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REUSE OF TYRE STEEL FIBRES AS CONCRETE REINFORCEMENT

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SYNOPSIS

To attain economically viable and environmentally friendly tyre recycling, it is necessary to develop new applications and products, which will use tyre by-products (especially the steel cord) as raw materials. The authors demonstrate that the steel fibres recovered from used tyres can be used to reinforce concrete elements. This application has a great potential, as it is estimated that more than 500,000 tonnes of high quality steel fibres could be recovered annually from used tyres in the EU alone. This paper presents the work carried out as part of various ongoing projects on the use of steel fibres in concrete construction. The first part of the paper deals with waste management issues, the methods used to recover steel fibres from tyres, and existing applications of used tyres. The second part presents the mechanical behaviour of concrete elements reinforced with these steel fibres and discusses the relevant design and economic issues. It is concluded that the use of these steel fibres in concrete construction will not just benefit the construction industry, but will also benefit the producers and recyclers of used tyres.

1. INTRODUCTION

The waste management of used tyres is of major concern for many environmental bodies and agencies worldwide. This is especially true in the European Union (EU), where environmental legislation is the driving force behind the waste management of used tyres. Following the implementation of various European Union (EU) directives[1,2], reuse of tyres and material recovery have become the most environmentally viable ways for disposing used tyres.

Material recovery from used tyres is undertaken by utilising either mechanical or thermal degradation processes. The former reduces tyres to steel fibres and granulated rubber and, the latter process breaks down the tyres into steel, char, liquids, and gases. To comply with the various EU directives, EU member states need to develop markets and applications, which will utilise used tyres as a secondary raw material. This is especially challenging for the recovered steel fibres (RSF), which are currently either used as scrap feed in steel manufacturing or disposed of to landfills.

RSF could be utilised as concrete reinforcement and recent research[3,4,5,6,7,8] shows that the application of RSF in concrete leads to an increase in concrete strength, ductility, and toughness. The use of RSF in concrete (like any other type of steel fibres) can eliminate the use of conventional reinforcement and can increase the speed of construction.

This paper presents the work performed on concrete elements reinforced with RSF (RSFRC). This work forms part of an EU Marie-Curie research fellowship[9], a PhD Thesis[10] funded by the University of Sheffield, and the completed project[11] "Demonstrating Steel Fibres from Waste Tyres as Reinforcement in Concrete", which was funded under the Partners in Innovation scheme by the UK Department of Trade and Industry.

The first part of the paper provides a general introduction on the waste management of used tyres in both the UK and EU. The most recent statistics for the arisings and waste management of used tyres are presented and the factors influencing these statistics are discussed. Then, the methods currently used to recover RSF from used tyres are presented. To highlight the need for developing new markets for RSF, the last section of this part presents existing engineering and industrial applications of whole tyres and their by-products. The second part describes the research carried out on the engineering and economic aspects related to the use of RSF in concrete.

PART A

2. WASTE MANAGEMENT OF USED TYRES

It is estimated[12] that, worldwide, more than one billion used tyres arise annually. Nearly a quarter of this amount arises in the EU alone, and approximately 50 million tyres reach the end of their lives in the UK per year.

There are many ways that used tyres can be managed, such as energy recovery, material recovery, retreading, exports, and disposal to landfill. Fig. 1 shows that, during 2002, the majority of used tyres in the EU were recovered and only one third of them were sent to landfill. Similar values were published[13] in the UK for 2001 (Fig. 2).

The waste management of used tyres is greatly influenced by environmental legislation. Typical examples are the EU Landfill[1] and Waste Incineration[2] directives. The former has already prohibited the disposal of whole tyres to landfill (from July 2003), and it will prohibit the disposal of tyre by-products to landfill by 2006. The European Tyre Recycling Association reported[12] that some of the EU member states (such as Sweden and Finland)[13] stopped the disposal of tyres to landfills by 2002. The implementation of the latter directive in the UK resulted in the application of environmental controls on the use of tyres for energy recovery. The main outcome of these controls was the short-term reduction in the use of tyres for energy recovery[13]. The implementation of the EU End-of-Life-Vehicle[14] directive is expected to increase further the amount of used tyres that would have to be reused or recycled, as this directive aims at ambitiously high rates of vehicle recovery and recycling.

The definition of waste is another obstacle that affects the recycling and reuse of used tyres in the UK. A used tyre and its constituents are waste materials and must be managed according to regulatory controls, until they are physically reused[13,15]. This naturally increases the cost of tyre recycling and prohibits the entry of new players into the industry. It is noted that the European Council has recently decided[16] to legally clarify the definition of waste and, hence, this action may have a favourable effect for the waste management of tyres.

The waste management of used tyres is also affected by economics factors and the public perception about recycled or reused products. A typical example is retread tyres, whose demand has constantly declined over the years following the reduction in the price of new tyres and the negative public perception about the quality of retread tyres[17].

3. RECOVERY OF STEEL FIBRES FROM TYRES

Tyre shredding and the cryogenic process can be used to mechanically recover RSF from used tyres. In addition, steel fibres can be recovered by utilising anaerobic thermal degradation, such as conventional pyrolysis and microwave-induced[18] pyrolysis of tyres. The amount of extracted steel fibres depends mainly on the type of tyre. Tyres of light vehicles contain up to 15% steel, whereas truck tyres contain up to 25% steel[15].

3.1 Shredding Process

The shredding process reduces tyres into rubber granules and steel fibres through a number of cutting and granulating stages. In the first stage of processing, a complete tyre is chopped or shredded until it is reduced to pieces ranging in size from about 50 to 150 mm. The rubber pieces, which still contain steel, are then fed into a second shredder that reduces them to smaller pieces (Fig. 3a). At the end of this stage, magnets are used to separate the steel from the rubber (Fig. 3-b). The rubber is then fed into a knife or hammer mill, where it is granulated to approximately 1 to 10 mm in size. The number of grinding cycles depends on the desired size of the rubber granules. During the granulating process, magnets are used to remove any remaining steel.

The steel extracted after the second stage of shredding and the final stage of grinding differs in quality. The former contains large pieces of rubber as well as much of the textile wire in long lengths. The cord is sometimes undamaged, but much of it is deteriorated into individual wires.

The latter is much finer, comprising mostly of thin individual steel wires, but still containing around 10% rubber and fluff.

Mechanical shredding is considered as a commercially mature and technologically reliable process. However, it can be quite costly, as the cutting blades require constant maintenance. The rate of deterioration of the blades is high because the tyre contains high strength steel and the steel in the bead is normally of a large diameter. It is noted that tyre shredding has increased over the years, as it is more economical to transport shredded tyres rather than whole tyres[13].

3.2 Cryogenic Process

The cryogenic process[19,20] involves the cooling of tyres, and their subsequent brittle fracturing and reduction to rubber, steel, and textile. In a typical cryogenic process, the used tyres are initially shredded at ambient temperature, and then transferred to a deep-freezing tunnel system. Inside the first tunnel section, the fragmented tyres are pre-cooled by a counter-current of gaseous nitrogen at approximately -120°C. The tyre pieces are then transferred into the main cooling tunnel, where they are cooled down below their embrittling temperature and, as a result, they become nearly brittle. At the next stage, the fragmented tyres are granulated through a series of mills, and are reduced to rubber, steel fibres, and textile. The steel and textile are separated, whereas the rubber granules are dried, passed through a steel extraction unit, and finally sieved.

The extracted steel is fairly clean, but it may loose its ductility, if it is cooled down below its embrittling temperature[21]. The cryogenic process is considered to be energy efficient because it requires less energy to separate the rubber from the steel rather than ambient-temperature processes[19]. However, the high cost of liquid nitrogen is the main drawback of this process.

3.3 Pyrolysis Process

Pyrolysis[22, 23] of tyres is the process where tyres are thermally decomposed, in the absence of oxygen, to their organic and inorganic components. The process generates gases (hydrogen, methane and other hydrocarbons), oil, and solid residuals of steel and char, which is a low grade carbon black. The balance between the end-products of the process can be altered by changing the imposed conditions, such as the heating temperature and duration. In a typical pyrolysis plant, used tyres are fed into a pyrolysis reactor, where they are heated to the desired temperature. The gases and the liquids are separated from the extracted vapours through a system of gas-liquid separators. At the end of the process, the steel is separated from the char and the char is ground.

The steel comes out of the process still containing some char on its surface. In most pyrolysis plants, the tyres are shredded before being fed to the reactor and, hence, the RSF are already damaged to a certain degree, as in the case of the shredding process.

Since the pyrolysis process is contained, the release of combustion gases is minimised[22]. Pyrolysis is energy efficient because the derived gases and oil have high calorific value and can be used for the energy requirements of the process. It is noted that it can be difficult to market some of the pyrolysis end-products due to their low quality (especially the char), and consequently, many pyrolysis plants are not economically viable[24].

3.4 Microwave Induced Pyrolysis Process

The microwave-induced pyrolysis process[18], called “Advanced Molecular Agitation Technology”, optimises microwave power at the molecular level to thermally decompose tyres to their constituents. According to the developers of this process[18], the microwaves excite the molecular bonds of the long-chain rubber hydrocarbons enough to break them into shorter hydrocarbons, which are released as volatile gases at a temperature around 350°C. The process operates at relatively low temperatures and hence, the derived steel cord and textile wire remain intact, while the rubber is converted to oil, gases, and char. Similarly to the conventional pyrolysis process, the gases can be used for the energy requirements of the process. The derived steel cord, shown in Fig. 4, can be cut to any length.

4. GENERAL ENGINEERING & INDUSTRIAL APPLICATIONS

Used tyres are being utilised in a variety of engineering and industrial applications and numerous examples are published in the literature. These applications can be divided into two main categories: a) the ones that use either whole or fragmented tyres, and b) the ones that use the tyre constituents, such as rubber, char and steel.

4.1 Whole and fragmented tyres

Whole tyres are used for the construction of retaining walls (such as in “green” housing)[25], floating breakwaters[12], boat fenders[12], artificial reefs[26,27] (Fig. 5), temporary roadways[12], slope stabilisation and erosion control[12]. They are also utilised in landfill engineering[12,15] for a number of applications, such as drainage systems to collect leachate and gas. Strips of tyres, extracted by cutting the sideways of whole tyres, can also be used to produce elements encapsulated with resin (such as roof tiles, floors, crash barriers, insulation and acoustic panels, and railway sleepers)[28].

Fragmented tyres (such as those obtained from the first stage of the shredding process) are used to stabilise slopes, to fill surface and septic drainage systems, and embankments[12,15]. They are also used as fuel for power generation[13].

4.2 Tyre constituents

Granulated rubber, extracted from the mechanical recycling of tyres, is utilised in the manufacturing of asphalt[29]. The use of rubber offers advantages such as improved durability of asphalt and reduction of the noise generated by traffic. The use of recycled rubber crumb as aggregate in concrete was also proposed[30]. However, this type of application is not currently viable because the cost of recycled rubber is much higher than that of natural aggregates.

Granulated rubber is also utilised in many industrial products. It is used in the production of new tyres[12], synthetic sport and playground surfaces[31], and expansion joints[12] for bridges and roads. Other products[12] include roof and floor tiles, porous drain pipes, office furniture and camping equipment.

Carbon black, extracted from the pyrolysis process, can be used in the manufacturing of tyres and industrial rubber products, as well as pigments (for printing inks, paints and plastics), as long as it is upgraded to high grade carbon black[22].

Whilst there is demand and established markets for the granulated rubber and carbon black, there are very few applications that utilise the RSF. Currently, the majority of RSF in the UK is either disposed of to landfills or used as scrap feed in steel manufacturing. One possible area of application is concrete construction, where industrially manufactured steel fibres are successfully replacing conventional reinforcement bar (re-bar) in a range of applications (such as sprayed concrete, slabs-on-grade, and precast elements).

PART B

5. CONCRETE REINFORCED WITH RSF

To facilitate the introduction of RSF in concrete construction, the authors undertook research in the following engineering aspects: a) characterisation of various types of RSF, b) development of appropriate concrete mixes and examination of mechanical properties of concrete elements reinforced with RSF (RSFRC), d) development of demonstration products, and e) development of appropriate design guidelines. These aspects will be examined in detail in the following. Economic and safety aspects were also examined.

5.1 Engineering aspects

Two types of RSF were considered: a) shredded fibres (SRSF) and b) fibres obtained from the microwave-induced pyrolysis process (PRSF). The thickness of SRSF was around 0.23 mm, whereas the thickness of PRSF ranged from 0.8 to 1.5 mm. Steel fibres obtained from virgin tyre cord (VSF) and two types of industrially produced steel fibres (denoted ISF-1 and ISF-2) were also examined (see Fig. 6).

Material characterisation of RSF was one of the main tasks of the above research. Single and double pull-out tests were performed to evaluate the optimal fibre length required by each type of RSF in order to develop sufficient bond with concrete. Experimental results[5] showed that the type of bond failure depended on the anchorage length of the fibres. It was also determined[10] that the strength of SRSF and PRSF was best utilised, when the fibre length was about 20 and 50 mm respectively. These lengths are similar to the lengths of equivalent industrial fibres.

One of the main problems, encountered when mixing RSF in fresh concrete, is the tendency of the fibres to ball together, which spoils the concrete. RSF have irregular geometrical properties, and if they originate from the shredding process, they often contain rubber particles on their surface (Fig. 6).

One of the main objectives of the research was the development of appropriate concrete mixes and the optimisation of fibre length distribution so as to maximise the amount of fibres in a given mix. This involved the examination of the properties of concrete at fresh and hardened states. The slump test, and the concrete compressive and flexural strengths were evaluated by using standard tests[6,8]. The results showed that the addition of moderate amounts of RSF improved both the concrete's compressive and flexural strength. However, as the amount of fibres increases further, the compressive strength decreases due to an increase in air entrapped in concrete. The research findings suggested that the maximum RSF content (by weight), which could be effectively used in concrete, was 6% and 2% for the PRSF and SRSF respectively. Standard bending tests on prisms reinforced with PRSF, VSF or ISFs showed that a similar behaviour is exhibited by all fibres, despite their big differences (see Fig. 7)[10].

Two RSFRC demonstration products were also developed to illustrate the commercial potential of RSF. The first product was a precast RSFRC slab (Fig. 8) used for drainage cover. The design of the slab was based on that of a reinforced concrete slab of an existing drainage system[32]. This product was chosen because the design of the reinforced concrete slab was fairly complex due to the configuration of the drainage holes. The use of steel fibre reinforced concrete (SFRC) in such geometrically complex elements simplifies their design and offers savings in the assembly and placing of the reinforcement. The mechanical behaviour of three slabs reinforced in different ways (RSFRC containing SRSF, RSFRC containing PRSF, and slurry infiltrated concrete reinforced with SRSF) was examined. Central-load bending tests were performed to determine whether the slab would satisfy the loading conditions adopted for pavements by BS-EN-124[33]. The first two types of slabs passed the B125 loading condition (125 kN point load), whereas the slurry infiltrated slab satisfied the C250 condition (250 kN point load). This demonstrated the commercial potential of suitably designed RSFRC slabs in drainage applications such as car parks, carriageways, and hard shoulders for all types of vehicles.

SFRC has high energy-absorption capacity, which makes it ideal for high-impact and explosive loading and, hence, a high-impact resistant slab was the second product developed (Fig. 9). The slab was cast with slurry infiltrated concrete that contained a high volume of SRSF. The slab was successfully tested to impact loading, and preliminary analysis indicated that it could be successfully applied as wall panelling in security-sensitive buildings or as a crash barrier in carriageways.

Another important task undertaken was the development of a general framework for design as well as simple guidelines for the effective use of RSF in concrete[9]. The framework of an existing design guideline, developed by RILEM[34] for conventional SFRC, was considered. Following an examination of the relevant literature[35,36], it was confirmed[7] that this guideline overestimates the bending resistance of SFRC due to a number of issues not related to the fibre type (such as the test adopted for the evaluation of flexural strength and the derivation of concrete's tensile stress block). It was suggested that the RILEM guideline could be used for the design of RSFRC, and new tests have been proposed to improve the accuracy of predicting the bending resistance of SFRC.

5.2 Economic and other aspects

The current demand for re-bars in concrete in the UK[37] is about 1 million tonnes per year and 12 million tonnes per year in the EU[37]. The cost for re-bar is currently increasing due to the high worldwide demand for steel (notably China) and it now stands at over £350 per tonne. Steel fibres are a niche within the reinforcement market and, in the UK, this niche is estimated[38] at 10,000 tonnes per annum. As steel fibres are replacing re-bars in a range of new applications (including suspended slabs), this amount is projected[38] to increase to 20,000 tonnes by 2005 (150,000 tonnes per year in the EU). The UK price of industrially produced steel fibres (ISF) ranges from £450 to £10,000 per tonne. The value[39] of RSF (as scrap material) ranges from £30 to £80 per tonne. However, not all RSF are suitable as scrap feed and much ends up in landfills.

Table 1 shows the amount of steel fibres that could be potentially recovered in both the UK and EU. It is evident that the potential supply of RSF would exceed the current demand for steel fibres. However, RSF will be offered to the market at a range of prices depending on their properties. It is likely that most RSF will be priced below the market value of conventional rebar. It is anticipated that demand for steel fibre reinforcement would increase, if prices decrease, new concrete applications are introduced, and practising engineers are more informed about the benefits of this type of construction.

The extensive use of RSF in construction will benefit both producers and recyclers of used tyres. It is expected that this application would encourage the material recovery of large amounts of used tyres and, hence, the costs associated with material recovery would be reduced due to improved economics of scale[15]. In addition, this application would provide a more viable and sustainable waste management solution rather than the use of RSF as scrap feed in steel manufacturing.

The reduced cost of reinforcement in concrete will benefit the manufacturers and customers of such products. In addition, environmental benefits will come from the reduction of tyre by-products going to landfill and reduction in the need for producing virgin steel fibres. A good market for used tyres will also reduce the problem of fly tipping of tyres.

By-products of used tyres, such as RSF, are not considered[15] hazardous to human health and, in addition, steel fibres are considered to be safer to handle than re-bar because they are part of the concrete mix, which is pumped into place. However, health and safety risks may exist when physically handling concrete elements with RSF exposed on the surface. Hence, guidelines related to these issues need to be developed.

The geometrical irregularity of RSF can be a potential market barrier and, hence, guidelines may be required for specification and testing prior to commercial use. Currently, the main obstacle to developing RSF as concrete reinforcement is the lack of a simple and cost-effective process for sorting and packaging the RSF. In addition, the legal uncertainty regarding the definition of waste may create problems to manufacturers wishing to process RSF.

6. DISCUSSION AND CONCLUSIONS

The waste management of used tyres is influenced by environmental legislation and various techno-economic factors. Hence, to develop economically viable and environmentally friendly end-of-life tyre processing businesses, it is necessary to develop new markets, which will use the by-products of used tyres as secondary raw materials.

Currently, there is a large variety of applications and products using rubber and carbon black recycled from tyres, but RSF are used as scrap feed in steel manufacturing or end up in landfills.

The authors demonstrated that the use of RSF in concrete leads to an increase in concrete strength, ductility, and toughness. It is concluded that the behaviour of concrete reinforced with these fibres can be comparable to that of concrete reinforced with industrially produced steel fibres. The fibres could therefore be used in a range of applications, such as foundations, impact barriers, drainage cover slabs and slurry infiltrated concrete. RSF have the potential for offering an environmentally friendly way of dealing with tyre fibres, and provide a cheaper alternative for concrete reinforcement.

To facilitate the use of these fibres in concrete construction, it is necessary to develop an inexpensive process for sorting and packaging these fibres.

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Tables

Table 1. Potential annual amount of steel fibres recycled from used tyres

	United Kingdom[13] (metric tonnes)		European Union[12] (metric tonnes)	
	Tyres	Steel Fibres	Tyres	Steel Fibres
Total arising	481,500	72,225[a]	2,660,000	399,000[a]
Material Recovery	107,000	16,050[a]	558,600	83,790[a]

a: based on a steel content of 15% by weight

LIST OF CAPTIONS

Figure 1. EU statistics[12] for waste management of used tyres during 2002

Figure 2. UK statistics[13] for waste management of used tyres during 2001

Figure 3. Rubber (a) and steel (b) extracted from the second stage of the shredding process

Figure 4. Recycled steel derived from the microwave-induced pyrolysis of tyres (courtesy of AMAT Ltd[18])

Figure 5. Artificial reef made from used tyres (Courtesy of Glenelg Scuba [27])

Figure 6. Types of examined steel fibres

Figure 7. Flexural behaviour of steel fibre reinforced concrete prisms

Figure 8. Precast cover slab for drainage channels

Figure 9. Prototype of high-impact resistant slab

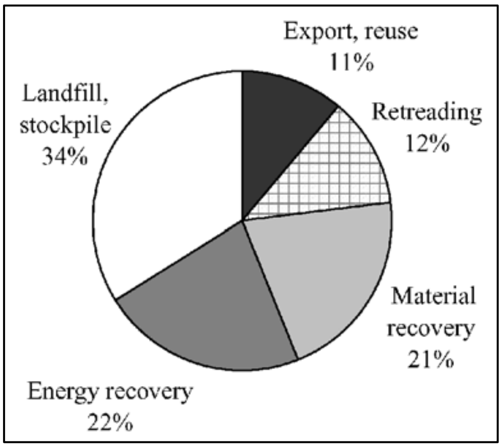
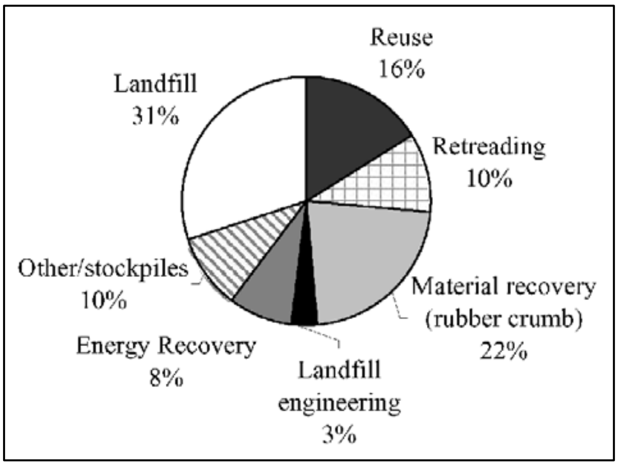


Figure 1.



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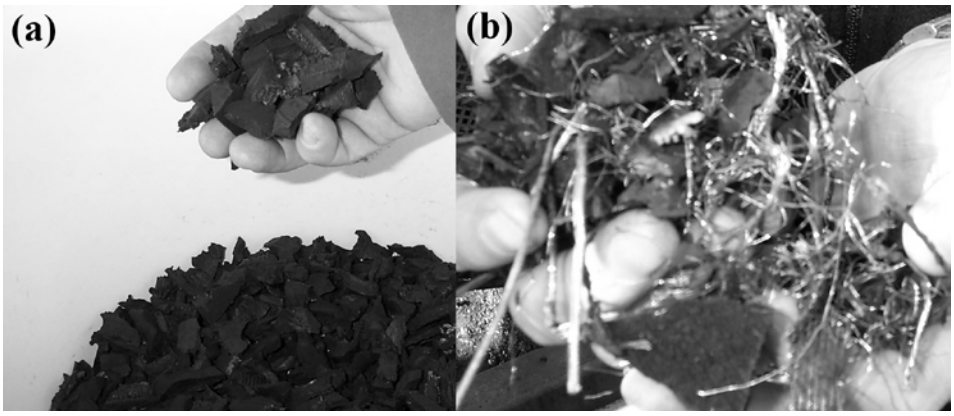
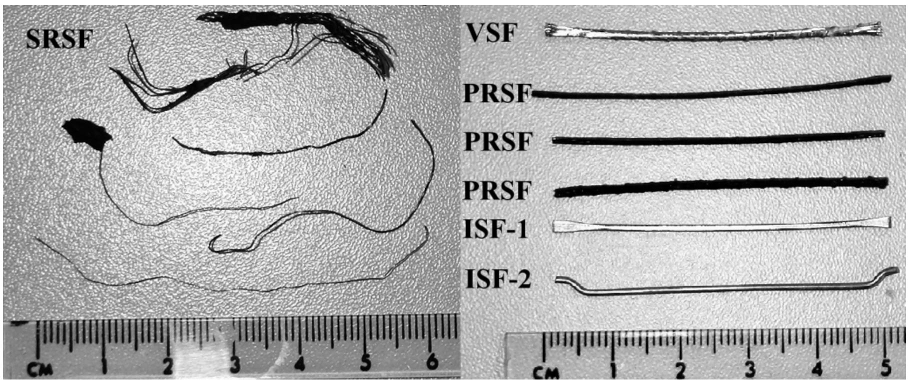


Figure 3.

Figure 4.

Figure 5.



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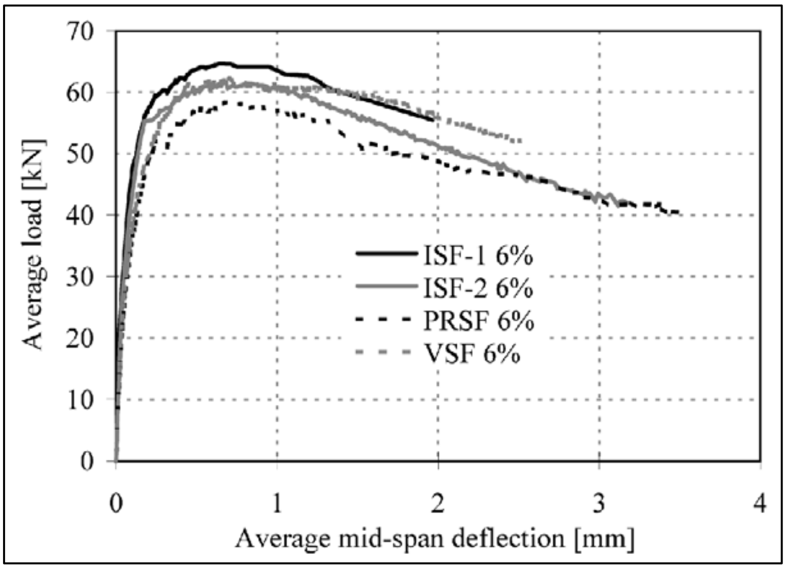

Figure 7.

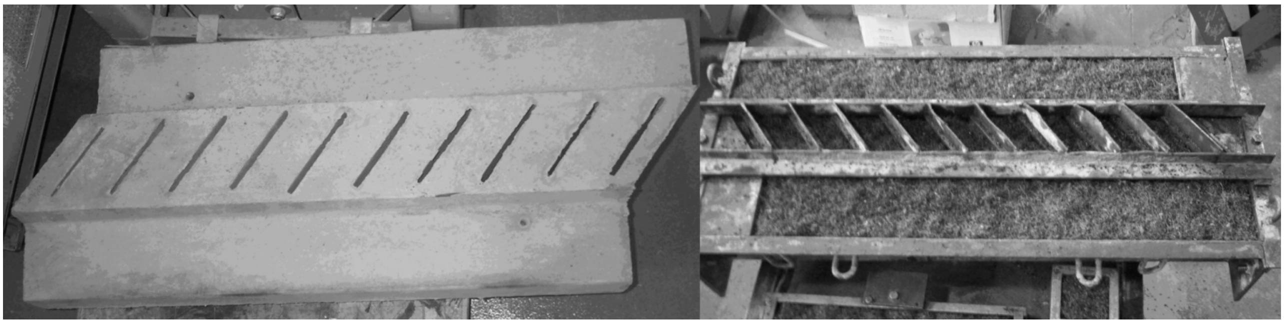

Figure 8.

Figure 9.