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Performance of concrete structures with waste tyre recycled aggregates

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Summary

The concrete industry is known to leave an enormous environmental footprint on Planet Earth. First, there are the huge volumes of material needed to produce the billions of tons of concrete worldwide each year. Then there are the CO_2 emissions caused during the production of Portland cement. Together with the energy requirements, water consumption and generation of construction and demolition waste, these factors contribute to the general appearance that concrete is not particularly environmentally friendly or compatible with the demands of sustainable development.

In this context large number of papers focused on new concrete materials that would be more suitable with environmental necessity than ordinary Portland concrete. Among these materials, one of the most discussed is rubberized concrete. Rubberized concrete is obtained by incorporating rubber particles, obtained from recycled end-of-life tyres, as a replacement for mineral aggregates.

The main objective of this work is to investigate the properties of three concrete mixtures: an ordinary Portland concrete mixture and two rubberized mixture with increasing percentage of rubber substitution. Compressive strength, modulus of elasticity, splitting tensile strength, flexural strength, bond-slip behavior and water permeability were evaluated and a comparison of the results for the different rubberized concrete mixtures was proposed in order to define if concrete incorporating rubber particles can be used in structural members.

The rubberized concrete mixtures showed lower unit weight compared to reference ordinary concrete. The results of compressive strength, tensile strength and bond-slip behavior indicated no substantial differences among ordinary Portland concrete mixture and rubberized concrete mixtures. Meanwhile, flexural strength and water permeability decresed by increasing the rubber replacement ratio.

1. Introduction

Concrete is the most important building material. Worldwide, more than 10 billion tons are produced each year. The first applications of this material in construction goes back to the historical period of ancient Rome, when there was a need to found a material composed by easily accessible raw materials, with a great strength capability and workability. All these reasons make concrete popular today, in fact if properly designed and produced, concrete has excellent mechanical and durability properties. It is moldable, adaptable, relatively fire resistant, generally available and affordable. Moreover, composition of concrete is quite simple: water, cement, fine aggregate (sand) and coarse aggregate. Maybe the most intriguing characteristic is the fact it is engineered material, which means it can be engineered to satisfy almost any reasonable set of performance specifications, more so than any other material currently available. Over the past several decades, the demand for concrete has been increasing rapidly due to growth in infrastructure development.

But this popularity comes with a significant price, which is all too often overlooked: alone for the huge volumes produced every year, concrete has an enormous impact on environment (Meyer, 2009). First, the production of each ton of Portland cement releases almost one ton of carbon dioxide into the atmosphere. Worldwide, the cement industry alone is estimated to be responsible for about 6% of all carbon dioxide (CO_2) generated. The production of Portland cement is also very energy intensive.

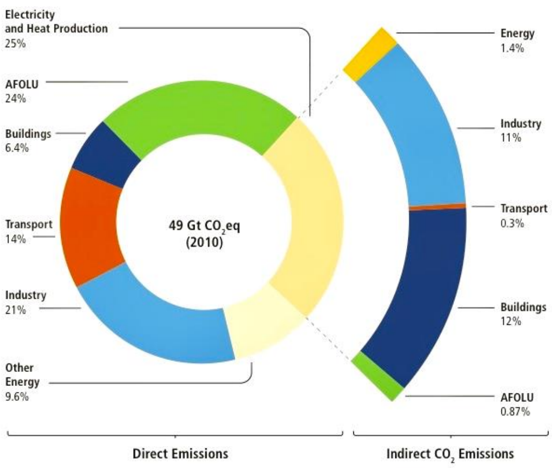


Fig. 1 - Global greenhouse gas emissions by economic sector (IPCC, 2014)

The other problem is that the production of concrete requires large amounts of water, which is particularly scarce in those regions of earth that are not characterized with an abundance of fresh water. Third, the demolition and need of disposal of concrete structures, pavements, etc., creates another environment issue. Construction and demolition debris contribute a considerable fraction of solid waste in developed countries, and concrete constitutes its largest single component. Finally, there are the vast amounts of natural resources needed to produce those billions of tons of concrete each year. River sand is one of the main ingredients in concrete production and it is used as fine aggregate. The heavy demand for concrete has resulted in the over-exploitation of river sand in the river bed, and this led to a range of harmful consequences, including increased river bed depth, water table lowering and intrusion of salinity into rivers.

1.1. Environmental issues in cement's production

Cement production has undergone a tremendous development from its beginnings some 2000 years ago. While the use of cement in concrete has a very long history, the industrial production of cements started in the middle of the 19th century, first with shaft kilns, which were later on replaced by rotary kilns as standard equipment worldwide. Today's annual global cement production reached 2.8 billion tons, and is expected to increase to some 4 billion tons per year (Schneider *et al.*, 2011). At the same time, the cement industry is facing challenges such as cost increases in energy supply, requirements to reduce CO_2 emissions, and the supply of raw materials in sufficient quantities and amounts.

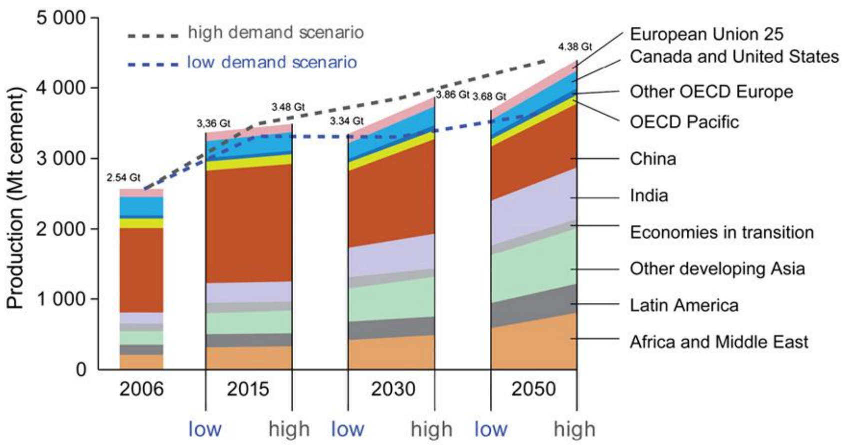


Fig. 2 - Global cement production (WBCSD and IEA, 2009)

The manufacturing process for the cement industry consists of three main steps: raw material preparation, clinker production and cement production. In raw material preparation, quarrying is done first, then followed by pre-homogenization and grinding of raw materials. During clinker production, burning of fuels to provide heat and chemical reaction occurs in a cement kiln. A chemical reaction between pre-homogenized raw materials and fuel's ash in the cement kiln produces clinker that is then stored in clinker silos. During cement production, blending of clinker with grinding aids for final adjustment occurs, followed by storage, then shipment (Ishak, Hashim and Ting, 2016).

The decarbonation reaction of raw materials – normally limestone (conversion limestone to lime) or calcium carbonates rich materials in cement kiln – contributes to about 50% of the total CO_2 emission of a cement plant while the combustion of fuels in the cement kiln leads to 40% of the total CO_2 emissions (Benhelal *et al.*, 2013). About two thirds of the total energy consumption for cement production are used for particle size reduction and about 2% of the electricity produced globally is used during the grinding process of raw materials (Katsioti *et al.*, 2009).

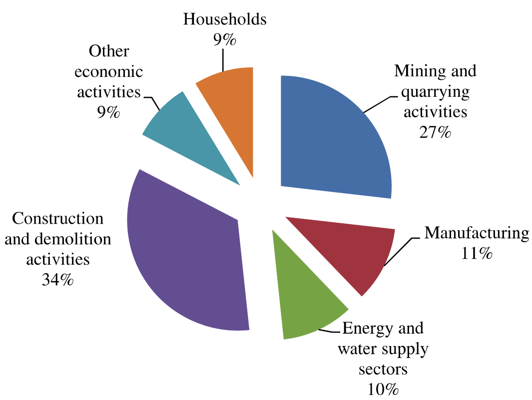
Cement industry is a significant contributor of greenhouse gas emission. It was found that reducing the emission may lead to substantial reduction of overall greenhouse gas emission. The main strategies that can be followed in order to reduce energy consumption, and therefore reduce emissions, in the short and medium term are: replacing currently used raw materials by materials that are less energy intensive to produce or have smaller CO_2 emissions or improving energy efficiency through process redesign of fossil fuel replacement.

During the last 20 years specific energy consumption in European cement plants has been reduced by about 30%, and dust emissions have been reduced by 90% as the industry has invested heavily in process redesign and various emission abatement techniques (Kookos *et al.*, 2011). As cement industry is able to use alternative materials and fuel to reinforce its competitiveness and at the same time contribute to solutions to society's waste problems there is a significant interest in exploring further this opportunity to improve its environmental footprint.

1.2. Construction and demolition concrete waste

The exploitation of natural resources, in particular non-renewable resources, for construction purposes leads to millions of tons of construction and demolition waste every year. Since most countries have no specific processing plan for these materials, they are sent to landfill instead of being reused and recycled in new construction.

According to Eurostat, the total amount of waste generated in the European Union in 2014 was over 2.5 billion tons, of which almost 34% (860 million tons) derived from construction and demolition activities and 27% (672 million tons) belonged to mining and quarrying operation. In 2014 these two economic sectors generated more waste than any other (Silva, De Brito and Dhir, 2014).



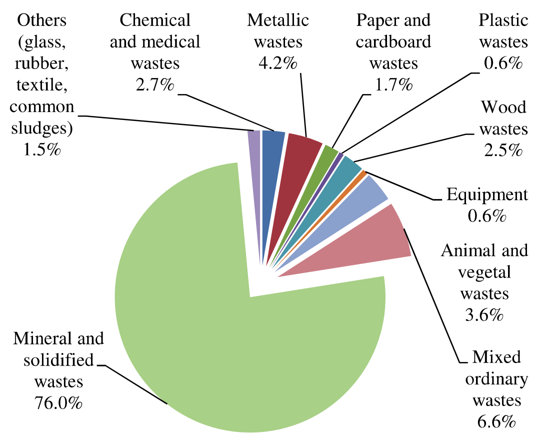


Fig. 3 - Total waste generated in European Union according to economic activity and waste category (Eurostat, 2016)

Of the total waste generated by the construction and demolition activities, and mining and quarrying operation, 97% was mineral waste or soils (excavated earth, road construction waste, demolition waste, dredging spoil, waste rocks, tailing and others). From these data comes out that construction sector generates the greatest waste fraction within the European Union. Therefore, recycling this waste is fundamental to reduce the volume of dumped waste. On the other hand, recycling has another environmental advantage, that of decreasing the consumption of natural resources. Construction and demolition waste plants have been proved to be economically viable as well as having a positive environmental impact. One of the ways of recycling under evaluation is using this waste in concrete production, for which construction and demolition waste have a great potential.

1.3. River sand availability

Globally, between 47 and 59 billion tons of material is mined every year (Steinberger, Krausmann and Eisenmenger, 2010); this is twice the yearly amount of sediment carried by all of the rivers of the world. Although more sand and gravel are mined than any other material, reliable data on their extraction in certain developed countries are available only for recent years. The absence of global data on aggregates mining makes environmental assessment very difficult and has contributed to the lack of awareness about this issue.

The demand for aggregates stems from a wide range of sectors, including production of glass, electronics and aeronautics. However, its largest use is in construction and land reclamation (UNEP, 2014). Considering the enormous quantity of concrete produced around the world, due to the boom in urbanization and industrialization, it gives rise to different sustainability issues. River sand is produced by the weathering/abrasion of the gravel bed and also it is one of the most used and economically available natural building material.

The availability of river sand for the preparation of concrete has become scarce due to the excessive and non-scientific methods of mining from the river beds. This has called for several harmful consequences, including increased river bed depth, lowering of the water table, exposure of bridge substructures, major impact on rivers, deltas and coastal and marine ecosystems, loss of land through river or coastal erosion and decrease in the amount of sediment supply (Dan Gavriletea, 2017).

Table 1 - Summary of the main consequences of extraction of aggregates

Impacts on	Description
Biodiversity	Impacts on related ecosystem (for example fisheries)
Land losses	Both inland and coastal through erosion
Hydrological function	Change in water flows, food regulation and marine currents
Water supply	Through lowering of the water table and pollution
Climate	Directly through transport emissions, indirectly through cement production
Landscape	Coastal erosion, changes in deltaic structures, quarries, pollution of rivers
Extreme events	Decline of protection against extreme events (flood, drought, storm surge)

However, a shift to marine and coastal aggregates mining has occurred due to the decline of inland resources. River and marine aggregates remain the main sources for building and land reclamation. For concrete, in-stream gravel requires less processing and produces high-quality material, while marine aggregate needs to be thoroughly washed to remove salt. If the sodium is not removed from marine aggregate, a structure built with it might collapse after few decades due to corrosion of its metal structures (Limeira, Agullo and Etxeberria, 2010). Also, desert sand, which seems to stretch across the globe forever, does not serve this purpose due to its consistency and chemical properties. This is mainly due to its lack of silicon dioxide compounds and the fact that desert sand is too fine and smooth, containing too much clay, iron oxides and lime (Chilamkurthy, A.V. Marckson, S. T. Chopperla, 2016).

As such, finding an alternative material to river sand has became imperative. Over the past several decades, an enormous amount of research has been carried on the use of solid waste as a substitute/replacement material for fine aggregate.

1.4. Waste materials and by-product in concrete

Large quantities of waste materials and by-products are generated from manufacturing processes, service industries and municipal solid waste, etc. As a result, solid waste management has became one of the major environmental concerns in the world. With the increasing awareness about the environment, scarcity of land-fill space and due to its ever increasing cost, waste materials and by-products utilization has became an attractive alternative to disposal (Batayneh, Marie and Asi, 2007). High consumption of natural sources, high amount production of industrial wastes and environmental pollution require obtaining new solutions for a sustainable development.

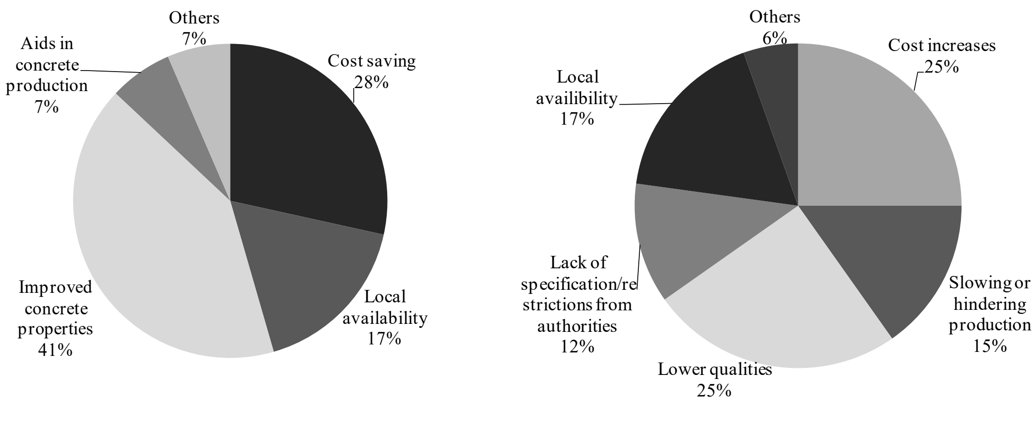


Fig. 4 - Benefits and barriers of using waste material as partial replacement of cement (Jin and Chen, 2013)

During recent years there has been a growing emphasis on the utilization of waste materials and by-products in construction materials. Utilization of waste materials and by-products is a partial solution to environmental and ecological problems. Use of these materials not only helps in getting them utilized in cement, concrete and other construction materials, it helps in reducing the cost of cement and concrete manufacturing, but also has numerous indirect benefits such as reduction in landfill cost, saving energy and protecting the environment from possible pollution effects. Further, their utilization may improve the microstructure, mechanical and durability properties of mortar and concrete (Siddique, 2007).

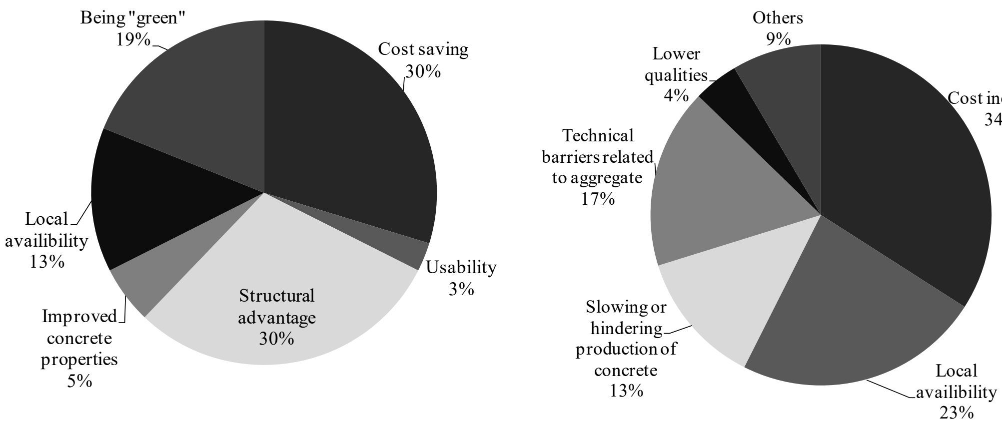


Fig. 5 - Benefits and barriers of using waste material as alternative aggregates in concrete (Jin and Chen, 2013)

Significant research has been going on in various part of the word on this subject. Some waste materials and by-products have established their credentials in their usage in cement-based materials and for others research is in progress the potential applications. In the following paragraphs, several waste material and by-product are described from their sources to the possible uses in concrete production.

1.4.1. Coal fly ash

Coal fly ash is a by-product of the combustion of pulverized coal in thermal power plants. It is removed by the dust collection system from the exhaust gases of fossil fuel power plants as very fine, predominantly spherical glassy particles from the combustion gases before they are discharged into atmosphere. The cementitious properties of fly ash have been known for some time. However, its use became more widespread after clean air regulations forced power plants to install scrubbers and electrostatic precipitators to trap the fine particles, which earlier went up the smokestacks and into the environment.

Fly ash is an important pozzolan, which has a number of advantages compared with regular Portland cement. First, the heat of hydration is lower, which makes fly ash a popular cement substitute for mass structures. Possibly the most important advantage of fly ash is the fact that it is a by-product of coal combustion, which otherwise would be a waste product to be disposed of a great cost. Moreover, concrete produced with fly ash can have better strength and durability properties than concrete produced normally. It is widely available, namely wherever coal is being burned. Finally, fly ash is generally less expensive than Portland cement (Meyer, 2009).

The relatively slow rate of strength development of fly ash concrete is a disadvantage in applications where high early strength is required. But in many situation, especially those involving mass concrete structures such as dams and heavy foundation, which are not loaded to their design values in short times after their placement, it is quite common to specify 90-day strengths instead of the conventional 28-day strengths (Siddique, 2003).

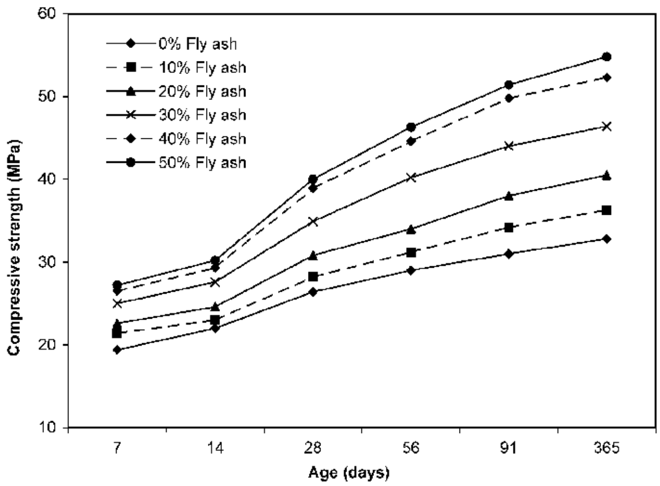


Fig. 6 - Compressive strength versus age in fly ash concrete (Siddique, 2003)

If normal strength development is critical, accelerators are available to speed up the hydration rates of fly ash concrete mixes. A more serious problem concern the need for quality control. The physical and chemical properties of fly ash can vary considerably from power plant to power plant, primarily because of the differences in the sources of coal. The wide variety of chemical composition and quality poses challenges. But the fly ash industry has improved the quality control in recent years and developed technologies to effectively separate unburned residues.

1.4.2. Ground granulated blast furnace slag

Ground Granulated Blast Furnace Slag (GGBS) is a by-product of the manufacturing of iron in a blast furnace where iron ore, limestone and coke are heated up to 1500°C. It is the glassy granular material formed when molten blast furnace slag is rapidly chilled, as by immersion in water. Its cementitious properties have been known for some time. Since 1950s, use of GGBS as a separate cementitious material has become widespread in many different countries. Because of its generally beneficial properties, such slag is not used as partial Portland cement replacement, but also as aggregate (Meyer, 2009).

The optimum cement replacement level is often quoted to be about 50% and sometimes as high as 70% and 80%. Like fly ash, GGBS also improves many mechanical and durability properties of concrete and generates less heat hydration. In many situations so-called ternary systems, that is blends of ordinary Portland cement, fly ash and GGBS, have become popular (Majhi, Nayak and Mukharjee, 2017). In Europe the practice of pre-bending cements and various pozzolans is widespread. The cost of slag and of Portland cement is generally the same.

1.4.3. Silica fume

Silica fume is a by-product resulting from the reduction of high-purity quartz with coal or coke and wood chips in an electric arc furnace during the production of silicon metal or ferrosilicon alloys. The silica fume, which condenses from the gases escaping from the furnaces, has a very high content or amorphous silicon dioxide and consists of very fine spherical particles (Siddique, 2007). In recent years significant attention has been given to the use of pozzolan silica fume as a concrete property-enhancing material, as a partial replacement for Portland cement, or both. The initial interest in the use of silica fume was mainly caused by the strict enforcement of air-pollution control measures in various countries to stop release of the material into the atmosphere. This siliceous material improves both strength and durability of concrete.

Silica fume was initially viewed as a cement replacement material and in some areas it is still used as such. In general application part of the cement may be replaced by a much smaller quantity of silica fume. For example, one part of silica fume can replace three or four parts of cement (mass to mass) without loss of strength, provided the water content remains constant (Holland and Detwiler, 2006). Because of limited availability and the current high price, silica fume is being used increasingly as a property-enhancing material. In this role silica fume has been used to provide concrete with very high compressive strength or with very high levels of durability or both.

1.4.4. Recycled concrete

Traditional disposal of construction and demolition waste in landfills is no longer an acceptable option, especially in developed countries, where the remaining landfill capacity has been estimated to last for only a few more years. In *Table 2* there are the amounts of construction and demolition waste material generated and recovered annually in Italy.

Table 2 - Annual production and recovery percentages of construction and demolition waste materials in Italy (ISPRA, 2014)

Waste category	Quantity generated (tons)	Quantity recovered (tons)	% recovered
Ferrous metal waste and scrap	4.153.033	3.490.709	84%
Non-ferrous metal waste and scrap	499.442	343.546	69%
Mixed metal waste	140.422	90.516	64%
Glass wastes	60.235	42.409	70%
Plastic wastes	34.112	7.082	21%
Wood wastes	151.407	78.533	52%
Construction and demolition wastes	33.756.796	25.245.403	75%

The technical problems of incorporating recycled concrete aggregates into new concrete mixes are well known and have been addressed through research. Most of these can be attributed to the large amount of fines found in recycled concrete, but recent studies suggest that also this problem is solvable (Kabir, Al-Shayeb and Khan, 2016). Recycled aggregates have generally lower densities than the original material used, because of the cement mortar that remains attached to the aggregate particle. This is also the main reason for the larger water absorption of recycled concrete aggregates compared with that of virgin aggregate. Another source of concern is the variety of contaminants that can be found in recycled concrete as a result of demolition of existing structures, such as plaster, soil, wood, gypsum, asphalt and rubber. Since even small amounts of such contaminants can severely degrade the strength or durability of the concrete made with them.

Concrete produced with recycled concrete aggregate is generally of lower quality. Recycled aggregates causes a reduction of strength and in elastic modulus, an increase in creep and shrinkage deformations, as well as higher permeability of concrete, which decreases its durability (Bravo *et al.*, 2015). The use or recycled concrete aggregate is largely a matter of economics, with a number of factors playing a role. Probably the foremost among these is the cost of transportation of both construction and demolition debris from the demolition site to the nearest suitable landfill and of the virgin aggregate from its source to the construction site. Another factor is the cost of land-filling construction and demolition debris, which has a tendency of increasing faster than the rate of inflation.

1.4.5. Post-consumer glass

When waste glass is crushed to sand-like particle size, similar to that of natural sand, it exhibits properties of an aggregate material. The uses of glass products have increased tremendously resulting in large amounts of waste glass. There are two type of waste glasses: colored and colorless. Most colorless waste glasses are recycled effectively. Colored waste glasses with their low recycling rate are generally dumped into landfill sites (Siddique, 2007). However, with storage of landfill sites, land filling is becoming more and more difficult. Since glass is not biodegradable, landfill do not provide an environment-friendly solution. Different studies have been made for the use of waste glass in cement and concrete industries. Some of this studies used waste glass as an aggregate, others used it as a cement replacement.

Waste glass and natural sand have approximately the same physical properties, this make waste glass an interesting material to be used as an aggregate in the production of concrete. Compressive, flexural and tensile strength was found to decrease as the percentage of the waste glass exceeded a certain value (Topçu and Canbaz, 2004).

Table 3 – Hardened concrete properties of concrete with waste glass (Topçu and Canbaz, 2004)

Waste glass (%)	Compressive strength (MPa)	Tensile strength (MPa)	Flexural strength (MPa)	Dynamic modulus of elasticity (GPa)
0	23,5	2,59	4,5	37
15	21,67	2,34	5,27	59,98
30	19,55	2,29	3,97	25
45	16,12	2,35	5,24	27
60	12,04	1,63	3	22,58

The poor shape of the coarse waste glass aggregate caused a decrease in adhesive strength between the waste glass aggregate and the cement paste and produced a low strength concrete. This means that the particle size of the glass waste plays a vital role in the performance of concrete (Jani and Hogland, 2014).

1.4.6. Recycled plastics

Of the millions of tons of the plastic discarded each year, only a relatively small percentage is being recycled. Plastics come in many different forms and chemical formulations. This complicates the recycling process as well as their use in concrete production. Because the different types of plastic are typically commingled, it is barely economical to separate them in volume. De-polymerization or chemically breaking plastics down to their virgin components is not possible with currently available technologies. Many plastics can be recycled back into blank feedstock to be used as input for thermosetting or plastic manufacturing (Meyer, 2009).

A major obstacle for the use of recycled plastic in concrete is the poor bond between the plastic particles and the cement matrix, which can reduce the strength and other mechanical properties considerably, depending on the percentage of aggregate replaced by shredded plastic.

1.4.7. Recycled tyres

The hundreds of millions of scrap tyres generated each year in developed countries pose a serious environmental problem. Tyre dumps are unsightly and pose significant health hazard as breeding grounds for mosquitoes as well as fire hazards. Some tyre fires have been reported to burn for months and even years. Therefore the disposal of tyres in regular landfills is often prohibited. One unfortunate consequence is an increase in illegal dumping of scrap tyres, with their accompanying environmental problems (Rashad, 2016).

Fig. 7 – Waste rubber landfill

Probably the most meaningful method of recycling used tyres is to reuse them after retreading. The most common disposal method of old tyres seems to be to burn them for the production of steam and electricity or heat. The use of tyres as an alternative fuel in cement kilns is widespread throughout the United States and Europe. Their value as fuel is considerably less than that of the original material, so that such a use constitutes an example of downcycling (Brown *et al.*, 2001). A different use of scrap tyres is in hot mix asphalt or as crumb rubber for modifying binder in asphalt pavements (Navarro *et al.*, 2005).

Although some of these and other applications have been more or less successful, they either result in too much loss in value, or they not generate enough volume to make a noticeable dent in the existing stockpiles of scrap tyres. This leaves use of tyre rubber as an ingredient in concrete production as a major viable alternative (Meyer, 2009). From a strictly economic point of view, a simple replacement of fine or coarse aggregate still implies a certain degree of downcycling, unless specific properties of the rubber can be exploited that natural sand and gravel or crushed stone do not have.

The most common ways of recycling rubber in cement composites and concrete is to use it as shredded, chipped, ground or crumb rubber, with sizes ranging from shredded pieces as large as 450 mm to powder particles as small as 75 μm. Because of the large differences between Young's moduli of rubber and cement matrix, major differences in the mechanical properties are to be expected between concrete with conventional natural aggregate and rubberized concrete. Most significant is the loss in compressive and tensile strength as well as stiffness with increasing rubber content. The strength loss is to be expected, since the rubber particles not only constitute weak inclusions, they are also responsible for significant tensile stresses in the cement matrix, which lead to earlier cracking and failure (Eldin and Senouci, 1993).

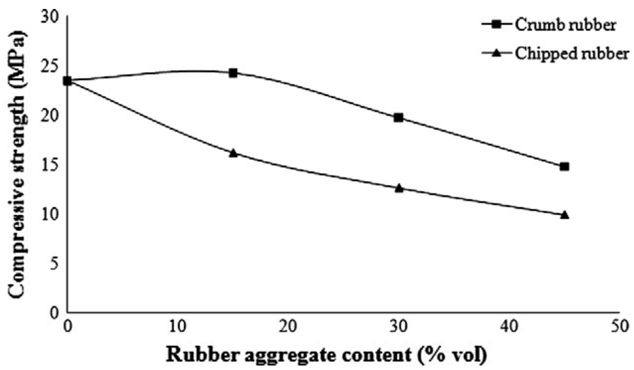


Fig. 8 – Compressive strength loss in concrete with rubber particle (Najim and Hall, 2010)

On the other hand, the rubber particles have a restraining effect on crack propagation, which leads to a significant increase in strain capacity, ductility and energy absorption capacity. Other potential advantages of the rubber derive from its sound absorption capacity as well as its thermal properties.

1.4.8. Other recycled materials

Numerous other material have been proposed as substitutes for conventional ingredients of concrete. Most important among these materials are ashes of many different kinds. In addition to fly ash and GGBS, there are other ashes with more or less pronounced pozzolanic properties that lend themselves to partial replacement of Portland cement. For example, the is rice husk ash, the residue from burning rice husk and an agricultural by-product of the production of rice, of which millions of tons are produced world-wide each year. The rice husk ash has been shown to have valuable cementitious properties and therefore has been proposed as a supplementary cementitious material (Mehta and Folliard, 1995).

Most large metropolitan areas are facing major solid waste disposal problems. One solution is to burn the solid waste in so-called waste-to-energy facilities. However, the disposal of the ash even in conventional landfills is problematic because the fly ash in particular is considered a hazardous material as it contains unacceptable levels of toxic elements.

Another potential source for concrete production is dredged material (Mehta and Folliard, 1995). Since dumping in the ocean is no longer an option, the material has to be deposited in engineered landfills at great cost, because much of it is highly contaminated with heavy metals, dioxins, oils, etc. Treatment methods are already available, which render the material suitable for concrete production, because the heavy metals can be encapsulated chemically such that they cannot leach out.

Recycled carpet fibers have also been proposed to replace virgin fibers in fiber-reinforced concrete (Meyer, C; Shimanovich, S and Vilkner, 2002). Millions of tons of old carpets need to be disposed of each year, constituting another sizeable fraction of solid waste. Since carpet fibers are typically made of nylon, recycled fibers have been shown to improve some mechanical properties of concrete.

2. Current status of research on rubberized concrete

Among all the materials discussed in the previous section, the present works deals with the recycling of used tyre rubber as a partial replacement of fine and coarse aggregate in concrete materials. Therefore, the first part of this chapter will introduce the waste tyre management, from their disposal to energy and material recovery. Then, it will summarize and compare the results obtained in previous studies undertaken to better understand the performance characteristics for scrap vehicle tyres to be utilized as an alternative to conventional aggregates in concrete.

2.1. Used tyre environmental problem

In recent decades, worldwide growth of automobile industry and increasing use of car as the main means of transport have tremendously boosted tyre production. About 1.4 billion tyres are sold worldwide each year and subsequently as many eventually fall into the category of end of life tyres. Moreover, the amount of end of life tyre in Europe, US and Japan are about to increase because of the projected growing number of vehicles and increasing traffic worldwide (Lo Presti, 2013). These tyres are among the most problematic sources of waste, due to the large volume produced and their durability.

The US Environmental Protection Agency reports that 290 million scrap tyres were generated in 2003 (EPA, 2007). Of the 290 million, 45 million of these scrap tyres were used to make automotive and truck tyre re-treads. In Europe every year, 355 million tyres are produced in 90 plants, representing the 24% of world production. In addition, European Union countries have millions of used tyres that have been illegally dumped or stockpiled (Rashad, 2016). The inadequate disposal of tyres may, in some cases, pose a potential threat to human health. The tyre stores water for a long period because of its particular shape and impermeable nature providing a breeding habitat for mosquitoes and various pests. Tyre burning, which was the easiest and cheapest method of disposal, causes serious fire hazards.

Fig. 9 – Disposal tyre burning

Once ignited, it is very difficult to extinguish as the 75% free space can store lot of free oxygen. In addition, the residue powder left after burning pollutes the soil. The oil that is generated from the melting of tyres can also pollute soil and water (Sofi, 2017).

In order to face this problem, in Europe in 1989, a used tyres group composed of experts from the main tyre manufacturers producing in Europe, was sent up to strategic guidance of the European Tyre and Rubber Manufacturers Association (ETRMA). This group was dedicated to the managements of end of life tyres. Also thanks to this group, since 1996, the collection rate has increased steadily while there has been a continuous decline in the land filling of used tyres. In 2013, about 3.6 million tons of waste tyres were generated in European Union countries, of which an estimated 2.7 million tons were recovered and recycled, which represent a treatment rate of 96% (ETRMA, 2015). This confirms Europe as one of the most active areas in the world in the recovery of end of life tyre.

2.2. End of life tyre as a raw material

The tyre is a complex and high-tech safety product representing a century of manufacturing innovation, which is still on-going. From the material point of view the tyre is made up of three main components materials: elastomeric compound, fabric and steel.

Table 4 – Typical materials used in tyre manufacturing in Europe according to the percentage of the total weight of the finished tyre that each material class represent (Sienkiewicz *et al.*, 2012)

Materials	Passenger tyre	Truck tyre
Natural rubber (%)	22	30
Synthetic rubber (%)	23	15
Carbon black (%)	28	20
Steel (%)	13	25
Fabric, fillers, accelerators, antiozonants, etc. (%)	14	10
Average weight	New 8,5 kg Scrap 7 kg	New 65 kg Scrap 56 kg

The fabric and steel form the structural skeleton of the tyre with the rubber forming the “flesh” of the tyre in the tread, side wall, apexes, liner and shoulder wedge (Siddique and Naik, 2004). This engineering process is necessary to transform natural rubber in a product able to ensure performance, durability and safety. In fact, natural rubber is sticky in nature and can easily deform when heated up and it is brittle when cooled down. The reason for inelastic deformation of not-vulcanized rubber can be found in the chemical nature as rubber is made of long polymer chains. These polymer chains can move independently relative to each other, and this will result in a change of shape. By the process of vulcanization cross-links are formed between the polymer chains, so the chains can’t move independently anymore. As a result, when stress is applied the vulcanized rubber will deform, but upon release of the stress the rubber article will go back to its original shape. Compounding is finally used to improve the physical properties of rubber by incorporating the ingredients and ancillary substances necessary for vulcanization, but also to adjust the hardness and modulus of the vulcanized product to meet the end requirements (Lo Presti, 2013).

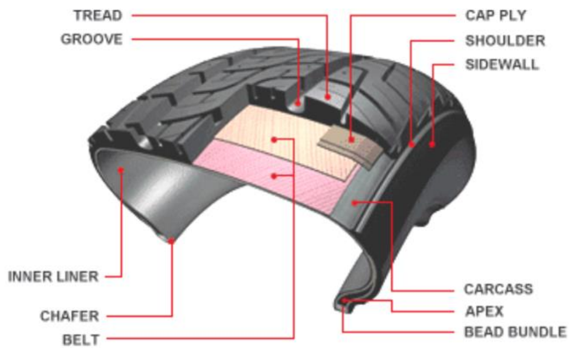


Fig. 10 – Tyre anatomy (checkthatcar.com)

From the structural point, the main components of a tyre are the tread, the body, side wall and the beads. The tread is the raised pattern in contact with the road. The body supports the tread and gives the tyre its specific shape. Beads are metal-wire bundles covered with rubber, which holds the tyre on the wheel (Czajczyńska *et al.*, 2017).

2.2.1. Life tyre cycle

The tyre life cycle traditionally compries five main stages, which includes extraction, production, consumption, collection of used tyres and waste management.

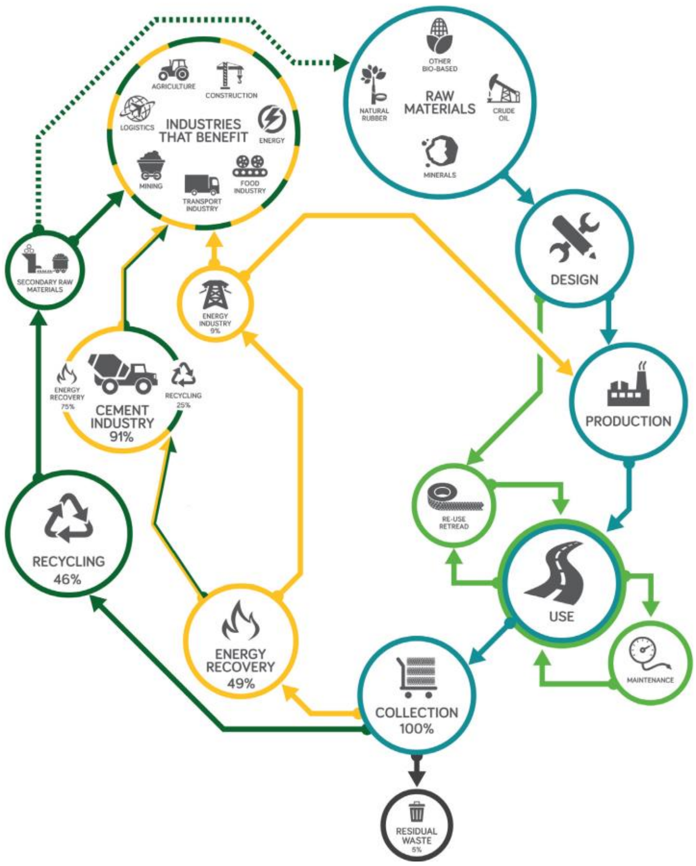


Fig. 11 – Tyre life cycle (ETRMA, 2015)

For tyres, the first step of production is the design stage. The raw materials are considered and how they can best be used to produce a recyclable product. It is during the consumption phase that the environmental impact of tyres goes at its greatest. To better this situation systems able to extend the life of tyre are necessary: tyres need to be maintained and technology is helping by ensuring the correct pressures and loadings, reminding about wheel position rotation. Tyre pressure monitoring is now mandatory on all new cars in Europe, the future will bring more digital input into tyre maintenance. Commercial vehicle and truck tyres will be regrooved and retreated as often as the manufacturers recommends. All this serves to extend the life of tyre and mitigate the demand on natural resources.

Until 2003, end of life tyre were allowed to landfill, which was definitely outlawed in 2006 also for shredded tyres by the Landfill Directive (Council Directive, 1999). Today, legislation has driven the tyre sector towards recovery and recycling. With collection rates in much of Europe at 100% of arisings, the tyre industry is halfway to a circular economy. Of that 100% collection figure there is an estimated 5% considered as residual waste, with unknown recovery routes. The balance goes largely to energy recovery (49%) and recycling (46%). The biggest part that goes to energy recovery is used in the cement kilns. In this phase recycled tyres become secondary raw materials that can go into new products.

2.2.2. From end of life tyre to scrap-tyres

A tyre may contain more than one compound and more than one type of rubber. For example on a car tyre there will be a sidewall rubber, a casing rubber and a top tread rubber, all adding different elements to the performance of a tyre. The detailed composition of a tyre is very complex and any rubber recovered from a tyre may contain an amalgam of different compounds, and yet this material presents homogeneous properties when adequately sampled.

Separating and devulcanizing these compounds to recover them is a difficult task. So, the rubber in recycled tyres is often treated as a complex resource and recycled in its entyrely as shred, crumb, granulate or powder. Each of these stages of size reduction has its own characterization and one style of size reduction will create an end product with different properties to that created by another system (Sofi, 2017).

Two of the key differences are in granulates and powders produced by ambient and cryogenic size reduction (Lo Presti, 2013). In the former, ambient shredding and granulation produces a tearing effect that leaves a coarse surface area. The grater the surface area of the granulate or powder produced by ambient processes, the more surface active the product becomes and it has properties that give it greater binding potential in new mixes, either in rubber, or in elastomer mixes for remolding.

Cryogenic size reduction usually requires an initial ambient shred to downsize the tyre, the shred is then fed into a hammer mill in a very low temperature nitrogen atmosphere and the tyre is literally smashed into granulate or powder. The form of the product by this method is cuboid, it has flat surfaces and a low surface activity ratio. However, it is physically easier to create microscopic powders by cryogenic size reduction and by making the powders finer, it is possible to create a similar surface area per weight compared to ambient grinding (ETRMA, 2015). Therefore, cryogenic powders can then be used in new compounds and other processes such as rubberized asphalt.

2.2.3. Classification of scrap-tyres

Tyres may be divided into two types: car and truck tyres. Car tyres are different from truck tyres with regard to constituent materials, especially natural and synthetic rubber contents. Considering the high production volume of car tyres as compared to truck tyres, the former is usually of more interest to researches.

In most of the researches performed, usually three broad categories of discarded tyre rubber have been considered such as chipped, crumb and ground rubber:

- Shredded or chipped rubber to replace the gravel. To produce this rubber it is needed to shred the tyre in two stages. By the end of stage one, the rubber has length of 300-400 mm long and width of 100-230 mm wide. In the second stage its dimension changes to 100-150 mm by cutting (Siddique and Naik, 2004).
- Crumb rubber that replaces for sand, is manufactured by special mills in which big rubbers change into smaller torn particles. In this procedure, different sizes of rubber particles may be produced depending on the kind of mills used and the temperature generated. In a simple method, particles are made with a range of 0,425-4,75 mm (Ganjian, Khorami and Maghsoudi, 2009).
- Ground rubber that may replace cement is dependent upon the equipment for size reduction. The processed used tyres are typically subjected to two stages of magnetic separation and screening. Various size fractions of rubber are recovered in more complex procedures. In micro-milling process, the particles made are in the range of 0,075-0,475 mm (Najim and Hall, 2010).

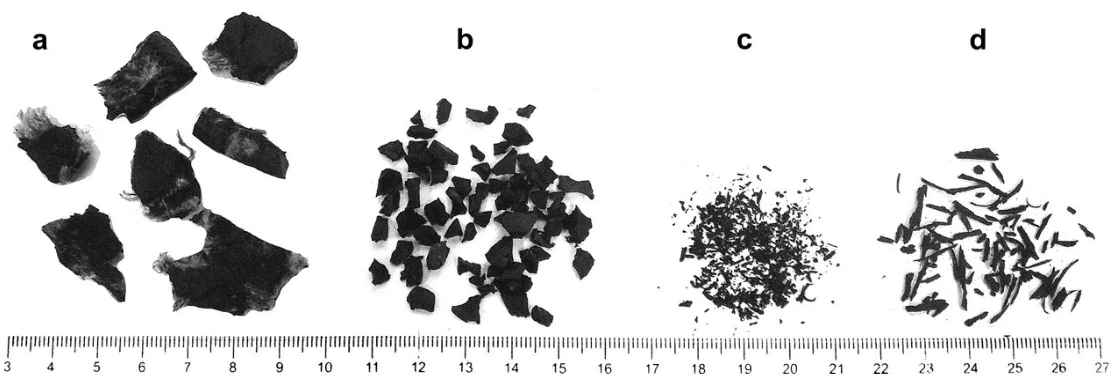


Fig. 12 – Classification of rubber aggregates: (a) chipped, (b) crumb, (c) granular and (d) fibre (Najim and Hall, 2010).

2.2.4. End of life tyre derived products

End of life tyres can't be considered as a simple waste to be disposed because they are, in fact, a resource of renewable materials and energy. After shredding and removal of steel and fabric components, the remaining rubber is reduced to rubber granules. Applications of end of life tyres rubber granules include molded rubber products such as wheels for caddies, dustbins, wheelbarrows and lawnmowers, urban furniture and sign posts.

Rubber and powder are also to be found as flooring for playgrounds, as athletic tracks, as shock absorbing mats for school and stables, as paving blocks or tiles for patios and swimming pool surrounds as well as roofing materials. One of the main uses of end of life tyre granules is rubber infill of artificial turf, for example in football fields. In this way, characteristics such as elasticity, weather resistance and extremely good aging properties are maintained.

Fig. 13 – Athletic tracks, 100% made of end of life tyres.

Utilization of scrap tyres in asphalt pavements construction is one of the most successful cases of end of life tyres recycling. Use of crumb rubber modified asphalt started from 1980s and the asphalt industry can recycle up to 40% scrap tyres in each year. Crumb rubber modified asphalt is defined as modified asphalt composed of virgin asphalt and no less than 15% crumb rubber by the weight of virgin asphalt. The benefits of using rubber asphalt binder include three parts: decreased traffic noise, improved pavement performance and reduced maintenance cost (Ding *et al.*, 2017).

Whole tyres are predominantly used in civil engineering applications. Those applications vary from coastal protection, erosion barriers, artificial reefs, breakwaters, avalanche shelters, slope stabilization, road embankments and landfill construction operations, sound barriers, insulation.

Among existing alternatives, recycling waste to produce novel concrete materials is an attractive option that could potentially combine environmental and performance advantages. As a result, in recent years, several investigations have been conducted to assess the feasibility of using recycled rubber materials in concrete.

2.3. Properties of rubberized concrete

Material tests on both fresh and hardened concrete indicated that the replacement of mineral aggregates with rubber particles modifies significantly the mechanical properties of the new composite material. On the one hand, concrete is an implicitly brittle material which is a function of the strength of the cement paste, whereas rubber is a hyper-elastic incompressible material with high Poisson ratio and has a high tensile strength. The combination of the two results in a novel material benefitting from the strength of the concrete matrix, which governs the elastic constitutive behavior, and the energy absorption properties of rubber.

2.3.1. Density

The effect of rubber aggregates in concrete mixtures as replacement of fine and coarse aggregates on concrete density has been investigated by several authors. It is clear that rubberized concrete is lighter than the common concrete since rubber has a lower specific gravity than mineral aggregates.

In fact, previous studies confirmed that density of concrete decrease with the increase in the percentage of rubber content (Khatib and Bayomy, 1999; Topçu, 1995; Benazzouk *et al.*, 2007). For example, Aiello and Leuzzi (2010) reported that mixtures prepared by adding 50% by volume of rubber shreds, showed a density decay of about 6% and, in the same way, mixtures obtained including 75% by volume of rubber particles presented more than 8% unit weight decrease.

Same results have been achieved by Fattuhi and Clark (1996), *Fig. 14* shows that the addition of either low-grade rubber and rubber crumb resulted in a reduction of concrete density. However, for a similar rubber content, concrete containing low-grade rubber possessed lower densities and the difference in density increased as the rubber content increased. This difference may be due to the higher content of textile fibers in the low-grade rubber, and hence, lower mass.

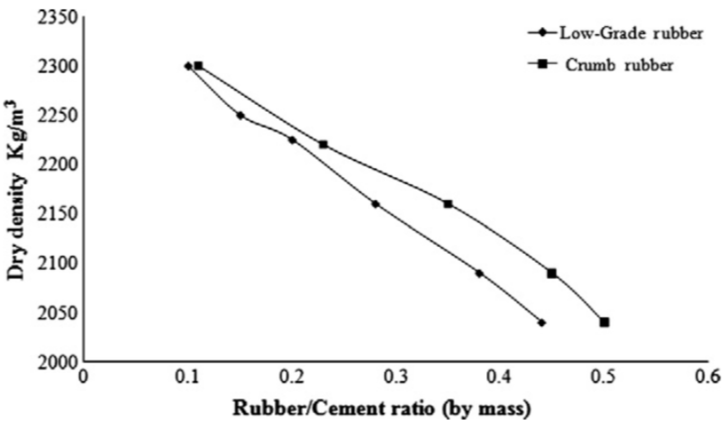


Fig. 14 – Influence of type and quantity of rubber on density of concrete (Fattuhi and Clark, 1996).

Interestingly, many researchers have observed a strong positive correlation between the mix percentage air content and the percentage of weight rubber aggregates. Bing and Ning (2014) noted that the addiction of rubber particles reduces the dry unit weight as expected, considering the lower density of rubber particles compared to that of coarse aggregate. However, a calculation based on the density difference between rubber particles and coarse aggregates shows that the simple replacement of coarse aggregate by rubber is insufficient to justify the observed amplitude of the decrease in unit weight.

Such a result was explained with the variation of the air content induced by the rubber particles (Najim and Hall, 2010). This may be due to the non-polar nature of rubber particles and their tendency to entrap air in their rough surfaces. Also, when rubber is added to a concrete mixture, it may attract air as it has the tendency to repel water and then air may adhere to the rubber particles (Siddique and Naik, 2004).

2.3.2. Workability

Many studies have been conducted to evaluate the workability of rubberized concrete by testing the slump of the mixture. In general, researches have observed a significant reduction in one point workability (slump) as the rubber aggregate content was raised. It is currently hypothesized that this reduction can be attributed to the higher level of inter-particle friction that occurs between the rubber aggregate and the other mix constituents (owing to the surface texture of the rubber particles) as well as the overall reduction in the unit weight of the plastic mix (Batayneh, Marie and Asi, 2008; Güneyisi, Gesoğlu and Özturan, 2004)

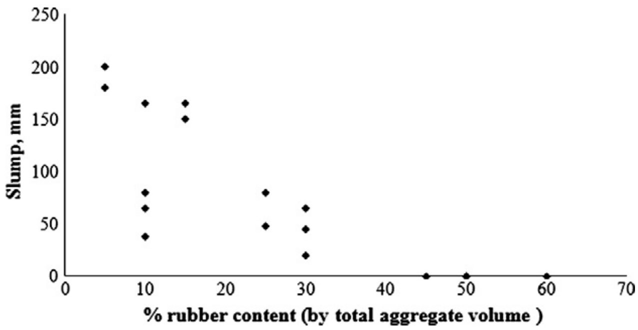


Fig. 15 – Effect of aggregate replacement ratio on slump of rubber concrete (Najim and Hall, 2010)

Reda Taha *et al.* (2008) observed that the magnitude of reduction of slump depends not only by the percentage of rubber but also upon the size of rubber particles. In fact, they found that the effect of slump seems more pronounced with chipped tyre rubber compared with crumbed tyre rubber particles due to the relatively larger size of the former.

A different result has been achieved by Aiello and Leuzzi (2010). They noted that workability of fresh concrete is slightly improved by the partial substitution of coarse or fine aggregate with rubber shreds. In fact, their control mixture (concrete without rubber replacement) presented a S4 class consistency characterized by a fluid behavior, whereas all mixtures obtained by adding rubber particles instead of coarse of fine aggregate showed a S5 class consistency and, thus, a hyper-fluid behavior. This means that rubberized concrete can be mixed, casted and vibrated using equipment and procedures adopted for conventional concrete. These results are in good agreement with workability measurements reported by Raghavan, Huynh and Ferraris (1988) where recycled tyre rubber-filled cementitious composite achieved workability comparable or better than the control mortar.

2.3.3. Compressive strength

The impact of using the scrap tyre rubber aggregate as a partial replacement for natural aggregates, on the compressive strength has been well documented (Topçu, 1995; Aiello and Leuzzi, 2010; Bompa *et al.*, 2017; Fantilli, Chiaia and Gorino, 2016; Eldin and Senouci, 1993). Across a large number of previous studies, all reported that the compressive/tensile and static modulus of elasticity of rubberized concrete decreases significantly with increased quantities of rubber aggregate replacement. The two mechanisms responsible for this general reduction in strength are:

- Significant disparity between the modulus of elasticity for rubber aggregates and hardened cement paste;
- Poor development of the interfacial transition zone.

These two mechanisms are largely interdependent since weak of interfacial transition zone bonding leads to initiation and propagation of microcracks that develop around the perimeter of the rubber particles and, under loading, the differential strain rates between rubber and hardened cement paste exacerbate the problem (Najim and Hall, 2010).

Aiello and Leuzzi (2010) showed that the replacement of coarse aggregate in concrete lowered the compressive strength more than the substitution of the fine aggregate. In their study rubberized concrete mixtures prepared with 50% and 75% by volume of coarse aggregate replacement, presented, respectively, a decrease in compressive strength of about 54% and 62% compared with control mixture. Whereas, mixtures obtained with 50% and 75% by volume of fine aggregate substitution, showed, respectively, a compressive decay of about 28% and 37%, compared to the control mixture. These results confirm previous research work carried out by Topçu (1995) and Khatib and Bayomy (1999). However, results reported by Fattuhi and Clark (1996) indicate the opposite trend.

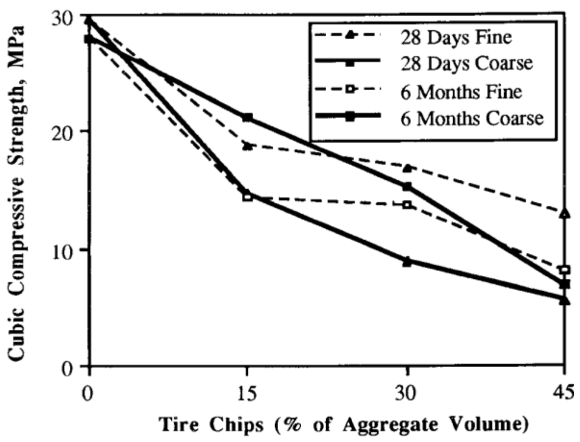


Fig. 16 – Changes in cubic compressive strength with the amount of rubber content (Topçu, 1995)

Eldin and Senouci (1993) investigated on two different groups of concrete mixtures: the first group contained chipped rubber, obtained by mechanical grinding, and the second one contained crumb rubber, obtained by cryogenic grinding. As confirmed by other researches, the reduction in compressive strength was observed to be higher in the first group. Because of their low modulus of elasticity, chipped rubber particles behave as weak inclusions in the hardened concrete mass, producing high internal tensile stress that are perpendicular to the direction of the applied compression load. Since the cement paste is much weaker in tension than in compression, the specimen will start failing under tension before it reaches its compression limit. The generated tensile stress concentrations at the top and bottom of the rubber aggregate result in many tension cracks that form along the tested specimen. These cracks will rapidly propagate in the cement paste until they encounter rubber aggregate. Because of their ability to withstand large tensile deformations, the pieces of rubber aggregate will act as springs, delaying the widening of the cracks and preventing full disintegration of the concrete mass. The continuous application of the compression load on the specimen causes generation of more cracks as well as widening of existing cracks. This process will continue until the stresses overcome the bond between the cement paste and rubber aggregate.

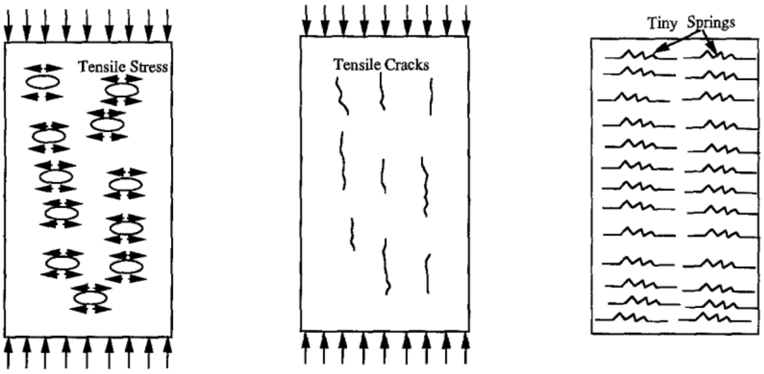


Fig. 17 – Modeling of rubberized concrete with chipped rubber as gravel replacement under compression (Eldin and Senouci, 1993)

An important research contribution on compressive strength of rubberized concrete was given by Bompa *et al.* (2017). Their paper describes an experimental program carried out on rubberized concrete in which fine and coarse mineral aggregates are replaced by rubber particles. Cylindrical and cubic samples with up to 60% rubber replacement have been tested under uniaxial compression to assess complete stress-strain response. The test results and observation permit the definition of a series of prediction expressions for the target mechanical properties of rubberized concrete for structural purposes as well as an analytical model for the detailed characterization of uniaxial stress-strain response as a function of the volumetric rubber ratio. The validation of the proposed expressions for mechanical properties, undertaken against an extensive database of 238 concrete mixes including the mixes investigated in this study and in many previous papers, demonstrate their suitability for typical design procedures. A detailed examination of the results obtained in their experimental program, as well as from the database, showed that the main parameters governing the strength of rubberized concrete are the volumetric replacement ratio, the size of replaced aggregate and characteristics of rubber particles. It was also observed that strength degradation can be affected by the testing arrangement, control and instrumentation, which increase the uncertainty in modelling. To represent the compressive strength degradation for practical application, a parametric equation was developed:

$$f_{cr} = \frac{1}{1 + 2\left(\frac{3\lambda\rho_{vr}}{2}\right)^{3/2}} f_{c0}$$

in which f_{cr} represent the rubberized concrete and f_{c0} the reference strength of the conventional concrete. The volumetric rubber ratio ρ_{vr} and the type of replaced aggregate are incorporated in the formulation. The latter is represented by a factor λ which accounts for the size range of the mineral aggregate replaced.

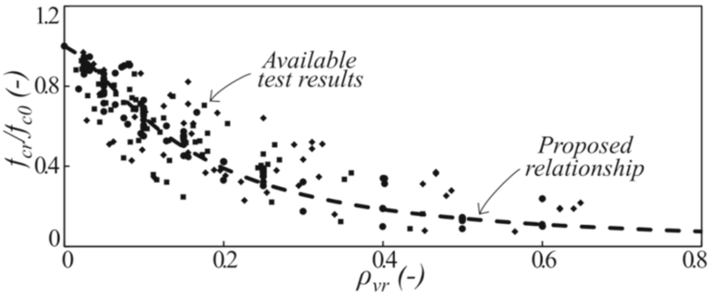


Fig. 18 – Compressive strength as a function of volumetric rubber ratio ρ_{vr} (Elghazouli *et al.*, 2018)

To avoid significant reduction in compressive strength, several researches have recommended the maximum rubber aggregate content should not exceeded between 20% (Khatib and Bayomy, 1999), 25% (Khaloo, Dehestani and Rahmatabadi, 2008) and less than 30% (Zheng, Huo and Yuan, 2008). Another way to minimize the reduction of compressive strength in rubberized concrete is using silica fume in the concrete mixture. In fact, the use of silica fume considerably enhances the mechanical properties of both plain and especially rubberized concretes and decreases the rate of strength loss accompanied by the addition of rubber (Güneyisi, Gesoğlu and Özturan, 2004).

2.3.4. Tensile strength

As seen for compressive strength, all the previous studies on mechanical properties of rubberized concrete reported that tensile strength of concrete decreases with increased percentage of rubber replacement as coarse and fine aggregate (Ganjian, Khorami and Maghsoudi, 2009; Khatib and Bayomy, 1999; Bompa *et al.*, 2017; Eldin and Senouci, 1993).

Ganjian, Khorami and Maghsoudi (2009) tested splitting tensile strength of two different rubber concrete mixture, one realized with coarse aggregate replaced by chipped tyre rubber and the other with crumb tyre rubber. The percent reduction of tensile strength in the first mixture was about twice that of the second mixture for lower percentage of replacements. The reduction in tensile strength with 7,5% replacement was 44% for the first mixture and 24% for the second mixture as compared to the control mixture.

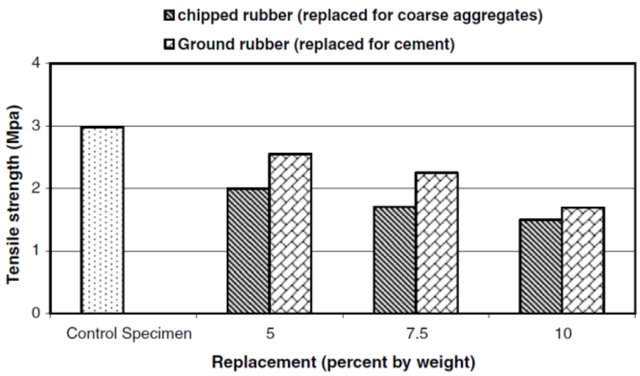


Fig. 19 – Results of tensile strength test (Ganjian, Khorami and Maghsoudi, 2009)

Tyre rubber as a soft material can act as a barrier against crack growth in concrete. Therefore, tensile strength in concrete containing rubber should be higher than the control mixture. However, the results showed the opposite of this hypothesis. The reasons for this behavior may be due to the following variables:

- The interface zone between rubber and cement may act as a micro-crack due to weak bonding between the two materials; the weak zone accelerates concrete breakdown.
- During crack expansion and when it comes in contact with rubber particle, the exerted stress causes a surface segregation between rubber and cement paste. Therefore, it can be said that rubber acts just as a cavity and a concentration point leading to quick concrete breakdown

In their study, Eldin and Senouci (1993) analyzed the mode of tension failure of rubberized concrete cylindrical specimen subjected to splitting tensile test. The failure in this test was not a brittle failure, in fact, the specimens exhibited a ductile mode of failure and a high capability of absorb plastic energy. The concrete mass was able to withstand loads even when it was highly cracked. The specimen never separated into two halves under splitting tension loading. This could happen because the rubber aggregate has the ability to undergo large elastic deformation before failing. Therefore, a tension crack starts at the cement paste or at a mineral aggregate particle and propagates until it reaches a piece of rubber aggregate. Rubber does not fail under the tension stresses capable of failing cement past and mineral aggregate; much higher stresses are required. A tension crack can propagate throughout a specimen only by going around the rubber aggregate, prolonging its path and increasing the area of failure surface.

2.3.5. Flexural strength

In the same way for compressive and tensile strength, flexural strength of rubberized concrete decreases as the content of rubber particle increase (Fantilli, Chiaia and Gorino, 2016; Bompa *et al.*, 2017; Raghavan, Huynh and Ferraris, 1998; Aiello and Leuzzi, 2010; Toutanji, 1996; Khatib and Bayomy, 1999).

According to Toutanji (1996) a significantly smaller reduction in flexural strength was observed as compared to compressive with increases in the tyre chip contents. The flexural strength specimens lost up to 35% of their flexural strength.

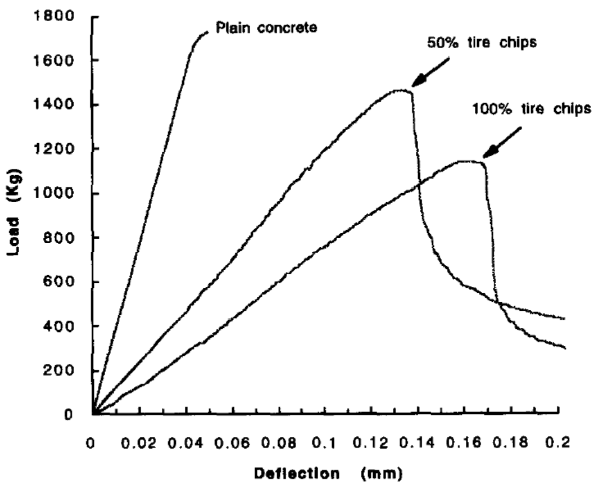


Fig. 20 – Load-deflection curves for plain and rubber tyre concrete beams (Toutanji, 1996)

Load-deflection curves for specimens containing 0, 50 and 100% rubber aggregate obtained in this study are shown in *Fig. 20*. As Toutanji noted, the failure of specimens containing rubber tyre chip exhibited a ductile mode of failure as compared to the control specimens. The specimens exhibited a higher capacity to absorb energy. The specimens were capable of withstanding measurable post failure loads and undergoing significant displacement. This was due to the ability of the rubber aggregate to undergo large elastic deformation before the failure of the specimen took place. The failure was initiated in the extreme fiber of the tension region of the beam specimens, in which cracks propagated in the mortar until they reached the rubber aggregate. When cracks reached the rubber particle and, because of the elastic properties and low modulus of elasticity, the rubber prolonged and sustained a portion of the applied load, which leads to an increase in the area of the failure surface.

Similar to compression strength, a larger reduction of flexural strength was observed when the coarse aggregate rather than fine aggregate was substituted by rubber particles. Aiello and Leuzzi (2010) reported that rubberized concrete mixtures obtained with 50% and 75% by volume of coarse aggregate replacement, both presented a decrease in flexural strength, referred to control mixture, of about 28%. Whereas, mixtures prepared with 50% and 75% by volume of fine aggregate substitution, showed, respectively a decay of about 5,8% and 7,3%, referring to the control mixture.

Fig. 21 – Particular of the cracked section of a specimen after a flexural strength test (Aiello and Leuzzi, 2010)

2.3.6. Bond-slip behavior

In normal concrete, the bond strength between deformed bars and concrete is developed by chemical adhesion and steel-concrete friction followed by the mechanical interlocking of the rebar ribs. Breakdown in bonds can occur in many ways depending on the system of forces. However, in general there are two types of bond failure:

- Splitting failure, when the internal forces between the concrete and reinforcement cause splitting in the concrete cover;
- Pullout failure, where the bar is pulled out and leaves the surrounding concrete generally intact.

For plain bars, the principal mechanisms resisting bond stress are adhesion and friction between the bar surface and the surrounding concrete. These bars are not perfectly smooth and a small bursting force is induced as tension develops in the reinforcement. These bars normally fail by pulling out of the concrete once the adhesion and friction mechanism are lost. For ribbed bars, the principal mechanism of resistance is the bearing of the concrete against the deformations and irregularities on the surface of the bar. These forces induce ring tension and radial cracks in concrete. If the ratio cover/bar diameter is small, then these cracks extend from the bar to the concrete surface and failure occurs by splitting. If the cover/diameter ratio is large, or significant quantities of transverse reinforcement are present, then failure occurs by shearing of the concrete. The magnitude of the ultimate bond stress for this type of failure is much greater than for splitting type failures (Chana, 1990). Previous studies on deformed bars showed that the governing parameters in bond behavior are those related to mechanical bond, rather than chemical adhesion and friction.

Limited information exists on steel-concrete bond behavior in rubberized concrete. Test on 20 mm rebar pull-out resistance were performed by Hall and Najim (2014) on plain and self-compacting rubberized concrete samples with rubber replacement of 18% and 14%, respectively, in equal quantities of both coarse and fine aggregate. These tests showed that maximum bond strength $\tau_{b,max}$ decreases as the mineral aggregates are replaced by rubber.

Also Bompa and Elghazouli (2017) focused on examining the bond strength and the bond-slip relationship, as well as on evaluating the influence of bar diameter and controlled external confinement on the bond behavior. A direct comparison between specimens with 16 mm and 20 mm rebars shows a minimal influence of the rebar size on the bond-slip response, when the concrete section to rebar size ratio is in the same range. Rubberized concrete mixtures with 20% and 40% replacement by volume of sand and gravel show similar $\tau_{b,max}$ ranges for control mixture, whereas rubberized concrete with 60% replacement shows higher variation. Generally, a clear influence of concrete type is observed both from the $\tau_{b,max}$ and also by the level of energy dissipated in the post-peak bond-slip regime. Normal concrete and rubberized concrete with 20% replacement specimens developed a more brittle response compared to rubberized concrete obtained with higher replacement percentages.

2.4. Non-structural properties of rubberized concrete

From previous investigations, it is clear that the implementation of waste rubber particles has a negative effect on the mechanical properties of concrete. Despite this fact, several studies demonstrated that rubber can be used in concrete to benefit of its high insulation properties to enhance the thermal and acoustical insulation properties of concrete (Marie, 2017; Aliabdo, Abd Elmoaty and Abdelbaset, 2015; Sukontasukkul, 2009). Furthermore, increasing the amount of rubber in concrete significantly increases impact time and energy dissipation capacity (Atahan and Yücel, 2012).

2.4.1. Sound absorption

The ability of material to absorb sound can be measured using the sound absorption coefficient (α). Sound waves propagate through material by the combined effect of scattering and absorption as $\alpha = \alpha_{\text{scattering}} + \alpha_{\text{absorption}}$. The $\alpha_{\text{scattering}}$ is related to grain size in polycrystalline materials and $\alpha_{\text{absorption}}$ is related to phenomena such as: energy loss by internal friction (viscosity), thermal conductivity, relaxation, variation in molecules kinetic energy, variations in density, diffusion due to pressure gradient and thermos diffusion (Philippidis and Aggelis, 2005).

Attenuation coefficient of conventional concrete and rubberized concrete at different percentages of sand replacement by rubber particles obtained by Aliabdo, Abd Elmoaty and Abdelbaset (2015) are shown in *Fig. 22*. It can be seen that the attenuation coefficient increases with the increase in rubber content. The increase of sound attenuation comparing to conventional concrete is 14%, 24%, 46%, 58% and 69% ate percentages of sand replacement by rubber particles 20%, 40%, 60%, 80% and 100% respectively.

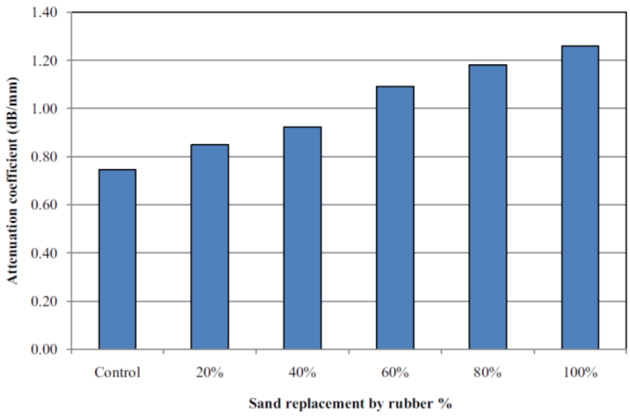


Fig. 22 – Attenuation coefficient of conventional concrete and rubberized concrete at different percentages of sand replacement (Aliabdo, Abd Elmoaty and Abdelbaset, 2015)

The test results of Sukontasukkul (2009) confirmed the same sound insulation properties of rubberized concrete. Sukontasukkul stated that rubberized concrete achieved higher noise reduction coefficient comparing to that of conventional concrete. Albano *et al.* (2005) reported that the enhancement of sound attenuation can be attributed to the porosity of rubberized concrete which influences directly the propagation of sound waves.

2.4.2. Thermal conductivity

Thermal properties are very important in many construction applications. When a temperature gradient exists, there is an energy transfer from the high temperature region to the low temperature region. It can be said that the energy is transferred by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient.

Aliabdo, Abd Elmoaty and Abdelbaset (2015) measured the thermal conductivity of six different concrete mixtures obtained with different replacement levels of crumb rubber. Thermal conductivity (k) was determined with the Lee's method and it was found to decrease with the increasing of rubber content. The thermal conductivity of conventional concrete was 1,45W/m°C and the deduction in k-values at 20% and 100% rubber content was 34% and 59% respectively.

Table 5 – Thermal conductivity (k) for conventional concrete and rubberized concrete at different percentages of sand replacement by rubber particles (Aliabdo, Abd Elmoaty and Abdelbaset, 2015)

Sand replacement by rubber (%)	Thermal conductivity K (W/m°C)	Reduction (%)
Control	1,45	-
20	0,96	34
40	0,85	41
60	0,73	50
80	0,67	54
100	0,60	59

Rana and Dina (2011) evaluated thermal conductivity for rubberized concrete and reported the same reduction in thermal conductivity for rubberized concrete, as the reduction in k-value was 26,7% at 15% rubber content comparing to that for traditional concrete.

According to Benazzouk *et al.* (2008) the reduction of thermal conductivity in rubberized concrete is due to the insulating effect of rubber particle, which has a lower thermal conductivity compared to that of cement matrix. Furthermore, the thermal conductivity decreases with decreasing unit weight as shown in *Fig. 23*, so it is also related to air content in the matrix. In fact, the more the air voids ratio, the lighter the specimen and the lower its thermal conductivity.

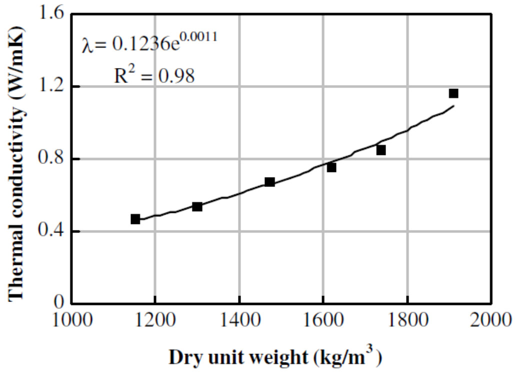


Fig. 23 – Relationship between thermal conductivity and dry unit weight (Benazzouk et al., 2008)

Also Sukontasukkul (2009) studied the thermal conductivity at different percentages of sand replacement by crumb rubber using the hot plate method. All mixtures of rubberized concrete exhibited a lower heat transfer rate and a higher heat resistivity than plain concrete. The rates of which depended on the crumb rubber size and the proportion of crumb rubber in the mix. With respect to size, the rate of heat transfer was found to decrease as the crumb rubber decreased. With respect to content, concrete with the large sized crumb rubber gave the highest value of heat transfer rate, and those that have small sized crumb rubber showed smaller value.

2.4.3. Impact resistance

Although the compression, tensile and flexural strengths of plain concrete generally decreases with increasing rubber aggregate content, the addition of chipped rubber aggregate can increase impact resistance substantially in both the first crack and failure stages (Najim and Hall, 2010).

Fattuhi and Clark (1996) tested two slabs obtained with two different concrete mixtures: the first one was made with ordinary concrete (without rubber), while the second one contained about 11% of low-grade rubber relative to the total solids content by weight (a rubber to cement ratio of about 0,44). The test consisted in dropping three times an hammer from initial height of 1 m for the first drop and 2 m for the others two drops. Examination of the slabs showed that both suffered cracking in all direction. However, the slab containing rubber had a larger spread of cracks over the tension face. After the second drop, the maximum crack width in the ordinary concrete slab was 0,16 mm, while that for the slab containing rubber was 0,50 mm. After the third drop, the maximum crack widths increased to 0,3 mm and 2,0 mm for the plain concrete and rubberized concrete slabs, respectively. These results showed that both slabs sustained the impact of the drop hammer, despite the lower compressive strength of the rubberized concrete. This behavior is presumably due to the higher strain rate which leads, in turn, to an increase energy absorption.

One of the most promising application of recycled tyres in roadside safety appurtenances is concrete safety barriers. In order to investigate the capability of energy absorption of rubberized concrete, Atahan and Sevim (2008) performed dynamic impact tests on free standing New Jersey shaped safety barriers. They reported that energy absorbed increased with increased amounts of shredded tyre chip in concrete. The energy absorption between the 0 and 100% rubber chip cases was as large as 187%, which is significant. This means that kinetic energy on the impacting vehicle con be effectively absorbed by the safety barrier when rubber content increased. In this way, during a crash with rubberized concrete barriers, the chances of occupant injury are reduced due to reduction in collision energy absorbed by vehicle and occupants.

Fig. 24 – A typical New Jersey barriers used in dynamic impact tests before and after impact (Atahan and Sevim, 2008)

2.5. Purposes of the present work

Structural performances of concrete obtained with a partial natural aggregate replacement with crumb rubber have been investigated from early 1990s until these days.

Apart from the reduction in the unit weight of concrete, the replacement of mineral aggregates with rubber also results in a decrease of compression strength, tensile strength, flexural strength and elastic modulus. Previous studies have shown that the modification of mechanical properties is mainly a function of the percentage of rubber replacement. In addition to the results achieved investigating the mechanical properties, several other researches have substantiated the impact resistance and energy dissipation capacity of rubberized concrete.

In several cases reduction in mechanical properties makes rubberized concrete a non-structural material, since the strength performances required by standards are no longer respected. For these reasons, most current application of rubber in concrete have been primarily for use as non-structural elements such as crash barriers, floor surfaces and sound barriers. In fact, the inherent energy absorption capabilities of rubberized concrete make it an evident candidate for impact related applications. Although the deployment of rubberized concrete in primary structural members has not examined in the same level of details as for non-structural applications, the potential merits offered by the material have attracted attention, particularly in application in which ductility, energy dissipation and seismic resistance are required.

In this context, in order to give a contribute to development in the utilization of rubber in concrete for structural members, this work purposes a complete overview on the mechanical properties of concrete obtained by a partial substitution of natural aggregate with different volume percentage of waste tyre rubber particles, having the same dimension of the replaced aggregate. In particular, the experimental research that will be presented in next chapters consists in the preparation and testing of a normal control concrete mixture and four rubberized concrete mixtures. The objective of this work is to investigate how rubber content influences concrete properties, so mix design is the same for all mixtures except from quantity of rubber replacement. During the preparation of concrete mixtures, particular attention was given to workability of concrete. In fact, a slump test was done for each mixture, in order to observe how workability changes with different percentages of rubber content.

For each mixture, cylindrical samples are tested under uniaxial compression to assess the complete stress-strain response, including the post-peak behavior. Additionally, flexural tests on beam samples, and splitting tests on cylindrical specimens, are carried out on flexural and tensile strength, respectively. Another mechanical test that was executed on cylindrical specimens is elastic modulus test. The test results and observations allow a first mechanical characterization of the several rubberized concrete mixtures.

The following and most important step of this study regards with the examining the complete bond-slip behavior between reinforcement bars and concrete incorporating rubber particles. In this work thirty pull-out tests in which reinforcement bars embedded in concrete cubic specimens of normal and rubberized concrete are described. The experimental investigation focused on examining the bond strength of rubberized concrete evaluating the influence of rubber content and bar diameter. In fact, pull-out tests are carried on with two different diameter of reinforcement bar for each of the five mixtures prepared.

Another concrete property that has been investigated in this work is water permeability. Water permeability is one of the prime factor which influences the durability of concrete. Using the standard testing environment, the water permeability was calculated on cylindrical samples in order to establish how rubber content influences it.

3. Materials and methods

Overall one hundred thirty-five (135) samples of which 90 cylindrical samples, 15 beams and 30 cubic with reinforcement bar specimens were prepared to assess mechanical properties, water permeability and thermal conductivity of rubberized concrete with various replacement ratios of natural mineral aggregates. Cylindrical samples were tested on compressive strength, elastic modulus, splitting tensile strength and water permeability. Beams were tested on flexural strength and then cubic specimens with the reinforcement bar were used for pull-out tests.

A total of five concrete mixture were prepared: a control mixture of normal concrete and four rubberized concrete mixtures. Rubberized concrete mixtures were obtained by replacing increasing percentages of natural aggregates with an equivalent volume of rubber particles having the same dimensions.

3.1. Materials

The concrete recipe used in this study was already used in other experimental researches at Politecnico di Torino, in which it was possible to obtain concrete with strength class C30/37 (Eurocode 2).

Table 6 – Recipe for one cubic meter of concrete

Component	Dosage
Cement (CEM II – 42,5R)	370 kg
Water	185 l (w/c=0,5)
Additive	3,70 kg (1% c.w.)
Aggregate 1 (3-8)	386,1 kg
Aggregate 2 (0-2)	433,8 kg
Aggregate 3 (0-5)	905,8 kg

As indicated in the recipe, also in this research it has been used cement type CEM II/A with strength class 42,5R. This cement is based on Portland type clinker mixed with natural cementitious materials, in this case limestone. The additive utilized in this study was a superplasticizer "Compactcrete 39 T 100" produced by Addiment, it was used in quantity equal to 1% of the cement weight and allowed to decrease the water/cement ratio.

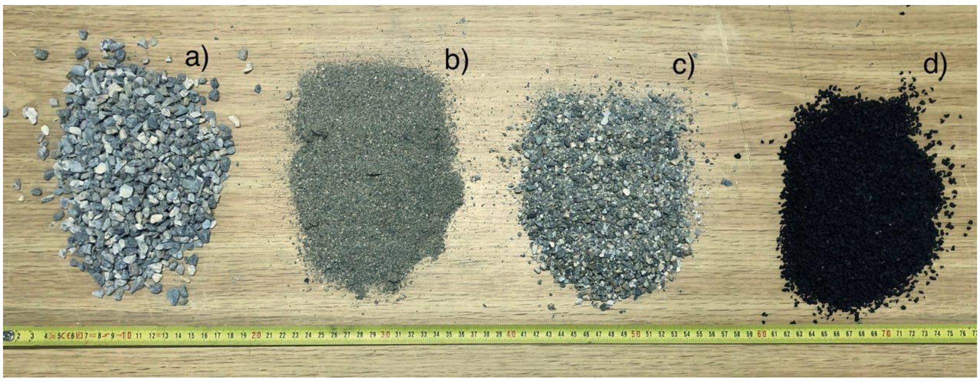


Fig. 25 – Aggregates used in rubberized concrete: a) gravel b) fine sand c) river sand d) rubber

The other materials used to develop the concrete mixtures in this study were tyre rubber aggregates, and three types of natural aggregates:

- Aggregate 1 (gravel), nominal size between 3mm and 8mm;
- Aggregate 2 (fine sand), nominal size between 0mm and 2mm;
- Aggregate 3 (river sand), nominal size between 0mm and 5mm.

The quantities of these three aggregates were determined by mix optimization. First of all it was necessary to define the particle size distributions of the three aggregates by an electromechanical sieve shaker, following EN 933-1:2012. In *Fig. 26* it can be seen the graduation curves for the natural aggregates.

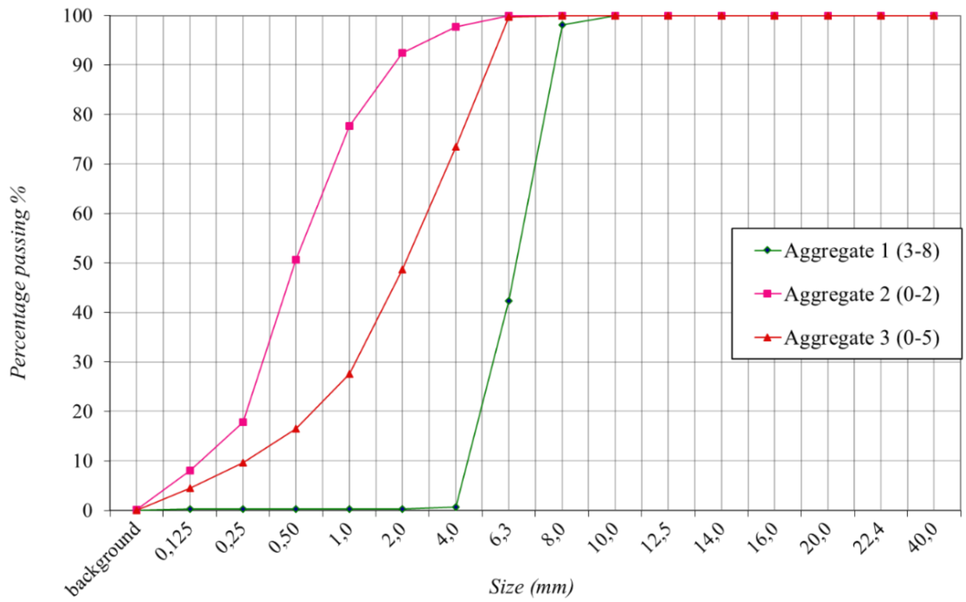


Fig. 26 – Sieve analysis for Aggregate 1, Aggregate 2 and Aggregate 3

Gradation of aggregates has a significant role on material performance. Therefore, after determining the gradation of each aggregate, it is important to define how to mix these aggregates, that is to find the percentages of content for each type of aggregate. In this context, the best gradation is one that produces the maximum density. This would involve a particle arrangement where smaller particles are packed between the larger particles, which reduces the void space between particles. This create more contact between aggregates, which in concrete would increase stability and reduce water infiltration. A widely used equation to describe a maximum density gradation was developed by Fuller. Fuller distribution is a typical wide particle size distribution that is applied to concrete aggregate gradations to achieve maximum packing density. The equation used is:

$$P = 100 \cdot (d/D_{max})^k$$

where d is the diameter (mm) of aggregate in each size group; P is the cumulative percentage volume of aggregate under the dimension d; D_{max} is the maximum diameter (mm) of aggregate in all size group; and k is the Fuller exponential, generally $k = 0{,}50$.

Between all the possible mixtures that can be obtained with these three aggregates, the one that guaranteed the maximum density was the one that approached the theoretical curve of Fuller between the upper and lower limits. Considering the maximum diameter $D_{max} = 8mm$, through an Excel solver, it was possible to identify the percentages of the three aggregates that respected this rule and they are shown in *Table 7*.

Table 7 – Mix design of the natural aggregates

Aggregate 1 (3-8)	Aggregate 2 (0-2)	Aggregate 3 (0-5)
22%	25%	53%

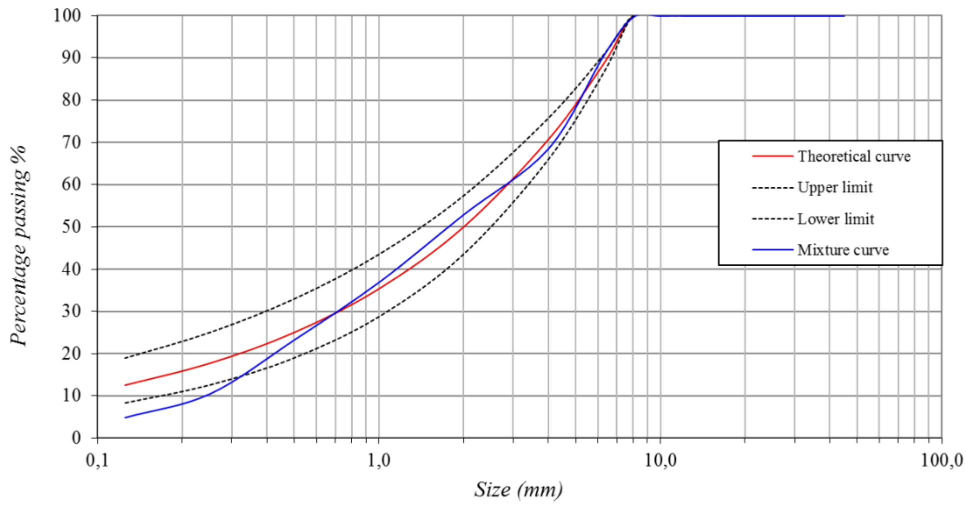


Fig. 27 – Fuller mix optimization of the three natural aggregates

Crumb rubber used in this experimental research was obtained from a local industrial unit in Potenza. The rubber was recovered by a shredding process of used tyres and then separated from steel by an electromagnetic process. Crumb rubber produced by this company has a nominal size between 4mm and 0mm. The particle size distribution of crumb rubber aggregate was determined following EN 933-1:2012, so the graduation curve for crumb rubber can be seen in *Fig. 28*.

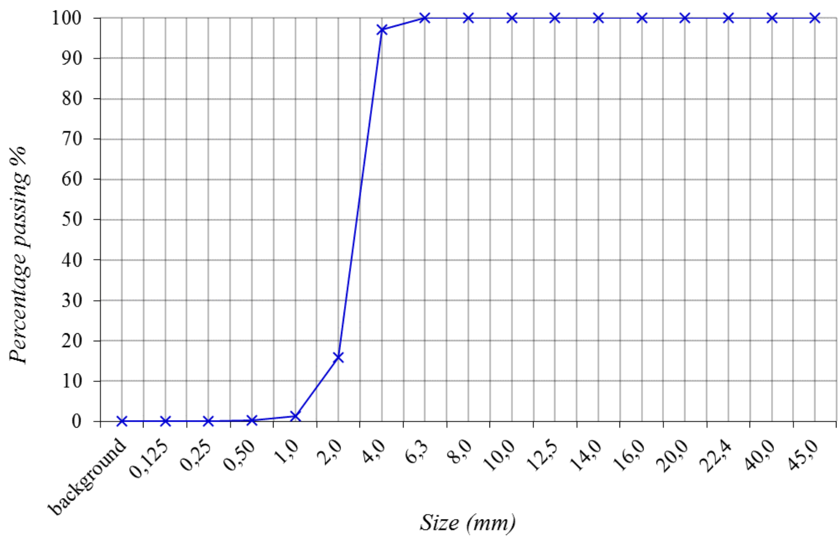


Fig. 28 – Sieve analysis for waste rubber aggregate

In order to not modify the gradation curve of the natural aggregates found with the Fuller mix optimization, the idea was to maintain the same dimensions by replacing the aggregates with rubber particles with equal size. Exanimating the sieve analysis comparison between natural aggregates and crumb rubber, showed in *Fig. 29*, it was noted that gradation distribution of rubber was similar to that one of the Aggregate 3 (0-5), the river sand.

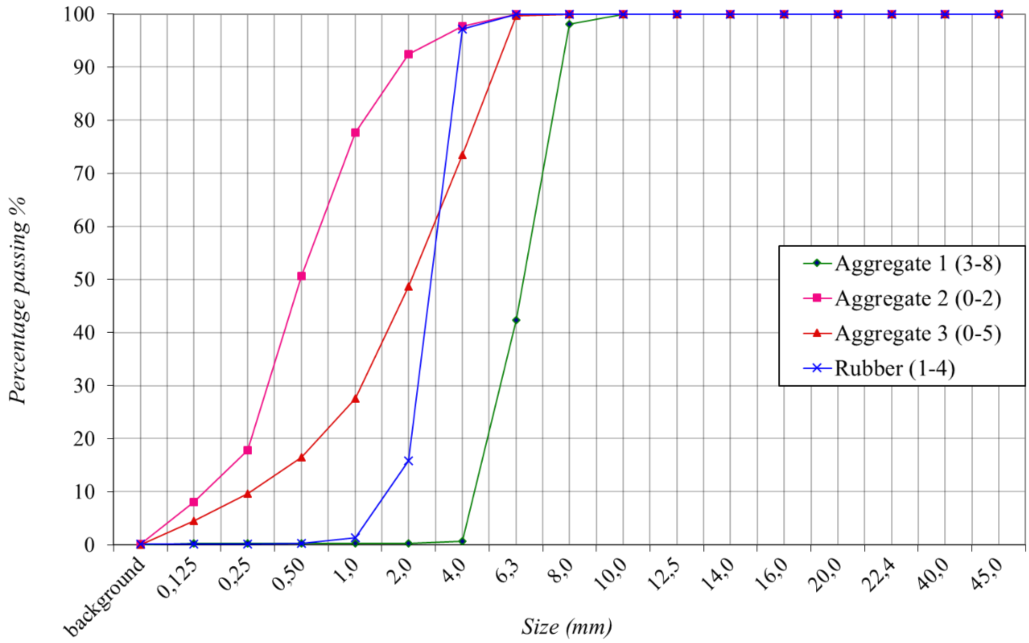


Fig. 29 – Sieve analysis comparison between natural aggregates and waste rubber aggregate

In particular, the two curves intersected in a range included between 1,0 mm and 4,0 mm grain dimension. Therefore, replacement between rubber particles and natural aggregates was made with the fractions between 2,0 mm and 4,0 mm and between 1,0 mm and 2,0 mm. The four rubberized concrete mixtures were obtained by substituting these fractions of Aggregate 3 in percentages of 25%, 50%, 75% and 100% with an equal fraction in volume of crumb rubber.

The percentage of Aggregate 3 obtained from the mix design was 53% by weight of all the aggregates used, while the fractions between 2,0 mm and 4,0 mm and between 1,0 mm and 2,0 mm obtained from the sieve analysis of the river sand were 25% and 21% by weight respectively. This means that the maximum percentage of crumb rubber replacement was about 46% in terms of Aggregate 3 and about 24% in terms of total aggregates.

The substitution of crumb rubber in place of fractions of Aggregate 3 described above was performed so as not to change the volume of the mixtures. For this reason, before making the replacement, it was necessary to establish the ratio between the unit weight of the river sand and that one of the crumb rubber. It resulted that the unit weight of the Aggregate 3 was 1,80 g/cm^3 and the unit weight of crumb rubber was 0,55 g/cm^3:

$$\frac{1{,}80\ g/cm^3}{0{,}55\ g/cm^3} = 3{,}2$$

3.2. *Trial mixes*

Before proceeding to the preparation of the concrete mixtures for the experimental research, four different trial mixes were prepared and tested by compression:

1. Trial mix of thirty liters with 50% of rubber replacement of Aggregate 3 fractions 1-2mm and 2-4mm;
2. Trial mix of thirty liters with 100% of rubber replacement of Aggregate 3 fractions 1-2mm and 2-4mm;
3. Trial mix of forty-five liters with 100% of rubber replacement of Aggregate 3 fractions 1-2mm and 2-4mm, by imposing a water/cement ratio equal to 0,50;
4. Trial mix of forty-five liters without rubber replacement, by imposing a water/cement ratio equal to 0,50.

The quantities of materials necessary for a concrete mixture of thirty liters were deduced following the concrete recipe indicated in *Table 6*.

Table 8 – Materials utilized for thirty liters concrete mixtures

Component	Dosage (30 liters mix)
Cement (CEM II/A – 42,5R)	10,2 kg
Water	5,1 l (w/c=0,5)
Additive	0,102 (1% c.w.)
Aggregate 1 (3-8)	12 kg
Aggregate 2 (0-2)	13,5 kg
Aggregate 3 (0-5)	28,2 kg

Fig. 30 – Materials ready to be mixed

An electromechanical sieve shaker was used to separate fractions 2-4mm and 1-2mm of crumb rubber and Aggregate 3 in order to make the substitution. As already explained, the replacement of rubber in place of river sand was executed by maintaining the same volume and aggregate dimension of the mixture. Considering the ratio between crumb rubber and river sand unit weight equal to 3,2, it was passible to make the 50% and 100% replacement as showed in *Table 9*.

Table 9 – Substitution of crumb rubber in place of Aggregate 3

Component	Replacement 50%		Replacement 100%	
	1-2 mm	2-4mm	1-2mm	2-4mm
Aggregate 3	2,9 kg	3,5 kg	5,8 kg	6,6 kg
Rubber	0,9 kg	1,1 kg	1,8 kg	2,1 kg

During the preparation of rubberized concrete with substitution of 50% it was used an additional amount of water because the mixture seemed dry. The final w/c ratio resulted to be 0,55. Six cubic specimens with 16 mm side were casted and tested under compression: three of them seven days after casting and the remaining three after fourteen days. In the same way, during the preparation of rubberized concrete with substitution of 100% it was modified the w/c ratio to 0,59 by adding an additional amount of water. Also in this case, six cubic specimens were casted and tested in compression as before.

Fig. 31 – Casting of trial concrete mixture cubic specimens

Average results of these tests are reported in *Table 10*. Through results of compression strength at seven and fourteen days, by using an expression of the compressive strength of concrete at various age reported in Eurocode 2, it was possible to estimate the compressive strength at 28 days. The expression is:

$$f_{ck}(t) = \beta_{cc}(t) \cdot f_{ck}$$

with

$$\beta_{cc}(t) = \exp\left\{s\left[1-\left(\frac{28}{t}\right)^{1/2}\right]\right\}$$

where f_{ck} is the compressive strength at 28 days; $\beta_{cc}(t)$ is a coefficient which depends on the age of the concrete; t is the age of the concrete in days; s is a coefficient which depends on type of cement (=0,20 for cement strength classes CEM 42,5R).

Table 10 – Cubic compression strength of trial mixes after seven and fourteen days and prevision of 28 days strength through Eurocode 2

t [days]	Replacement 50% (w/c=0,55)	Replacement 100% (w/c=0,59)
	$f_{ck,cube}$ [MPa]	$f_{ck,cube}$ [MPa]
7	21,84	14,78
14	24,78	16,23
28 (estimated)	27	18

Since the objective of the research was to observe the performance of concrete with different rubber percentage of replacement without varying other components of mixtures, it was decided to impose w/c=0,50 for all mixtures. For this reason, in the other two trial mixes it was increased the quantity of superplasticizer to 1,5% of concrete weight to preserve the workability of concrete. The forty-five liters trial mixtures were prepared following the concrete recipe described before (*Table 6*).

Table 11 – Materials utilized for forty-five liters concrete mixtures

Component	Dosage (45 liters mix)
Cement (CEM II/A – 42,5R)	15,3 kg
Water	7,65 l (w/c=0,5)
Additive	0,23 (1,5% c.w.)
Aggregate 1 (3-8)	18,1 kg
Aggregate 2 (0-2)	20,2 kg
Aggregate 3 (0-5)	42,3 kg

In this case eight cubic samples for each mixture was obtained and tested under compression: four of them seven days after casting and the remaining after fourteen days.

Fig. 32 – Compression strength test on cubic sample obtained from trial mix

Table 12 – Cubic compression strength of trial mixes after seven and fourteen days and prevision of 28 days strength through Eurocode 2

t [days]	Replacement 100% (w/c=0,50)	Replacement 0% (w/c=0,50)
	$f_{ck,cube}$ [MPa]	$f_{ck,cube}$ [MPa]
7	15,34	29,15
14	17,10	32,77
28 (estimated)	19	36

The results observed in these trial mixes was useful to have a preview of workability and compression strength of the mixtures with rubber particles. It was evident that compression strength of concrete deceased with increasing of rubber percentage, as noted in most of studies on rubberized concrete. Since the strength achieved with this concrete recipe resulted a high as expected it was possible to proceed with the preparation of the five mixtures provided for by this study.

3.3. Experimental program and preparation of the rubberized mixtures

In order to establish the volume of each concrete mixture, the first step in the preparation of concrete was to define type of tests and number of specimens needed for each test. The main target of this research was to determine the bond-slip behavior of rubberized concrete but, before doing this, it was necessary a mechanical characterization of each mixture.

The mechanical characterization was done with tests on compressive strength, modulus of elasticity, tensile strength and flexural strength. For each concrete mixture, it was decided to prepare five cylindrical samples for compression strength test and for splitting tensile strength, elastic modulus was measured on the same specimens dedicated to compression test. Three beams were prepared for flexural strength tests. Bond-slip tests were performed on a total of six cubic specimens for each mix: three were prepared using 12 mm reinforcement bars and the other three using 16 mm bars.

Other properties of rubberized concrete that was interesting to investigate was concrete permeability and thermal conductivity. Three more cylindrical samples were prepared and used for these tests, in thermal conductivity tests two 30 mm tall specimens were necessary and they were obtained by cutting one of these cylinders.

Table 13 – Specimens prepared for each concrete mixture

Test	n° specimens
Compression (and modulus of elasticity) test	5 cylindrical samples
Splitting tensile test	5 cylindrical samples
Flexural test	3 beams
Pull-out test	6 cubic samples with a reinforcement bar
Permeability	3 cylindrical samples
Thermal conductivity	2 30 mm tall samples

The total volume of all specimens for each concrete mixture was estimated to be about 160 liters. In order to prevent any material losses during concrete preparation and casting, it was decided to prepare mixes of 180 liters volume. Considering the concrete recipe introduced before, it was possible to determine the components for each concrete mixture are showed in *Table 14*.

Table 14 – Materials utilized for 180 liters concrete mixtures

Component	Dosage (45 liters mix)
Cement (CEM II/A – 42,5R)	61,2 kg
Water	30,6 l (w/c=0,5)
Additive	0,918 (1,5% c.w.)
Aggregate 1 (3-8)	72,12 kg
Aggregate 2 (0-2)	81,00 kg
Aggregate 3 (0-5)	169,14 kg

As rubber replacement interested only the two fractions of 1-2 mm and 2-4mm of Aggregate 3, it was necessary to separate them. For this reason, preparation of rubber concrete mixtures consisted mainly in sieving the whole quantity (about 676 kg) of Aggregate 3 needed for each concrete mixture. In this phase it was used an electromechanical sieve shaker, both river sand and crumb rubber were sieved in order to obtain fractions 1-2 mm and 2-4 mm to make the substitutions. Quantities of 1-2 mm and 2-4 mm fractions of Aggregate 3 and crumb rubber involved in the substitution are showed in *Table 15*.

Fig. 33 – Electromechanical sieve shaker

Table 15 – Quantities of fractions 1-2mm and 2-4mm of Aggregate 3 obtained from sieving and to be replaced for each rubberized concrete mixture and equivalent in volume amount of rubber needed

Concrete mixtures	Fractions [mm]	Aggregate 3 [kg]		Crumb rubber [kg]
		Obtained from sieving	To be replaced	
RuC_25	1-2	36,6	9,1	2,8
	2-4	41,4	10,3	3,2
RuC_50	1-2	36,7	18,3	5,7
	2-4	41,8	20,9	6,5
RuC_75	1-2	37,0	27,8	8,7
	2-4	40,7	30,5	9,5
RuC_100	1-2	36,7	36,7	11,5
	2-4	41,5	41,5	13,0

Once sieving was completed, it was possible to proceed on casting the five concrete mixtures. It was decided to cast every other day, in this way there was a day between two consecutive concrete jets to remove specimens from the formworks and to prepare all the materials required for the next concrete casting. The first mixture to be casted was RuC_0, then the other mixtures were prepared in order of increasing percentage of rubber replacement.

Fig. 34 – Substitution between fraction 2-4mm of crumb rubber and river sand equivalent in volume

Before proceeding with concrete casting, it was necessary to prepare all the formworks for the different types of specimens. Particular attention was paid to the preparation of pull-out test samples: as this test had to be performed on cubic samples with a ribbed steel bar, it was required to pose a reinforcement bar in cubic formworks. The positioning of these steel bars had to be done in the same way for all the specimens, in this way dispersion of results was limited.

Fig. 35 – Formworks for pull-out test cubic specimens

It was used steel formworks for pull-out specimens and beams and cardboard formworks for cylindrical samples. First steps of concrete casting were oil the formworks to disarm concrete and wet the cement mixer. Then all aggregates were put into the cement mixes in order from the biggest (gravel) to the finest (fine sand) and they were mixed with a part of water provided from the recipe. Once that the aggregates were well mixed and wet, it was possible to put cement and the remaining part of water added a little at a time. At this point the materials were left to mix for about 20 minutes before to put the concrete mixture in the formworks. The same procedures were followed for all five concrete mixes, the only thing to change was the quantity of rubber replacement.

Fig. 36 – Preparation of cylindrical samples in cardboard formworks

Fig. 37 – Cylindrical specimens and pull-out test specimens just after concrete casting

3.4. Specimens details

Eighteen cylindrical samples were prepared for each concrete mixture, that means a total of ninety cylindrical specimens. To obtain these cylinders Φ150 x 300 mm cardboard formworks were used. Each cylinder was classified according to type of test just after concrete casting. Cylindrical samples used for compressive strength and modulus of elasticity determination needed to be cut and leveled on the upper and lower surface. In *Table 16* it is showed how each specimen was nominated according to type of test it was prepared for.

Table 16 – Classification of samples according to type of test

Rubberized mixture	Compression test	Splitting tensile test	Pull-out test		Permeability	Flexural test
			12mm bar	16mm bar		
RuC_0	RuC_0_C	RuC_0_T	RuC_0_12	RuC_0_16	RuC_0_P	RuC_0_F
RuC_25	RuC_25_C	RuC_25_T	RuC_25_12	RuC_25_16	RuC_25_P	RuC_25_F
RuC_50	RuC_50_C	RuC_50_T	RuC_50_12	RuC_50_16	RuC_50_P	RuC_50_F
RuC_75	RuC_75_C	RuC_75_T	RuC_75_12	RuC_75_16	RuC_75_P	RuC_75_F
RuC_100	RuC_100_C	RuC_100_T	RuC_100_12	RuC_100_16	RuC_100_P	RuC_100_F

Fig. 38 – Example of label applied on each cylindrical specimen

Six cubic pull-out specimens were prepared for each rubberized concrete mixture: three of them were 120 mm side with 12 mm embedded deformed bar and the other three were 160 mm side with 16 mm embedded deformed bar. Both 12 mm and 16 mm reinforcement bars were about 600 mm length and made of a grade B450C steel. Each bar was prepared in order to have an unbounded zone inside the cubic specimen. This unbounded zone had to be half of the total embedded length and it was realized by applying a plastic sheet on the steel.

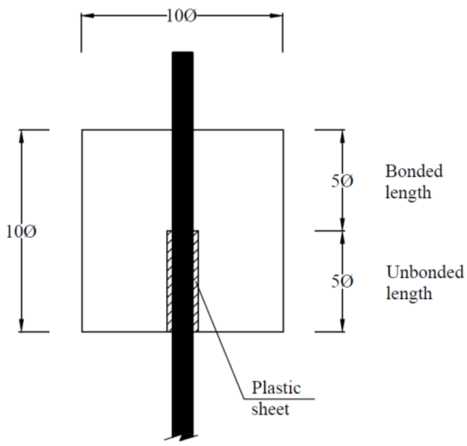


Fig. 39 – Pull-out test specimen (Φ is bar diameter)

Samples for flexural strength test were 160 x 160 x 640 mm beams. Three beams for each mixture were prepared, for a total of fifteen beams.

Fig. 40 – Beam just after rubberized concrete casting

3.5. Workability

In order to evaluate the influence of waste tyre rubber particles, replacing mineral aggregate, on workability of fresh rubberized concrete, slump test were performed according to UNI EN 12350-2 (2001). Results of slump tests are reported in *Table 17*. It can be noted that workability of fresh concrete is not changed by the partial substitution of Aggregate 3 with crumb rubber. In fact, the five mixtures exhibited approximately the same behavior, since they have all presented S1 class consistency (UNI EN 206-1, 2000).

Table 17 – Results of slump tests

Concrete mixture	Slump [mm]	Class consistency
RuC_0	30	S1
RuC_25	20	S1
RuC_50	10	S1
RuC_75	20	S1
RuC_100	10	S1

This means that rubberized concrete can be mixed, cast and vibrated using equipment and procedures adopted for conventional concrete. Moreover these results are similar to that one obtained by Aiello and Leuzzi (2010).

Fig. 41 – Slump test on mixture RuC_75

From this point onwards, results of only the first three mixtures (RuC_0, RuC_25 and RuC_50) are presented because the remaining two will be tested later and involved in other experimental research.

3.6. Density

One of the most important effect of replacing mineral aggregate with crumb rubber is the reduction in unit weight of concrete. Density measure showed in *Table 18* were obtained by weighing the cylindrical specimens before compressive strength and splitting tensile tests.

Table 18 – Density of normal concrete and rubberized concrete mixtures

Concrete mixture	Unit weight [kg/m^3]	Decrease
RuC_0	2330	-
RuC_25	2303	1,2%
RuC_50	2244	3,7%

Comparing the density obtained for the two mixtures of rubberized concrete and for the measurements obtained for the reference concrete RuC_0, decreasing in unit weight can be noted. In particular, RuC_25 showed a density decay of 1,2% and RuC_50 showed a density decay of 3,7%.

As expected, because of the low density of rubber, a gradual decay of the concrete density was observed with increasing the percentage of mineral aggregate replaced. These results confirms as reported in previous researches concerning density of concrete prepared with waste tyre rubber aggregates (Khatib and Bayomy, 1999; Topçu, 1995; Benazzouk *et al.*, 2007).

3.7. Testing arrangement

3.7.1. Compression test

Compressive strength test was divided into two different phases: in the first part of the test modulus of elasticity was determined according to UNI EN 12390-13 (2013); then the maximum compressive strength was obtained. Five cylindrical specimens, with height of about 300 mm (cylinders were cut and leveled before test) and base diameter of 150 mm, were cast for each mixture. Such samples were subjected to uniaxial compressive loads through a Galdabini Zwick-Roell compression testing machine (maximum load capacity = 5000 kN).

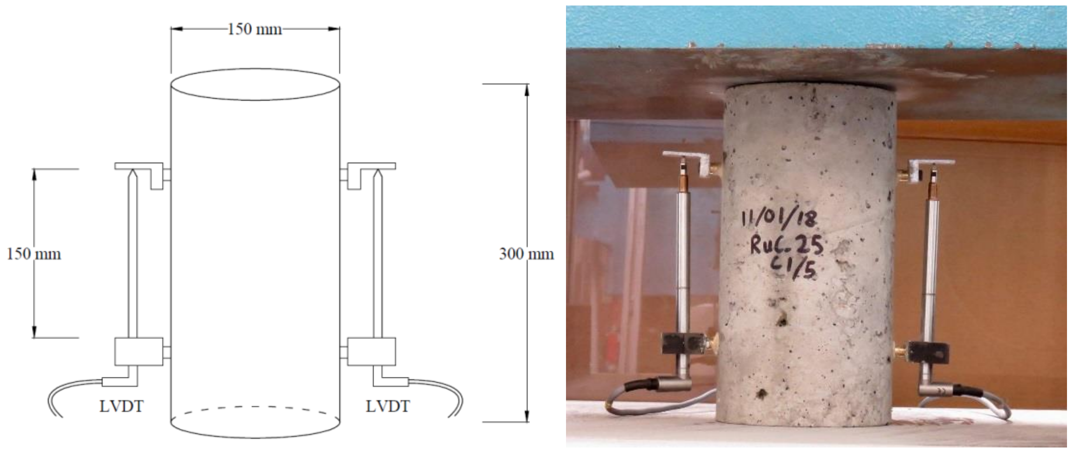


Fig. 42 – Compressive strength test configuration

As showed in *Fig. 42* two LVDTs (Linear Variable Displacement Transducer) were placed on the central part of each cylinder to evaluate the local strain on a base of 150 mm. Determination of secant modulus of elasticity was performed by determination of initial and stabilized secant modulus of elasticity according to UNI EN 12390-13 (2013).

The specimen was carried out to three preloading cycles to check wiring stability and positioning. The applied stress to specimen was a rate of (0,6 ± 0,2) MPa/s up to the lower stress σ_b, and kept to the nominal value for 20 s. Forwards, the stress was reduced at a rate of (0,6 ± 0,2) MPa/s down to the preload stress σ_p, and held for a period of 20 s. After the three cycles, the preload stress was maintained for 60 s. Subsequent, three loading cycles were carried out. The stress was increased at a rate of (0,6 ± 0,2) MPa/s from the preload stress to the lower stress and maintained for 20 s. At the end of this period, the stress was reduced at σ_b and kept 20 s.

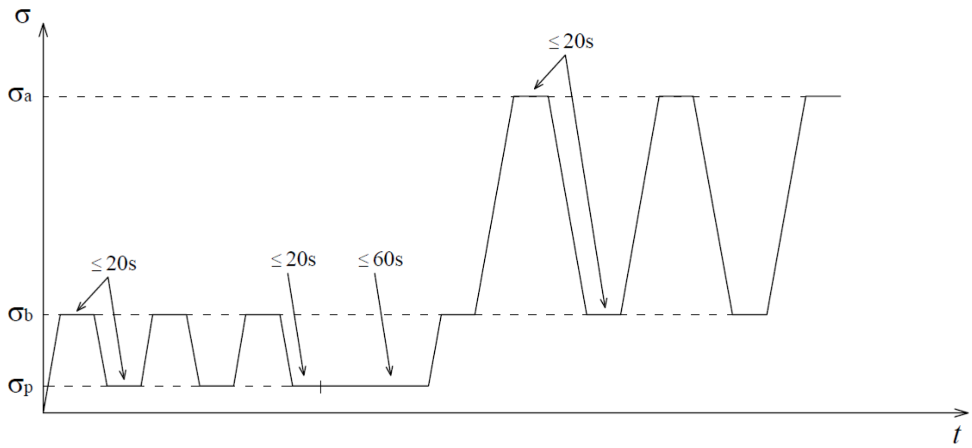


Fig. 43 – Experimental determination of modulus of elasticity (UNI EN 12390-13, 2013)

After this phase the specimen was carried out to rupture by imposing a constant velocity (0,01 mm/s) of the stroke. In this way it was possible to measure the maximum compression stress reached by the specimen.

3.7.2. Splitting tensile strength test

Splitting tensile strength test on concrete cylinders is a method to determine the tensile strength of concrete. In fact, concrete is very weak in tension due to its brittle nature and is not expected to resist the direct tension. Concrete develops cracks when subjected to tensile force, for example in case of concrete members subjected to bending. Thus, it is necessary to determine the tensile strength of concrete to determine the load at which concrete members may cracks.

Splitting tensile strength test was executed according to UNI EN 12390-6 (2010) with a Baldwin Zwick-Roell universal testing machine (maximum load capacity = 500 kN). A centering device was used for specimen placement and wood strips for load distribution. Once specimen was positioned and centered and checked the position of wood strips it was possible to apply the load with constant velocity equal to 0,05 MPa/s until the sample is broken.

Fig. 44 – Splitting tensile strength test setup

3.7.3. Flexural test

In order to investigate on flexural response of rubberized concrete members, three points bending test was executed on three beams for each concrete mixture. Flexural strength of test specimens was determined according to UNI EN 14651 (2005).

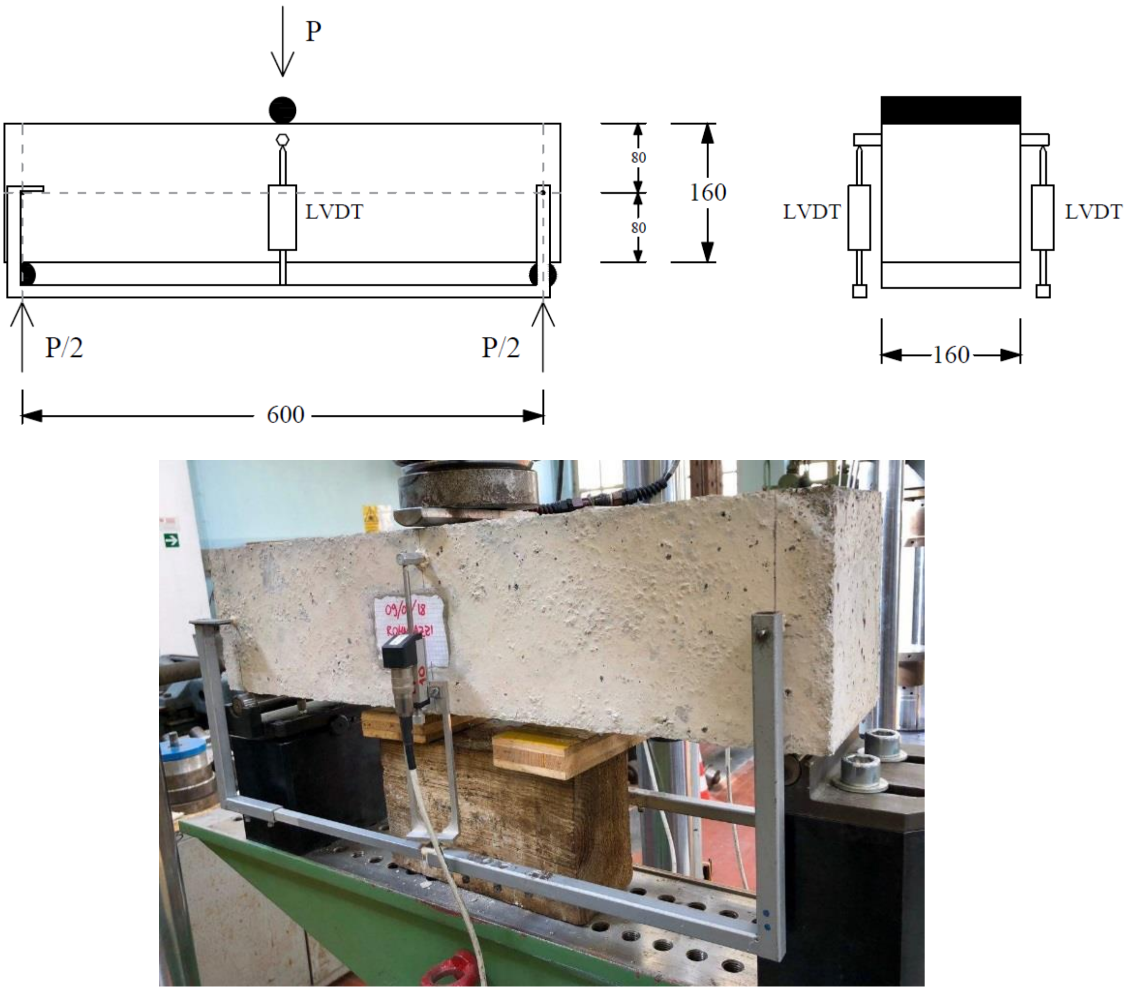


Fig. 45 – Three points bending testing arrangement

In order to register load-deflection curves of concrete members, two LVDTs were placed as showed in *Fig. 45*. The two LVDTs, one for each side of the beam, were positioned with two frames that were anchored in correspondence with neutral axis of the beam above the supports. After positioning and correctly centering the specimen on the MTS servo-hydraulic universal testing machine (maximum capacity load of 100 kN), the tests were executed with a constant velocity of the stroke equal to 0,08 mm/min.

3.7.4. Permeability of concrete test

Water permeability is the prime factor which influences the durability of concrete. Water permeability was calculated in terms of depth of water penetration according to UNI EN 12390-8 (2009).

Fig. 46 – Permeability test

In *Fig. 46* specimen during permeability test is showed: the specimen was locked and pressure of water acted on the lower surface of the cylinder. The specimens were positioned in the equipment, pressure of water was (500 ± 50) kPa and it was applied for (72 ± 2) h. After pressure was applied for this period, the specimens were removed, dried on the surface under pressure and then were broken into two parts in order to measure the maximum water penetration.

3.7.5. Bond-slip response test

Pull-out tests were carried out in order to analyze the bond-slip behavior of the specimens at different percentage of rubber replacement. Three concrete mixtures were tested: the control mixture without rubber necessary for comparison and the rubberized concrete mixtures RuC_25 and RuC_50.

For each concrete mixture six specimens were tested under displacement control, with a rate equal to 0,2 mm/min, using a Baldwin Zwick-Roell testing machine with a capacity of 500 kN. The relative displacement between the steel and concrete was measured up to bond failure by means of an LVDT positioned on the unloaded end of the reinforcement bar. Therefore, the parameters measured was the slip between the deformed bar and cubic concrete sample and the force F, showed in *Fig. 47* which was later converted into bond tension.

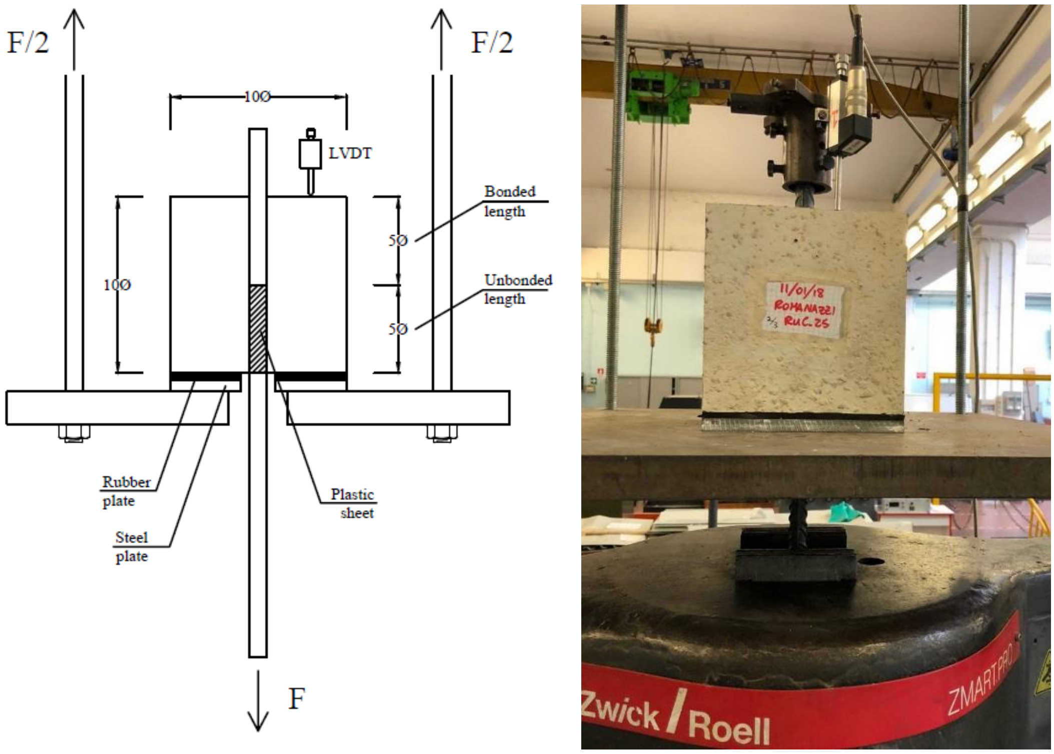


Fig. 47 – Pull-out test configuration

4. Results

4.1. *Mechanical properties of rubberized concrete*

4.1.1. *Stress-strain response*

Material characterization tests on rubberized concrete and normal concrete cylinders were carried out to assess the influence of rubber content on the constitutive behavior. Despite four total rubberized concrete mixtures were prepared, only two of them have been tested. In particular, the investigated rubber replacement ratios were 6% (RuC_25) and 12% (RuC_50) of the total aggregate volume, as described previously in this work. *Fig. 48a-c* depict five stress-strain recorded test curves for each mixture. The stress-strain curves include both pre-peak and post-peak behavior as recorded in the tests. The post-peak response is plotted down to about 10% of the compressive strength f_c. During the ascending branch the strains are computed with the measures of the two LVDTs, whereas in the softening stage the shortening of the whole specimen is assumed to be coincident with the stroke of the loading machine.

The main parameters of the stress-strain response are showed in *Table 19*. They include the values of compressive strength f_c for each specimen (i.e., the peak of the σ-ε curves), the strain at the peak of stress ε_{c1}, the modulus of elasticity E_c obtained as described in the previous section and the average values for each concrete mixture. The comparative assessment of σ-ε curves from *Fig. 48a-c* shows no clear change in compressive strength with the increase of rubber content. In fact, as can be also seen from *Table 19*, average values of compressive strength are practically the same, about 30 MPa for all three examined mixtures.

Table 19 – Results of compressive strength tests

Concrete mixture	Specimen	f_c [MPa]	$f_{c,average}$ [MPa]	ε_{c1} [%]	$\varepsilon_{c1,average}$ [%]	E_c [MPa]	$E_{c,average}$ [GPa]
RuC_0	RuC_0_C_1	30,5	30,0	0,27	0,37	25529	25,8
	RuC_0_C_2	28,9		0,39		23732	
	RuC_0_C_3	30,7		0,42		25369	
	RuC_0_C_4	28,2		0,43		25630	
	RuC_0_C_5	31,7		0,32		28932	
RuC_25	RuC_25_C_1	36,4	30,9	0,28	0,28	31954	26,9
	RuC_25_C_2	34,7		0,30		29395	
	RuC_25_C_3	21,3		0,25		21109	
	RuC_25_C_4	38,5		0,31		29160	
	RuC_25_C_5	23,7		0,28		23250	
RuC_50	RuC_50_C_1	31,6	30,3	0,26	0,24	25093	24,8
	RuC_50_C_2	32,3		0,25		25314	
	RuC_50_C_3	30,1		0,21		25922	
	RuC_50_C_4	29,7		0,23		25828	
	RuC_50_C_5	27,6		0,27		22255	

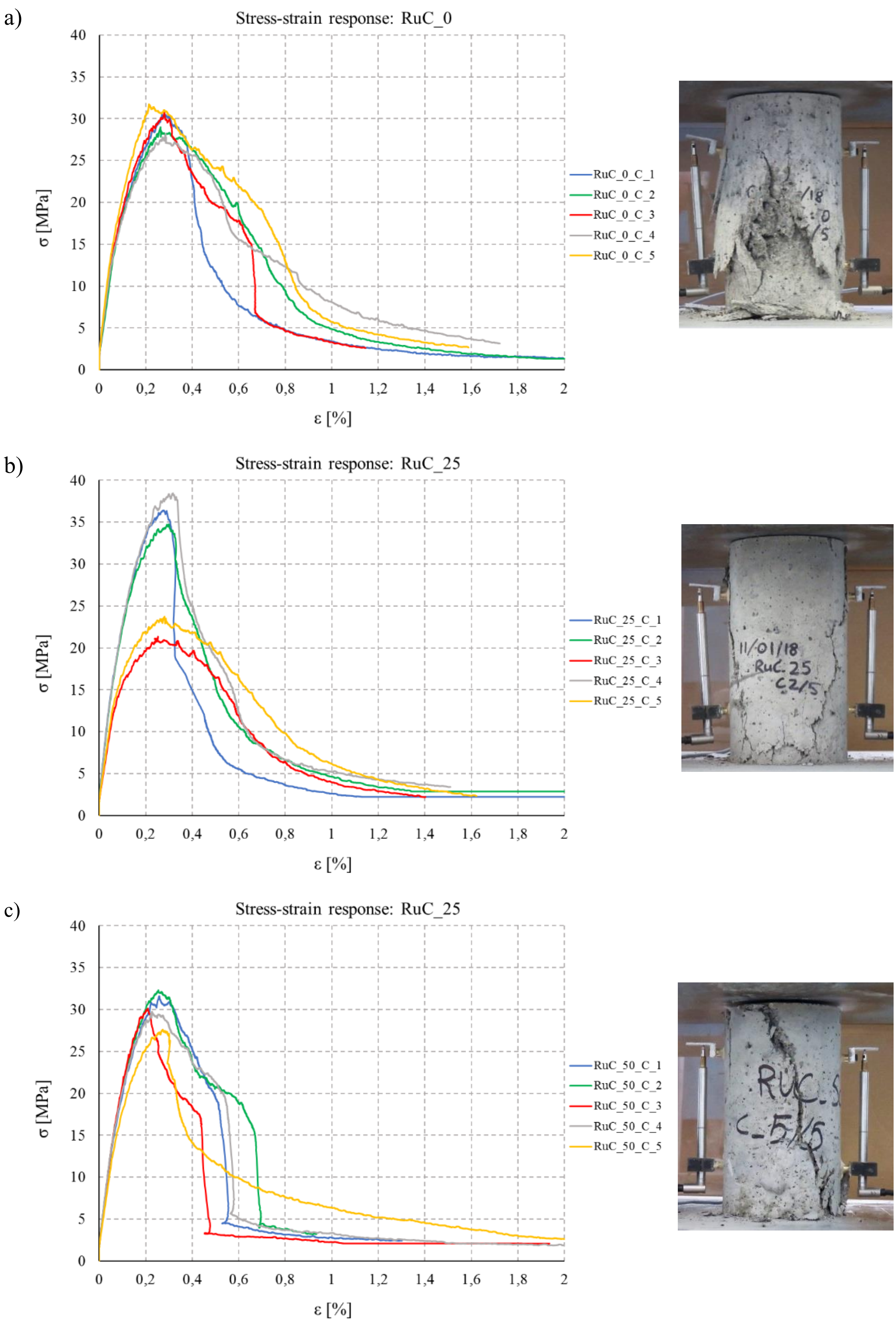


Fig. 48 – Stress-strain relationship and specimen after failure for a) normal concrete RuC_0, b) rubberized concrete with 6% replacement RuC_25, c) rubberized concrete with 12% replacement RuC_50

Main differences between normal and rubberized concrete can be found in values of strain ε_{c1} corresponding to the compressive strength of each specimen. It can be noted that normal concrete specimens reach maximum value of stress under compression after bigger deformation than the rubberized concrete specimens. Moreover, graphic curves of stress-strain response in *Fig. 48a-c* shows more brittle post-peak behavior in rubberized concrete than normal concrete.

4.1.2. Post-peak analysis

In the post-peak phase, the formation of an inclined cracked band is evidenced, which subdivides the cylindrical specimen into two progressively sliding blocks (*Fig. 49*).

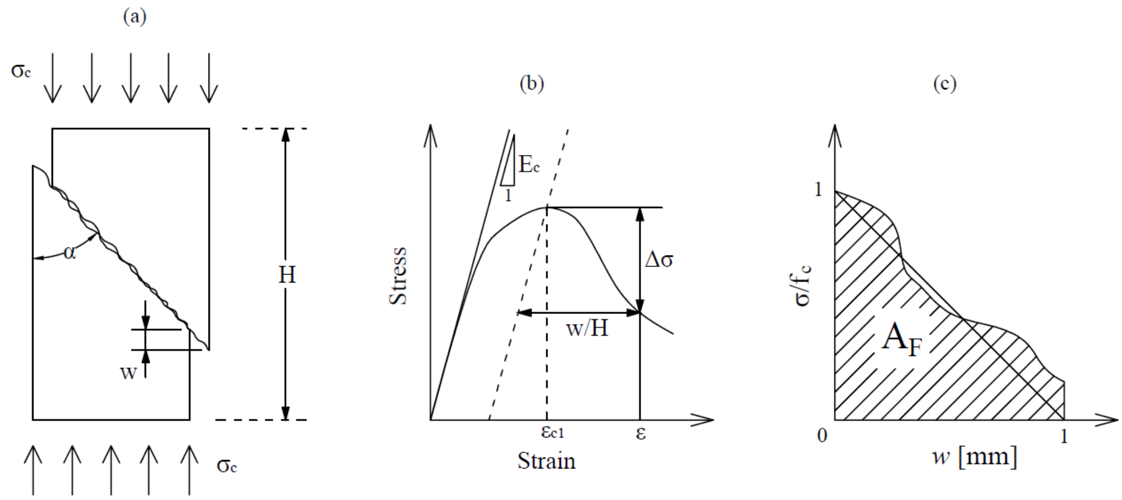


Fig. 49 – The post-peak behavior of concrete cylinders under compression: a) kinematic variables involved during failure, b) idealized stress-strain relationship, c) Post-peak response in terms of relative stress *vs.* inelastic shortening w

The photographs of the specimens after the failure showed in *Fig. 51*, confirm the presence of inclined cracks in all the three concrete mixtures. The inelastic displacement of the specimen, and the sliding of the block along the sliding surface, are the parameters governing the mean post-peak compressive strain ε of the specimen. The inelastic displacement *w* can be obtained by calculating the post-peak branch of an idealized stress strain diagram (*Fig. 51*), in the following form:

$$w = H \cdot \left(\varepsilon - \varepsilon_{c1} + \frac{\Delta\sigma}{E}\right)$$

In this way, a new material property, defined by the non-dimensional function σ/f_c-*w*, can be introduced to reproduce univocally the post-peak stage of a generic cement-based material in compression.

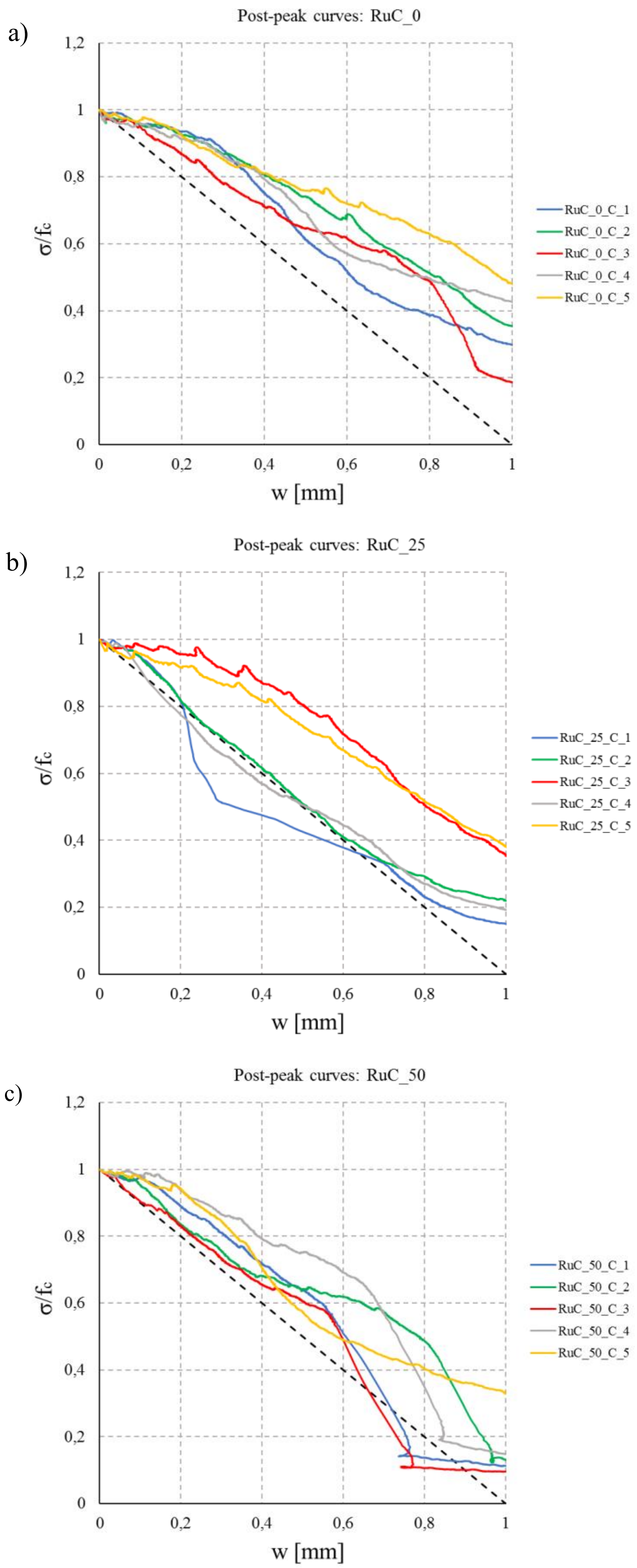


Fig. 50 – Post-peak curves: a) control concrete mixture RuC_0, b) rubberized concrete with 6% replacement RuC_25, c) rubberized concrete with 12% replacement RuC_50

(a) (b) (c)

Fig. 51 – Some of tested specimens after failure in compression: a) RuC_0, b) RuC_25, c) RuC_50

Post-peak stage of the three concrete mixtures is described in *Fig. 50* by the σ/f_c-w curves and the area A_F under the curves (i.e., the ductility in compression). In the three diagrams, one for each concrete mixture, five curves are reported to represent the post-peak response of each specimen. All the curves are limited to w = 1 mm and the corresponding values of A_F, computed in the range w ~ 0-1 mm are reported in *Table 20*.

Table 20 – Area A_F under the curves σ/f_c-w for each specimen

Concrete mixture	Specimen	A_F [mm]	$A_{F,average}$ [mm]
	RuC_0_C_1	0,64	
	RuC_0_C_2	0,68	
RuC_0	RuC_0_C_3	0,65	0,68
	RuC_0_C_4	0,65	
	RuC_0_C_5	0,76	
	RuC_25_C_1	0,48	
	RuC_25_C_2	0,54	
RuC_25	RuC_25_C_3	0,72	0,59
	RuC_25_C_4	0,53	
	RuC_25_C_5	0,66	
	RuC_50_C_1	0,57	
	RuC_50_C_2	0,63	
RuC_50	RuC_50_C_3	0,52	0,59
	RuC_50_C_4	0,66	
	RuC_50_C_5	0,57	

From average values of A_F it is clear that rubber content influences ductility of concrete in compression. In fact, the area under curves σ/f_c-w decreases with the increasing of substitution ratio between rubber and mineral aggregates. This means that fracture propagation is accelerated by the presence of rubber particle and fracture energy dissipated is lower in rubberized concrete than in normal concrete.

4.1.3. Tensile strength

As compressive strength, also tensile strength is quite constant in all three tested mixtures. Results of splitting tensile tests are showed in *Table 21* together with average values and standard deviation of each concrete mix.

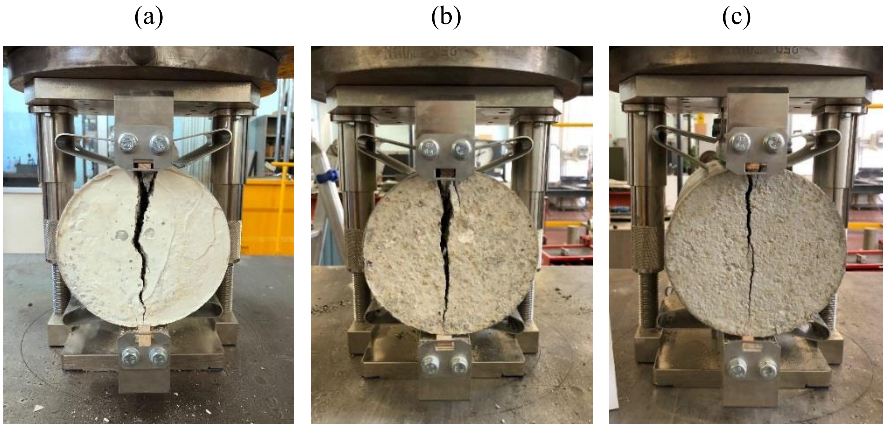


Fig. 52 – Specimen after failure in splitting tensile test: a) RuC_0, b) RuC_25, c) RuC_50

Table 21 – Results of splitting tensile tests

Concrete mixture	Specimen	f_{ct} [MPa]	$f_{ct,average}$ [MPa]	St. dev. [MPa]
	RuC_0_T_1	1,69		
	RuC_0_T_2	1,41		
RuC_0	RuC_0_T_3	2,67	2,3	0,70
	RuC_0_T_4	2,93		
	RuC_0_T_5	2,82		
	RuC_25_T_1	3,31		
	RuC_25_T_2	2,24		
RuC_25	RuC_25_T_3	2,49	2,7	0,44
	RuC_25_T_4	2,98		
	RuC_25_T_5	2,44		
	RuC_50_T_1	3,16		
	RuC_50_T_2	1,53		
RuC_50	RuC_50_T_3	1,12	2,1	0,80
	RuC_50_T_4	2,19		
	RuC_50_T_5	2,50		

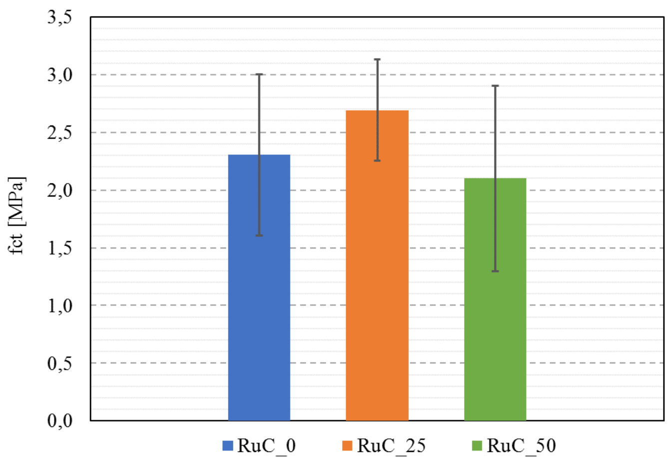


Fig. 53 – Average tensile strength values

Rubberized concrete mixtures with 6% and 12% replacement of total volume of aggregate show no clear reduction in tensile strength compared to normal concrete. Despite this, failure mode of specimens is different for rubberized concrete and normal concrete. In *Fig. 52* it can be noted that fracture is more closed in specimens with rubber particle than in normal concrete specimen. Moreover, in case of rubberized concrete mixture RuC_50, after removing of specimen from the centering device it remains a single block and it does not separate into two parts (*Fig. 54*).

Fig. 54 – Concrete RuC_50 specimen after splitting tensile test

4.1.4. Flexural strength

The results of the three points bending tests on beams are reported in *Fig. 56*, where the load-midspan deflection curves (P – δ) are depicted. In *Table 22* are showed maximum load values P_{max}, the corresponding deflection δ_{cr} and the flexural tensile strength $f^{f}_{ct,L}$, together with their averages.

(a) (b) (c)

Fig. 55 – Beams after failure three points bending tests: a) RuC_0, b) RuC_25, c) RuC_50

Table 22 – Results of three points bending tests

Concrete mixture	Specimen	P_{max} [kN]	$P_{max,average}$ [kN]	δ_{cr} [mm]	$\delta_{cr,average}$ [mm]	$f^{f}_{ct,L}$ [MPa]	$f^{f}_{ct,L,average}$ [MPa]
	RuC_0_B_1	19,5		0,09		4,3	
RuC_0	RuC_0_B_2	21,8	20,8	0,06	0,07	4,8	4,7
	RuC_0_B_3	22,2		0,07		4,9	
	RuC_25_B_1	16,9		0,09		3,7	
RuC_25	RuC_25_B_2	15,5	16,6	0,06	0,08	3,4	3,6
	RuC_25_B_3	17,4		0,08		3,8	
	RuC_50_B_1	18,0		0,09		3,9	
RuC_50	RuC_50_B_2	17,0	16,9	0,10	0,09	3,7	3,7
	RuC_50_B_3	15,8		0,09		3,5	

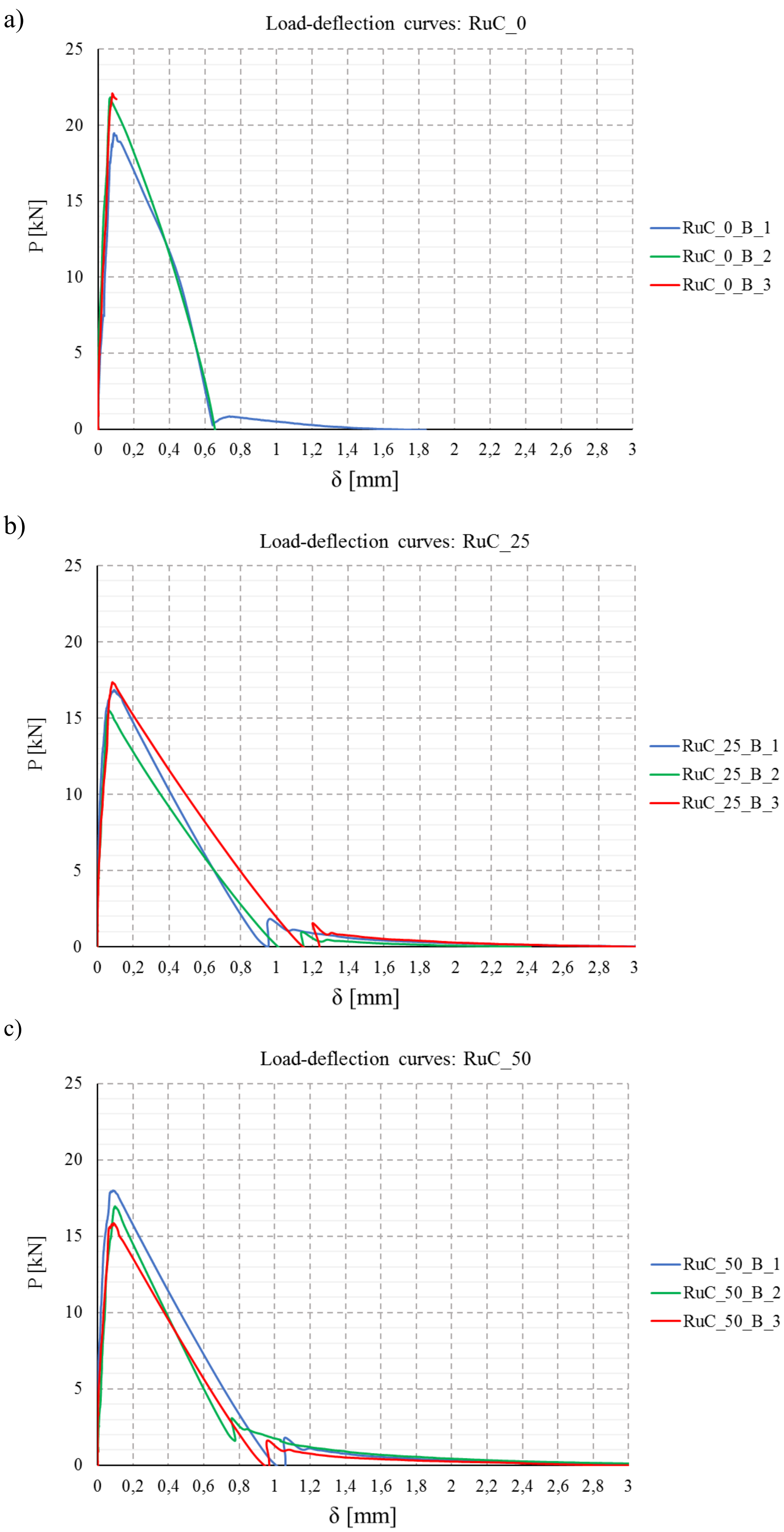


Fig. 56 – Load-deflection curves for a) normal concrete RuC_0, b) rubberized concrete with 6% replacement RuC_25, c) rubberized concrete with 12% replacement RuC_50

Unlike the case of compressive and tensile strength in which no variation has been registered, flexural strength decreases with the increasing of rubber content. In particular, the maximum load is 20% lower in case of rubberized concrete mixtures than normal concrete mixture. Comparing load-deflection curves of normal concrete and rubberized concrete it can be observe that rubberized concrete beams exhibit a slight improvement of the residual flexural stress.

4.1.5. Bond-slip behavior

Bond-slip behavior of cubic samples with embedded 12 mm and 16 mm deformed bar is showed in *Fig. 57a-c* and *Fig. 58a-c* respectively. From a direct comparison among Portland control concrete mixture and rubberized concrete mixtures it comes out that bond-slip behavior is very similar in all the three mixtures. In fact, not only the average maximum of bond stress τ_{max} are quite constant (*Table 23*) despite increasing quantity of rubber in concrete, but also the post-peak τ-s regime remains unchanged. Also, no differences are found by changing bar diameter: both samples embedded 12 mm and 16 mm bars shows a maximum bond stress near to 18 MPa. During pull-out test on control concrete mixture without rubber, the specimen RuC_0_16_2 exhibited a behavior that was very different from the others of the same category (*Fig. 58a*). For this reason, it was decided to consider this result unacceptable and to not include it in determination of τ_{max} average value. All tested specimen developed a pull-out failure, this means that the bar is pulled out and leaves the surrounding concrete intact.

Table 23 – Results of pull-out tests

Concrete mixture	Specimen	Bar diameter [mm]	τ_{max} [MPa]	$\tau_{max,average}$ [MPa]
RuC_0	RuC_0_12_1 RuC_0_12_2 RuC_0_12_3	12	16,5 20,7 19,1	18,8
RuC_25	RuC_25_12_1 RuC_25_12_2 RuC_25_12_3	12	21,6 17,3 18,7	19,2
RuC_50	RuC_50_12_1 RuC_50_12_2 RuC_50_12_3	12	18,4 18,6 20,1	19,0
RuC_0	RuC_0_16_1 RuC_0_16_2 RuC_0_16_3	16	18,3 ~~13,0~~ 17,1	17,7
RuC_25	RuC_25_16_1 RuC_25_16_2 RuC_25_16_3	16	20,0 19,0 18,6	19,2
RuC_50	RuC_50_16_1 RuC_50_16_2 RuC_50_16_3	16	18,7 17,5 16,9	17,7

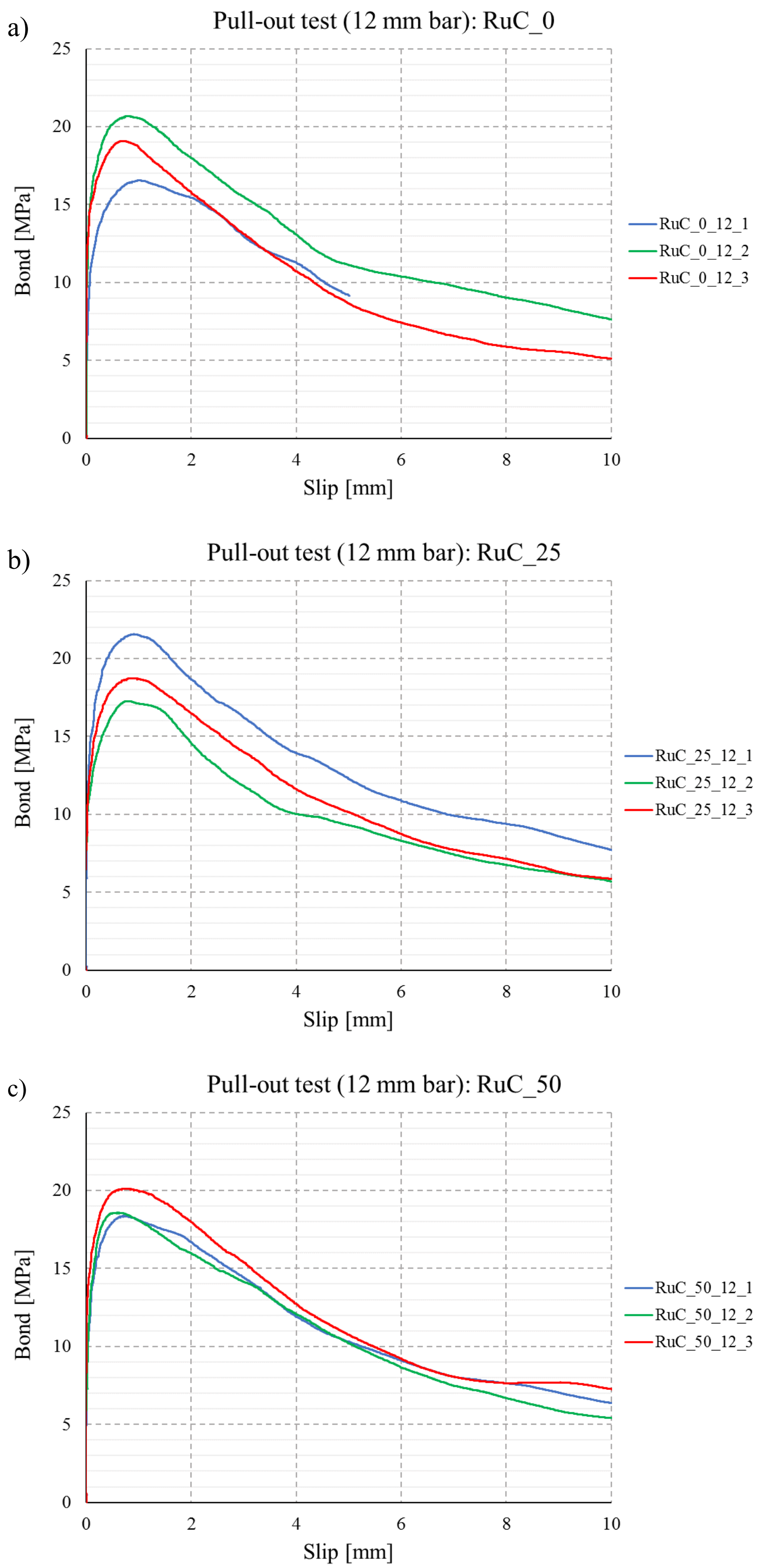


Fig. 57 – Bond-slip behavior for specimen with 12 mm embedded deformed bar: a) normal concrete RuC_0, b) rubberized concrete with 6% replacement RuC_25, c) rubberized concrete with 12% replacement RuC_50

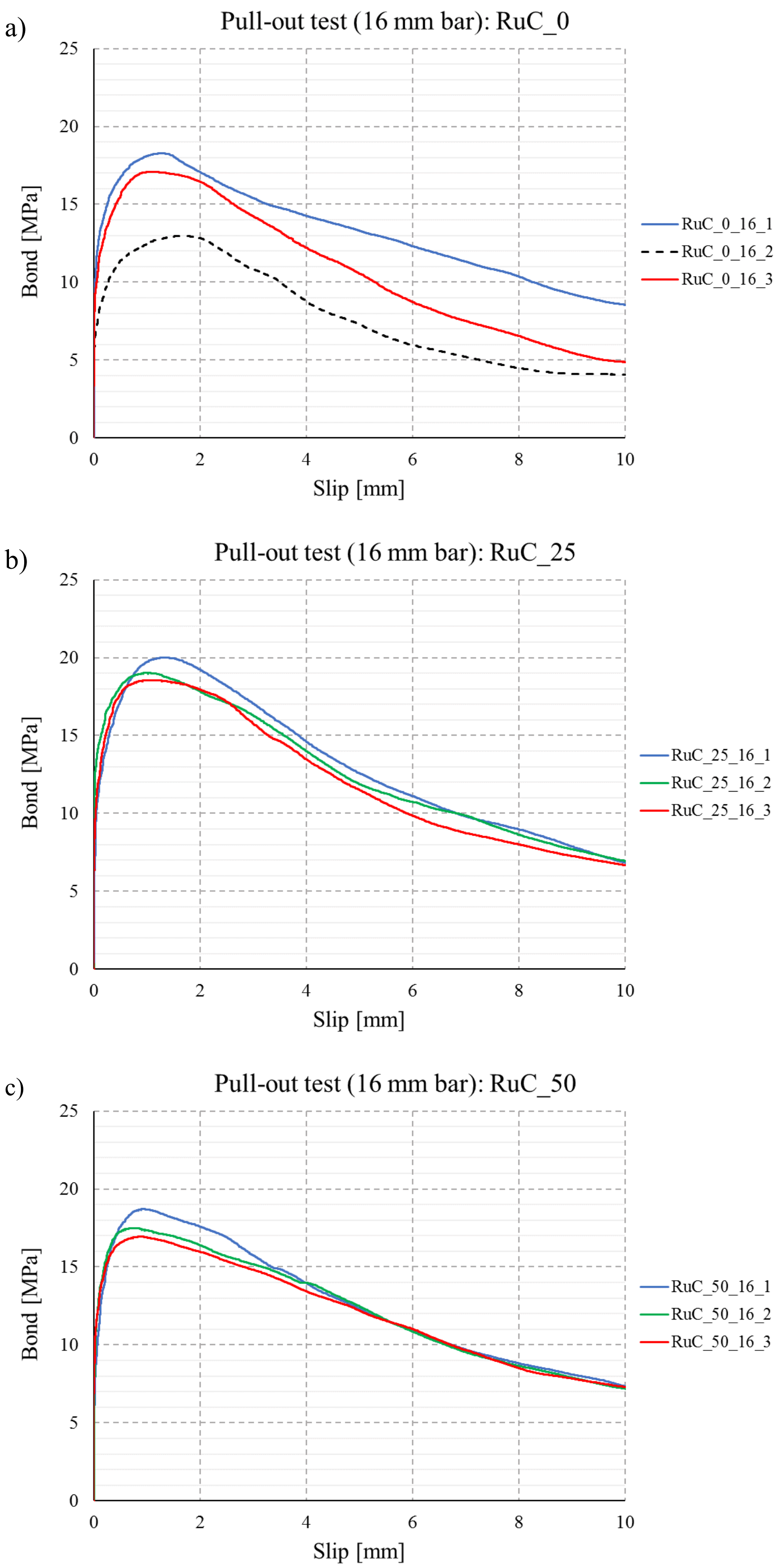


Fig. 58 – Bond-slip behavior for specimen with 16 mm embedded deformed bar: a) normal concrete RuC_0, b) rubberized concrete with 6% replacement RuC_25, c) rubberized concrete with 12% replacement RuC_50

Fig. 59 – Specimen of the three concrete mixtures after pull-out failure

4.2. Water permeability of rubberized concrete

Table 24 presents the amount of water permeability in the Portland concrete mixture and the two rubberized concrete mixtures. It can be noted from this table that when rubber content increases from 6% to 12% in total aggregates volume replacement, water permeability decreases by 47% and 69% respectively as compared with control mixture.

Table 24 – Results of water permeability tests

Concrete mixture	Specimen	Water penetration [mm]	Average water penetration [mm]
RuC_0	RuC_0_P_1	~~214~~	68
	RuC_0_P_2	106	
	RuC_0_P_3	31	
RuC_25	RuC_25_P_1	65	36
	RuC_25_P_2	23	
	RuC_25_P_3	20	
RuC_50	RuC_50_P_1	21	21
	RuC_50_P_2	25	
	RuC_50_P_3	16	

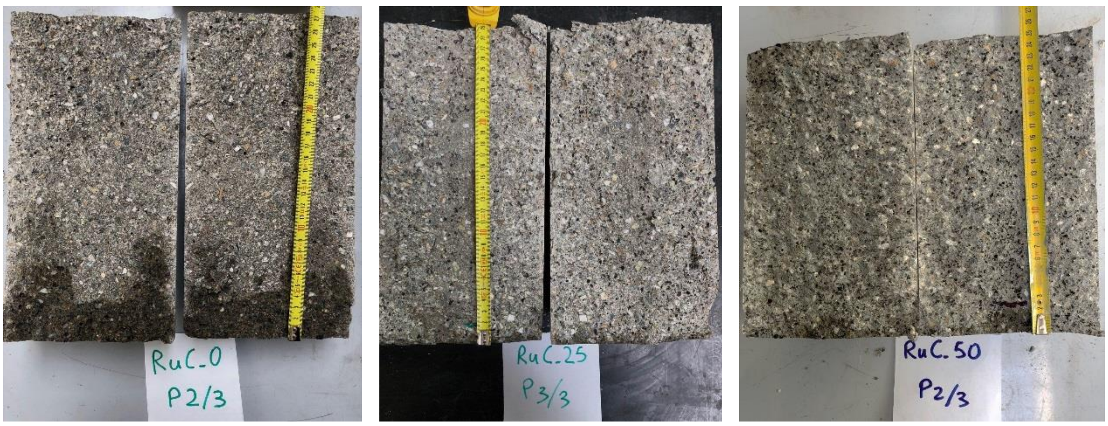


Fig. 60 – Water penetration measurement after permeability test

5. Discussions and conclusions

The experimental research presented in this work examined the mechanical properties of concrete materials incorporating rubber particles, obtained from recycled tyres, as a replacement for mineral aggregates. A complete overview on the main mechanical properties has been purposed about three different concrete mixtures: an ordinary Portland control mixture, used as reference in results analysis, and two rubberized concrete mixtures obtained by replacing 6% and 12% by aggregates volume with crumb rubber. The mechanical properties that have been investigated was compressive strength, modulus of elasticity, tensile strength, flexural strength and bond-slip behavior. Moreover, water permeability was determined for each of these concrete mixtures.

From compression strength tests it comes out that no substantial differences occurred between stress-strain response of ordinary concrete and rubberized concrete. In fact, all the three mixtures exhibited the same compressive strength and very similar modulus of elasticity values. These homogeneity in results between stress-strain response of normal concrete and rubberized concrete with rubber replacement up to 12% by total aggregates volume is mainly due to the modality with which the substitution was made and to the reduced size of rubber particles used (from 1 mm to a maximum of 4 mm). In fact, as described before, substitution was made between specific fractions of aggregate and rubber with the same dimension after a phase of accurate sieving of material. Regarding post-peak response, rubberized concrete mixtures exhibited a more brittle behavior than ordinary concrete. This is due to the fact that fracture propagation in concrete is accelerated by the presence of rubber particles that do not hinder the crack path as mineral aggregates do. As the compressive strength, also modulus of elasticity is quite constant despite the increase amount of rubber.

Several authors found out that the addition of coarse rubber chips in concrete reduced the compressive strength more than the inclusion of fine crumb rubber (Topçu, 1995; Khatib and Bayomy, 1999; Eldin and Senouci, 1993; Aiello and Leuzzi, 2010). This confirms that use of rubber particles with small dimension helped to have no consequences on compressive strength.

Moreover, the percentages of substitution played an important role. In this case the substitution ratios were 6% and 12% by total aggregate volume and no variation in compressive strength was registered. On the other hand, for example, Bompa *et al.*, (2017) tested three rubberized concrete mixes with 20%, 40% and 60% rubber replacement by volume of mineral aggregates and obtained a reduction of 35%, 68% and 76% respectively on compressive strength respect to the control mix. Addotionally, a detailed analysis of a database on average tests results from several rubberized concrete mixtures and their reference concrete mixes, including tests undertaken in their studies, was carried out. In this way, Bompa *et al.* defined a series of prediction expressions to estimate the compressive strength of rubberized concrete materials as a function of its volumetric rubber ratio. In *Fig. 61* it is showed a comparison between compressive strength degradation curve as a function of rubber ratio in case of fine aggregates replacement and compressive strength results obtained in this study (red markers). Black marker in figure indicates the compressive strength results found in literature of rubberized concrete obtained with rubber in place of fine aggregates. It can be noted that results of this experimental research are apart from the curve proposed by Bompa *et al.*

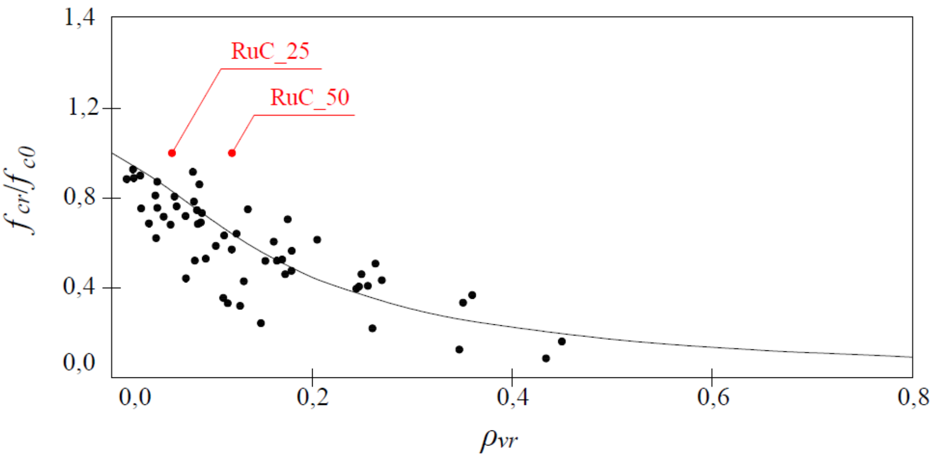


Fig. 61 – Compressive strength degradation curve defined by Bompa *et al.* (2017) as a function of volumetric rubber ratio in case of fine aggregates replacement compared with compressive strength results obtained in this study

As in case of compression strength, also values of tensile strength are quite constant in the three mixtures. This means that also tensile strength is substantially no influenced by increasing of rubber content up to 12% by aggregates volume replacement. Other authors that focused their studies on tensile strength of rubberized concrete observed that tensile strength decreases by increasing of rubber content. Ganjian, Khorami and Maghsoudi (2009) reported that the reduction in tensile strength with 7.5% replacement of chipped rubber (maximum size about 10 mm) in place of mineral aggregates was 44% and 24% for the rubberized concrete mixture obtained with ground rubber (maximum size 1,2 mm). This means that reduction was higher for coarse rubber particles than fine particles. Also Eldin and Senouci (1993) investigated on the influence of rubber particles dimension and obtained similar results.

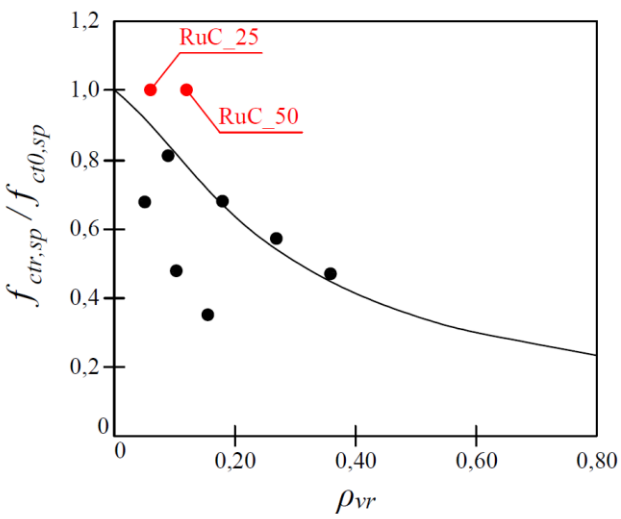


Fig. 62 – Tensile strength degradation comparison between relationship obtained by Bompa *et al.* and results purposed in this work

As in case of compressive strength, Bompa *et al.* (2017) defined a tensile strength degradation curve based on previous studies. It is interesting to compare their results with tensile strength values obtained in this work. It can be noted from *Fig. 62*, results of this experimental research are not aligned with the prediction made by Bompa *et al.*

Results of three points bending tests shows that flexural strength of rubberized concrete is lower than flexural strength or ordinary Portland concrete. In fact, maximum loads reached by rubberized concrete specimens were 20% lower than control concrete mixture. Considering the behavior observed in compression and splitting tensile tests, in which the three mixtures exhibited similar response, the most important factor in reducing flexural strength is lack of good bonding between rubber particles and cement paste. Flexural strength of rubberized concrete was analyzed also by Aiello and Leuzzi (2010). In their experimental research, a larger reduction of flexural strength was observed when the coarse aggregate rather than fine aggregate was substituted by rubber particles. Rubberized concrete mixtures prepared with 50% and 75% by volume of coarse aggregate replacement, both presented a decrease in flexural strength, referred to the control mixture, of about 28%. Whereas mixtures obtained with 50% and 75% by volume of fine aggregate substitution, showed, respectively, a decay of about 5,8% and 7,3% to the control mixture. Similar results were obtained also by Toutanji (1996).

Declared in the first part of this study, the main purpose was to investigate the influence of rubber particles presence inside concrete member on bond-slip behavior. From a total of thirty tested specimens, including ordinary Portland concrete and rubberized concrete samples, it comes out that rubber content up to 12% by aggregates volume replacement ratio has no influence on the bond properties. It can be observed that bond-slip behavior is quite constant on the three concrete mixtures. In fact, not only values of maximum bond strength τ_{max} are similar but also failure mode and post-peak behavior quite the same.

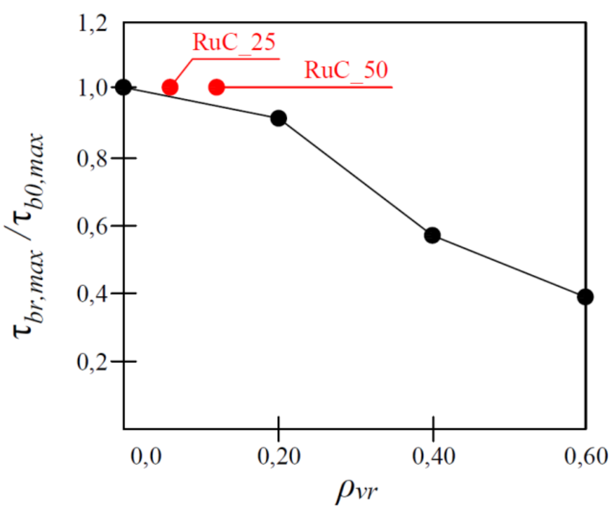


Fig. 63 – Maximum bond stress degradation according to Bompa and Elghazouli (2017) (black markers) and results achieved in this work (red markers)

Bond-slip response of rubberized concrete was mainly investigated by Bompa and Elghazouli (2017). By comparing their results with results achieved in this experimental research it can be noted that, unlike compression and tensile strength, maximum bond stress degradation is similar in both studies. In fact, Bompa and Elghazouli reported that rubber content has less dtrimental influence on the bond properties in comparison with its influence on the uniaxial compressive strength.

Regarding water permeability tests, it was observed that water penetration inside concrete cylindrical specimens decreases by increasing rubber particles content. This slight decrease in depth penetration of water in concrete is due mainly to the reduced dimension of rubber aggregates utilized and to the low percentage of aggregate volume replaced. Different behavior has been observed by Ganjian, Khorami and Maghsoudi (2009) and Bisht and Ramana (2017) that report a rise in water penetration in rubberized concrete mixtures.

Large number of previous studies have reported an important decreasing in mechanical properties due to rubber particles presence inside concrete members. In this work instead, thanks to low ratios of rubber replacement in place of mineral aggregates, the mix design approach and the reduced size of rubber aggregates in place of fine aggregates, no substantial variation has been observed. This means that, according to the results showed in this work, rubberized concrete with substitution up to 12% by total aggregates volume can be used in structural applications. It is sure that more experimental researches on these mixtures are needed in order to confirm these achievements. In fact, it will be interesting to investigate in detail on the possibilities offered by this mix design approach. Moreover, mechanical properties of rubberized concrete mixtures with substitution percentages higher than 12% can be tested to understand the maximum replacement ratio able to guarantee concrete structural performances recommended by standards. Regarding properties of rubberized concrete that have not been investigated in this work, researches on impact energy dissipation, sound attenuation, thermal conductivity and blast resistance are required. With addition of rubber particles with coarse dimension, concrete members may become comparatively ductile and so able to absorb more energy during impacts or sound wave propagation.

Possible applications of rubberized concrete structures in civil engineering are: structures in which no high mechanical performances, especially compressive strength, are required; members subjected to high deformations (like zone of bridge piers in contact with the deck); paving slabs or jersey barriers where vibration damping or impact resistance are required.

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