Maran K. and Kumar A., *Effect of steel and synthetic fibers on shear strength of RC beams without shear* stirrups, *Construction and building materials* 2015, 83, 150-158.

[65] Sivakumar A. *Influence of hybrid fibers on the post crack performance of high strength concrete*: Part I. Experimental investigations. J Civ Eng Constr Technol 2011, 2, 147–59.

[66] Stephen J. On *behavior of high-strength concrete columns: cover spalling, steel fibers and ductility*. ACI Struct J 2001, 8, 583–589.

[67] Suhaendi S, Horiguchi T, *Effect of short fibers on residual permeability and mechanical* properties *of hybrid fibre reinforced high strength concrete after heat exposition*, Cem. Concr. Res. 36 (9) (2006) 1672–1678.

[68] Susetyo J, Gauvreau P, and Frank J. *Steel Fiber-Reinforced Concrete Panels in Shear:* Analysis *and Modeling*. 2013, ACI Structural Journal, March-April, 284-296.

[69] Ventura-Gouveia A, Barros J, Azevedo A. *Crack constitutive model for the prediction of* punching *failure modes of fibre reinforced concrete laminar structures*. Comput Concrete 2011, 8(6), 735–755.

[70] Xu LH, Xu HR, Chi Y, Zhang YY. *Experimental study on tensile strength of steel–polypropylene hybrid fiber reinforced concrete*. Adv Sci Lett 2011, 4, 911–916.

[71] Zamanzadeh Z, Lourenço L, Barros J, *Recycled Steel Fibre Reinforced Concrete failing in bending and in shear*, Construction and Building Materials 2015, 85, 195–207.

[72] Zeiml M, Leithner D, Lackner R. *How do polypropylene fibers improve the spalling behavior of in-situ concrete?* Cement Concrete Research 2006, 36, 929–942.