STEEL FIBRE-REINFORCED RUBBERISED CONCRETE BARRIERS AS FORGIVING INFRASTRUCTURE

Thomaida Polydorou[1], Kyriacos Neocleous[2], Rogiros Illampas[3], Nicholas Kyriakides[4], Abdulaziz Alsaif[5], Christis Chrysostomou[6], Kypros Pilakoutas[7] and Diofantos Hadjimitsis[8]

[1]Marie Skłodowska-Curie Postdoctoral Research Fellow, Department of Civil Engineering and Geomatics, Cyprus University of Technology
[2]Senior Research Fellow, Department of Civil Engineering and Geomatics, Cyprus University of Technology
[3]Research Associate, Department of Civil Engineering and Geomatics, Cyprus University of Technology
[4]Lecturer, Department of Civil Engineering and Geomatics, Cyprus University of Technology
[5]PhD Candidate, Department of Civil and Structural Engineering, The University of Sheffield
[6]Professor of Civil Engineering and Geomatics, Vice-Rector for Economic Planning and Development, Cyprus University of Technology
[7]Professor of Construction Innovation, The University of Sheffield, Cyprus University of Technology
[8]Professor of Civil Engineering and Geomatics, Vice-Rector for Academic Affairs, Cyprus University of Technology

Abstract:

One of the top ten goals by the European Union's White Paper on Transport is to reduce road fatalities. With the most vulnerable road users, motorcyclists, suffering frequent fatalities in crashes involving road barriers, the European Road Assessment has indicated the critical need to adopt improved barrier designs. While both steel guardrail and concrete barriers are encountered nowadays as road safety measures, accident statistics reveal lower numbers of motorist deaths when collisions involve concrete rather than steel. Aiming to reduce road fatality rates further by increasing the energy absorption of concrete barriers significantly, this paper investigates the incorporation of End-of-life tyre materials (e.g. steel wires and rubber particles) into concrete and the formulation of a suitable fibre-reinforced rubberised concrete mixture. The compressive strength of various rubberised concrete mixtures using cement replacements such as fly ash and silica fume was assessed experimentally, and an optimised mixture was selected. A numerical material model was calibrated based on the selected mixture. A case study barrier was simulated on LS-DYNA using the calibrated material and its performance under impact loading was investigated through numerical simulations. The scope of the paper is to present the experimental work and the resulting calibrated numerical model, and illustrate the preliminary results of the numerical study.

Keywords: End-of-life tyres, Energy absorption, Impact, Resource Efficiency, Rubberised Concrete, Safety Barriers, Steel fibres.

i. Background information

While the world is turning to a more circular economy, researchers are investigating the re-use of End-of-life tyre components in high added value applications. With concrete being the second most consumed material in the world after water, incorporating End-of-life tyre components into concrete is expected to reduce the amount of dangerous waste significantly.

This research examines the development of steel fibre-reinforced rubberised concrete barriers; an ideal application for the reuse of End-of-life tyres, while concurrently a safer type of road safety barriers that will absorb impact energies and reduce collision severity.

Management of End-of-Life tyres is a major environmental concern in many countries; stockpiling of End-of-Life tyres is not only aesthetically unpleasing but also dangerous and in Europe has been outlawed through the implementation of EU Waste Legislation (Directive 2008/98/EC, 2008), (Pilakoutas & al., 2004). Recycling of tyre rubber (Fig. 1) in construction materials and road furniture is an ideal solution to a significant environmental, health, and aesthetic problem (Khaloo & al., 2008), (Khatib & al., 1999), (ETRA, 2016). Thus, by incorporating recycled tyre rubber into concrete, the waste issue is tackled extensively thus promoting circular economy in Europe (EC, 2015), but also provide a safer material that has been proved to reduce crash severity (Elchalakani, 2015).

Fig. 1 Recycled Tyre Rubber particles

The critical need to adopt improved barrier designs to protect vulnerable road users has been identified by the European Road Assessment Program (EuroRAP 2008), following the observation of frequent fatalities involving road barriers and motorists. Thus, the goal of reducing fatalities in road transport has been set by the EU's Transport White Paper, but despite the recent reduction of road fatalities in the European Union overall, recent statistics raise concerns as the decrease rate is currently slowing down and for certain members, there was an increase in fatalities in recent years. So far, data indicate that the goal of reducing road fatalities to half by 2020 will not be reached (EC 2011).

The need for road safety measures such as forgiving infrastructure has captured the attention of the European Commission Joint Research Centre (EC 2012), followed by the observation that the most vulnerable road users are motorcyclists, moped and other light-powered 2-wheeler riders (EC 2015). Since most accidents are caused by human error, infrastructure designed in such a way as to interfere with or block the development of driving errors can assist in decreasing the number of fatal road incidents. Safety barriers and guardrails have been placed on roads to serve this purpose, but in certain cases the outcome seems discouraging. It is reported that the collision between a motorcyclist and the common steel highway barrier guardrail (Fig. 2) is in fact more harmful than the collision between a motorcyclist and the ground (Jama & al. 2011), (Daniello & Gabler 2011).

In addition to the high numbers of human lives lost on highways, the cost of serious crashes involving motorcyclists cost a significant 2.3 billion euros annually in the UK alone (EuroRAP 2008).

Nevertheless, the European road restrain systems standard does not consider motorcycle collisions, while common practice around the globe is to place concrete safety barriers temporarily or permanently on highways to protect motorists from roadside hazards and oncoming traffic, these barriers being designed with only cars and heavy vehicles in consideration (CEN 2013), (CEN 2006).

Even though concrete crush barriers take vehicle collisions into consideration, the rigidity of plain and traditionally reinforced concrete imposes large deceleration forces to impacting vehicles, resulting into extensive damages and high risk or vehicle occupant injuries (Atahan & Sevim 2008).

Previous research by Elchalakani (2015), has recommended the use of Rubberised Concrete for road safety barriers, a material invented following the interest of recycling End-of-life tyres. In addition to rubber, recycling of End-of-Life tyres also yields recycled tyre steel wires, which have limited alternative applications for their use; the most common one being scrap feed in steel making. It is rather preferred that recycled tyre steel wires are reused in high-value applications that can benefit from the materials' exceptional physical properties (Tlemat, Pilakoutas & Neocleous 2006), (ETRA, 2016). In this research, recycled steel fibres are investigated as reinforcement, significantly aiding the flexural behaviour of rubberised concrete. In addition, to reduce the rubber particles' detrimental effect on the compressive strength of the material, this study investigates the effects of cement replacing binders such as Pulverised Fly Ash (PFA) and/or Silica Fume (Micro-silica, MS) as well as the addition of recycled tyre steel fibres on the compressive strength of rubberised concrete. In addition to improving safety, the use of recycled rubber and steel wires (obtained from End-of-life tyres) supports the Horizon 2020 Transport Research and Innovation Act priorities for sustainability and resource efficiency.

ii. State of the Art

Currently, the most commonly encountered barriers worldwide are made of either steel or concrete. In comparing the two, it is reported by Daniello & Gabler (2011), that the fatality risk for the most vulnerable road users; motorcyclists, is much higher when steel highway guardrail (Fig. 2) is encountered.

Fig. 2 Steel Highway Barrier Guardrail Barrier (Image courtesy of CIDAUT/Motoprotec)

In addition to being less hazardous, concrete barriers require reduced installation costs and exhibit lower whole life costs than steel guardrails, due to no repair requirements following an impact (Williams, 2007).

The benefit of requiring no repair after collision is attributed to the rigidity of the material, but this is counteracted by the low energy absorption capability of the rigid concrete barriers. To minimise this disadvantage, previous research by Elchalakani (2015) and Khalil, Abd-Elmohsen & Anwar (2015), recommends using rubberised concrete for safety barriers, but as the authors note, further investigation is required for the development of a durable product of high impact resistance that will be able to reduce severity of collisions (Elchalakani 2015), (Khalil, Abd-Elmohsen & Anwar 2015).

Concrete with a high rubber content is an ideal material for road safety barriers; expected to aid in reducing vehicle damages, motorist injuries and fatalities in road transport. The energy absorbing material can act as a means of forgiving infrastructure, reducing the severity of collision caused by human error. The main disadvantage of this material is that with increasing rubber content there is a reduction in compressive strength, raising concerns on the mechanical performance and resilience of rubberised concrete barriers (Atahan & Sevim 2008), (Khalil, Abd-Elmohsen & Anwar 2015). This disadvantage can be minimised with the addition of discontinuous recycled tyre steel fibres (Fig. 3), since these fibres will provide strength improvements while maintaining high deformability (Pilakoutas 2016).

Fig. 3 Recycled Tyre Steel Fibres

While Rubberised Concrete is a promising material, challenges regarding its performance have not been addressed sufficiently (Elchalakani 2015), (Khalil, Abd-Elmohsen & Anwar 2015), as discussed next.

The decrease in compressive strength with increasing rubber content is attributed to the higher Poisson's ratio of the rubber, compared to the replaced mineral aggregates, as well as to the poor bonding observed between the rubber particles and the cement paste, also referred to as weak Interfacial Transition Zone (ITZ). The bonding between rubber particles and cement paste at their ITZ was studied through Scanning Electron Microscopy (SEM) images, where gaps due to lack of bonding were visible and limited hydration products were observed around the rubber particles (Raffoul & al. 2016).

Even though previous research agrees that increasing rubber content results to a significant decrease in compressive strength, some argue that the rubber bonds well to the cement matrix (Bignozzi & Sandrolini 2006), (Benazzouk & al. 2007).

It is rather difficult to come to conclusions at the time, since rubber particles obtained from different recycling plants or even the same plant, vary significantly when it comes to contamination levels (e.g. rubber dust, textile/polymeric fibre) and surface roughness. In addition, there are no methods established for the characterisation of recycled rubber properties.

So far, providing an optimum gradation of rubber particles is shown to improve rubberised concrete compressive strength due to better packing of the mixture contents. In addition, admixtures such as plasticizers and super-plasticisers are used to achieve better consolidation of the mixture at predetermined water to binder ratios.

In this application, recycled tyre steel fibres will provide the additional strength required for rubberised concrete to sustain collision impact loads while also improving ductility and toughness of the material (Pilakoutas 2016).

iii. Preliminary Material Investigation

To suit the needs of a forgiving infrastructure application, a rubberised concrete mixture with 60% of the concrete aggregate by volume being replaced by rubber particles was investigated. To keep consistent with recommendations by previous research (Raffoul & al. 2016), a fine aggregate to coarse aggregate ratio of 1.22 was kept, and the rubber particles included in the mixture were of equal size to the natural aggregate being replaced. The fresh concrete workability and short term compressive strength values were obtained for 8 rubberised concrete mixtures, where binder types and content was varied, concluding to an optimised mix design based on workability and 28-day compressive strength.

Following previous research recommendations, a trial mixture with a water to binder ratio of 0.35 was attempted, but limited workability caused difficulties during the casting process and in addition, the concrete cubes tested for compressive strength after 7-days and 28-days of curing resulted in much lower compressive strength values compared to the literature. Since large variability is reported in the literature regarding rubber particle density, following the fact that the trial mix specimens exhibited significantly lower compressive strengths than expected, it was suspected that the trial mixture included more rubber than it was intended; due to variability in particle density, which plays a significant role in rubberised concrete mix design.

The trial mix included rubber particles from 3 different sources coming from 3 different countries in Europe (i.e Croatia, Cyprus and the UK). A representative sample of all types of rubber particles from the sources used in this study was tested for its apparent particle density (Fig. 4), following EN 1097-6 (CEN 2013).

The average particle density of the representative sample was determined to be 0.8, 27.3% lower than the initial assumption of 1.1, assumed based on values reported by Raffoul & al. (2016).

Fig. 4 Measuring the Apparent Particle Density of lightweight aggregate

In addition to the lower compressive strengths observed, the unacceptable mixture workability prompted the researchers to investigate the recycled rubber particles for water retention, even though rubber is generally considered hydrophobic. Since there is no standard or approved method for testing the water absorption of recycled tyre rubber particles, the European Standard for water absorption of lightweight aggregate, EN 1097-6 (CEN 2013) was followed.

The water absorption test (Fig.5) revealed that impurities of the rubber particles including textile fibres indeed absorb water, reducing the amount of water available for cement hydration and production of adequate Calcium Silicate Hydrate (C-S-H), the main source of concrete strength; this fact explains both the workability issues and the reduced compressive strengths of the trial mixture.

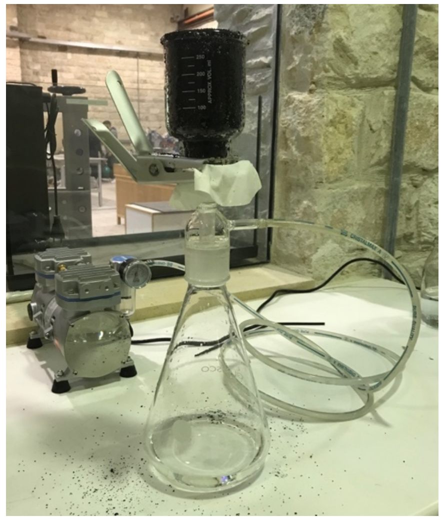

Fig. 5 Measuring the water absorption of fine lightweight aggregate

The mix design was therefore modified, taking into consideration the apparent particle density of the rubber samples used in the study, as well as the amount of water retained by impurities in the rubber sample. The optimum steel fibre-reinforced rubberised concrete mix design is shown in Table 1, listing all constituents per cubic meter of concrete, except for the case of the super-plasticiser where the amount is in Liters per cubic metre of mix.

Table 1 Optimum mix design

Mix Constituent	Amount (kg/m^3)* *unless otherwise noted
Cement	400.0
Silica Fume (Micro-silica)	100.0
Fine Natural Aggregate	310.5
Coarse Natural Aggregate	378.0
Fine Rubber Particles	169.7
Coarse Rubber Particles	207.0
Recycled Steel Fibres	25.0
Water	225.0
Super-plasticiser	3.375 (L/m^3)

It should be noted that due to the variability in rubber particle properties, it is critical to study the specific rubber sample properties before developing a rubberised concrete mix design.

Difficulties arise since there are no specified methods for recycled tyre rubber particle properties, therefore it is recommended that appropriate methods are developed, to attain a fair material characterisation of the rubber particles used in concrete.

Another important aspect of successful rubberised concrete casting is specimen consolidation; during trial mixture casting, it was observed that consolidation of fresh, rubberised concrete specimen using a vibrating table rather than rod tampering played a significant role in mixture cohesion and consequently in compressive strength development.

Early compressive strength was evaluated for all trial mixtures through cube testing at 7 days and 28 days after casting, following the standard method described by EN 12390-3:2009/AC:2011 (CEN 2011) and using a standard compressive testing machine with a load capacity of 3000 kN, at a loading rate of 0.4 MPa/s.

The study investigated the effects of using Pulverised Fly Ash (PFA) and/or Silica Fume (Micro-silica, MS) replacing part of the cement, on the compressive strength of rubberised concrete, as well as the variance in compressive strength with the addition of recycled tyre steel fibres (SF). The trial mixture characteristics are shown in Table 2.

Table 2 Trial Mixture Variables

Mix ID	Variable
A	Original Mix (Cement only, No PFA or MS)
B	Original Mix + 25 kg/m^3 SF
C	20% of cement replaced by PFA
D	C + 25 kg/m^3 SF
E	20% of cement replaced by MS
F	E + 25 kg/m^3 SF
G	10% of cement replaced by PFA & 10% of cement replaced by MS
H	G + 25 kg/m^3 SF

The compressive strength reached by each trial mix is shown in Fig. 6. The mix with the highest early compressive strength performance, or optimum mix, was the one with 20% of the cement replaced by Silica Fume (MS), also including 25 kg/m^3 recycled steel fibres, (Mix ID F). The trial mix reached an average compressive strength of 7.1 MPa at 7 days and 8.3 MPa at 28 days, values that match the expectations based on previous studies (Raffoul & al. 2016), (Alsaif & al. 2018) for rubberised concrete with a high amount of natural aggregate, 60% in this case, replaced by rubber particles.

It should be noted that the best performing trial mixtures were Mix E and Mix F, both including identical amounts of Silica Fume as cement replacement. The additional constituent of Mix F, compared to Mix E, is the 25 kg/m^3 of Recycled Steel Fibres, to which the increased compressive strength of Mix

F compared to Mix E is attributed. The fibres increased the 7-day compressive strength by 12% and the 28-day compressive strength by 14.2%.

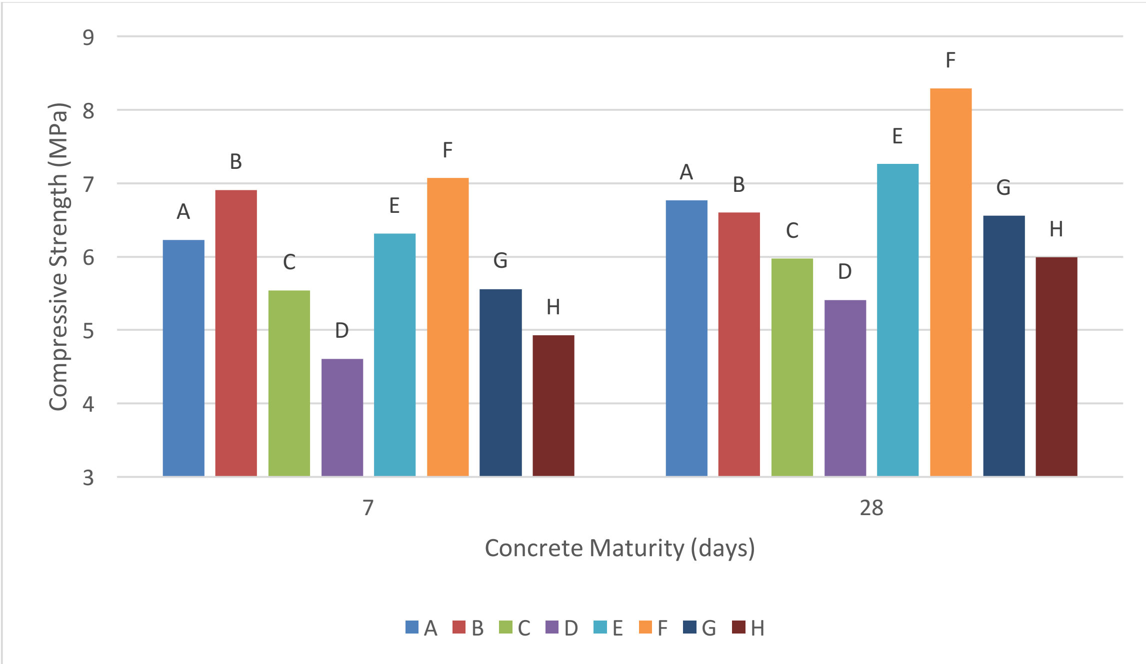

Fig. 6 Average compressive strength per trial mix

iv. Steel fibre-reinforced rubberised concrete flexural behaviour

The experimental behaviour of steel fibre-reinforced rubberised concrete (with 60% aggregate replacement) was investigated by Alsaif & al. (2018). Stress-strain characteristics and normalised modulus of elasticity of the steel fibre-reinforced rubberised concrete were obtained through cylinder testing under compression, according to EN 12390-3:2009/AC:2011 (CEN 2011).

The flexural strain capacity, flexural strength and elastic modulus in flexure were also determined by Alsaif & al. (2018) for the desired material for safety barriers, steel fibre-reinforced rubberised concrete with 60% of aggregates replaced by rubber particles. An average value of 4.2 MPa flexural strength was reported through 3-point bending of prisms (Alsaif & al. 2018). The flexural modulus of elasticity determined following the elastic theory principles, using the secant modulus of the load-deflection curves obtained by the prism bending tests, revealed an average value of 10.1 GPa (Alsaif & al. 2018). The average strain capacity, δ_{fmax}, obtained by examination of the flexural bending stress-deflection curves reported was 0.55mm (Alsaif & al. 2018).

v. Calibration of ANSYS LS-DYNA Material Model

In order to examine the performance of steel fibre-reinforced rubberised concrete for road safety barriers subjected to impact loading, the explicit Finite Element (FE) code LS-DYNA, implemented in ANSYS software was selected. The behaviour of the concrete material was simulated using the constitutive model developed by Riedel & al. (1999), i.e. RHT/CONC-35 model. This is an advanced plasticity model suited for modelling the response of quasi-brittle materials under dynamic loading. Post-yield and post-failure behaviour under tensile and compressive stresses are characterised by strain hardening, while shear induced damage is represented by strain softening. Strain rate effects in compression and tension are represented through increase in fracture strength with plastic strain rate.

The input parameters required for the formulation of the RHT/CONC-35 were hereby derived using experimental material data. For the steel fibre-reinforced rubberised concrete with 60% of natural aggregates replaced by rubber particles, the modulus of elasticity (E) of the specimens, obtained using the secant modulus from the experimental stress strain curves following the fib model code (fib 2010), averaged a value of 4.7 GPa (Alsaif & al. 2018).

A value of ν= 0,2 was assumed for Poisson's ratio. Shear modulus (G) was computed from the elastic modulus (E) and Poisson's ratio ν, using the relation given in Equation 1.

$$G = \frac{E}{2(1+v)} \tag{1}$$

The compressive strength was defined according to the average, 28-day cube compressive strength of the optimum trial mix discussed in section iii of this document. The material response under tension was defined based on the outcomes of the experimental bending tests carried out by Alsaif & al. (2018).

To estimate the axial tensile strength from the experimental mean value of flexural strength reported by Alsaif & al. (2018), Equation 2, proposed in the fib Model Code (2010) was adopted:

$$f_{ten} = f_{flex} * \frac{0.06\, hb^{0.7}}{1 + 0.06\, hb^{0.7}} \tag{2}$$

In Equation 2, hb represents the depth of the prism subjected to flexural bending, (hb=100mm).

Yielding in compression and tension were assumed to initiate at 40% and 90% of the maximum allowable stress respectively, based on the stress-strain constitutive relations given in fib Model Code (2010).

The adopted model assumes a bilinear strain hardening response in uniaxial compression. A "hardening" slope was computed to define the pre peak fracture surface as described in the ANSYS Explicit Dynamics Analysis Guide (2017). This was estimated using the compressive strength and elastic modulus values, and considering a strain of 0,0025 at peak compressive stress (Alsaif & al 2018).

The default values proposed in ANSYS Explicit Dynamics Analysis Guide (2017) LS-DYNA Keyword User's Manual (2017) were adopted for all other modelling parameters. The modified input data used in this study to simulate the behaviour of steel fibre-reinforced rubberised concrete are summarised in Table 3.

Table 3 ANSYS LS-DYNA Material Input Parameters

Property	SFRRC-60 Value
Density (kg/m3)	1884
Compressive Strength, fc (MPa)	8.3
Tensile Strength*, ft/fc	0.3
Bulk Modulus, E (GPa)	4.7
Shear Modulus, G (GPa)	1.96
Elastic strength/f_t	0.9
Elastic strength/f_c	0.4
Hardening slope	4.5

*expressed as a function of compressive strength

vi. Numerical Analysis

The numerical analysis conducted involved the simulation of a standard size road safety barrier (base width = 414mm, top surface width = 243mm and height = 813mm). The barrier was subjected to concentrated loading that was generated by the impact of a steel sphere (sphere diameter = 100mm). An initial velocity of 33.33 m/s was assigned to the sphere, representative of the maximum highway speed allowed on intercity highways in Cyprus (100 km/hr), increased by a 20% factor of safety.

The barrier was discretized into hexagonal solid elements with an average side length of 0,072 m. The calibrated RHT/CONC-35 material model was assigned to the barrier's elements. Translational degrees of freedom of the nodes at the base of the barrier were constrained, assuming fixed support.

The impacting sphere was modelled as a deformable body and was assigned Structural Steel properties using a default material model implemented in ANSYS LS-DYNA. The sphere was placed at a distance of 2 metres from the safety barrier face. The travelling direction of the steel sphere was set to be perpendicular to the barrier's geometric centre, to maximise the impact forces.

A hard body interaction that precludes penetration was assumed in the direction perpendicular to the contact surface. In the tangential direction, frictionless contact was assigned in order to eliminate the effect of friction in the energy absorption capacity of the barrier.

According to the analysis, the maximum force generated at the time of impact is 911.55 kN. The principal stresses that develop on the barrier at the time of impact (t=0.0525 sec.), at the time where maximum principal stress is experienced by the barrier body (t=0.05625), or 3.75 milliseconds after impact and at t= 0.075, or 22.5 milliseconds after impact, are shown in the contour diagrams of fig. 7.

The analysis predicts that a maximum compressive stress of 2.16 MPa will occur at time t= 0.05625. The maximum tensile stress of 8.82 MPa also occurs at time t=0.05625. These values indicate that complete crushing or cracking failure of the material will not occur, however the compressive and tensile yielding points of the material are exceeded as a result of the impact load.

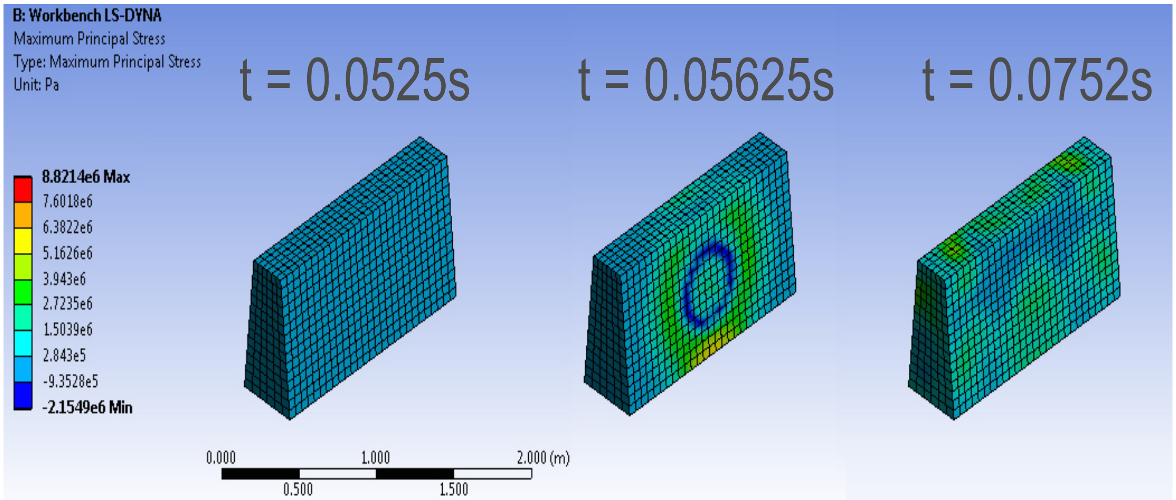

Fig. 7 Maximum Principal Stresses on steel fibre-reinforced rubberised concrete barrier model at various times

The evolution of the maximum displacement on the barrier body with respect to time is shown in Fig. 8. A maximum deformation of 1.1661 mm was computed; being experienced at t=0.0675 seconds, 15 milliseconds after the sphere impacts the steel fibre-reinforced rubberised concrete barrier.

It is worth noting that following the impact of the sphere, the barrier continues to oscillate with respect to a new equilibrium position. This indicates impact will cause the development of residual deformations to the barrier body (approximately 1mm).

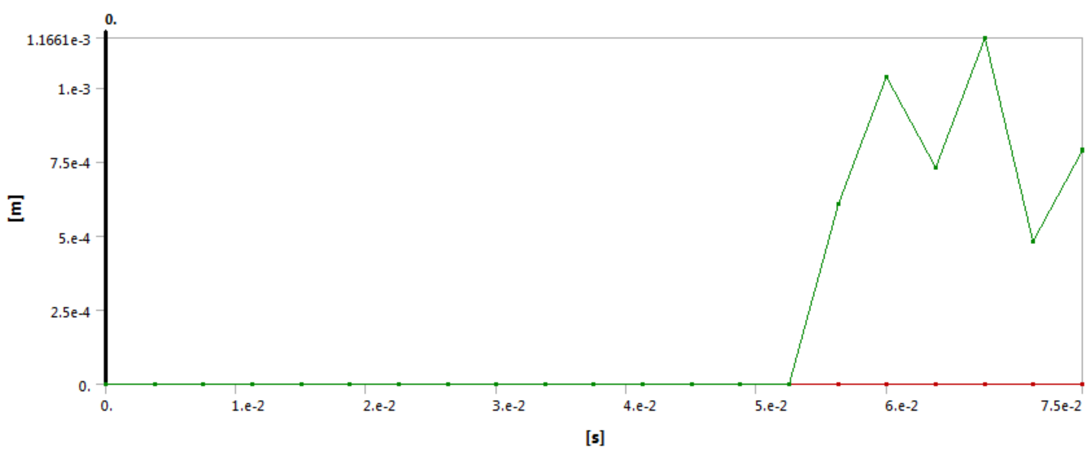

Fig. 8 Barrier deformation with respect to time

The internal energy of the barrier and kinetic energy of the sphere for the duration of the simulation is shown in Fig. 9 and Fig. 10 respectively. The predicted response is considered to be promising, since approximately 500 J from the total impact energy of 1180.8 J, remain as internal energy in the barrier (Fig. 9). In addition, EN Standards referring to fibre reinforced concrete specify a minimum energy absorption capacity of 500J which is surpassed by the barrier examined in this study (EN 14487-1 2005).

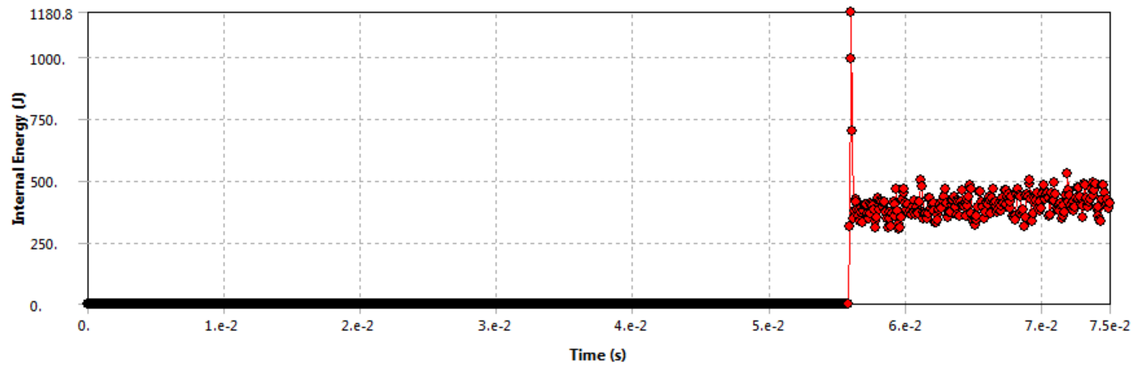

Fig. 9 Barrier Internal Energy with respect to time

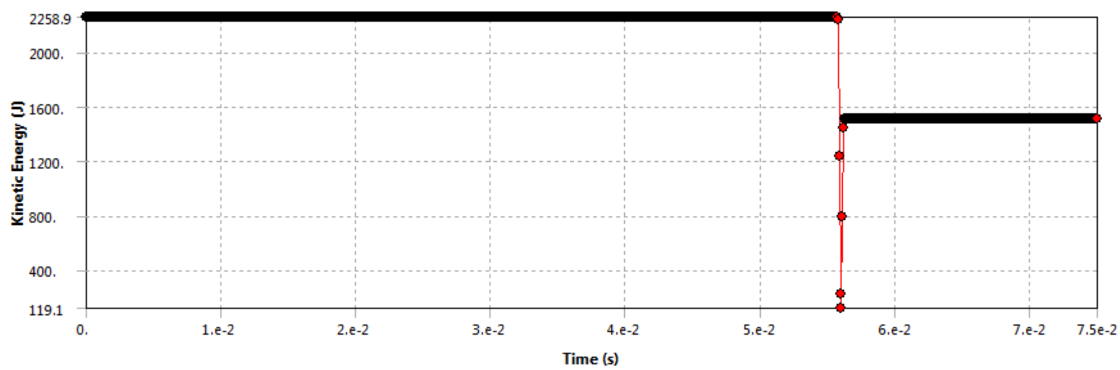

Fig. 10 Sphere Kinetic Energy with respect to time

vii. Conclusions

To reduce road fatalities, the paper proposes the fabrication of road barriers made with fiber-reinforced rubberised concrete with high energy absorption properties. To investigate this possibility, the scope of this paper was to proceed to a calibration of a numerical material model for fiber-reinforced rubberised concrete using experimental results and illustrate the numerical performance of a case study barrier.

The experimental investigation revealed that rubber-particle properties can be crucial in developing successful rubberised concrete mixtures, thus, it is recommended that appropriate methods are developed for determining the properties of recycled tyre rubber particle properties.

Regarding the mechanical properties of rubberised concrete, it is critical to provide enough water for the cement to hydrate sufficiently and produce adequate hydration products so the required material compressive strengths will be reached. In addition, it is suggested that rubberised concrete specimen should be always consolidated using a vibrating table, to attain better mixture cohesion and consequently compressive strength development.

As far as the numerical investigation is concerned, a barrier model has been set up for the numerical impact assessment of steel fibre-reinforced rubberised concrete barriers as a means of forgiving infrastructure. The predicted response is considered to be promising, since a substantial amount of the energy lost by the sphere is absorbed by the barrier with limited residual displacement. In addition, EN Standards referring to fibre reinforced concrete specify a minimum energy absorption capacity of 500J which is surpassed by the barrier examined in this study (EN 14487-1 2005).

Further analysis will follow in ANSYS LS-DYNA to optimise the geometry of the barrier and impact behaviour using models of actual vehicles.

Acknowledgement

This research has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 748600.

References

Alsaif, A., Koutas, L., Bernal, S. A., Guadagnini, M. & Pilakoutas, K. (2018), "Mechanical performance of steel fibre reinforced rubberised concrete for flexible concrete pavements", Construction and Building Materials 172 (2018) 533–543.

ANSYS Inc., (2017), "ANSYS Explicit Dynamics Analysis Guide", ANSYS, Inc., Canonsburg, PA, USA.

Atahan, A. O. & Sevim, U. K. (2008), "Testing and comparison of concrete barriers containing shredded waste tire chips", Materials Letters 62 (2008) 3754–3757.

Benazzouk A., Douzane, O., Langlet T., Mezreb K., Roucoult J. M. & Quéneudec M. (2007), "Physico-mechanical properties and water absorption of cement composite containing shredded rubber wastes", Cem. Concr. Compos. 29 (10) (2007) 732– 740.

Bignozzi, M. C. & Sandrolini, F. (2006), "Tyre rubber waste recycling in self-compacting concrete", Cem. Concr. Res. 36 (4) (2006) 735–739.

BS EN 1317-2:1998+A1:2006 (2006), "Road restraint systems — Part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers", European Committee for Standardization, Brussels, Belgium.

BS EN 1317-5:2007+A2:2012 (2013), "Road restraint systems - Part 5: Product requirements and evaluation of conformity for vehicle restraint systems", European Committee for Standardization, Brussels, Belgium.

CYS EN 1097-6:2013 (2013), "Tests for Mechanical and Physical Properties of Aggreegates – Part 6: Determination of particle density and water absorption", European Committee for Standardization, Brussels, Belgium.

CYS EN 14487-1 (2005), "Sprayed concrete – Part 1: Definitions, specifications and conformity", European Committee for Standardization, Brussels, Belgium.

Daniello, A. & Gabler, H. (2011), "Fatality risk in motorcycle collisions with roadside objects in the United States", Accident Analysis and Prevention 43 (2011) 1167–1170.

Directive 2008/98/EC (2008), Official Journal of the European Union, Directive 2008/98/EC of the European Parliament and of the Council on Waste and Repealing Certain Directives, Brussels, Belgium.

Elchalakani, M. (2015), "High strength rubberized concrete containing silica fume for the construction of sustainable road side barriers", Structures 1 (2015) 20–38.

EN 12390-3:2009/AC:2011 (2011), "Testing hardened concrete – Part 3: Compressive strength of test specimens", European Committee for Standardization, Brussels, Belgium.

European Commission (2011), “White Paper on Transport – Roadmap to a single European transport area – Towards a competitive and resource efficient transport system”, Luxembourg, Luxembourg.

European Commission (2012), Report EUR 25211 EN. “Scientific Assessment of Strategic Transport Technologies”, Luxembourg, Luxembourg.

European Commission (2015). “Closing the loop – An EU action plan for the circular economy”, Brussels, Belgium.

European Commission (2015), “Road safety in the European Union – Trends, statistics and main challenges”, Brussels, Belgium.

European Road Assessment Program (2008), “Barriers to change: Designing safe roads for motorcyclists”, Brussels, Belgium.

European Tyre Recycling Association (ETRA) Projects (2016), Retrieved from http://www.etra-eu.org/joomla/projects, September 2016.

Fib (2010), “Model Code for Concrete Structures 2010”, Federal Institute of Technology, Lausanne-EPFL, Section Génie Civil, Switzerland, 2010, p. 978-3.

Graeff, A. G., Pilakoutas K., Neocleous K. & Peres, M. V. N. N. (2012), “Fatigue resistance and cracking mechanism of concrete pavements reinforced with recycled steel fibres recovered from post-consumer tyres”, Engineering Structures 45 (2012) 385-395.

Jama H. H., Grzebieta, R. H., Friswell, R., & McIntosh, A. S. (2011), “Characteristics of fatal motorcycle crashes into roadside safety barriers in Australia and New Zealand”, Accident Analysis and Prevention 43 (2011) 652–660.

Khalil, E., Abd-Elmohsen, M. & Anwar, A. M., (2015), “Impact Resistance of Rubberized Self-Compacting Concrete”, Water Science 29 (2015) 45-53.

Khaloo A. R., Dehestani, M. & Rahmatabadi, P. (2008), “Mechanical properties of concrete containing a high volume of tire–rubber particles”, Waste Management 28 (2008) 2472–2482.

Khatib Z. K., & Bayomy, F. M. (1999), “Rubberized Portland cement concrete”, Journal of Materials in Civil Engineering, 1999, 11(3): 206-213.

Pilakoutas, K., Neocleous, K. & Tlemat, H. (2004), “Reuse of tyre steel fibres as concrete reinforcement”, Engineering Sustainability 157 (ES3), 131-138.

Pilakoutas, K. (2016), “Mechanical behaviour of steel fibre-reinforced rubberized concrete: preliminary results of the FP7 Anagennisi project, Personal Communication, June 2016, Limassol, Cyprus”.

Raffoul, S., Garcia, R., Pilakoutas, K., Guadagnini, M. & Medina, N. F. (2016), “Optimisation of rubberised concrete with high rubber content: An experimental investigation”, Construction and Building Materials 124 (2016) 391-404.

Riedel, W., Harwick, W., White, D. M. & Clegg, R. A., (2003), “Advanced Material Damage Models for Numerical Simulation Codes”, Final Report to the European Space Agency Project No. 12400/97/NL/PA(SC), EMI Report I 75/03, Ernst-Mach-Insitute, Freiburg, Germany (2003).

Riedel, W., Thoma, K., Hiermaier S. & Schmolinske E. (1999), “Penetration of Reinforced Concrete by BETA-B-500, Numerical Analysis using a New Macroscopic Concrete Model for Hydrocodes”, Proc. (CD-ROM) 9, Internationales Symposium, Interaction of the Effects of Munitions with Structures, Berlin Strausberg, 03-07 May 1999, pp 315 – 322.

RILEM (2002), "Test and design methods for steel fibre reinforced concrete. Bending test. Final Recommendation", RILEM TC 162-TDF, Materials and Structures 35,579-582, 2002.

Tlemat, H., Pilakoutas, K. & Neocleous, K. (2006), "Stress-strain characteristics of SFRC using recycled fibres", Materials and Structures 39 (3):365-377, 2006.

Twincletoes Eco-Innovation project (ECO/11/304521) (2016), Reused Tyre wire Steel Fibres (RTSF). Retrieved from https://www.sites.google.com/site/twincletoesproject/, September 2016.

Williams, G. L. (2007), "Whole Life Cost-Benefit Analysis for Median Safety Barriers", PPR 279. HA Task Ref No. 3/372/R22. Transport Research Laboratory, Wokingham, United Kingdom.

23rd Annual European Tyre Recycling (ETRA) Conference (2016), Retrieved from http://www.etra-eu.org/joomla/conference/23rd-annual-european-tyre-recycling-conference, September 2016.