anagennisi Innovative Reuse of all Tyre Components in Concrete

Directorate – General for Research & Innovation

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Table of Contents

Abbreviations

Acronym or Symbol	Term	Description
AFRP	**Aramid fibre-reinforced polymers**	FRP comprising aramid fibres
CFRP	**Carbon fibre-reinforced polymers**	FRP comprising carbon fibres
CR	**Coarse aggregate replacement**	% of coarse aggregates replaced by coarse rubber particles (by volume)
CRuC	**Confined rubberised concrete**	Concrete confined by any means
	Fibre content	Usually expressed as weight of fibres per cubic meter of concrete (kg/m3)
FRP	**Fibre-reinforced polymers**	Typically used to describe any composite material made of high-strength fibres in epoxy matrices.
FR	**Fine aggregate replacement**	% of fine aggregates replaced by fine rubber particles (by volume)
FRP-CRuC	**FRP-confined rubberised concrete**	Rubberised concrete confined with FRP jackets
MSF	**Manufactured steel fibres**	Virgin steel fibres manufactured in various shapes to be used in reinforced concrete as reinforcement
	Mineral/conventional aggregates	Natural aggregates used in conventional concrete (both fine and coarse)
PP fibres	**Polypropylene fibres**	Manufactured polypropylene fibres that can be used as reinforcement in concrete
PP_m fibres	**Multifilament polypropylene fibres**	
RTPF	**Recycled tyre polymer fibres**	Post-processed Polymer fibres from end-of-life tyres for use as reinforcement/additive in concrete
RTP	**Recycled tyre polymer**	Polymer from end-of-life tyres (contains rubber)
RTSF	**Recycled tyre steel fibres**	Post processed steel fibres from end-of-life tyres for use as structural reinforcement in concrete
RTSC	**Recycled Tyre Steel Cords**	Multi-filament Steel Cord from end-of-life tyres
RTCF	**Recycled Tyre Cord Filaments**	Steel filaments derived from end-of-life tyres
$RTPF_m$	**Mixed Recycled tyre polymer fibres**	Post-processed Polymer fibres from end-of-life tyres for use as reinforcement/additive in concrete as received from shredding process
	Rubber content	Usually expressed as % of the fine aggregate (FA) and/or coarse aggregate (CA) volume
RuC	**Rubberised concrete**	Concrete with rubber particles as replacement of a fraction of mineral aggregates
SFRC	**Steel fibre reinforced concrete**	Concrete reinforced with steel fibres
SFRRuC	**Steel fibre reinforced rubberised concrete**	Rubberised concrete internally reinforced with steel fibres

RTR	**Recycled tyre rubber**	Rubber from post-consumer tyres. It is consider waste, and can be used in reinforced concrete in the form of small particles (in sizes similar to mineral aggregates) after following certain processing techniques.
RC	**Reinforced Concrete**	Conventional Concrete provided with longitudinal reinforcement and with/without transverse reinforcement
RRuC	**Reinforced Rubberised Concrete**	Reinforced Rubberised Concrete provided with longitudinal reinforcement and with/without transverse reinforcement
CRRuC	**Confined Reinforced Rubberised Concrete**	Reinforced Rubberised Concrete confined by any means and provided with longitudinal reinforcement and with/without transverse reinforcement
FRP-CRRuC	**FRP-Confined Rubberised Concrete**	Reinforced Rubberised Concrete confined with FRP jackets and provided with longitudinal reinforcement and with/without transverse reinforcement

List of Tables

List of Figures

1 Executive summary

Around one billion tyres are discarded each year, with post-consumer tyre arisings for EU countries alone exceeding 3M tonnes per year. Tyres comprise roughly 80% rubber, 15% steel wire and 5% textile reinforcement by mass. Nearly 50% of all recycled tyres/components end up as fuel, in low grade applications or in landfill. Less than 25% of the energy required to produce rubber is recovered by incineration. All tyre constituents (rubber, high strength steel cord and wire, high strength textile reinforcement) are high quality materials and the aim of Anagennisi was to recycle them as reinforcement in structural concrete applications. For that purpose, all materials were cleaned, sorted and classified using standardised or novel techniques developed during the project.

Rubber particles were used to substitute conventional aggregates in plain concrete (up to 60% total aggregate replacement) which results in severe loss in compressive strength, but increase in lateral strain. To regain the compressive strength, Rubberised Concrete (RuC) was confined with Aramid FRP jackets and the results showed compressive strengths up to 90 MPa and, more significantly, axial deformations up to 6% (normal concrete 0.2%). This high deformability can be utilised in seismic and other applications. The seismic performance of RC medium and large scale piers was assessed using AFRP confined RuC (CRuC) in targeted regions of the piers. The results showed that AFRP CRuC improved the energy dissipation up to 50% and increased ductility up to 25% - (compared to RuC). Successful shake table tests were also conducted on buildings with CRuC elements and base isolation columns. Based on material tests, numerical models were developed to predict the short-term structural behaviour as well as the free shrinkage and creep deformations of RuC and CRuC.

Recycled Tyre Steel Fibres (RTSF) can partially replace manufactured steel fibres to increase the flexural strength of concrete – saving on virgin materials and reducing energy input requirements by 97%. RTSF fibres are shorter and much thinner than manufactured steel fibres, helping to control cracks at the micro and meso level. Extensive tests on the flexural behaviour of RTSF reinforced concrete showed that fibre blends (with manufactured steel fibres) result in optimum mechanical characteristics, outperforming each fibre type on its own. Steel fibres do not have a significant impact on free shrinkage, but help prevent or control cracking under restrained conditions. No cracking was observed after a period of 9 months for restrained specimens with 50% restraint.

Recycled Tyre Polymer Fibres (RTPF) were easy to integrate in mortar and concrete easy using novel integration methods. The results show that they can decrease initial plastic and autogenous shrinkage and can potentially substitute virgin polypropylene fibres. RTPF reinforced concrete showed remarkable resistance to spalling when subjected to elevated temperatures, confirming the potential of these fibres for fire-induced concrete spalling mitigation.

Several demonstration projects were undertaken in five European countries to convince contractors and infrastructure owners of the benefits of the examined tyre by-products. These projects included slabs on grade, tunnel linings, precast concrete elements (rubberised poles and railway sleepers) and a repair screed application. Design recommendations and examples were developed for all three tyre constituents. Work was undertaken on the environmental (LCA) and cost (LCCA) life cycle assessment of the aforementioned demonstration projects to demonstrate the potential benefits.

2 Summary of project context and objectives

An estimated one billion tyres are produced each year and a similar (but slightly lower) number runs out their service life. Post-Consumer Tyre arisings for EU countries (2010) were found to be 3,400,000 tonnes per year. This roughly corresponds to one car tyre of around 8 kg per person each year. Analysis of the destination for EU arisings shows that 10% still goes to landfill. The introduction of EC legislation has clearly resulted in a major reduction in the proportion of tyres going to landfill (from 62% in 1992). However, only just over a third of post-consumer tyres are currently recycled each year with a similar proportion still being incinerated for energy recovery.

The tyre is made of vulcanised rubber, often using different types of rubber for different parts. The rubber is placed in layers many of them structurally reinforced with corded steel wire or polymer textiles. Adjacent to the rim, stronger bead steel reinforcement is required to keep the tyre in place. The bead wire normally comprises of relatively thick (millimetres) cold drawn wire bundles. Tyre rubber in general comprises natural rubber (21% car-c, 53% truck-t), synthetic rubber (30% c, 12%t), fillers such as carbon black and silica (34% c, 35% t) and other materials, such as oils, sulphur and zinc oxide (15% c, 11% t). The target of Anagennisi project was to find high value uses in structural applications for the constituent materials of post-consumer tyres. Rather than using highly engineered materials as cheap fillers or fuel, Anagennisi aimed to use the rubber, steel and polymer fibres for their intrinsic physical properties in high value concrete applications and novel structural solutions. After appropriate sorting and cleaning processes, classified rubber particles, Recycled Tyre Steel Fibres (RTSF) and Recycled Tyre Polymer Fibres (RTPF) could be obtained and used in concrete construction.

a) Rubber from Post-Consumer Tyres

In general, the rubber can be extracted from tyres through mechanical means (shredding and granulating). This method is used by the majority of tyre recyclers in Europe. Pyrolysis (breaking down the rubber to hydrocarbons, powders and oil), and cryogenics (freezing and then shattering) also exist in some parts of Europe. In mechanical tyre decomposition, steel is removed by magnets and free textile by vacuum. Recycled rubber crumb is classified according to its type and size, as well as, freedom from steel. Rubber crumb is considered a product rather than waste and can be shaped and/or bonded with polymers to produce carpet underlay and other flooring materials such as rubber tiles, sidewalks, livestock mats, playgrounds, sport surfaces. It can also be moulded for various types of bumpers, curbs, pallets and railway sleepers. Rubber can also be used in rubber modified asphalt and as aggregate in rubberised concrete or polymer concrete. Rubber aggregates can be classified as shred or chips, granulate, or powders. Unfortunately, at the moment nearly 50% of the recycled rubber still ends up as fuel or in lower grade applications such as mulch or tyre derived aggregate for backfill and landfill.

b) Steel

The steel used in tyres is of high quality and strength. It is used in wire bundles in the tyre bead and in cord form in the belt and inner liner. The bead wire is sometimes extracted before tyre shredding whilst the cord invariably gets broken down to steel fibres when the tyre is crushed. Until recently, due to its contamination and fineness, much of the recovered steel was sent to landfill as it can cause problems in the steel furnace filters. However, with appropriate post-processing (cleaning and briquetting), steel can be re-melted for steel production.

c) Polymer Textile

High quality and strength textile fibres, such as aramid, rayon, nylon and polyester cords, are used to provide reinforcing strength in tyres. During the shredding process, the cords break down and expand into greyish fibre agglomerates (fluff). Storage of recycled polymer textile is a problem, since it is flammable and can be carried away by wind. Until recently, most textile reinforcement ended up in landfill or was used as fuel for incineration. Recently, there are some products using this material for insulation purposes, carpet blends and underlays.

d) Possible Construction Applications

The construction industry is the largest user of materials, with concrete being the most widely used structural material. Concrete uses cement as a binder and sand and aggregates as structural fillers. Hard and low porosity aggregates are normally used to enhance strength and durability, but the use of small amounts of rubber (less than 1%) in concrete or FRC can impart significant ductility. The use of high volume fractions of rubber aggregate, however, can lead to a “softer” (less stiff) concrete and significant reduction in compressive strength. Concrete is inherently weak in tension and it is normally reinforced with steel rebars or fibres (e.g. glass, steel, polymer). Rubber is a highly durable material, but has good strength, flexibility and a remarkable ability to maintain its volume under stress. This makes it an ideal candidate as aggregate for concrete, provided its lateral dilation is controlled through high confinement. The expected result is a highly deformable but strong structural element, which offers the opportunity to integrate structures, such as bridges, rather than use discontinuities and expensive bearings.

The steel cord used as tyre reinforcement is a very high strength cord of fine wires (0.1- 0.3mm). The same cord is currently being chopped up for use in limited volumes for high security applications, such as safes, and is sold in the market for more than €3000/tonne. At the same time, when extracted from tyres the same cord is either discarded or at best re-melted. Steel fibre reinforcement for concrete has a sizable market, mostly with thin wire (0.5-1mm). Hence, to consider tyre wire for concrete applications seems natural. However, most early attempts lead to failure due to balling of the tyre wire. Hence, though knowledge of how to avoid balling whilst maintaining efficiency is what led to a first breakthrough, developing industrial processes to sort and classify the wire is still challenging. Beyond that, finding appropriate markets to utilise the product and achieving market acceptance is also important and requires innovation. As for all construction products used in the European market, CE marking is compulsory. As RTSF, due to their peculiar geometrical characteristics, are not covered by any of the harmonised standards, the alternative European Organisation for Technical Assessment (EOTA) route has to be followed and a relevant European Assessment Document (EAD) is necessary to be developed.

The polymer textile reinforcement in tyres is of equal high quality and durability. Similar manufactured polymer fibres are used in concrete for shrinkage control. Finding methodologies of introducing these fibres into concrete without balling requires innovation. Furthermore, processing to clean the fibres is also a challenge, as well as finding ways of classifying them. Existing tests for assessing the shrinkage control properties of RTSF and RTPF proved to be inadequate and new tests were developed during the project.

Project Objectives:

The aim of this project was to develop innovative solutions to reuse all tyre components in high value innovative concrete applications with reduced environmental impact. To achieve this aim, the Anagennisi project had to overcome scientific and technological challenges through the following objectives:

1. Development of novel high deformability confined rubberised concrete materials and recycled steel and wire reinforcement suitable for concrete applications
2. Development of high deformability RC elements using rubberised concrete and recycled fibres suitable for integral bridge elements and base isolation systems for vibrations and seismic applications
3. Development of concrete mixes using recycled steel fibres for use in various concrete applications, including slabs on grade, precast concrete, sprayed concrete and screeds
4. Development of concrete mixes using recycled tyre polymer fibres for shrinkage crack control in concrete elements, precast concrete, sprayed concrete and screeds
5. Undertaking at least five mini demonstration projects using the developed materials/applications in several countries
6. Development and implementation of design guidelines standardised as well as LCA/LCCA protocols

The above objectives address the following specific expected impacts as detailed in the Environment work programme.

3 Main scientific and technological results/foregrounds

The main achievements of Anagennisi project are presented below per Work Package (WP). Before the three tyre by-products (Recycled rubber, Recycled Tyre Steel Fibres (RTSF) and Recycled Tyre Polymer Fibres (RTPF)) can be used in concrete, they must be cleaned, sorted, characterised and classified. Standard classification procedures already exist for recycled rubber, so only limited characterisation work was undertaken on rubber.

Types and Quality Assurance of Recycled Steel Fibres (WP1): Two types of RTSF were used within Anagennisi project and both of them were produced using the mechanical process: Unsorted RTSF are produced during the recycling process of waste tyres as a raw material for production of steel, whilst sorted RTSF are acquired during specially developed screening process. Both types are irregular in shape and vary in length and diameter.

Another type of recycled steel fibres is the Recycled Tyre Cord Filaments (RTCF or for simplicity TCF). TCF are made from the same material as RTSF, but are extracted from unvulcanised tyre cut-off rubber belts by using a cryogenic reduction method rather than mechanical reduction. This cryogenic method extracts the tyre cord as a whole, without any residual rubber or other impurities. The cord comprises 10-14 individual filaments. Having the cord as a whole, it is possible to cut it in predetermined lengths (usually from 6 to 24 mm, depending on the application) obtaining the same fibre length for all filaments (on the contrary with RTSF, where due to the mechanical shredding, the fibre length distribution is quite wide). When the tyre cord is cut in longer lengths (>35 mm), the cord remains intact and the filaments are kept together without getting untangled: These fibres are called Recycled Tyre Steel Cords (RTSC). RTSC of 60mm length, were used in the tunnel lining demonstration project. Table 1 shows the overall geometrical and mechanical properties of various types of recycled steel fibres.

Table 1 Geometrical and mechanical properties of various types of recycled steel fibres

Fibre type	Length (mm)	Diameter (mm)	Tensile strength (N/mm^2)	Shape
Unsorted RTSF	0 – 15 (85% of fibres)	0.1-0.4	~2500	Irregular (wavy)
Sorted RTSF, RTCF	15– 40 (70% of fibres)	0.12-0.38	~2500	Irregular (wavy)
RTSC	Any length according to the application requirements	0.9	2800	straight

To characterise RTSF, an innovative 'Quality Assurance (QA) system' was developed by Twincon Ltd, able to characterise RTSF using photogrammetry techniques (Figure 1). A sample of approximately 10k fibres are fed into the QA system where a high-speed camera takes snapshots of the fibres. The camera is connected to a computer where the photos are uploaded and analysed by a specially developed software which identifies each fibre length and produces the fibre length distribution chart.

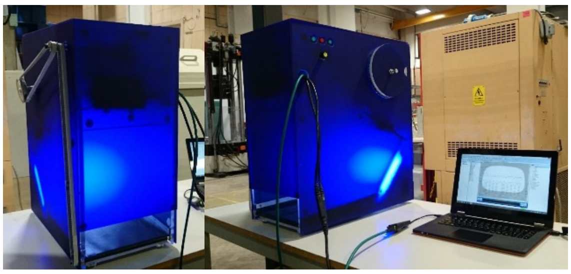


Figure 1 QA system

Cleaning RTPF (WP1): RTPF cleaning devices (two small-scale and one medium-scale) were designed and manufactured to cope with the RTPF demand for laboratory testing. Figure 2 shows a schematic of the small-scale device consisting of four sieves with various openings which can clean RTPF, whilst figure 2b shows a sample of RTPF after cleaning.

Figure 2 a) Schematic representation of RTPF cleaning device, b) sorted RTPF after cleaning

RTPF integration into concrete (WP1): RTPF are too tangled to be used directly in concrete. A prototype machine for the integration and dispersal of RTPF into fresh concrete was developed. This prototype uses the vibration of plastic strings to separate the fibres (Figure 3a). The untangled fibres are integrated into the concrete mix using a blower, which blows the fibres directly to the mixer through anti-static pipes (Figure 3b).

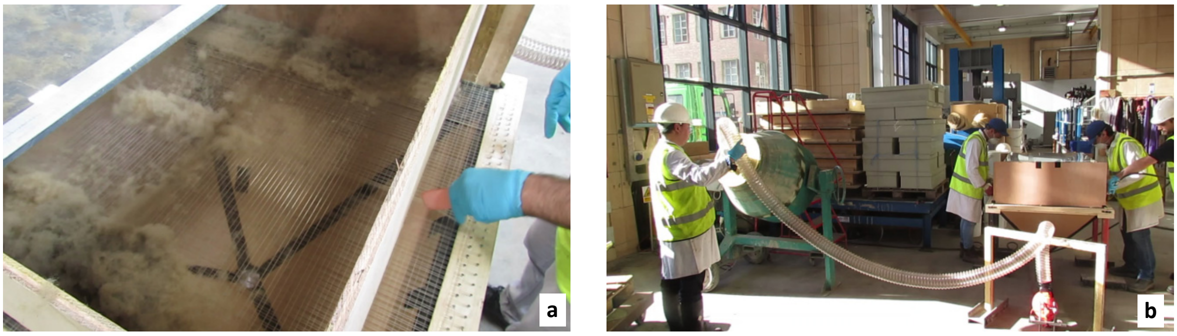


Figure 3 Fibre integration stages. a) strings being excited b) fibres being integrated into the concrete mix

Chemical and thermal properties of RTPF (WP1): To identify the chemical and thermal properties of RTPF, Fourier Transform InfraRed spectroscopy and thermogravimetry were performed. The chemical analysis showed that the chemical base of the polymer fibres extracted from end-of-life tyres contained three polymers: PET (Polyethylene terephthalate), PBT (Polybutylene terephthalate) and Polyamide 66 [7]. The melting point of sorted RTPF ranged from 210^{o}C to 260^{o}C. Their decomposition started above 300 ^{o}C, reaching a mass loss of 50% at about 400^{o}C leaving negligible residues.

Geometrical characteristics of RTPF (WP1): RTPF appeared to cover a wide range of diameters ranging from 10.0 to 38.0 μm for mixed RTPF and 8.0 to 38.0 μm for sorted RTPF (Table 2). Regarding RTPF length distribution analysis, 600 samples of mixed RTPF fibres and 1000 samples of sorted RTPF fibres were examined. The analysis showed that more than 80% of fibres were shorter than 12 mm.

Table 2 Geometrical properties of RTPF

Parameter		Mixed RTPF	Sorted RTPF
Length, mm		8.4 ± 3.8	9.5 ± 4.6
Fineness, μm (Diameter)	type 1	30.9 ± 2.5	30.1 ± 2.0
	type 2	20.7 ± 1.8	20.2 ± 1.7
	type 3	13.2 ± 1.8	12.4 ± 1.8

Compressive behaviour of unconfined and FRP Confined Rubberised Concrete (CRuC) (WP2): Extensive laboratory studies were conducted to investigate the monotonic and cyclic compressive behaviour of plain and FRP confined rubberised concrete. The test parameters were: a) the type of Fibre Reinforced Polymer (FRP) confining material (Carbon or Aramid), b) the confinement pressure (number of FRP layers), c) the cylinder size (100 and 200 mm diameter cylinders) and d) type of loading (monotonic or cyclic). For plain RuC, the results showed that the compressive RuC strength and axial strain capacity decreased, as the rubber content increased, regardless of the replacement type. The lateral strain capacity increased considerably, with increasing rubber content. For mix 60FR60CR (60% fine and 60% coarse aggregate replacement with rubber particles by volume), the compressive strength reduced by 88%, whereas the axial strain reduced by 35% and the lateral strain increased by 303% with respect to the plain mix.

For CRuC, the results showed that the lateral confinement with FRP jackets was effective and mitigated the detrimental effects of rubber on concrete performance. RuC cylinders wrapped with 4 layers of AFRP achieved stress and strain capacities of around 90 MPa and 6% respectively, despite the high rubber content (60% total aggregate replacement). Such axial strains have never been achieved before in conventional concrete. The envelope of the cyclic behaviour followed a similar path as the monotonic behavior (Figure 4).

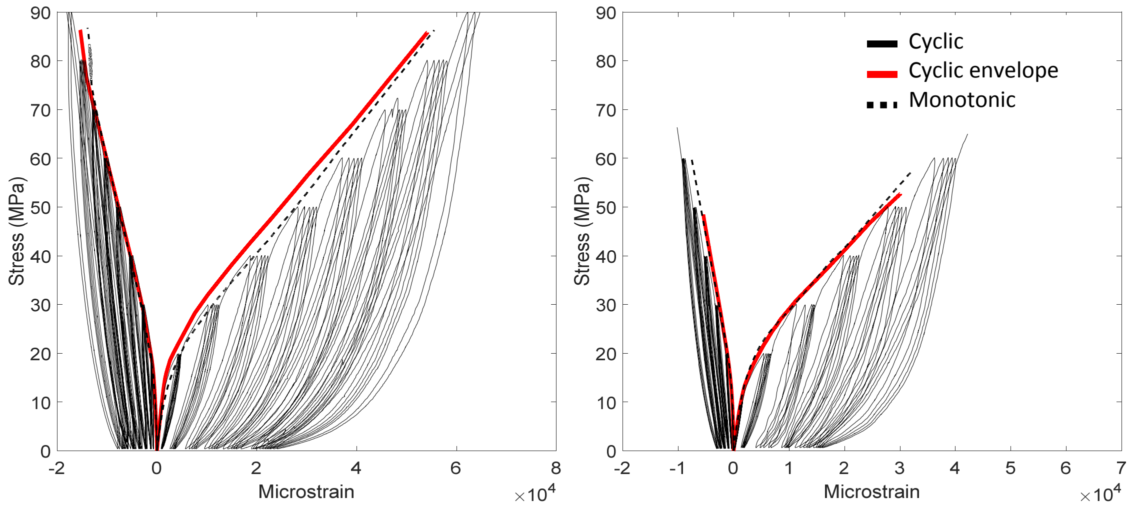


Figure 4 Cyclic and monotonic stress-strain behaviour of rubberised concrete cylinders wrapped with 4 layers of AFRP (left) and CFRP (right)

Predicting the compressive behaviour of RuC and CRuC (WP2): One of the main objectives of Anagennisi project was not only to develop highly deformable elements but to predict their behaviour too. Hence, reliable and practical-to-use constitutive models were developed for the behaviour of rubberised concrete with or without confinement based on the test results performed in the

Anagennisi project. Figure 5 shows the uniaxial constitutive model for plain RuC. In the initial stage, degradation and post-crushing of concrete is observed. The material is defined up to stress ratios below the elastic limit $\sigma/f_{cr} \leq 0.3$. The second stage is defined by a second degree polynomial function, which is bounded by the elastic strain limit $\varepsilon_{cr1,el}$ and the crushing strain $\varepsilon_{cr1,1}$. The post-crushing stage is dependent on the post-peak crushing energy ($g_{c,2}$), represented by a triangular distribution. The uniaxial tension behaviour of rubberised concrete (Figure 6) can be predicted using a bi-linear behaviour.

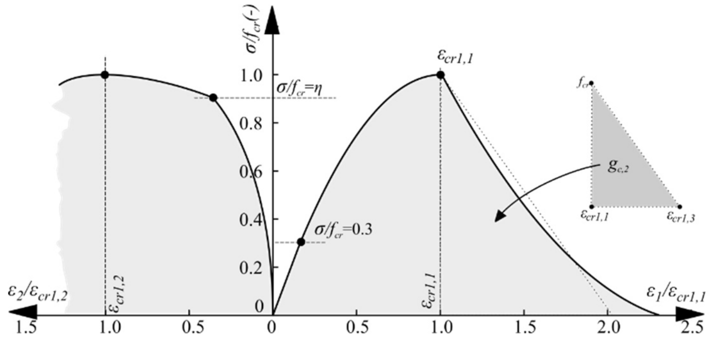


Figure 5 Uniaxial constitutive model for plain rubberised concrete

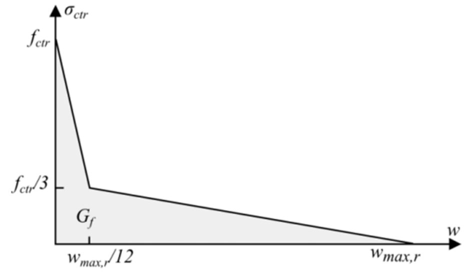


Figure 6 Assumed stress-strain diagram in tension

The model to predict the full stress-strain behaviour of FRP CRuC was based on the confinement model proposed by Mander et al. for steel-confined concrete using an iterative procedure by increasing the confinement ratio. The active confinement model assumes that a constant confinement pressure (active-confinement) is applied externally to the concrete core, while the axial stress increases, leading to stress-strain curves at the various volumetric confinement ratios (ω_W), (Figure 7).

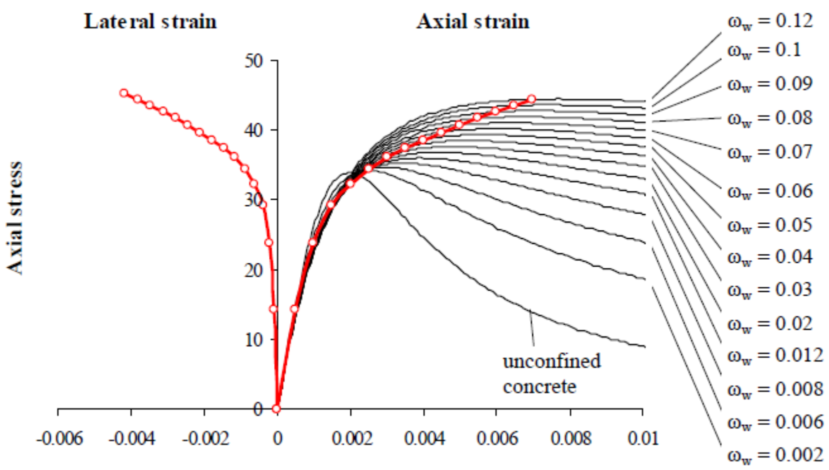


Figure 7 Iterative procedure of the model developed by Papastergiou (2010)

Figure 8 shows the predicted curves using the proposed model as well as the experimental stress-strain curves for 2, 3 and 4 layers of AFRP confinement. The maximum deviation in the ultimate stress and axial strain predictions, compared to experimental results, was found to be less than 6% and 9%, respectively.

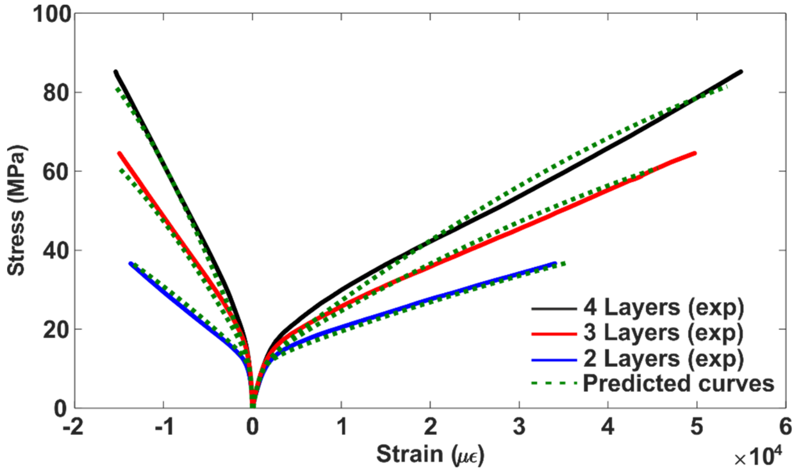


Figure 8 Prediction of the model and experimental results for 2, 3 and 4 layers AFRP confinement

Predicting shrinkage deformations and creep on RuC and CRuC (WP2): Mathematical models were developed to predict the total shrinkage or creep deformations for plain or confined RuC with 60% replacement of both coarse and fine aggregates. These models were calibrated based on the Anagennisi experimental results.

Medium and large-scale tests using RuC and AFRP CRuC (WP2): This study investigated the behaviour of Reinforced Rubberised Concrete (RRuC) and Aramid Fibre Reinforced Polymer Confined Rubberised Concrete (AFRP CRRuC) columns reinforced with longitudinal and transverse reinforcement bars. The experimental study focused on structural members incorporating large proportions of rubber particles as a replacement for mineral aggregates (60% by volume). Four medium-scale specimens and eight large-scale specimens were tested. From the medium scale specimens, 2 were made of conventional reinforced concrete (RC), one of rubberised reinforced concrete (RRuC) and 1 was an externally confined rubberised reinforced concrete member (CRRuC). The 8 large scale members were equally divided in RRuC and CRRuC (Figure 9).


a)

b)

c)

Figure 9 Large scale specimens a) Formwork, b) Rubberised concrete column c) AFRP confined column

The columns were designed and cast to replicate typical circular bridge piers. The specimens were scaled-down and had a diameter 250-350 mm and moment cantilever length 1000-1350 mm. The bottom part of the columns was cast using either regular concrete, rubberised concrete (RuC), or AFRP CRRuC. The columns were tested in reverse cyclic loading until failure to examine the load and deformation capacity of the specimens. The results indicated that AFRP CRRuC was effective at enhancing the energy dissipation (up to 169% and up to 44%) and deformation capacity (up to 33% and up 35%) of the columns in comparison to counterpart specimens cast with rubberised concrete RRuC or conventional RC columns, respectively. It is also shown that yielding of the longitudinal reinforcement controlled the behaviour of the column specimens. These results were in line with previous research on structural elements cast with RuC.

Figure 10a and Figure 11a show the lateral load vs lateral displacement curves of unconfined and AFRP confined (3 layers) RuC mixes (both 60% rubber replacement), respectively, whilst Figure 10b and Figure 11b illustrate their corresponding modes of failure.

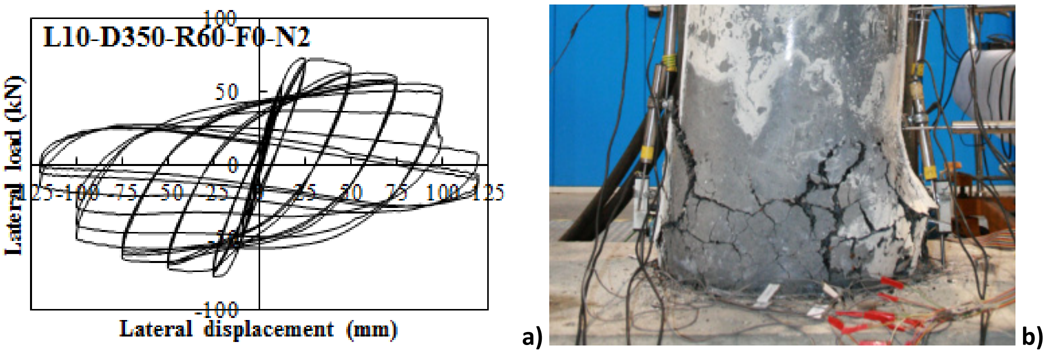


Figure 10 a) Lateral load-deformation response, b) Damage level at large lateral deformations

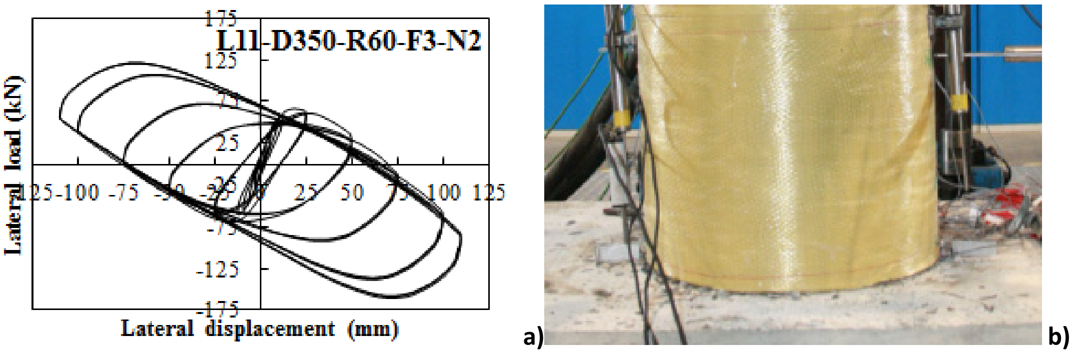
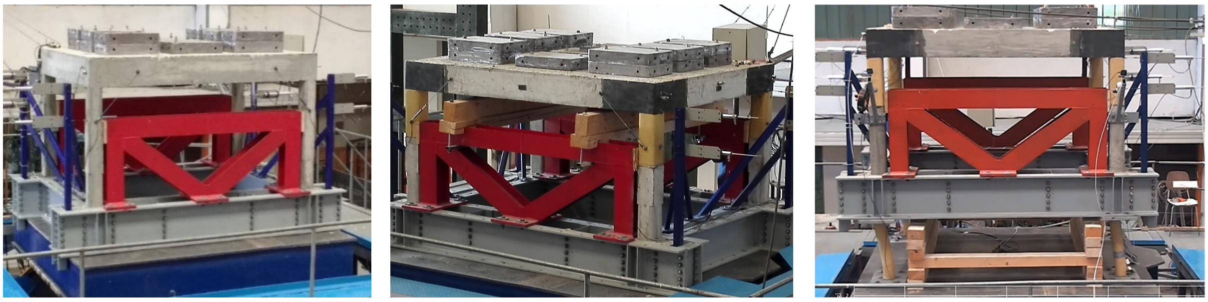


Figure 11 a) Lateral load – deformation response, b) column after testing

Shake Table Tests (WP2): The aim of this task was twofold: 1) to assess the seismic behaviour of vulnerable conventional concrete buildings and improve their performance by using rubberised concrete at regions where enhanced deformability is needed, and 2) to study the performance of a new seismic isolation system comprising slender FRP confined rubberised concrete elements. Hence, the experimental programme was split in two parts. In the first part of the experimental programme, three half-scale, one-storey 3D concrete frames, comprise short columns, were built and tested under several seismic excitations (simulated by a shaking table). One frame was cast in conventional concrete as a reference specimen (Figure 12a), a second frame was cast in rubberised concrete (Figure 12b), whereas a third frame comprised a combination of elements with either conventional or rubberised concrete.



(a) (b) (c)

Figure 12 (a) Conventional concrete frame, (b) rubberised concrete frame fixed to the shaking table, and (c) rubberised concrete frame supported on a base-isolation system comprising FRP-confined rubberised concrete columns

In the second part of the experimental programme, the third frame of the first experimental programme, which had only minor damages, was supported on four slender FRP-confined rubberised concrete columns as a means of base isolation (Figure 12c).

All frames were subjected to a sequence of ground excitations with increasing amplitude (Figure 13). For the first frame (conventional concrete), the excitations started at a maximum ground acceleration of 0.13g and gradually increased to 0.22g, 0.30g, 0.40g, 0.80g and finally to 1.60g. For the second frame, the excitations started at 0.28g and gradually increased to 0.54g, 0.86g, 1.0g, 1.07g, 1.91g, 2.03g, 2.37g, and 2.61g. For the third frame (including the seismic isolation test), the excitations started at 0.13g, and gradually increased to 0.27g, 0.46g, 0.64g, 1.0g, 2.35g and 2.67g. After the end of each excitation, the frames were visually inspected for damage/cracks.

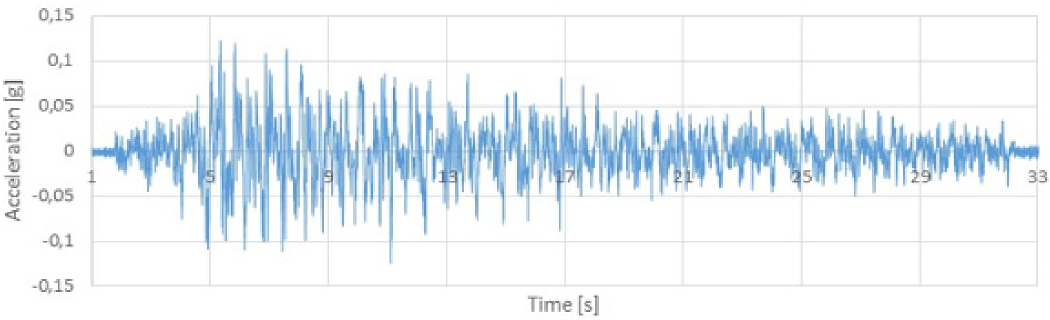


Figure 13 Excitation signal used in all tests; acceleration was amplified according to the desired level of maximum acceleration.

The main achievements of this task are summarised below:

- The innovative solution that proposed to replace conventional concrete with FRP-confined rubberised concrete elements in locations where high-deformability is needed, proved to be extremely promising, as it allowed the structure (3D frame) to survive earthquakes with at least 65% higher peak ground acceleration.
- Targeted use of rubberised concrete, only at regions where needed, improved the cost-efficiency of the suggested method, without scarifying mechanical performance.
- The novel base isolation system proposed, was proved to be quite promising by limiting damages in the superstructure and reducing the top floor accelerations by approximately 25%. Nevertheless, significant permanent damage of the column elements acting as base isolators, highlighted the need design ruled limiting the permitted lateral deformation of such elements.

Flexural performance of SFRC prisms and circular slabs using manufactured fibres and sorted Recycled Tyre Steel Fibres (RTSF) (WP3): Regarding RTSF, extensive experimental work was undertaken to examine new applications for fibre blends using RTSF for: slabs on grade, suspended slabs, precast concrete elements, pumpable and self-compacting concrete and mortar, sprayed concrete and repair screeds. This experimental investigation focused mainly on the flexural behaviour of Steel Fibre Reinforced Concrete (SFRC) using manufactured (AFT) and/or RTSF at different dosages and blends. The main objective of this experimental project was to investigate the behaviour of the SFRC mixes for slabs on grade (30 kg/m^3) and suspended slabs (45 kg/m^3) using a typical concrete mix and fibre dosages which are frequently in practice. The programme comprised 3-point testing on SFRC prisms and centrally loaded SFRC slabs (Figure 14 and Figure 15, respectively). For both dosages, it was found that the synergetic effect of manufactured fibres and RTSF appeared to enhance the flexural concrete behaviour compared to mix which contained only manufactured fibres or RTSF.

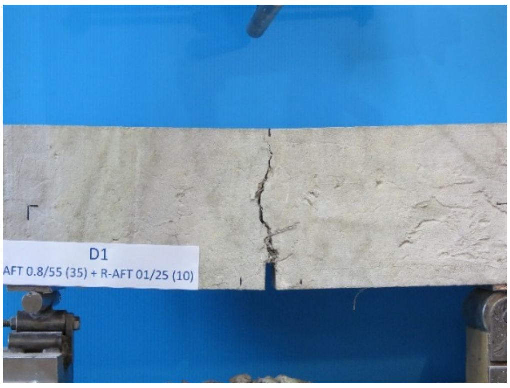


Figure 14 Typical failure of 3-point testing

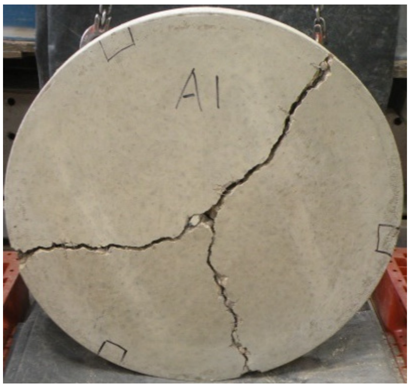


Figure 15 SFRC slab after flexural testing

Surface finishing of industrial flooring using RTSF (WP3): A common surface finishing issue in industrial SFRC floors using Recycled Tyre Steel Fibres (RTSF) is that a large number of fibres appears on the surface of a slab creating aesthetic as well as health and safety concerns. Anagennisi project developed a mitigation method to eliminate this effect based on an experimental investigation which used various types of surface hardeners (dry shakes). The surface finishing was assessed visually as well as by performing pull-out tests. A typical slab-on-grade concrete mix design was used with a hybrid fibre dosage of 20 kg/m^3 of manufactured steel fibres + 10 kg/m^3 of RTSF. The study concluded that a potential solution to the surface finishing problem, common in industrial concrete slabs with RTSF, could be addressed by using 10 kg/m^2 of surface hardener.

A restrained shrinkage investigation on large scale concrete SFRC strips using manufactured fibres and Recycled Tyre Steel Fibre (WP3): An experimental study was conducted on restrained shrinkage performance of outdoor large scale SFRC specimens (40 m long) using RTSF and undulated steel manufactured fibres (UND) on their own or blended together (Figure 16). The purpose of the testing programme was to provide visual evidence of how well different fibre blends resist the onset of restrained shrinkage cracking as well as establish the degree of restraint, typical of slab-on-grade applications. Five SFRC mixes were cast in total, using various fibre dosages such as 30, 35 and 45 kg/m^3. The strips were monitored for free and restrained shrinkage deformations for a period of more than 3 months. Crack width measurements were also taken a year after casting by using a detection microscope.

Figure 16 Finished concrete strips

All mixes showed similar behaviour in free shrinkage measuring a deformation of around 200 με. Restrained shrinkage varied significantly and this was also shown in the crack formation. The best performance was observed on mix C [UND 0.8/55 (30)], where no cracks were observed. Plain concrete mix (A), mix D [RTSF (30)] and mix E [UND +1/60 (35) + RTSF (10)] developed a longitudinal crack of around 600 mm long with thicknesses of 0.33, 0.1 and 0.46 mm, respectively. In case of hybrid mix B [UND 0.8/55 (20) + RTSF (10)], four cracks were measured with dimensions of 500-600 mm length and with a thickness of 0.4-0.5 mm.

Flexural performance of Hybrid Steel Fibre Reinforced Concrete Elements after long term free or restrained shrinkage deformations (WP3): Experimental work was undertaken to investigate the effect of hybrid steel fibres on non-uniform free and restrained concrete shrinkage. Various SFRC mixes were studied using manufactured fibres on their own or blended with Recycled Tyre Steel Fibres (RTSF) or Recycled Tyre Polymer Fibres (RTPF). The main aim of this study was to assess not only the shrinkage behaviour of SFRC but also obtain its residual flexural performance after 10 months of shrinkage deformations. Free shrinkage specimens were kept in two environmental conditions (mist room (MR): 95% RH, 25oC and control room (25oC and 50% RH) (CR). The restrained shrinkage specimens (RS) were also kept in the control room. It was observed that all SFRC mixes showed higher free shrinkage strains than plain concrete mix (mix P). On average, the restrained factor for all mixes (except mix R30: 0.3) varied between 0.5 and 0.6.

Compressive and Flexural Behaviour of Steel Fibre Reinforced Rubberised Concrete (WP3): The main objective of this study was to investigate the effect of steel fibres [manufactured steel fibres (MSF) and/or Recycled Tyre Steel Fibres (RTSF)] on both fresh and mechanical (compressive and flexural) properties of RUbberised Concrete (RuC) using Waste Tyre Rubber (WTR). The key parameters examined through ten different mixes were: (i) WTR content (0%, 20%, 40% or 60% replacement of aggregates by volume), and (ii) content of MSF and/or RTSF (0, 20 kg/m^3 MSF + 20 kg/m^3 RTSF, or 40 kg/m^3 RTSF). The replacement of conventional aggregates with rubber particles, as expected, reduced workability and unit weight, and increased air content of the fresh concrete mixes. Steel fibres decreased workability and increased air content, while marginally increased unit weight. The compressive and flexural strength, as well as the modulus of elasticity decreased with increasing rubber content. The addition of steel fibres in conventional concrete enhanced compressive strength (i.e. by 30% in cubes) and did not affect modulus of elasticity.

In case of RuC, MSF and /or RTSF reinforcement considerably counterbalanced the loss in flexural strength due to rubber (from 50% to 9.6% loss, compared to conventional concrete) and increased compressive strength and modulus of elasticity (up to 12.5% and 28.4%, respectively) (Figure 17). Strain capacity and post-peak energy absorption behaviour were enhanced by the addition of fibres and were further improved by the inclusion of rubber. This effect was more pronounced in RuC mixes. Free shrinkage strain increased with increasing rubber content as a result of the lower stiffness of rubber particles.

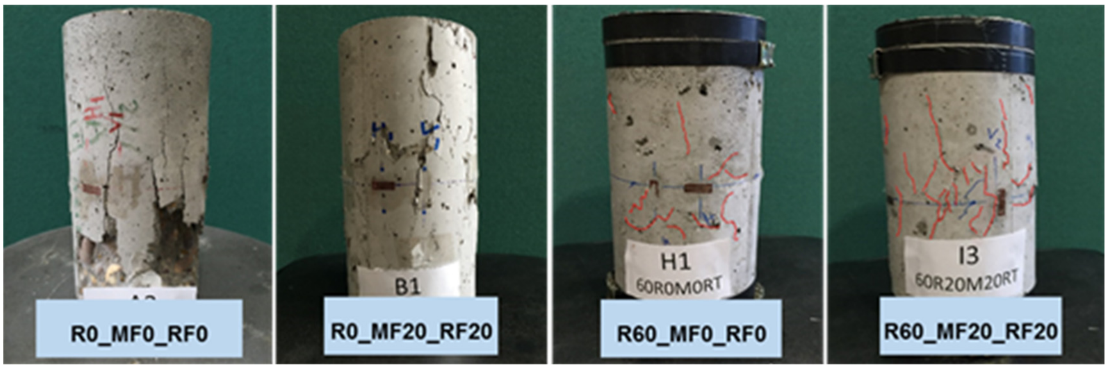


Figure 17 Typical failure of the concrete cylinders

Effect of fibre length on the flexural performance of fibre reinforced concrete using Recycled Tyre Cord Fibres (from 6mm to 24mm) (WP3): This study included an experimental work on the flexural performance of Steel Fibre Reinforced Concrete (SFRC). SFRC prisms were reinforced with different lengths of short Recycled Tyre Cord Filaments (RTCF). For this investigation, the performance of a typical concrete mix was evaluated using a 30 kg/m3 fibre dosage (conventionally placed concrete – usually used for slabs on grade), in seven mixes reinforced with RTCF in different lengths. RTCF was made from tyre cord extracted from pre-vulcanised rubber tyre belts and cut in different lengths (6mm, 9mm, 12mm, 15mm, 18mm, 21mm, 24mm). Since RTCF are made from the same material as Recycled Tyre Steel Fibres (RTSF), the outcome of this study can be used to improve RTSF quality production and further understand RTSF reinforced concrete.

Overall, adding RTCF fibres can enhance flexural strength compared to plain concrete, but it was found that satifactory post-crack performance (f_{R4}> 2MPa) can only be achieved from a fibre length longer than 12mm. This suggest the critical length of RTCF (15mm) contributing to effective flexural toughness in concrete and in practice fibre length less than 15mm can therefore be excluded by screening or any other technique.

Punching shear behaviour of Hybrid Steel Fibre Reinforced Concrete (HSFRC) (WP3): A study was performed to investigate the punching shear behaviour of (HSFRC) flat slabs and footings using Manufactured steel Fibres (MF) on their own or blended with Recycled Tyre Steel Fibres (RTSF) at various dosages. Figure 18a and Figure 18b show the typical setup for slabs and footings, respectively. For slabs, mix 20M20R (20 kg/m^3 of MF + 20 kg/m^3 of RTSF) proved to be a good alternative compared to the concrete mix 40M0R (40 kg/m^3 of MF) which used only manufactured fibres. Mix S5 (10M45R) performed equally well with mix 40M0R in terms of punching shear capacity.
For footings, all series performed equally well with minor variations. Compared to series F1 (no fibres + no punching shear reinforcement), punching shear load for series F2 (40 kg/m^3 of MF) decreased by 3% and increased by 2% for series F3 (20 kg/m^3 of MF + 20 kg/m^3 of RTSF) and F4 (10 kg/m^3 of MF + 45

kg/m^3 of RTSF). Based on the above results, it can be concluded that HSFRC footings, can replace manufactured fibres by 50% (F3) or even in higher dosages (F4) and achieve similar shear capacity and deformation with manufactured SFRC mixes (F2).

a) b)

Figure 18 Test setup for: a) slabs; b) footings

Fatigue performance of HSFRC (WP3): An experimental work was conducted on two HSFRC mixes using Manufactured steel Fibres (MF) on their own or blended with RTSF. To minimise testing time, a special frame was manufactured suitable to test three specimens simultaneously under fatigue loading (Figure 19). All specimens reached 2 million cycles at stress levels of S=0.3 and S=0.5. Series 40M0R (40 kg/m^3 of MF) exhibited the best fatigue resistance amongst all series since all specimens reached 2 million cycles even at stress level of S=0.7. Series 20M20R (20 kg/m^3 of MF + 20 kg/m^3 of RTSF) also demonstrated good fatigue resistance since 2 out of 3 specimens survived at S=0.7 stress level. Significant deterioration was observed at stress level of S=0.9 for all series. Both series 20M20R and 40M0R resisted much higher displacements than PC (plain concrete) at higher stress levels. The results showed that hybrid series 20M20R can be a good alternative of a concrete mix reinforced only with MF at the same total fibre dosage.

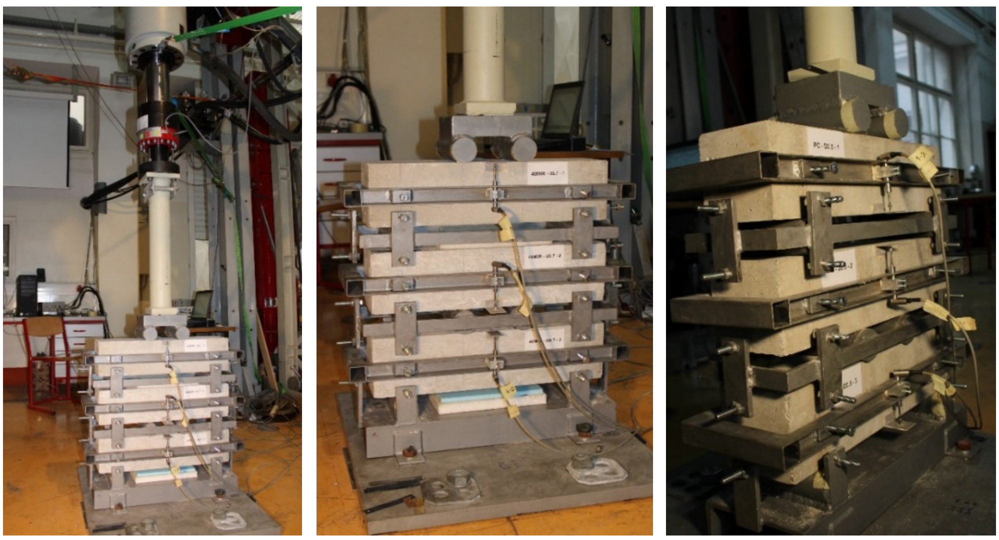


Figure 19 Fatigue test setup

Flexural behaviour of slab-like HSFRC (WP3): This research work investigated the flexural performance of HSFRC slab-like beams using various ratios of conventional flexural reinforcement combined with either manufactured steel fibres (MF) on their own or blended with RTSF. Figure 20 shows the experimental setup.

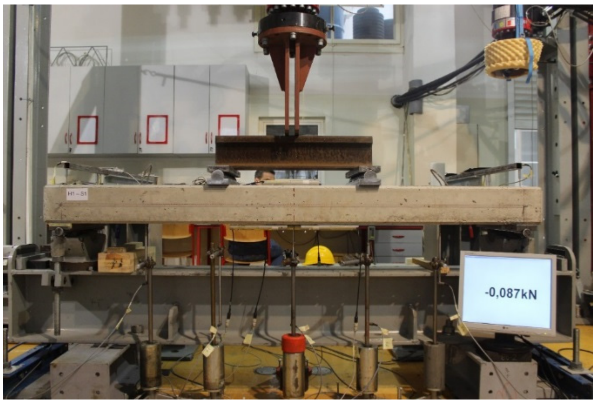


Figure 20 Flexural testing setup

When compared to series PC (no fibres + 5F12 – 5x 12mm rebars), the average yielding load for series H1 (20 kg/m^3 of MF + 20 kg/m^3 of RTSF + 5F12) increased by 9.2% whilst for series H2 (20 kg/m^3 of MF + 20 kg/m^3 of RTSF + 4F12) and H3 (20 kg/m^3 of MF + 20 kg/m^3 of RTSF + 4F10) decreased by 8.8% and 30%, respectively. Regarding deflections, at 100 kN load, series H1 showed 10.6% smaller deflections whilst series H2 demonstrated 14% higher deflection compared to series PC. HSFRC specimens exhibited smaller cracks than PC specimens (besides H3 series). Series H1 showed 50% smaller maximum crack widths compared to series PC. Series H2 showed 15-33% smaller values compared to PC. As expected, series H1 exhibited the best flexural behaviour, whilst series H3 showed a poor behaviour when compared to series PC. Series H2 showed improvement regarding cracking control regarding PC series, with relatively small decrease of yielding load. Hence, series H2, with 20% less conventional reinforcement, could be a good alternative for bridge decks when sustainability and durability are required.

Wear of SFRC using RTSF (WP3): Steel fibres (manufactured or blended with unsorted and sorted RTSF) had a beneficial effect on the mass loss when concrete was exposed to abrasion. Increased RTSF dosages led (hybrids with 10 kg of manufactured fibres, such as 20M10R$_s$ and 20M10R$_{s*}$) to decreasing the mass loss from 13 to 30 % compared to 30M0R mix (30 kg/m^3 of manufactured fibres).

Behaviour of SFRC using RTSF on freeze and thaw conditions (WP3): Based on the mix requirements (environmental exposure class XF1), a maximum decrease of RDM of 25% is allowed, while for concretes exposed to XF3 a total decrease after 56 cycles should be below 15%. The obtained results indicated that all tested mixes for task 3.1 can be used for concrete elements exposed to environmental conditions described in XF1, whilst for environmental class XF3, additional incorporation of air entraining admixture is required. Mixes tested within task 3.3 indicated higher freeze-thaw resistance which may be explained by higher quantities of entrapped air. Freeze-thaw results indicated that tested mixes can be used without air entraining admixture for exposure class XF1. For aggressive environments, higher dosages of air entraining admixture is required.

Accelerated corrosion on SFRC using manufactured and/or RTSF (WP3): Regarding the corrosion rate of steel reinforcement in FRC, the experimental work included testing of three FRC mixes with RTSF and/or manufactured steel fibres. Accelerated corrosion was imposed using potenciostatic anodic polarisation of specimens immersed in 3.5% NaCl solution. The results showed that there was an evident corrosion on both types of steel fibres, whereas their presence reduced corrosion of steel reinforcement since part of the corrosion current was consumed on corrosion of fibres. Considerable corrosion was visible in case of RTSF mixes, probably because of higher fibre dosages with smaller cross section.

Performance of conventional and rubberised SFRC subjected to wet and dry cycles (WP3): After 5 months of wet-dry cycles in accelerated chloride corrosion condition, no sign of deterioration or cracks were observed. There was a noticeable increase in the compressive strength of all mixes after 5 months of wet-dry cycles, compared to 28-day compressive strength. The mean 28-day compressive strength of the control plain concrete mix, M1, was reduced by 54% 86% when 30% and 60% of fine and coarse aggregates were replaced with rubber particles, respectively.

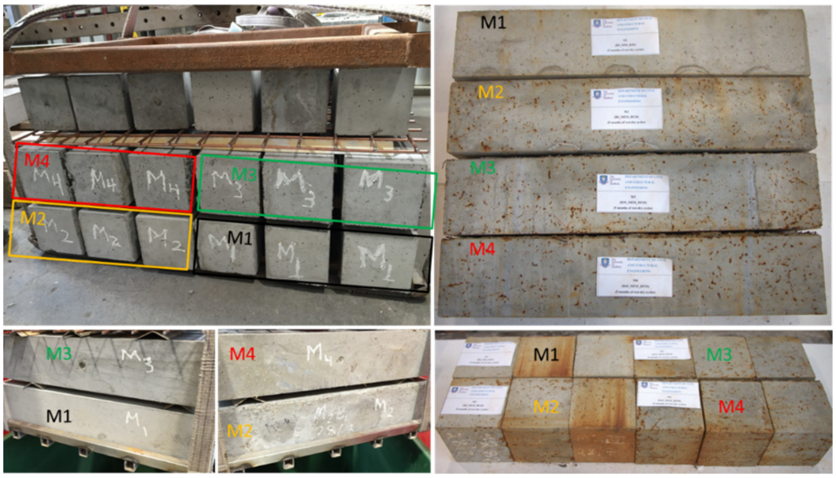


Figure 21 Specimens before (left) and after completing the wet-dry cycles (right)

The addition of fibres to the conventional concrete mix, M2, enhanced the 28-day flexural strength by 28%, compared to control mix, M1. Although the 28-day flexural strength decreased with higher rubber replacements, the inclusion of steel fibres successfully mitigated the adverse effect of rubber. The 28-day flexural strength reduction of SFRRuC mixes, M3 and M4, was 11.7% and 44%, respectively, compared to control mix, M1.

Effect of RTPF on fresh and hardened concrete properties (WP4): During this study, a plain concrete mix, mixes with monofilament (PP_m) and fibrillated (PP_f) fibres, mixes with different dosages of mixed RTPF ($RTPF_m$), mixed RTPF type 1 ($RTPF_{m1}$) and sorted RTPF ($RTPF_s$) were evaluated.

The obtained results indicated that fibres decreased workability and increase air content in fresh concrete, especially for mixes with mixed RTPF (both types, at dosages > 5 kg/m^3). The results of mechanical properties showed that, compared to the reference mixes, the addition of sorted RTPF and both mixed types of RTPF fibres (at 5 kg/m^3) did not induce degradation of mechanical properties (compressive strength and modulus of elasticity, in particular). The addition of both types of mixed RTPF types (at dosages > 10 kg/m^3) induced further decrease in the mechanical properties which can be directly correlated to the air content in fresh mix.

Shrinkage behaviour of RTPF reinforced concrete (WP4): The experimental work included concrete deformability properties (autogenous deformations, total shrinkage and restrained shrinkage). Early age deformations were studied for the following mixes: plain concrete mix, mixes with monofilament (PP_m) and fibrillated (PP_f) fibres, mixes with different dosages of mixed RTPF ($5RTPF_m$, $10RTPF_m$), and sorted RTPF ($1RTPF_s$, $2RTPF_s$, $5RTPF_s$). RTPF (both mixed and sorted) significantly influenced the early age concrete deformations. The results showed that mixed RTPF (at dosages > 5 kg/m^3) and sorted RTPF (at dosages > 1 kg/m^3) decreased autogenous deformation compared to plain concrete mix (PC). Figure 22 shows the results of autogenous deformation measurements for mixes comprised mixed RTPF.

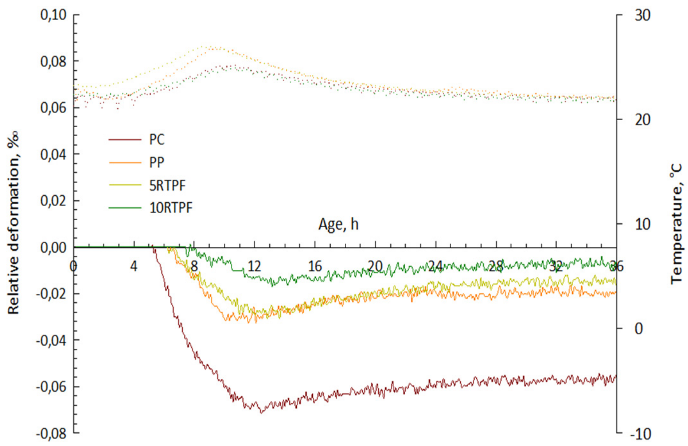


Figure 22 Results of the autogenous deformation for mixed RTPF

For the total shrinkage during the drying phase, no strong conclusion can be drawn. Even though the addition of fibres did not affect total shrinkage, restrained shrinkage was significantly affected. Substituting PP with mixed RTPF (at dosages > 10 kg/m^3) led to improved concrete behaviour, increasing tensile stresses that concrete can withstand prior to cracking, compared to concrete with 1 kg/m^3 of PP fibres. Figure 23 show the time history of the restrained shrinkage measurements for mixes OC, PP_f and $15RTPF_m$.

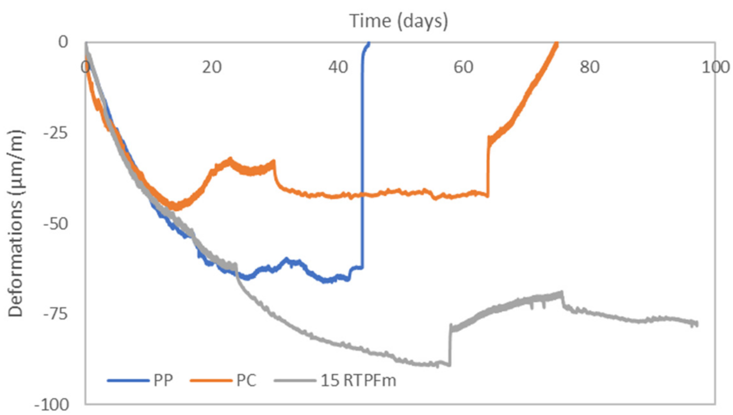


Figure 23 Restrained shrinkage deformations for ring specimens

Self-compacting concrete reinforced with RTPF (WP4): The conclusions for conventional concrete on the influence of RTPF addition on fresh concrete properties can also be applied, whilst the results of the compressive strength indicated that the fibre addition did not affect the compressive strength of

SCC (at dosages ≤ 2 kg/m^3). The highest effect of fibres was observed in the results of autogenous deformations: RTPF decreased the autogenous shrinkage by more than 47%.

Sprayed concrete with RTPF (WP4): Autogenous shrinkage results showed that the addition of RTPF$_m$ improved the performance. In detail, 1.8 kg/m^3 of RTPF$_m$ (mix 1.8RTPF$_m$) reduced autogenous shrinkage (compared to plain mix SC) by 35%. Restrained shrinkage results showed that, compared to plain concrete, concrete mixes reinforced with RTPF$_m$ withstood higher stresses induced from restrained shrinkage (Figure 24). Substituting 0.9 kg/m^3 of PP$_m$ with 0.9 kg/m^3 of mixed RTPF$_m$ increased tensile stresses that concrete can withstand prior to cracking by up to 116 % compared to plain concrete, 36% compared to concrete at 0.9 kg/m^3 of PP$_m$ fibres and 4% less than the concrete mix with 1.8 kg/m^3 of PP fibres.

a) b)

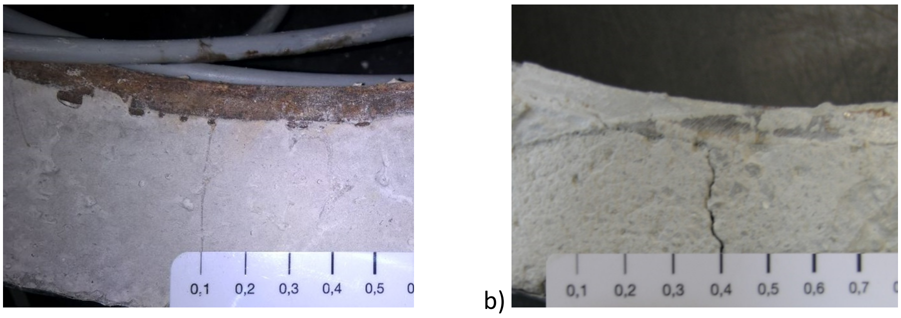


Figure 24 Crack widths by visual inspection: a) 0.9 RTPF$_m$, b) sprayed concrete

Screeds reinforced with RTPF on their own or blended with RTSF (WP4): Two types of fibres were used as reinforcement in the screed mixes: sorted Recycled Tyre Polymer Fibres (RTPF) and sorted Recycled Tyre Steel Fibres (RTSF). The results indicated the beneficial effect of adding RTSF or RTPF fibres to the screeds, in terms of abrasion resistance. Tests on plastic and restrained shrinkage showed that 0.9 kg/m^3 of sorted RTPF can successfully mitigate early-age plastic concrete cracking (Figure 30).

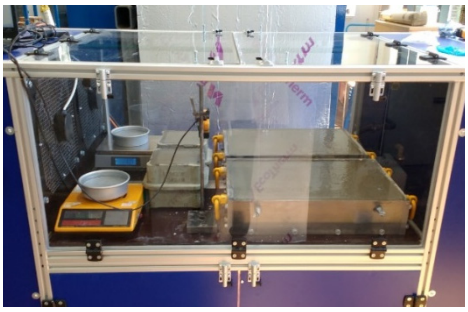


Figure 25 Restrained shrinkage test setup

Durability properties of concrete with RTPF (WP4): Durability tests were performed on mixes reinforced with 3 types of RTPF (mixed, type 1 and sorted) and their performance was compared to plain concrete (OC) and concrete with monofilament (PP$_m$) and fibrillated PP fibres (PP$_f$).

Regarding capillary absorption, the addition of all types of fibres improved concrete resistance to penetration of fluids. However, when higher dosages of RTPF were used, this positive effect on penetrability properties was diminished, mostly due to the rubber attached to the fibres. In case of water permeability, gas permeability and chloride diffusion, no significant benefit of RTPF on the concrete properties was observed.

Significant positive influence in concrete resistance to scaling was observed caused by freezing and thawing with de-icing salts. Several mixes with mixed RTPF met the criteria for both XF2 and XF4 exposure classes without addition of air entraining admixture. Freeze-thaw resistance without the presence of chlorides showed that all tested mixes with RTPF without air entraining can be used for concrete elements exposed to environmental conditions described in XF1 and XF3 exposure classes.

Durability of hybrid FRC mixes reinforced with RTSF and RTPF (WP4): The use of both RTSF and $RTPF_m$ in concrete, had a positive effect on water permeability and wear resistance properties of FRC, when they were used as substitution of manufactured fibres; regarding freeze and thaw properties the improvement was significant: After 28 cycles, the total amount of cumulative mass loss was 2 times lower than for mixes reinforced with recycled fibres, compared to the mix reinforced with manufactured fibres.

Development of specialised radiant panel for high heating rate and high temperature spalling (WP4): During this study, a specialised Radiant Panel Heating System (RPHS) was designed and manufactured, to perform fire tests on concrete and assess its fire spalling behaviour when reinforced with Recycled Tyre Polymer Fibres (RTPF), as a replacement of manufactured Polypropylene fibres (PP) (Figure 26). The RPHS is based on an electric radiant heating vertical panel. The thermal loading is actively controlled by measuring the exposed surface of the specimen using a high precision infrared thermometer.

Figure 26 Vertical radiator and control unit

The fire-spalling behaviour of concrete with RTPF was assessed by performing six fire tests on concrete slabs with dimensions of 250 x 500 x 500 mm. Three specimens were made of plain concrete (Figure 27 a-c) whilst another three specimens were reinforced with 2 kg/m^3 of RTPF (Figure 27 d-f). The specimens were subjected to an axial stress of 10 MPa, which was 20% of their compressive strength at ambient-temperature. The specimens were exposed to the ISO fire curve. A heat transfer analysis was conducted in Abaqus to model the temperature in a concrete specimen and a numerical model was developed which was also verified by the experimental results. Figure 27 shows the outcome of the spalling tests. The three plain concrete specimens experienced severe spalling. The spalling time recorded were 10 min 49 s for specimen P1, 9 min 51 s for specimen P2 and 9 min for specimen P3. The specimens of mix F (2 kg/m^3 RTPF) did not spall. This implies the incorporation of RTPF can prevent fire-induced spalling. The results showed that RTPF had a strong potential to replace manufactured PP fibres for the mitigation of fire-induced spalling in concrete structures/infrastructure.


(a)

(b)

(c)

(d)

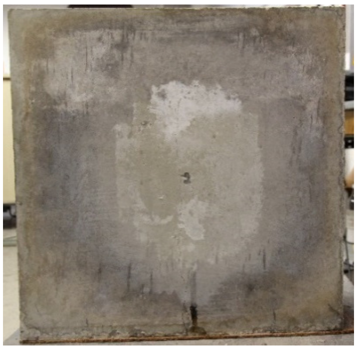
(e)

(f)

Figure 27 Specimens after fire-induced spalling tests. a) P1 b) P2 c) P3 d) F1 e) F2 f) F3

Design recommendations and examples for RuC, RTSF and RTPF reinforced concrete applications (WP2, WP3, WP4): One of the main achievements of Anagennisi project, was the development of design recommendations for applications reinforced with either of the three main materials. Based on the research findings obtained through the extensive experimental work, design tools and representative examples were included and can be a useful tool for engineers. Apart from design, the design recommendations covered several practical aspects regarding the adoption of confined rubberised concrete and RTSF in the construction industry, including manufacturing processes, materials specifications and LCA/LCCA analysis.

Demonstration project – Suspended slab using RTSF (WP5): Comsa SAU constructed a Steel Fibre Reinforced Concrete suspended slab using conventional steel rebars and Recycled Tyre Steel Fibres (RTSF). The suspended slab was the roof of a sanitary hut at a recreational summer camp (Camping La Siesta) located in Salou (Tarragona – Spain). The slab thickness, width and length were of 0.15m, 5.65m and 7.46m, respectively, covering an area of 42 m^2. In total, 8 m^3 of concrete were cast, which contained 240 kg of sorted RTSF (fibre dosage: 30 kg/m^3) supplied by Twincon Ltd.

Figure 28 Finished sanitary hub

Demonstration project – Slabs on grade using hybrid SFRC (manufactured fibres + RTSF) (WP5): Two demonstration sites were identified, to apply the technology developed within Anagennisi project on slabs on grade. On both cases, Hybrid Steel Fibre Reinforced Concrete (HSFRC) was used, reinforced with manufactured and Recycled Tyre Steel Fibres (RTSF). Both slabs were monitored for shrinkage deformations for a few months using surveying instrumentation as well as visual identification of cracks.

The first slab on grade was cast in Bosnia and Herzegovina by Dulex Ltd: The geometrical characteristics of the slab on grade were: thickness 0.20 m, width 30 m and length 40 m, covering a plan area of 1200 m^2. The slab is located at a plant for prestressed concrete elements. Since the slab was supposed to carry heavy precast concrete elements and steel moulds, it was decided the maximum load capacity of slab to be at 2000 kg/m^2. The design was undertaken using the fourth edition of Concrete Society Technical Report No.34 following limit state conditions which were in line with Eurocode 2. Manufactured (straight with hooked ends) steel fibres (MF) type DE 30/0.6 at 20 kg/m^3 and Recycled Tyre Steel Fibres (RTSF) at 10 kg/m^3, were used. In total, 240 m^3 of concrete were cast. Approximately, 5 tonnes of manufactured steel fibres and 2.5 tonnes of sorted RTSF were supplied by Dulex LtD and Twincon Ltd, respectively. To assure a uniform dispersion of RTSF in concrete, additional modifications of standard fibre blower, were required. During casting, the compaction was first performed using concrete pokers. The finishing was done using a laser-guided levelling finisher (Figure 17).

Figure 29 Laser-guided levelling

The second slab on grade was cast in Didam, Holland: Twincon Ltd undertook the construction of an indoor SFRC slab on grade (plan view dimensions of 30 x 20 m, thickness of 0.15 m) that would be used as a general storage facility. The fibres used, were a blend of 20 kg/m^3 of manufactured undulated steel fibres (0.8 mm diameter and 50 mm length) and 10 kg/m^3 of RTSF. The design and construction methodology was the same as followed for the slab in Bosnia. Figure 30 shows the finished slab.

Figure 30 Finished floor

Demostration project – Tunnel lining using recycled steel fibres (WP5): COMSA SAU applied the knowledge on sprayed concrete on two tunnel lining sections (located in a motorway in Spain) using Recycled Tyre Steel Cords (RTSC) at 30 kg/m^3. Both tunnel segments were monitored since their construction, using different instruments (strain gauges, convergence strips and pressure cells). Both segments were completed successfully with no reported issues (Figure 31).

Figure 31 Spraying the 300mm-thick concrete layer

Demostration project – Precast concrete elements (WP5): A demonstration project was performed by Cyprus University of Technology (CUT) on road safety poles using Steel Fibre Reinforced Rubberised Concrete (SFRRuC) reinforced with Recycled Tyre Steel Fibres (RTSF). Figure 32 shows the SFRRuC road safety poles which were confined with a steel tube on the lower end of the pole, to support the pole connection to its foundation and reinforced centrally with an 8mm Glass Fibre-Reinforced Polymer (GFRP) rebar.

Figure 32 Safety road poles cast with steel fibre-reinforced rubberised concrete

A central location in the city of Limassol (Cyprus) was selected to serve the demonstration purposes and provide easy access for monitoring the project. The installation site is near the historic church of Ayia Napa in Limassol, and right outside a local bank branch (Figure 33).

Figure 33 Anagennisi's safety road poles installed in the historic centre of the city of Limassol

Demostration project – Repair screed using recycled steel filaments (WP5): Twincon Ltd undertook a screed application on a damaged concrete floor at a farmhouse located in Sheffield, United Kingdom. Tyre Cord Filaments (TCF) were used as reinforcement in the screed mix to increase its toughness. TCF is made from exactly the same material as Recycled Tyre Steel Fibres (RTSF) however, the fibres can be cut in determined lengths since the extraction procedure uses a cryogenic method which extracts the steel cords from unvulcanised tyre belts as a whole. The existing slab was repaired with an additional layer of fibre reinforced pumpable screed varying in depth from 0 - 70 mm at the worst affected areas.

Manual integration was performed with no balling issues due to the relatively short fibres used. The final fibre dosage was of 20 kg/m^3 and included the 12 mm TCF. Figure 34 shows the casting procedure.

Figure 34 Casting of fibre reinforced screed

Demostration project – Insulated Concrete Formwork (ICF) walls using RTSF (WP5): Twincon Ltd undertook a demonstration project on Insulating concrete form (ICFs) walls at a farmhouse located in Sheffield, United Kingdom. ICFs are hollow blocks or boards that are made up of polystyrene which plays the role of a mould for cast-in-place concrete walls as well as insulating material. The forms stay in place permanently after the concrete is cured and function as a thermal and acoustic insulator. The forms do not contribute to the structural capacity of the wall (Figure 35).

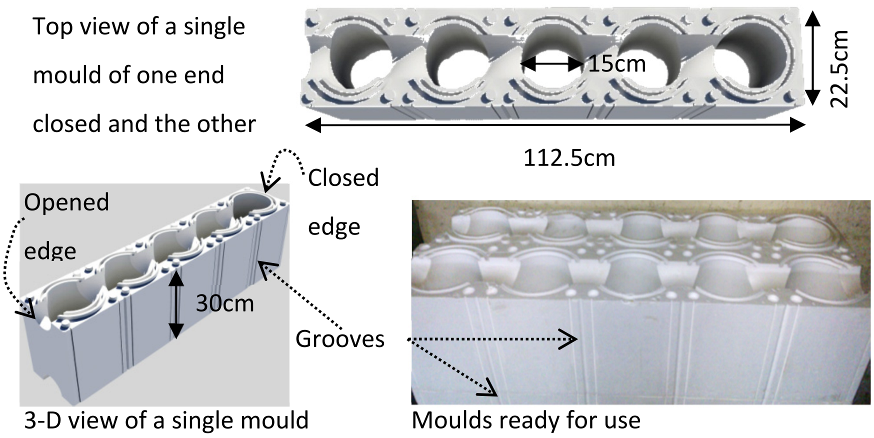


Figure 35 Polystyrene moulds used to build the screen-grid system

Concrete was ordered as self-compacting ready mix that contained Recycled Tyre Steel Fibres (30 kg/m^3) delivered to the construction site. No vibrator was used to compact the concrete in the moulds. The project was completed with no reported technical issues. Figure 36 shows a snapshot of the casting procedure.

Figure 36 Casting concrete into screen-grid ICF moulds in constructing a high wall, with supporting scaffolding

Life cycle assessment (LCA) and a life cycle cost analysis (LCCA) of demonstration projects (WP5): This task undertook the environmental and cost life cycle assessment of a flexible suspended slab constructed with hybrid reinforced concrete, a slab-on-grade constructed with hybrid steel fibre-reinforced concrete, and two sprayed steel fibre-reinforced concrete tunnel linings.

A “cradle to cradle” life cycle assessment was carried out and, hence, the system boundary on the flow diagram of each analysed structure was extended from the Product Stage (waste processes and extraction of raw materials), to the Construction Process, Use Stage and End-of-Life. The system boundary also included the benefits/burdens arising from the Reuse/Recovery/Recycling potential of each demonstration. Thus, the study considers the use of the demolished steel fibre-reinforced concrete (SFRC) as a substitute of mineral aggregates. To account for the multi-functionality of End-of-Life/Recycled products, only 50% of the environmental inventory for the End-of-Life and Recycling potential was allocated to the current life-cycle. An indicative analysis of the slab on grade which was cast in the Netherlands is presented below. The full results of the LCA and LCCA of all Anagennisi project are publicly accessible.

Slab-on-grade: The slab-on-grade was constructed in the Netherlands by Anagennisi participant TWINCON. The results of the LCA (Table 3) indicated that the Product stage (A1-3) had the highest impact, followed by the Construction stage (A4-5). Furthermore, by considering the Recycling potential of this demonstration, it is possible to have an environmental benefit (Figure 37). However, this is a minor one, since the use of recycled aggregate avoids the production of a primary material with a low environmental impact (i.e. natural river aggregate).

Table 3 Selected impact results for the slab-on-grade

	Climate change midpoint, excl biogenic carbon [kg CO2-Equiv.]	Ecotoxicity freshwater midpoint [CTUe]	Eutrophication terrestrial midpoint [Mole of N eq.]	Ionizing radiation midpoint, human health [kBq U235 eq]	Resource depletion water, midpoint [m³ eq.]
A1-3	32698.9	1679.9	312.1	1277.3	43.7
A4-5	932.0	283.9	5.8	16.4	1.0
B2-5	0.0	0.0	0.0	0.0	0.0
C1-4 (50%)	507.7	472.0	6.9	11.6	1.3
D (50%)	-1674.1	-42.5	-9.8	-59.6	-2.4

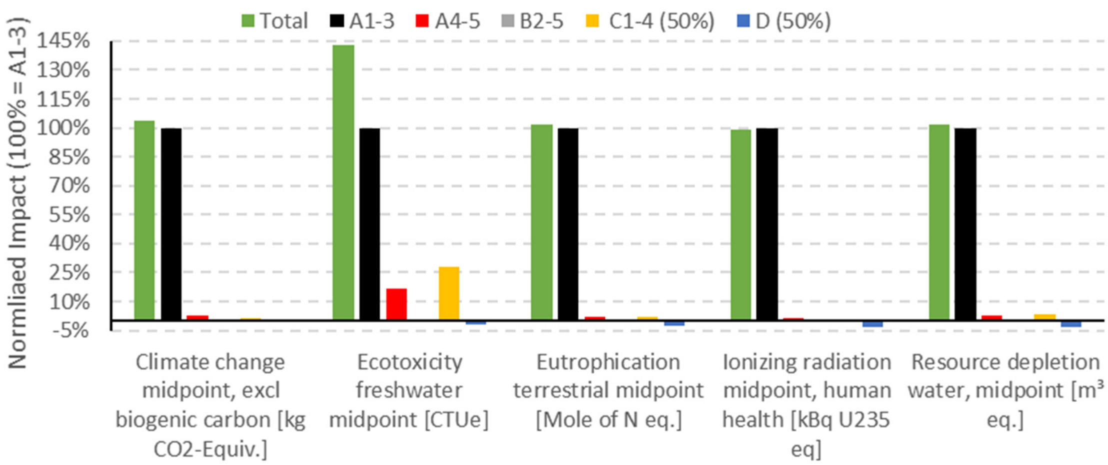


Figure 37 Normalised impact results for the various stages of the life cycle of the slab-on-grade

The LCCA results for the slab-on-grade, outlined in Table 4, indicate that there is a similar cost between stages A1-5 and C1-4. Furthermore, a substantial economic benefit (up to 36% of the initial material costs) can be obtained by considering the recycling potential of the concrete slab (considering the high cost of mineral aggregate in the Netherlands).

Table 4 Life cycle costing for slab-on-grade

	Materials	Personnel	Equipment	Fuel	Electricity	Total
A1-5	€ 10,217.2	€ 5,156.6	€ 3,179.8	€ 832.0	€ 5.4	€ 19,391.1
C1-4	€ 0.0	€ 5,442.9	€ 9,040.0	€ 2,252.0	-	€ 16,734.8
D	-€ 3,651.5	-	-	-	-	-€ 3,651.5

4 The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

The impact strategy approach of Anagennisi project, focused on reducing the waste production and pressure on raw materials. Up to 50% of the potential 3.4M tonnes of tyre arisings per year in Europe could be used for structural applications, eliminating wastes going to landfill and reducing or even eliminating the amount being incinerated. To improve resource efficiency and reduce environmental impacts, Anagennisi project aimed to reduce the demand for raw materials such as:

- Rubber (e.g. for bridge bearings or base isolation) in the EU this could be up to 1M tonnes rubber tonnes/year,
- Steel and polymer fibre reinforcement in concrete; up to 200k tonnes/year of steel wire and up to 100k tonnes/year of polymer fibre.

Currently, the European market for new steel fibre is estimated at 120k tonnes per year and the world market at 0.5M tonnes per year. In addition, the EU market for steel reinforcement is 10M tonnes per year.

The aim was to enhance the sustainability of concrete construction by using recycled materials and less materials (due to thinner structural elements). Substantial contribution towards the sustainable supply of raw materials of economic importance in Europe through the development of a sustainable supply of reused steel and polymer fibres for concrete reinforcement and recycled rubber in bearings and base isolation systems.

4.1. Environmental benefits and resource efficiency

1. Recycled Rubber to be used as a new type of high value aggregate leading to more flexible elements and new isolation systems. Recycled rubber crumb is the main product produced by tyre recyclers and is mainly used in making sport surfaces and other products, not directly competing with new rubber. None-the-less the products to be produced may replace products that use new rubber, such us bridge bearings and base isolation units. Recycled rubber may also be used in structural applications utilising confined concrete elements, where it is possible to attain significant environmental benefits. To attain the same design criterion (e.g. curvature ductility), confined rubberised concrete elements would require less concrete volume and reinforcing materials than conventional confined concrete elements. For instance, 40% less concrete and 70% less steel rebars and AFRP sheets are needed in a confined concrete column to attain a curvature ductility of 7.

2. RTSF to replace an equivalent amount of new steel fibres currently produced from wire rod. The input for the production of RTSF is recycled tyre wire, which if it is clean enough can be used for re-melting, but it is normally stockpiled and occasionally still landfilled, despite the EU landfill directive. The production of RTSF involves re-cutting and re-sieving only, which together with the conventional tyre recycling processes utilises electricity at the rate of 166.3 kWh/tonne of RTSF. For the new steel fibres, environmental indicators were obtained from worldsteel.org and Gabi-6 databases for wire rod production and these were used to estimate potential savings. It should be noted that the manufacture of new steel fibres includes further energy input for the drawing and cutting process, estimated at 220 kWh/tonne of new steel fibres. The analysis conducted by Anagennisi partners showed that that each tonne of RTSF eventually saves one tonne of new steel fibre with estimated overall reductions per tonne of RTSF:

- CO_2, 1.9 tonnes
- Toxic emissions, all heavy metal emissions (Cadmium 0.00006 kg/tonne, Chromium 0.000338 kg/tonne, Lead 0.00265 kg/tonne, Mercury 0.000914 kg/tonne)
- Irritants including gases such as Hydrogen Chloride 0.0534 kg/tonne, Hydrogen Sulphite 0.0991 kg/tonne, Sulphur Dioxide 3.59 kg/tonne, Nitrogen oxides 2.84 kg/tonne, and smaller amounts of other Nitrogen and Nitrous oxides
- Air quality: Dust 1.39 kg/tonne
- Fresh water pollution including Ammonia 0.00035 kg/tonne, as well as traces of heavy metals (Cadmium, Iron 0.129 kg/tonne, Lead, Nickel, Zinc), Nitrogenous matter, Phosphate and Phosphorous.

3. RTPF to replace an equivalent amount of new polymer fibres currently produced from new chemicals (petro-chemicals). The input for the production of RTPF is recycled polymer textile, which if it is briquetted can be used for incineration, but it is normally stockpiled and occasionally still landfilled, despite the EU landfill directive. The production of RTPF requires only cleaning using specialised cleaning systems and this can be done with less than 2 kWh/tonne. Depending on the application, the RTPF can replace a polymer based alternative currently used in concrete. It is estimated that each tonne of RTPF could eventually save one tonne of new polymer fibre with estimated overall reductions per tonne of RTPF:

- CO_2, 2.2 tonnes
- Toxic emissions, all heavy metal emissions (Cadmium 0.00007 kg/tonne, Chromium 0.00052 kg/tonne, Lead 0.00203 kg/tonne, Mercury 0.00033 kg/tonne)
- Irritants including gases such as Hydrogen Chloride 0.00157 kg/tonne, Hydrogen Sulphite 0.0612 kg/tonne, Sulphur Dioxide 2.67 kg/tonne, Nitrogen oxides 3.1 kg/tonne, and smaller amounts of other Nitrogen and Nitrous oxides
- Air quality: Dust (PM2.5, PM2.5-10) 0.285 kg/tonne
- Fresh water pollution including Ammonia 0.00035 kg/tonne, as well as traces of heavy metals (Cadmium 0.0012 kg/tonne, Iron 0.279 kg/tonne, Lead, Nickel, Zinc).

4.2. Dissemination activities

Improved communication and transfer of knowledge to policy making, business and to the general public was another key objective. Apart from lobbying the construction profession, tyre recycling industry and local authorities, the consortium used the project dissemination tools to campaign for the importance of the developed technologies for future prosperity. LCA and LCCA studies have been undertaken to quantify the environmental and socioeconomic impacts. This work was coupled with work on design recommendations and mini demonstration projects.

Public understanding of science is the key for relevant policy making, hence five public lectures were given at several forums of industry, professional and policy experts, aiming to inform it for the activities and the key outcomes of the project, whilst highlighting the economic and societal benefits. Table 5 provides a brief description of each public lecture.

Table 5 Dissemination via Public Lectures

Contributors (presenter in bold)	Institution/ Company	Title of public lecture	Event
Dr Maurizio Guadagnini	University of Sheffield	Fibre Reinforced Polymer Reinforcements	IStructE Yorkshire Regional Group Session, The Rose Bowl Building, Leeds, Metropolitan University, UK, 20 May 2014 ***Audience:*** Chartered Structural Engineers, Graduate Structural Engineers, Academics, Researchers, Students
Prof. Kypros Pilakoutas	University of Sheffield	Fibre Reinforced Concrete; Recycled Tyre Steel Fibres	IStructE Yorkshire Regional Group Session, The Rose Bowl Building, Leeds, Metropolitan University, UK, 20 May 2014 ***Audience:*** UK Chartered Structural Engineers, Graduate Structural Engineers, Academics, Researchers, Students
Prof. Kypros Pilakoutas and **Dr Reyes Garcia**	University of Sheffield	Future Materials; Future of Concrete	VISION, The Future of the Built Environment, The event for Architects, Specifiers, Clients and Suppliers, OLYMPIA, London, UK, 3 June 2015 (Figure 38) ***Audience:*** Architects, Construction Companies, Exhibitors, Construction Material Suppliers
Prof. Kypros Pilakoutas	University of Sheffield	Anagennisi - Innovative reuse of all tyre components in concrete	Sustainable Waste Management, ETEK - Technical Chamber of Cyprus, Nicosia, Cyprus, November 2015 ***Audience:*** Policy Makers, Chartered Structural Engineers, Graduate Structural Engineers, Academics, Researchers, Students
Ms Samar Raffoul, Dr. David Escolano-Margarit, Prof. Kypros Pilakoutas, Dr Maurizio Guadagnini	University of Sheffield	Rubberised Concrete: Material and Applications	IStructE Yorkshire Regional Group Session, The Diamond, University of Sheffield, UK, 17 May 2017 (Figure 39) ***Audience:*** Chartered Structural Engineers, Graduate Structural Engineers, Academics, Researchers, Students

Figure 38 Dr Garcia giving a public lecture to a broad audience during "VISION" event

Figure 39 Ms Raffoul and Dr Escolano-Margarit giving a public lecture during the IStructE event

Apart from the public lectures, Anagennisi consortium delivered five industry seminars in United Kingdom, Greece, Romania and Italy. Table 6 provides the details for all industry events. All presentations for both public lectures and industry events are publicly accessible on Anagennisi website: www.anagennisi.org

Table 6 Industry events

Presenters	Institution/Company	Event	Date
Guadagnini M., Pilakoutas K., Hajirasouliha I., Papastergiou P., Garcia R. and Raffoul S.	University of Sheffield	Recycled Rubber Products and Applications for roads, Urban Furniture and transport - International Seminar for a Safer and more Sustainable City Life, Turin, Italy (Organised by ETRA)	30 Oct, 2014
Professor Kypros Pilakoutas, Dr Kyriacos Themistocleous, Dr Reyes Garcia, Dr Dan Bompa, Dr Harris Angelakopoulos, Dr Ana Baričević, Professor Alejandro Pérez Caldentey	University of Sheffield, Cyprus University of Technology, Imperial College, Twincon Ltd, University of Zagreb, Fhecor	Research/Industry seminar, London, UK (Organised by USFD and Imperial College)	6 Jul, 2015
Same as above	Same as above	2nd Research/Industry seminar, Athens, Greece (Organised by USFD)	30 Nov, 2015
Same as above	Same as above	3rd Research/Industry seminar, Iasi, Romania (Organised by TUIasi)	27 Jun, 2016
Same as above	Same as above	4th Industry Seminar for Dissemination, Rome, Italy (Organised by ETRA)	29 Nov, 2016
Professor Kypros Pilakoutas, Dr Maurizio Guadagnini	University of Sheffield	Final industry event for dissemination, Sheffield, United Kingdom (Organised by USFD)	31 May, 2017

4.3. Exploitation of results

Anagennisi investigated the reuse of all tyre components in concrete to develop materials/solutions which can be applied in structures (such as buildings, bridges and tunnels) as well as have non-structural uses in roads or pavements with reduced environmental impact. The materials extracted from tyres are: steel fibre (RTSF), rubber and polymer/textile fibres (RTPF). All three, are high quality materials with potential to have unique contributions to reinforced concrete. Based on the experimental research performed within Anagennisi project, the main exploitable results/applications are listed below:

Recycled rubber particles:

Recycled rubber particles can be used to replace conventional aggregates in concrete and with confinement, create a new concrete which can dissipate more energy by increasing concrete deformability up to 6% (Rubberised concrete – RuC):

Reinforced concrete bridge piers and abutments can be partially replaced by reinforced RuC. Some of the advantages of rubberised concrete in structural members of integral bridges are: reduced restraining forces induced by the deck movements due to more flexible piers and abutments. Reduced shear forces at the piers and abutment walls, and also the axial forces in the deck. Full transition slabs made of rubberised concrete could accommodate the movements. This would eventually allow for longer integral bridges.

RuC can be also used as an alternative to lead-rubber bearings for base isolation of structures. It requires Fibre Reinforced Polymers (FRP) confinement to enhance compressive strength and deformability.

Recycled Tyre Steel Fibres:

Whilst steel fibre manufactured specifically as reinforcement for concrete (SFRC) is a well-established product, Anagennisi project assessed structural applications for the steel fibres extracted from tyres to replace a portion of the energy demanding manufactured fibres. The largest existing market for steel-fibre reinforced concrete (SFRC) is in the construction of the industrial flooring. These applications may either be in the form of ground slabs, or suspended slabs. The former is essentially a non-structural application where the steel fibres are introduced into the concrete mix to control and/or eliminate shrinkage cracking; the latter is viewed as a structural application in which fibres primarily provide the necessary strength to enable the slab to resist the applied flexural and shear loads (as well as controlling shrinkage). Irrespective of the type of slab, steel fibres provide a cost effective and environmentally friendly alternative to the use of traditional rebar mesh reinforcement and allow the construction of 'jointless' floors where significant proportion of the construction joints normally used for shrinkage control can be eliminated.

Another promising application using recycled steel fibres is tunnel linings. This application was not only experimentally verified but also demonstrated in-situ on an actual demonstration project.

Recycled Tyre Polymer Fibres:

The tyre polymer fibres are intended to have non-structural uses, mainly to control crack development due to plastic shrinkage and explosive spalling due to fire:

Anagennisi research showed that an effective way to control autogenous shrinkage deformations as well damage caused due to restrained concrete shrinkage, is to add RTPF in the concrete mix. When fire resistance of a concrete structural member is critical for the overall performance of a structure, then appropriate dosages of RTPF in the concrete mix can be used to prevent completely damage associated to high temperatures. Similarly to sprayed concrete using RTSF, RTPF can also been used in applications comprising spraying concrete. They have the potential to be a competitive replacement of manufactured polymer fibres (PP) as well as reduce rebound.

Details of potential exploitation of foreground knowledge is provided in "Additional Template B2: Overview table with exploitable foreground".