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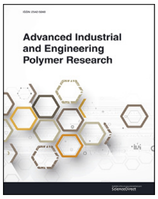

Novel uses of recycled rubber in civil applications

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A B S T R A C T

Waste tyres and their accumulation is a global environmental concern, as 1.5 billion of waste tyres are generated annually in the world. The products are not biodegradable and, if disposed of in landfills and stockpiles, are recognized for leaching toxic chemicals into the surrounding environment, acting as breeding grounds for mosquitoes, and fueling inextinguishable fires. The potential of using rubber from worn tyres in many civil engineering works has been studied for more than 30 years, and their application in construction materials comprises cementitious concrete, asphalts, and granulates for earth structures. Recycling of tyres in these field represents a suitable way of disposal for both environmental and economic reasons. Therefore, the aim of this review is to present the state of the art in tyre recycling in civil applications. In particular, the re-use of waste tyres in cement-based materials has been discussed, and then the recycling of waste tyres in bituminous mixtures and in geotechnical applications has been reviewed. This review is mainly focused on the physical properties of construction materials when recycled rubber is incorporated, trying to highlight the effects deriving from the interaction between rubber and these materials, and analyzing the proposed technological approaches from a material science perspective.

1. Introduction

Recycling end-of-life tyres (ELTs) is one of the most important environmental issues facing scientific and governmental organizations around the world [1]. It is estimated that one billion tyres ends its life every year, about half of which is recycled, and the rest is landfilled [2]. Scrap tyres are generated and accumulated in large volumes, causing an increasing threat to the environment if not handled properly [3]. These tyres are often deposited in an uncontrolled manner, because of the noticeable rapid depletion of sites available for waste disposal, causing major environmental problems [4]. Moreover, water accumulation inside the tyres provides ideal temperature and moisture conditions for the spread of mosquitoes, mice, rats and vermins [5]. At the same time, the quantity of oxygen present within the tyres is sufficient to cause fire in appropriate conditions, because of their inflammable components, with negative impacts on the atmosphere and on human health [6]. In order to eliminate the negative effects of these deposits and to support a sustainable development, it is crucial to improve existing recycling technologies of tyres and to develop new applications for ELTs [7,8]. After being shredded into smaller pieces, rubber from worn tyres can often be reused in engineering applications as ground tyre rubber (GTR) [9,10]. One of the active research projects is the partial replacement of conventional aggregates with waste tyre rubber in concrete and pavement applications [11]. Although this approach shows a tremendous potential, it comes with its own challenges such as weak inherent strength of the rubber and poor adhesion with the inorganic matrices, which limit the use of GTR as an aggregate replacement in large quantities [12]. To overcome these drawbacks, researchers considered various rubber treatment methods that not only improve the bond performances, but also significantly increase the mechanical properties of the rubber filled concrete [13]. The potential of using rubber from worn tyres in many civil engineering works has been studied for more than 30 years [14]. Applications where tyres can be used and where the addition of tyre rubber has proven to be effective in protecting the environment and conserving natural resources include the production of cement mixtures, road construction and geotechnical applications [15]. Recycling of tyres in the applications mentioned above represents a suitable mean of disposal for both environmental and economic reasons, due to the large amount of waste rubber consumed [16].

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2. Tyres rubber in concrete

Green construction has been an important aspect of the concrete industry in the last decades. The use of waste materials in the manufacturing of concrete is advantageous for both an economical perspective, with the use of low cost waste parts, and from an environmental point of view, thanks to the recycling of the waste [17]. Studies of cement-based products modified with tyres rubber have been conducted for many years [18], as the addition of shredded scrap tyres into concrete alters it properties, providing also some favorable characteristics [19]. For instance, the ordinary Portland cement based concrete is generally brittle, and the addition of rubber can lead to the so called rubberized concrete, with a higher ductility and impact resistance [20–22]. Tyre rubber can be used to produce concrete for specific applications and tailorable properties, if a proper selection of the quantity, of the shape and of the chemical nature of tyre particles is performed [23]. Rubberized concrete is also used in many applications such as pavements, sidewalks, and road barriers, where concrete is subjected to dynamic loading deriving from moving vehicles or people walking on sidewalks [24]. Waste tyres can be also used to partially replace the aggregates in concrete and in mortar [25–27]. This Chapter deals with the physical properties of cements modified with waste rubber, with a particular focus on the properties of the concrete both in the fresh and in dry state and its durability issues.

2.1. *Fresh concrete properties*

2.1.1. *Workability*

The workability, defined as the ease with which concrete can be mixed, transported and been put into molds, is affected by the interactions of tyre rubber particles and mineral aggregates. To evaluate the workability of fresh concrete, a slump cone mold is filled with a fresh concrete mixture, then the mold is removed from the concrete by a steady upward lift in a vertical direction with no lateral or torsional motion. Immediately after the removal of the slump cone, the slump is measured and recorded by determining the difference between the height of the mold and that of the highest point of the slumped test mixture (Fig. 1). Grade and proportion of rubber aggregates in concrete or cement mixture directly influence the workability. A higher rubber content has generally been found to reduce workability of concrete [23]. The possible reasons for this reduction include:

Fig. 1. Representative image of a typical slump test mixture (reprinted from Ref. [32]).

- reduction of surface area and roughness of aggregates, which increases particles friction within the concrete, that requires more energy to flow
- high water absorption of rubber particles, which increases water requirement
- reduction of the plastic unit weight of concrete, due to entrapment of air in its jagged surface texture and relatively low specific gravity of the tyre rubber.

Holmes et al. reported a decrease in workability with increasing crumb rubber concentration [28]. This was due to the decreased flowability of larger rubber particles, which implies the use of a higher water/cement (w/c) ratio for elevated concentrations of rubber in the mix. A drop in the slump height of 50% was observed when compared to the control sample when the crumb rubber content increased from 0 to 120 kg/m^3. Zheng et al. measured large reductions in the initial slump by 43% and 57% at a crumb rubber content of 45 vol%, utilized to respectively replace fine and coarse aggregates. This reduction was attributed to a higher level of interparticle friction that occurs between rubber aggregates and other mix constituents, due to the surface texture of the rubber particles and the overall reduction of the unit weight of the plastic mix [29]. However, Elchalakani found that the reduction in slump height is less than 15% for rubber concentrations till 40%, due to the larger admixture amount used for the high strength concrete [30]. Raffoul et al. reported that the workability of concrete filled with crumb rubber and chipped rubber was similar, especially at high levels of aggregate replacement). However, the combined replacement of both fillers (crumb and chipped rubber) led to a reduction in the flowability of 34%. In any case, the resulting compound was more cohesive and homogeneous with respect to the plain mix [31].

Guneyisi et al. found that the slump of the concrete with and without fumed silica gradually decreased for two different w/c ratios with increasing rubber content [33]. At a rubber concentration of 50% with respect to the total aggregate volume, the slump decreased near to zero and the mix was not workable. Moreover, the observed drop in the slump was more remarkable for low w/c concretes. In a paper of Thomas et al., scrap tyre rubber was employed as a partial substitute of natural fine aggregates in high strength cement concrete, and a super plasticizer based on a polycarboxylic-ether polymer was added to improve the workability [34]. Values for the workability above 0.91 were obtained for all the mixes with a rubber replacement level till 20%. A higher demand of superplasticizer was necessary in the case of concrete containing fillers like silica fumed, as its nanometric sized particles can partially adsorb the superplasticizer on their surface [35]. On the contrary, some researchers found improvements in the workability with the substitution of natural aggregates with rubber particles. Huang et al. reported an increase of the slump height as the rubber particle replacement percentage increased, suggesting that using an appropriate amount of lightweight aggregate in place of natural aggregate could effectively improve slump properties of the mixture [36]. Also Aiello et al. reported that the workability of fresh concrete was improved by the partial substitution of coarse or fine aggregates with rubber shreds [37]. The control mixture was characterized by a fluid behavior, whereas all mixtures obtained by adding rubber particles instead of coarse or fine aggregates showed a hyper-fluid behavior. So rubberized concrete could be mixed, cast and vibrated using equipment and procedures adopted for conventional concrete. The workability of the rubberized concrete could be improved by adding an air-entraining agent due to the generation of micro air bubbles, as described by Benazzouk et al. [38]. For the concrete containing 50% rubber particles, the slump improved to a value from 100 mm to 169 mm. Consequently, mixing water could be reduced to maintain the pristine workability, and it enhanced the mechanical properties of the resulting concrete.

2.1.2. Density

The specific weight of concrete modified with waste rubber is reduced as the level of substitution of aggregates with tyre particles increases. This reduction can be attributed to the specific weight of tyre rubber, being lower than that of traditional aggregates (0.9–1.2 g/cm^3 for tyre rubber and 2.6–2.7 g/cm^3 for aggregates) [28,31,39], and also to the air entrapment in its jagged surface texture [40]. In most cases, the density of rubberized concrete reduces from 10% to as high as 30% when compared to a plain control concrete mix [28,41,42]. Su et al. reported that the reduction in the density of the concrete was minimum for the incorporation of GTR aggregate with a size 3 mm, while finer rubber aggregates (0.5 mm and 0.3 mm size) showed a slightly higher level of reduction [32]. Also, Sukontasukkul et al. reported a relatively higher reduction with the inclusion of smaller size crumb rubber [43]. Pacheco et al. showed a reduction of 45% in the density of the final concrete when tyre chips partially replaced coarse aggregates, 34% when crumb rubber replaced fine aggregates and 33% for concrete in which both coarse and fine aggregates were replaced [44]. Bravo et al. noted that the incorporation of fine, mechanically-ground, rubber aggregates led to concrete mixes with lower density than those made with fine cryogenically grinded rubber particles. This phenomenon was related to the more angular shape of mechanically-ground aggregates, which led to a greater void volume in the concrete and thus to a lower density [45]. Therefore, a high shear rate mixing system was required to prepare a workable concrete if fine aggregate was replaced by crumb rubber, in order to mitigate the gradual increase in viscosity [46].

2.2. Mechanical properties

2.2.1. Compressive strength

Rubberized concrete compressive strength is commonly reduced by the presence of rubber particles in cement formulation, making it relatively softer than conventional cement, promoting thus the formation of accelerated cracks around rubber aggregates that can cause a rapid failure of the specimens [47]. The decrease in compressive strength could also be caused by a weaker bond between the rubber aggregates and the cement paste, leading to a non-uniform stress distribution within the material [48]. Rubber aggregates have low specific gravity and they are hydrophobic, causing rubber particles to move upwards in vibration during the preparation of the cement paste, resulting in inhomogeneity on the top surface of the concrete [49]. Another problem is air penetration into concrete due to the hydrophobic nature of rubber aggregates [38]. Besides these factors, the size, shape, and surface texture of the incorporated rubber aggregates, the type of surface modifier, and the mixing conditions have an influence on the compressive strength. The failure in compression tests of rubberized samples was found to be gradual, without a total collapse or the formation of a major crack. It was observed that during cracking rubberized concrete is able to maintain its shape without shattering to pieces. Images of failed samples with rubber contents of 0%, 20% and 40% are shown in Fig. 2(a–g). Unlike the neat concrete, in the other specimens there were not major cracks responsible for the failure. Results showed that the rubberized concrete specimens under the compressive test exhibited a gradual shear failure mode if samples contained a limited concentration of rubber. On the contrary, a splitting tensile failure pattern was observed for samples with elevated rubber amounts [50].

Fig. 3 illustrates the effect of crumb, chipped and shredded rubber aggregate replacement on the 28-day compressive strength, according to different literature papers. Note that $f_{c,R}$ and $f_{c,0}$ are the compressive strength of the cube at 28 days at a certain rubber volume concentration and that of the plain concrete, respectively.

A gradual decrease in compressive strength was noticed by Thomas et al. as the percentage of crumb rubber increased [34]. At 7 days, the maximum compressive strength (65 MPa) was obtained

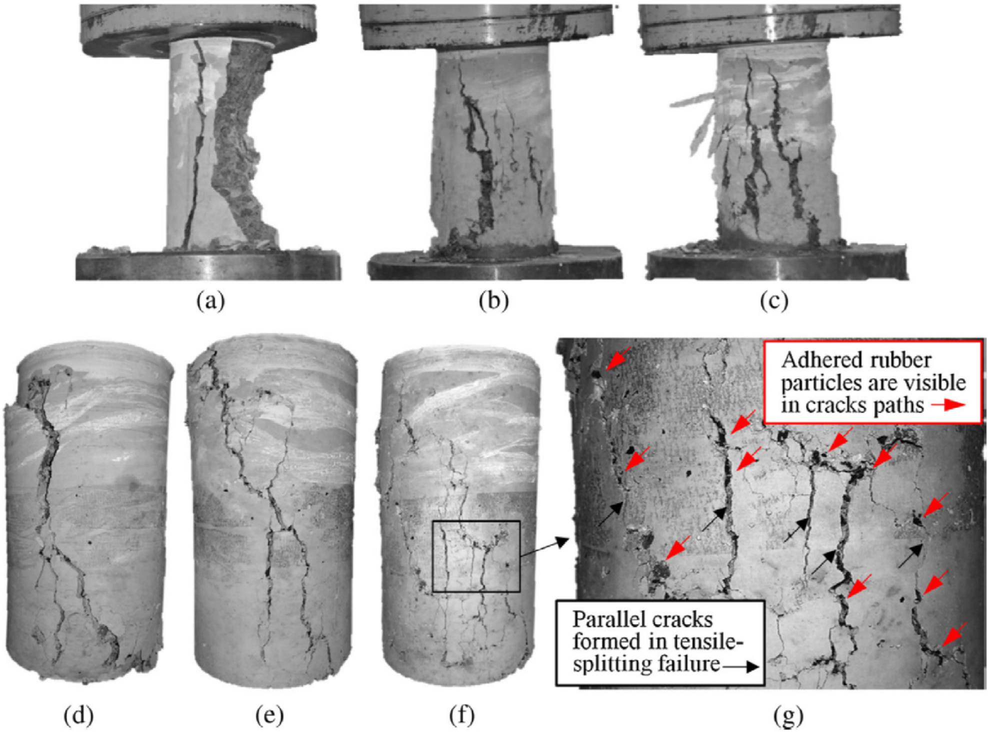

Fig. 2. Effect of the rubber content on the concrete cracking and failure mode. (a and d) No rubber, conical failure mode; (b and e) 20% rubber content, conical-shear failure mode; (c, f and g) 40% rubber content, splitting-tensile bottom and formation of parallel cracks (reprinted from Ref. [50]).

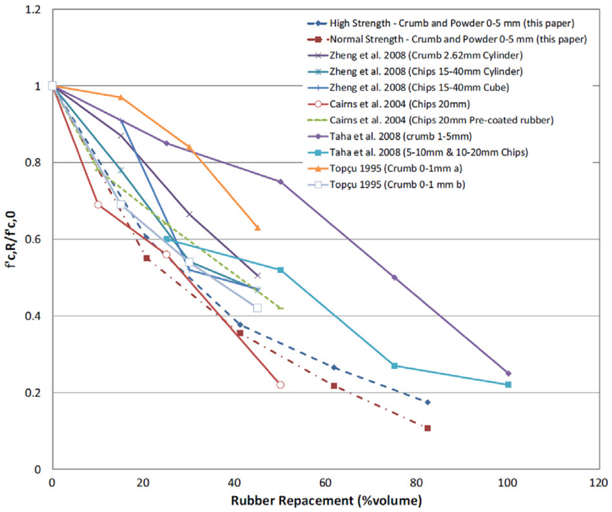

Fig. 3. Reduction in compressive strength with increasing rubber content reported in different literature works (reprinted from Ref. [30]).

for the control mix and the minimum value (27 MPa) for the mix with the highest content of crumb rubber. The same trend was observed for the compressive strength at 28 and 90 days. At 28 days, a strength above 60 MPa was obtained for all the mixes in which the amount of rubber was lower than 10%, while at 90 days all the mixes in which the crumb rubber was lower than 12.5% crossed the 60 MPa threshold, obtaining thus the classification as a high strength M60 concrete. The replacement of fine aggregates with rubber produces higher compressive strength when compared to an equal percent replacement of coarse aggregates [51]. The work by Aiello et al. suggested that the partial inclusion of rubber shreds instead of coarse or fine mineral aggregates caused a progressive loss in compressive strength with increasing the amount of replaced aggregates [37]. It was also observed that replacing rough aggregates in concrete reduced compression strength more than replacing fine aggregates. Cement mixtures prepared with 50% and 75% per volume of coarse aggregate replacement showed, respectively, a reduction in compression strength of approximately 54% and 62%, compared to the control mixture. Instead, the mixtures obtained by fine aggregate replacement at 50% and 75% showed a compression strength decay of approximately 28% and 37%, respectively, compared to the control mixture. For lower rubber replacement levels (such as 5%) the compressive strength was reduced by only 5% when compared to the control mixture. Replacements of 7.5% and 10% of powder rubber reduced the strength by 10–23%, respectively [49]. Different types of rubber led to a different degree of reduction, as highlighted by Gesoglu et al. [52]. When the rubber content was increased up to 30%, the reduction in compressive strength was as high as 44%, 48%, and 69% for concretes with crumb rubber, tyre chips and mixed rubber, respectively.

As reported by Khaloo, the reduction of compression strength in rubberized concrete restricts their use for structural applications when the rubber concentrations exceeds 25% [53]. Reduction in rubber concentration and rubber particle pre-treatment are required to enhance the strength and the other mechanical properties of the resulting concrete. As stated by Gesoglu et al., due to this significant decrease in compressive strength, the use of rubber particles in pervious concretes should be encouraged, especially in the case of pavements, which mostly require limited concrete compressive strength [42]. Others applications could be road barriers, thin overlays, concrete panels, paving blocks, and materials for thermal and acoustic insulation [31]. A wide variety of pretreatments is available, ranging from an inexpensive and easy treatment with water, up to complicated and expensive physical, chemical, and mechanical processes. According to the work of Mohammadi et al., the use of a water-soaking treatment to prepare rubberized concrete led to a relatively modest strength reduction [50]. Samples prepared with rubber treated by water-soaking had 22% higher compressive strengths if compared to the untreated ones. It has been found by Liu et al. that the pretreatment using synthetic resin significantly increased the strength of the rubberized concrete, if compared to other modifiers [54]. The compressive strength of crumb rubber filled concrete prepared with pretreated rubber using synthetic resin increased of 12% as compared to the untreated ones. Then, the synthetic resin modifier could represent an interesting option to increase the mechanical strength of crumb rubber filled concrete. A typical treatment for tyre-rubber particles consists in immersing them in a NaOH solution, to improve rubber adhesion with the cement paste. Since NaOH solution treatment can provide an alkaline ambient around the rubber particles, an improved interphase can be obtained when the treated rubber is incorporated into the concrete. In addition, NaOH solution treatment improves the hydrophilicity of rubber aggregate, reducing the porosity between rubber particles and cement paste and enhancing thus the adhesion between rubber and the cement matrix [55]. As confirmed by Guo et al. [56], the NaOH solution treatment could enhance the bonding strength between rubber aggregates and cement paste, leading to an increase of 23% in the compression strength compared to the samples with untreated rubber aggregates. The strength loss of the samples with 15% and 25% NaOH solution treated rubber aggregates were 3.4% and 25.4% respectively, which could both still fulfill the requirements for a rigid pavement design. The experimental results demonstrated that NaOH-treated rubber concrete could be successfully applied in the construction field with very limited processing costs of rubber particles. Similar results were found by Youssf et al. in their paper in which the pre-treatment of rubber using NaOH solution increased the concrete compressive strength by 6% and 15% at 7 and 28 days, respectively, compared with non-treated rubber concrete at the same rubber amount. In this sense, this pre-treatment can partially compensate the loss of mechanical strength due to rubber introduction. Guneyisi et al. suggested the use of fumed silica to enhance the mechanical features of rubberized concretes and to limit the strength loss due to the addition of rubber [33]. This positive effect was evident and consisted in a strength increment of 43%, depending on the amounts of silica fumed and rubber used [35]. Moreover, Xie et al. noted that the marked decrease of compressive strength of concrete with rubber introduction could be significantly reduced by the incorporation of silica fumed when the rubber content was less than 20% [57]. Although the concrete with rubber was more porous than that with natural aggregates, when the rubberized concrete was mixed with silica fumed, part of this nanofiller penetrated the pores, improving thus the interphase between the cement matrix and aggregates. Furthermore, hydration process filled the cracks originally present in the concrete, resulting in an improvement in the mechanical properties of the rubberized concrete.

2.2.2. Flexural strength

One of the positive characteristics of rubberized concrete is its increased toughness, as the material under a critical load breaks with a certain amount of deformation instead of disintegrating completely at low deformation levels [58]. The decreasing trend of flexural strength of rubberized concrete with the increase in rubber content is quite similar to that observable in compressive strength. However, compared to the reduction in compressive


(a) (b)

Fig. 4. (a) Rubberized concrete beam after the cracking and (b) particular of the cracked section of the beam (reprinted from Ref. [37]).

strength, flexural strength reduction is much steeper due to tensile stress applied on the outer surface of the material [47,59,60]. The debonding of rubber from the cement matrix is one of the factors that reduces the flexural strength of rubberized concrete, but it increases its toughness. Fig. 4 shows the cracked section of a rubberized cement beam under flexural loads. The presence of coarse rubber chips avoided the sudden separation of the beam into two pieces, as generally happened for plain concrete specimens [37].

A gradual reduction in the flexural strength was noticed by Thomas et al. as the percentage of crumb rubber increased [34]. At 7 days, the maximum value (6.2 MPa) was observed for the mixes with 0% and 2.5% crumb rubber and the minimum one (4.6 MPa) was observed for the samples with 17.5% and 20% crumb rubber. At 28 days, the maximum value (7.3 MPa) was obtained in the mix with 2.5% crumb rubber and minimum value (5.5 MPa) was noticed for the samples with 20% crumb rubber. The same trend has been observed at 90 days, where the maximum and minimum values were 7.9 MPa and 5.7 MPa, respectively. Similar results were found also by Bisht et al., as they observed that flexural strength of crumb rubber concrete decreased with the rubber content in the concrete, and this decreasing trend was in line with the variations observed in compressive strength values [61]. With incorporation of 4% and 5.5% crumb rubber, strength decreased by 2.9% and 16.5% respectively. Ganijan et al. reported that the reduction in flexural strength occurred for both coarse and fine aggregates replacement, and only the decreasing rate was different [49]. A reduction of 37% with respect to the control sample was observed if coarse aggregates were replaced by chipped rubber at 10%, while a reduction of 29% was recorded for the mixture in which fine aggregates were replaced with ground rubber. In this work it was stated that the most important factor in reducing flexural strength was a lack of bonding between rubber particles and cement paste, and that the debonding of chipped rubber was weaker than that observed for powdered rubber. Khorrami et al. found a reduction in flexural strength of 31% with respect to the control sample when coarse aggregates were replaced by shredded rubber with a concentration of 7.5 wt% [62]. Najim et al. reported a flexural strength decrease of 11% for 5 wt% rubber replacement and a reduction of 39% for 15 wt% rubber replacement [63]. The addition of rubber decreased the load bearing capacity, whilst increasing the maximum strain values. The maximum deflection increased from 0.039 mm for the reference mix up to 0.051 mm for the 10% mix, which corresponded to maximum stress values of 16.8 and 14.9 MPa, respectively. Elchalakani et al. found a reduction in flexural strength of 72% at 40% rubber concentration in concrete, while a slightly lower reduction (69%) was found for the same rubber replacement level by adding silica fumed in the cement formulation [30]. Aiello et al. noticed a greater loss of flexural strength when coarse aggregates were replaced by rubber particles rather than fine aggregates [37]. For fine aggregates replacement levels of 50 and 75 vol%, the flexural strength reduction was respectively 5.8% and 7.3%, while for the same replacement level of coarse aggregates, a 28.2% strength reduction was detected. Gupta et al. observed that the reduction in flexural strength was also dependent on the shape of the rubber particles [64]. If fine particles were used as partial replacement of fine aggregates, a reduction in flexural strength was observed due to the poor interlocking. However, they reported that the flexural strength of concrete with 10% of rubber fine particles and different contents of rubber fibers having aspect ratio 8–10 increased with the fiber amount, thanks to the better bridging effect provided by the fibers. Yilmaz et al. studied the feasibility of utilizing fly ash and rubber waste in Portland cement, and contrary to other literature studies, flexural strength of rubberized concrete samples showed higher values than the control mix, probably because of the effect of the different shape of rubber fillers utilized [65]. Flexural strength of control mix was evaluated as 0.51 MPa and 0.73 MPa at 14 and 28 days, respectively. The mixtures with a 20% of rubber presented a maximum flexural strength of 1.40 MPa at 28 days for particles 0.5–1.0 mm in diameter. The increase in rubber waste content from 20% to 30% decreased the flexural strength of the mixtures, and this decrease was reported to be lower as the size of tyre rubber particles decreased. Also, Ganesan et al. reported an improvement in the flexural strength with the increase in the rubber content in the cement mix [66]. For rubber contents of 15% and 20% in rubberized concrete specimens, the strength respectively increased by 15% and 9% in comparison to plain concrete specimens. This was explained by the better tensile load carrying capacity of the rubber particles. Moreover, the addition of tyre steel fibers at volume fractions of 0.5% and 0.75% to the rubberized concrete specimens resulted in an increase in the flexural strength by 26% and 35%, respectively.

For as regards the flexural properties of mortar when sand is replaced by rubber, it has been found that the flexural strength of mortar increased with increasing the rubber replacement level. Al-Akhras et al. reported that the flexural strength increased with increasing tyre rubber ash content from 2.26 MPa for control mortar to 2.91 MPa for mortar containing 10% tyre rubber ash at 7 days and from 3.48 MPa for control mortar to 5.00 MPa for mortar containing 10% tyre rubber ash at 28 days [67]. The corresponding increase at 28 days was 12%, 27%, 32%, and 43% at tyre rubber ash contents of 2.5%, 5%, 7.5%, and 10%, respectively, compared to control mortar. The increase in mortar strength with tyre rubber ash content was explained considering that tyre rubber ash behaved as a filler in mortar mixtures. This was particularly significant in the interfacial zone regions where tyre rubber ash produced a more efficient packed structure, producing thus a denser and more homogeneous transition zone. Wu et al. found that the addition of styrene acrylate rubber could improve the flexural strength of mortar, especially after 28 days [68]. The maximum increase of flexural strength was found for rubber contents between 15 and 25%.

2.2.3. Modulus of elasticity

It has been shown that the inclusion of rubber in concrete is able to increase its ductility and stress control capability, because of the soft structure of rubber aggregates. This leads to the development of several micro-tensile cracks under load, leading to significant elastic deformation and increased energy absorption prior to failure [39]. Rubberized concrete, compared to plain concrete, exhibits higher values of strain at break, but lower values of elastic modulus and stress at break [60]. The reduction in strength and elastic modulus is primarily due to the relatively low strength and elastic modulus of the rubber. As the percentage of rubber increases, the properties of the concrete are increasingly controlled by the properties of the rubber. Atahan et al. found that this is especially evident when the rubber replacement level exceeded 60% [69]. Beyond this limit, strength and elastic modulus dropped sharply, suggesting that at this concentration the rubber had greater control of the properties than concrete. Increasing aggregate amount resulted in a statistically significant decrease in static elastic modulus, due to the consequent decrease in cement amount [42]. Ganijan et al. found that the modulus of elasticity of concrete was reduced with the replacement of rubber for aggregates or cement [49]. The reduction in modulus of elasticity was 17–25% in the case of 5–10% aggregate replacement by chipped rubber, while higher levels of reduction (i.e., 18–36%) were observed for powdered rubber. A similar trend was found by Li e al., and the decrease of elastic modulus was higher when finer rubber particles were used as aggregates with respect to the bigger ones [70]. In particular, when 10% of aggregates were replaced by rubber particles with 4 mm of size, a stiffness reduction of 28% was found, while a drop of 42% was detected if the size of the rubber particles decreased to 0.17 mm. Similar results were found also in the work of Feng et al. [71]. Milder reductions in the modulus of elasticity were recorded by Noaman et al. in rubberized steel fibre reinforced concrete [58]. The modulus of elasticity was reduced by 8.3%, 13.7%, and 17.4% with rubber contents of 5%, 10%, and 15%, respectively. Pelisser et al. observed that the stiffness reduction was smaller in comparison to the decrease in the compressive strength for rubberized concrete [41]. The decrease in the elastic modulus was 49% for the concrete with a replacement level of 10% sand aggregate by recycled tyre rubber, in comparison to the reference concrete. Once again, this was because the elastic modulus of rubber is much smaller than that of the sand, thereby making the concrete with rubber more compliant. The strain modulus for concrete with 10% of rubber modified with alkaline activation and silica fumed addition showed a reduction of 17% at 28 days, compared to the plain concrete. In this case, the results obtained for the modified concrete were closer to those shown by conventional concrete. Najim et al. suggested that a pre-treatment of the rubber particles could mitigate the decrease of the elastic modulus upon rubber replacement [63]. An improvement of the secant static modulus of elasticity of 15% and 10% was found for mortar pre-coated crumb rubber aggregates and cement pre-coated crumb rubber aggregates, respectively, if compared to the control sample. This behavior could be attributed to the improvement in adhesion between the rubber aggregates and the cement paste and/or to an increase in the mechanical interaction due to the rough surface morphology of mortar-coated rubber particles. This suggested that interphase stress transfer was more effective in the cement paste and mortar pre-coated samples than in the neat rubber aggregates.

At a general level, it can be therefore concluded that, although it causes a decrease of compressive strength and of elastic modulus, the addition of a limited amount of rubber in concrete could be favorable for the seismic safety of civil structures [70].

2.3. Durability issues

2.3.1. Water absorption and permeability

Water ingression from surface to the core of concrete is either by permeability through interconnected macroscopic pores or by sorptivity (capillary suction) through microscopic pores within the hydrated cement matrix [72]. Studies have reported inconsistent results with regards to water absorption capacity of rubberized concrete. While some studies observed a considerable decrease in water absorption upon the inclusion of rubber particles, there are several works that reported exactly the opposite trend. Ganijan et al. found that water absorption was reduced but depth of water penetration was increased [49]. It appeared that water permeability in concrete containing powdered rubber was non-uniform in such a way that, even though water absorption was lower than that of the control mixture, its water permeability was increased. The reason for this behavior was attributed to the existence of capillaries filled with water in the concrete containing rubber. This was also due to lack of adhesion between rubber particles and cement paste, and interfacial surface between cement paste and rubber grains acted as the bedding for pressurized water to flow in the concrete containing rubber. Consequently, with the same or lower water absorption than the control mixture, water permeability of the concrete containing rubber was increased with respect to the unfilled material [73]. Bravo et al. highlighted that not only the size of the replaced aggregate is important to the increase of water absorption, but also the roughness of the particles should be taken into account [45]. A decrease of the permeability coefficient (K) with the increase of rubber content was found also by Gesoglu et al. [42]. For instance, K value of the control mix was 0.46 cm/s, which was reduced to 0.13 cm/s and to 0.15 cm/s in the mixes at a rubber concentration of 10% and 20%, respectively. Moreover, small rubber particles seemed to affect the permeability more than larger ones, as they filled better the pores between natural aggregates. A 10% rubber replacement diminished the permeability coefficient by 28%, while the reduction was as high as 68% at a replacement level of 20%. Nevertheless, K of the rubberized concretes produced in this study fell between the recommended limits (0.025 and 0.61 cm/s) for pervious concretes. The type of porosity that affects the phenomenon of capillary absorption is not the same that is responsible for the water absorption by immersion. In the first case, fine porosity is involved, allowing the generation of differences in pressure that cause the water to penetrate the concrete, while in the second case larger pores influence the amount of water that is absorbed [45]. About a 55% water uptake per mass of control samples after immersion into the water was observed by Kashani et al. [72]. This water uptake was substantially reduced of the 50% by increasing rubber content, especially for rubber amounts of 20–30 wt%, even if the samples had comparable porosity. A similar result was observed by Si et al., but in this study the water absorption values tended to increase when the rubber content was higher than 35% [55]. Sukontasukkul et al. observed different results for concrete filled with crumb rubber having two different particles sizes [43]. While the concrete with bigger crumb rubber particles showed higher water absorption, the concrete with small size rubber particles showed lower water absorption than control conventional concrete. The increased water absorption in case of concrete with bigger rubber particles was attributed to the air entrapment on rubber surface due to their hydrophobicity.

The increase in void content of rubberized concrete is due to factors such as the propensity of light crumb rubber to float in the mixtures at the fresh state, which made the compaction of specimens containing crumb rubber difficult and ineffective. Consequently, the percentage of voids in rubberized mixtures increased as the crumb rubber concentration increased [74]. Moreover, rubber particles repel water during mixing, thereby allowing the air entrapment on their surface. Upon hardening, voids are formed inside the Crumb Rubber Concrete (CRC) mixture [75].

2.3.2. Freeze - thaw resistance

It is known that extreme environmental conditions can cause durability problems in concrete, and freeze-thaw is a physical phenomenon that can seriously damage concrete structures (Fig. 5). Porous concrete can absorb water that can increase its volume in the solid phase, causing thus deterioration of concrete and representing also a major cost for an aging infrastructure [76]. The freeze-thaw resistance of concrete can be increased by the inclusion of rubber particles, that behave like traditional air-entraining agents. In fact crumb rubber particles, due to their non-polar rough surface, promote the formation of very small pores in which the temperatures can fall to −78 °C without the generation of ice crystals [26].

Therefore, the use of discarded tyres particles as an additive in the concrete is appropriate for those applications in which an elevated strength is not needed, but the durability is important. In fact, Topcu et al. suggested that the use of the rubberized concrete could be really advantageous in regions with a cold climate, that are particularly exposed to the freeze-thaw effect [76]. A noticeable improvement in the freeze-thaw resistance associated to the use of crumb rubber concrete has been found also by Richardson et al. [78]. The optimum crumb rubber particle size was lower than 0.5 mm. The use of smaller crumb rubber particles size permits crumb rubber to be contained in the surface laitance, which is subject to the initiation of freeze-thaw induced cracking. In contrast, the freeze-thaw resistance of concrete is reduced when the size of crumb rubber exceeded 60 mesh, since the effect of air-entraining becomes stronger as the crumb rubber size decreases [79]. As evidenced by Benazzouk [38], the level of air-entrapment could not only be correlated with the dimension of rubber particles but also with their morphology, texture, and specific area. The positive effect played by rubber introduction on the freezing-thawing resistance of pervious concrete was particularly evident after 300 cycles, as shown by Gesoglu et al. [80]. The freeze-thaw degradation led to a 34% mass loss in plain concrete after 300 cycles, while the corresponding loss in rubberized concrete was in the range between 2.7% and 4.1%. As measured by Liu et al. [54], the strength loss after 25 cycles of freezing-thawing of the reference concrete was 5.8%, while the strength deterioration in concrete with 20% crumb rubber modified by ethoxyline resin was only 1.2%. Si et al. demonstrated that the freeze-thaw resistance of concrete could be improved if the rubber aggregates were chemically treated [55]. The addition of NaOH solution treated rubber aggregates in concrete decreased the water absorption and increased the void content. These voids were responsible for the improved freeze-thaw resistance and durability of the resulting concrete samples.

Fig. 5. Frost heaving damage on a concrete structure (reprinted from Ref. [77]).

2.3.3. Drying shrinkage

At a general level, the addition of crumb rubber particles increases the drying shrinkage of concrete. The low stiffness and good flexibility of rubber aggregates reduce the internal restraint and consequently increase the dimensional change caused by the shrinkage. The high porosity and diffusivity of rubberized concrete can also help to accelerate the loss of capillary water and thus the drying shrinkage [81]. It has been shown that the more rubber is added, the greater the shrinkage during drying. Aggregates play a key role in concrete shrinkage, the increase in rubber content implies a decrease in aggregate content, therefore, the shrinkage of rubberized concrete increases with the increase in rubber content. Moreover, the increase in porosity as a result of the addition of rubber particles in the concrete can also contribute to the greater shrinkage of the concrete with rubber particles [82]. Huang et al. found that the drying shrinkage of concrete increased with the tyre rubber content. At 28 days, the drying shrinkage steadily increased of 50% as the tyre rubber concentration increased from 0% to 40% [82]. The shrinkage of rubberized concrete seemed to depend on the crumb rubber size as well as their content, as coarse rubber particles were found to exhibit higher shrinkage than the finer ones [43]. Bravo et al. highlighted that drying shrinkage was influenced only by the size of the aggregates incorporated and not by their shape. Moreover, they showed that the shrinkage could increase of 43% for a fine aggregate replacement level of 15% [45]. Also, for rubberized mortar the drying shrinkage was slightly higher than that of the plain mortar. However, the observed increase of the shrinkage level was too small to cause drying shrinkage damages when the rubber content in the mortar was less than 25% [55].

2.3.4. Abrasion resistance

The abrasion resistance of any pavement is the most important property since all the surfaces will interface to the tyre and foot pressure directly. A rough surface is required for pervious concrete pavements to resist to the skidding, sliding and the breaking friction of the vehicles, in order to reduce the abrasion effect. Gesoglu et al. evidenced a positive effect played by rubber addition in concrete to improve its abrasion resistance [80]. In particular, an increase in the rubber content from 0% to 20% resulted in a systematical enhancement of the abrasion resistance. This could be due to the holding effect of rubber particles, that were able to preserve the integrity of cement paste. Moreover, fine crumb rubber enhanced the abrasion resistance of pervious concrete more than tyre chips and coarser crumb rubber particles. In particular, the depth of wear decreased from 0.91% to 0.17% when natural aggregates in concrete were replaced by 20% of fine crumb rubber. A relative decrease of the abrasion rate of 59% and 81% with respect to the control sample was obtained in concrete containing fine crumb rubber at a content of 10% and 20%, respectively. At the same rubber amount, the decrease in the wearing was as much as 39% and 58% at the same replacement levels when tyre chips were utilized. Similar results were also found by Thomas et al. [83].

Crumb rubber particles present in concrete restrict the grinding of the concrete surface, because they are present on the smooth surface of concrete and act as a brush, thus minimizing the action of the abrasive dust that can be present on the concrete surface. On the contrary, Gupta et al. observed that the depth of wear in rubber ash containing concrete increased with the rubber amount [64]. The depth of wear was 1.17 mm for reference mix with w/c ratio 0.45, whereas it increased to 1.42 mm for a rubber content of 20% at the same w/c ratio. A similar results was also found by Sukontasukkul et al. [84]. In this case, crumb rubber particles were pulled off during the rotation of the abrading cutter, creating voids on the sample surface. These voids pre-disposed the samples to higher degradation and wear, causing the increase of the mass loss observed in the rubberized mixtures [85].

2.3.5. Chloride ion penetration

The corrosion of reinforced concrete in the marine environment and/or in the presence of ice salt is one of the greatest threats to the durability of concrete structures. It has been proven that the addition of rubber aggregates, promoting the saturation of fine holes in the concrete, can reduce the degree of corrosion of the steel in concrete [86]. Because of the change of the surface tension promoted by rubber aggregates, they can change the local pressure in fine pores, reducing thus the degree of corrosion of the inner steel. Thomas et al. replaced natural fine aggregates with crumb rubber with a substitution level from 0% to 20%, observing that the depth of chloride penetration within the concrete was slightly reduced with a crumb rubber concentration of 7.5% [87]. This reduction in the depth of chloride penetration was due to the fact that rubber particles did not absorb water and simultaneously did not allow the passage of chloride ions. When the crumb rubber concentration was higher than 7.5%, a gradual increase in the depth of chloride ion penetration was noticed. After 91 days, the depth of penetration was 21 mm for the control mix, 22 mm for the mix with 10% crumb rubber and 25 mm for the sample with a rubber concentration of 20%. Similar trends were also found by Bravo et al. [45] and by Gesoglu et al. [88]. Since corrosion resistance of reinforced concrete strongly depends by water absorption kinetics and by internal packing of concrete [89], chloride diffusion coefficient of rubberized concretes was found to decrease with the increase of water/cement ratio. Therefore, rubberized cement mixtures can be used in applications where there is a need for low chloride ion penetration and in structures where corrosion of the reinforcement must be avoided [90].

2.3.6. Acid and sulfate resistance

It is well known that concrete exposed to aggressive sulfuric acid environment can be easily destroyed by acid erosion, because alkaline cement hydration products can react with hydrogen ions, thus negatively affecting the durability and increasing the maintenance costs of civil infrastructures. Sulfuric acid in groundwater, chemical waste or deriving from the oxidation of sulfur bearing compounds can attack concrete structures. Moreover, concrete parts in industrial zones are susceptible to degradation due to acid rains, mainly composed by sulfuric acid [91]. As reported by Xie et al., rubber particles in modified concrete could act as a bridge between concrete constituents, limiting thus the generation of cracks and the surface deterioration [18]. Moreover, rubber in the presence of sulfuric acid can improve the adhesiveness with the concrete matrix, limiting the decrease of the compressive strength due to acidic media exposure [92].

2.3.7. Carbonation resistance

Since the presence of additional voids and cracks can facilitate the ingression of CO_2 within the concrete structures, large contents of rubber aggregates can result in the generation of a more porous microstructure. For this reason, rubberized concrete has been generally found to exhibit lower carbonation resistance than conventional plain concrete. At a crumb rubber concentration of 10%, Thomas et al. noted a gradual increase in the depth of carbonation after 91 days of exposure to a controlled environment, and increasing the rubber content to 20% the depth of carbonation increased to 27% [89]. A similar result was also found by Bravo et al. in a paper in which natural aggregates were partially replaced by rubber filler. In this work the increase in carbonation depth was due to the higher water content of rubberized concrete, needed to maintain the workability of the mixtures, and to the greater void volume between rubber aggregates and the cement paste [45]. An increase in carbonation depth of 13% was reported by Thomas et al. for concrete samples with 20% crumb rubber after 91 days and at a water/cement ratio of 0.5 [93]. Gupta et al. attributed the increase in carbonation depth of the rubberized concrete to an improper compaction, that generated a preferential path to CO_2 diffusion within the concrete structure [64].

2.3.8. Thermal conductivity

The addition of recycled rubber powder generally improves the thermal insulation ability of concrete. This enhancement is influenced by the size of rubber particles, with finer size particles leading to better results [94]. Such this improvement in thermal insulation capability would lead to lower energy demand, which in turn translates into economic savings [95]. For instance, Iqbal reported a thermal conductivity value of 1.25 W/mK for conventional concrete and 0.79 W/mK for recycled aggregate-rubberized concrete at a rubber amount of 20 wt%, with a relative decrease of 37% [96]. The rate of heat transfer was found to decrease as the size of the crumb rubber decreased, as highlighted in a study of Sukontasukkul [97]. In a study of Fraile-Garcia et al., the thermal behavior of light concrete construction elements prepared with different amounts of rubber particles from end-of-life tyres has been investigated [95]. Closed test cells were built and subjected to several heating/cooling cycles, recording the temperature within the cells and in their enclosures. It was found that the construction elements with recycled rubber optimized the thermal insulation capacity of the cells, as long as the percentage of rubber was maintained below 20%, without substantially affecting the mechanical properties of the concrete. At this rubber content, the temperature gradient between interior and exterior parts of the cells increased to 5.6%, and the inner temperature of the cell remained stable despite changes in external temperature. Different rubber waste materials could be added to concrete to improve its thermal insulation capability. Yesilata et al. studied the incorporation of waste polyethylene terephthalate (PET) bottles and tyre rubber pieces in concrete to decrease its thermal conductivity [98]. These fillers were shredded into small pieces of different shapes and lined into fresh concrete before hardening. The results showed that waste PET and rubber particles remarkably lowered the thermal transmittance of ordinary concrete. In particular, it was found that the insulation performance was improved by 18.5% through the addition of rubber. The reuse of waste rubber in concrete seems thus to be good choice for promoting a cleaner environment and reducing the insulation costs. This type of rubberized concrete could be recommended for constructive solutions that require substantial thermal insulation without an excessive increase in porosity, such as enclosures in buildings for industrial or agricultural use, and for many other applications in which structural concrete is not required.

2.3.9. Sound absorption and insulation

Sound absorption is defined as the incident sound that strikes a material and is not reflected. In this sense, concrete is often used as

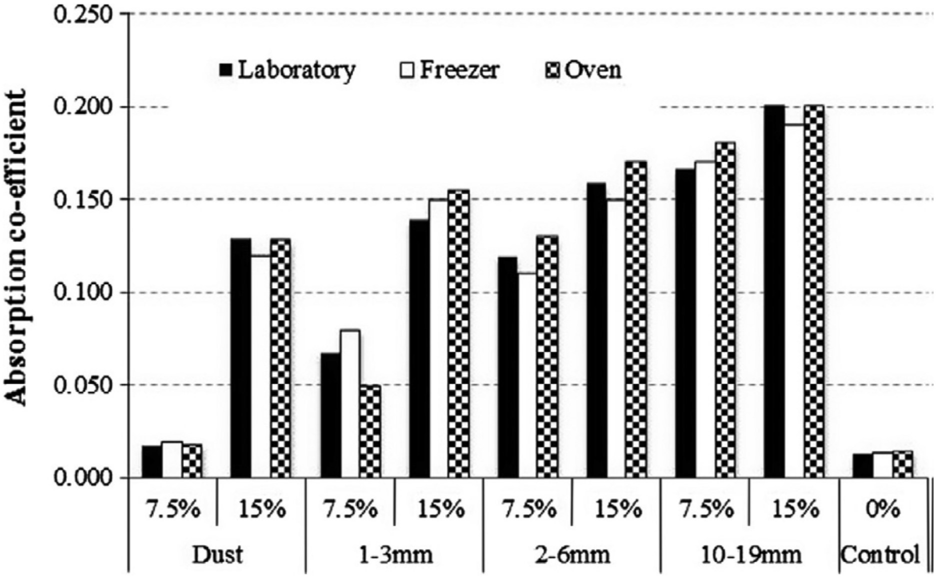

Fig. 6. Sound absorption coefficients for rubberized concrete and plain concrete (reprinted from Ref. [28]).

external coating to prevent sound transmission through reflection. However, when sound waves strike concrete cladding panels, they are reflected away but are not reduced in magnitude, and it could represent a problem in enclosed spaces. Rubberized concrete has been found to be more effective than plain concrete in absorbing sound in low, normal, and high temperature environment. As reported by Holmes at al., better absorption coefficients were observed for higher rubber replacement levels (about 15%) [28]. Acoustic absorbance properties were found to be affected by the size and concentration of rubber particles in concrete, and increasing the mean dimension and relative amount of the elastomeric filler within the cement mixture led to an increase in absorption coefficient, as it is possible to observe in Fig. 6.

For as concerns the acoustic insultation properties, a rubber content of 20% in concrete showed a better response than the standard concrete, for low frequencies up to 140 dB in the case of airborne insulation, and up to 190 dB in the case of impact sound insulation. In the first case, the relative improvement was up to 50%, while in the second case the insulation improvement was as low as 15%. Therefore, highly filled construction elements could be conveniently applied to insulate from very low frequency sounds, such as low frequency instruments (bass guitar, bass drum, etc.), low frequency road traffic vehicles (heavy trucks, tractors, etc.), barking dogs, green cuts, and chainsaws. An explanation for this behavior can be found in the interface between concrete and rubber. The microvoids present in the interface are able to attenuate and even absorb low frequency sound waves, while their efficacy for high frequency waves is much lower [99]. A pre-treatment aiming to modify the surface of the recycled rubber aggregates to reduce the interfacial bonding with the cement matrix was found to improve the sound insulation properties of rubberized lightweight aggregate concretes. As reported by Zhang et al. [100], a simple cement slurry coating pre-treatment resulted in a weaker bonding between the rubber aggregates and the cement paste, with a consequent increase of the vibration absorption capacity and an enhancement of the noise insulation properties. Noise reduction effect increased by 58.3% and 67.9% for concrete prepared with recycled rubber aggregates at replacement levels of 50% and 75%, respectively. Ghizdavet et al. showed that materials made of concrete with 5% of rubber had exceptional values of the sound absorption coefficient ranging from 0.82 to 0.93, in contrast to the control samples with sound absorption values from 0.22 to 0.37 [101]. It has been argued that this remarkable effect was due to the presence of a large number of rubber grains on the concrete surface and by the samples texture produced accidently by the mechanical damaging of the specimens during the preparation stage. In fact, quite good absorbance values (0.6–0.7) were obtained by simply producing artificial macroscopic pores in the plain material. The acoustic absorption capability of concrete is a function of porosity and of the pore constriction in the cement matrix, which increases the frictional losses. Therefore, porous concrete with bigger size aggregates has a higher porosity but lower frictional loss, resulting in a markedly lower sound absorption coefficient. This implies that finer and well-connected pores may be more efficient in dissipating sound than larger pores [102]. Also the shape of the rubbers particles has a significative effect, as reported in the study of Angelin et al. [100]. The sound attenuation was higher for rubberized concrete with fibrous rubber than with spheroidals elastomeric particles. It was thus recommended to use the fibrous rubber fillers for structural elements that need to provide good acoustic performance.

2.4. Rubberized concrete for additive manufacturing technologies

Nowadays, the integration of advanced technologies and traditional manufacturing methods is a strategy that is deeply exploited in different industrial sectors, such as biomedicine, automotive, aerospace, and design. Unlike traditional methods of casting cementitious materials into molds or formworks, additive manufacturing has gained increased popularity in the construction sector due to the possibility of combining digital technologies and new insights from material science to allow freeform constructions, without the use of expensive formworks [103].

In the challenge of proposing increasingly sustainable building materials, rubber particles of 0–1 mm and 2–4 mm in diameter were used to replace the mineral fraction of a concrete 3D printable mixture by Sambucci et al. [104]. In this study, they used a concrete extruder mounted onto a robotic arm in order to print civil structures through a layer-by-layer deposition, as shown in Fig. 7. The replacement of mineral aggregates by GTR particles modified the surface tension of the fresh compound, increasing its fluidity and ensuring a more efficient layer-by-layer deposition process in terms

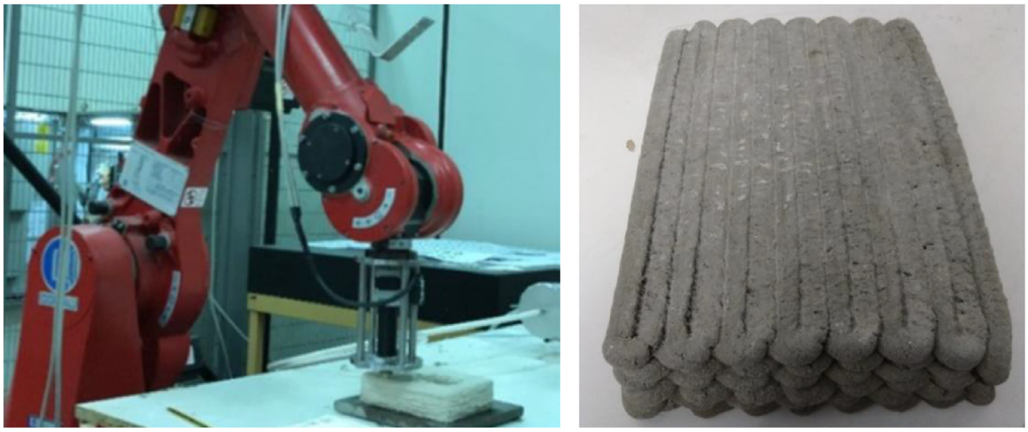

Fig. 7. Representative image a 3D printing system and of a rubber-cement slab after 28 days of curing (reprinted from Ref. [105]).

of adhesion between the deposited strands, compaction of the hardened material, and mechanical isotropy. It has been found that the incorporation of rubber particles improved the printing quality of the mixes over the plain mortar also in terms of inter-layer adhesion, promoting the mechanical isotropy of the hardened material. This effect was a consequence of the change in rheology that rubber induced in the cementitious mixes, increasing its fluidity and bringing appropriate conditions of humidity between the printed layers [105]. The ductility of the material increased upon the addition of rubber particles, but its compressive and flexural strength was reduced, due to the low density and the poor rubber-cement interfacial bonding. Therefore, these materials could find application where structural deformability is a primary requirement and limited stresses are involved (e.g., flexible paving bricks, flexible sub-base for pavements, anti-shock barriers).

The replacement of 40% sand with crumb rubber was shown to be optimum for 3D printing applications by Ye et al. [106]. The tensile strength and strain at break of the printed material was 4.7 MPa and 7.5%, respectively, but still lower than those realized by traditional mold-cast technique. The obtained samples showed a limited anisotropy in flexural strength, but a significant anisotropy in flexural deformability, compressive and flexural energy dissipation capacity. Partial sand replacement with rubber provided good mechanical properties, but it is clear that replacing the entire amount of sand with tire rubber would be the optimal solution to increase the recycling rate of rubber and to save natural resources. A 3D-printed cementitious mortar with cement-coated recycled crumb rubber was developed by Liu et al. [107]. In this work, three different cement/rubber weight ratios (i.e., 0.25, 0.40 and 0.55) were designed, to achieve a different extent of cement coating on the rubber surface. The strength in the direction parallel to layer deposition gradually increased with the dosage of cement coating, while in parallel direction the maximum strength increment was registered for a cement/rubber ratio of 0.4 (25.7%). Moreover, the anisotropy in the compressive strength of 3D-printed specimens was more pronounced for higher ratios of coating, while it was almost negligible in the 3D-printed specimens with a cement/rubber ratio of 0.25.

3. Tyres rubber in asphalt

Nowadays, the utilization of waste materials in pavements construction has gained much attention, in order to consume them without compromising the pavement quality [14]. The use of scrap tyre rubber as a modifier for asphalt has been developed for more than 50 years. However, since the late 1980s, the emphasis for this approach was focused on the use of scrap tyres to partially solve the environmental problems related to the end of life management of solid waste [14]. Pavement performance is a key component in determining if the use of scrap tyre rubber is cost-effective. The benefits of using rubber modified asphalts have been widely experienced and recognized, and the incorporation of GTR into asphalts is likely to increase in the future [108]. In fact, the combination of asphalt with polymers can inhibit the formation of cracks and can prolong pavement life [109]. More generally, road pavements are mostly built with asphalt mixtures, to provide good long-term performance and increase the constructive quality. Asphalt mixtures are typically viscoelastic materials, mainly composed by an asphalt binder, mineral fillers and aggregates. The asphalt mixture performance is dependent on the filler properties, and the interaction between the fillers and the binder can greatly influence the mechanical performance of the resulting materials [110]. Plastic deformation caused by vehicle traffic loads on pavement surface is one of the most problematic types of deterioration in road engineering. Such deformations reduce the service life of the pavement and increase the rehabilitation and maintenance costs. Many studies documented the impact of fillers on the improvement of the fatigue life, moisture susceptibility and rutting resistance of asphalt mixtures [110]. Many design factors should be taken into account for these issues, such as the mineral skeleton, the aggregate properties, the filler content and the binder quantity [111]. For example, the type of bitumen used in the asphalt mix strongly influences the plastic deformation of the resulting material, since the mixtures can be manufactured with conventional bitumen or bitumen modified with elastomeric or thermoplastic polymers. Modified bitumen has been considerably developed in the last decades, and it generally has a higher viscosity, lower thermal susceptibility and higher plastic deformation resistance with respect to conventional bitumen [112]. However, the price of polymer-modified binders is considerably higher than that of conventional bitumen, and it could often limit its use. For this reason, it is necessary to seek cost-effective ways to mitigate and/or prevent rutting in pavement surfaces. In this sense, the use of crumb rubber from end-of-life tyres in bituminous mixes could represent a viable approach to improve mix performance and prevent plastic deformation. The addition of crumb rubber to asphalt mixes generally enhances the viscosity and elasticity of the bitumen and, at the same time, increases its resistance to aging and to rutting [112]. This chapter deals with the methods of incorporating recycled rubber in asphalt mixtures, with a discussion on the main features of the resulting materials in terms of workability and plastic deformability.

3.1. Approaches to incorporate rubber into asphalts

Crumb rubber or reclaimed plastics can be incorporated in asphalt mixtures with two approaches: the wet process or the dry process. Fig. 8 reports a schematic description of both techniques.

The technology with most evidence of success, demonstrated by roads built in the last 40 years, is the rubberized asphalt mixture obtained through the so-called wet process. Since 1960s, asphalt mixtures produced with the wet method have been used in different parts of the world to solve different quality problems and, despite some downsides, in the most cases they enhanced the performances of the road pavements [14]. The wet process, in which the crumb rubber works like a binder modifier, has been initially developed by Charles McDonald. In this technology the crumb rubber (or plastics), added in concentrations between 5 wt% and 25 wt% with respect to the bitumen, is first mixed with the bitumen, and it is then added to the mix as a modified binder [113]. The reaction stage between rubber (or plastic) and the bitumen is called digestion time, and it usually takes place in conditioned containers in the mixing plants. Digestion time is one of the critical parameters that determine the final performances of the asphalt mixtures. An appropriate digestion time before compaction could assist the interaction between asphalt and the added rubber [110]. An elevated rubber content produces binders with viscosity above 1500 cPs at 177 °C [114], and an elevated viscosity of the modified bitumen allows a better coating of the aggregate particles, without exudation or drainage problems, increasing also the elasticity and the resilience at high temperatures of the resulting material. However, it also shows some limitations, like dimensional instability, elevated mixing temperatures (around 180 °C), and the need of an expensive equipment. In fact, as also reported in Fig. 9, in the wet process waste rubber (or plastics) is blended with bitumen at high temperatures to produce bituminous binders that can be then mixed with the aggregates. Therefore, the wet process requires a specific equipment to shred the rubber into powder and mix it with hot asphalt binder afterward. Studies demonstrated that blending of rubber and asphalt through the wet process is a physical procedure in which rubber particles could absorb the lightweight components contained within the asphalt to form a dispersed viscoelastic phase at high temperature. Plastics with relatively low melting point, especially polyethylene, are suitable for this process [108]. In the wet process, high temperature and long mixing time

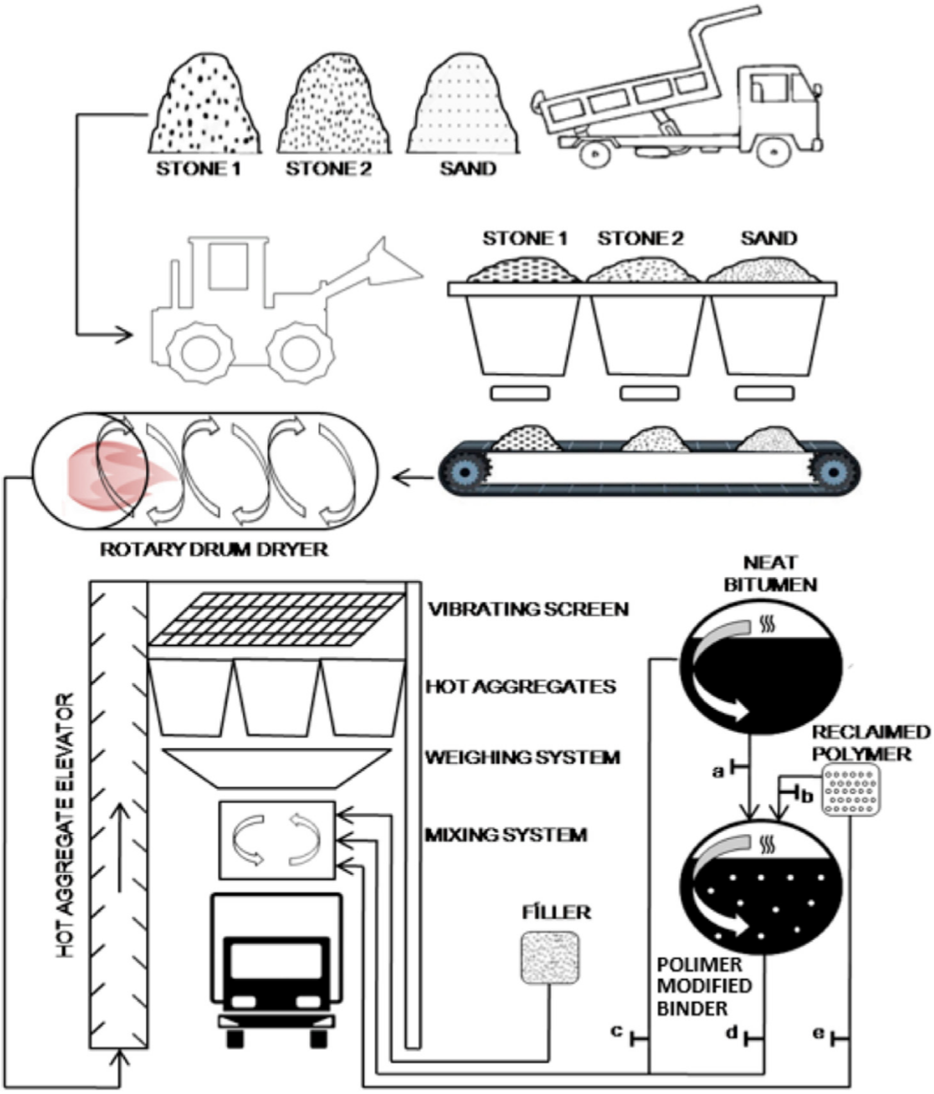

Fig. 8. Schematic representation of the wet and dry process in a discontinuous asphalt plant. Valves (a, b, d) open = wet process; valves (c, e) open = dry process (reprinted from Ref. [108]).

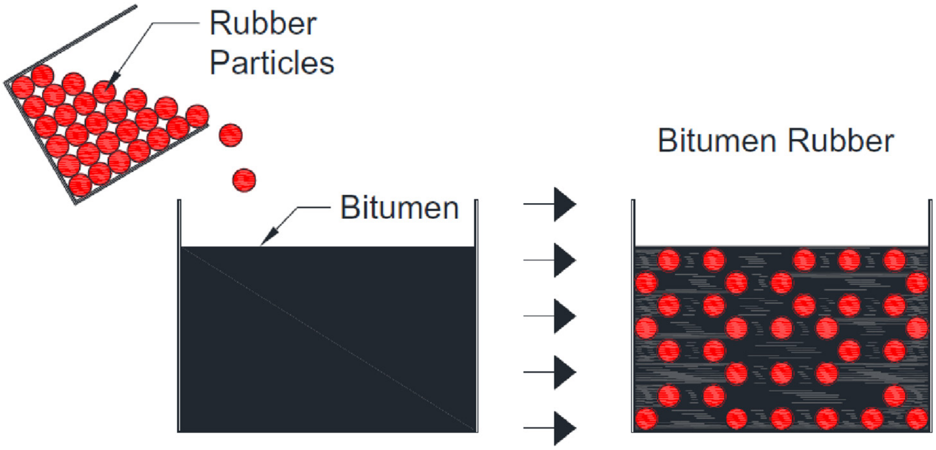

Fig. 9. Schematic representation of the preparation of the bitumen/rubber mixture in the wet method (reprinted from Ref. [116]).

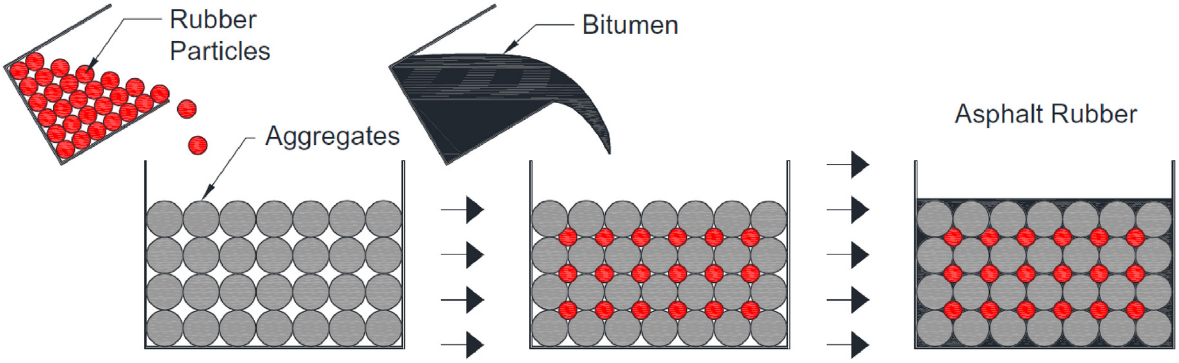

Fig. 10. Representative scheme of the dry process for the preparation of modified asphalt (reprinted from Ref. [116]).

are both needed to obtain homogeneously mixed rubber modified asphalt. On the other hand, it has been reported that the wet process, if performed elevated temperatures, could also lead to hazardous emissions by the rubber particles, with some serious environmental concerns [115].

The second process to incorporate rubber into the asphalt is the dry process, in which the crumb rubber partially replaces the aggregates in the mix. For instance, this kind of mixtures has been distributed in Scandinavia under the trade names ‘Skega Asphalt’ or ‘Rubit’. This technology has been then patented in the United States in 1978 under the trade name PlusRide [117]. Generally speaking, in the dry process the crumb rubber, with particles size between 0 and 2 mm, is added directly in the mixing process to replace 1–3 wt% of the fine aggregates, as schematized in Fig. 10. Recycled rubber and/or plastics are added directly into the mixture as either aggregate replacement or as mixture modifier. The aggregate replacement approach is commonly used with recycled plastics with high melting point, such as PET and polystyrene (PS), while the mixture modifier approach is virtually applied to all types of recycled plastics (e.g., polyethylene, polypropylene, PET, and PS), except for polyvinyl chloride (PVC) due to hazardous chloride emissions concerns [110]. When recycled plastics with a melting point below the mixture production temperature are utilized in the dry process, they will melt upon mixing with the hot aggregates and produce plastic-coated aggregates with potentially improved physical and surface properties. In this sense, the dry technology seems a relatively simple and energy-saving process. Although dry process has some advantages, like higher crumb rubber concentration, it has been less utilized with respect to the wet process in the last decades, because it produced unsatisfactory results deriving from a poor interaction between the crumb rubber and bitumen [2]. In order to overcome this limitation, it is necessary to have a digestion time between 45 and 180 min before placing the mixture on site [118]. In this way, the crumb rubber added in the dry process partially loses its elastic behavior and can also act as a binder modifier. Therefore, nowadays the main disadvantage of this technology is the need to have long digestion times [114].

The absorption of paraffin and maltenes by the carbon black transferred to the bitumen and the rubber respectively resulted in an improved asphalt pavement, with increased stiffness and higher resistance to permanent deformation with respect to asphalt pavements made with conventional bitumen or with a styrene-butadiene-styrene (SBS)-modified bitumen. The role played by carbon black in bitumen modification is not negligible and could be as important as that played by the rubber [119]. It can be therefore concluded that the main difference between dry and wet techniques is that the wet method modifies more effectively the properties of the binder, since the crumb rubber particles directly interact with it [120].

3.2. *Stability and flowability*

Marshall stability test, showed in Fig. 11, analyses the flow of bitumen and is applicable to the mix design of bitumen and aggregates with maximum size of 2.5 cm. It is extensively utilized in routine test programs for the paving jobs. The stability of the mix is defined as the maximum load sustained by a compacted specimen at a standard temperature of 60 °C. The flow of the mix is measured

Fig. 11. Experimental apparatus utilized for the Marshall stability test (reprinted from Ref. [121]).

as the deformation (in units of 0.25 mm) between no load and the maximum load sustained by the specimen during stability test (flow value may also be measured by deformation units of 0.1 mm).

Upon rubber introduction in the mixture, it is also possible that the height of the Marshall test specimens increases by an average of 3 mm after compaction and cooling, because rubber deformed during the compaction could partially recover its shape when cooled to ambient temperature [122]. This test is utilized to determine the optimum binder content for a specific aggregate mix type and traffic intensity. The ratio of stability to flow is recognized as an indicator of the resistance of the material to shear stress and is also related to the mixture's resistance to permanent deformation. Therefore, high ratio values indicate that the asphalt mixture will present higher stiffness and creep resistance [123]. Marshall stability test can give also important indications of the performance of the mixture at high temperatures [124]. Asphalt mixtures with lower flow values are less susceptible to permanent deformation at high service temperature but are more sensitive to low temperature thermal cracking. Because the specific gravity of rubber is far lower than that of the aggregates, the density of rubber modified asphalt mixtures decreases with the rubber content. Considering the lower compressive strength and the higher elasticity of rubber, the stability and flow of the mixtures decrease with the rubber concentration [125]. Therefore, the incorporation of crumb rubber in dry-process bituminous mixes generally improves their resistance to permanent deformation, thanks to the elasticity of the rubber particles [126]. The performance of the resulting asphalt depends on the internal morphology of the mixture, and in particular by the aggregate distribution and connectivity [127]. A higher compaction load at relatively low temperature can lead to a better aggregate connectivity, resulting in better mixture stability. According to the work of Moreno et al., digestion time did not significantly affect the choice of the optimal bitumen content in the mix [126], but the properties of the mixtures obtained through the dry method were influenced by the digestion time. Ozturk et al. reported an optimal digestion time of about 90 min [128], while according to Moreno et al. the duration of this process could be shortened to 45 min, leading to a more effective mix production at the worksite [118]. Nguyen et al. observed that the ideal content of crumb rubber required to significantly improve the Marshall stability is 2 wt% [113]. At this rubber concentration, the Marshall stability values of dense-graded mixes were increased of almost 70% when the digestion time was increased from 1 to 5 h. The digestion time played an important role in enhancing the Marshall stability of the mixes, and it was assumed that the swelling and the softening of crumb rubber particles due to the absorption of the aromatic oils contained in the asphalt binder continued throughout the whole digestion process. Bakheit et al. prepared samples for the Marshall test mixing through wet and dry method coarse rubber aggregates, fine rubber aggregates, and mineral filler [129]. The results indicated that the Marshall stability of both mixing methods increased with the addition of crumb rubber up to a concentration of 12%, and then decreased, because of the detrimental effect played by a higher air void content, compaction difficulties and rubber segregation [119]. Nonetheless, using fine rubber particles as filler, which tend to be homogeneously distributed within the asphalt mixture, could help to obtain an easier compaction [2]. Moreover, particular attention should be devoted to the mixing system, as low shear forces used to mix rubber particles and bitumen led a to reduction in Marshall stability and an increase in vertical deformation, implying also a reduction in the rutting performance [130].

3.3. *Rutting resistance*

Rutting is the permanent deformation of pavement layers that can accumulate over time. It is the result of deformation that can occur in one or more asphalt pavements layers (Fig. 12). If it occurs on the uppermost layer, it is called surface rutting, while if the main component of deformation originates in the sub-grade it is defined structural deformation. Asphalt concrete under the influence of freight traffic is subjected to stress and, especially in the highways, rutting is commonly due to high canalizations and high repetition traffic [131].

The deformational properties of the pavement are also a critical factor in determining its rutting propensity. The probability of generation of shear strains in asphalt concrete is higher when the pavement temperature is high [133]. Asphalt modified with different rubber and plastic wastes could show remarkably different compatibility and rheological properties of the resulting blends, but the addition of waste plastic generally enhances the rutting resistance of the asphalt [134]. The addition through a dry process of large quantities of crumb rubber to the mix (1.5 wt%) greatly improved its response to plastic deformations and so the rutting resistance [118]. Even for lower crumb rubber contents (0.5% and 1.0%), the deformation values were similar to those obtained with a high-performance bitumen. Arabani et al. found that the stiffness modulus of asphalt samples containing different amounts of tyre thread was noticeably higher in comparison to that of unfilled samples [133], with a consequent increase of the rutting resistance. Moreover, this stiffness modulus enhancement was not associated to an increase of the brittleness of the samples. These pavements could be therefore used in sites subjected to an almost permanent load. As evidenced by Cao et al., the addition of tyre rubber in asphalt mixtures using the dry process improved the resistance to permanent deformation also at high temperature (>60 °C) and resistance to cracking at low temperature (10 °C). The asphalt mixture containing 3% of tyre rubber showed the best performance both at high and low temperatures, as confirmed by rutting tests and indirect tensile tests [125]. Moreover, it was reported by Nguyen et al. that the rutting resistance of asphalt mixtures prepared through dry process was similar to that of the corresponding mixtures prepared through wet process, and the dry process could be thus utilized to develop asphalt mixtures applied

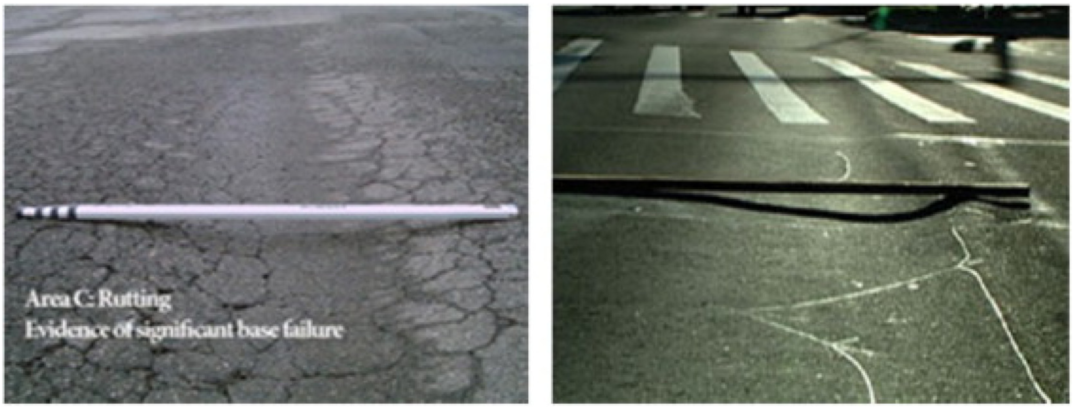

Fig. 12. Examples of rutting phenomena in asphalt pavements (reprinted from Ref. [132]).

in flexible pavement to mitigate rutting distress [113]. The Hamburg Wheel Tracking test was conducted to evaluate the rutting resistance of rubberized asphalt mixes, and it was highlighted that dense-graded mixtures with 1.5% and 2% crumb rubber had similar levels of rut depth (2.08 mm and 2.09 mm, respectively), while unmodified asphalt normally ranged from 6 to 10 mm. Tahami et al. evaluated the possibility to use high contents of crumb rubber powder as filler in asphalt mixes, providing further developments in the dry method by considering the effect played by the curing process, and utilizing micro-scale sized rubber fillers [2]. In their work, the conventional filler was replaced with a rubber concentration of 20, 40 and 60 wt%. The rut depth obtained through wheel track test highlighted that a 20% rubber replacement led to an improved rutting resistance, while the addition of a higher rubber content in the asphalt mix did not exhibit a proper rutting resistance compared to control mix. However, when the 60 wt% rubber filled asphalt sample was exposed to 2 h curing in oven at 165 °C, this mix exhibited better rutting resistance than the control mix, indicating that if the performances of the mixes at elevated rubber contents were weakened, they could be improved by the curing process. Moreno et al. found the dry process to be more effective than the wet process to compound crumb rubber in asphalt, as the dry-process prepared mix with 1.5% crumb rubber led to lower permanent deformation values than the reference sample made with polymer-modified bitumen [120]. The dry-process mixes showed a higher elastic modulus than the corresponding wet-process samples. In both cases, the mixtures with the largest concentration of crumb rubber were more elastic than the rubberized mixes with lower rubber amounts. Because of the resilience of the rubber, they were able to better recover the applied deformation. Chen et al. studied asphalt mixtures modified with different ground tyre rubber (GTR) amounts, ranging from 2.6% up to 4.5% [135]. One dense-graded asphalt mixture was modified with 2.6 wt% GTR, and it was designated as 2.6% DGTR. In Fig. 13, the rutting depth of the eight mixtures is shown, and all the samples presented a rutting depth after 5000 wheel passes below the 12.5 mm threshold, passing thus the criteria of the rutting test. The addition of GTR in dense-graded mixture could enhance the rutting resistance, but its rutting depth after 5000 passes increased rapidly. The rut depths for GTR modified mixtures varied between 3.3 mm and 6.8 mm after 20000 passes, demonstrating thus an excellent rutting resistance.

Feiteira Dias et al. evaluated the performance of dry process fine crumb rubber asphalt mixtures placed on the Portuguese road network [136]. As the rubber particles were very fine (i.e., nominal size <0.6 mm), the interaction between the rubber and the binder occurred more easily, allowing a certain modification of the heated bitumen. The mixture with 1.5% of fine rubber showed a better rutting resistance with respect to the control mix, because of the increased viscosity of the mixture. This could be particularly useful for locations where in-service pavement temperatures are very high. In another study performed by Picado-Santos et al. on rubberized asphalt on Portuguese road network, a pavement containing crumb rubber mixed with the dry method allowed a reduction of the construction costs of the 40% and showed a minimum durability of 12 years, if exposed to the open traffic (see Fig. 14) [137].

Bakheit et al. modified the dry method for cryogenically mixing grinded crumb rubber with asphalt and aggregates at different relative concentrations, and the rutting resistance of the resulting materials was then assessed [129]. It was observed that the dynamic stability, defined as the number of cycles required to produce 1 mm of rut depth, increased with the rubber content. Moreover, the addition of cryogenically grinded rubber led to a better permanent deformation resistance than the control mix both for dry and wet method prepared mixtures. In order to improve the performances of dry mixed rubberized asphalt, Yan et al. verified that amorphous poly-alpha olefin compounded with GTR in modified asphalt had noticeable high temperature and aging resistance [138]. Few literature works reported a worse rutting resistance of modified asphalts prepared with the dry method with respect to those developed with the wet ones, due to the longer digestion times required to achieve good properties in the dry technique [114]. For instance, Riekstins et al. reported a weaker resistance to rutting, fracture toughness and low-temperature resistance for all the mixtures obtained with the dry method [122]. Rubber modified asphalt manufactured by wet process exhibited significantly better fatigue and low-temperature resistance than the control mixtures, even in the case of polymer-modified bitumen. Instead, dry process rubber modified asphalt gave unsatisfactory results, probably because of the limited cohesion between aggregates, bitumen, and rubber.

3.4. *Noise absorption properties*

Environmental noise is a worldwide problem that negatively affects the quality of life of urban population. Functional characteristics of pavements, such as the acoustic properties, are strongly affected by the construction technology, the climatic and service conditions. As a result, a limited number of studies focused on this issue can be found in literature. The sound emission due to the interaction between tyre and pavement and the sound absorption capability of the asphalt are also function of the pavement surface type and texture, the pavement stiffness, the design and pattern of the tire [139]. Eskandarsefat et al. investigated the noise absorption capability of an asphalt containing 1% of crumb rubber added

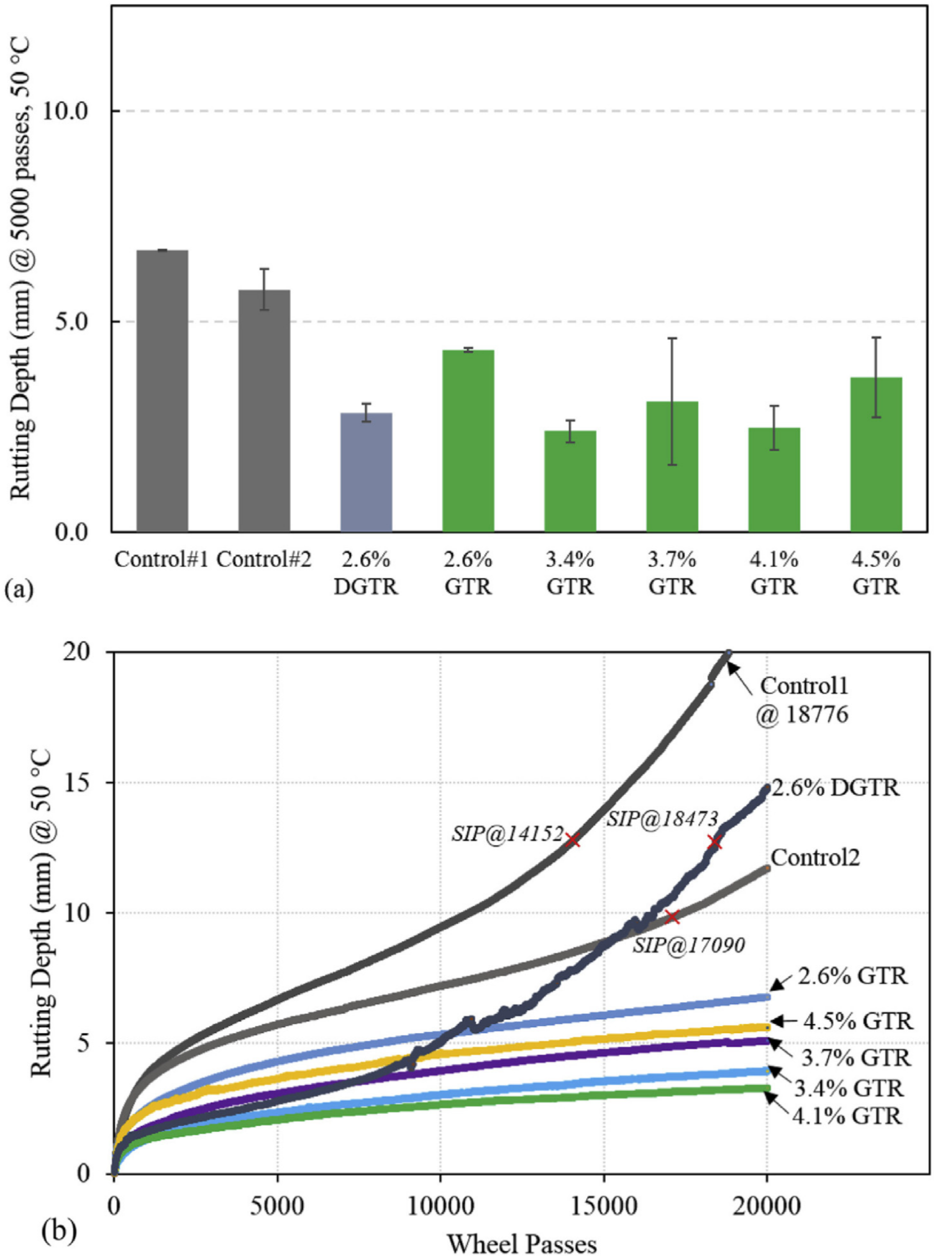

Fig. 13. (a) Average rutting depth of asphalt mixtures after 5000 passes at 50 °C; (b) rutting depth development of asphalt mixtures at 50 °C. SIP = Stripping Inflection Point (reprinted from Ref. [135]).

through the wet method by using close proximity measurements [140]. These acoustic tests did not show any significant difference in the asphalt samples with and without rubber. This could be expected, since the different asphalts presented similar mix design, surface texture, and stiffness values. This result was confirmed also by previous studies, that showed no significant noise absorption difference in the samples with and without rubber powder, until a rubber content of 8% [139,141]. On the contrary, Paje et al. found a significant noise reduction (around 2.5 dB at 80 km/h) when 20 wt% of crumb rubber was added by a wet process into the bitumen [142]. Acoustical monitoring with a semi-anechoic chamber (shown in Fig. 15) highlighted that the noise reduction, due to the incorporation of crumb rubber, mainly took place in a frequency interval between 630 Hz and 2 kHz, that corresponds to the typical frequency spectrum generated by traffic noise. The capacity to reduce tyre/pavement noise of the rubber mixture decreased by around 0.5 dB after 3 years in service conditions, while the conventional mixture without rubber, taken as reference, showed a reduction rate of around 0.15 dB per year [143].

Therefore, considering the effect of the introduction of recycled rubber on the physical properties of asphalts, it can be generally concluded that the reuse of rubber from waste tyres not only improves the environmental impact of asphalts by reducing deposits at landfills, but also gives higher added value mixtures with better physical features [120].

4. Tyre rubber in geotechnical applications

In addition to the civil engineering applications discussed in the previous chapters, several studies have been carried out in order to evaluate the feasibility of the addition of rubber waste in geotechnical applications, where used tyres can replace

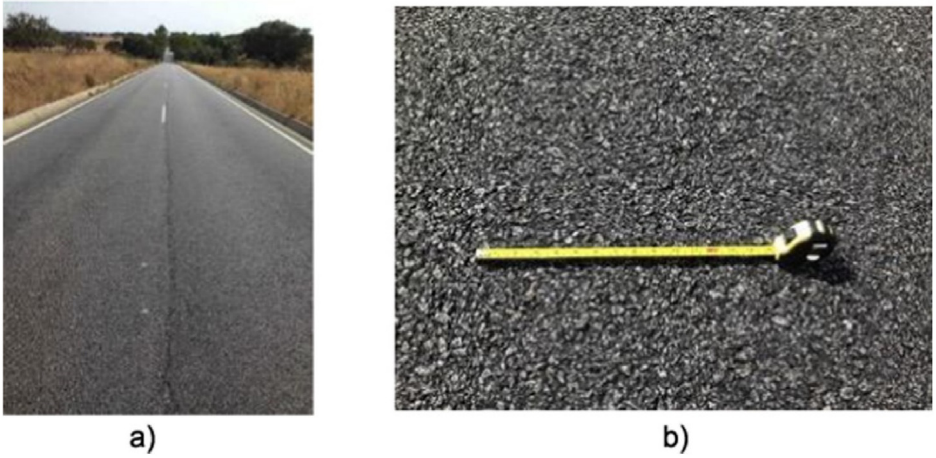

Fig. 14. General (a) and detailed (b) views of the prevailing pavement condition after 8 years (reprinted from Ref. [137]).

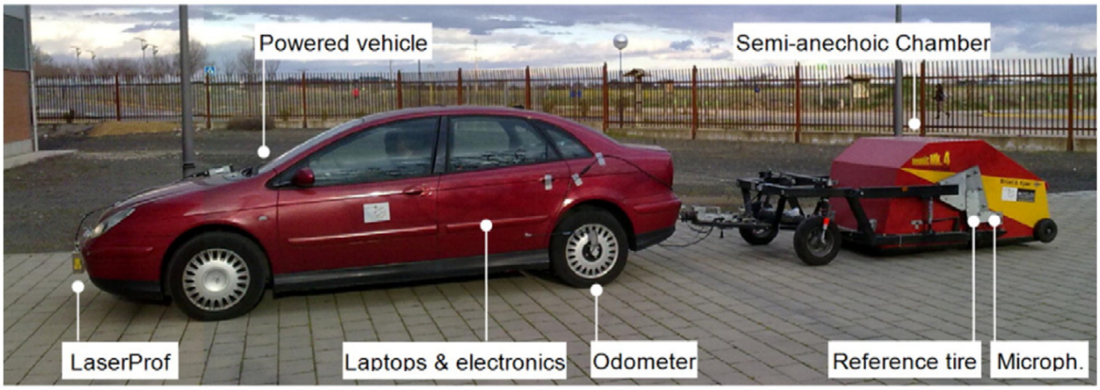

Fig. 15. Equipment for the simultaneous measure of tire/pavement noise and surface profile following identical wheel-paths (reprinted from Ref. [143]).

conventional construction materials such as inerts or aggregates. The design engineer is responsible for determining the appropriateness of using scrap tyres for the specific application, in order to guarantee both the easiness of the construction and the environmental protection. Generally speaking, the utilization of rubber in geotechnical engineering is based upon the unique characteristics of this material, as listed below [144]:

- high durability of tyres constituents, such as carbon black and antioxidants, that can enhance the resistance to wear, chemical decomposition, and sunlight
- rubber is relatively impervious to moisture absorption
- rubber tyres have a low density, and they are a poor thermal conductor, giving thus better thermal insulation properties than soil or aggregates
- rubber has an elevated hydraulic conductivity.
- rubber has a high compressibility and is able to absorb vibrations.
- rubber has good acoustic insulation properties.

ELTs have been used for constructing soil retaining walls, where the tyres are filled with soil or crushed rocks (see Fig. 16). This system shows excellent drainage and superior stability compared to conventional retaining soils, and it could be applied for sea

Fig. 16. Representative images of retaining walls reinforced with ELTs (reprinted from Ref. [146]).

embankments, in order to inhibit erosion near sea, for artificial reefs in marine environments, for temporary and heavy-load roads, and for off-shore breakwaters [145].

High-performance composite panels can be developed using waste tyres sandwiched between stable precast concrete skins. This modular wall system can be used for sound barriers, retaining walls, cyclone shelters, sea and blast walls, and even for racetrack impact barriers [147]. Crumb rubber collected from end-of-life tyres and short fibers can be introduced into the epoxy matrix core to produce sustainable and eco-friendly railway sleepers, having reduced cost and better mechanical performances [148]. By using rubber crumbs as drainage layer in green roofs in place of porous stone currently used in some commercial solutions, it is also possible to reduce the consumption of these natural materials, which require large amounts of energy in their manufacturing process [149]. Moreover, whole or low-processed scrap tyres can be applied in natural disaster risk reduction applications, such as earth retaining structures, seismic retrofitting systems, load-bearing elements, and drainage systems [150]. Beside these applications, the crumb rubber is widely used in geotechnical engineering to replace aggregates, and their application is expected to further increase in the future [11]. Waste tyres can be crushed into small pieces and mixed with soil or sand to achieve beneficial performances, in terms of better elastic deformation and shear strength, and higher permeability.

Waste rubber is also widely used to strengthen sand and expanded clay soils, thanks to the good interaction between rubber particles and soil, as demonstrated by direct shear, triaxial, swell-shrinkage, and uniaxial pull-out tests. Saberian et al. highlighted that recovered concrete aggregates containing no more than 0.5% of fine and coarse rubber could be successfully used for constructing the base and the subbase of pavements [151], while a further increase in the size and content of rubber had a negative effect on the permanent deformation behavior of the concrete. This reduction could be traced back to the main rubber skeleton in the samples, that prevented the contact of rigid particles. As reported by Contreras-Marín et al., rubber granulates from ELTs possessed instead a great potential as backfill material behind retaining walls, leading to a decrease in lateral earth pressure, as a result of the low unit weight and lack of cohesion of the tire granulates [152]. Jaramillo et al. evaluated the potential of recycled tire rubber, used both as chips and in fiber form, for clay soil reinforcement [153]. Regardless to the size, 5% rubber addition resulted in similar maximum dry density values, while the optimum moisture content was influenced by its specific surface area. Tire rubber introduction improved the mechanical behavior of natural soil, and fiber reinforcement led to a superior interfacial bonding if compared to rubber chips. The elastic behavior of clay soil was enhanced by the rubber introduction, especially at limited stress levels. In a study of Eslami et al., the effectiveness of a mixture of clay soil and rubber waste, utilized as a sustainable construction material, was investigated [154]. Rubber inclusion in the clay soil mixture caused a reduction in the compression strength with respect to the neat clay, and the elasticity of the mixtures decreased with the rubber content. The modulus of elasticity declined sharply until a rubber amount of 10%, and then gradually decreased for higher rubber concentrations. A comparison between the modulus of elasticity of the mixtures containing recycled rubber with different shape indicated that the higher stiffness values were obtained by using granular rubber. On the basis of these results, an optimal amount of 10% granular rubber was identified for these clay soil mixtures. A reduction in compression strength was also detected in soil samples containing waste rubber, and the extent of this reduction was dependent by the shape of the rubber introduced.

However, there are still some environmental concerns related to the use of GTR in geotechnical applications, due to the potential release of toxic and/or pollutant additives contained in the rubber on water and on aquatic organisms, and this issue should be further explored in the future [155].

5. Conclusions

ELTs are one of the most important environmental problems facing scientists and governmental organizations around the world. Millions of ELTs are generated and stockpiled every year, often in an uncontrolled manner, representing an environmental threat for the future generations, as they are durable and not naturally biodegradable. Furthermore, the sites available for disposal of tyres are getting fewer and landfilling of worn tyres has been recently banned in many countries. Therefore, it is crucial to find ways for their alternative utilization by means of recycling. Recycling tyres in civil applications seems to be an interesting option, both from an environmental and economic point of view, considering also that the material consumed could be very large. In fact, the addition of even small amounts of waste tyre rubber in constructions could enable a large volume of stockpiled tyres to be eliminated. Although further research needs to be done in the future, tyre rubber can be successfully used in a substantial number of civil engineering applications, and it is an attractive alternative to develop more durable and sustainable materials with increased performances. Waste rubber, mainly coming from tyres and with different size and shape, can be re-used in the production of rubber composites, as an aggregate or additive in cement products (also processed through novel additive manufacturing techniques), in road construction, as lightweight fill for embankments or as backfill material for retaining walls.

The use of crumb rubber and tyre granules in concrete has been the subject of many research projects in the recent years. The results of these studies show that rubber modified concrete can be used in applications where the mechanical properties are not of primary importance. While compression and flexural strength are reduced by the presence of rubber, toughness and crack resistance are improved. Moreover, freeze-thaw resistance and properties related to the water absorption, like corrosion resistance, can be improved by the introduction of crumb rubber in the mixture. Also, thermal insulation and acoustic absorption are enhanced if compared to plain concrete. Moreover, waste tyre rubber can be used as a bitumen modifier or as aggregate in asphalt mixtures. This can be performed either by the wet or by the dry process. Roads made of rubberized asphalt mixed with aggregates have been widely developed around the world, with satisfactory results. Rubberized asphalt has been proven to have a better workability, rutting resistance, and good noise absorption properties, and its service life can be longer than that of conventional asphalt. Moreover, it is possible to build roads made of rubberized asphalt in a wide range of climatic conditions. Tyre chips could be also utilized in geotechnical applications, because they can provide excellent drainage and superior stability to wall systems in unstable soil conditions. The use of tyre rubber as a lightweight geomaterial for embankments or for retaining walls, and as soil reinforcement, is very promising and should be further promoted in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] S. Ramarad, M. Khalid, C.T. Ratnam, A.L. Chuah, W. Rashmi, Waste tire rubber in polymer blends: a review on the evolution, properties and future, Prog. Mater. Sci. 72 (2015) 100–140.
[2] S.A. Tahami, A.F. Mirhosseini, S. Dessouky, H. Mork, A. Kavussi, The use of high content of fine crumb rubber in asphalt mixes using dry process, Construct. Build. Mater. 222 (2019) 643–653.
[3] F.D.B. de Sousa, Devulcanization of elastomers and applications, in: Elastomers, Intech, 2017.
[4] F.D.B. de Sousa, C.H. Scuracchio, G.-H. Hu, S. Hoppe, Devulcanization of waste tire rubber by microwaves, Polym. Degrad. Stabil. 138 (2017) 169–181.
[5] L. Asaro, M. Gratton, S. Seghar, N. Aït Hocine, Recycling of rubber wastes by devulcanization, Resour. Conserv. Recycl. 133 (2018) 250–262.
[6] J. Domingues, T. Marques, A. Mateus, P. Carreira, C. Malça, An additive manufacturing solution to produce big green parts from tires and recycled plastics, Procedia Manuf. 12 (2017) 242–248.
[7] J. Araujo-Morera, R. Verdejo, M.A. López-Manchado, M. Hernández Santana, Sustainable mobility: the route of tires through the circular economy model, Waste Manag. 126 (2021) 309–322.
[8] S. Seghar, L. Asaro, M. Rolland-Monnet, N. Aït Hocine, Thermo-mechanical devulcanization and recycling of rubber industry waste, Resour. Conserv. Recycl. 144 (2019) 180–186.
[9] L. Bockstal, T. Berchem, Q. Schmetz, A. Richel, Devulcanisation and reclaiming of tires and rubber by physical and chemical processes: a review, J. Clean. Prod. 236 (2019), 117574.
[10] A.J. Bowles, G.D. Fowler, C. O'Sullivan, K. Parker, Sustainable rubber recycling from waste tyres by waterjet: a novel mechanistic and practical analysis, Sustain. Mater. Technol. 25 (2020), e00173.
[11] W. Ferdous, A. Manalo, R. Siddique, P. Mendis, Y. Zhuge, H.S. Wong, W. Lokuge, T. Aravinthan, P. Schubel, Recycling of landfill wastes (tyres, plastics and glass) in construction – a review on global waste generation, performance, application and future opportunities, Resour. Conserv. Recycl. 173 (2021), 105745.
[12] H. Chittella, L.W. Yoon, S. Ramarad, Z.-W. Lai, Rubber waste management: a review on methods, mechanism, and prospects, Polym. Degrad. Stabil. 194 (2021), 109761.
[13] K. Formela, Sustainable development of waste tires recycling technologies – recent advances, challenges and future trends, Adv. Ind. Eng. Polymer Res. 4 (3) (2021) 209–222.
[14] D. Lo Presti, Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures: a literature review, Construct. Build. Mater. 49 (2013) 863–881.
[15] A. Mohajerani, L. Burnett, J.V. Smith, S. Markovski, G. Rodwell, M.T. Rahman, H. Kurmus, M. Mirzababaei, A. Arulrajah, S. Horpibulsuk, F. Maghool, Recycling waste rubber tyres in construction materials and associated environmental considerations: a review, Resour. Conserv. Recycl. 155 (2020), 104679.
[16] S.M.A. Qaidi, Y.Z. Dinkha, J.H. Haido, M.H. Ali, B.A. Tayeh, Engineering properties of sustainable green concrete incorporating eco-friendly aggregate of crumb rubber: a review, J. Clean. Prod. 324 (2021), 129251.
[17] Y. Li, S. Zhang, R. Wang, F. Dang, Potential use of waste tire rubber as aggregate in cement concrete – a comprehensive review, Construct. Build. Mater. 225 (2019) 1183–1201.
[18] X. Shu, B. Huang, Recycling of waste tire rubber in asphalt and portland cement concrete: an overview, Construct. Build. Mater. 67 (2014) 217–224.
[19] A. Moustafa, M.A. ElGawady, Mechanical properties of high strength concrete with scrap tire rubber, Construct. Build. Mater. 93 (2015) 249–256.
[20] A.A. Al-Attar, H.M. Hamada, B.A. Tayeh, P.O. Awoyera, Exploring engineering properties of waste tire rubber for construction applications - a review of recent advances, Mater. Today Proc. 53 (2022) A1–A17.
[21] O. Youssf, J.E. Mills, R. Hassanli, Assessment of the mechanical performance of crumb rubber concrete, Construct. Build. Mater. 125 (2016) 175–183.
[22] R. Roychand, R.J. Gravina, Y. Zhuge, X. Ma, O. Youssf, J.E. Mills, A comprehensive review on the mechanical properties of waste tire rubber concrete, Construct. Build. Mater. 237 (2020), 117651.
[23] A. Hamdi, G. Abdelaziz, K.Z. Farhan, Scope of reusing waste shredded tires in concrete and cementitious composite materials: a review, J. Build. Eng. 35 (2021), 102014.
[24] O. Youssf, J.E. Mills, T. Benn, Y. Zhuge, X. Ma, R. Roychand, R. Gravina, Development of crumb rubber concrete for practical application in the residential construction sector – design and processing, Construct. Build. Mater. 260 (2020), 119813.
[25] J. Xu, Z. Yao, G. Yang, Q. Han, Research on crumb rubber concrete: from a multi-scale review, Construct. Build. Mater. 232 (2020), 117282.
[26] A. Siddika, M.A.A. Mamun, R. Alyousef, Y.H.M. Amran, F. Aslani, H. Alabduljabbar, Properties and utilizations of waste tire rubber in concrete: a review, Construct. Build. Mater. 224 (2019) 711–731.
[27] A. Sofi, Effect of waste tyre rubber on mechanical and durability properties of concrete – a review, Ain Shams Eng. J. 9 (4) (2018) 2691–2700.
[28] N. Holmes, A. Browne, C. Montague, Acoustic properties of concrete panels with crumb rubber as a fine aggregate replacement, Construct. Build. Mater. 73 (2014) 195–204.
[29] L. Zheng, X. Sharon Huo, Y. Yuan, Experimental investigation on dynamic properties of rubberized concrete, Construct. Build. Mater. 22 (5) (2008) 939–947.
[30] M. Elchalakani, High strength rubberized concrete containing silica fume for the construction of sustainable road side barriers, Structures 1 (2015) 20–38.
[31] S. Raffoul, R. Garcia, K. Pilakoutas, M. Guadagnini, N.F. Medina, Optimisation of rubberised concrete with high rubber content: an experimental investigation, Construct. Build. Mater. 124 (2016) 391–404.
[32] H. Su, J. Yang, T.-C. Ling, G.S. Ghataora, S. Dirar, Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes, J. Clean. Prod. 91 (2015) 288–296.
[33] E. Güneyisi, M. Gesoğlu, T. Özturan, Properties of rubberized concretes containing silica fume, Cement Concr. Res. 34 (12) (2004) 2309–2317.
[34] B.S. Thomas, R. Chandra Gupta, Properties of high strength concrete containing scrap tire rubber, J. Clean. Prod. 113 (2016) 86–92.
[35] M. Mazloom, A.A. Ramezanianpour, J.J. Brooks, Effect of silica fume on mechanical properties of high-strength concrete, Cement Concr. Compos. 26 (4) (2004) 347–357.
[36] L.-J. Hunag, H.-Y. Wang, Y.-W. Wu, Properties of the mechanical in controlled low-strength rubber lightweight aggregate concrete (CLSRLC), Construct. Build. Mater. 112 (2016) 1054–1058.
[37] M.A. Aiello, F. Leuzzi, Waste tyre rubberized concrete: properties at fresh and hardened state, Waste Manag. 30 (8–9) (2010) 1696–1704.
[38] A. Benazzouk, O. Douzane, K. Mezreb, M. Quéneudec, Physico-mechanical properties of aerated cement composites containing shredded rubber waste, Cement Concr. Compos. 28 (7) (2006) 650–657.
[39] M.M. Reda Taha, A.S. El-Dieb, M.A. Abd El-Wahab, M.E. Abdel-Hameed, Mechanical, fracture, and microstructural investigations of rubber concrete, J. Mater. Civ. Eng. 20 (10) (2008) 640–649.
[40] Z.K. Khatib, F.M. Bayomy, Rubberized Portland cement concrete, J. Mater. Civ. Eng. 11 (3) (1999) 206–213.
[41] F. Pelisser, N. Zavarise, T.A. Longo, A.M. Bernardin, Concrete made with recycled tire rubber: effect of alkaline activation and silica fume addition, J. Clean. Prod. 19 (6–7) (2011) 757–763.
[42] M. Gesoğlu, E. Güneyisi, G. Khoshnaw, S. İpek, Investigating properties of pervious concretes containing waste tire rubbers, Construct. Build. Mater. 63 (2014) 206–213.
[43] P. Sukontasukkul, K. Tiamlom, Expansion under water and drying shrinkage of rubberized concrete mixed with crumb rubber with different size, Construct. Build. Mater. 29 (2012) 520–526.
[44] F. Pacheco-Torgal, Y. Ding, S. Jalali, Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): an overview, Construct. Build. Mater. 30 (2012) 714–724.
[45] M. Bravo, J. de Brito, Concrete made with used tyre aggregate: durability-related performance, J. Clean. Prod. 25 (2012) 42–50.
[46] E. Güneyisi, M. Gesoglu, N. Naji, S. İpek, Evaluation of the rheological behavior of fresh self-compacting rubberized concrete by using the Herschel–Bulkley and modified Bingham models, Arch. Civ. Mech. Eng. 16 (1) (2016) 9–19.
[47] F. Aslani, Mechanical properties of waste tire rubber concrete, J. Mater. Civ. Eng. 28 (3) (2016), 04015152.
[48] Z. Chen, L. Li, Z. Xiong, Investigation on the interfacial behaviour between the rubber-cement matrix of the rubberized concrete, J. Clean. Prod. 209 (2019) 1354–1364.
[49] E. Ganjian, M. Khorami, A.A. Maghsoudi, Scrap-tyre-rubber replacement for aggregate and filler in concrete, Construct. Build. Mater. 23 (5) (2009) 1828–1836.
[50] I. Mohammadi, H. Khabbaz, K. Vessalas, In-depth assessment of Crumb Rubber Concrete (CRC) prepared by water-soaking treatment method for rigid pavements, Construct. Build. Mater. 71 (2014) 456–471.
[51] K.A. Stallings, S.A. Durham, M.G. Chorzepa, Effect of cement content and recycled rubber particle size on the performance of rubber-modified concrete, Int. J. Sustain. Eng. 12 (3) (2018) 189–200.
[52] M. Gesoglu, E. Güneyisi, O. Hansu, S. İpek, D.S. Asaad, Influence of waste rubber utilization on the fracture and steel–concrete bond strength properties of concrete, Construct. Build. Mater. 101 (2015) 1113–1121.
[53] A.R. Khaloo, M. Dehestani, P. Rahmatabadi, Mechanical properties of concrete containing a high volume of tire-rubber particles, Waste Manag. 28 (12) (2008) 2472–2482.
[54] H. Liu, X. Wang, Y. Jiao, T. Sha, Experimental investigation of the mechanical and durability properties of crumb rubber concrete, Materials 9 (3) (2016) 172.
[55] R. Si, S. Guo, Q. Dai, Durability performance of rubberized mortar and concrete with NaOH-Solution treated rubber particles, Construct. Build. Mater. 153 (2017) 496–505.
[56] S. Guo, Q. Dai, R. Si, X. Sun, C. Lu, Evaluation of properties and performance of rubber-modified concrete for recycling of waste scrap tire, J. Clean. Prod. 148 (2017) 681–689.
[57] J. Xie, C. Fang, Z. Lu, Z. Li, L. Li, Effects of the addition of silica fume and rubber particles on the compressive behaviour of recycled aggregate concrete with steel fibres, J. Clean. Prod. 197 (2018) 656–667.
[58] A.T. Noaman, B.H. Abu Bakar, H.M. Akil, Experimental investigation on compression toughness of rubberized steel fibre concrete, Construct. Build. Mater. 115 (2016) 163–170.

[59] D. Raghavan, H. Huynh, C.F. Ferraris, Workability, mechanical properties, and chemical stability of a recycled tyre rubber-filled cementitious composite, J. Mater. Sci. 33 (7) (1998) 1745–1752.

[60] M.K. Batayneh, I. Marie, I. Asi, Promoting the use of crumb rubber concrete in developing countries, Waste Manag. 28 (11) (2008) 2171–2176.

[61] K. Bisht, P.V. Ramana, Evaluation of mechanical and durability properties of crumb rubber concrete, Construct. Build. Mater. 155 (2017) 811–817.

[62] M. Khorrami, A. Vafai, A.A. Khalilitabas, C.S. Desai, M.H.M. Ardakani, Experimental Investigation on mechanical characteristics and environmental effects on rubber concrete, Int. J. Concrete Struct. Mater. 4 (1) (2010) 17–23.

[63] K.B. Najim, M.R. Hall, Mechanical and dynamic properties of self-compacting crumb rubber modified concrete, Construct. Build. Mater. 27 (1) (2012) 521–530.

[64] T. Gupta, S. Chaudhary, R.K. Sharma, Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate, Construct. Build. Mater. 73 (2014) 562–574.

[65] A. Yilmaz, N. Degirmenci, Possibility of using waste tire rubber and fly ash with Portland cement as construction materials, Waste Manag. 29 (5) (2009) 1541–1546.

[66] N. Ganesan, J. Bharati Raj, A.P. Shashikala, Flexural fatigue behavior of self compacting rubberized concrete, Construct. Build. Mater. 44 (2013) 7–14.

[67] N.M. Al-Akhras, M.M. Smadi, Properties of tire rubber ash mortar, Cement Concr. Compos. 26 (7) (2004) 821–826.

[68] K.-R. Wu, D. Zhang, J.-M. Song, Properties of polymer-modified cement mortar using pre-enveloping method, Cement Concr. Res. 32 (3) (2002) 425–429.

[69] A.O. Atahan, A.Ö. Yücel, Crumb rubber in concrete: static and dynamic evaluation, Construct. Build. Mater. 36 (2012) 617–622.

[70] L. Li, S. Ruan, L. Zeng, Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles, Construct. Build. Mater. 70 (2014) 291–308.

[71] W.X. Feng, Y.D. Wei, L.J. Li, F. Liu, Y.Q. Chen, Experimental study on constitutive equation of high strength crumb rubber concrete to uniaxial compression, J New Build Mater 2 (2) (2010) 12–15.

[72] A. Kashani, T.D. Ngo, P. Mendis, J.R. Black, A. Hajimohammadi, A sustainable application of recycled tyre crumbs as insulator in lightweight cellular concrete, J. Clean. Prod. 149 (2017) 925–935.

[73] A. Meddah, M. Beddar, A. Bali, Use of shredded rubber tire aggregates for roller compacted concrete pavement, J. Clean. Prod. 72 (2014) 187–192.

[74] O. Onuaguluchi, D.K. Panesar, Hardened properties of concrete mixtures containing pre-coated crumb rubber and silica fume, J. Clean. Prod. 82 (2014) 125–131.

[75] B.S. Mohammed, K.M. Anwar Hossain, J.T. Eng Swee, G. Wong, M. Abdullahi, Properties of crumb rubber hollow concrete block, J. Clean. Prod. 23 (1) (2012) 57–67.

[76] İ. Topçu, A. Demir, Durability of rubberized mortar and concrete, J. Mater. Civ. Eng. 19 (2007) 173–178.

[77] X. Wang, Y. Wu, X. Shen, H. Wang, S. Liu, C. Yan, An experimental study of a freeze-thaw damage model of natural pumice concrete, Powder Technol. 339 (2018) 651–658.

[78] A. Richardson, K. Coventry, V. Edmondson, E. Dias, Crumb rubber used in concrete to provide freeze–thaw protection (optimal particle size), J. Clean. Prod. 112 (2016) 599–606.

[79] X. Zhu, C. Miao, J. Liu, J. Hong, Influence of crumb rubber on frost resistance of concrete and effect mechanism, Procedia Eng. 27 (2012) 206–213.

[80] M. Gesoğlu, E. Güneyisi, G. Khoshnaw, S. İpek, Abrasion and freezing–thawing resistance of pervious concretes containing waste rubbers, Construct. Build. Mater. 73 (2014) 19–24.

[81] A. Alsaif, L. Koutas, S.A. Bernal, M. Guadagnini, K. Pilakoutas, Mechanical performance of steel fibre reinforced rubberised concrete for flexible concrete pavements, Construct. Build. Mater. 172 (2018) 533–543.

[82] X. Huang, R. Ranade, W. Ni, V.C. Li, On the use of recycled tire rubber to develop low E-modulus ECC for durable concrete repairs, Construct. Build. Mater. 46 (2013) 134–141.

[83] B.S. Thomas, R.C. Gupta, P. Kalla, L. Cseteneyi, Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates, Construct. Build. Mater. 59 (2014) 204–212.

[84] P. Sukontasukkul, C. Chaikaew, Properties of concrete pedestrian block mixed with crumb rubber, Construct. Build. Mater. 20 (7) (2006) 450–457.

[85] O. Onuaguluchi, Effects of surface pre-coating and silica fume on crumb rubber-cement matrix interface and cement mortar properties, J. Clean. Prod. 104 (2015) 339–345.

[86] H. Zhu, J. Liang, J. Xu, M. Bo, J. Li, B. Tang, Research on anti-chloride ion penetration property of crumb rubber concrete at different ambient temperatures, Construct. Build. Mater. 189 (2018) 42–53.

[87] B.S. Thomas, R.C. Gupta, V.J. Panicker, Recycling of waste tire rubber as aggregate in concrete: durability-related performance, J. Clean. Prod. 112 (2016) 504–513.

[88] M. Gesoğlu, E. Güneyisi, Strength development and chloride penetration in rubberized concretes with and without silica fume, Mater. Struct. Materiaux et Constructions 40 (2007) 953–964.

[89] B.S. Thomas, R.C. Gupta, P. Mehra, S. Kumar, Performance of high strength rubberized concrete in aggressive environment, Construct. Build. Mater. 83 (2015) 320–326.

[90] N. Oikonomou, S. Mavridou, Improvement of chloride ion penetration resistance in cement mortars modified with rubber from worn automobile tires, Cement Concr. Compos. 31 (6) (2009) 403–407.

[91] M.T. Bassuoni, M.L. Nehdi, Resistance of self-consolidating concrete to sulfuric acid attack with consecutive pH reduction, Cement Concr. Res. 37 (7) (2007) 1070–1084.

[92] K. Bisht, P.V. Ramana, Waste to resource conversion of crumb rubber for production of sulphuric acid resistant concrete, Construct. Build. Mater. 194 (2019) 276–286.

[93] B.S. Thomas, R.C. Gupta, Long term behaviour of cement concrete containing discarded tire rubber, J. Clean. Prod. 102 (2015) 78–87.

[94] S. Herrero, P. Mayor, F. Hernández-Olivares, Influence of proportion and particle size gradation of rubber from end-of-life tires on mechanical, thermal and acoustic properties of plaster–rubber mortars, Mater. Des. 47 (2013) 633–642.

[95] E. Fraile-Garcia, J. Ferreiro-Cabello, M. Mendivil-Giro, A.S. Vicente-Navarro, Thermal behaviour of hollow blocks and bricks made of concrete doped with waste tyre rubber, Construct. Build. Mater. 176 (2018) 193–200.

[96] I. Marie, Thermal conductivity of hybrid recycled aggregate – rubberized concrete, Construct. Build. Mater. 133 (2017) 516–524.

[97] P. Sukontasukkul, Use of crumb rubber to improve thermal and sound properties of pre-cast concrete panel, Construct. Build. Mater. 23 (2) (2009) 1084–1092.

[98] B. Yesilata, Y. Isıker, P. Turgut, Thermal insulation enhancement in concretes by adding waste PET and rubber pieces, Construct. Build. Mater. 23 (5) (2009) 1878–1882.

[99] E. Fraile-Garcia, J. Ferreiro-Cabello, B. Defez, G. Peris-Fajanes, Acoustic behavior of hollow blocks and bricks made of concrete doped with waste-tire rubber, Materials 9 (12) (2016) 962.

[100] B. Zhang, C.S. Poon, Sound insulation properties of rubberized lightweight aggregate concrete, J. Clean. Prod. 172 (2018) 3176–3185.

[101] Z. Ghizdăveţ, B.-M. Stefan, D. Nastac, O. Vasile, M. Bratu, Sound absorbing materials made by embedding crumb rubber waste in a concrete matrix, Construct. Build. Mater. 124 (2016) 755–763.

[102] A.C. Corredor-Bedoya, R.A. Zoppi, A.L. Serpa, Composites of scrap tire rubber particles and adhesive mortar – noise insulation potential, Cement Concr. Compos. 82 (2017) 45–66.

[103] A. Pajonk, A. Prieto, U. Blum, U. Knaack, Multi-material additive manufacturing in architecture and construction: a review, J. Build. Eng. 45 (2022), 103603.

[104] M. Sambucci, D. Marini, A. Sibai, M. Valente, Preliminary mechanical analysis of rubber-cement composites suitable for additive process construction, J. Composites Sci. 4 (3) (2020) 120.

[105] M. Sambucci, M. Valente, Influence of waste tire rubber particles size on the microstructural, mechanical, and acoustic insulation properties of 3D-printable cement mortars, Civil Eng. J. 7 (6) (2021) 937–952.

[106] J. Ye, C. Cui, J. Yu, K. Yu, J. Xiao, Fresh and anisotropic-mechanical properties of 3D printable ultra-high ductile concrete with crumb rubber, Compos. B Eng. 211 (2021), 108639.

[107] J. Liu, S. Setunge, P. Tran, 3D concrete printing with cement-coated recycled crumb rubber: compressive and microstructural properties, Construct. Build. Mater. 347 (2022), 128507.

[108] L. Brasileiro, F. Moreno-Navarro, R. Tauste-Martínez, J. Matos, M. Rubio-Gámez, Reclaimed polymers as asphalt binder modifiers for more sustainable roads: a review, Sustainability 11 (3) (2019) 646.

[109] A.F. de Almeida Júnior, R.A. Battistelle, B.S. Bezerra, R. de Castro, Use of scrap tire rubber in place of SBS in modified asphalt as an environmentally correct alternative for Brazil, J. Clean. Prod. 33 (2012) 236–238.

[110] Y. Ma, H. Zhou, X. Jiang, P. Polaczyk, R. Xiao, M. Zhang, B. Huang, The utilization of waste plastics in asphalt pavements: a review, Cleaner Mater. 2 (2021), 100031.

[111] W. Zheng, H. Wang, Y. Chen, J. Ji, Z. You, Y. Zhang, A review on compatibility between crumb rubber and asphalt binder, Construct. Build. Mater. 297 (2021), 123820.

[112] G.M. Duarte, A.L. Faxina, Asphalt concrete mixtures modified with polymeric waste by the wet and dry processes: a literature review, Construct. Build. Mater. 312 (2021), 125408.

[113] H.T. Tai Nguyen, T. Nhan Tran, Effects of crumb rubber content and curing time on the properties of asphalt concrete and stone mastic asphalt using dry process, Int. J. Pavement Res. Technol. 11 (3) (2018) 236–244.

[114] F. Chavez, J. Marcobal, J. Gallego, Laboratory evaluation of the mechanical properties of asphalt mixtures with rubber incorporated by the wet, dry, and semi-wet process, Construct. Build. Mater. 205 (2019) 164–174.

[115] F. Gong, S. Guo, S. Chen, Z. You, Y. Liu, Q. Dai, Strength and durability of dry-processed stone matrix asphalt containing cement pre-coated scrap tire rubber particles, Construct. Build. Mater. 214 (2019) 475–483.

[116] L. da Silva, A. Benta, L. Picado-Santos, Asphalt rubber concrete fabricated by the dry process: laboratory assessment of resistance against reflection cracking, Construct. Build. Mater. 160 (2018) 539–550.

[117] N.A. Hassan, G.D. Airey, R.P. Jaya, N. Mashros, M.A. Aziz, A review of crumb rubber modification in dry mixed rubberised asphalt mixtures, Jurnal Teknologi 70 (4) (2014) 127–134.

[118] F. Moreno, M.C. Rubio, M.J. Martinez-Echevarria, The mechanical performance of dry-process crumb rubber modified hot bituminous mixes: the

influence of digestion time and crumb rubber percentage, Construct. Build. Mater. 26 (1) (2012) 466–474.
[119] F.J. López-Moro, M.C. Moro, F. Hernández-Olivares, B. Witoszek-Schultz, M. Alonso-Fernández, Microscopic analysis of the interaction between crumb rubber and bitumen in asphalt mixtures using the dry process, Construct. Build. Mater. 48 (2013) 691–699.
[120] F. Moreno, M. Sol, J. Martín, M. Pérez, M.C. Rubio, The effect of crumb rubber modifier on the resistance of asphalt mixes to plastic deformation, Mater. Des. 47 (2013) 274–280.
[121] A. Gandi, A. Cardenas, D. Sow, A. Carter, D. Perraton, Study of the impact of the compaction and curing temperature on the behavior of cold bituminous recycled materials, J. Traffic Transport. Eng. 6 (4) (2019) 349–358.
[122] A. Riekstins, J. Baumanis, J. Barbars, Laboratory investigation of crumb rubber in dense graded asphalt by wet and dry processes, Construct. Build. Mater. 292 (2021), 123459.
[123] I. Rodríguez-Fernández, F. Tarpoudi Baheri, M.C. Cavalli, L.D. Poulikakos, M. Bueno, Microstructure analysis and mechanical performance of crumb rubber modified asphalt concrete using the dry process, Construct. Build. Mater. 259 (2020), 119662.
[124] H. Yu, Z. Zhu, Z. Leng, C. Wu, Z. Zhang, D. Wang, M. Oeser, Effect of mixing sequence on asphalt mixtures containing waste tire rubber and warm mix surfactants, J. Clean. Prod. 246 (2020), 119008.
[125] W. Cao, Study on properties of recycled tire rubber modified asphalt mixtures using dry process, Construct. Build. Mater. 21 (5) (2007) 1011–1015.
[126] F. Moreno, M.C. Rubio, M.J. Martinez-Echevarria, Analysis of digestion time and the crumb rubber percentage in dry-process crumb rubber modified hot bituminous mixes, Construct. Build. Mater. 25 (5) (2011) 2323–2334.
[127] A.O. Yucel, H.I. Ozturk, M. Guler, Influence of warm mix additive on internal structure of dry process crumb rubber modified mixtures, J. Clean. Prod. 313 (2021), 127959.
[128] H.I. Ozturk, F. Kamran, Laboratory evaluation of dry process crumb rubber modified mixtures containing Warm Mix Asphalt Additives, Construct. Build. Mater. 229 (2019), 116940.
[129] I. Bakheit, H. Xiaoming, Modification of the dry method for mixing crumb rubber modifier with aggregate and asphalt based on the binder mix design, Construct. Build. Mater. 220 (2019) 278–284.
[130] S. Noura, A.M. Al-Sabaeei, G.I. Safaeldeen, R. Muniandy, A. Carter, Evaluation of measured and predicted resilient modulus of rubberized Stone Mastic Asphalt (SMA) modified with truck tire rubber powder, Case Stud. Constr. Mater. 15 (2021), e00633.
[131] Y. Li, P. Hao, C. Zhao, J. Ling, T. Wu, D. Li, J. Liu, B. Sun, Anti-rutting performance evaluation of modified asphalt binders: a review, J. Traffic Transport. Eng. 8 (3) (2021) 339–355.
[132] G.H. Shafabakhsh, M. Sadeghnejad, Y. Sajed, Case study of rutting performance of HMA modified with waste rubber powder, Case Stud. Constr. Mater. 1 (2014) 69–76.
[133] M. Arabani, S.M. Mirabdolazimi, A.R. Sasani, The effect of waste tire thread mesh on the dynamic behaviour of asphalt mixtures, Construct. Build. Mater. 24 (6) (2010) 1060–1068.
[134] Y. Ma, S. Wang, H. Zhou, W. Hu, P. Polaczyk, M. Zhang, B. Huang, Compatibility and rheological characterization of asphalt modified with recycled rubber-plastic blends, Construct. Build. Mater. 270 (2021), 121416.
[135] S. Chen, D. Ge, D. Jin, X. Zhou, C. Liu, S. Lv, Z. You, Investigation of hot mixture asphalt with high ground tire rubber content, J. Clean. Prod. 277 (2020), 124037.
[136] J.L. Feiteira Dias, L.G. Picado-Santos, S.D. Capitão, Mechanical performance of dry process fine crumb rubber asphalt mixtures placed on the Portuguese road network, Construct. Build. Mater. 73 (2014) 247–254.
[137] L.G. Picado-Santos, S.D. Capitão, J.L.F. Dias, Crumb rubber asphalt mixtures by dry process: assessment after eight years of use on a low/medium trafficked pavement, Construct. Build. Mater. 215 (2019) 9–21.
[138] K. Yan, H. Sun, L. You, S. Wu, Characteristics of waste tire rubber (WTR) and amorphous poly alpha olefin (APAO) compound modified porous asphalt mixtures, Construct. Build. Mater. 253 (2020), 119071.
[139] G. Licitra, M. Cerchiai, L. Teti, E. Ascari, L. Fredianelli, Durability and variability of the acoustical performance of rubberized road surfaces, Appl. Acoust. 94 (2015) 20–28.
[140] S. Eskandarsefat, C. Sangiorgi, G. Dondi, R. Lamperti, Recycling asphalt pavement and tire rubber: a full laboratory and field scale study, Construct. Build. Mater. 176 (2018) 283–294.
[141] U. Sandberg, J. Ejsmont, Tyre/road Noise, Reference book, Informex, 2002.
[142] S.E. Paje, J. Luong, V.F. Vázquez, M. Bueno, R. Miró, Road pavement rehabilitation using a binder with a high content of crumb rubber: influence on noise reduction, Construct. Build. Mater. 47 (2013) 789–798.
[143] V.F. Vazquez, J. Luong, M. Bueno, F. Teran, S.E. Paje, Assessment of an action against environmental noise: acoustic durability of a pavement surface with crumb rubber, Sci. Total Environ. 542 (Pt A) (2016) 223–230.
[144] J.M. Kathib, Sustainability of Construction Materials, CRC Press, 2009.
[145] H. Hazarika, Y. Fukumoto, Sustainable solution for seawall protection against tsunami-induced damage, Int. J. GeoMech. 16 (5) (2016) C4016005.
[146] F. Belabdelouahab, H. Trouzine, Research and enhancement of used tyres, such as material innovative in Algeria, Phys. Procedia 55 (2014) 68–74.
[147] M.J. Moghadam, A. Zad, N. Mehrannia, N. Dastaran, Experimental evaluation of mechanically stabilized earth walls with recycled crumb rubbers, J. Rock Mech. Geotech. Eng. 10 (5) (2018) 947–957.
[148] P. Yu, A. Manalo, W. Ferdous, R. Abousnina, C. Salih, T. Heyer, P. Schubel, Investigation on the physical, mechanical and microstructural properties of epoxy polymer matrix with crumb rubber and short fibres for composite railway sleepers, Construct. Build. Mater. 295 (2021), 123700.
[149] A. Vila, G. Pérez, C. Solé, A.I. Fernández, L.F. Cabeza, Use of rubber crumbs as drainage layer in experimental green roofs, Build. Environ. 48 (2012) 101–106.
[150] M. Lamour, A. Cecchin, Repurposed materials in construction: a review of low-processed scrap tires in civil engineering applications for disaster risk reduction, Construct. Build. Mater. 293 (2021), 123368.
[151] M. Saberian, J. Li, Long-term permanent deformation behaviour of recycled concrete aggregate with addition of crumb rubber in base and sub-base applications, Soil Dynam. Earthq. Eng. 121 (2019) 436–441.
[152] E. Contreras-Marín, M. Anguita-García, E.M. Alonso-Guzmán, A. Jaramillo-Morilla, E.J. Mascort-Albea, R. Romero-Hernández, C. Soriano-Cuesta, Use of granulated rubber tyre waste as lightweight backfill material for retaining walls, Appl. Sci. 11 (13) (2021).
[153] N.A.D. Jaramillo, J.W. dos Santos Ferreira, J.A.C. Malko, M.D.T. Casagrande, Mechanical behavior of clayey soil reinforced with recycled tire rubber using chips and fibers, Geotech. Geol. Eng. 40 (6) (2022) 3365–3378.
[154] A. Eslami, D. Akbarimehr, Failure analysis of clay soil-rubber waste mixture as a sustainable construction material, Construct. Build. Mater. 310 (2021), 125274.
[155] L. Liu, G. Cai, J. Zhang, X. Liu, K. Liu, Evaluation of engineering properties and environmental effect of recycled waste tire-sand/soil in geotechnical engineering: a compressive review, Renew. Sustain. Energy Rev. 126 (2020), 109831.