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Recovered Tire-Derived Aggregates for Thermally Insulating Lightweight Mortars

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Abstract: In this study, seven mortar mixes were prepared by replacing natural sand by crumb rubber ,CR, (10%, 25%, 50%, 60%, 75% and 100%). The properties of mortars, both in their fresh and hardened states, were studied. Key characterisitcs, including density, water absorption coefficient, porosity, thermal conductivity, heat capacity, shrinkage/swelling, elastic modulus, compressive strength, flexure strength, fracture energy and performance after exposure to heat, were evaluated. The results obtained showed that as the CR fraction increased, density, initial setting time, and workability decreased but mortars with CR fractions ranged between 25% and 50% are lightweight and can be used for repairing as they fulfill satndards. It was observed that strengths and stiffness decreased with higher CR content while shrinkage increased for CR percentage higher than 60%. However, up to 50% of CR content the mortars obey to the standards for repair. Interestingly, incorporating up to 50% waste tires proved to improve comfort and thermal resistance without affecting thermal inertia. A slight increase in the mass loss is observed when mortars are exposed to high temperatures. Mortars containing CR between 25% and 50% can be classified as lightweight and thermally insulating mortars, suitable for repairing concrete structures in accordance with industry standards.

Keywords: Crumb Rubber; mortar; mechanical properties; thermal properties; bond strength; fire

1. Introduction

1.1. ELT management: state of the art

The management of tire waste, as well as rubber-based products including rubber belts used for mining, building, and manufacturing, is one of the major global environmental challenges of our era. The increasing volume of tire waste is becoming a major concern; while classified as non-hazardous waste, tire waste poses environmental and public health riks (Dabic-Miletic, Simic, and Karagoz 2021) due to the following reasons:

- Tires are not biodegradable products composed of natural and/or petroleum-based rubber as well as, steel reinforcements, textile fibers, and various chemicals like sulfur, zinc oxide and carbon black. In addition, rubber undergoes treatemts that enhance its durability and resistant, making the product more difficult to degrade and recycle.

- Used tires consume large amounts of landfill space as they are both bulky and heavy. This trend is expected to continue as there are no alternative technologies that can reduce the accumulation of rubber waste in the near future.

- When left illicitly in the landscape, tires become an ideal mosquito incubators. These mosquitoes can transmit diseases such as zika, malaria, yellow fever and dengue fever.

- They are also difficult to extinguish in the event of fire. The treatment of tire rubbers to enhance their resistance increases their calorific value, causing them to burn for longer periods. As a result, tires require more time and effort to extinguish when ignited. In addition, tire fires release gas pollutants, including CO, SO_2 and NO_2.

- They accumulate hazardous gases, leachates and parasites. The heavy metals and chemicals containied in used tire may gradually decompose on contact with other liquids in the landfill and leach out into the environment. Leachates may contain harmful and carcinogenic substances and contaminates soil, groundwater and farmland.

With about 1.1 billion vehicles on the roads worldwide, approximatively 1.7 billion new tires are produced per year to satisfy the demand (Forrest 2019). Hence, millions of end-of-life tires (ELT) are discarded, representing a serious threat to the environment and health (Dong et al. 2019). According to World Business Council for Sustainable Development (WBCSD 2021), about 1 billion tires worldwide (around 17 million tons) reach the end of of their life cycle every year. This trend is expected to persist and the number of ELTs could increase up to 1.2 billion by 2030 (Azevedo et al. 2012; Thomas, Gupta, and Panicker 2016,Abbas-Abadi et al. 2022; Arulrajah et al. 2019). Moreover, it is reported that the global end-of-life tire (ELT) management market is expected to grow at a compound annual growth rate (CAGR) of 4.87% over the period 2023 to 2032(ASDReports 2023). Against this backdrop, and in keeping with the challenges of the environment, the collection and recycling of used tires is becoming a vital global issue. The success of ELT recycling programs often depends on regulatory instruments, as well as the voluntary management of the system by the tire industry.

According to information collected within the framework of the tire industry's project (TIP) covering 45 countries (Argentina, Brazil, China, India, Indonesia, Japan, Mexico, Nigeria, Russia, South Africa, South Korea, Thailand, USA and 32 European countries (EU27 plus UK, Norway, Serbia, Switzerland and Turkey)), over 29.1 million tons (metric) of ELT are generated annually and 97% of ELT are recovered (China, the United States of America, and Europe recover the most ELTs). In addition, 25.6 million tons of ELT are recycled, excluding those used in civil engineering and backfill projects. This figure includes ELT collected in China and the corresponding end use is undetermined (WBCSD 2019, 2021). This means that 88% of ELT produced is treated, and the percentage rises to 90% when considering civil engineering and backfill uses. The development of ELT management is promising, particularly in countries like Argentina, Mexico, Nigeria, South Africa, Thailand and Russia, where recovery rates are still relatively low, as reported recently (Consulting 2022; Valentini and Pegoretti 2022).

Table 1. ELT generated in various countries (in metric kilotons) and recovered for various purposes.

Country	Total ELT generated	Energy	Material	Civil/backfill	other	Total ELT recovered	ELT recovered (%)
China (2018)	14545	0	5650	0	8895	5650	39
United States (2017)	3700	1442	1227	326	706	2995	81
Europe +(2017)	3425.5	1180	1855.5	105.5	283.5	3141	92
India (2015)	2749.8	600	2094.8	0	55	2694.8	98
Japan (2017)	849	619.5	160.5	1	68	781	92
Russia 2017)	800	6	154	0	640	160	20
Indonesia (2017)	684.4	376.4	136.9	0	171.1	513.3	75
Brazil (2017)	587.9	206.1	379.1	0	2.7	585.2	100
Thailand (2012)	515	75.4	202.3	0	237.3	277.7	54
Mexico (2017)	467.5	67.1	27.9	0	372.5	95	20

South Korea(2017)	319.4	160	120.9	0	38.5	280.9	88
South Africa (2015)	204	9.4	41.5	0	153	50.9	25
Argentina (2018)	150	0	9.6	0	140.4	9.6	6
Nigeria (2017)	113	2.8	2.8	0	107.3	5.6	5

The main recycling methods for ELT in the 45 countries listed above are energy recovery and material recovery. These methods are followed to a lesser extent by civil/mining engineering applications, including water retention basins, tire-based aggregates for road construction, backfilling, and rehabilitation of land or mining sites. Table 1 summarizes the distribution of ELT in the countries consuming the highest number of tires based on recent data extracted from the report of the World Business Council for Sustainable Development (WBCSD 2019).

The statistics presented in Table 1 highlight the need for a concerted effort to reduce the number of ELT collected but not recovered (i.e. landfilling, stockpiling and uncertain end-use). The promotion of ELT recovery and reuse is a key concern shared by many countries worldwide.

In the Middle East, millions of tires are discarded annually, presenting a significant challenge. As a short-term solution, these non-biodegradable wastes have been stockpiled in urban facilities, illegally dumped in remote areas, or discarded in landfills (Salman Zafar 2022). In Kuwait alone, around 50 million tires have been found in landfills, and a further 3 to 3.5 million are discarded each year. Severe road conditions and intense heat require tires to be renewed every two years, further exacerbating the volume of waste (Fayez Obaid Al Mazrouei 2023).

Developing countries face challenges in managing solid waste, including ELT with limited published statistics on this subject. This issue is commonly attributed to the lack of policies, regulatory frameworks, and adequate infrastructure for waste collection, sorting, recycling and recovery, and these factors vary from one country to another. For tire wastes, another factor can be added related to the limited influence of legislation on the quality of tire imports leading to the importation of second-hand tires (tire retreads) that have a limited lifespan once mounted on vehicles. As a result, ELTs in developing countries tend to accumulate in waterways and on land, posing serious health and environmental risks. Uncontrolled open dumping and open burning are the main ELTs treatment and final disposal systems employed. This waste management challenge is particularly serious in countries with rapidly growing urban areas(Ferronato and Torretta 2019; Johannes et al. 2021; UNEP 2018). In some African countries, some attempts have been made recently by researchers to explore recycling and recovery options for used tires. In Ethiopia, ELTs are shredded and used as an energy source (Tyre-Derived Fuel "TDF") in cement kilns to replace coal in the pre-calcining process (Gebreslassie, Bahta, and Mihrete 2023). In Cameroon, ELTs are valorised as materials for the manufacture of O-rings with properties close to those found on the market(Bogno et al. 2023). However, these initiatives remain relatively marginal and at limited scale.

Similar practices are observed in the 14 Pacific Island countries and Timor-Leste (PIC), where ELT production is rapidly increasing due to insufficient quality control of imported tires. Like in Africa, used tire imports tend to have a shorter life and generate large volumes of scrap tires. It is estimated that approximately 22,000 tons of tires are illegally stored, buried or burned with an annual disposal rate of 6,706 tons, or 670,600 tires. The lack of environmental management for ELT can be explained by the absence of specific legislation concerning ELT management, with the exception of occasional references to tire burning as a measure to combat atmospheric pollution in some countries (Palau, Fiji, Kiribati and Cook Islands). Samoa is the only country in the region to have implemented an import restriction. Small-scale shredding operations are underway in Papua New Guinea (PNG), on Majuro Atoll and in Palau, and studies on shredding processes are underway in Samoa. The potential use of shredded tires is primarily as clinker in PNG's cement kilns, and as a fuel source for other applications (SEREP 2022).

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In Australia, an average of 450,000 tons of waste tires -the equivalent of 56 million equivalent passenger units (EPU) tires entering the waste stream- was generated between 2015 and 2020 (Tyre Stewardship Australia (TSA) 2021). The end of Life Tires "EOLTs" often end up in landfills or stockpiles that can take centuries to decompose. It should be noted that in 2009-10, Australia generated approximately 48.5 million EPU tires that entered the waste stream compared to 41.8 million in 2007-08 (Brindley et al. 2012).

Australia's end-of-life tires are categorized according to whether they are passenger, truck or off-road (OTR). Passenger tires include those of passenger vehicles, motorcycles and caravans, as well as trailers for domestic use. Truck tires are those for buses, light and heavy commercial vehicles, motor vehicles, trailers and semi-trailers, and fire-fighting vehicles. OTR tires are those employed on machinery or equipment used in sectors like agriculture, mining, construction and demolition. While Australia has generally achieved good recovery rates for passenger car, bus and truck tires, this is not the case for off-road tires "OTR". These have consistently low recovery rates, below 11%, throughout Australia. When OTR products reach the end of their life, they are usually stored or buried on site, sent to landfill or dumped or burned illegally. Australian EOLT tires have been recovered for domestic reuse (recycling, energy recovery, civil engineering, licensed and unknown landfill), for export (reuse and retreating, recycling and energy recovery) and some are not recovered at all. Unrecovered EOLTs have been disposed of locally in pits or landfills, stockpiled or illegally dumped into the environment.

According to some sources (Brindley et al. 2012; Consulting 2015; Shanley Authors Matt Genever Kyle, Paul Randell John Rebbechi, and - 2017; Tyre Stewardship Australia (TSA) 2021, 2022), almost passengers and truck tires are recovered while the recovery rate for OTR tires is very low even it has grown since 2009-2010 (Table 2). Australia's National Waste Policy, enacted in 2018, has set an ambitious an overall ELT recovery target of 80% by 2030. To reach this goal, OTR tire recovery would need to reach 55% to 60%. For this purpose, tires derived products "TDP" recovery activities for recycling and energy recovery should increase. The promotion of TDF markets could play a significant role as an attractive alternative fuel source and an efficient starting point for ELT management.

Table 2. ELT generated and recovered in Australia in tons.

		Passenger & motorbike	Truck & bus	Off-the-road	Total
2009-2010					
	Consumption of new tires	168901	156095	173382	498377
	Generation of waste tyres	105581	117391	164775	387747
	Recovery / Reuse of waste tyres	79060	43476	9568.416	132104
	Waste tyres recovery rate	0.75	0.37	0.06	0.34
2013-2014					
	Consumption of new tires	154518	183682	198887	537087
	Generation of waste tyres	122686	127369	158276	408331
	Recovery / Reuse of waste tyres	88335	53430	12299	154064
	Waste tyres recovery rate	0.72	0.42	0.08	0.38
2018-2019					
	Consumption of new tires	223000	195000	127000	545000
	Generation of waste tyres	188000	156000	119000	463000

	Recovery / Reuse of waste tyres	167320	138840	13090	319250
	Waste tyres recovery rate	0.89	0.89	0.11	0.69
2019-2020					
	Consumption of new tires	226000	197000	128000	551000
	Generation of waste tyres	185000	152000	113000	450000
	Recovery / Reuse of waste tyres	164650	136800	15820	317270
	Waste tyres recovery rate	0.89	0.90	0.14	0.71
2021-2022					
	Consumption of new tires	227600	194400	141000	563000
	Generation of waste tyres	187600	157800	113600	459000
	Recovery / Reuse of waste tyres	169800	146300	14200	330300
	Waste tyres recovery rate	0.91	0.93	0.13	0.72

In France, according to some sources (Pneumatiques 2023; Venice GRAF et al. 2022), all EOL collected tires are fully recovered and/or reused. For example, in 2021, 567,762 tons of tires were marketed, 572,370 tons of EOL tires were collected and fully recovered, with 15.3% reused, 35.8% recycled materials, 46.8% energy recovery, and 2% Civil Engineering. In 2020, some 477,200 tons of tires were placed on the national market. The collection rate for used tires was around 85%, not representative of performances because of the effects of the COVID19 health crisis. The main recovery methods for these tires are energy recovery in cement works (around 44%), followed by material recovery in the form of granulation (18%) and second-hand sales / retreating (16%). The processing rate in 2021 has risen sharply compared with 2020 (+29.6 points). This can be explained by the low level of marketing in 2020, due to the health crisis, and by the fact that collection in 2021 returned to levels similar to those prior to the health crisis. This level of collection has enabled a significant volume of tires to be processed, hence the sharp rise in the processing rate. On the other hand, it should be remembered that Article L. 541-10-1 (16°) of the Environment Code, introduced by Article 62 of Law no. 2020-105 of February 10, 2020 on the prevention of waste and the circular economy, provides a broader producer responsibility (EPR) system for tires and specifies that the procedures for approving eco-organizations and individual systems are applicable from January 1, 2023. The management of tire waste has been based on the EPR principle since the early 2000s. In this context, one of the objectives of this decree is to develop new "material" recovery processes for EOL tires. Over the past few years, material recovery has accounted for around 36% of the collected EOL tires, with energy recovery accounting for the largest proportion (around 46%). It should be noted that these regulations recommend to reduce energy recovery. With this regulatory limit, and considering the reconsideration of the use of waste rubber aggregates in the manufacture of synthetic turf, it's clear that new recovery strategies for EOL tires are needed.

In this context, this research work aims to establish new methods for ELT material recovery. It should be pointed out that the use of ELT for energy recovery, which involves burning tires, should be discouraged, restricted or even prohibited to promote material recycling in accordance with the waste management hierarchy (energy recovery is at the lower end of the waste hierarchy and can be considered close to disposal).

*1.2. Recovery of ELT tires as **Tyre Derived Aggregate for mortars/concrete applications: state of the art***

The disposal of waste tires is a challenging task because of their slow aging, heavy mass, and non-biodegradable structure. To preserve the environment and natural resources, the reuse of crumb rubber is becoming crucial. Some of the major applications of crumb rubber are in the automotive industry, recycled rubber and plastic products, sport facilities, asphalt-based road building, shock absorption and safety, adhesives and sealants, and construction structures (e.g. hospitals, industrial and bathroom flooring, floor tile, foundation waterproofing, and dams). Recent studies (Bianco, Panepinto, and Zanetti 2021; Charlotte B Merlin 2020; Rincón et al. 2014) point out that the phases of tire repurposing, from collection to scrapping, seem to generate little to no health and environmental concerns. However, it is also concluded that more research should be conducted.

Among the successful civil engineering applications, there is an increasing interest in reusing crumb rubber as a substitute for aggregates in cement-based mortar and concrete (Grinys, Sivilevičius, and Daukšys 2012; Guo et al. 2017; Liu et al. 2012; Thomas and Chandra Gupta 2016; Thomas and Gupta 2016). Fine aggregates have been replaced with rubber particles of different sizes (Su et al. 2015). Experimental data revealed that rubber aggregates considerably affect workability and water permeability, while their effects on fresh density and concrete strength is comparatively less pronounced. In a different study, a significant reduction in compressive strength and tensile splitting strength was reported, but a higher flexibilitywas highlighted, which was viewed as a positive gain in rubberized concrete (Lv et al. 2015). Similarly, low percentages of rubber substitution (2-12%) proved to induce significant reduction in compressive strength and elastic modulus. Nevertheless, experimental evidence indicated that the substitution of aggregates with rubber particles improved the deformability of concrete (Li, Ruan, and Zeng 2014). Replacing 25% of rubber with silica fume proved to have no significant effect on the workability of concrete but it decreased the compressive strength (Gupta, Sharma, and Chaudhary 2015). Interestingly, these authors noted that compressive strength and elasticity moduli (static and dynamic) increased on partial replacement of cement by silica fume. Beside the negative effect of the partial substitution of fine aggregates with crumb rubber on the physical and mechanical properties of concrete, the rubber size, and content were found to have significant positive effect on the abrasive and freeze-thaw properties of concrete (Gesoğlu et al. 2014). An increase in porosity was also observed upon increasing rubber content, which contributed to a decrease in the mechanical properties (Onuaguluchi 2015). Unlike the use of rubber in concrete, there is a limited number of studies on the use of CR in mortar. For example, a recent study (da Silva et al. 2015) investigated the microstructure of mortar embedding recycled tire rubber, which showed that rubber particles increased the volume of micropores in cementitious pastes.

The rational justification for introducing a composite embedding fine crumb rubber is twofold; CR contributes to mitigating the environmental impact of scrape tires and reduces the deadweight of structural mortar, which would otherwise be an overload. The environmental benefits of this approach are not limited to rubber repurposing; they also include the reduction of natural sand fraction in mortar. Natural sand is one of the depleting natural resources and replacing it with crumb rubber is innovative in sustainable design. A CR to NS replacement ratio towards 100% produces results in densities close to 1500kg/m^3, which is an ultra-weight mortar. While published data were limited to 50% replacement ratio, this paper offers a complete range of measurements (up to 100%) for the first time. Despite recent efforts to investigate the fracture energy in crumb rubber concrete (Grinys et al. 2013; Han, Yang, and Xu 2018), more research is needed to investigate the fracture of mortars embedding large amounts of rubber.

To summarize, based on the numerous published papers, there are around 675 articles dealing with the recovery of tire wastes in concrete and/or mortar as aggregates (87% of these publications concern concrete while only 13% are on mortars). Moreover, according to some review papers dealing with the state-of-the-art on this theme (Al-Attar et al. 2021; Qaidi et al. 2021; Rashad 2016; Surehali, Singh, and Biligiri 2023), it appears that existing studies on concrete consider crumb rubber aggregates at percentages less than 30% by volume. Some works deal with replacements greater than 30% (Aiello and Leuzzi 2010; Alsaif et al. 2018; Khaloo, Dehestani, and Rahmatabadi 2008; Marie 2016) and only few studies focus on total replacement (Atahan and Yücel 2012; Batayneh, Marie, and Asi 2008; Khaloo et al. 2008; Marie 2016; Medina et al. 2017). In addition, it appears (Figure 1) that most published investigations deal with mechanical properties (very little of them on fracture) and durability (mainly regarding water absorption). Few papers deal with the application of rubberized concrete in the construction industry and most of them are reported in a review paper (Kara De Maeijer et al. 2021). The use of rubberised concrete is often motivated by its low density, good sound absorption, good durability against chemical attack, freez-thaw and chloride ion diffusion, enhanced damping capacity, impact resistance to bending, and toughness.

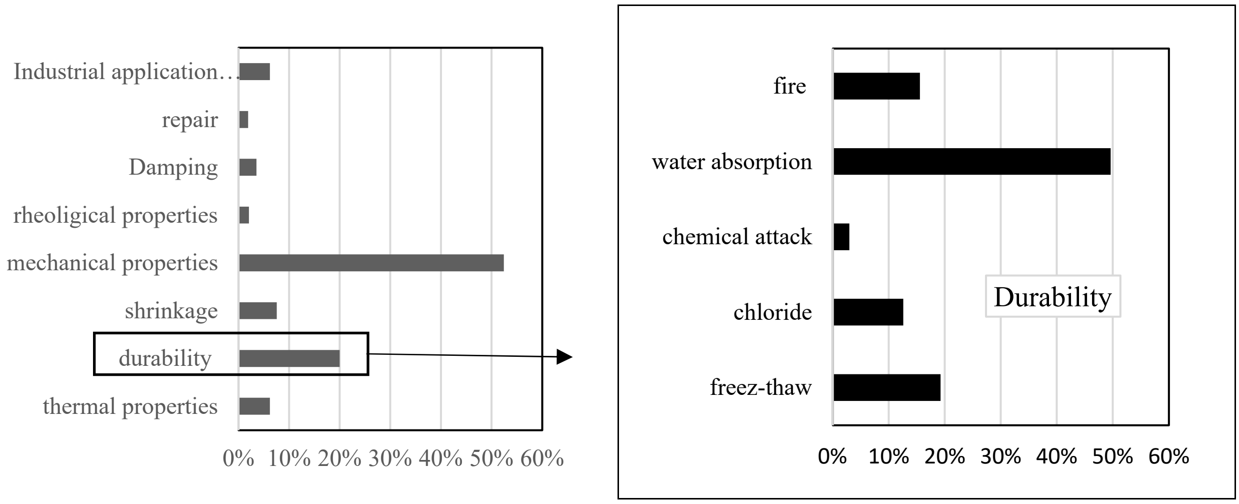

Figure 1. Field of literature studies concerning the recovery of tire wastes in concrete.

Few studies have investigated the use of rubber crumb in plasters and mortars or plasters/mortars applied to exteriors, (Han Zhu, Norasit Thong-On, and Xiong Zhang 2002) established that it is possible to manufacture exterior walls with rubberized mortar, (Zakeremamreza et al. 2023) investigated the effectiveness of alkali-activated used tire rubber mortar in the repair of damaged reinforced concrete beams.

This work aims to examine the potential use of high volumes crumb rubber tire waste in mortars intended for the repair/rehabilitation of buildings concrete walls. To achieve this goal, several properties required for the repair mortar must be studied. These properties include workability, which determines how easy the mortar can be mixed, applied and used for surface finishing; adhesion to the substrate, which depends on the mortar's properties and the substrate's surface conditions; thermal insulation; and resistance to crack propagation.

1.3. Objectives of this research and novelty

Existing papers do not comprehensively address all the essential properties of CR mortars required for repair or rehabilitation in accordance with current standards. Despite the extensive body of research into the effects of crumb rubber on certain physical properties, little effort has been dedicated to the applications of rubber-embedding mortar/concrete.

This research aims to develop a new product for repair/rehabilitation that does not generate an excess load on the structure and its foundations. The proposed solution is anticipated to reduce energy consumption in buildings (in this case, heating and air-conditioning) by improving thermal insulation, increase the potential for recycling EOL tires as a "recovery material", and reduce the use of natural sand, which is currently the world's second most consumed resource after water.

In this work we investigate the effects of incorporating CR waste on the properties of cement-based mortars (mixing, workability, setting time, density, thermal conductivity, strength, stiffness, shrinkage, fracture energy, fire safety and adhesion between the concrete support and CR mortars). In particular, we aim to develop thermally insulating lightweight mortars (TILMs) for repair applications and ensure that they comply with the following standards:

- NF EN 1504-3 defining the classes of products according to their performance: classes R4 and R3 for structural repair and classes R2 and R1 for non-structural repair.

- EN 206-1 prescribing the minimum compressive strength class at 28 days for structural applications (LC8/9 minimum) and its density class from D1.0 ($800 \leq \rho\left(\frac{kg}{m^3}\right) \leq 1000$)o D2.0 ($1800 < \rho\left(\frac{kg}{m^3}\right) \leq 2000$).
- NF P 18-840 defining the key characteristics for a good repair, namely very good adhesion to the support, mechanical compatibility with existing concrete, controlled shrinkage, permeability, resistance to chemical aggression from carbon dioxide, chlorides and/or sulphates, and workability. Hence, CR and NS have been characterized by their granulometries, densities, water absorption coefficients, and heat capacities measured using a deferential scanning calorimetry (DSC) test. At the fresh state, mortars were characterized by evaluating its density, workability (to verify the conformity to NF P 18-840), setting time and air content tests. At the hardened state, mortar was tested by measuring its density (to check its density class), porosity, three-point bending, and compressive strength (resistance class) to verify the influence of CR on the physical and mechanical performance of mortar. The adhesion of CR mortars to the support, the mechanical compatibility with existing concrete and the shrinkage were also assessed.

2. Materials and Methods

2.1. Materials

Semi-crushed natural sand was substituted by crumb rubber aggregates. CR was provided by DeltaGOM and produced in a recycling platform of non-reusable tires from different categories (including heavy vehicles, passenger vehicles, agrarian, and motorcycles). For all mixes, Portland cement (CEM II/A-L 42.5) and limestone filler (HP-OG) of respective densities 3.09 and 2.7 g/cm3 were used. The latter was instrumental in increasing the mortar viscosity. To ensure high workability, a superplasticizer of type MC-Power Flow-3140 was employed in all developed mixtures.

2.2. Experimental procedures

Granulometry, density, water absorption, and deferential scanning calorimetry tests were carried out to characterize the CR and NS. To determine the size distribution of CR and NS, sieving was conducted according to the French Standard (NF EN 933-1 2009). The density and water absorption coefficient of CR and NS were measured by the pycnometer method according to the French Standard (NF EN 1097-6 2014). As the density of CR is low, the measurement was performed in ethanol.

At the fresh state, the mortar was subjected to workability testing versus time (90 minutes) by using slump tests performed according to the French standard NF EN 12350-2 (2010). The slump was measured using a special mini cone whose dimensions are deduced from Abram's cone by a homothetic ratio of two (upper diameter = 50 mm, lower diameter =100 mm, and height = 150 mm). In addition, the setting time was measured using a penetration resistance test and the air content was measured using an aerometer, according to the French Standard (NF EN 12350–7 2012).

At the hardened state of mortar, the French Standard (NF P 18-459 2010) was applied to determine the density, WA coefficient, and total porosity. These measurements were carried out after exposing the specimens to vacuum for 4 hours and immersing them in water for 44 hours. The following expressions were used to calculate the coefficient of water absorption and porosity, respectively:

$$WA = \frac{M_{air}-M_{dry}}{M_{dry}} \quad \text{and} \quad n = \frac{M_{air}-M_{dry}}{M_{air}-M_{w}}$$

where M_{air} is the mass of aggregates at the saturated surface-dried state, M_{dry} is the mass of aggregates at oven dried state and M_w is the mass of aggregates in water.

The thermal conductivity and volumetric heat capacity of all mortars were determined according to ISO 22007-2. The samples were previously dried at 60°C. The tests were conducted on prismatic specimens (4x4x16 cm^3) using a hot disc machine based on the Transient Plane Source with 80 mW output power and 40s measuring time.

Drying tests were performed on prismatic samples cured in water for 28 days after demoulding. The samples were then placed in the oven at 60°C and 40% RH, while the mass was measured continuously during drying for up to 16 days.

Shrinkage tests were performed on prismatic samples demoulded 24h after casting and stored in a room at 20°C and 50% RH according to the NF P15-433 standard. The length variation of the specimens was evaluated using an apparatus equipped with a reference bar and a digital indicator.

The flexural strength test was carried out on prismatic specimens (40x40x160 mm) using an Instron machine of capacity 30 kN according to the French standards (NF EN 196-1 2006). Compressive strength was tested on cubic mortar specimens (40x40x40 mm) and was performed using a servo-hydraulic machine of capacity 3500 kN with a loading rate of 0.5 MPa/s.

The dynamic modulus of elasticity (Ed) is estimated based on resonance frequency measurements, according to the standard NF EN ISO 12680-1 using a E-Meter MK II device supplied by James Instruments.

The fracture energy, Gf, was estimated using standard three-point bending tests performed on pre-notched specimens (RILEM 1985). For each specimen, a mode I crack propagated in the midsection of the beam under the applied load. During this process crack mouth opening displacement (CMOD) and deflection versus applied load were both recorded using linear variable differential transformers (LVDTs). For each experimental point, the test was repeated at least 3 times.

Pull-out tests have been carried out according to the EN 1542 standard and the guidelines of the AFGC. A 2 cm layer of mortar was applied to a concrete slab measuring 30 cm x 30 cm x 10 cm and of resistance class C25/30. Seven concrete slabs have been elaborated in order to apply the 7 mortar mixes (MCR-0% to MCR-100%). Before applying the repair mortar, the surface of the slabs was cleaned, and its roughness was determined using volumetric patch and Elcometer 224 gauge. Then, on each slab / mortar 5 circular cracks with a diameter of 50 mm and a depth of 4 mm were performed. A steel cylinder of diameter 50 mm was then glued to the area delimited by the circular crack using epoxy glue. A tensile load was applied to the cylinder at a constant rate of 0.05 MPa/sec using a Proceq DY-216 dynamometer, until failure occurred. Such a process made it possible to evaluate the concrete/mortar bond strength.

Finally, the effect of heat treatment on the behavior of cured mortars at 28 days of age was investigated using an electrical furnace (of maximum temperature 750°C and volume 1.35 m^3) and a TGA testing device (STA 449 F1Jupiter, developed by Netzsch).

2.3. Characteristics of CR and NS

The size distribution curves show that both materials were comparable although CR had slightly fewer fine particles (<2 mm) than NS (Figure 2a). Their fineness moduli (FM) were calculated according to the French Standard (NF EN 12 620 2008) and it can be seen that CR had a greater fineness modulus than NS (Fig. 2a). Moreover, microscopic observations underlined that the CR particles had rough surfaces while NS particles were round (Figure 2b).

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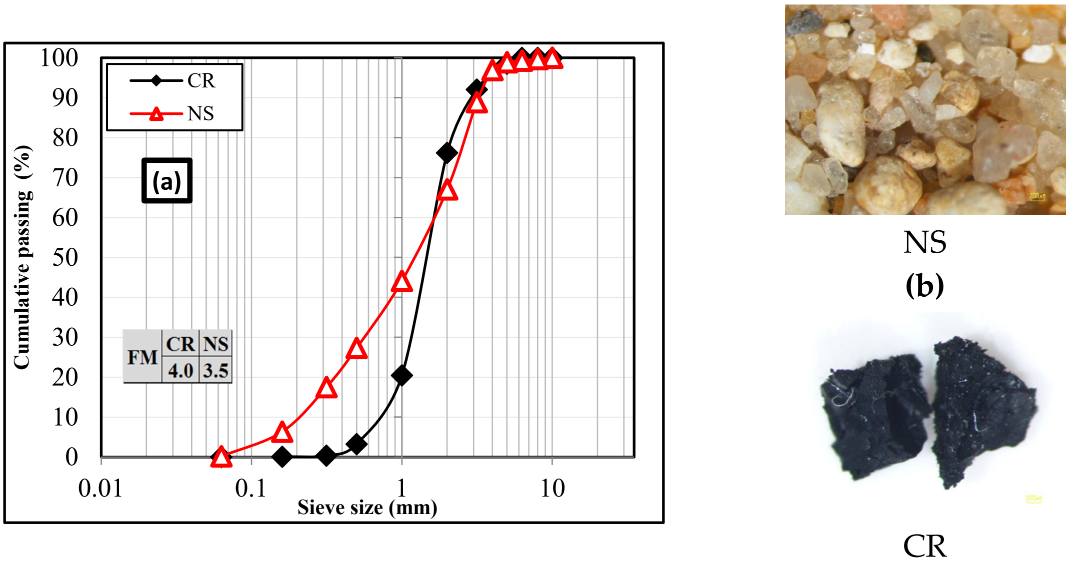

Figure 2. (a) Size distribution curves and (b) microscopic observations.

The relative densities ($\rho_{rd}^{NS(orCR)}$) and the water absorption coefficients of NS and CR were determined according to the French Standard (NF EN 1097-6 2014). For sand, the test was carried out in water but for CR it was conducted using an ethanol solution because CR has low density. The experimental results are presented in Table 3 showing that CR exhibits a low density, which can be critical for the mix design, especially in terms of segregation. Moreover; the particle size ratio R_s used to quantify the relative size of shredded tire particles (CR) and sand particles with similar shape gradations is calculated ($R_s = \frac{D_{50}^{CR}}{D_{50}^{NS}}$ where D_{50} is the particle size corresponding to 50% passing). Several authors (Lee, Yun, and Choi 2015; Liu, Cai, and Liu 2020; Xiao, Nan, and McCartney 2019; Yang et al. 2022) have established that the relative size ratio is one of the main factors influencing the thermal properties of granular mixtures. They have shown that the incorporation of large insulating aggregates is more favourable to thermal conduction than the presence of small insulating particles, for mixtures with the same volumetric fractions of each constituent. Consequently, the thermal insulating effect of small shredded tires (with lower Rs values such as $R_s < 1$) is much greater than that of large particles (with high Rs values) due to their ability to surround larger sand particles. In this case, the ratio is slightly greater than 1, implying that the insulating effect should be effective without being very significant.

Table 3. Density and water absorption of NS and CR.

Materials	Size (mm)	ϱ_{rd} (g/cm³)	WA_{24h} (%)	R_s
Natural sand (NS)	0.063-5	$2.58^{\pm 0.02}$	$0.98^{\pm 0.1}$	**1.2**
Crumb rubber (CR)	0.5-5	$0.91^{\pm 0.01}$	$0.2^{\pm 0.1}$	

Batch leaching tests in a neutral medium (leaching with deionized water pH=7) were carried out according to the NF EN 12457-1 standard to have information about the constituent concentration release from CR particles. The purpose of this leaching test is to compare the composition of leachates with the threshold values and detect contaminants, which could be mobile in water and could be harmful to the environment.

In this study, the pH of the solution was measured before and after batch leaching using a static pH test. The concentrations of inorganic species leached in water were determined by inductively coupled plasma (ICP) spectroscopy and expressed in mg/l. The results show that the pH values of the influent and leachate are similar (7.5 and 7, respectively). Moreover, the concentrations of leached pollutants are below the limit values set by the Environmental Protection Agency in 2011 (as shown

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in Table 4). This confirms that the use of these wastes as sand to prepare mortars for building applications is safe and environmentally friendly.

Table 4. Concentrations of inorganic species leached in contact with water.

Element	**Concentration mesurée en mg/l**	**Limit values associated with level 2 environmental characterization** (Cerema 2011)
Ba	0.007	0.5
Cr	0	2
Mo	0	2.8
Ni	0.001	0.8
Cu	0.002	50
Zn	0.203	50
Cd	0	0.16
Hg	0.006	0.04
Pb	0	0.5
Sb	0	0.2
As	0	0.5
Se	0.007	0.4

2.4. Mortar mixtures

In order to determine the dosage of superplasticizer and the spread flow behaviour of the cement paste, the mini cone test was carried out. The spreading versus superplasticizer percent weight obtained experimentally is shown in Figure 3. It can be seen that the spreading increased with the superplasticizer weight and reached an asymptotic plateau at 2.5%; no significant change was observed in terms of cement paste fluidity beyond this level. The result shown in Figure 3 was obtained for plain mortar and 1.5% of superplasticizer by weight was deemed adequate when CR was embedded in the paste.

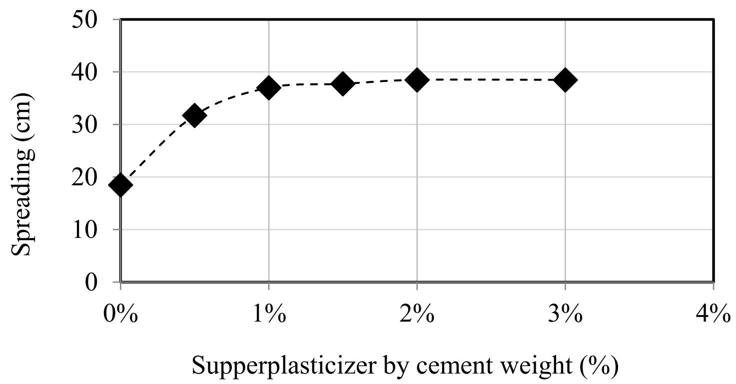

Figure 3. Saturation dosage of the superplasticizer.

Seven rubber-cement matrix mixes with different percentages of natural sand substitution by crumb rubber were investigated. The mortar mixes were designed by blending cement Portland type I, sand, water and limestone filler. The design was augmented with a reference/control case not containing rubber. In this study, the volumetric ratio of substitution, r_v, is defined by:

$$r_v = \frac{V_{CR}}{V_{NS} + V_{CR}}$$

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where V_{CR} is the volume of crumb rubber and V_{NS} is the volume of natural sand. The rubber contents in the seven mixes were 0%, 10%, 25%, 50%, 60%, 75% and 100%. The designed mixes of mortar are presented in Table 5. In this table, the mixes were designated such that "M" denoted mix, "CR" abbreviated "crumb rubber", and the following number represented the percentage of sand replacement by CR in volume. The water-cement (W/C) and water-binder (W/B) were constant for all mixes; it can be seen that the density of mortar at the fresh state decreased as the replacement ratio increased.

Table 5. Mix design of the different mortars.

Constitutions (Kg/m³)	**MCR-0%**	**MCR-10%**	**MCR-25%**	**MCR-50%**	**MCR-60%**	**MCR-75%**	**MCR-100%**
Cement	400	400	400	400	400	400	400
Water	219	219	219	219	219	219	219
Superplasticizer	6	6	6	6	6	6	6
Limestone filler	300	300	300	300	300	300	300
Natural Sand (NS)	1328	1163	939	585	445	233	0
Crumb Rubber (CR)	0	47	117	234	281	351	427
Theoretical density	2253	2135	1980	1744	1651	1509	1352
W/C	0.55	0.55	0.55	0.55	0.55	0.55	0.55
W/B	0.31	0.31	0.31	0.31	0.31	0.31	0.31
r_v (%)	0	10	25	50	60	75	100
Density (Kg/m³)	2241 ± 5	2121 ± 2	2030 ±1 2	1815 ± 17	1763 ± 16	1692± 8	1447 ± 6
Air content "a (%)"							

3. Results and discussion

3.1. Mortar at the fresh state

A testing campaign was conducted on the fresh mortar to estimate early age paste properties including density, workability, air content, and setting time of each mixture. The experimental results of density and air content are summarized in Table 5. Figure 4-a shows that air content increases linearly with replacement ratio as follows

$$a(\%) = 0.04r_v + 2.64 \ with \ R^2 = 0.93$$

Moreover, the total setting time was measured using the penetration resistance test at ambient room temperature (20 °C). The experimental results, as shown in Figure 4-b, indicate that the setting time decreases when the replacement ratio increases. These results do not suggest a specific threshold for acceptable performance, but they provide designers with ranges of variation in air content and setting time relative to the replacement ratio that can be instrumental for practical applications. The total variation in air content is approximately200% and the principles of homogenization suggest that at this level, the volume of air alone can have great effects on porosity and, consequently, on the mechanical and thermal properties (Karrech, Strazzeri, and Elchalakani 2021; Strazzeri, Karrech, and Elchalakani 2020). The increase in air content with the increase in crumb rubber aggregates "CR" fraction is attributed to their non-polar nature and their surface roughness leading to air bubbles entrapment (Figure 2b). This phenomenon has been confirmed by several authors (K. and M. 1999; Siddique and Naik 2004).

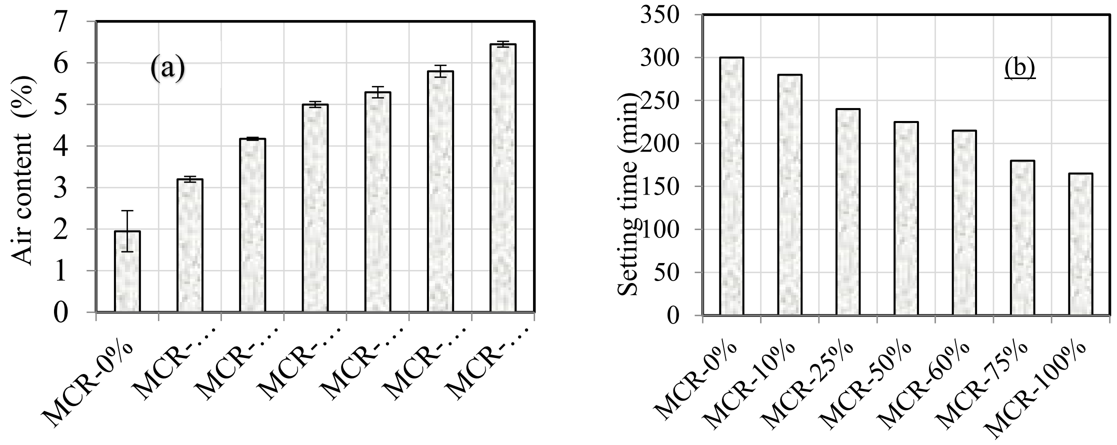

Figure 4. Variation of air content versus replacement ratio and slump of fresh mortar.

Figure 5 shows the results of slump testing for various specimens obtained according to NF EN 12350-2 and NF EN 1015-3 standards. It indicates that workability significantly decreases when the CR content exceeds 60%. These results confirm the trend observed in the literature (Sukontasukkul and Tiamlom 2012; Turatsinze and Garros 2008). Once again, Figure 5 does not provide a specific threshold for adequate workability but gives a range of variations that assist designers in selecting the appropriate mixture depending on the sought application. It should be noted that for repair mortars, EN NF 1015-2 standard recommends a spread of $175^{\pm 10}$ mm (obtained using EN NF 1015-3 standard) if the density of the mortar in the fresh state exceeds 1200 kg/m^3. As the mixes in Table 4 have densities higher than 1200 kg/m3, it can be concluded that mortars with $r_v \leq 60\%$ comply with these recommendations.

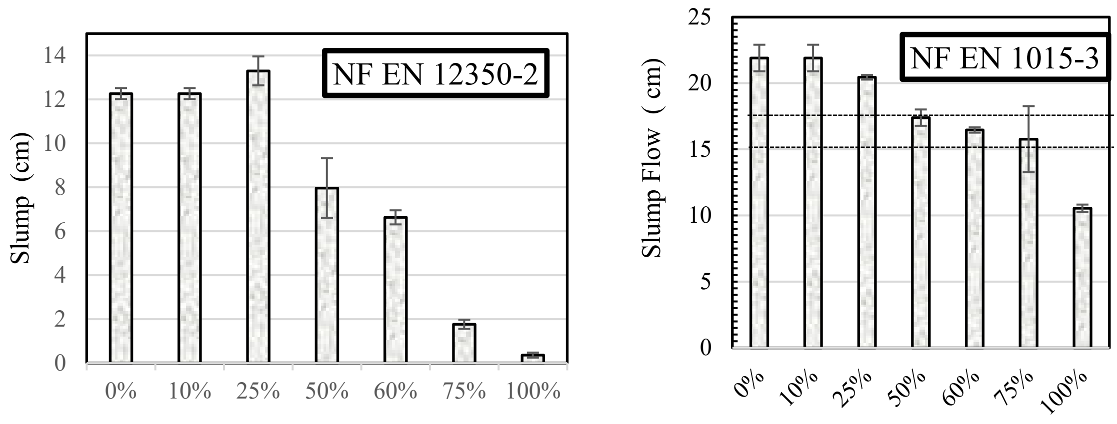

Figure 5. a: Workability of the different mixes as a function of CR rates.

Moreover, all the mixes maintained their slumps for about 20 minutes. After this period, a sharp drop in workability was observed especially when the CR content exceeded 60%, as indicated in Figure 6. In this figure, the relative slump is denoted as $S_{sr} = \frac{S_t}{S_i}$ where S represents the designed the slump, "t" represents the time in minutes and "i" represents the initial slump.

Therefore, from a workability point of view, mortars with $r_v \leq 60\%$ can be considered suitable for repair work, aligning with the recommendations of standard EN NF 1015-3.

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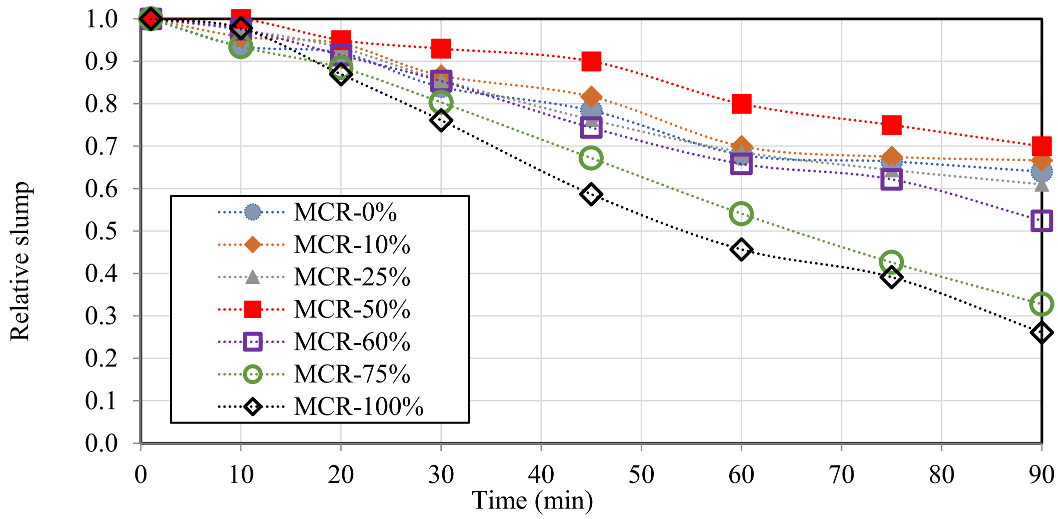

Figure 6. Relative slump of mortar versus time.

3.2. Characterization of mortars at hardened state

a. Density and porosity

The density of the different hardened mortars was measured after subjecting the specimens to vacuum for 4 hours and immersing them in water for 44 hours. The experimental results are represented graphically in the left-hand side "LHS" of Figure 7. It can be seen that the mortar density decreased as the ratio of crumb rubber to sand increased; this was due to the low density of rubber as compared to the density of sand. For example, fully substituting NS by CR (MCR-100%) reduced the overall density by 50% compared to the control mortar. The results obtained in terms of density variation with respect to replacement ratio agreed with published data (Sukontasukkul and Tiamlom 2012; Turatsinze, Bonnet, and Granju 2005; Turki et al. 2009). The experimental results were generally comparable with the literature as can be seen in the right-hand side "RHS" of Figure 5 (Nadal Gisbert et al. 2014; Sukontasukkul and Tiamlom 2012; Turatsinze et al. 2005; Turki et al. 2008). While existing data were limited to 50% replacement ratio, our experimental results covered a complete range of measurements (up to 100%) for the first time and showed that the density reduced with the replacement ratio according to the following equation:

$$\rho_{ap}(g/cm^3) = 2.17e^{-0.01r_v} \; with \; R^2 = 0.88$$

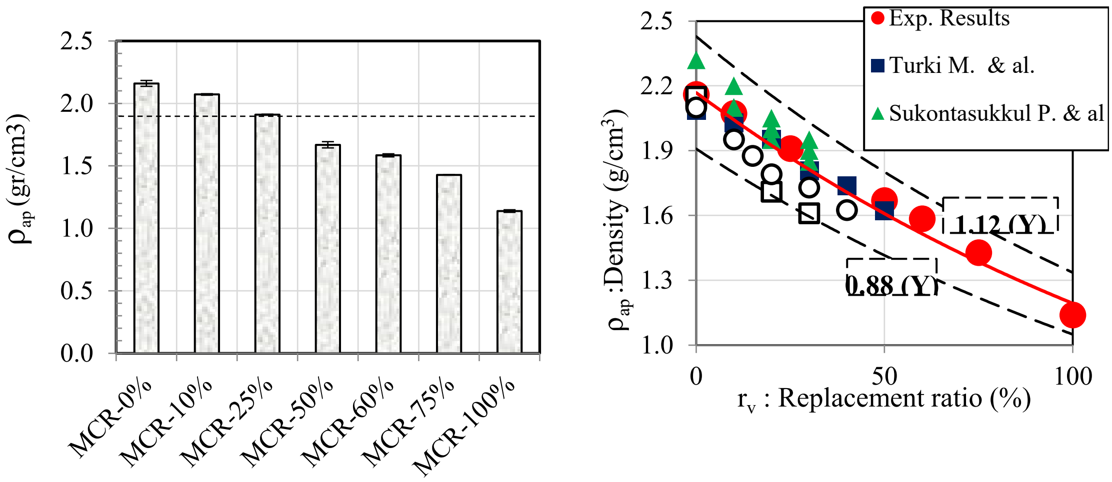

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Figure 6. Density and water absorption coefficient of mortars.

Moreover, it should be noted that for $r_v \geq 25\%$ the mortar can be considered as light because its density is less than 1900 kg/m³. The standard EN 206-1 prescribes for lightweight concrete a range of density varying from 1800-2000 kg/m3 to 800-1000 kg/m3 (Classes D1.0 to D2.0). Hence the mortar can be considered lightweight for $r_v \geq 25\%$ with Class D1.0 for MCR-25% and Class D1.2 for MCR-100%.

The results in terms of water absorption are presented in Figure 7. It can be seen that the WA coefficient increases with CR content. In particular, when NS was entirely replaced with CR, WA reached its maximum and exhibited a disproportional increase. These findings are in accordance with the literature (Angelin et al. 2015; Sukontasukkul and Tiamlom 2012; Turatsinze and Garros 2008; Uygunoğlu and Topçu 2010). The increase in WA relative to CR replacement rate is well described by the following equation:

$$WA(\%) = 7e^{0.01r_v} \quad with \;\; R^2 = 0.89$$

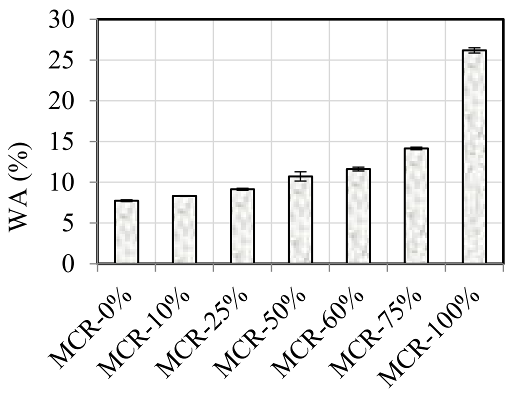


Figure 7. Water absorption versus replacement ratio.

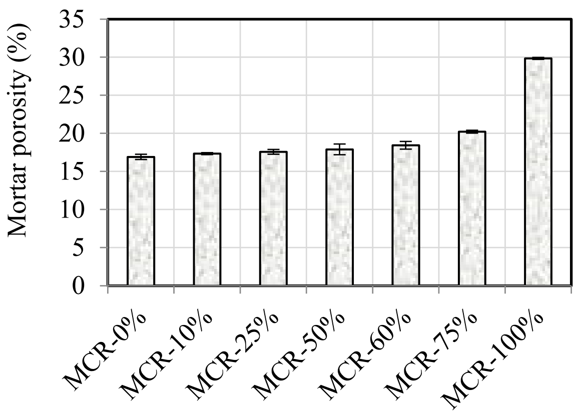


Figure 8. Effect of crumb rubber content on mortar porosity.

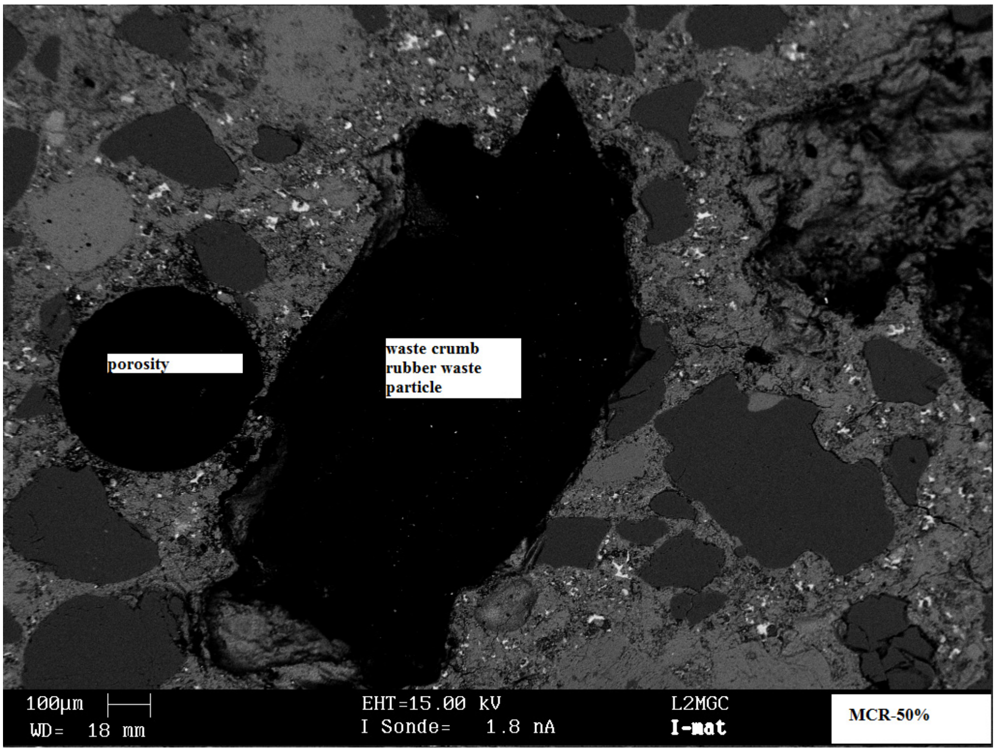
Figure 8 shows the obtained results in terms of the overall porosity accessible to water (combining the pore spaces in the cement paste and between the interfaces) versus replacement ratio. It can be observed that the mortar porosity increases by increasing the CR content. This growth is slow for $r_v \leq 50\%$, but it becomes significant otherwise. It can be described by the following system of equations:

$$\begin{cases} (n - n_0)_{(\%)} = 0.02r_v(\%) + 0.13 & with \;\; R^2 = 0.922 \\ (n - n_0)_{(\%)} = 0.07e^{0.05r_v(\%)} & with \;\; R^2 = 0.999 \end{cases}.$$

Some authors established that replacing natural sand by CR particles generates pores accessible to water proportionally to the crumb rubber content (Angelin et al. 2015; Gupta et al. 2015). It should be outlined that, in this research, water to cement ratio was kept constant at 0.55, which is not the case in the previous studies (Gupta et al. 2015; Uygunoğlu and Topçu 2010). Moreover, it is important to indicate that existing studies were limited to less than 50% replacement ratio, usually with fine and coarse rubber aggregates. As part of this work, we investigate a full range of replacement ratios (from 0 to 100%) in order to obtain more comprehensive results. In addition, we focuse on fine rubber crumb to avoid extended interfacial transition zones.

The increase of the porosity can be attributed to several factors (for a given W/C ratio). It can be partially explained by the entrapment of air by rubber particles during mixing (Uygunoğlu and Topçu 2010). Some authors have attributed the increase in porosity to poor adhesion between the rubber particles and the mortar matrix, a phenomenon more pronounced with CR spheroid particles (Angelin et al. 2019; Noor Azline et al. 2022).

In the present study, SEM observations do not show decohesion between the cement matrix and the waste crumb rubber particles (Figure 9). In addition, the EDS of the sample indicates that the interface is thin compared to the grain sizes. This can be deduced by observing the variation of elemental concentrations. For example, from the left to the right, the figure starts with a large concertation of C indicating the presence of a rubber particle until 300 micrometers. Between 300 and 350 micrometers the concentration of Ca increases while the concentration of C decreases indicating a cementitious interface of about 50 micrometers. In addition, Figure 9 shows that at no moment, the concentrations reach zero simultaneously, which means that the specimen does not include major pore spaces at least in the path that is indicated in the figure. Consequently, the increase in mortar porosity cannot be ascribed to debonding between the rubber particles and the cement matrix. However, microcracks and small voids may exist at the transition zone which be responsible od the increase of the porosity (Angelin et al. 2019; Noor Azline et al. 2022).



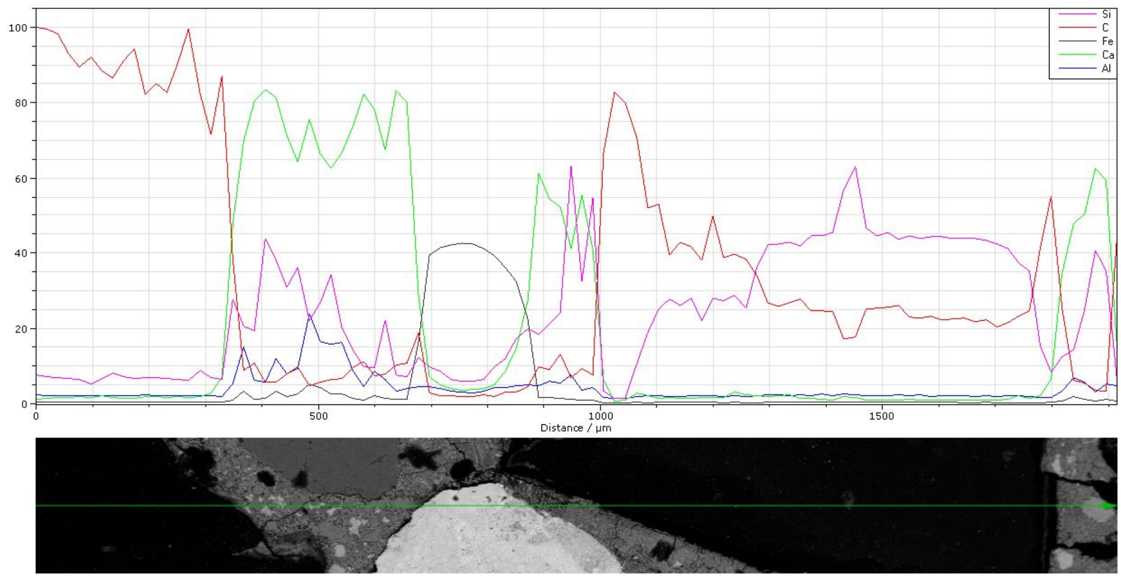


Figure 9. Scanned Electron Microscopy images indicating the quality of adhesion between cement binder and rubber particles.

Hence, it can be concluded from this study that the increase in porosity is mainly attributed to the higher occluded air content associated with higher CR rates. This phenomenon is particularly pronounced for $r_v > 50\%$ (Figure 10)

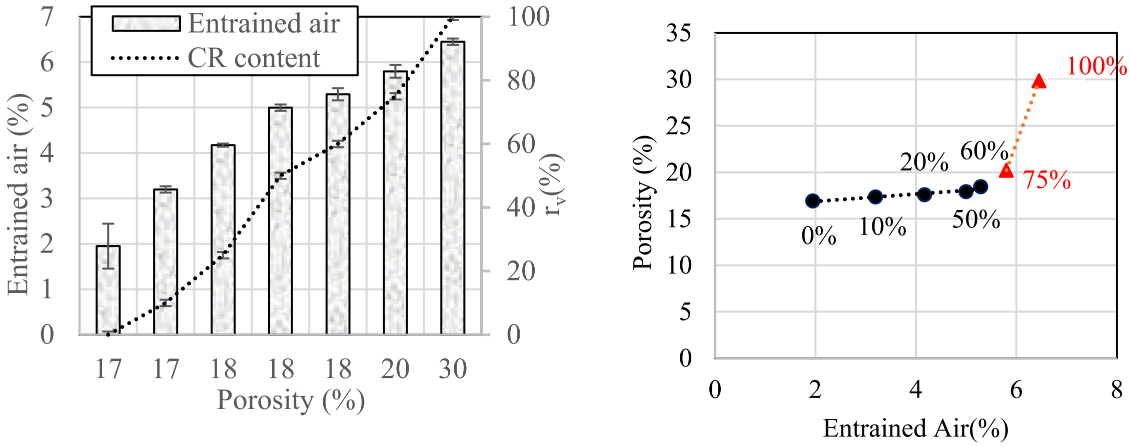


Figure 10. Effects of CR incorporation on the porosity and air content of the mortar mixes.

The figure depicting the evolution of density versus porosity (Figure 11a) confirms the expected correlation between porosity and density for rubberized mortars. More importantly, it indicates that the variation of porosity versus NS-CR replacement ratio becomes non-linear close to 100% CR. This is somewhat in alignment with the behavior in terms of water absorption. On the basis of literature works and the experimental results obtained in this study a relationship between both properties is established:

$$\rho_{ap}(g/cm^3) = 3e^{-0.93n(\%)} \quad with \;\; R^2 = 0.82$$

Likewise, an increase in WA is noticed when the porosity accessible to water rises (Figure 11b). Based on the results of the present study and those of the literature (Angelin et al. 2019; Turgut and Yesilata 2008), the evolution is expressed as follows:

$$WA(\%) = 2.19e^{0.09n(\%)} \quad with \;\; R^2 = 0.93.$$

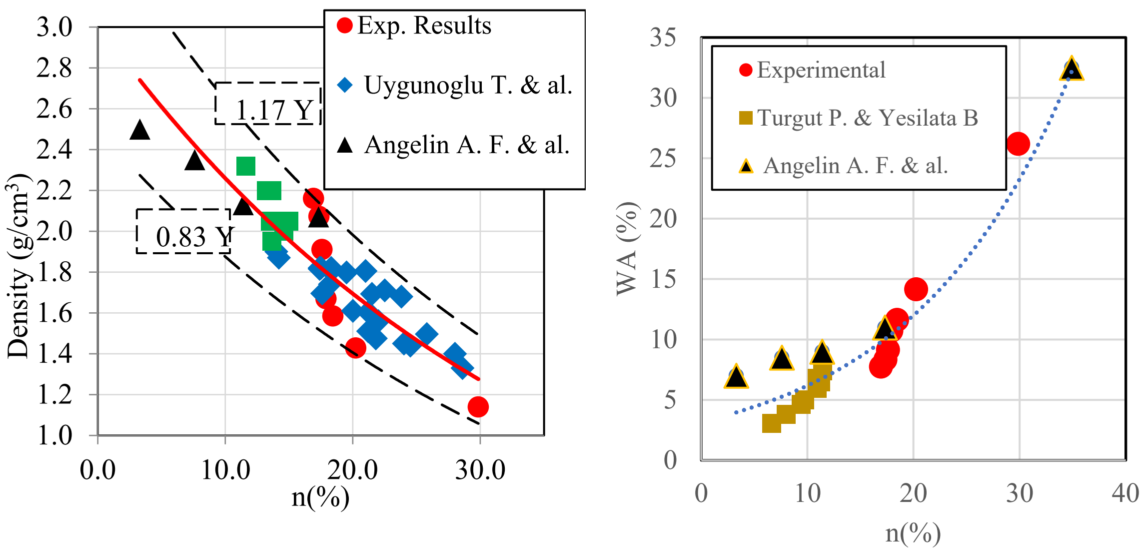


Figure 11. Evolution of the mortar density and water absorption coefficient versus its porosity.

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b. Thermal properties

The results obtained show that the thermal conductivity of the mortars decreases by increasing the CR content, highlighting the greater capacity of the mortar to resist cold and heat for a given thickness (Figure 12(a)). Indeed, the higher the thermal resistance of the product ($R = e/\lambda$), the better its insulation properties. It is well known that shredded tire particles are almost adiabatic with $0.193 \leq \lambda(W/mK) \leq 0.213$ (Yang et al. 2022) or $\lambda(W/mK) = 0.25$ according (Xiao et al. 2019). I contrast, natural sands have higher thermal conductivity ranging between 1.8 to 3.6 W/mK depending on factors such as chemical composition (particularly quartz), grain size, porosity and degree of saturation (Xiao et al. 2019). Some authors claim that thermal conductivity of sand consisting mainly of quartz, ranges between 3 and 8 W/mK. (Lee et al. 2015). In all cases, the thermal conductivity of tire crumb rubber particles "CR" is at least 10 times lower than that of natural sand. Consequently, the thermal conductivity of rubberized mortars decreases with increasing the ratio "CR". This decrease is enhanced when the relative particle rises. It can be observed that this is the case (Figure 12a) since the relative reduction in thermal conductivity between the reference mortar and that containing 100% CR is 82%.

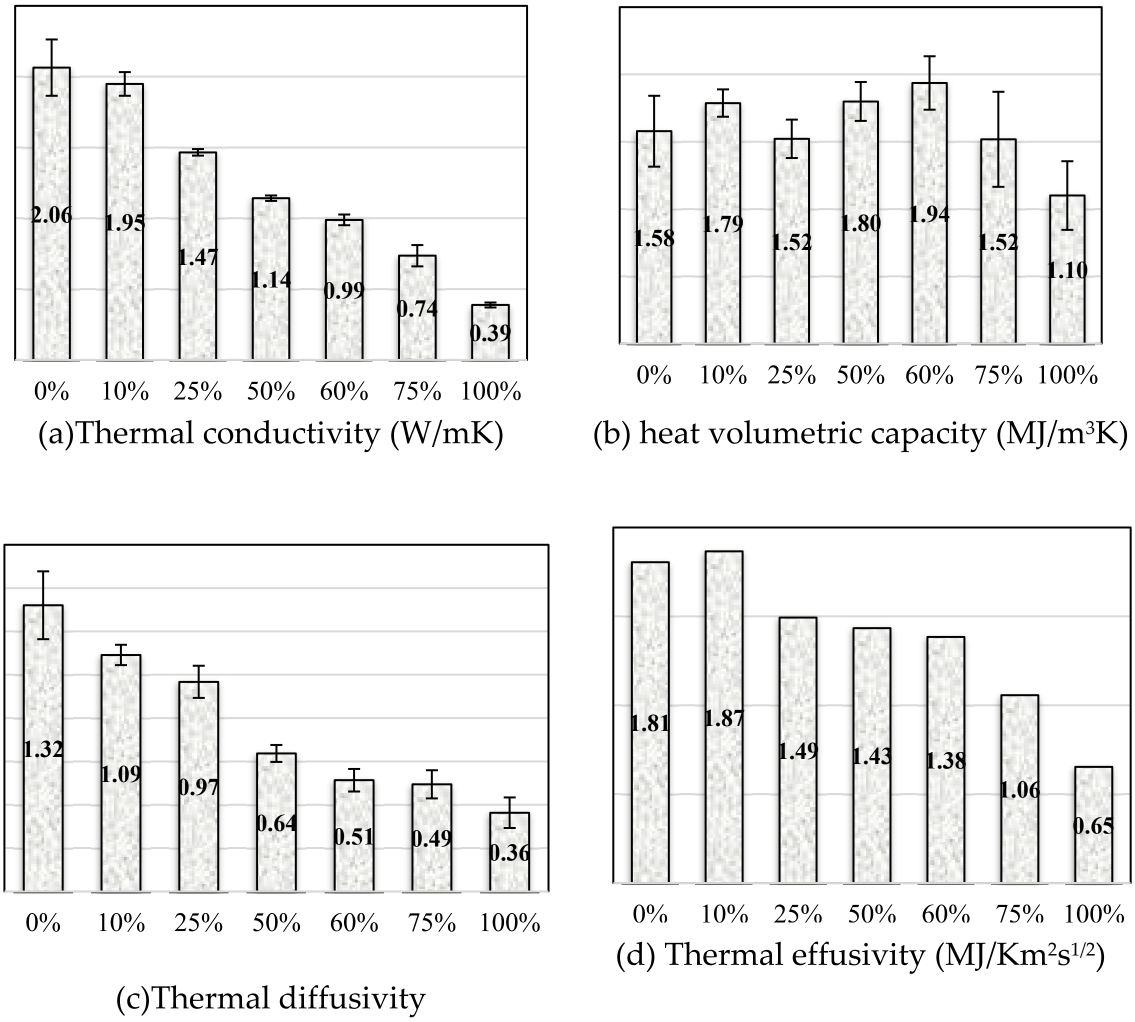

Figure 12. Thermal properties of the mortars as a function of the CR content (%).

The thermal inertia of mortars, a term widely used to describe the ability of a material to store heat, is characterized by the diffusivity "a " $\left(a = \frac{\lambda}{C}\right)$ and the effusivity "e" $\left(e = \sqrt{\lambda C}\right)$. Both properties depend on the volumetric heat capacity (Figure 12b) and thermal conductivity (Figure 12 a).

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Diffusivity characterizes the rate of thermal energy exchange between the mortar and its environment. Thus, good comfort requires low diffusivity so that this exchange takes place as slowly as possible. It can be observed that the increase in the CR content strongly lowered the thermal diffusivity (Figure 12c). For example, the relative decrease in diffusivity is 61% for $r_v = 60\%$. However, regarding the variation of temperature, the effusivity is the preponderant property. Therefore, the repair/rehabilitation mortar must have a high thermal effusivity to store the maximum energy and mitigate the effects of heat/cold waves inside a building. The results obtained show that the effusivity does not increase with the increase of CR content (Figure 12d). It is reduced by around 20% for 60% of CR content and 64% for 100% of CR content.

Based on these results, it can be concluded, that the use of mortars incorporating up to 60% of waste tires improves comfort and thermal resistance without affecting significantly thermal inertia.

However, it should be noted that the mortars developed do not comply with the French Environmental Regulation 2020 "RE 2020"(Ademe 2023). Depending on the climatic zone, the latter recommends minimum thermal resistances R of 2.1 to 3.2 W/m² for renovated wall and floor insulation solutions. Furthermore, RE 2020 generally recommends an average insulation thickness "*e*" of 15 to 20 cm for walls, 20 to 25 cm for ceilings and 10 to 20 cm for floors. Thus, for a thickness of 20 cm, the developed mortars do not meet the requirements of RE 2020, even though a substantial increase in thermal resistance exceeding 50% has been observed (Figure 13a), which can be described by the following equation:

$$R = \frac{e(m)}{\lambda(W/mK)} = 0.088e^{0.016r_v(\%)} \quad with \;\; R^2 = 0.965 \;\; .$$

Several authors have attempted to correlate thermal conductivity with density (Aliabdo, Abd Elmoaty, and Abdelbaset 2015; Bala and Gupta 2021; Benazzouk et al. 2008). It is proposed in this study to establish relationship between the normalized thermal conductivity (λ/λ_o) and the normalized density (ρ/ρ_o) in order to avoid the effects of control mortar-related parameters affecting these two properties and to study only the impact of incorporating crumbled rubber tire particles. It can be observed an increase of the normalized thermal conductivity as the normalized density increases (Figure 13b). The relationship between these two parameters is well described by the following equation.

$$\frac{\lambda}{\lambda_o} = 0.048e^{2.978\left(\frac{\rho}{\rho_o}\right)} \quad with \; R^2 = 0.88$$

where $\lambda_o$and ρ_o are the thermal conductivity and the density of the control mortar respectively.

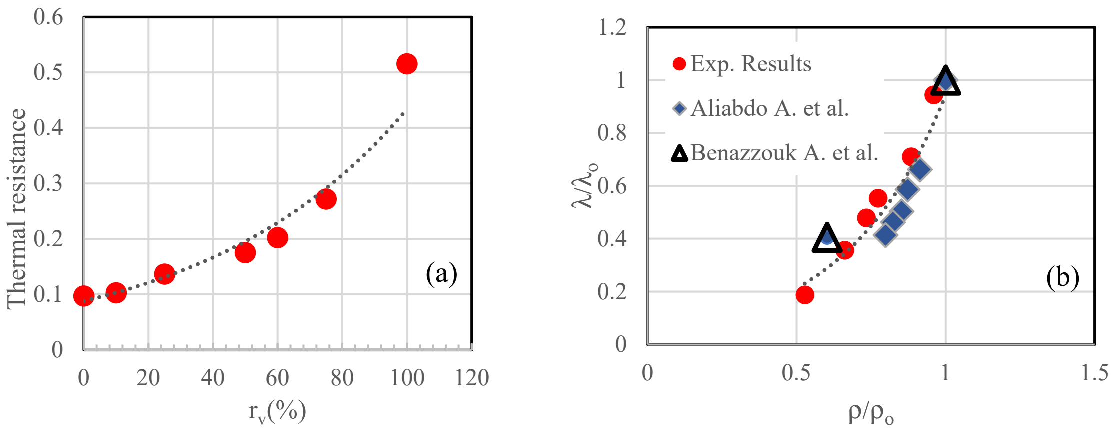

Figure 13. Effects of incorporating tire crumb rubber particles on the thermal properties of mortars.

c. Drying /Shrinkage

Given the influence of crumb rubber on porosity and water absorption, it is important to analyse its impact on drying and shrinkage. Drying and shrinkage are important causes of damage in concrete structures, especially when contraction is prevented, which induces tensile stresses. It is known that shrinkage increases with the volume fraction of paste in concrete and reduces with relative humidity (Bissonnette, Pierre and Pigeon 1999). In this study, we investigated the effect of fine crumb rubber on these phenomena when humidity, water-to-cement ratio, and water content were fixed.

The results in terms of drying shrinkage of mortar with crumb rubber compared to plain mortar are shown in Figure 14. These results reveal that crumb rubber had a significant effect on drying; while MCR-0% took about 15 hours to fully dry, MCR-100% dried within 5 hours, which indicates that rubberized mortar dries 3 times faster. This can be explained by the abundance of pore spaces and high-water absorption in mortar with high CR replacement ratios. The results also show that shrinkage increased significantly with the crumb rubber content beyond 60%. This can be explained by the weaker structural performance of rubber particles compared to sand particles; the formers being much more flexible offer low confinement for mortar which leads to higher shrinkage (Sukontasukkul and Tiamlom 2012). It is known that shrinkage occurs during cement hydration as the hardening phases continue to cure (Angelin et al. 2015). Shrinkage strongly impacts the overall strength of cement mortar as it is associated with microcracks that concentrate stresses and may lead to failure. It can be noticed that the shrinkage of all the mixes is quite similar for $r_v \leq 60\%$; the obtained values at 28 days vary between -875$\mu\varepsilon$ to -1000 $\mu\varepsilon$.

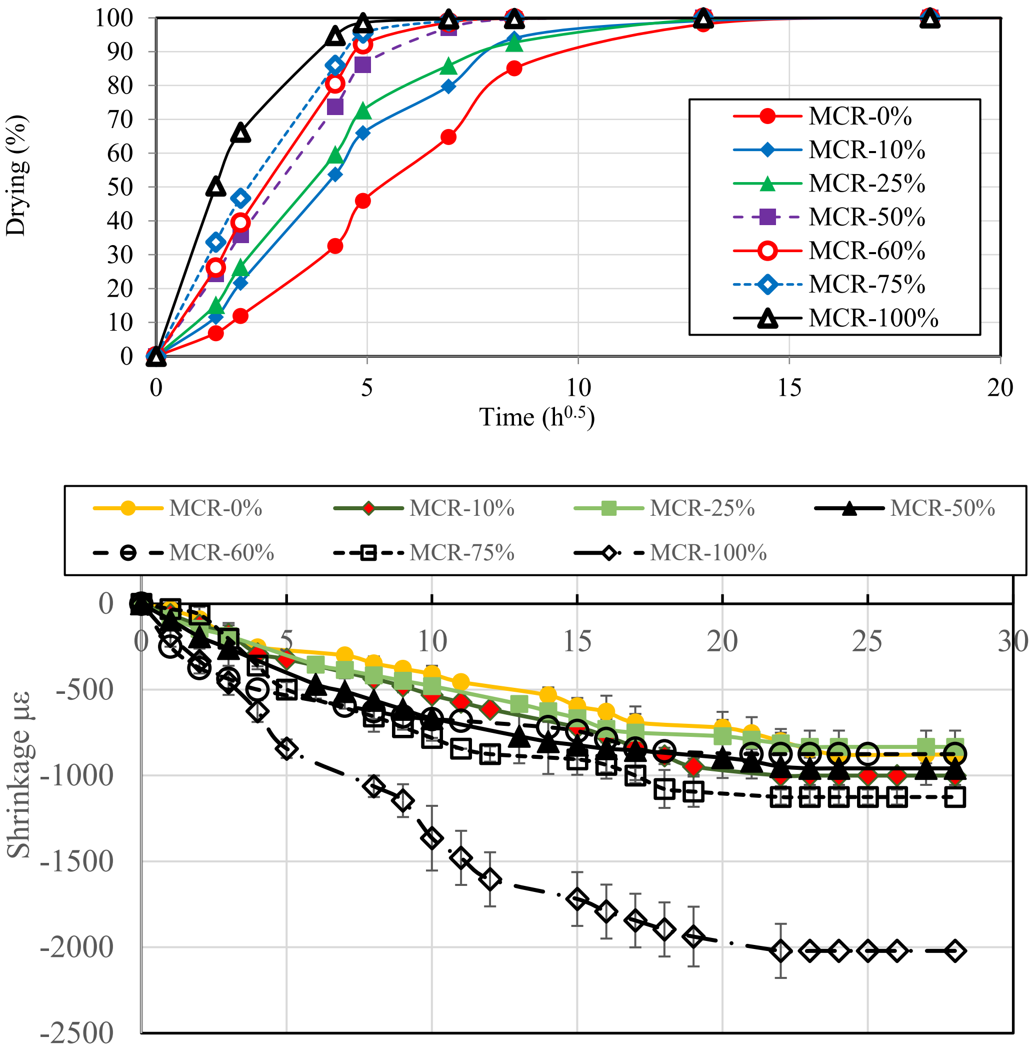

Figure 14. Drying versus time $\sqrt{hours}$ and shrinkage time (days) for various mixes.

d. Compressive strength

The mechanical properties of mortar were tested after 7, 14, 28 and 90 days of curing. The experimental results in terms of compressive strength are presented in Figure 15. It can be seen that the compressive strength increases with time during the curing process, irrespective of the replacement ratio. For example, at 10% CR content, compressive strength increased from 28.85 MPa at 7 days to 43.68 MPa at 90 days. However, the figure shows that at a fixed age, the compressive strength decreases with the CR replacement ratio. For example, specimens at age 28 days exhibited strengths of 38.52 MPa, 32.38 MPa, 19.28 MPa, 9.7 MPa, 7.7 MPa, 4.27 MPa and 2.41 MPa when the CR content was 0%, 10%, 25%, 50%, 60%, 75%, and 100%, respectively. A significant drop in resistance can be seen beyond 25%.

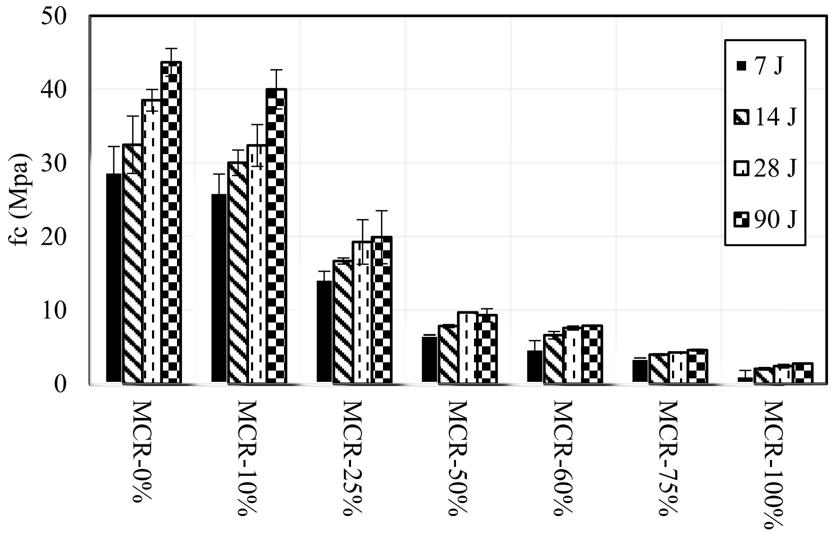

Figure 15. Effect of crumb rubber content on compressive strength.

The NF EN 1504-3 standard defines 4 classes of repair products according to the performance of mortars: structural repair mortars (e.g. Class R4 for $f_c \geq 45MPa$and Class R3 for ($f_c \geq 25MPa$) and non-structural repair mortars (Class R2 for $f_c \geq 15MPa$ MPa and Class R1 for $f_c \geq 10MPa$). It can be observed that up to 50% of CR content, the proposed mortars are within the range prescribed by the standard but can be used solely as non-structural repair products for civil engineering buildings.

It should be noted that EN 206-1 prescribes the minimum compressive strength class at 28 days for structural applications lightweight concretes at LC8/9 minimum with density classes from D1.0 to D2.0. It can be observed that mortars incorporating up to 50% CR are conform to EN 206-1. Figure 16 compares the results of the present work with previous studies; overall, our results agree with the average of published data, despite the large discrepancy that can be seen around the average (Correia et al. 2010; Onuaguluchi 2015; Sukontasukkul and Tiamlom 2012; Turatsinze and Garros 2008; Turki et al. 2009; Uygunoğlu and Topçu 2010). However, this experimental campaign covers a wider range of CR contents.

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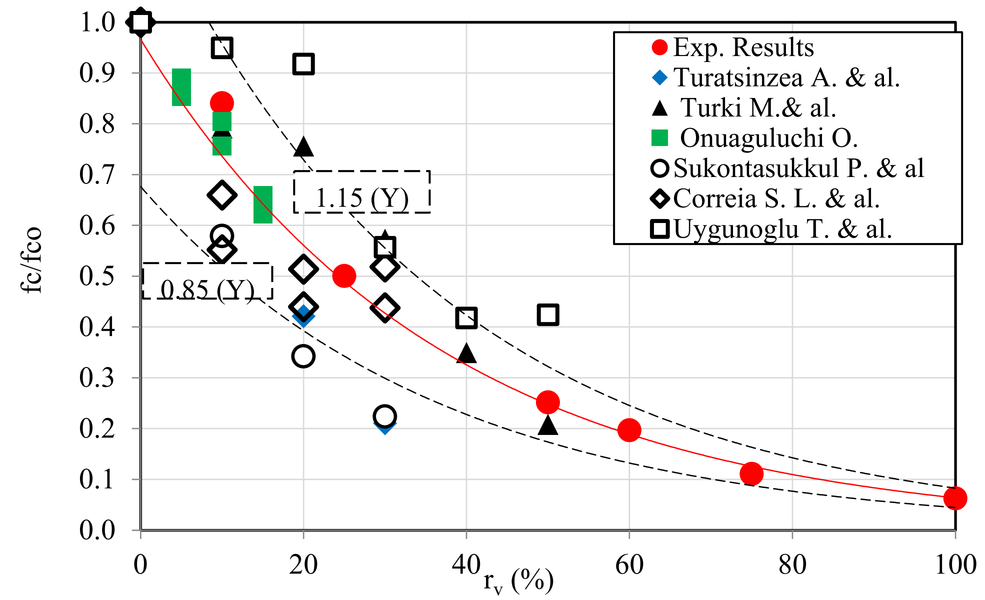

Figure 16. Effect of crumb rubber content on the normalized compressive strength – comparison with published data.

Based on the published data and the current results, an empirical expression of compressive strength at a replacement ration CR was obtained:

$$\frac{f_c}{f_{co}} = 0.97e^{-0.03r_v} \quad wit\ R^2 = 0.85$$

where f_{co} is the compressive strength of control mortar, r_v is the ratio of rubber/sand replacement (ranging from 0 to 100%).

Moreover, it appears that a relationship can be established between the compressive strength and the density of mortars incorporating CR (Figure 17):

$$\frac{f_c}{f_{co}} = 0.002e^{6.21\left(\frac{\rho}{\rho_o}\right)} \quad with\ \ R^2 = 0.97$$

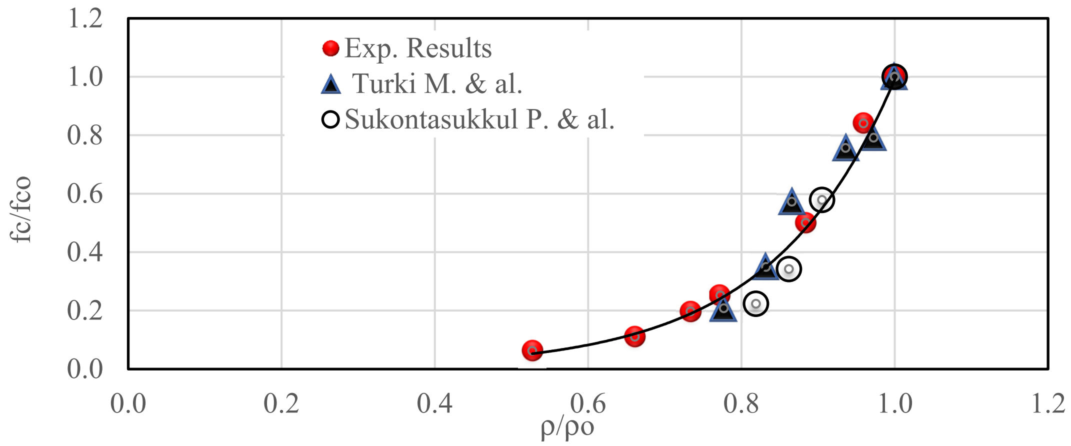

Figure 17. Evolution of compressive strength of rubberized mortars.

e. Flexure/Tensile strength

The experimental results in terms of flexural strength are presented in Figure 18. As for compressive strength, it can be seen that it increases with time irrespective of the replacement ratio. For example, at 25% CR content, flexural strength increased from 3.8 MPa at 7 days to 4.71 MPa at 90 days. However, the figure shows that at a fixed age, flexural strength reduced with the CR replacement ratio. For example, specimens of age 90 days have strengths of 9.3 MPa, 7,45 MPa, 4.71 MPa, 3.5 MPa, 2.75 MPa, 2.15 MPa, and 1.35 MPa when the CR content is 0%, 10%, 25%, 50%, 60%, 75%, and 100%, respectively. In coherence with the compressive strength tests, the results show a significant drop in resistance, as can be seen beyond 25%.

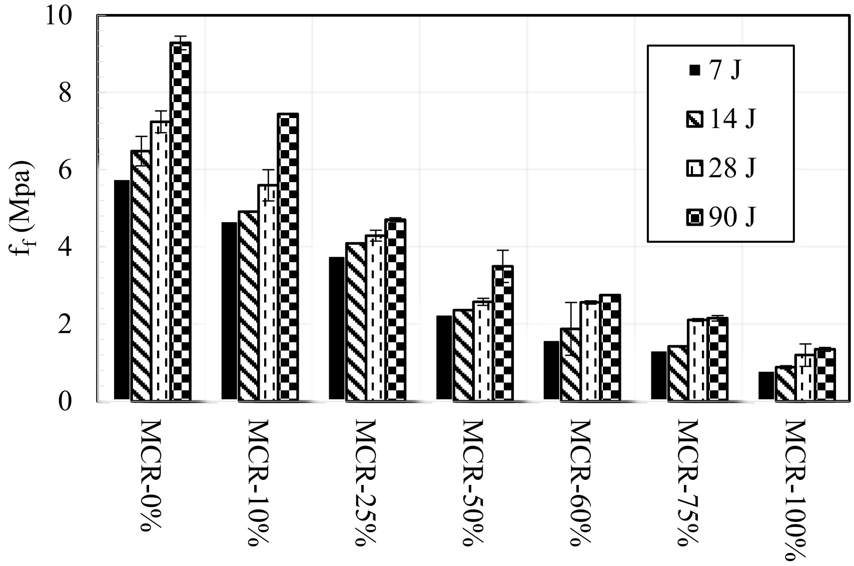

Figure 18. Effect of crumb rubber content on flexural strength during the curing.

Figure 19 compares the results of the present work with previous studies in terms of compressive strength versus flexural strength. Overall, our results are comparable with the average of published data despite the discrepancy that can be seen around the average (Angelin et al. 2015; Herrero, Mayor, and Hernández-Olivares 2013; Nadal Gisbert et al. 2014; Onuaguluchi 2015; Turatsinze et al. 2005). It should be remembered that our experimental campaign covered a wider range of CR content ($0 \leq r_v(\%) \leq 100$) . Based on the published data and the current results, an expression between flexural and compressive strengths of the different mortars is established:

$$f_c = 5.36 f_f \quad with \quad R^2 = 0.77$$

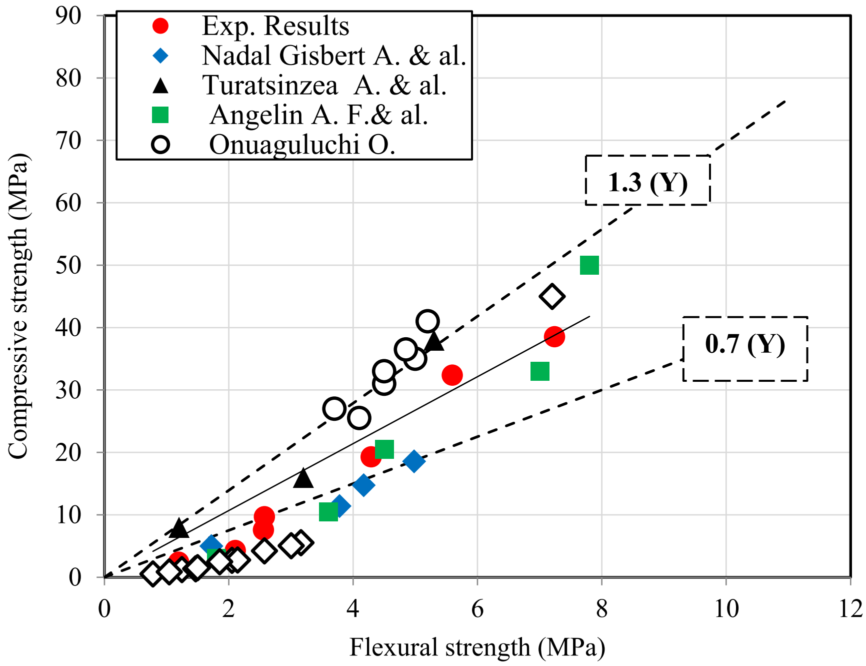

Figure 19. Correlation between flexural and compression strength.

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To assess the effect of incorporating tires crumb rubbers particles in mortars, normalized flexural strength is plotted against normalized density, and a relationship between these two properties is established (Figure 20). It can be outlined that the decrease in the relative density due to the presence of CR particles leads to a decrease in the relative flexure strength. It can be outlined that the decrease in the relative density due to the presence of CR particles leads to a decrease in the relative flexure strength:

$$\frac{f_f}{f_{fo}} = 0.015e^{4.19\left(\frac{\rho}{\rho_o}\right)} \quad with \ R^2 = 0.85$$

where f_{fo} is the flexure strength of the control mortar.

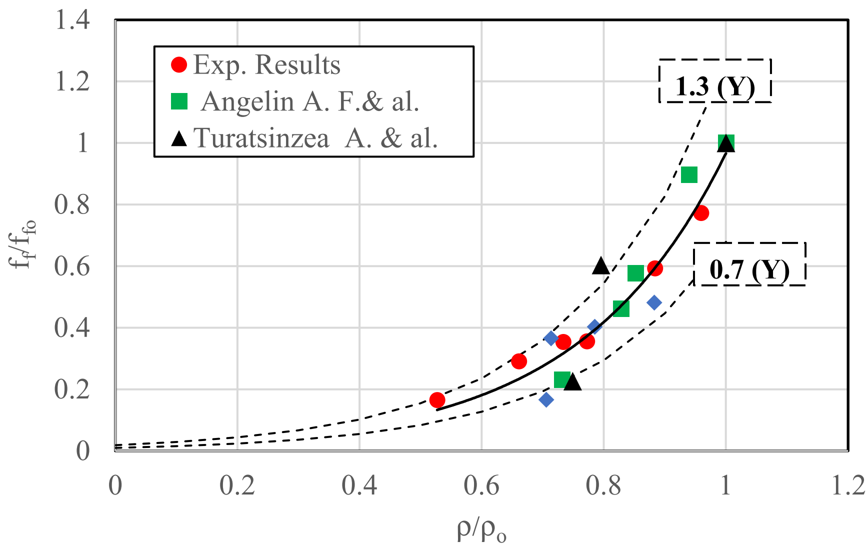

Figure 20. Evolution of the normalized flexure strength versus normalized density of rubberized mortars.

While the NF EN 1504-3 standard for repair mortars doesn not specify a tensile strength requirement, direct tensile tests were carried out on cylindrical specimens measuring 11 cm in diameter and 22 cm in length. The results are shown in Figure 21 with a significant decrease in tensile strength observed for CR content above 25% and an overall mechanically more ductile behavior for $r_v \geq 75\%$. However, the tensile strength can be considered as satisfactory up to 60% as it is higher than 1.5 MPa.

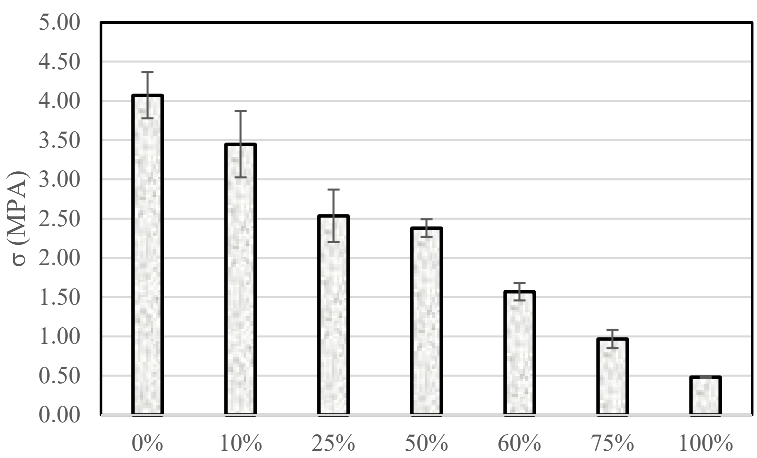

Figure 21. Effect of crumb rubber content on splitting tensile strength.

f. Fracture energy

Figure 22 shows the load-CMOD curves obtained for various CR replacement ratios. Similar results were obtained in terms of force versus deflection. These results underline a more resilient behaviour and greater resistance to crack propagation as the incorporation rate of crumb rubber tires particles increases. This is particularly obvious at ratios in excess of 50%.

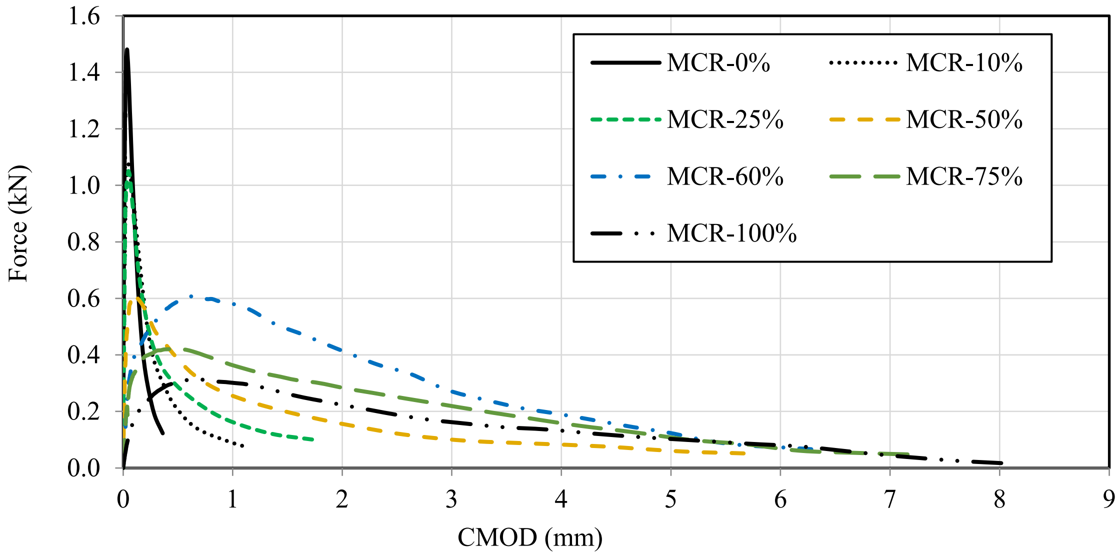

Figure 22. Load-displacement response of the structure used to predict the fracture energy.

Figure 23 depicts the fracture energy obtained as follows (RILEM 1985) :

$$G_f = \frac{W + (m_b + 2m_l)g\delta_0}{A_{lig}}$$

where W is the area below the load-deflection curve, m_b is the mass of the beam portion between the support points, m_l is the mass of any support arrangement excluding the machine, g is the gravitational acceleration constant, δ_0 is the deflection upon failure and A_{lig} is the fracture zone area.

It can be seen that fracture energy increased when the CR replacement ratio increased. This result is coherent with the previous results suggesting the increase of microcrack networks and aggregate-cement interfaces commensurate with the crumb rubber softness. Defects, including microcracks, tend to coalesce and propagate, leading to greater energy dissipation when the CR replacement ratio increases especially for $r_v \geq 50\%$.

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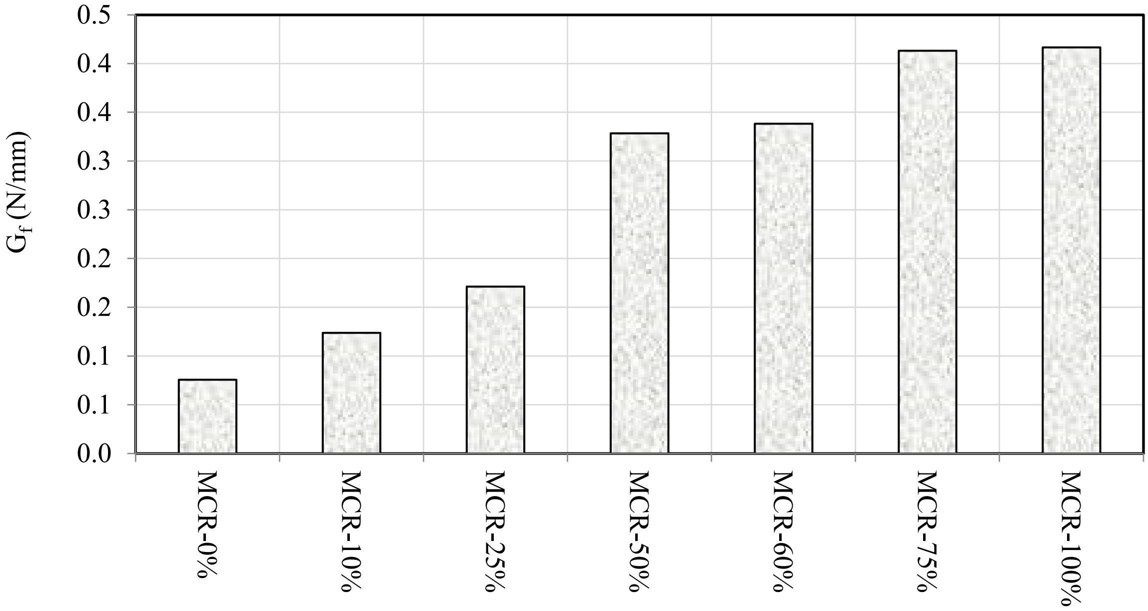


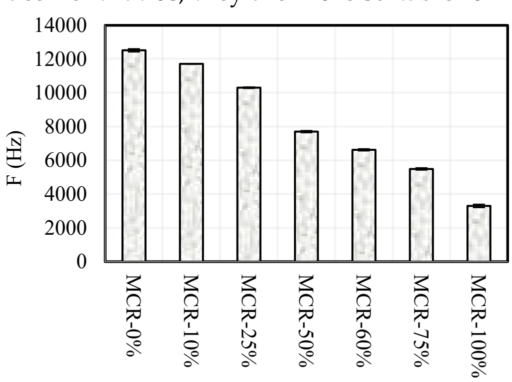
Figure 23. Fracture energy at various CR contents.

g. Elastic modulus

The determination of Young's modulus, E, for different mortar formulations is of a great interest as it is related to the creep behaviour. As shown in the LHS of Figure 24, the resonance frequency decreases with an increase in CR content in the mortar. For example, the frequency decreases from 12,526 Hz to 3,305 Hz as CR increases from 0% to 100%. This suggests that the damping ability of the mortars increases with higher CR content.

On the RHS of Figure 24, the variation of the dynamic elastic modulus with respect to CR replacement is depicted. It can be seen that the modulus follows the trends of the resonance frequency; it decreases with an increase in CR replacement suggesting a higher creep ability.

According to NF EN 1504-3, structural repair mortars should have an elastic modulus higher than 20 GPa for class R4 and 15 GPa for class R3, while there are no requirements for non-structural repair classes. It can be observed that mortars with up to 25 % of CR replacement can be used as structural repair products for civil engineering buildings based on this property, while for higher CR replacement ratios, they are more suitable for non-structural applications.



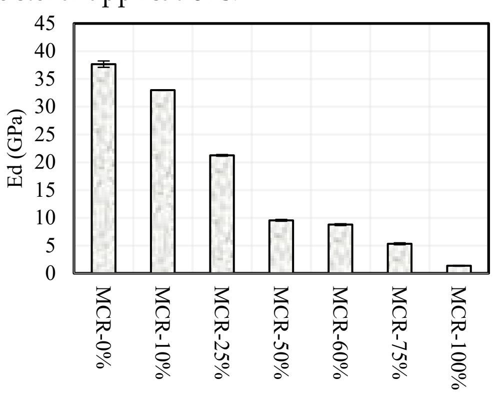


Figure 24. The resonance frequency measurements and the dynamic modulus of elasticity (Ed) according to the standard NF EN ISO 12680-1.

Figure 25 shows the non-linear relationship between the dynamic modulus E_d and the density ρ_{ap} obtained based on our new experimental results and published data (Nadal Gisbert et al. 2014; Sukontasukkul and Tiamlom 2012; Turki et al. 2008, 2009) The figure also confirms the agreement

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between our results and the published experimental data, with the distinction that our measurements encompass a broader range of crumb rubber replacement ratios.

Moreover, it can be seen that the relationship between the elastic modulus and the incorporated crumb rubber rate follows the same trend as that established for the compressive strength:

$$\frac{E_d}{E_{do}} = 0.95e^{-0.03r_v} \quad with \quad R^2 = 0.79$$

where E_{d0} is the elastic modulus of plain mortar and r_v is the ratio of rubber/sand replacement in (%).

It is also interesting to highlight that a relationship has been established linking the normalized modulus to the normalized density, demonstrating that as the density decreases, the resistance to elastic deformation also decreases for mortars incorporating tire crumb rubber particles:

$$\frac{E_d}{E_{do}} = 0.0003e^{8.29\left(\frac{\rho}{\rho_o}\right)} \quad with \;\; R^2 = 0.82$$

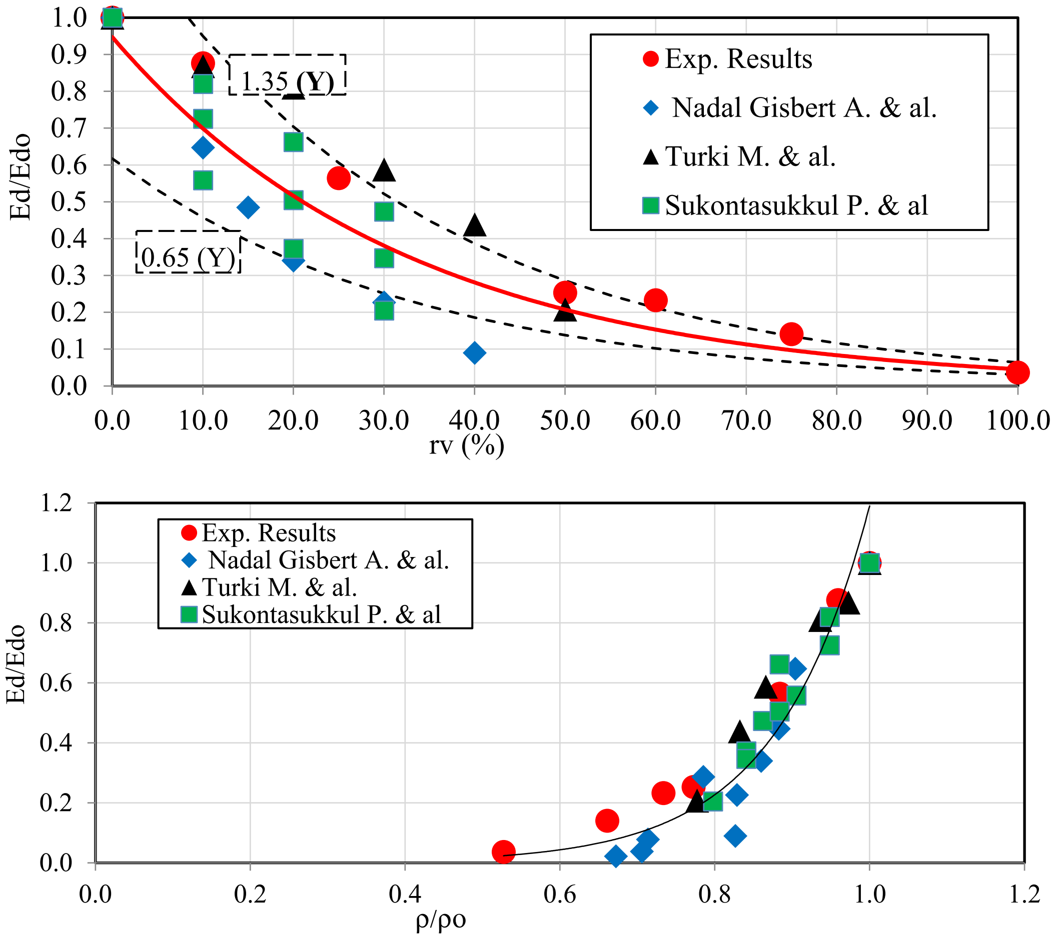


Figure 25. Dynamic modulus of the different mortars.

3.3. Pull out

The roughness values obtained for different concrete slabs where each rubberized mortar formula was applied are shown in Figure 26. The roughness values obtained are very close, ranging between 0.44 mm and 0.37mm.

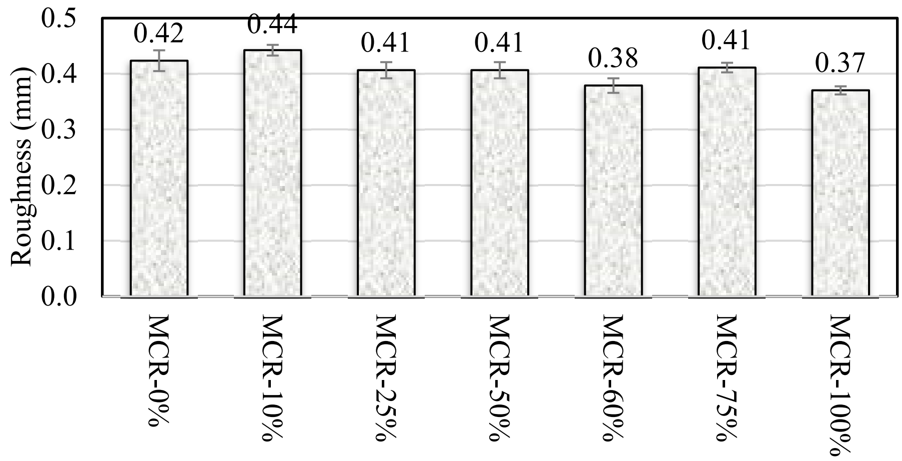
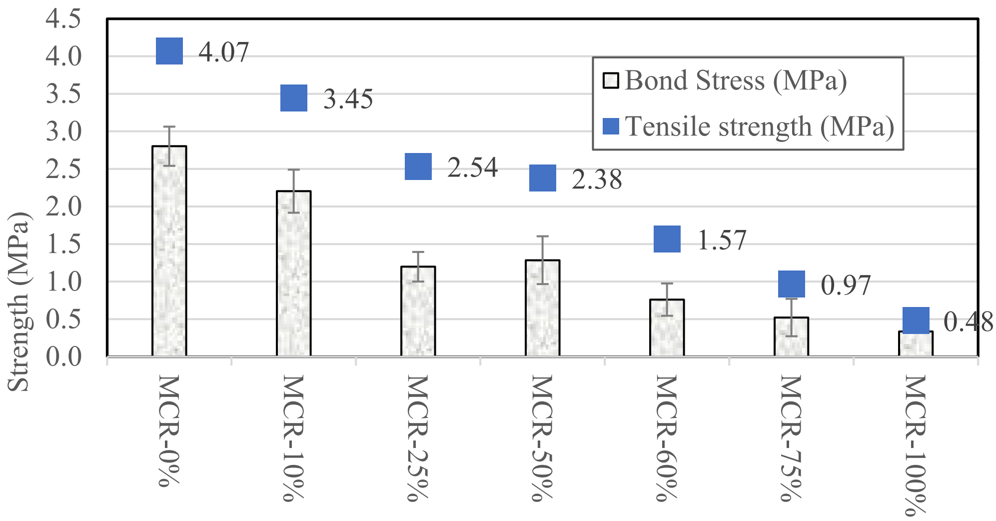


Figure 26. The roughness of the concrete surface before repairing.

The bond strength decreases when the mortar contains more CR ratio. However, adhesion remains of good quality and no decohesion has been observed.



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MCR-0%: adhesive failure mode	MCR-10%:: adhesive failure mode	MCR-50%: adhesive/cohesive failure mode

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MCR-60% cohesive failure mode	MCR-75% cohesive failure mode	MCR-100% cohesive failure mode

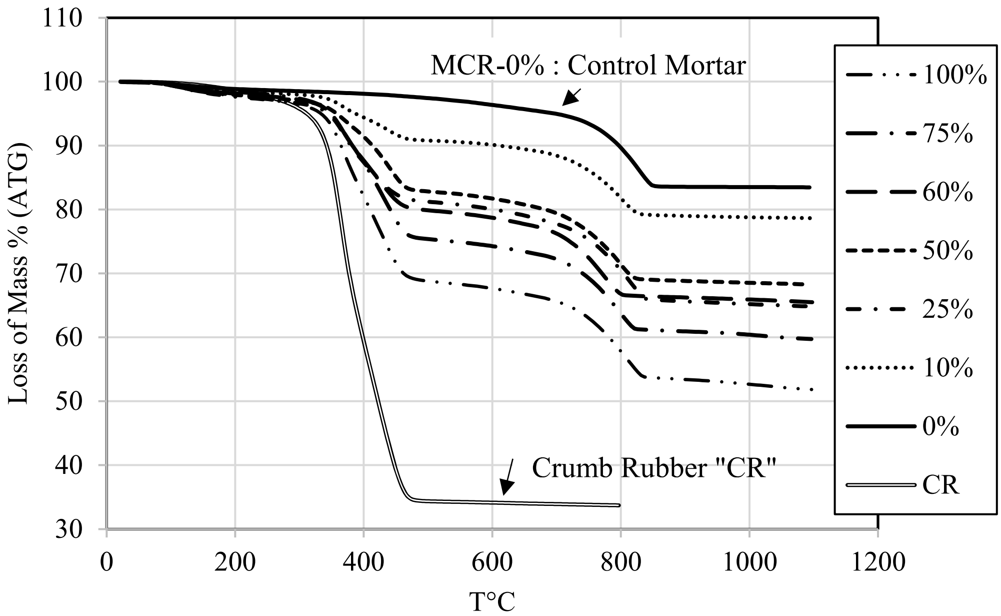
Figure 27. Pull out tests results.

The obtained bond strengths values are lower than the tensile strength values of the rubberized mortars (Figure 27). The failure mode was adhesive for $r_v \leq 50\%$, cohesive for $r_v = 100\%$ and mixed for $60\% \leq r_v \leq 75\%$.

The NF EN 1504-3 standard prescribes bond strengths $\geq 2MPa$ for Class R4; $\geq 1.5MPa$ for Class R3, $\geq 0{,}8MPa$ for class R2 and noi specific requirement for Class R1. It can be observed that mortars with $25 \leq r_v \leq 60\%$ can be used as non-structural repair products.

3.4. Fire resistance of cured mortars

As shown in Figure 28a, mass losses increased with the increase in temperature and crumb rubber content. In other words, mortar embedding crumb rubber lost more weight than plain mortar when temperature increased (Figure 28b). This is mainly explained by the increase of the CR content characterized by the highest value of total mass loss.



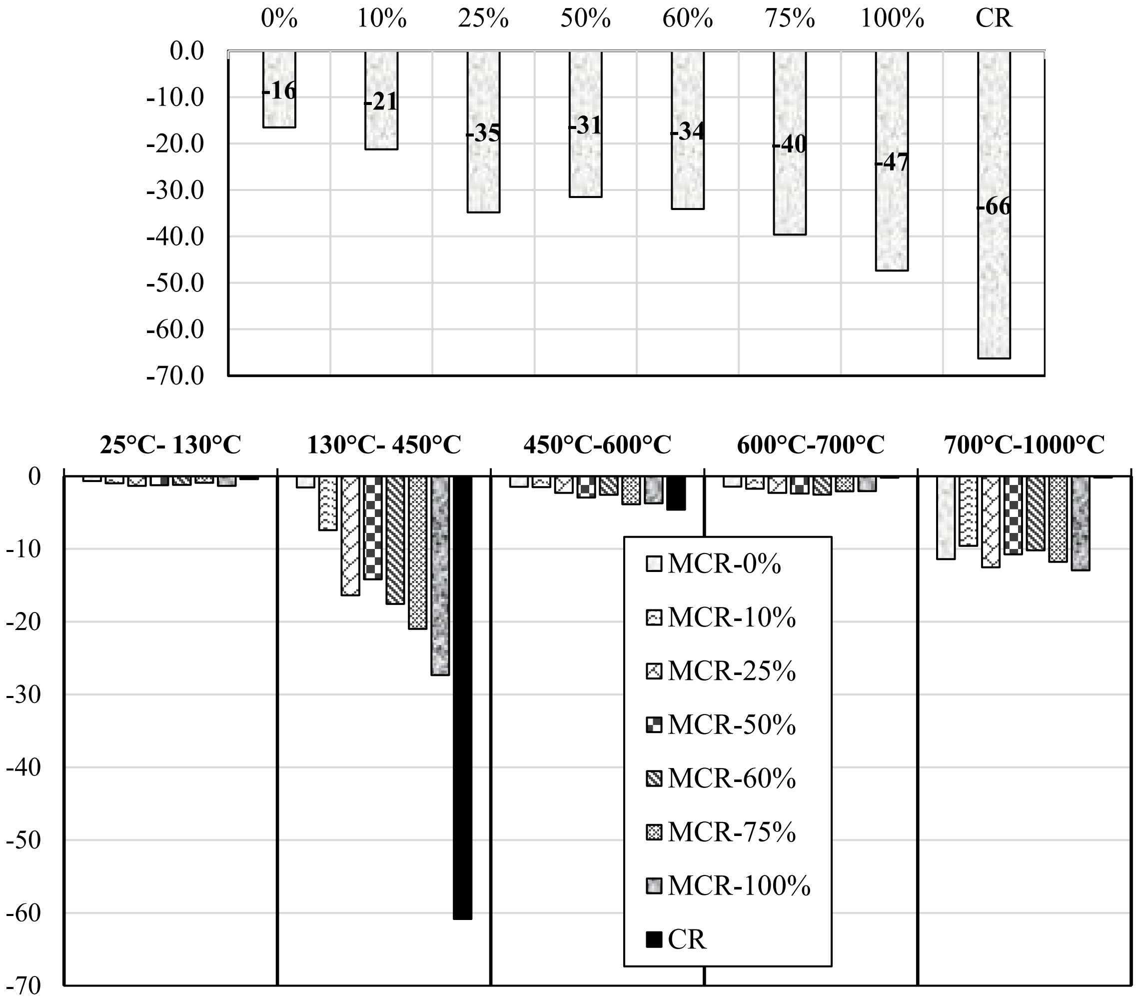


Figure 28. a: TGA curves of CR aggregates ans the different mortars The thermal gravimetric; b: Total mass loss of the mortars (%) as a function of $r_v(\%)$; c: mass loss (%) in the different range of temperatures.

Results reported in Figure 28c indicate that CR mass loss was about 61% between 130°C and 450°C. This increase is explained by the pyrolysis of polyisoprene and the decomposition of butadiene from vulcanized rubber.

For mortars, the increase in mass loss with temperature resulting from phase change in the cement paste is well described in the literature (Malik, Bhattacharyya, and Barai 2021). Based on this study, it can be concluded that:

- Between room temperature and 150°C, the variation of mass is essentially due to the release of volatiles (water and organic compounds).
- Between 450°C and 600°C the mass loss is mainly attributed to the decomposition of the portlandite ($Ca(OH)_2 \rightarrow CaO + H_2O$) and the end of the decomposition of the crumb rubber particles.
- Between 600°C and 700°C the mass loss is due to the dehydration of the CSH gel.
- Beyond 700°C to 1000°C, the loss of mass is attributed to the decomposition of calcite ($CaCO_3 \rightarrow CaO + CO_2$) and the end of CSH decomposition.

In light of the analysis of thermal gravimetric results, mortar specimens at 28 days age, with CR to NS replacement ratios of 0%, 10% and 25%, were placed in an oven for 24 hours at temperatures of 300 °C (where the effect of CR is predominant: decomposition and pyrolysis), 450 °C (decomposition of CR and portlandite) and 600 °C (decomposition of CR, portlandite and dehydration of CSH). After heat treatment, the specimens were cooled at ambient conditions and weighed to evaluate their mass losses.

The variation of compressive strength in mortar incorporating CR due to exposure to high temperature are shown in Figure 29. The curves show that the compressive strength decreases with the increase in the temperature of exposure. However, this decrease is independent of CR content, as shown in the RHS of Figure 29, where the compressive strength of the mortar after exposure at a specific temperature is normalized by the strength obtained at room temperature.

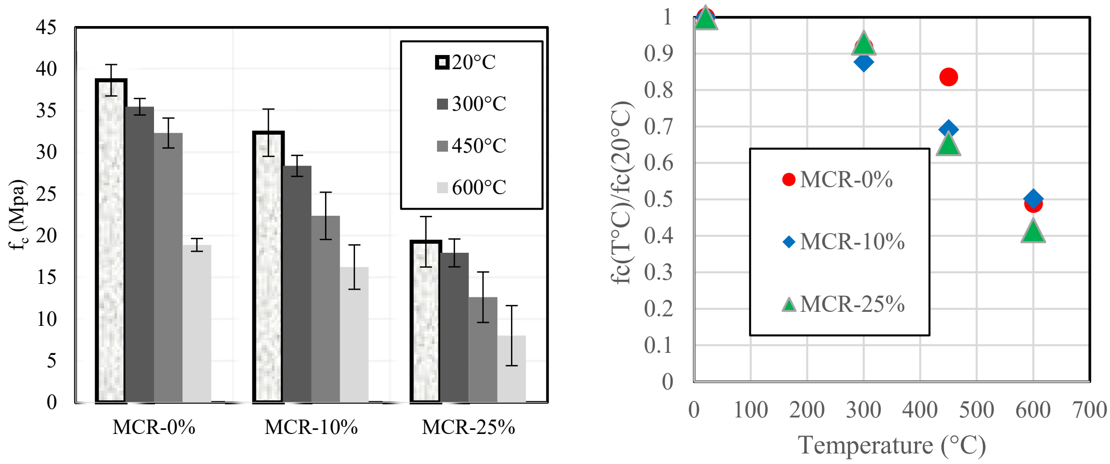


Figure 29. Effect of temperature on the strength of mortars embedding CR.

4. Conclusions

The main objective of this research is to develop new mortars for repair and rehabilitation that do not generate overloading on the ground, reduce energy consumption in buildings and increase the recycling potential of EOL tires as a "recovery material". In addition, the use of scrap tires will reduce the use of natural sand, which is currently the second most consumed resource in the world after water and faces potential shortages.

Eight mixtures, including control mortars and mortars with different percentages of crumb rubber particles (0%, 10%, 25%, 50%, 60%, 75% and 100%), were developed and tested. All experimental tests were carried out in compliance with relevant standards. The goal were to study the behaviour of crumb rubber particles, the behaviour of the different mixes in both fresh and hardened states and the effectiveness of mortars containing the highest percentage of crumb rubber particles as repair/rehabilitation products. In addition, the results obtained were compared with those reported in the published literature, making it possible to establish valuable relationships between the mortar properties and crumb rubber particle content. Selected mortars were also subjected to elevated temperatures in order to reproduce the impact of fire on compressive strength.

The main results obtained are listed below:

- Crumb rubbers obtained from EOL tires can be used with confidence as aggregates in mortars. Leaching tests revealed low levels of leached pollutants, confirming that CR particles can be considered safe for both health and the environment, particularly when embedded in a cementitious matrix.
- The air content of early-age mortar paste increases linearly with the CR replacement ratio. Entrapped air bubbles have a significant effect on the hardened behavior since they can concentrate stresses or facilitate the infiltration of damaging elements.
- The increase in the CR content reduces the setting time and the workability of mortars. However, mixes with $r_v \leq 60\%$ can still be used for repair work as they meet recommended standards.
- The apparent density decreases as the CR fraction increases. According to standards, mortars with $r_v \geq 25\%$ are classified as lightweight mortars. Moreover, an increase in porosity, mainly attributed to the higher occluded air content associated with higher CR rates, is observed particularly for $r_v > 50\%$.

- Since the number and volume of pore spaces and the surface area of cement-rubber interfaces vary with CR content, water absorption increases accordingly. In this study, it was established that both the normalized water absorption coefficient and the bulk density vary in the same way with the CR replacement ratio: $\frac{\rho_{ap}}{\rho_{ap,o}} = \frac{WA}{WA_o} = e^{-0.01r_v}$.
- Similarly, drying shrinkage increases with time and CR content due to the corresponding increase in number and volume of pore spaces and cement-rubber interfaces. However, it is established that this increase is more significant for mixes with $r_v > 60\%$.
- The mechanical properties decrease as the CR content increases. This was verified in terms of compressive, flexural and tensile strengths as well as the elastic modulus. Nevertheless, mortars with $25 \leq r_v(\%) \leq 50$ can be used as lightweight mortars according standard recommendations. Up to 50% of CR content, the proposed mortars fall within the range prescribed by the standard as non-structural repair products for civil engineering buildings.
- A similar relationship links the normalized compressive strength and normalized modulus of elasticity to rubber content $\frac{f_c}{f_{co}} = \frac{E}{E_o} = e^{-0.03r_v}$. This relationship was established on the basis of our new experimental results and those reported in the literature. However, it should be emphasized that all normalized mechanical properties are highly dependent on the normalized density. Expressions relating these properties have been established to isolate the effect of rubber incorporation.
- Incorporating up to 50% of waste tires improves comfort and thermal resistance without affecting thermal inertia. Experimental data indicate that thermal conductivity significantly decreases with respect to CR. However, the changes in volumetric heat capacity with CR are not as large, which explains the little changes observed in terms of thermal effusivity.
- The fracture energy increases with the increase in CR content. The increase in the density of microcrack networks and aggregate-cement interfaces weakens the material embedding soft crumb rubber. These defects coalesce and propagate, which results in the increase of energy dissipation with higher CR replacement ratios.
- Pull-out test results show that the bond strength decreases with increasing CR content. However, the obtained bond strengths conform to standards for non-structural repair applications when $25 \leq r_v \leq 60\%$.
- Mass losses due to heat treatment increase with higher crumb content and/or temperature. However, the variations remain below 12% in the temperature range considered (20 to 600°C)

In summary, mortars embedding CR can be used to lighten structures given their low density. When applied to the repair/rehabilitation structures, lightweight mortar provides additional strength without hindering the portability. The mortars developed with $25 \leq r_v \leq 50\%$ can be classified as lightweight mortars with an improved thermal comfort according to standards and be used as non-structural repair products.

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Data Availability Statement: All data, models, and code generated or used during the study appear in the submitted article

References

Abbas-Abadi, Mehrdad Seifali, Marvin Kusenberg, Hamed Mohamadzadeh Shirazi, Bahman Goshayeshi, and Kevin M. Van Geem. 2022. "Towards Full Recyclability of End-of-Life Tires: Challenges and Opportunities." *Journal of Cleaner Production* 374.

Ademe. 2023. *Les Exigences Réglementaires Pour Les Travaux de Rénovation*.

Aiello, M. A., and F. Leuzzi. 2010. "Waste Tyre Rubberized Concrete: Properties at Fresh and Hardened State." *Waste Management* 30(8):1696–1704. doi: https://doi.org/10.1016/j.wasman.2010.02.005.

Al-Attar, Alyaa A., Hussein M. Hamada, Bassam A. Tayeh, and Paul O. Awoyera. 2021. "Exploring Engineering Properties of Waste Tire Rubber for Construction Applications- A Review of Recent Advances." Pp. A1–17 in *Materials Today: Proceedings*. Vol. 53. Elsevier Ltd.

Aliabdo, Ali A., Abd Elmoaty M. Abd Elmoaty, and Mostafa M. Abdelbaset. 2015. "Utilization of Waste Rubber in Non-Structural Applications." *Construction and Building Materials* 91:195–207. doi: 10.1016/j.conbuildmat.2015.05.080.

Alsaif, Abdulaziz, Susan A. Bernal, Maurizio Guadagnini, and Kypros Pilakoutas. 2018. "Durability of Steel Fibre Reinforced Rubberised Concrete Exposed to Chlorides." *Construction and Building Materials* 188:130–42. doi: https://doi.org/10.1016/j.conbuildmat.2018.08.122.

Angelin, A. F., E. J. P. Miranda, J. M. C. Dos Santos, R. C. C. Lintz, and L. A. Gachet-Barbosa. 2019. "Rubberized Mortar: The Influence of Aggregate Granulometry in Mechanical Resistances and Acoustic Behavior." *Construction and Building Materials* 200:248–54. doi: 10.1016/j.conbuildmat.2018.12.123.

Angelin, Andressa F., Matheus F. F. Andrade, Rodrigo Bonatti, Rosa C. Cecche Lintz, Luísa A. Gachet-Barbosa, and Wislei R. Osório. 2015. "Effects of Spheroid and Fiber-like Waste-Tire Rubbers on Interrelation of Strength-to-Porosity in Rubberized Cement and Mortars." *Construction and Building Materials* 95:525–36. doi: https://doi.org/10.1016/j.conbuildmat.2015.07.166.

Arulrajah, Arul, Alireza Mohammadinia, Farshid Maghool, and Suksun Horpibulsuk. 2019. "Tire Derived Aggregates as a Supplementary Material with Recycled Demolition Concrete for Pavement Applications." *Journal of Cleaner Production* 230:129–36. doi: 10.1016/j.jclepro.2019.05.084.

ASDReports. 2023. *GLOBAL END-OF-LIFE TIRE (ELT) MANAGEMENT MARKET FORECAST 2023-2032*.

Atahan, Ali O., and Ayhan Öner Yücel. 2012. "Crumb Rubber in Concrete: Static and Dynamic Evaluation." *Construction and Building Materials* 36:617–22. doi: https://doi.org/10.1016/j.conbuildmat.2012.04.068.

Azevedo, F., F. Pacheco-Torgal, C. Jesus, J. L. Barroso de Aguiar, and A. F. Camões. 2012. "Properties and Durability of HPC with Tyre Rubber Wastes." *Construction and Building Materials* 34:186–91. doi: https://doi.org/10.1016/j.conbuildmat.2012.02.062.

Bala, Anu, and Supratic Gupta. 2021. "Thermal Resistivity, Sound Absorption and Vibration Damping of Concrete Composite Doped with Waste Tire Rubber: A Review." *Construction and Building Materials* 299.

Batayneh, Malek K., Iqbal Marie, and Ibrahim Asi. 2008. "Promoting the Use of Crumb Rubber Concrete in Developing Countries." *Waste Management* 28(11):2171–76. doi: https://doi.org/10.1016/j.wasman.2007.09.035.

Benazzouk, A., O. Douzane, K. Mezreb, B. Laidoudi, and M. Quéneudec. 2008. "Thermal Conductivity of Cement Composites Containing Rubber Waste Particles: Experimental Study and Modelling." *Construction and Building Materials* 22(4):573–79. doi: 10.1016/j.conbuildmat.2006.11.011.

Bianco, Isabella, Deborah Panepinto, and Mariachiara Zanetti. 2021. "End-of-Life Tyres: Comparative Life Cycle Assessment of Treatment Scenarios." *Applied Sciences* 11(8).

Bogno, Bachirou, Paul-Salomon Ngohe Ekam, Mohammadou Sali, Dieudonné Kidmo Kaoga, Abderrezak Guenounou, and Michel Aillerie. 2023. "Waste Recovery and Sustainable Development. A Case Study of Material Development from Used Tires in Africa." *Smart Grid and Renewable Energy* 14(06):107–29. doi: 10.4236/sgre.2023.146007.

Brindley, Fraser., Emma. Mountjoy, Gavin. Mountjoy, and Council of Australian Governments. Standing Council on Environment and Water. 2012. *COAG Standing Council on Environment and Water Study into Domestic and International Fate of End-of-Life Tyres : Final Report*. Hyder Consulting.

Cerema. 2011. *Acceptabilité Environnementale En Technique Routière*.

Charlotte B Merlin. 2020. *Life Cycle Assessment of Waste Tyre Treatments: Material Recycling vs. Coincineration in Cement Kilns*.

Consulting, Hyder. 2015. *Stocks and Fate of End-of-Life Tyres - 2013-14 Study*.

Consulting, Mra. 2022. *End of Life Tyre Management: Thermal Processing Options*.

Correia, Sivaldo L., Tânia Partala, Felipe C. Loch, and A. M. Segadães. 2010. "Factorial Design Used to Model the Compressive Strength of Mortars Containing Recycled Rubber." *Composite Structures* 92(9):2047–51. doi: https://doi.org/10.1016/j.compstruct.2009.11.007.

Dabic-Miletic, Svetlana, Vladimir Simic, and Selman Karagoz. 2021. "End-of-Life Tire Management: A Critical Review." *Environmental Science and Pollution Research* 68053–68. doi: 10.1007/s11356-021-16263-6/Published.

Dong, Minhao, Mohamed Elchalakani, Ali Karrech, Mostafa Fahmi Hassanein, Tianyu Xie, and Bo Yang. 2019. "Behaviour and Design of Rubberised Concrete Filled Steel Tubes under Combined Loading Conditions." *Thin-Walled Structures* 139:24–38. doi: https://doi.org/10.1016/j.tws.2019.02.031.

Fayez Obaid Al Mazrouei, Khaled Chaaraoui and Zaid Bdour. 2023. "Tyre Recycling in the Middle East: On the Wheels of Change." *Waste & Recycling Middle East and Africa* 13(3):14–16.

Ferronato, Navarro, and Vincenzo Torretta. 2019. "Waste Mismanagement in Developing Countries: A Review of Global Issues." *International Journal of Environmental Research and Public Health* 16(6).

Forrest, Martin J. 2019. *Recycling and Re-Use of Waste Rubber*. De Gruyter.

Gebreslassie, Mulualem G., Solomon T. Bahta, and Alazar S. Mihrete. 2023. "Development of Alternative Fuel for Cement Industries: The Case of Messebo Cement Factory in Ethiopia." *Waste Management Bulletin* 1(3):58–70. doi: 10.1016/j.wmb.2023.07.003.

Gesoğlu, Mehmet, Erhan Güneyisi, Ganjeena Khoshnaw, and Süleyman İpek. 2014. "Abrasion and Freezing–Thawing Resistance of Pervious Concretes Containing Waste Rubbers." *Construction and Building Materials* 73:19–24. doi: https://doi.org/10.1016/j.conbuildmat.2014.09.047.

Grinys, Audrius, Henrikas Sivilevičius, and Mindaugas Daukšys. 2012. "Tyre Rubber Additive Effect on Concrete Mixture Strength." *Journal of Civil Engineering and Management* 18(3):393–401. doi: 10.3846/13923730.2012.693536.

Grinys, Audrius, Henrikas Sivilevičius, Darius Pupeikis, and Ernestas Ivanauskas. 2013. "FRACTURE OF CONCRETE CONTAINING CRUMB RUBBER." *Journal of Civil Engineering and Management* 19(3):447–55. doi: 10.3846/13923730.2013.782335.

Guo, Shuaicheng, Qingli Dai, Ruizhe Si, Xiao Sun, and Chao Lu. 2017. "Evaluation of Properties and Performance of Rubber-Modified Concrete for Recycling of Waste Scrap Tire." *Journal of Cleaner Production* 148:681–89. doi: https://doi.org/10.1016/j.jclepro.2017.02.046.

Gupta, Trilok, Ravi K. Sharma, and Sandeep Chaudhary. 2015. "Impact Resistance of Concrete Containing Waste Rubber Fiber and Silica Fume." *International Journal of Impact Engineering* 83:76–87. doi: https://doi.org/10.1016/j.ijimpeng.2015.05.002.

Han, Qing-Hua, Guang Yang, and Jie Xu. 2018. "Experimental Study on the Relationship between Acoustic Emission Energy and Fracture Energy of Crumb Rubber Concrete." *Structural Control and Health Monitoring* 25(10):e2240. doi: https://doi.org/10.1002/stc.2240.

Han Zhu, Norasit Thong-On, and Xiong Zhang. 2002. "Adding-Crumb-Rubber-into-Exterior-Wall-Materials." *Waste Manage & Research* 20:407–13.

Herrero, S., P. Mayor, and F. Hernández-Olivares. 2013. "Influence of Proportion and Particle Size Gradation of Rubber from End-of-Life Tires on Mechanical, Thermal and Acoustic Properties of Plaster–Rubber Mortars." *Materials & Design* 47:633–42. doi: https://doi.org/10.1016/j.matdes.2012.12.063.

Johannes, Hendro Putra, Michikazu Kojima, Fusanori Iwasaki, and Ellen Putri Edita. 2021. "Applying the Extended Producer Responsibility towards Plastic Waste in Asian Developing Countries for Reducing Marine Plastic Debris." *Waste Management and Research* 39(5):690–702. doi: 10.1177/0734242X211013412.

Kara De Maeijer, Patricia, Bart Craeye, Johan Blom, and Lieven Bervoets. 2021. "Crumb Rubber in Concrete—the Barriers for Application in the Construction Industry." *Infrastructures* 6(8).

Karrech, A., V. Strazzeri, and M. Elchalakani. 2021. "Improved Thermal Insulance of Cement Stabilised Rammed Earth Embedding Lightweight Aggregates." *Construction and Building Materials* 268:121075. doi: https://doi.org/10.1016/j.conbuildmat.2020.121075.

Khaloo, Ali R., M. Dehestani, and P. Rahmatabadi. 2008. "Mechanical Properties of Concrete Containing a High Volume of Tire–Rubber Particles." *Waste Management* 28(12):2472–82. doi: https://doi.org/10.1016/j.wasman.2008.01.015.

K., Khatib Zaher, and Bayomy Fouad M. 1999. "Rubberized Portland Cement Concrete." *Journal of Materials in Civil Engineering* 11(3):206–13. doi: 10.1061/(ASCE)0899-1561(1999)11:3(206).

Lee, Junghwoon, Tae Sup Yun, and Sung Uk Choi. 2015. "The Effect of Particle Size on Thermal Conduction in Granular Mixtures." *Materials* 8(7):3975–91. doi: 10.3390/ma8073975.

Li, Lijuan, Shenghua Ruan, and Lan Zeng. 2014. "Mechanical Properties and Constitutive Equations of Concrete Containing a Low Volume of Tire Rubber Particles." *Construction and Building Materials* 70:291–308. doi: https://doi.org/10.1016/j.conbuildmat.2014.07.105.

Liu, Feng, Guixuan Chen, Lijuan Li, and Yongchan Guo. 2012. "Study of Impact Performance of Rubber Reinforced Concrete." *Construction and Building Materials* 36:604–16. doi: https://doi.org/10.1016/j.conbuildmat.2012.06.014.

Liu, Lulu, Guojun Cai, and Xiaoyan Liu. 2020. "Investigation of Thermal Conductivity and Prediction Model of Recycled Tire Rubber-Sand Mixtures as Lightweight Backfill." *Construction and Building Materials* 248. doi: 10.1016/j.conbuildmat.2020.118657.

Lv, Jing, Tianhua Zhou, Qiang Du, and Hanheng Wu. 2015. "Effects of Rubber Particles on Mechanical Properties of Lightweight Aggregate Concrete." *Construction and Building Materials* 91:145–49. doi: https://doi.org/10.1016/j.conbuildmat.2015.05.038.

Malik, Manisha, S. K. Bhattacharyya, and Sudhirkumar V. Barai. 2021. "Thermal and Mechanical Properties of Concrete and Its Constituents at Elevated Temperatures: A Review." *Construction and Building Materials* 270.

Marie, Iqbal. 2016. "Zones of Weakness of Rubberized Concrete Behavior Using the UPV." *Journal of Cleaner Production* 116:217–22. doi: https://doi.org/10.1016/j.jclepro.2015.12.096.

Medina, Nelson Flores, Darío Flores Medina, F. Hernández-Olivares, and M. A. Navacerrada. 2017. "Mechanical and Thermal Properties of Concrete Incorporating Rubber and Fibres from Tyre Recycling." *Construction and Building Materials* 144:563–73. doi: https://doi.org/10.1016/j.conbuildmat.2017.03.196.

Nadal Gisbert, A., J. M. Gadea Borrell, F. Parres García, E. Juliá Sanchis, J. E. Crespo Amorós, J. Segura Alcaraz, and F. Salas Vicente. 2014a. "Analysis Behaviour of Static and Dynamic Properties of Ethylene-Propylene-Diene-Methylene Crumb Rubber Mortar." *Construction and Building Materials* 50:671–82. doi: https://doi.org/10.1016/j.conbuildmat.2013.10.018.

Noor Azline, M. N., A. B. Nabilah, S. Nor Azizi, and A. A. Farah Nora Aznieta. 2022. "A Comparative Investigation on Mechanical Strength of Blended Concrete with Surface Modified Rubber by Chemical and Non-Chemical Approaches." *Case Studies in Construction Materials* 17. doi: 10.1016/j.cscm.2022.e01444.

Onuaguluchi, Obinna. 2015. "Effects of Surface Pre-Coating and Silica Fume on Crumb Rubber-Cement Matrix Interface and Cement Mortar Properties." *Journal of Cleaner Production* 104:339–45. doi: https://doi.org/10.1016/j.jclepro.2015.04.116.

Pneumatiques, France Recyclage. 2023. *ANTICIPER PROGRESSER &*.

Qaidi, Shaker M. A., Youkhanna Zayia Dinkha, James H. Haido, Msheer Hasan Ali, and Bassam A. Tayeh. 2021. "Engineering Properties of Sustainable Green Concrete Incorporating Eco-Friendly Aggregate of Crumb Rubber: A Review." *Journal of Cleaner Production* 324:129251. doi: https://doi.org/10.1016/j.jclepro.2021.129251.

Rashad, Alaa M. 2016. "A Comprehensive Overview about Recycling Rubber as Fine Aggregate Replacement in Traditional Cementitious Materials." *International Journal of Sustainable Built Environment* 5(1):46–82. doi: https://doi.org/10.1016/j.ijsbe.2015.11.003.

RILEM. 1985. "Determination of the Fracture Energy of Mortar and Concrete by Means of Three-Point Bend Tests on Notched Beams." *Materials and Structures* 18(4):287–90. doi: 10.1007/BF02472918.

Rincón, Lídia, Julià Coma, Gabriel Pérez, Albert Castell, Dieter Boer, and Luisa F. Cabeza. 2014. "Environmental Performance of Recycled Rubber as Drainage Layer in Extensive Green Roofs. A Comparative Life Cycle Assessment." *Building and Environment* 74:22–30. doi: https://doi.org/10.1016/j.buildenv.2014.01.001.

Salman Zafar. 2022. "Disposal of Waste Tires." *Https://Www.Ecomena.Org/Methods-for-Tire-Recycling/*.

SEREP. 2022. *Research Report: Assessment of End-of-Life Tyres in the Pacific*.

Shanley Authors Matt Genever Kyle, Karl O., Farrell Paul Randell John Rebbechi, and Roadcor -. 2017. *National Market Development Strategy for Used Tyres Final Strategy Client Client Contact*.

Siddique, Rafat, and Tarun R. Naik. 2004. "Properties of Concrete Containing Scrap-Tire Rubber – an Overview." *Waste Management* 24(6):563–69. doi: https://doi.org/10.1016/j.wasman.2004.01.006.

da Silva, Fabiana Maria, Luisa Andréia Gachet Barbosa, Rosa Cristina Cecche Lintz, and Ana Elisabete P. G. A. Jacintho. 2015. "Investigation on the Properties of Concrete Tactile Paving Blocks Made with Recycled Tire Rubber." *Construction and Building Materials* 91:71–79. doi: https://doi.org/10.1016/j.conbuildmat.2015.05.027.

Strazzeri, V., A. Karrech, and M. Elchalakani. 2020. "Micromechanics Modelling of Cement Stabilised Rammed Earth." *Mechanics of Materials* 148:103540. doi: https://doi.org/10.1016/j.mechmat.2020.103540.

Su, Haolin, Jian Yang, Tung-Chai Ling, Gurmel S. Ghataora, and Samir Dirar. 2015. "Properties of Concrete Prepared with Waste Tyre Rubber Particles of Uniform and Varying Sizes." *Journal of Cleaner Production* 91:288–96. doi: https://doi.org/10.1016/j.jclepro.2014.12.022.

Sukontasukkul, Piti, and Koshi Tiamlom. 2012. "Expansion under Water and Drying Shrinkage of Rubberized Concrete Mixed with Crumb Rubber with Different Size." *Construction and Building Materials* 29:520–26. doi: https://doi.org/10.1016/j.conbuildmat.2011.07.032.

Surehali, Sahil, Avishreshth Singh, and Krishna Prapoorna Biligiri. 2023. "A State-of-the-Art Review on Recycling Rubber in Concrete: Sustainability Aspects, Specialty Mixtures, and Treatment Methods." *Developments in the Built Environment* 14. doi: 10.1016/j.dibe.2023.100171.

Thomas, Blessen Skariah, and Ramesh Chandra Gupta. 2016. "Properties of High Strength Concrete Containing Scrap Tire Rubber." *Journal of Cleaner Production* 113:86–92. doi: https://doi.org/10.1016/j.jclepro.2015.11.019.

Thomas, Blessen Skariah, and Ramesh Chandra Gupta. 2016. "A Comprehensive Review on the Applications of Waste Tire Rubber in Cement Concrete." *Renewable and Sustainable Energy Reviews* 54:1323–33. doi: https://doi.org/10.1016/j.rser.2015.10.092.

Thomas, Blessen Skariah, Ramesh Chandra Gupta, and Vinu John Panicker. 2016. "Recycling of Waste Tire Rubber as Aggregate in Concrete: Durability-Related Performance." *Journal of Cleaner Production* 112:504–13. doi: https://doi.org/10.1016/j.jclepro.2015.08.046.

Turatsinze, A., S. Bonnet, and J. L. Granju. 2005. "Mechanical Characterisation of Cement-Based Mortar Incorporating Rubber Aggregates from Recycled Worn Tyres." *Building and Environment* 40(2):221–26. doi: https://doi.org/10.1016/j.buildenv.2004.05.012.

Turatsinze, A., and M. Garros. 2008. "On the Modulus of Elasticity and Strain Capacity of Self-Compacting Concrete Incorporating Rubber Aggregates." *Resources, Conservation and Recycling* 52(10):1209–15. doi: https://doi.org/10.1016/j.resconrec.2008.06.012.

Turgut, Paki, and Bulent Yesilata. 2008. "Physico-Mechanical and Thermal Performances of Newly Developed Rubber-Added Bricks." *Energy and Buildings* 40(5):679–88. doi: 10.1016/j.enbuild.2007.05.002.

Turki, M., E. Bretagne, M. J. Rouis, and M. Quéneudec. 2009a. "Microstructure, Physical and Mechanical Properties of Mortar–Rubber Aggregates Mixtures." *Construction and Building Materials* 23(7):2715–22. doi: https://doi.org/10.1016/j.conbuildmat.2008.12.019.

Turki, M., I. Ben Naceur, M. Makni, J. Rouis, and K. Saï. 2008a. "Mechanical and Damage Behaviour of Mortar–Rubber Aggregates Mixtures: Experiments and Simulations." *Materials and Structures* 42(10):1313. doi: 10.1617/s11527-008-9451-1.

Tyre Stewardship Australia (TSA). 2021. *AUSTRALIAN TYRE CONSUMPTION AND RECOVERY*.

Tyre Stewardship Australia (TSA). 2022. *Domestic and International Markets for Used Tyres and Tyre-Derived Products TSA Levy-Paying Tyre Importers and Autobrands*.

UNEP. 2018. *AfricA Waste Management*.

Uygunoğlu, Tayfun, and İlker Bekir Topçu. 2010. "The Role of Scrap Rubber Particles on the Drying Shrinkage and Mechanical Properties of Self-Consolidating Mortars." *Construction and Building Materials* 24(7):1141–50. doi: https://doi.org/10.1016/j.conbuildmat.2009.12.027.

Valentini, Francesco, and Alessandro Pegoretti. 2022. "End-of-Life Options of Tyres. A Review." *Advanced Industrial and Engineering Polymer Research* 5(4):203–13.

Venice GRAF, Sarah PÉRENNÈS, Louise ROUQUETTE, and Thomas GRANDIN. 2022. *Pneumatiques – Rapport Annuel – Données 2021*.

WBCSD. 2019. *Global ELT Management-A Global State of Knowledge on Regulation, Management Systems, Impacts of Recovery and Technologies*.

WBCSD. 2021. *End-of-Life Tire (ELT) Management Toolkit End-of-Life Tire Management Toolkit 2*.

Xiao, Yang, Bowen Nan, and John S. McCartney. 2019. "Thermal Conductivity of Sand–Tire Shred Mixtures." *Journal of Geotechnical and Geoenvironmental Engineering* 145(11). doi: 10.1061/(asce)gt.1943-5606.0002155.

Yang, Yu Ling, Tao Zhang, Krishna R. Reddy, Jiang Shan Li, and Song yu Liu. 2022. "Thermal Conductivity of Scrap Tire Rubber-Sand Composite as Insulating Material: Experimental Investigation and Predictive Modeling." *Construction and Building Materials* 332. doi: 10.1016/j.conbuildmat.2022.127387.

Zakeremamreza, Amin, Mohammad E. Kianifar, Chidera Chibuisi, Ehsan Ahmadi, and Mohammad R. Salami. 2023. "A High-Performance Rubberised Alkali-Activated Mortar for Repair of RC Beams." *Construction and Building Materials* 400. doi: 10.1016/j.conbuildmat.2023.132610.