The Egyptian International Journal of Engineering Sciences and Technology

Vol. 30 (2020) 1–11

https://eijest.journals.ekb.eg/

Rubberized concrete properties and its structural engineering applications – An overview

Hesham M. Fawzy[a], Suzan A. A. mustafa[b], Fady A. Elshazly[c*]

[a]Professor and dean of faculty of engineering, Zagazig university, Egypt
[b]Professor of structural Analysis and Mechancs, Faculty of engineering, Zagazig university, Egypt
[c]Demonstrator at structural engineering dep., Faculty of engineering, Zagazig university, Egypt

A R T I C L E I N F O

Keywords:

Concrete.
Rubcrete.
Crumb Rubber.
CFST.
RUCFST.
Axial compressive.
Deficiencies.
FRP.
CFRP.
GFRP.

A B S T R A C T

This paper presents a review on rubberized concrete mixes and their properties such as strength, ductility, sound and water absorption, in addition to acid and sulphate resistance. Moreover, it discusses a review about using rubberized concrete in structural elements and its effect on ultimate compressive strength and ductility. Rubberized concrete mixes exhibit lower strength than ordinary concrete mixes. On the other hand, rubberized concrete has higher ductility and energy dissipation behaviour. Rubberized concrete with its lightweight showed a high resistance to freeze-thaw and sulphate and acid attacks in comparison with ordinary concrete. The most common structural member is Rubberized Concrete Filled Steel Tubes (RUCFST). In addition to the aforementioned merits of rubberized concrete, the confining effect of the steel tube recoups the reduction in concrete compressive strength caused by rubber inclusion. Limited researches concerned in strengthening and repairing of deficient Concrete Filled Steel Tubes (CFST) with different types of Fibre Reinforced Polymers (FRP). There is noticeable effect of using these FRP materials on RUCFST sections, ultimate strength and ductility.

1. Introduction

Rubber is a vital material that is included in a numerous number of industrial fields. One of these fields is vehicles manufacturing in which rubber is used in several applications such as rubber tires. The annual manufacture of rubber tires can be approximately estimated by billions. Among this number, 1000 million tires were estimated to end their lifetime annually. Huge percent of this number is only disposed in landfills without treatment. Tires disposal in landfills consumes large areas of land. An urgent need to get rid of waste tires beneficially and in an eco-friendly way is needed [1]. One of the easiest and cheapest ways to get rid of waste tires was to burn them. Burning tires produces benzene compounds emissions that harm people, plants and animals in addition to the harmful effect on the global warming. The burning process produces harmful powder that can adversely affect the soil fertility [2-5]. Using rubber tires to produce fuel isn't economic and produces low quality fuel in comparison with petroleum products. Rubber can be used in several applications such as construction of roads, water barriers, geotechnical field, retaining walls, in concrete mixes and other applications [2, 6, 7].

One of the possible ways to get rid of the tires disposal in landfills is to use the rubber content existing in the tires after passing through chemical and mechanical processes in concrete mixes as partial replacement of fine or coarse aggregate. Adding rubber to concrete mixes produces Rubberized Concrete mixes (RUC). Several studies about adding rubber to the concrete mix showed that adding rubber can enhance several properties of concrete such as ductility, energy dissipation and sound absorption.

* Corresponding author. Tel.: +20100 0656533
E-mail address: Fadiame@zu.edu.eg

Rubberized concrete mixes are economic and easy to produce. They have good resistance to acid and low water absorption. Rubberized concrete has lower strength capacity than ordinary concrete, so in fields that strength isn't important, rubberized concrete may be used to get benefit from its additional properties over normal concrete. Rubberized concrete can be used in architectural uses such as nailing concrete, pedestrian sidewalks, precast roofs in green buildings, jersey barriers and skid resistant ramps [8]. Rubberized concrete can be used in applications that need lightweight such architectural light units, architectural decorations and facades of buildings. It can be used in areas with repeated high change in temperature such as freezing and thawing, sports courts such as gym halls, tennis courts, basketball courts, waiting areas for passengers in airports and entertainment areas. Failure modes of rubberized concrete in several researches showed that rubberized concrete mix exhibits failure with no disintegration in opposite of ordinary concrete mix. Rubberized concrete has good resistance against shocks and sound waves. It can be used in structural elements to maintain enhancement of ductility that is very important in seismic areas, in construction of highways to provide absorbance against shocks and in explosions barriers.

2. Environmental challenges

Waste materials vary between solid, liquid and gaseous materials. Rubber tires belong to solid waste materials that can't be disposed in landfills without hazardous effects on environment. In case of disposal of tires in landfills, huge areas of land will be consumed with no benefit. Waste tires' landfills may exhibit uncontrolled fires that may burn all near places in addition to harmful emissions that can cause air pollution and damage soil fertility as well. To avoid all these possible hazards, new ways to get rid of waste tires are needed and one of these ways is to recycle waste tires and treat them to be used in rubberized concrete mixes. This way can decrease the amount of waste tires in landfills in addition to use them in beneficial purposes.

3. Scrap tires recycling

Recycling process to produce crumb rubber used in concrete mixes contains several steps such as shredding, separation of textile and steel existing in the tires and grains production. Then, crumb rubber is classified according to different sizes to be used in the suitable application. To produce crumb rubber in different grains, it must pass through the grinding process that can be carried out at surrounding temperature with and without being under wet condition, at high temperature and at freezing temperature. The first type is grinding at the surrounding temperature in which rubber is grinded using mills. The second type is grinding at the surrounding temperature under wet condition in which water is used to reduce the increasing temperature and after the end of the process, rubber particles are dried. The third type is grinding at high temperature about 130^{o}C in which rubber is produced in grains ranged from 1 to 6 mm. The fourth type is grinding at temperature of freezing in which rubber is cooled below its temperature to be in glass case then, it is shredded using an impact type mill.

According to size, crumb rubber can be used as replacement in concrete mix as follows:

- As replacement of coarse aggregate:

In this type, tires are prepared through two stages. The first stage includes cutting rubber until it reaches pieces with length of 100 to 230 mm and the second stage produces rubber grains with size ranges from 13 to 76 mm that can be used as a replacement of coarse aggregate.

- As replacement of fine aggregate:

This type of crumb rubber requires mills with special requirements at different temperatures as these two factors control the size of the manufactured grains that ranges from 0.425-4.75 mm.

- As partial replacement of cement [9-15]:

Rubber grains' size range from 0.075 mm to 0.475 mm. This type requires using micro-milling process to create this reduction in grains' size. Fig. 1 shows the manufactured rubber and waste tire chips proposed by Kang et al. [16].

a b

Fig. 1. Types of crumb rubber. (a) Manufactured (ground) rubber and (b) Waste tire chips [16].

4. Rubberized concrete properties

Rubberized concrete (RUC) is a concrete mix that includes crumb rubber particles as a replacement of fine or coarse aggregate. Many researches concerned about this type of concrete with different names as Rubcrete, Crumb Rubber Concrete (CRC), Rubber Included Concrete (RIC) and Tire Rubber-Filled Concrete. The following paragraphs discuss the mix properties in fresh and hardened stages.

4.1. Fresh concrete properties

4.1.1. Workability

It can be defined as mixing, handling and compaction of concrete mix. Workability gives the concrete mix the ability to be poured in any shape. Holmes et al. [17] elucidated that the increase of rubber grades and content led to a decrease in the workability, which might be a result of flowability reduction of large particles. This agreed with Dong et al. [18]. Bravo and Brito [2] showed that rubberized concrete using freezed ground rubber exhibited higher slump than mechanically ground rubber as a result of higher roughness of mechanically ground rubber. Su et al. [19] mentioned that the decrease in rubber grains size led to a decrease in the slump. Aiello and Leuzzi [20] elucidated that the slump was slightly improved by using rubber shreds as partial replacement of fine or coarse aggregate. Elchalakani [21] showed that using suitable quantity of admixtures led to higher workability of rubberized concrete contains rubber powder and crumb rubber in comparison with ordinary concrete. Khatib and Bayomy [22] concluded that according to workability, an upper level of 50% of total aggregate volume may be used to produce rubberized concrete mixes.

4.1.2. Bulk density

Gesoglu et al. [23, 24] showed that rubberized concrete had weight lower than ordinary concrete by 2-11% in agreement with Holmes et al. [17]. Pelisser et al. [25] showed that rubberized concrete with recycled rubber exhibited lower density than that for ordinary concrete by 13% and the reduction in density was about 9% in case of adding silica fumes as a result of the higher densification of the concrete mix structure. Torgal et al. [26] studied three mixes of rubberized concrete. The first mix was by using tire chips as partial replacement of coarse aggregate, the second mix was by using crumb rubber as partial replacement of fine aggregate and the third mix was by using a combination of tire chips and crumb rubber. They concluded that the density reduction in comparison with ordinary concrete was about 45%, 34% and 33%, respectively.

4.2. Hardened concrete properties

4.2.1. Compressive strength

Eldin and senouci [27] used rubber as a replacement of fine or coarse aggregate. The replacement ratios were 25%, 50%, 75% and 100%. They used Edgar chips with sizes of 19 mm, 25 mm and 38 mm. They used Preston rubber passing from a 2 mm sieve as a replacement of fine aggregate. They tested experimentally more than 200 cylinders with 150 mm in diameter and 300 mm in height. The results showed that using rubber as a replacement of coarse aggregate led to a loss in the compressive strength by 85% and tensile splitting strength by 50% depending on rubber content percentage. In case of replacing fine aggregate with rubber, there was up to 65% reduction in the compressive strength. On the other hand, the mix showed higher capability in absorption of energy under compressive and tensile loads. Schimizze et al. [28] studied two rubberized concrete mixes; the first contained fine rubber particles while the other contained coarse rubber particles. The results showed a loss in compressive strength up to 50% according to the rubber percentage compared to the control mix. Khatib and Bayomy [22] showed that the strength of the concrete mix decreased systematically with the increase in the rubber content. They illustrated that the rubber content must be at most 20% of the total aggregate volume as over this portion a high reduction in the concrete strength was noticed. Grrick [29] studied rubberized concrete by replacement of 15% of coarse aggregate volume by rubber as two phases material as tire fibre and chips. The results showed a reduction in strength and stiffness; however, the impact resistance and cracking resistance were enhanced. At peak load, the control concrete disintegrated while the rubberized concrete deformation was considerable without complete disintegration. The results showed that rubberized concrete with rubber fibre exhibited lower stress concentration than in case of using rubber chip that referred to the capability of the mix with rubber fibre to attain higher loads than in case of rubber chips.

Kaloush et al. [30] used crumb rubber to produce rubberized concrete mix. They declared that for every

50 Ibs of rubber addition, the unit weight decreased nearly 6 pcf. They mentioned that adding rubber to the concrete mix led to a decrease in the strength and one of the reduction reasons was the air voids composed inside the concrete mix that increases with the increase in the rubber proportion. They showed that this effect could be reduced by adding a de-airing material into the concrete mixer. Ganjian et al. [9] outlined some factors that controlled the loss in compressive strength of rubberized concrete. The first factor was the soft cement paste around rubber particles which caused quick cracks propagation around rubber particles during load application. The second factor was the lack of bond between rubber and cement paste in comparison with natural aggregate and cement paste. The third factor was that compressive strength of the mix depended on the properties of the materials composing the mix. So, the replacement of one material with rubber particles reduced the overall compressive strength. The fourth factor was due to the lack of bond between rubber and other materials. In addition to the low specific gravity of rubber that made rubber particles move upward during vibrating of the concrete mix. The composition of the top layer in such case would have high concentration of rubber particles that reduced the compressive strength as a result of non-homogenous concrete mix. Dong et al. [18] studied rubberized concrete mix with and without coated rubber. They elucidated that rubberized concrete mix using coated rubber with a silane coupling agent exhibited higher compressive strength than without coated rubber as a result of the increase in bond between rubber and cement due to rubber improved interface. Serge and joekes [31] showed that using of NaOH solution in treatment of rubber is so useful specially in case of using tires rubber not manufactured rubber particles. Their results showed an increase in the bond strength between rubber and cement which led to enhancement in strength. Olivares et al. [32] studied rubberized concrete with adding crumbed tire fibres. They showed that adding of rubber up to 5% didn’t affect in a significant way the mechanical properties or elastic modulus of the concrete mix.

4.2.2. Flexural strength and flexural stiffness

Su et al. [19] used rubber particles as 20% replacement of fine aggregate and this led to a decrease in the flexural strength by 12.8%. They noticed that the loss in the flexural stiffness decreased with the decrease in rubber particles size. This was a result of the increased compaction of rubberized concrete mix due to smaller size of rubber particles. Aiello and Leuzzi [20] elucidated that using rubber particles as a replacement of coarse aggregate caused more reduction in flexural stiffness than using rubber particles as a replacement of fine aggregate. Elchalakani [21] observed an enhancement in flexural stiffness with the decrease in water to cement ratio and adding silica fume due to the effect of silica fumes in enhancement of bond. Yilmaz and Degirmenci [33] elucidated that adding rubber fibre to the concrete mix up to 20% achieved an increase in the flexural strength in comparison with control concrete mix. Ganesan et al. [34] studied self-compacting rubberized concrete. They showed that using of rubber content of 15% increased the strength by 15% while using of rubber content of 20% increased the strength by 9% in comparison with normal concrete mix.

4.2.3. Abrasion resistance

Sukontasukkul and Chaikaew [35] proposed a reduction in the abrasion resistance of rubberized concrete mixes in comparison with normal concrete. They showed that using several sizes of rubber particles in a same concrete mix had a better abrasion resistance than rubberized concrete with one rubber particles size. Gupta et al. [36] mentioned that using of rubber fibre was more effective as it exhibited lower wear depth than in case of using rubber powder. Kang et al. [16] studied rubberized concrete containing crumb rubber and concrete mix containing silica fumes. They showed that adding rubber adversely affected the compressive strength but this increased the abrasion resistance. They observed that using of silica fumes increased the compressive strength and abrasion resistance. They outlined that rubberized concrete exhibited higher abrasion resistance than concrete mix with silica fumes and normal concrete mix while concrete mix with silica fumes exhibited higher abrasion resistance than normal concrete mix. They showed that the increase in rubber content enhanced the abrasion resistance of rubberized concrete.

4.2.4. Modulus of elasticity

Ganjian et al. [9] studied rubberized concrete produced by using rubber particles as 5-10% replacement of aggregate and by using powdered rubber as 5-10% replacement. The loss in elasticity modulus was 17-25% in the first case and 18-36% in the second case. They observed a reduction in modulus of elasticity of 17-25% and 18-36% in case of using rubber with 5-10% as replacement of aggregate and in case of using powdered rubber respectively. Dong et al. [18] noticed that the modulus of elasticity of the rubberized concrete decreased with the increase in rubber content while in case of using coated rubber, the modulus of elasticity was higher than that in case of using uncoated rubber. Pelisser et al. [25] proposed that rubberized concrete exhibited lower compressive strength, rigidity and modulus of elasticity in comparison with normal concrete mix.

4.2.5. Water absorption

Onuaguluchi and Panesar [37] elucidated that the water absorption increased with the increase in the rubber content, meanwhile adding silica fumes led to a decrease in the water absorption of the rubberized concrete mix. Azevedo et al. [38] produced high performance rubberized concrete by using rubber particles as partial replacement of fine aggregate. They showed that the increase in the rubber content caused an increase in the water absorption and that partial replacement of cement by fly ash and metakaolin reduced the water absorption. Segre and joekes [7] showed that adding rubber to the concrete mix reduced water absorption as a result of low water absorption nature of rubber. Gesoglu and Guneyisi [4] elucidated that in case of self-compacting concrete, the water absorption increased with the increase in rubber content. Using fly ash as 40% replacement reduced the water absorption at testing after 90 days.

4.2.6. Shrinkage

Bravo and Brito [2] showed that the shrinkage of rubberized concrete mix increased with the increase in rubber content. Yung et al. [39] produced cylindrical rubberized concrete specimens with dimensions of 285 mm 750 mm. They replaced 5% and 20% of fine aggregate volume with rubber powder content. The results of 5% and 20% rubberized concrete mixes showed change in length of the specimens of 35% and 95% higher than normal concrete mixes, respectively. Sukontasukkul and Tiamlom [40] outlined that rubberized concrete using rubber powder exhibited more shrinkage than in case of rubberized concrete using crumb rubber. This might be as a result of the small size of rubber powder particles that allows grains to act as a spring.

4.2.7. Freeze-thaw resistance

Zhu et al. [41] studied the freeze-thaw resistance of the rubberized concrete mix. They used different sizes of rubber particles measured by mesh and produced by Beijing functional quantum technologies Co., LTD. They elucidated that in case of crumb rubber size below 60 mesh the resistance increased with the increase of the rubber fineness while in case of crumb rubber size more than 60 mesh, the increase in fineness of rubber led to reduction in the freeze-thaw resistance. Al-Akhras and smadi [42] studied rubberized concrete using powdered rubber. Normal concrete mixes exhibited low resistance against freezing and thawing and they achieved relative dynamic modulus of elasticity of 55% after 50 cycles of freezing and thawing. Rubberized concrete using powdered rubber as a replacement of fine aggregate achieved the same dynamic modulus of elasticity after 150 cycles of freezing and thawing. Rubberized concrete mix with replacement of 10% of fine aggregate content with powdered rubber achieved 60% relative dynamic modulus of elasticity after 225 cycles of freezing and thawing.

4.2.8. Thermal and acoustic properties

Topcu and Bilir [43] studied rubberized concrete mixes exposed to high temperature of 400^oC and 800^oC. At a temperature of 400^oC, the colour of the specimens became pink while at 800^oC, the colour of the specimens became light grey. At high temperatures, water in chemical bond, free water in capillary pores in concrete and water in Calcium Silicate Hydrate (C-S-H) and sulphoaluminate evaporate. At 300^oC this evaporation causes shrinkage in concrete. C-S-H gels start to decompose above 400^oC. At temperature of 530^oC, $Ca(OH)_2$ transforms to anhydrite lime. High temperatures cause cracking in concrete and decrease in compressive strength according to these reasons [44,45]. They [43] showed that high temperature led to loss in the compressive strength of the rubberized concrete mix as a result of rubber burning that left pores inside the concrete mix and this loss in compressive strength increased with the increase in rubber content. Ocholi et al. [46] studied thermal properties of rubberized concrete. They replaced 5%, 10%, 15%, 20% and 25% of coarse aggregate volume by rubber particles. Using 25% replacement of coarse aggregate with rubber particles reduced the thermal conductivity and the specific heat capacity of the mix by 29.4% and 29.7%, respectively, in comparison with normal concrete mix. For the same rubberized concrete mix, thermal resistivity increased by 29.4% while thermal diffusivity and thermal effusivity and decreased by 65.1% and 37.6%, respectively, in comparison with normal concrete mix. Holmes et al. [17] studied sound absorption properties of rubberized concrete. They outlined that at all different values of temperature, rubberized concrete sound absorption was more effective than ordinary concrete mix. Torgal et al. [26] showed that rubberized concrete is an effective absorber of sound and shaking energy. With the increase in rubber content and concentration, the ultrasonic modulus was reduced as a result of the porous nature of rubberized concrete. Gupta et al. [47] studied rubberized concrete by replacing fine aggregate by rubber fibre. They showed that at room temperature, there was a reduction in compressive strength by 22.6% and 53.2% in case of replacement of 5% and 25% of fine aggregate by rubber fibre, respectively. At 300^{o}C for 30 min exposure, the reduction in compressive strength was 7.5%, 7.4% and 7.8% for 5% replacement, 25% replacement and normal concrete, respectively. At 300^{o}C for 120 min exposure, the reduction in compressive strength was 18.5%, 23.3% and 14.1% for 5% replacement, 25% replacement and normal concrete, respectively. At 150^{o}C, the mass loss was similar for rubberized concrete and normal concrete as a result of water loss due to evaporation while over than 300^{o}C, the mass loss was higher in case of rubberized concrete than normal concrete as a result of voids occurrence in the mix due to decomposition of rubber fibre. At 300^{o}C for 120 min exposure, the reduction in static modulus was 46.1%, 49.2% and 45.7% for 5% replacement, 25% replacement and normal concrete, respectively. At 300^{o}C for 120 min exposure, the reduction in dynamic modulus was 61.3%, 63.6% and 60.5% for 5% replacement, 25% replacement and normal concrete, respectively. For permeability of chloride ion and water penetration depth, they outlined that at 300^{o}C for 120 min exposure, permeability increased with the increase in rubber content. Via microscopic analysis, they observed that the gap at interface of cement matrix and rubber fibre increased with the increase in temperature. Fawzy et al. [48] studied rubberized concrete by replacement of fine aggregate with crumb rubber. The replacement ratios of fine aggregate were 4%, 8%, 12% and 16%. They showed that at 70 ^{o}C and 200^{o}C, the surface of the specimen didn't show any cracks. At 400^{o}C, there were micro-cracks on the surfaces of all specimens. They outlined that the highest loss in compressive strength occurred in range of 200^{o}C to 400 ^{o}C as a result of C-S-H decomposition. They showed a reduction in splitting tensile strength after exposure to elevated temperature. The reduction in splitting strength was up to 16%, 27% and 32.9% at 70^{o}C, 200^{o}C and 400^{o}C, respectively, in comparison with normal concrete. They outlined reduction in flexural strength of rubberized concrete at elevated temperatures. The reduction in flexural strength was up to 15.6%, 37.3% and 43.45% at 70^{o}C, 200^{o}C and 400^{o}C, respectively, in comparison with normal concrete.

4.2.9. Acid and sulfate properties

Thomas et al. [49] studied the acid resistance of rubberized concrete mixes. The results showed that the rubberized concrete specimens attacked by acid exhibited higher water absorption than in case of ordinary concrete mix and this increase was directly proportional to the rubber content. Specimens of ordinary concrete exhibited removal of the top layer as a result of sulfuric acid action. In case of specimens with 20% crumb rubber, the top layer wasn't removed totally. The rubber particles and cement paste around them weren't affected by the acid. Yung et al. [39] studied the corrosion of rubberized concrete due to sulfate. In order to carry out the test, alternative wetting and drying cycles to sulfate were performed. The results showed that with the increase in the exposure period, the loss in weight increased. They elucidated that rubberized concrete mix of 5% rubber proportion passing through #30 sieve had the best sulfate media resistance.

4.2.10. Chloride penetration

Oikonomou and Mavridou [6] showed that the increase in rubber content in rubberized concrete led to a decrease in the chloride ion penetration. They used two proportions of rubber contents; 2.5% and 15%. This led to reduction in chloride ion penetration by 14.22% and 35.85%, respectively, in comparison with normal concrete mix. Bravo and Brito [2] concluded that increasing of rubber particles size led to an increase in the rubberized concrete resistance against chloride penetration. They observed that using rubber particles produced by cryogenic technique had lower resistance against chloride penetration than rubberized concrete with mechanically ground rubber particles. Gesoglu and Guneyisi [4] studied self-compacting rubberized concrete. They showed that the increase in rubber content led to reduction in the chloride resistance while adding fly ash to the rubberized concrete mix increased the chloride resistance. The chloride permeability decreased by 67%, 79% and 78% in cases of adding 20%, 40% and 60% of fly ash to the rubberized concrete, respectively, after 90 days curing.

4.2.11. Impact resistance and Fracture toughness

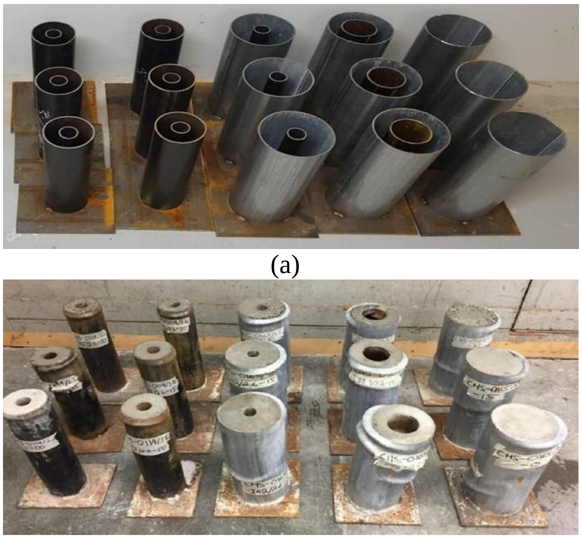
Hernández-Olivares et al. [50,51] studied static and dynamic behaviour of recycled tyre rubber-filled concrete. They showed that according to stability of cement-rubber interface, the optimum content of crumb rubber fibre was 5%. This case exhibited better damping capacity with no high variation in mechanical features of concrete. Taha et al. and Khaloo et al. [52,53] showed that rubberized concrete mixes toughness increased with the rubber content up to 25%. They outlined that over this ratio, toughness decreased as a result of the strength decrease. Sallam et al. [54] studied three rubberized concrete mixes with 10%, 20% and 30% replacement of sand volume with crumb rubber. They showed that existence of small size grains of rubber in the concrete mix increased the mix resistance against crack initiation under impact load. The failure mode of rubberized concrete with rubber grains of small size and the failure mode of normal concrete were the same under static and impact compression. Mubaraki et al. [55] studied the effect of replacing 10% of fine aggregate volume with crumb rubber on fracture toughness, crack path and crack initiation angle. They used Centre cracked circular disc specimen (CCCD). They showed that the location of crack initiation in notched CCCD specimen was found using numerical and experimental investigation at the point of the longest vertical coordinate on the notch surface for different inclination notch angle. They outlined that increasing the specimen thickness led to an increase in the normalized mode I stress intensity factor at the specimen mid plane. They observed that the plane stress fracture toughness wasn’t influenced by the replacement of 10% fine aggregate volume with rubber grains. Sukontasukkul et al. [56] studied double-layer concrete panels subjected to direct fire weapon to investigate the impact resistance. The panels consisted of rubberized and steel fibre reinforced concrete. They used the crumb rubber concrete layer to be subjected to the impact. They showed that the crumb rubber concrete layer could act as a cushion layer to absorb and dissipate the impact energy that led to reduction in the impact force exerted to the steel fibre reinforced concrete plate. Kaewunruen et al. [57] studied high-strength rubberized concrete by replacement of fine aggregate with micro-scale crumb rubber. They showed that crumb rubber improved the concrete’s damping ratio. They outlined that using crumb rubber of 180 and 400 micro led to the best improvement in comparison with normal concrete. They recommended to use crumb rubber in concrete as a micro-filler. AbdelAleem et al. [58] studied Self-Consolidating Rubberized Concrete (SCRC) mixtures reinforced with Synthetic Fibres (SFs) to investigate the impact resistance and mechanical properties. They outlined that adding SFs to SCRC mixtures enhanced the resistance of drop-weight impact and the resistance of flexural impact tests. They observed that using longer fibres enhanced the impact resistance.

5. Rubberized concrete in structural members

Rubberized concrete can be used in structural elements to get benefits of its outstanding properties prior to ordinary concrete. It can increase the ductility of structural elements and energy absorption. In case of structural elements in seismic areas, ductile behaviour has great importance and this can be guaranteed by using rubberized concrete. CFST elements can be designed with rubberized concrete core to increase the ductile behaviour of the elements with attaining acceptable bearing capacity of elements. Confining provided by the steel tube to the rubberized concrete core can enhance the overall behaviour of the RUCFST elements. Several researches studied using of rubberized concrete in structural elements. Duarte et al. [59] studied short (RUCFST) using recycled scrap tires to produce rubberized concrete mix. They used rubber grains with size 4 mm to 11.2 mm as replacement of various proportions of total aggregate volume. The results showed that rubberized concrete core led to an increase in the specimens’ ductility and a decrease in their strength. Youssf et al. [60] studied rubberized concrete produced using crumb rubber with and without confining by (FRP). Rubber particles which were used to produce the concrete mixes had two sizes of 1.18 mm and 2.36 mm as replacement of fine aggregate volume. The rubber crumbs were treated by NaOH solution before adding to the concrete mix. Six concrete mixes with different rubber portions as replacement of fine aggregate volume were produced. The results showed that using FRP sheets decreased effectively the loss in strength due to rubber addition, while it maintained the increased ductility caused by the rubber addition.

Liu et al. [61] studied analytically the RUCFST columns under cyclic loading. They presented charts relating load-lateral displacement relation, in addition to rigidity degradation curves. The results showed that increasing rubber content in the concrete mix led to a noticeable loss in the ultimate strength of the columns. However, it was observed that the effect of rubber content on the rigidity decay curves was moderate. Abendeh et al. [62] concerned mainly about studying the slippage behaviour of the rubberized concrete core inside the steel tube of the RUCFST sections. They performed push-out tests to measure the slippage. They noticed increase in the fresh concrete workability and reduction in the compressive strength of the rubberized concrete cores with increasing the rubber content. The results of the push-out test elucidated that circular cross sections were more efficient in providing bond strength than square cross sections. The loss in bond in case of square cross sections increased with the increase in the size of the section. Elchalakani et al. [63] presented an experimental study on short double-skin circular steel columns filled with rubberized concrete with different contents of rubber as shown in Fig. 2. Before adding rubber to the concrete mix, it was treated using NaOH. This led to an improvement of the bond between the concrete mix components and the added rubber. In addition, this led to a decrease in the segregation that might occur during concreting. The results showed that the ultimate compressive strength in case of rubberized concrete with 15% and 30% rubber content was lower than that of normal concrete mix by 50% and 79%, respectively. The results showed that adding of rubber to the concrete increased the ductility of the concrete filled steel tube up to 250 %. Cold-formed circular hollow steel tubes improved the ultimate strength as a result of confining effect. They recommended using concrete filled double skin steel tubes with rubberized concrete in structural members specially columns in seismic zones.

Jiang et al. [64] studied experimentally specimens of steel tubes filled with rubberized concrete and normal concrete to analyse the differences in the behaviour of the two types. A number of 36 specimens were tested experimentally. The main studied parameters were cross section geometry including circular, rectangular and square cross sections, the slenderness of the cross section and the rubber content. All specimens were tested under cyclic and monotonic lateral loads with normalized axial loads at several levels. The results showed that the concrete core provided efficient restraining of steel tubes against occurrence of local buckling. Thus, preventing premature failure that might occur due to local buckling. It was observed that the concrete damage controlled the ductility of the specimens. The cross-section slenderness had a great effect on the occurrence of the concrete damage which in turn influenced the ductility of the specimens.



(a) (b)

Fig. 2. Double-skin circular columns. (a) Steel tubes used and (b)Steel tubes filled with rubberized concrete [63].

The previous literature review shows some characteristics of rubberized concrete mix that are mainly ductility increase, sound absorption and light weight that is directly proportional to the rubber content in the concrete mix. Mechanical manufactured rubber particles can be used without treatment, while recycling rubber particles from waste tires may need to be treated by NaOH solution before using in the concrete mix to eliminate any Zinc stearate layers that may be produced during the tire manufacturing process. Treatment with NaOH solution can enhance the cohesion between the rubber and cement as this process makes the surface of rubber rough and porous. A lot of studies and researches tried to enhance the decreased strength and stiffness of rubberized concrete. Confining concrete with FRP can enhance the characteristics of the rubberized concrete.

6. Current research

Elshazly et al. [65] studied rubberized concrete mixes as a concrete core for short deficient concrete filled steel tubular columns with circular section under axial compressive load. In this study, mechanically manufactured rubber particles were used with grains size ranged from 1 to 3 mm as a replacement of fine aggregate volume as shown in

Fig. 3. Three different concrete mixes in proportion of rubber content of 0%, 5% and 15% to study the effect of rubberized concrete on ductility and ultimate bearing capacity of columns were investigated. Compressive strength of the different concrete mixes was obtained by testing standard concrete cubes as shown in Fig.4. FRP sheets were used to strengthen the deficient specimens to compensate the lost strength and eliminate the premature failure. Strengthening techniques included FRP type; Carbon Fibre Reinforced Polymers (CFRP) or Glass Fibre Reinforced Polymers (GFRP), number of FRP layers and orientation of fibres. Twenty-three specimens were studied including three concrete filled steel tubular columns with concrete mix of 0%,5% and 15% rubber content as control specimens. Twenty other specimens with transversal or longitudinal deficiency including 10 specimens with 5% rubber content in the concrete mix and 10 specimens with 15% rubber content in the concrete mix as shown in Fig.5.

Fig. 3. Rubber grains.

Fig. 4. Standard cubes after 28 days of curing.

(a)

(b)

Fig. 5. Tested specimens with normal concrete and rubberized concrete. (a) Bare specimens and (b) Strengthened specimens with CFRP or GFRP sheets [65].

The results of the study showed that adding rubber to the concrete mix enhanced the ductility of short rubberized concrete filled steel tubular columns. However, it decreased the ultimate bearing capacity of the tested columns comparing with normal concrete. Strengthening with FRP sheets enhanced the ultimate bearing capacity according to the number and orientation of the strengthening layers.

7. Conclusion

- The increase in rubber particles content leads to a decrease in the density of the concrete mix and this loss in density increases severely in case of using powdered rubber. As a result of reduced density, rubberized concrete can be produced in lightweight mixes to meet the requirements of several applications.
- Rubberized concrete has lower compressive strength in comparison with normal concrete mixes. The loss in compressive strength can be acceptable if the replacement of total aggregate content with rubber doesn’t exceed 20%. Over this ratio, severe reduction in the compressive strength is noticed. Treating rubber particles with any coupling agents can reduce the loss in compressive strength.
- Increasing rubber content in rubberized concrete mix increases abrasion resistance, water absorption and shrinkage. It enhances freezing and thawing resistance and sound isolation.
- Rubberized concrete exhibits lower modulus of elasticity than that of normal concrete mix. The reduction in modulus of elasticity increased with the increase in the rubber content. Using of coated rubber with a saline coupling agent in the rubberized concrete mix produces higher modulus of elasticity than in case of using uncoated rubber.
- Rubberized concrete has good resistance against acid attack. It has also high resistance against

penetration of chloride ion.

- Confining rubberized concrete either by steel tubes or FRP can enhance its ultimate strength with maintaining the ductility gained from adding rubber. Using rubberized concrete in structural members is an effective way to enhance their ductility which is so important for structural members specially in seismic areas.

References

[1] Rubber Manufacturer's Association. USA; 2014.
[2] Bravo, M. and De Brito, J., 2012. Concrete made with used tyre aggregate: durability-related performance. Journal of Cleaner Production, 25, pp.42-50.
[3] Benazzouk, A., Douzane, O., Mezreb, K. and Quéneudec, M., 2006. Physico-mechanical properties of aerated cement composites containing shredded rubber waste. Cement and Concrete Composites, 28(7), pp.650-657.
[4] Gesoğlu, M. and Güneyisi, E., 2011. Permeability properties of self-compacting rubberized concretes. Construction and Building Materials, 25(8), pp.3319-3326.
[5] Mohammed, B.S., Hossain, K.M.A., Swee, J.T.E., Wong, G. and Abdullahi, M., 2012. Properties of crumb rubber hollow concrete block. Journal of Cleaner Production, 23(1), pp.57-67.
[6] Oikonomou, N. and Mavridou, S., 2009. Improvement of chloride ion penetration resistance in cement mortars modified with rubber from worn automobile tires. Cement and Concrete Composites, 31(6), pp.403-407.
[7] Segre, N. and Joekes, I., 2000. Use of tire rubber particles as addition to cement paste. Cement and Concrete Research, 30(9), pp.1421-1425.
[8] Tomosawa, F., Noguchi, T. and Tamura, M., 2005. The way concrete recycling should be. Journal of Advanced Concrete Technology, 3(1), pp.3-16.
[9] Ganjian, E., Khorami, M. and Maghsoudi, A.A., 2009. Scrap-tyre-rubber replacement for aggregate and filler in concrete. Construction and Building Materials, 23(5), pp.1828-1836.
[10] Benazzouk, A., Douzane, O., Mezreb, K. and Quéneudec, M., 2006. Physico-mechanical properties of aerated cement composites containing shredded rubber waste. Cement and Concrete Composites, 28(7), pp.650-657.
[11] Benazzouk, A., Douzane, O., Mezreb, K., Laidoudi, B. and Quéneudec, M., 2008. Thermal conductivity of cement composites containing rubber waste particles: Experimental study and modelling. Construction and Building Materials, 22(4), pp.573-579.
[12] Fernández-Ruiz, M.A., Gil-Martín, L.M., Carbonell-Márquez, J.F. and Hernández-Montes, E., 2018. Epoxy resin and ground tyre rubber replacement for cement in concrete: Compressive behaviour and durability properties. Construction and Building Materials, 173, pp.49-57.
[13] Al-Tayeb, M.M., Abu Bakar, B.H., Akil, H.M. and Ismail, H., 2012. Effect of partial replacements of sand and cement by waste rubber on the fracture characteristics of concrete. Polymer-Plastics Technology and Engineering, 51(6), pp.583-589.
[14] Al-Tayeb, M.M., Bakar, B.A., Ismail, H. and Akil, H.M., 2012. Impact resistance of concrete with partial replacements of sand and cement by waste rubber. Polymer-Plastics Technology and Engineering, 51(12), pp.1230-1236.
[15] Fattuhi, N.I. and Clark, L.A., 1996. Cement-based materials containing shredded scrap truck tyre rubber. Construction and building materials, 10(4), pp.229-236.
[16] Kang, J., Zhang, B. and Li, G., 2012. The abrasion-resistance investigation of rubberized concrete. Journal of Wuhan University of Technology-Mater. Sci. Ed., 27(6), pp.1144-1148.
[17] Holmes, N., Browne, A. and Montague, C., 2014. Acoustic properties of concrete panels with crumb rubber as a fine aggregate replacement. Construction and Building Materials, 73, pp.195-204.
[18] Dong, Q., Huang, B. and Shu, X., 2013. Rubber modified concrete improved by chemically active coating and silane coupling agent. Construction and Building Materials, 48, pp.116-123.
[19] Su, H., Yang, J., Ling, T.C., Ghataora, G.S. and Dirar, S., 2015. Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes. Journal of Cleaner Production, 91, pp.288-296.
[20] Aiello, M.A. and Leuzzi, F., 2010. Waste tyre rubberized concrete: Properties at fresh and hardened state. Waste management, 30(8-9), pp.1696-1704.
[21] Elchalakani, M., 2015, February. High strength rubberized concrete containing silica fume for the construction of sustainable road side barriers. In Structures (Vol. 1, pp. 20-38).
[22] Khatib, Z.K. and F.M. Bayomy, 1999. Rubberized Portland cement concrete. J. Mater. Civil. Eng. ASCE, 11: 206-213.
[23] Gesoğlu, M., Güneyisi, E., Khoshnaw, G. and İpek, S., 2014. Investigating properties of pervious concretes containing waste tire rubbers. Construction and Building Materials, 63, pp.206-213.
[24] Gesoğlu, M., Güneyisi, E., Khoshnaw, G. and İpek, S., 2014. Abrasion and freezing–thawing resistance of pervious concretes containing waste rubbers. Construction and Building Materials, 73, pp.19-24.
[25] Pelisser, F., Zavarise, N., Longo, T.A. and Bernardin, A.M., 2011. Concrete made with recycled tire rubber: effect of alkaline activation and silica fume addition. Journal of Cleaner Production, 19(6-7), pp.757-763.
[26] Pacheco-Torgal, F., Ding, Y. and Jalali, S., 2012. Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): An overview. Construction and Building Materials, 30, pp.714-724.
[27] Eldin, N.N. and A.B. Senouci, 1993. Rubber-tire particles as concrete aggregate. J. Mater. Civil. Eng. ASCE, 5: 478-496.
[28] Schimizze, R., J. Nelson, S. Amirkhanian and J. Murden, 1994. Use of waste rubber in light-duty concrete pavements. In: Proceedings of ASCE 3rd Material Engineering Conference Infrastructure: New Material and Methods of Repair, San Diego, CA pp: 367-374.
[29] Gregory GRRICK, 2004. Analysis of waste tire modified concrete. In: 2004 ME Graduate Student Conference, Louisiana State University.
[30] Kaloush, K.E., Way, G.B. and Zhu, H., 2005. Properties of crumb rubber concrete. Transportation Research Record, 1914(1), pp.8-14.
[31] Serge, N. and I. Joekes, 2000. Use of tire rubber particles as addition to cement paste. Cem. Concr. Res., 30: 1421-1425.
[32] Hernandez-olivares, F., G. Barluenga, M. Bollati and B. Witoszek, 2002. Statics and dynamic behaviuour of recycled tyre rubber-filled concrete. Cem. Concr. Res., 32: 1587-1596.
[33] Yilmaz, A. and Degirmenci, N., 2009. Possibility of using waste tire rubber and fly ash with Portland cement as construction materials. Waste Management, 29(5), pp.1541-1546.
[34] Ganesan, N., Raj, J.B. and Shashikala, A.P., 2013. Flexural fatigue behavior of self-compacting rubberized concrete. Construction and Building Materials, 44, pp.7-14.
[35] Sukontasukkul, P. and Chaikaew, C., 2006. Properties of concrete pedestrian block mixed with crumb rubber. Construction and Building Materials, 20(7), pp.450-457.
[36] Gupta, T., Chaudhary, S. and Sharma, R.K., 2014. Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate. Construction and Building Materials, 73, pp.562-574.

[37] Onuaguluchi, O. and Panesar, D.K., 2014. Hardened properties of concrete mixtures containing pre-coated crumb rubber and silica fume. Journal of Cleaner Production, 82, pp.125-131.
[38] Azevedo, F., Pacheco-Torgal, F., Jesus, C., De Aguiar, J.B. and Camões, A.F., 2012. Properties and durability of HPC with tyre rubber wastes. Construction and building materials, 34, pp.186-191.
[39] Yung, W.H., Yung, L.C. and Hua, L.H., 2013. A study of the durability properties of waste tire rubber applied to self-compacting concrete. Construction and Building Materials, 41, pp.665-672.
[40] Sukontasukkul, P. and Tiamlom, K., 2012. Expansion under water and drying shrinkage of rubberized concrete mixed with crumb rubber with different size. Construction and Building Materials, 29, pp.520-526.
[41] Zhu, X., Miao, C., Liu, J. and Hong, J., 2012. Influence of crumb rubber on frost resistance of concrete and effect mechanism. Procedia Engineering, 27, pp.206-213.
[42] Al-Akhras, N.M. and Smadi, M.M., 2004. Properties of tire rubber ash mortar. Cement and Concrete Composites, 26(7), pp.821-826.
[43] Topçu, İ.B. and Bilir, T., 2009. Experimental investigation of some fresh and hardened properties of rubberized self-compacting concrete. Materials & Design, 30(8), pp.3056-3065.
[44] Topçu, İ.B. and Bilir, T., 2007. Effects of slag fineness on durability of mortars. Journal of Zhejiang University-SCIENCE A, 8(11), pp.1725-1730.
[45] Ünlüoğlu, E., Topçu, İ.B. and Yalaman, B., 2007. Concrete cover effect on reinforced concrete bars exposed to high temperatures. Construction and Building Materials, 21(6), pp.1155-1160.
[46] Ocholi, A., Ejeh, S.P. and Yinka, S.M., 2014. An investigation into the thermal performance of rubber-concrete. Academic Journal of Interdisciplinary Studies, 3(5), p.29.
[47] Gupta, T., Siddique, S., Sharma, R.K. and Chaudhary, S., 2017. Effect of elevated temperature and cooling regimes on mechanical and durability properties of concrete containing waste rubber fiber. Construction and Building Materials, 137, pp.35-45.
[48] Fawzy, H.M., Mustafa, S.A. and Abd El Badie, A.E.S., 2020. Effect OF Elevated Temperature on Concrete Containing Waste Tires Rubber. The Egyptian International Journal of Engineering Sciences & Technology, 29, pp.1-13.
[49] Thomas, B.S., Gupta, R.C., Mehra, P. and Kumar, S., 2015. Performance of high strength rubberized concrete in aggressive environment. Construction and Building Materials, 83, pp.320-326.
[50] Hernández-Olivares, F., Barluenga, G., Parga-Landa, B., Bollati, M., and Witoszek, B., (2007). Fatigue Behaviour of Recycled Tyre Rubber-Filled Concrete and Its Implications in the Design of Rigid Pavements, Construction and Building Materials, No. 21, pp. 1918–1927.
[51] Hernández-Olivares, F., Barluenga, G., Bollati, M., and Witoszek, B., (2002). Static and dynamic Behaviour of Recycled Tyre Rubber-Filled Concrete, Cement and Concrete Research, No. 32, pp. 1587–1596.
[52] Taha MMR, Asce M, El-Dieb AS, Abd El-484 Wahab MA, Abdel-Hameed ME, (2008). Mechanical, fracture, and microstructural investigations of rubber concrete. J Mater Civ Eng 20(10):640–649.
[53] Khaloo AR, Dehestani M, Rahmatabadi P, (2008). Mechanical properties of concrete containing a high volume of tire–rubber particles. Waste Manag 28(12):2472–2482.
[54] Sallam, H.E.M., Sherbini, A.S., Seleem, M.H. and Balaha, M.M., 2008. Impact resistance of rubberized concrete. Engineering Research Journal, 31(3), pp.265-271.
[55] Mubaraki, M., Abd-Elhady, A.A. and Sallam, H.E.M., 2013. Mixed mode fracture toughness of recycled tire rubber-filled concrete for airfield rigid pavements. International Journal of Pavement Research and Technology, 6(1), pp.8-14.
[56] Sukontasukkul, P., Jamnam, S., Sappakittipakorn, M. and Banthia, N., 2014. Preliminary study on bullet resistance of double-layer concrete panel made of rubberized and steel fiber reinforced concrete. Materials and structures, 47(1-2), pp.117-125.
[57] Kaewunruen, S., Li, D., Chen, Y. and Xiang, Z., 2018. Enhancement of dynamic damping in eco-friendly railway concrete sleepers using waste-tyre crumb rubber. Materials, 11(7), p.1169.
[58] AbdelAleem, B.H., Ismail, M.K. and Hassan, A.A., 2018. The combined effect of crumb rubber and synthetic fibers on impact resistance of self-consolidating concrete. Construction and Building Materials, 162, pp.816-829.
[59] Duarte, A.P.C., Silva, B.A., Silvestre, N., De Brito, J., Júlio, E. and Castro, J.M., 2016. Tests and design of short steel tubes filled with rubberised concrete. Engineering Structures, 112, pp.274-286.
[60] Youssf, O., Hassanli, R. and Mills, J.E., 2017. Mechanical performance of FRP-confined and unconfined crumb rubber concrete containing high rubber content. Journal of Building Engineering, 11, pp.115-126.
[61] Liu, Y.H., Bai, Y.K. and Jiang, G.H., 2011. Analytical behavior of rubber concrete-filled steel tubular columns under cyclic loading. In Applied Mechanics and Materials (Vol. 94, pp. 123-126).
[62] Abendeh, R., Ahmad, H.S. and Hunaiti, Y.M., 2016. Experimental studies on the behavior of concrete-filled steel tubes incorporating crumb rubber. Journal of Constructional Steel Research, 122, pp.251-260.
[63] Elchalakani, M., Hassanein, M.F., Karrech, A., Fawzia, S., Yang, B. and Patel, V.I., 2018, August. Experimental tests and design of rubberised concrete-filled double skin circular tubular short columns. In Structures (Vol. 15, pp. 196-210).
[64] Jiang, Y., Silva, A., Castro, J.M. and Monteiro, R., 2015. Experimental assessment of the behaviour of rubberized concrete filled steel tube members. International Conference on Behavior of Steel Structures in Seismic Areas, Shanghai, China.
[65] Elshazly F. A., Mustafa S. A. A., Shaban H. F., 2020. Strengthening deficient rubberized CFST short columns using FRP composites. Journal of construction and building materials (under publication).