CHAPTER 2

LITERATURE REVIEW

3.1. INTRODUCTION

Concrete is the dominated material used in the field of construction due its unique characteristics comparing to other material like steel, timber, asphalt and stone. Approximately 1.8 billion pounds is spent annually in the United Kingdom on concrete products, 600 million pounds is spent on building blocks and bricks and the other 400 million pound as fabricated structural components [2]. Concrete is a composite of filler materials, usually from natural aggregates, and cement paste as a binder. Its characteristics can vary widely due to the properties of its components and the mix design parameters. However, concrete is characterized by its versatility in applications, low cost, high durability and high mechanical strength. Moreover, the ability to be cast into any desired shape and configuration is the most important characteristics of concrete, which overcomes the shortage in other characteristics comparing to other construction materials [5].

Also, concrete have a good durability and should remain maintenance free for many years, if it has high quality fabrication and a proper mix design to resist the surrounding environmental conditions. The versatility in applications for concrete means that the design of the concrete mix can be modified, or even some additives can be used, to enhance specific properties of concrete to be suitable for the desired application. For instance, it can be designed to be resistance to chemical attacks, such as sulfate or acids. Also, it can be modified to resist cycles of freezing and thawing or from abrasion. Also concrete is excellent material for fire resistance, as it can maintain its structural integrity for a considerable period of time comparing to other materials like steel and timber.

Aggregates represent the major constituent of the bulk of the concrete mixture, about 50% to 80% of the volume of conventional concrete, so its properties affect the characteristics of the final product. Mehta and Monteiro [5] stated that, aggregates have been customarily treated as inert filler material in concrete, but due to the increasing awareness of the rule played by aggregates in determining many properties of concrete, the traditional view of the role played by aggregates as inert filler has been changed. Some characteristics of the used aggregates are required to control the properties of the resulted concrete. The characteristics of aggregates that affect concrete are; density, grading, moisture state, porosity, shape and surface texture. The crushing strength, hardness, elastic modulus and soundness of aggregates, have major effect on the durability properties of hardened concrete.

In spite of the beneficial characteristics of concrete, it has some weaknesses that limit its use in specific applications. Concrete is brittle material with very low tensile strength, so concrete is generally not loaded in tension as reinforcing steel is used to carry the tensile loads. Concrete also has low ductility, which means that it has low impact strength and even low toughness comparing to metals. Several solutions were produced to the construction industry to improve these characteristics. These solutions include; fiber reinforced concrete, latex modified concrete and finally rubberized concrete. The idea is to include other materials to concrete rather than natural aggregates, to improve its ductility.

This research focuses on developing a solution by using rubber particles to improve the weakness of concrete in impact resistance and toughness, and maintain an acceptable mechanical strength.

3.2. WASTE TIRES IN DIFFERENT COUNTRIES

Solid waste management is one of the major environmental concerns in the world. Each year millions of tires are generated worldwide. Landfills have been one of the most convenient ways of disposing waste tires. Tires are extremely durable and not naturally biodegradable, so they will remain in landfills with little degradation over time. Waste tires stock piles are dangerous and considered a potential environmental threat due to the fire hazards and creating a breeding ground for rats, mice and mosquitoes.

According to RMA (rubber manufacture association) [1], about 265.8 million scrap tires were produced in the United States in 2011 and more than 80 million tires are currently in stock piles. The quantity and types of waste tires produced in 2011 in the U.S is shown in Table 2.1

Table 2.1 The quantity and types of waste tires produced in 2011 in the U.S.

Tire class	Millions of tires	Market percentage	Average weight of a tire (kg)	Weight (millions of tons)
Light Duty Tires (passenger tires and light truck tires)	237.8	89.5%	11	2.60
Commercial Tires (Medium, wide base, heavy truck tires and tires from scrapped trucks and buses)	28.0	10.50%	54.4	1.5

In the United Kingdom, it is estimated that 37 millions car and truck tires are being discarded annually and this number is set to increase with the growth in road traffic by 63% by 2021, Cairns [2]. According to the European Tire and Rubber Manufacturer's Association, over 3.2 million tons of used tires, about 220 million tires, were generated in 2010. According to Maciej Sienkiewicz [6], the annual global production of tires is about 1.4 billion tires, which corresponds to an estimated 17 million tones of used tires each year. The total worldwide production of waste tires represents 2% of total annual solid waste.

In Egypt there is no organized method to dispose waste tires by dumping in landfills or recycling, tires are generally disposed by burning which produce toxic gases that affect human health, the environment and waste energy. Figure 2.1 shows large quantities of scrap tires disposed at open areas across the country. According to The Cabinet, Information and Decision Support Center (IDSC) [4], the number of registered licensed vehicles in Egypt is 4.1 million vehicles in 2007. There is no authorized estimation in Egypt about the total amount of waste tires generated annually, but there no doubt that there is huge number of waste tires through the country.

According to The Cabinet, the number of registered licensed vehicles in Egypt is 4.1 million vehicles in 2007. Private cars represent about 56%, light and heavy trucks 27% and motorcycles about 17%. According to United States department of transportation, the number of registered vehicles in the United States In 2007 was 246.5 million vehicles, private cars represent about 55% of total vehicles, light and heavy trucks represent 42%, and motorcycles represent 2.5%. According to the estimation by the rubber manufactures association [1], approximately 259.1 million scrap tires were produced in the United States in 2009. As the percentages of cars and trucks is quite similar in Egypt and the United States, with a quick comparison between number of vehicles and generated scrap tires in the United States and number of vehicles in Egypt, the number of scrap tires generated in Egypt could be as about 4.3 million scrap tires annually. Thus, there are about 11,700 scrap tires are generated every day.

Through last decade rubber recycling business began to appear through small-companies that use mechanical techniques to shred tires by cutting to different sizes, but most of the companies suffered from the low demanding market for the recycled rubber. In addition, the full cutting mechanical system cost about 3.5 million Euros to produce rubber powder, which is highly required for rubber products. The feasibility studies of tire recycling projects are very promising, but more research is needed to open new market for scrap rubber obtained from waste tires.

3.3. COMPOSITION OF TIRES

Rubber is manufactured from natural and synthetic sources. Natural rubber is obtained from the milky white fluid called latex, found in many plants, while synthetic rubbers are produced from unsaturated hydrocarbons. According to United States Environmental Protection Agency (EPA) [7], a tire is a composite of complex elastomeric formulations, fibers, textiles and steel cord. Tires are made of plies of reinforcing cords extending transversely from bead to bead, on the top of which a belt is located below the thread. Figure 2.2 shows the components of regular car tire. The typical materials used in tire manufacturing are given in Table 2.2.

Figure 2.1 Waste tires in an open area

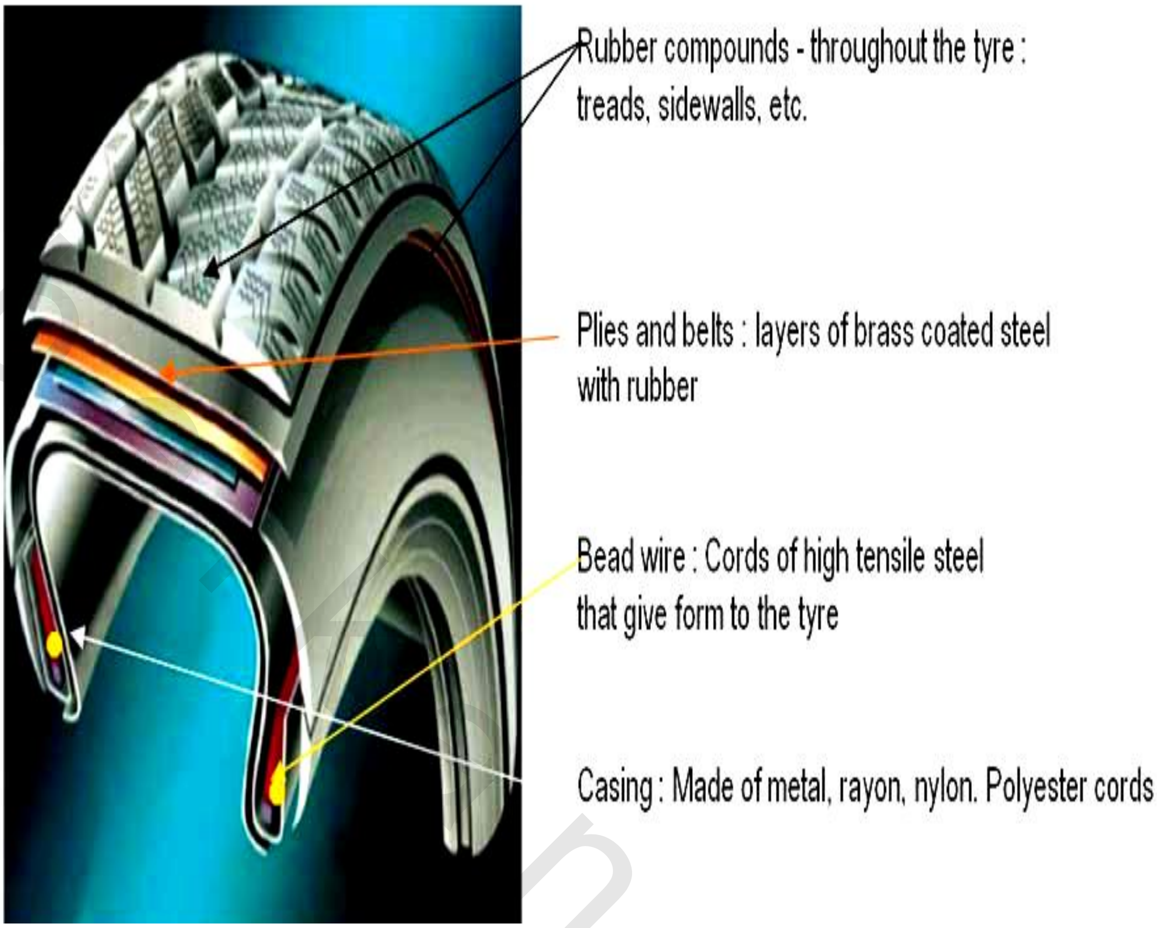


Figure 2.2 Components of regular car tire

Table 2.2 The typical materials used in tire manufacturing

Material	Passenger car	Trucks and buses
Rubber / Elastomers	48%	43%
Carbon black	22%	21%
Metal	15%	27%
Textile	5%	-
Zinc oxide	1%	2%
Sulphur	1%	1%
Additives	8%	6%

3.4. CLASSIFICATION OF SCRAP TIRES

According to Siddique & Naik [8] there are different types of waste rubber, which can be classified according to size to the following types; tire chips, ground rubber, crumb rubber, rubber powder and fibrous rubber. Rubber particles are obtained from waste tires by mechanical grinding or cryogenic processing. Mechanical grinding process consists of shredding the tire to smaller particles, magnetically separate steel fibers from rubber and separate textile fibers and dust by air. Moreover, the cryogenic processing is done by freezing rubber using liquid nitrogen, so the rubber turns to brittle state, then rubber is crushed by hammer to small particles. Mechanical grinding is the most common process due to the high cost of cryogenic process. Also, crumb rubber generated by mechanical grinding is more angular, while crumb rubber generated by cryogenic process is more granular in shape and smooth surface texture. Figure 2.3 shows the mechanical grinding process.

Figure 2.3 The mechanical grinding process.

3.4.1. Shredded and Chipped Tires

Tire shreds or chips involve only primary and secondary shredding. The size of the tire shreds produced in the primary shredding process can vary from as large as 300 to 460 mm long by 100 to 230 mm wide, down to as small as 100 to 150 mm in length, depending on the manufacturer's model and condition of the cutting edges [9]. Production of tire chips, normally sized from 76 mm to 13 mm, requires both primary and secondary shredding to achieve adequate size reduction. Figure 2.4 shows 20-30 mm tire chips.

Figure 2.4 20-30 mm rubber chips

3.4.2. Ground Rubber

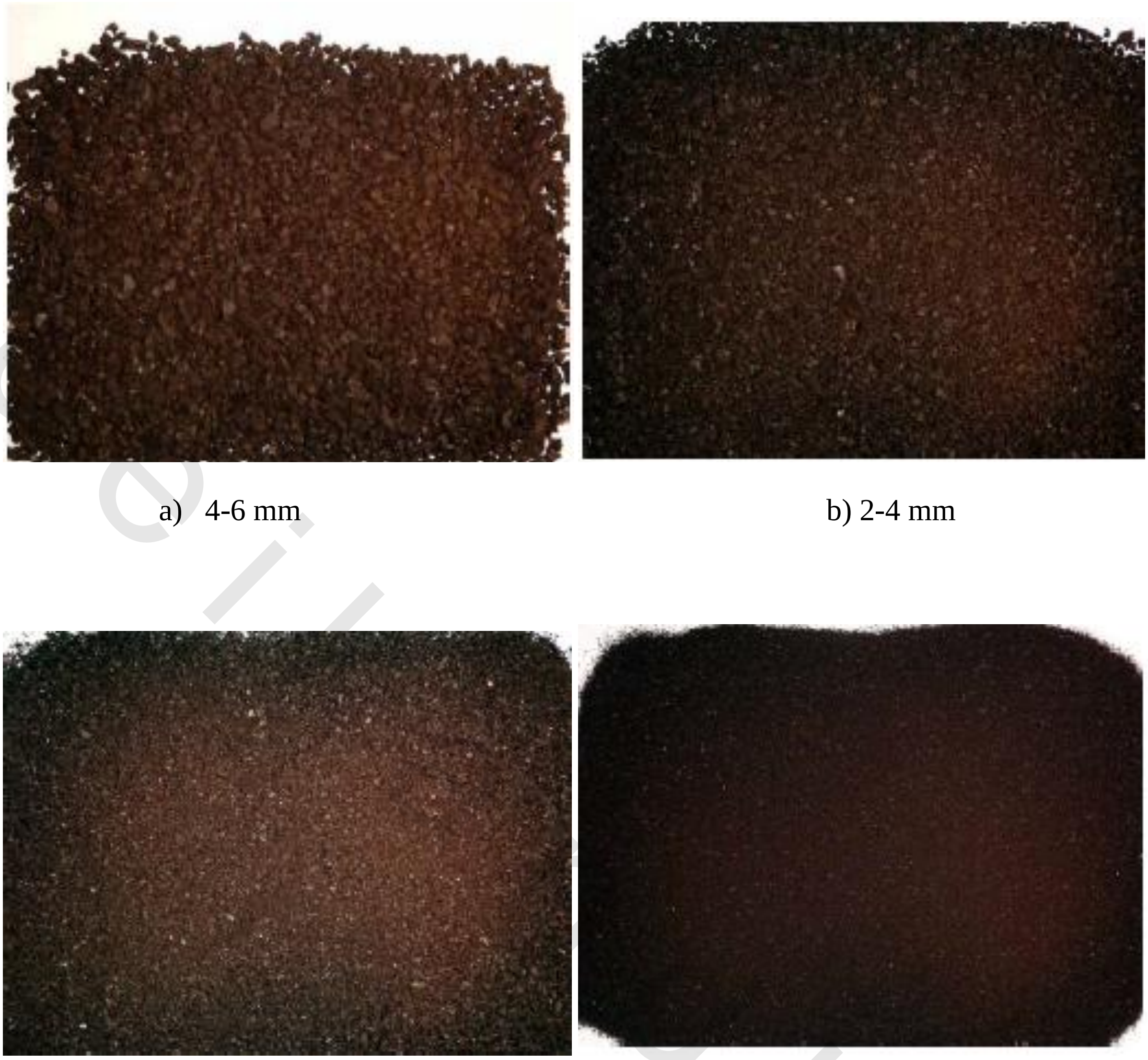
The size of ground rubber ranges from 0.15 mm (No. 100 sieve) to 19 mm (3/4 inch). It depends upon the type of size reduction equipment and intended applications. Ground rubber particles are subjected to a dual cycle of magnetic separation, then screened and recovered in various sizes [10]. Ground rubber of 10 mm size is shown in Figure 2.5.

3.4.3. Crumb Rubber and Rubber Powder

Crumb rubber and rubber powder consists of particles ranging in size from 4.75 mm (No. 4 Sieve) to less than 0.075 mm (No. 200 Sieve). Generally, cracker mill process, granular process and micro mill process are used to convert scrap tires into crumb rubber.

Figure 2.5 Rubber of 10 mm size

The cracker mill process tears apart or reduces the size of tire rubber by passing the material between rotating corrugated steel drums. By this process an irregularly shaped torn particles having large surface area are produced. The size of these particles varies from 5 mm to 0.5 mm (No. 4 to No. 40 Sieve), and are commonly known as ground crumb rubber. Granular process shears apart the rubber with revolving steel plates, producing granulated crumb rubber particles, ranging in size from 9.5 mm (3/8 inch) to 0.5 mm (No. 40 Sieve) [10]. Figure 2.6 shows different sizes of crumb rubber manufactured by mechanical processes.



a) 4-6 mm

b) 2-4 mm

b) 1.5-0.5 mm

d) 0.4 mm

Figure 2.6 Crumb rubber at different sizes

2.4.4 Fibrous Rubber

Fiber shaped rubber particles are generated as a byproduct of tires renewing process. The rubber is received as a bulk and the fibers are separated using mechanical grinding to different sizes. There is no known use of rubber fibers in the market, while it is very promising to use as an addition to concrete. Figure 2.7 shows different sizes of rubber fibers.

Figure 2.7 Different sizes of rubber fibers.

3.5. APPLICATIONS OF WASTE RUBBER

According to RMA (The Rubber Manufacture Association) [1], in 1990 about 17 % of existing rubber waste was recycled. Now this value reached about 80.4% in 2011. The progress of using recycled rubber was due to the new regulations as eliminating the storage areas for used tired (landfills) and encouraging the rubber recycling industry. Figure 2.8 shows the uses of waste tires in the U.S market. In 2011, markets for scrap tires were consuming 223 million, or 80.4%, of the 265.8 million annually generated scrap tires:

a) 37.7 % are used as tire-derived fuel

b) 24.5 % are converted into ground or crumb rubber and recycled into products and rubber-modified asphalt.

c) 8.9 % are recycled into cut/stamped/punched products and other uses.

d) 8 % are exported

e) 7.8 % are recycled or used in civil engineering projects

f) 13% are dumped in landfills.

In Egypt, there is no recognized methods to dispose used tired. Also, there are only few companies that work in waste rubber recycling, so there is a huge demand to encourage the rubber recycling industry in Egypt by stating new regulations concerning used tires.

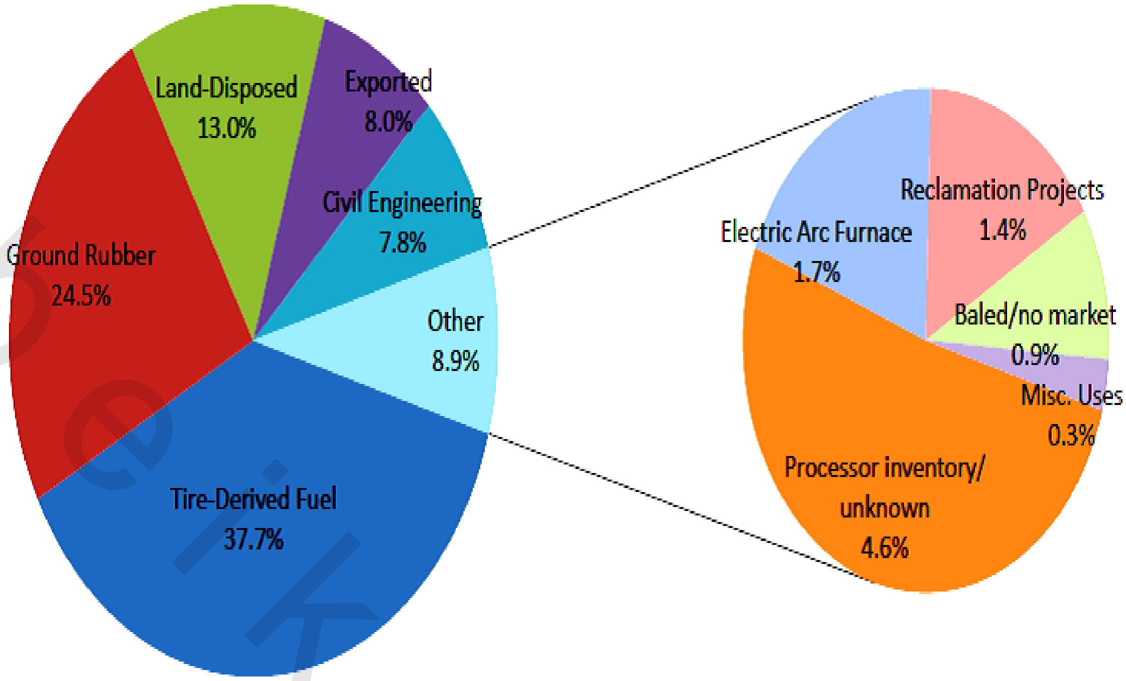


Figure 2.8 The uses of waste tires in the U.S market

3.5.1. Tire-Derived Fuel (TDF)

Scrap tires are used as fuel because of their high heating value. Using scrap tires as a fuel is not considered recycling, but it is considered a beneficial use. In 1991, about 11% of waste tires were used as tire derived fuel (TDF), and this value increased to 45% in 2003. Due to the environmental hazards, this value started to decrease and reached to 37% in 2011 [7].

There are several advantages to using tires as fuel:

- Tires produce the same amount of energy as oil and 25% more energy than coal;
- The ash residues from TDF may contain lower heavy metals content than some coals.

Many cases of opposition to TDF usage were reported earlier and are still being reported. Both whole and chipped tire burning is considered dangerous due to increased dioxin pollution. The use of waste tires as fuel is technically feasible but economically not very attractive [8]. The high cost of utilizing rubber as a fuel is caused by the chemical treatment procedures for the toxic emissions produced during the burning of TDF.

3.5.2. Civil Engineering Applications

Waste rubber, mostly 50 mm tire chips, can be used to replace conventional construction material, such as road fill, gravel, crushed rock or sand. The benefits of using tire chips instead of conventional construction materials are, amongst others, reduced density, improved drainage properties and good thermal insulation [7]. The methods listed below are examples of the successful uses of scrap tire chips in civil engineering applications:

3.5.2.1. Highway embankment fill

Rubber chips, which also known as tire derived aggregates, have proven to be a good solution for road embankment built on top of soft ground. The low unit weight of rubber reduces the weight of embankment, thereby reducing settlement if the embankment is on soft soil. Another application of rubber chips in highway embankment is insulation of sub-bases and bases from frost penetration in cold climates, as the thermal conductivity of rubber is much lower than that of common soils.

3.5.2.2. **Backfill behind retaining walls**

Rubber chips are used as light weight fill behind retaining walls to replace commonly used mineral aggregates or soil backfills. The low unit weight of rubber reduces the lateral earth pressure acting on the retaining walls, thus reducing the cost of the retaining wall. Also, rubber chips are a free drainage material and provide good frost insulation [11].

3.5.2.3. Landfill applications

Rubber chips are viable alternative for traditional landfill system components, as rubber has great thermal insulation, high internal friction and low unit weight.

The utilization of rubber waste in civil engineering applications has many drawbacks, which limit the recycling of rubber waste in that field. Generally, the shear strength of rubber chips is low against global stability failure (low resistance to horizontal forces), and the wires in the chips create some performance obstacles. Also, the potential release of contaminants from rubber chips may pose an environmental risk to public health if not properly addressed, as some investigations have shown that tire chips may leach out heavy metals when subjected to highly acidic solution with PH of 3.5 [12].

3.5.3. Ground Rubber Applications

Figure 2.9 shows the applications of ground rubber in the U.S in 2011.

3.5.3.1. **Athletic and recreational applications**

Examples and benefits of using scrap tires in this market segment include [1]:

- Ground cover under playground equipments, which possesses high impact attenuation/ability to absorb the energy from falling children and objects.

- Running track material, which increases a track’s resiliency and decreases stress on runners’ legs.

- Sports and playing fields – as a soil additive, increases the resiliency of the field thereby decreasing injuries, improves drainage, and enables better grass root structure.

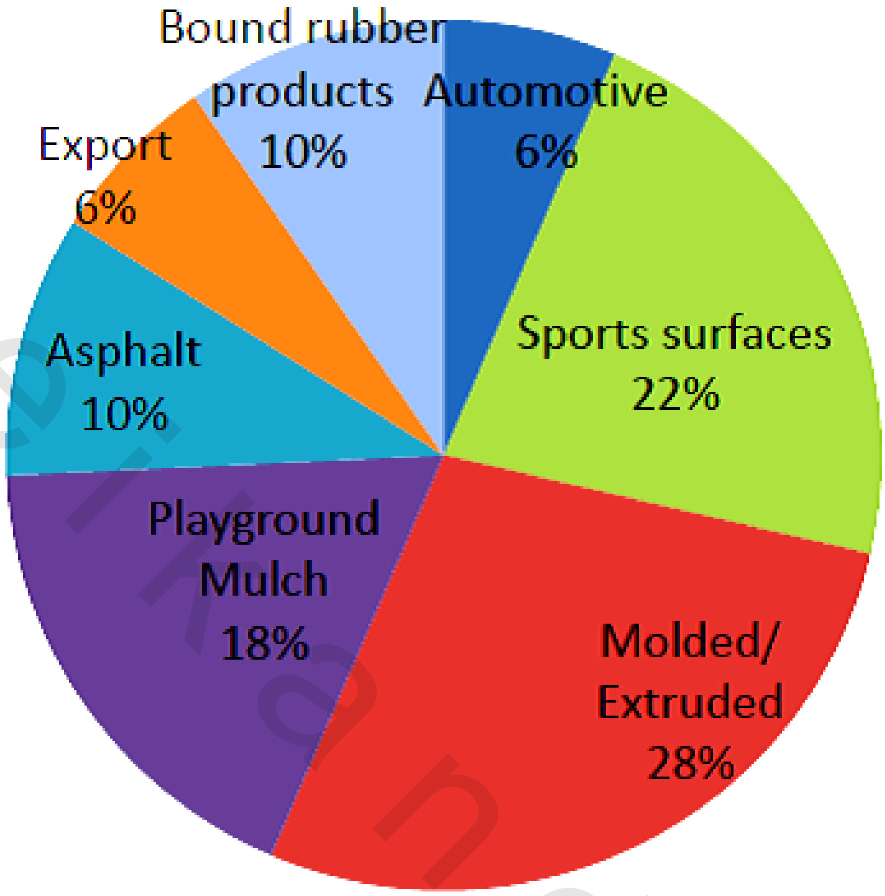


Figure 2.9 The applications of ground rubber in the U.S in 2011

3.5.3.2. Other uses of ground rubber

Examples of some products from waste rubber is shown in Figure 2.10

- Molded rubber products (e.g., carpet underlay, flooring materials, patio decks, railroad crossing blocks, livestock mats, roof walkway pads, rubber tiles and bricks, movable speed bumps).
- New tire manufacturing.
- Brake pads and brake shoes.
- Additive to injection molded and extruded plastics.
- Automotive parts.
- Agricultural and horticultural applications/soil amendments.
- Horse arena flooring.

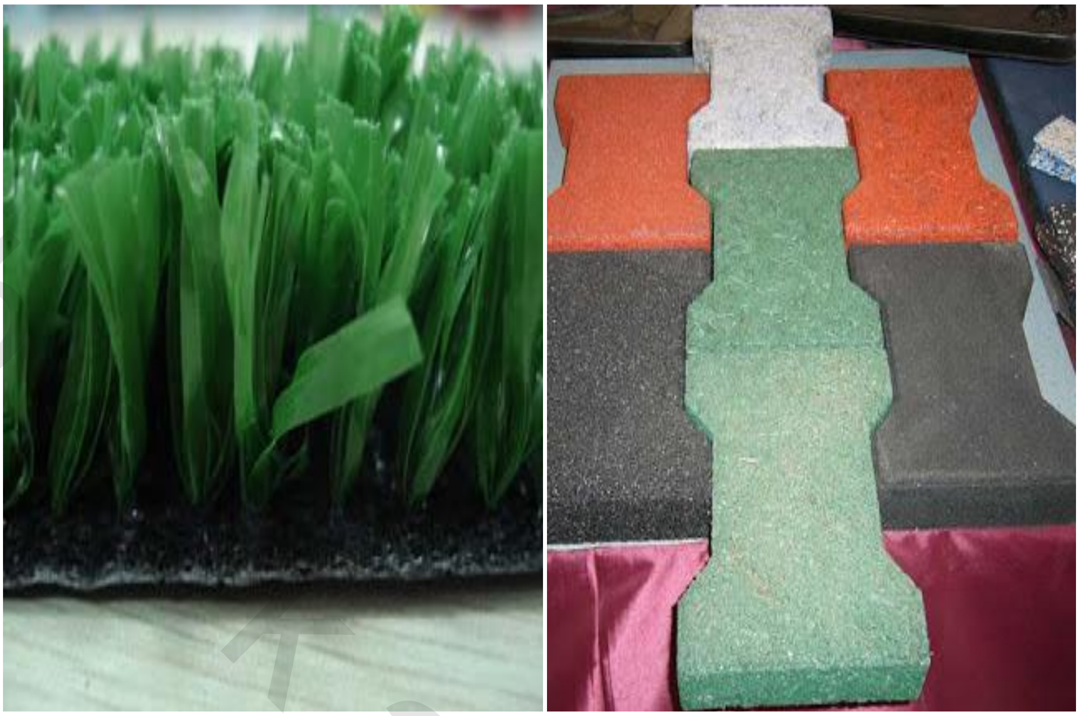


Figure 2.10 Examples on some products from waste rubber

3.5.3.3. Asphalt Rubber

Ground and crumb rubber, mostly 10 meshes and smaller are used in asphalt rubber. Asphalt rubber is a large market for ground rubber, consuming an estimated 12 million tires. California and Arizona use the most asphalt rubber in highway construction. Ground tire rubber can be blended with asphalt to beneficially modify the properties of the asphalt in highway construction. Size-reduced scrap tire rubber can be used either as part of the asphalt rubber binder and crack sealant or as an aggregate substitution (rubber modified asphalt concrete) [7].

Many investigations studied the use of waste rubber in asphalt mixes as binder enhancement or aggregate replacement [13-16]. Rubberized asphalt was actually conducted in several states in the USA, Furthermore, there is a road in Riyadh KSA was conducted using rubberized concrete. Utilizing rubber in asphalts mixes enhances durability, yields better skid resistance, reduces fatigue cracking and achieves longer pavement lifetime.

Benefits of using asphalt rubber include:

a) Higher durability for road surfaces;

b) Reduces road maintenance;

c) Cost effectiveness over the long term;

d) Lower road noise; and

e) Shorter breaking distances.

3.6. RUBBERIZED CONCRETE

As illustrated before in section 2.1, concrete has some weaknesses especially when impact resistance and toughness are required. To improve the ductility of concrete, implementation of rubber particles in concrete is studied by various investigations through the last decade. The difference between rubber particles and natural aggregates is that rubber particles are much more deformable than sand and coarse aggregate. Another difference is the low density of rubber particles, about $1.05t/m^3$ to $1.13t/m^3$, so it can be considered as lightweight aggregate. This section gives a general overview of previous investigations concerning the fresh and hardened properties of rubberized concrete.

3.6.1. Properties of Fresh Rubberized Concrete

Many studies had been conducted to evaluate the workability of rubberized concrete by testing the slump of the mixtures. In general, researchers observed a significant reduction in slump as the rubber aggregate content was increased. Khatib and Bayomy [17] investigated the workability of rubberized concrete. The study stated that the slump decreases with the rubber content increases. The results show that for rubber aggregate contents of 40% by total aggregate volume, the slump was close to zero and the concrete was not workable, so the mixtures had to be compacted using a mechanical vibrator. Mixtures containing fine crumb rubber were more workable than mixtures containing either coarse rubber aggregate or a combination of crumb rubber and tire chips.

Eldin and Senouci [18] reported that in general, the rubberized concrete mixes showed acceptable performance in terms of ease of handling, placement and finishing. However, they found that increasing the size or percentage of rubber aggregate decreased the workability of the mix and subsequently caused a reduction in the slump values. Also, the size of the rubber aggregate and its shape (mechanical grinding produces long angular particles) affected the measured slump. The slump values of mixes containing long, angular rubber aggregate were lower than those for mixes containing round rubber aggregate (cryogenic grindings). Round rubber aggregate has a lower surface/volume ratio, therefore less mortar will be needed to coat the aggregates, leaving more mortar which make concrete more workable. It is also observed that the presence of the steel wires introduced from the tire chips contributed to the workability reduction.

Gideon Momanyi Siringi [11] conducted two series of batches. In the study, crumb rubber was used as a replacement of fine aggregates by 7.5%. Also, tire chips were used as a replacement of coarse aggregate by 7.5%. The results showed that, crumb rubber improves concrete consistency since the slump recorded was higher. Gideon stated that concrete with crumb rubber would be more consistent, easy to flow, pump and compact when shaping the fresh concrete into desired shapes during construction. For the mixtures containing rubber chips, the slump increases slightly by an average of 1 inch at the same water/cement ratio when compared to the control. Gideon reported that concrete containing crumb rubber is more workable and easy to handle than concrete with tire chips.

In the investigation by Cairns [2], 20mm tire chips were used as a replacement of coarse aggregate by 10%, 25% and 50%. Three tests were conducted to evaluate the workability of the rubberized concrete. The three workability tests are the slump test, VeBe test and compacting factor test. Cairns reported that, rubberized concrete showed acceptable workability in terms of ease of handling, trawling, placement and finishing. The results showed that, workability of concrete decreases with increasing in rubber content. For the mixture with 50% rubber content; the slump value is zero, VeBe time is much higher than the control mixture and the compacting factor is also lower than control. Table 2.3 reveals the workability test results.

Table 2.3 The workability test results [2]

Samples	Slump test		VeBe time (sec)	Compacting factor
	Slump (mm)	Apparent workability		
Control	55	Medium	5	0.95
10% rubber	14	Low	8	0.91
25% rubber	3	Very low	10	0.88
50% rubber	0	Zero	26	0.85

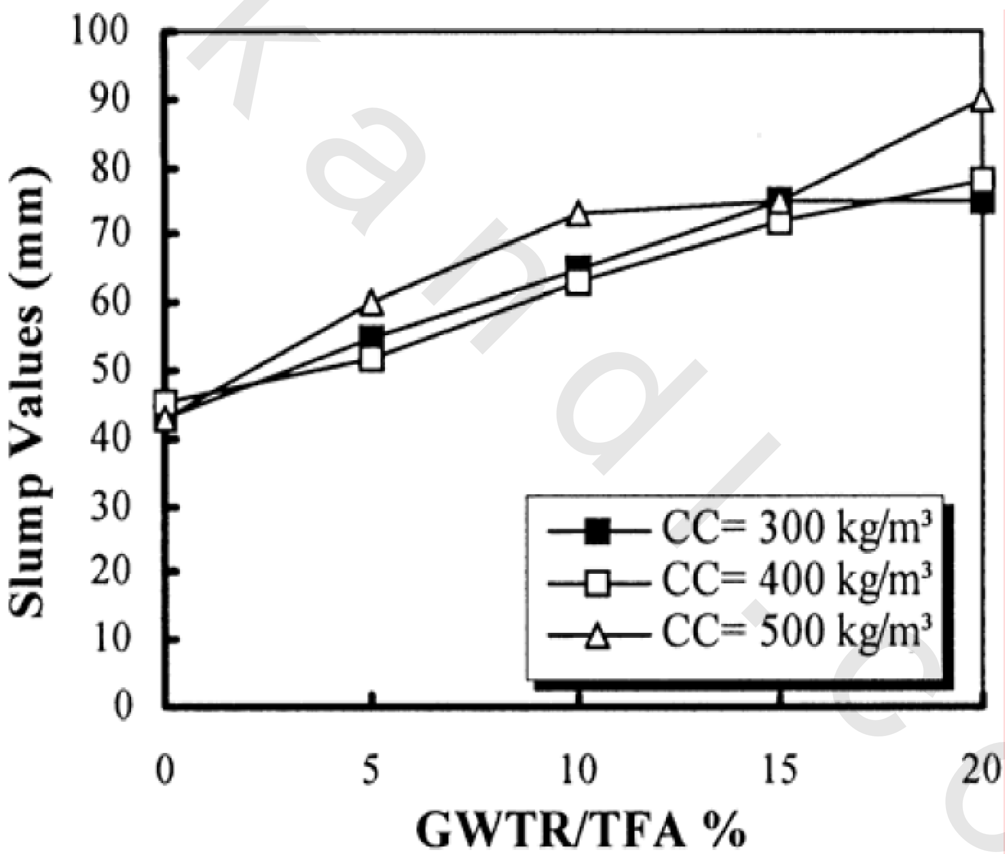


Figure 2.11 The slump values of different rubber contents [19]

Balaha [19] used 2mm crumb rubber as a replacement of fine aggregate by 5%, 10%, 15% and 20%. The study stated that, the slump of concrete increases with the increase of rubber content. The addition of rubber improves the slump of fresh rubberized from 30mm to about 70mm. Rubberized concrete with 15% and 20% rubber content have the maximum slump values. Figure 2.11 shows the slump values of different rubber contents. Also, Balaha studied the effect of rubber surface treatment on concrete consistency. Three types of surface treatments were used; silica fume, NaOH and Polyvinyl acetate (PVA). The maximum improvement in slump values was recorded for PVA and silica fume mixes, while treatment with NaOH solution decreases slump. Figure 2.12 reveals the effect of rubber surface treatment on slump values.

Ali et al. [20] reported that when rubber aggregate was added to the concrete, the air content increased considerably (up to 14%). Also, Khatib and Bayomy [17] observed that the air content increased in rubberized concrete mixtures with increase in rubber content. Cairns [2] stated that, the higher air content of rubberized concrete mixtures may be due to the non-polar nature of rubber particles and their ability to entrap air in their jagged surface texture. When non-polar rubber aggregate is added to the concrete mixture, it may attract air as it repels water. This increase in air voids content would certainly produce a reduction in concrete strength, as does the presence of air voids in plain concrete.

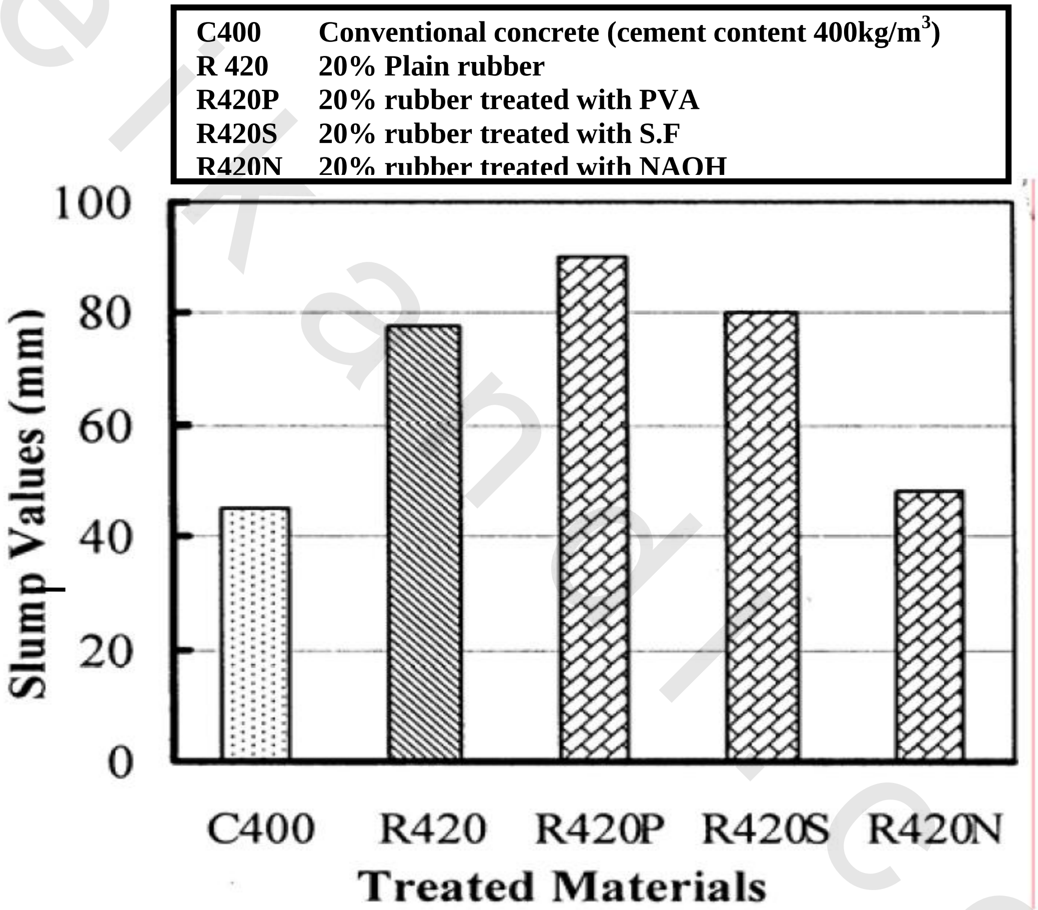


Figure 2.12 The effect of rubber surface treatment on slump values [19]

3.6.2. Properties of Hardened Rubberized Concrete

Several investigations studied the effect of utilizing crumb rubber as partial replacement of both fine and coarse aggregate on properties of concrete. As the compressive strength is the main characteristic studied in previous investigations to compare the rubberized concrete to ordinary concrete, all the previous investigations reported reduction in compressive strength with the increase of rubber content especially with coarse rubber aggregates.

The effect of rubber aggregate (ranging from 1 to 16 mm) and low grade rubber (<5 mm) aggregate replacement on the density of rubberized concrete was investigated by Fattuhi and Clark [21]. Fattuhi and Clark determined the relationship between the density and rubber/cement ratio (by mass), as shown in Figure 2.13. The replacement of natural aggregates with rubber aggregates tends to reduce the density of the concrete, which is attributable to the lower density of rubber comparing to mineral aggregates.

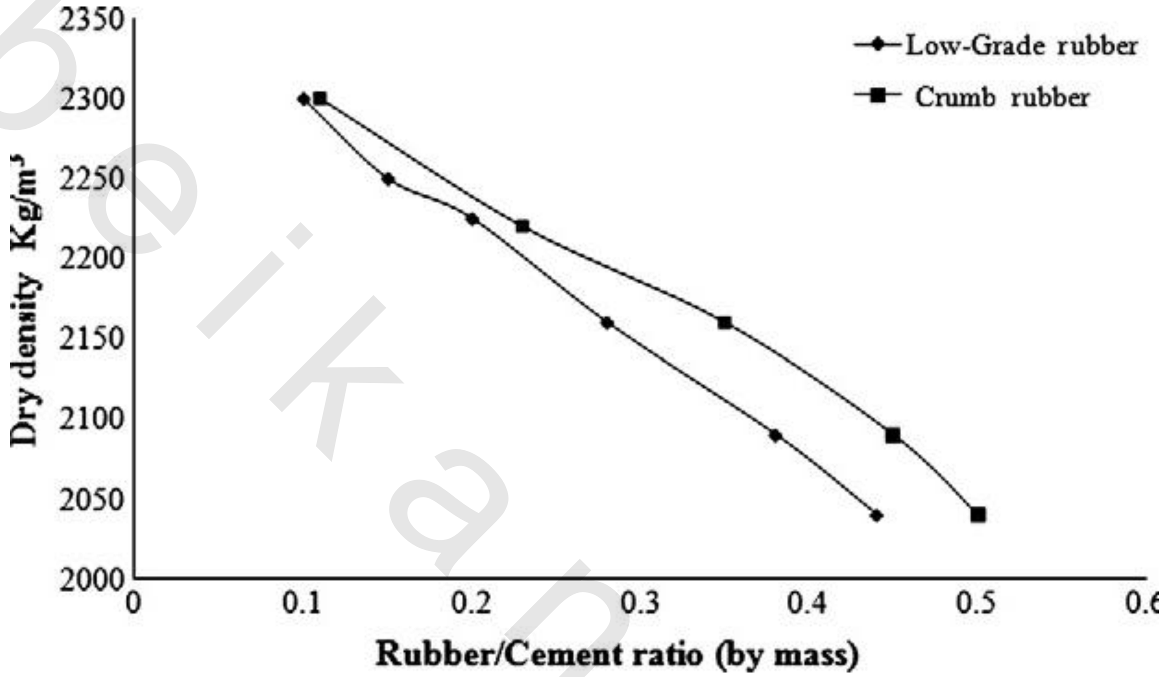


Figure 2.13 The relationship between the density and rubber/cement ratio (by mass) [21]

Topcu [3] studied the properties of rubberized concrete. Two sizes of rubber particles were used in the study; 0 to 1mm as a replacement of fine aggregate and 1 to 4mm as a replacement to coarse aggregate. In the study, the water/cement ratio of the batches was 0.6 to get average slump of 45mm and cement content was 357.5 kg/m^3. The fine and coarse rubber particles were included by replacing 15, 30 and 45% of the mineral aggregates by volume. Topcu reported that, at 45% coarse aggregate replacement, the reduction for compressive strength and tensile strength are 81% and 74%, respectively. At 45% fine aggregate replacement, the reduction for compressive strength and tensile strength are 56% and 64%, respectively. Figure 2.14 shows the compressive strength for rubberized concrete.

Also, the study stated that, all specimens withstood measurable post-failure compression load and underwent significant displacement. Also, displacement and deformations were partially recoverable upon loading. Topcu related this behavior to the fact that rubber particles have low modulus of elasticity, so high internal tensile stresses are produced perpendicular to the direction of the compression load applied. Thus, cement paste shows early failure because its weakness against tension, while rubber particles behave like springs which delay the widening of the existing cracks. Topcu suggested that rubberized concrete can be used in various applications such as; architectural applications as nailing concrete, in road constructions where high strength is not necessary, in wall panels that require low unit weight, in construction elements and jersey barriers that subjected to impact, in sound barriers as sound absorbers and in rail ways to fix the rails to the ground.

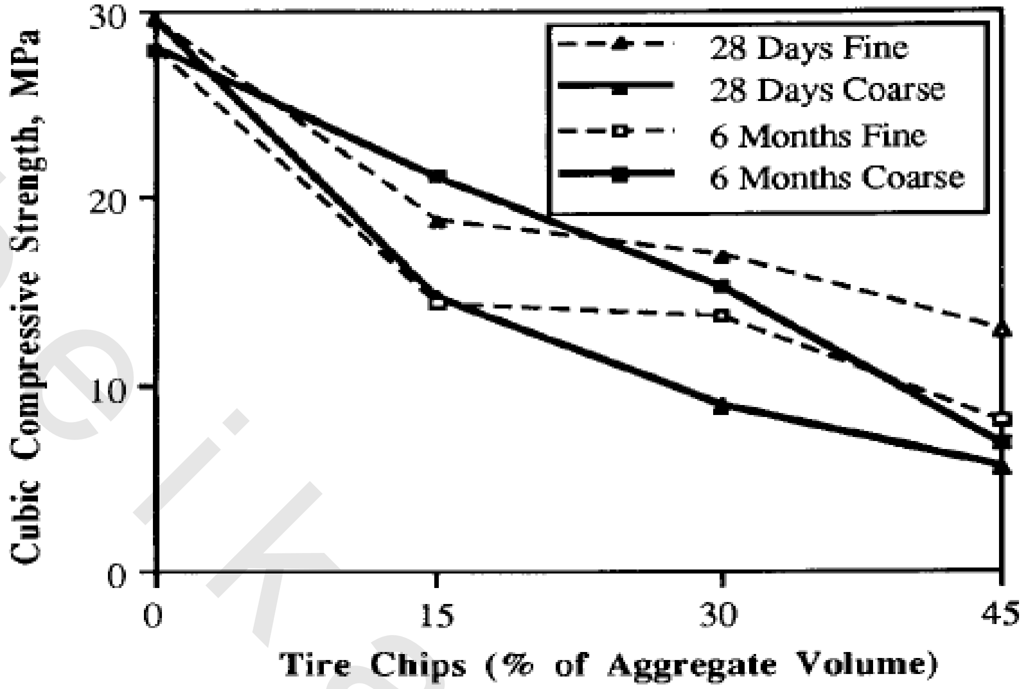


Figure 2.14 The compressive strength for rubberized concrete [3]

In the study by Khatib and Bayomy [17], two types of rubber aggregate were used, crumb rubber as fine aggregate replacement and tire chips as coarse aggregate replacement. From this work, compressive strength was reduced by 93% when coarse aggregate was fully replaced by tire chips. Also, crumb rubber caused compressive strength loss about 90% when fully fine aggregate replacement. For flexural strength, the reduction was more pronounced than compressive strength.

Eldin and Senouci [18] used rubber chips of 19 to 38 mm size to replace coarse aggregate and crumb rubber of 6 mm and 2 mm to replace fine aggregate. Their investigation reported that, when rubber aggregate is used as full replacement of coarse aggregate, compressive strength reduced by 85% compared with control mix without rubber aggregate. Whereas, the tensile strength also reduced by 65% of control mix. When rubber aggregate was used as full replacement of fine aggregate, compressive strength recorded smaller reduction by 65% of control mix compressive strength. Eldin and Senouci also reported that rubberized concrete exhibit ductile mode of failure in compression and split tests.

El Gammal [22] used waste rubber as partial and full replacement of coarse and fine aggregate. Rubber used in two shapes, chipped rubber as coarse aggregate replacement with the size of 100 to 150 mm, and crumb rubber particles as sand replacement. The gradation of crumb rubber used in the investigation was very close to that of sand. Compressive strength for the mix with 100% replacement of coarse aggregate by chipped rubber was reduced by 90% comparing to the control mix. Meanwhile, the full replacement of sand by crumb rubber reduced compressive strength by 80%. Figure 2.15 shows the compressive strength for rubberized concrete by El Gammal.

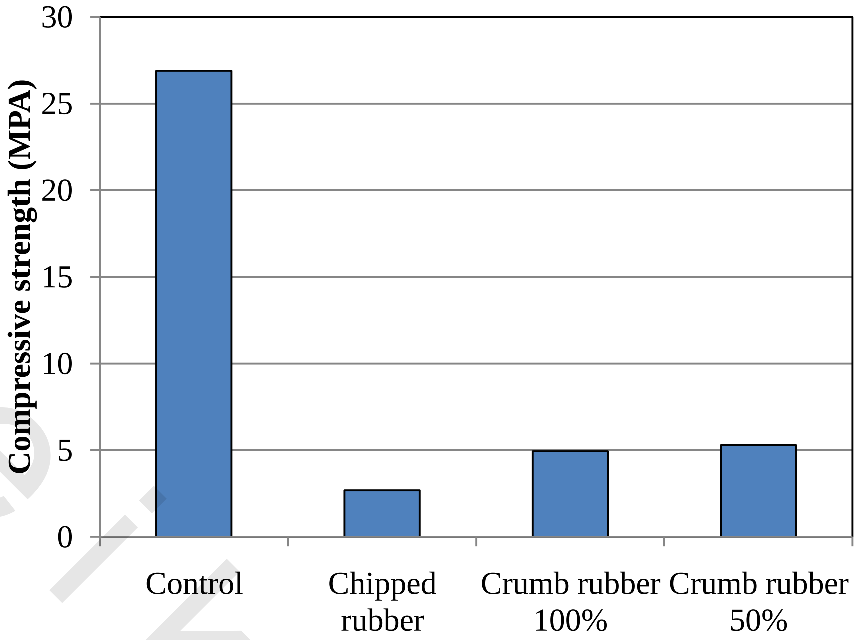


Figure 2.15 Compressive strength for rubberized concrete [22]

Fibrous and crumb rubber were used in the study by Hai Huynh et al. [23] as addition to cement mortar at small fractions. The study stated that fibrous rubber improves some properties of the mortar comparing to rubber granules .In particular, the crack width and crack length due to plastic shrinkage were reduced. Also, compressive and flexural strength of fibrous rubber concrete were improved comparing to crumb rubber. Moreover, mortar containing rubber fibers showed workability comparable to that of a mortar without rubber particles. Figure 2.16 shows flexural strength results by Hai Huynh for ground rubber mixes and 4.75mm fibrous rubber. Hernandez-Olivares et al. [24] and Raimundo K. Vieira et al. [25] also used fibrous rubber in their investigations and stated the same results.

Rubberized concrete exhibits ductile mode of failure as reported by previous investigations, also rubberized concrete shows enhancement in toughness. Gideon Momanyi Siringi [11] stated that, at 7.5% replacement of fine aggregate, crumb rubber improves the modulus of toughness by 54%. Also, at 15% replacement of fine aggregate, the modulus of toughness for crumb rubber concrete is 15% higher than that of control concrete. Therefore, the addition of crumb rubber into concrete improves toughness and impact resistance. Also, Gideon reported that, crumb rubber modified concrete has a lower elastic modulus, splitting tensile strength and modulus of rupture when compared with that of control concrete. Figure 2.17 shows stress-strain curves for control concrete and concrete with 7.5% crumb rubber as a replacement of fine aggregate.

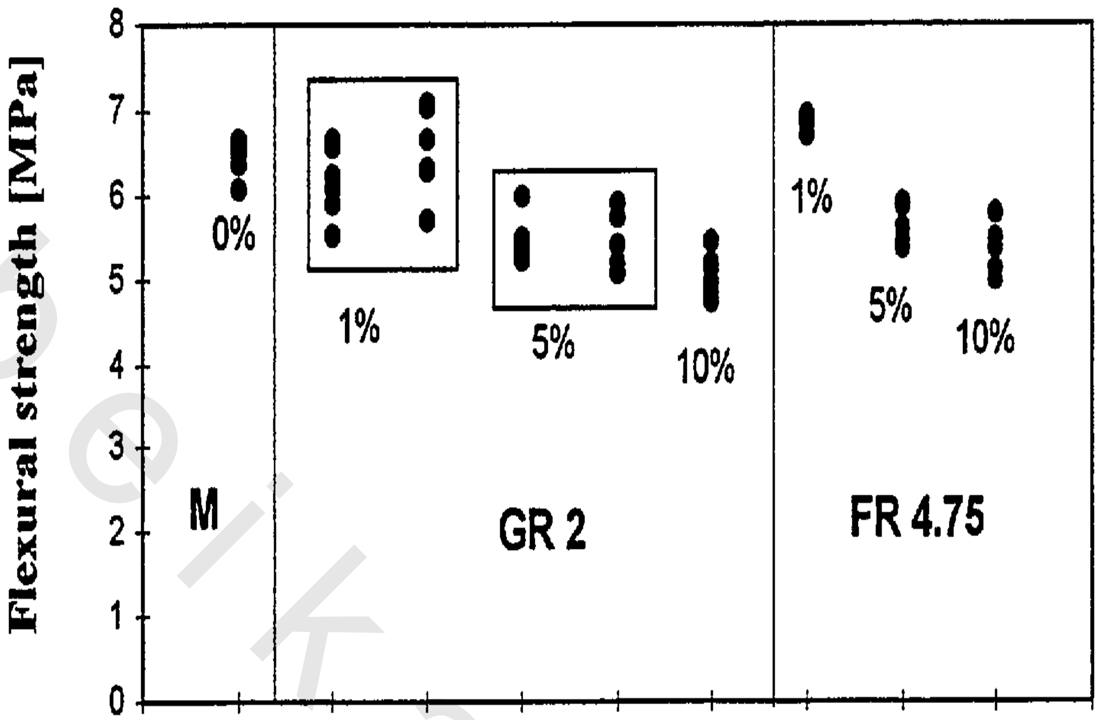


Figure 2.16 Flexural strength results by Hai Huynh for ground rubber mixes and 4.75mm fibrous rubber [23]

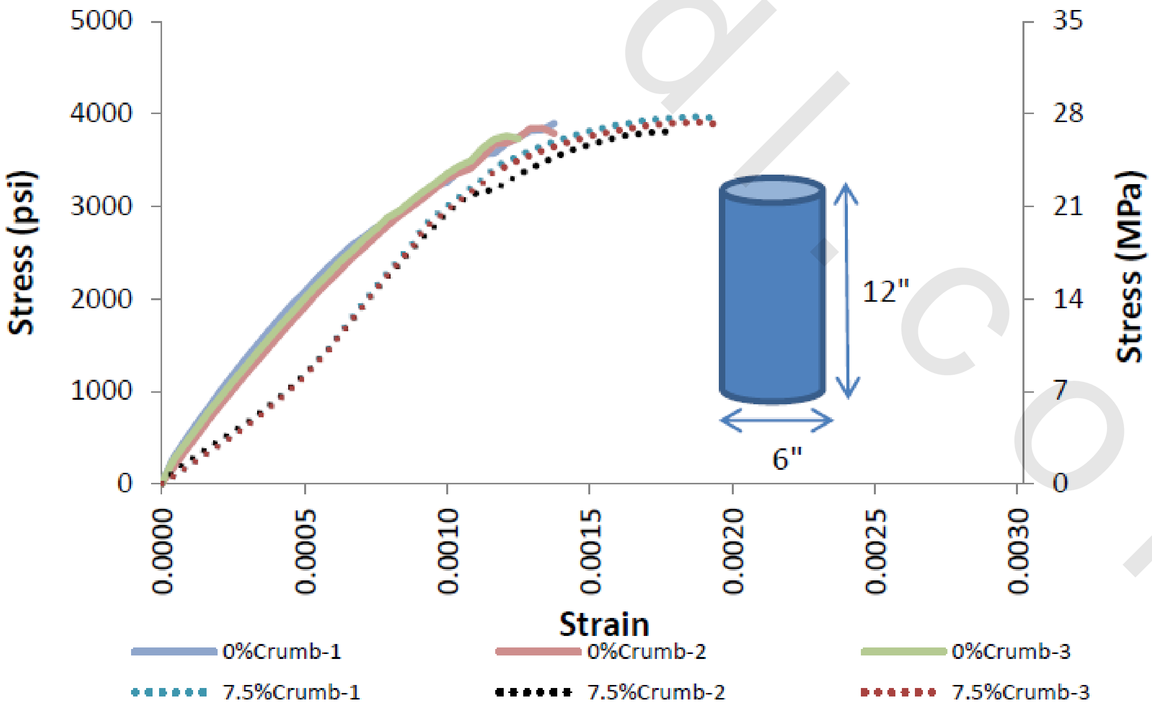
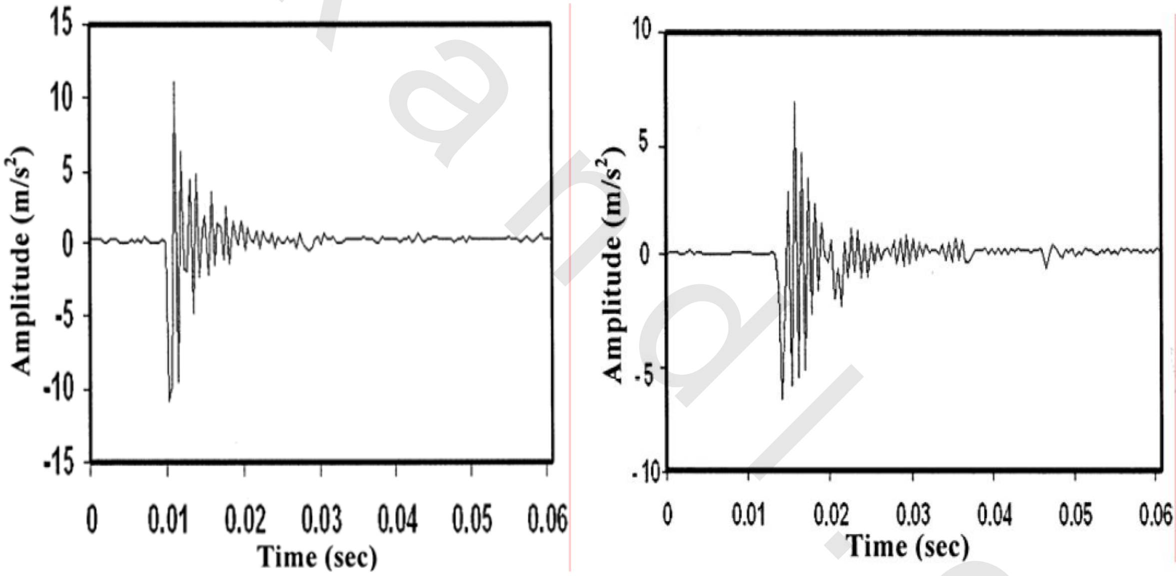


Figure 2.17 Stress-strain curves for control concrete and concrete with 7.5% crumb rubber as a replacement of fine aggregate [11]

Tantala et al. [26] used rubber chips as a replacement of coarse aggregates by 5 and 10%. Tantala found that toughness of concrete increases significantly when rubber aggregate is used. Concrete mixture with 5% rubber content obtained higher toughness than rubberized concrete with 10% rubber content, which is due to the large reduction in concrete compressive strength as the result of using at 10% rubber content. Goulias and Ali [27] reported that, the dynamic modulus of elasticity of concrete decreases with the increase in rubber content, which indicates more ductile and less stiff material.

Damping ratio of concrete was also studies by various investigations. The damping ratio of the materials is used to measure the ability of the material to decrease the amplitude of free vibrations on its body. M M Balaha et al. [19] stated that, the addition of 2mm rubber particles to concrete improves the damping ratio. The results showed that, the damping ratio of rubberized concrete, with 20% rubber content as a replacement of fine aggregates, is about 63% higher than normal concrete. Figure 2.18 shows the damping ratio of normal concrete and rubberized concrete with 20% rubber content. From this figure, it is clearly that the vibration amplitude of rubberized concrete specimen is less than the vibration amplitude of normal concrete.



a) Normal concrete b) Rubberized concrete

Figure 2.18 The damping ratio of normal concrete and rubberized concrete with 20% rubber content [19]

Chen et al. [28] studied the damping of rubberized concrete. Six different amounts of rubber powder were added in the concrete (0% to 7.5%). Plain concrete, with 35 MPa compressive strength, was used in this study. The 28 days compression test and the impact hammer test were performed to investigate the stress-strain relationships and damping ratios of the rubber concrete. The results revealed that the damping of the rubber concrete is 50-60% and 130-230% higher than the plain concrete when 0.5-2.5% and 5.0-7.0% weight of rubber powder were added into the concrete, respectively. The Young's modulus linearly decreased as the amount of added rubber increased.

Ching-Yao Lin et al. [29] studied the damping ratio of rubberized concrete containing 2mm and #40 (0.42mm) rubber powder. The results revealed that, at 2.5% replacement of fine aggregate by #40 rubber powder, the damping ratio of concrete increases by 94%. Also, the damping ratio of concrete increases by 56% when #10 rubber powder is used as a replacement of fine aggregate. Also, Goulias and Ali [27] reported a large decrease in concrete damping ratio of rubberized concrete with the increase in rubber content increase.

Topcu [3] and Fatuhi and Clark [21] recommended that the using of rubberized concrete in application where damping capacity of concrete is required like railways stations and machinery foundations. Topcu [3] indicated that, impact resistance of concrete increases when rubber aggregate is used in concrete mixtures. Many investigations recommended that sound and thermal insulation characteristics of rubberized concrete are very promising, but more research is needed in these characteristics of rubberized concrete [30-36].

3.6.3. Freezing and Thawing Resistance

Paine et al. [37] investigated the use of crumb rubber as an alternative to air-entrainment for providing freeze–thaw resisting concrete. Three sizes of crumb rubber, 0.5 to 1.5mm, 2 to 8mm and 5to 25 mm were used. Test results showed that there is potential for using crumb rubber as a freeze–thaw resisting agent in concrete. According to Siddique and Naik [8], the crumb rubber concrete has better freeze–thaw resistance than plain concrete, and the performance of crumb rubber concrete in terms of scaling was similar to that of air-entrained concrete (scaling gives an evaluation of the surface exposed to freezing and thawing cycles as measured by the loss of weight).

Savas et al. [38] carried out an investigation to study the rapid freezing and thawing (ASTM C 666, Procedure A) durability of rubber concrete. Various mixtures were made by incorporating 10%, 15%, 20%, and 30% ground rubber by weight of cement. Savas concluded that, rubberized concrete mixtures with 10% and 15% ground rubber (2 to 6 mm in size) exhibits durability factors higher than 60% after 300 freezing and thawing cycles, but mixtures with 20% and 30% ground rubber by weight of cement could not meet the ASTM standards.

Benazzouk and Queneudec [39] also studied the freeze–thaw durability of cement–rubber composites through the use of two types of rubber aggregates. The used types of the aggregates were: compact rubber aggregate (CRA) and expanded rubber aggregates (ERA). Volume-ratio of the aggregates ranged from 9% to 40%. The results showed improvements in the durability of the composite containing 30% and 40% rubber by volume. Improvement in the durability of the composite containing ERA type aggregates is better than composite made with CRA aggregates.

3.6.4. Surface Treatment of Rubber Particles

The bond between rubber surface and cement paste is the main parameter that control the reduction in mechanical concrete properties. Rubber surface texture is responsible for the week bond with cement paste, so improving the bond with cement paste can be achieved by using surface treatment of rubber particles before placing in the concrete mix. Segre and Joekes [40] stated that the final cost of the rubberized concrete could be minimized by using low cost pretreatment processes of rubber particles, which improve all mechanical characteristics of rubberized concrete.

There are several methods of pretreatment of rubber particles like washing with water, NaOH solution (by soaking rubber aggregate in NaOH solution for about 15 minutes and then rinsing it with water before placement in the mix), coupling agents and pre-coated rubber aggregate with cement paste

Cairns [2] used 10 mm crumb rubber; pre-surface treatment was used for rubber aggregate by cement paste. Two groups of mixes were performed one by using plain rubber and the other by using pre-coated rubber with cement paste. Two series of mixtures were performed with 20 mm coarse aggregate only and two other mixes with 10 and 20 mm coarse aggregate with 1:2 proportional ratio. The used rubber replacement levels were 10%, 25% and 50% by volume of coarse aggregate. Table 2.4 presents the control mixes used by Cairns.

Table 2.4 The control mixes used by Cairns [2]

Mix		**A**	**B**	**C**	**D**
Cement (kg/m^3)		382	438	382	438
W/C		0.55	0.48	0.55	0.48
Coarse Agg (kg/m^3)	10mm	-	-	422	409
	20mm	1266	1227	844	818
Fine Agg (kg/m^3)		543	526	543	526

Cairns reported a decrease in concrete workability up to zero slump value with 50% rubber replacement and more effort was needed to surface finishing. Cairns reported that, compressive and tensile strength reduces with increase in rubber content. Rubberized concrete with pre-coated rubber with cement paste obtained higher compressive and tensile strength than mixture with plain rubber, as shown in Table 2.5. Flexural strength of rubberized concrete with 10% and 25 % coated rubber were higher than control mix, while flexural strength reduced for concrete with 50 % rubber replacement. Flexural strength of rubberized concrete containing coated rubber is presented in Figure 2.19 .Abrasion tests were performed where rubberized concrete showed reduction in wearing resistance than control mixtures. Compressive strength test samples of the rubberized concrete are shown in figures 2.20 and 2.21.

Table 2.5 Reduction in compressive strength [2]

Coated rubber						**Plain rubber**				
Replacement%	A	B	C	D		Replacement%	A	B	C	D
10%	22%	7%	29%	2%		10%	31%	31%	17%	17%
25%	36%	24%	33%	19%		25%	44%	45%	38	26%
50%	58%	48%	48	28%		50%	78%	57%	63%	60%

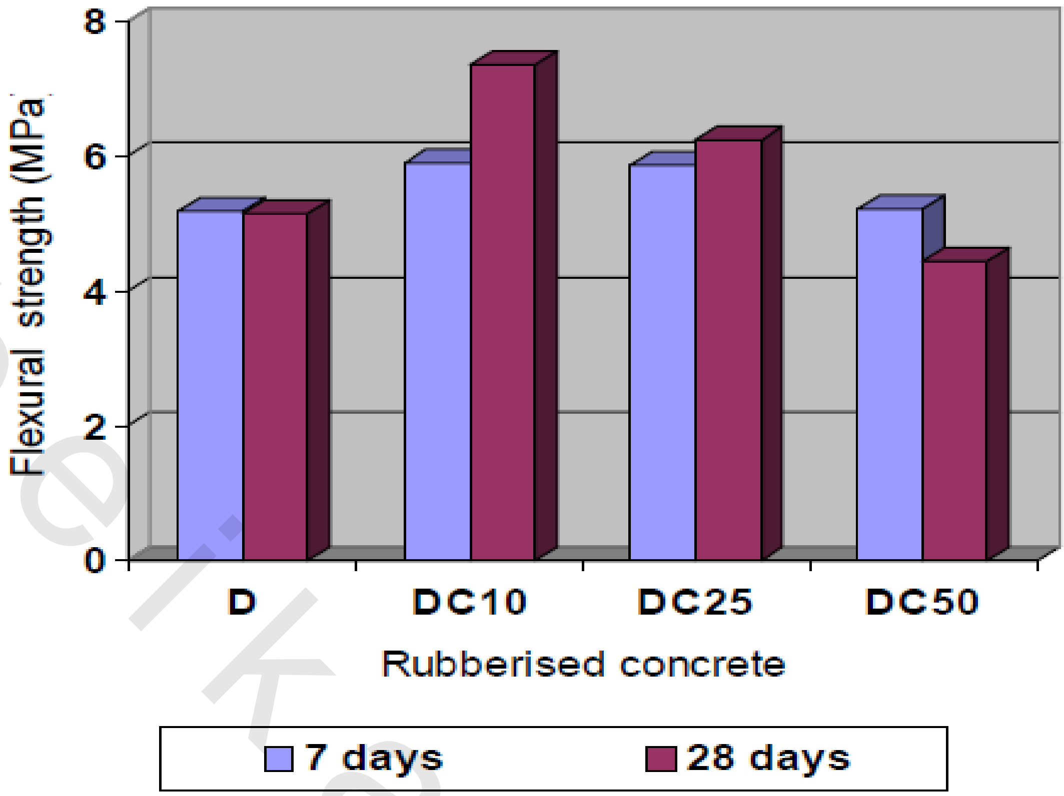


Figure 2.19 Flexural strength of concrete containing coated rubber chips [2]

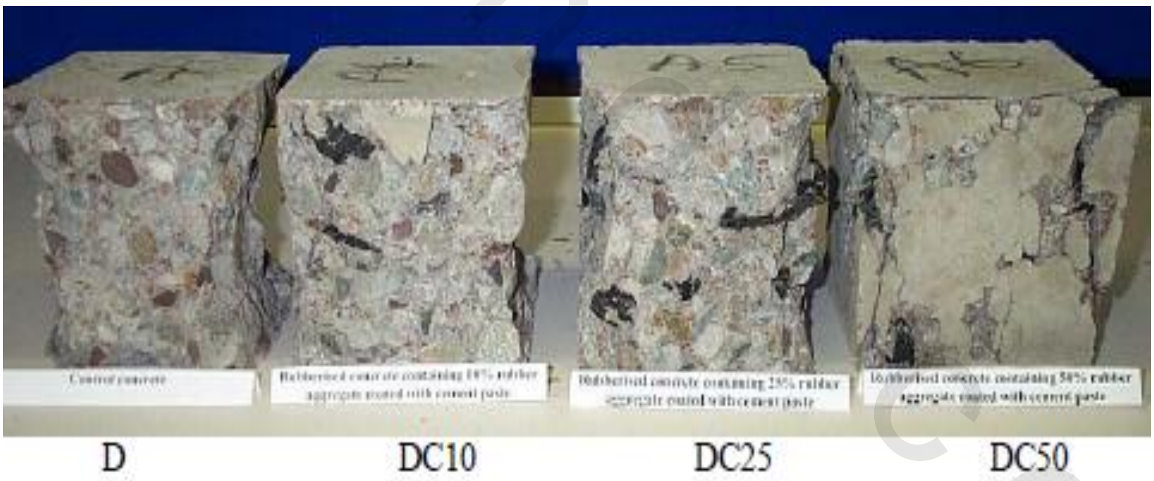


Figure 2.20 Compressive strength test samples of the rubberized concrete containing rubber particles coated with cement paste

M M Balaha et al. [19] compared three types of surface treatments for fine rubber particles. First, Balaha used PVA for treatment of rubber particles for 15 minutes before it were mixed with cement. Also, treatment with NaOH solution for about 15 minutes was used in the investigation. Finally, Balaha used silica fume as replacement to cement by 15% to enhance the bond between rubber particles and cement paste. The three methods of rubber surface treatment were compared to concrete with plain rubber. Rubber was used as a replacement of fine aggregates by 20%. The results showed that, PVA treatment gives the best results for compressive and tensile strength, as shown in figures 2.22 and 2.23. The treatment of rubber particles eliminates the reduction in compressive strength of normal concrete to only 14%, 15% and 17% for PVA, silica fume and NaOH respectively, while in the case of untreated rubber, the reduction is 27% at the same percent of rubber replacement.

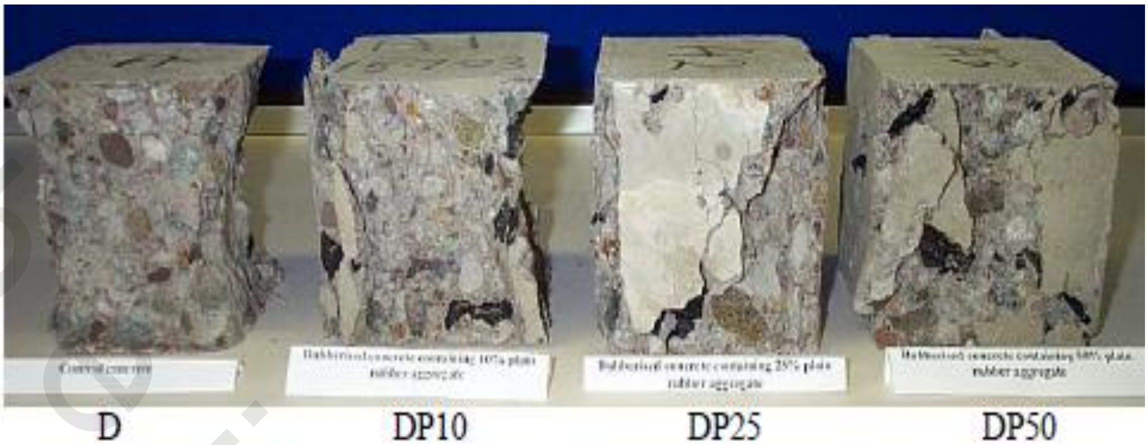


Figure 2.21 Compressive strength test samples of the rubberized concrete containing plain rubber particles

Also S. Herrero et al. [34], Liang Hsing Chou et al. [41] used treatment for rubber particles with 10% concentration NaOH solution to increase the adhesion between rubber particles and cement paste. Fernando Pelisser et al. [42] and Erhan Gu¨neyisi et al. [43] used silica fume in rubberized concrete to eliminate the reduction in mechanical properties. The previous studies showed that there is an improvement in rubberized concrete properties as a result of using NaOh solution for treatment of rubber particles.

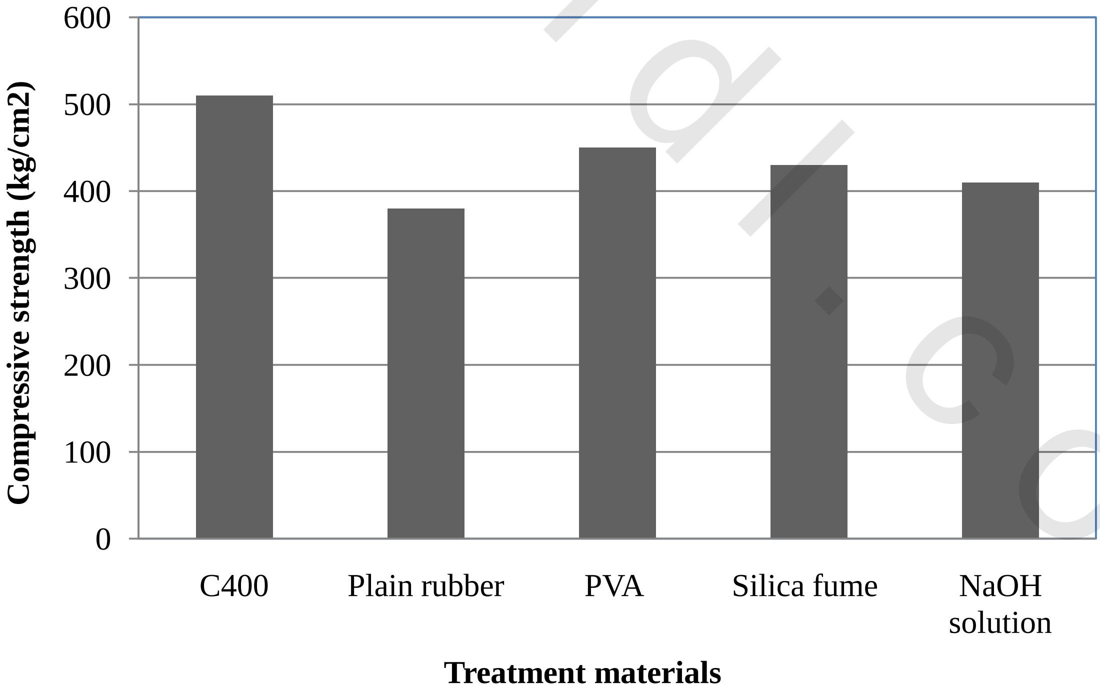


Figure 2.22 Compressive strength for different treatment methods [19]

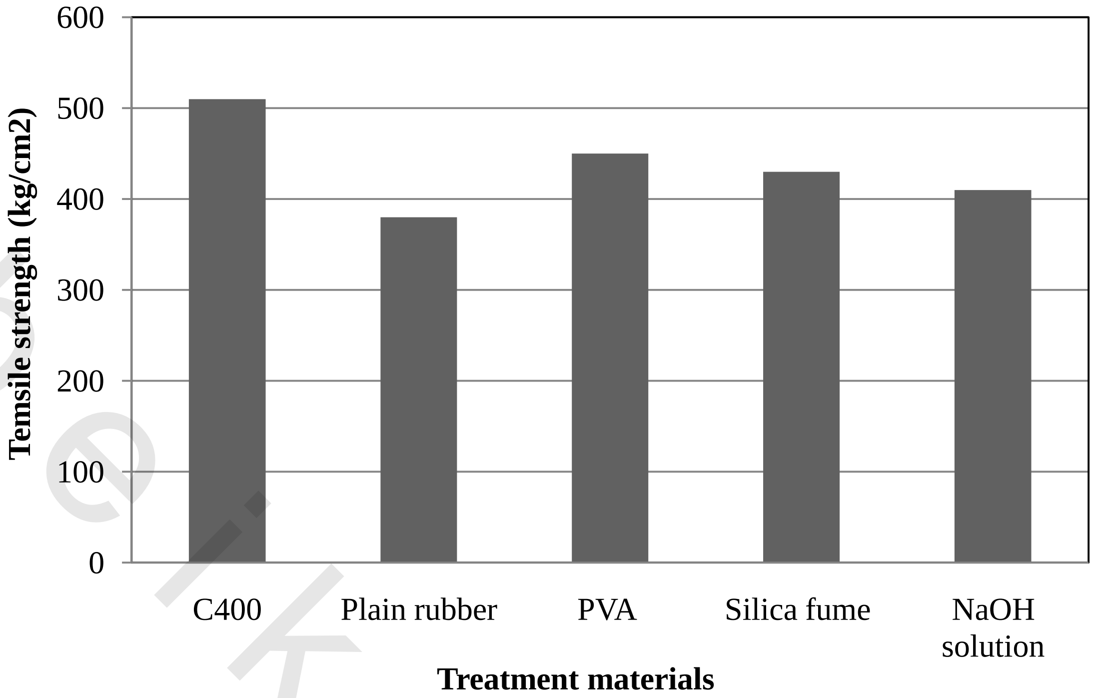


Figure 2.23 Tensile strength for different treatment methods [19]

Rostami et al. [44] pre-treated rubber aggregates with water and carbon tetrachloride (CCL4) solvent. Rostami reported that, washing rubber with water increases compressive strength by 16%, where compressive strength increases by about 57% when rubber aggregates are treated using CCL4. Li et al. [45] used pre coated rubber aggregate with cement paste. The results showed that, compressive strength of the mixture increases by 30% and flexural strength slightly increases comparing to rubberized concrete with plain rubber aggregate. Segre and Joekes [40] used pre treatment rubber aggregate with sodium hydroxide solution for 20 minutes before placing in the mix. Abrasion resistance tests were performed and resulted in large increase in abrasion resistance comparing to mixture with plain rubber which indicates to better adhesion between rubber aggregates and cement paste.

3.7. COST ANALYSIS OF RUBBERIZED CONCRETE

The quantity of rubber waste that is recycled in civil engineering applications is very low and there is a need to create new market for waste rubber in the construction field. Thus, the implementation of waste rubber particles in concrete is under investigation intensively through the last decade. However, rubberized concrete products need to be feasible in terms of cost, including material costs and production processes. The cost analysis presented in this section focuses on the use of rubber particles in regular concrete mixes and on rubberized concrete building blocks [8].

The cost of waste rubber depends mainly on its particle size. The available rubber aggregates vary widely in terms of aggregate size, as each supplier produce a specific rubber grade to meet a particular need in the market. The tire recycling processes involve the reduction of used tired into smaller pieces such as chips, crumb and powder. Also, along with size reducing, the fibers and steel wires are separated from the tires to provide a purer material, especially for crumb rubber and powder. However, as the number of processes increase (reduction in particle's size), the price of the produced rubber also increases [1]. In cost point of view, the current cost of recycled rubber presents a difficulty for using in rubberized concrete. The feasibility study of rubberized concrete is not very promising comparing to normal concrete. This is because of the high cost of waste rubber particles compared to that of mineral aggregate. In the future, it is expected that the cost of rubberized concrete will decrease. This is due to the development of rubber recycling industry, as the market potential of rubberized concrete develops. Table 2.6 presents approximate cost of waste rubber particles at different sizes [2, 11]. It should be noted that, the cost of recycled rubber varies widely depending on the source of the rubber and the amount of processes during the production.

Table 2.6 Approximate cost of waste rubber particles at different sizes

Rubber size	Product	Price in the United states	Price in Egypt	Price in the United kingdom	Prices in China	Current application
100 mm to 250 mm	Rubber shreds	10$ to 44$ / ton	-	-	-	Road embankment, backfill and landfill applications
50mm to 100mm	Rubber chips	15$ to 45$ / ton	-	-	-	Tire derived fuel (TDF), Road embankment, backfill and landfill applications
10mm to 50mm	Ground rubber	20$ to 65$ / ton	-	-	-	TDF, Road embankment, backfill and landfill applications
5mm to 10mm	Crumb rubber	180$ to 300 $		80£ to 160£ / ton		Mulch and playgrounds
3mm to 5mm	Crumb rubber	220$ to 360$ / ton	1000 L.E / ton	-	10$ to 100$ /ton	Sports surfaces
3mm to 0.8mm	Crumb rubber / Rubber powder	220$ to 400$ / ton	1250 L.E / ton	-	-	Rubber modified asphalt, molding
0.63mm	Rubber powder	300$ to 1200$ / ton	1500 L.E / ton	-	350$ to 700$ /ton	Rubber modified asphalt, molding

In rubberized concrete, rubber particles are usually used as aggregate replacement by volume. Table 2.7 presents the cost analysis for two available concrete mixes. One of them carried by Cairns [2] in The U.K, the mix proportions is illustrated as mix A in Table 2.4 in sec 2.6.4. The other mix is proposed in the present study. From this table, it is obvious that the cost of aggregate / m^3 of rubberized concrete is higher than that of conventional concrete. This increase in aggregate cost is about 53.4% and 435% in cost /m^3 based on the materials' prices in the U.K and Egypt, respectively.

However, the aim of the analysis is to determine the additional costs for rubberized concrete, which can be set against its benefits comparing to normal concrete. The potential benefits of rubberized concrete are under investigation, although that rubberized concrete is reported to obtain better impact resistance, toughness and ductility.

Table 2.7 The additional material costs for various mixes.

Concrete mix by Cairns		**Cost / m^3 of concrete**	**Increase of aggregate cost / m^3**
Type of replacement	Replacement of coarse aggregate	31.25 £ / m^3 of concrete	
Natural Aggregate	Weight / m^3 of concrete = 1250 Kg		
	Volume / m^3 of concrete = 0.471 m^3		
Rubber aggregate as 50% replacement	Volume / m^3 of concrete = 0.236 m^3	32.3 £ / m^3 of concrete	16.7 £
	Weight / m^3 of concrete = 269 Kg		53.4%
Concrete mix presented in the study		**Cost / m^3 of concrete**	**Increase of aggregate cost / m^3**
Type of replacement	Replacement of fine aggregate		
Natural Aggregate	Weight / m^3 of concrete = 750 Kg	33 L.E /m^3 of concrete	
	Volume / m^3 of concrete = 0.29 m^3		
Rubber aggregate as 50% replacement	Volume / m^3 of concrete = 0.145 m^3	160 L.E/m^3 of concrete	143.5 L.E
	Weight / m^3 of concrete = 160 Kg		435%

3.8. RESEARCH NEED

Almost all the previous investigations in rubberized concrete recommended that the use of waste rubber has a positive effect on ductility, toughness and impact resistance of concrete. Many investigators studied the propertied of rubberized concrete. It can be seen that, the properties of rubberized concrete varied widely due to the difference in the size, shape, source and texture of the used rubber particles. Thus, further investigation is needed to study the properties of rubberized concrete using the available materials in Egypt. Also, there is a lake in information about some properties of rubberized concrete [46-52].

According to Cairns [2], further work is needed to investigate rubberized concrete properties such as impact and vibration resistance. Gideon Momanyi Siringi [11] recommended further investigation in the behavior of rubberized concrete at high temperatures. Fernando Pelisser et al. [42] reported good adhesion between rubber particles and cement past when silica fume is used in rubberized concrete. Pelisser also reported that more investigation is needed to obtain the ideal rubberized concrete mix with the variables of surface treatment, rubber content and rubber particle size.