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Assessment of Thermal and Mechanical Properties of Cement-Based Materials—Part 1: Crumb Rubber Concrete

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Abstract: The energy performance of buildings and the high consumption of traditional building materials are considered to be the most important aspects that are related to the implementation of the sustainability concept in the construction industry with respect to the natural environment. At the same time, another important global ecological problem is represented by different types of waste resulting from existing industries. Therefore, it is necessary that civil engineering specialists find new solutions and materials that can improve the thermal and environmental performances of buildings by taking into consideration the large amounts of existing waste. Taking into account the fact that concrete is the most used material in the construction sector and that concrete elements have a significant influence over the overall energy performance of a building, the present paper takes under observation the use of tire rubber waste as a replacement for concrete aggregates. This study considers a replacement of 10%, 20%, and 30% of the 4–8 mm aggregates with crumb rubber cylindrical granules. The resulting values show an improvement in the thermal performance, but at the same time, the mechanical properties are reduced.

Keywords: sustainability; recycle; cement-based composites; energy performance; concrete; rubber waste; thermal performances; mechanical properties

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1. Introduction

Around 40% of energy consumption and 36% of greenhouse gas emissions are accounted for in the built environment [1]. Due to the recent energy efficiency legislation and decarbonization plans, by 2050, the balance of the energy efficiency of buildings should improve [2,3]. In the construction industry, using sustainable construction materials helps accumulate economic and environmental benefits [4] and may be the key to reducing emissions. The types of materials that are used in the construction process have a significant influence on the overall thermal transmittance of the building envelope. Mainly, the thermal conductivity of the materials and also the thicknesses of the layers that form the elements that separate the indoor space from the outdoor conditions can transform a building into a highly energy-efficient one. At the same time, in addition to the opaque construction elements, in order to reduce the final consumption of a building, it is necessary to take under consideration a significant number of aspects, such as the thermal performance of the windows and the surface of these elements, the sun orientation of the building, the air tightness, and how the owners are going to use the building. Thus, the choice of construction material is an important decision that is generally based on the personal preferences of the users and the cost level, but it has long-term consequences [5].

Concrete is the conventional solution for foundations and ground floor slabs in major seismic-risk countries. In contrast, the thermal resistance of concrete significantly influences the energy consumption of the building. Consequently, concrete with a high thermal resistance can significantly contribute to the energy efficiency of a building. To obtain the thermal conductivity performance necessary for an energy-efficient building and to take

into account principles of sustainable development, it is essential to analyze the solutions for the thermal improvement of concrete by using thermal insulation materials in the envelope elements with little impact on the environment.

There are studies about recycling waste materials and transforming them into other beneficial resources [6–10]. According to the 2018 World Bank report "*What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*", global annual waste generation is anticipated to increase by 70% to reach 3.4 billion tonnes over the next three decades from 2.01 billion tonnes in 2016 [11]. The increase in used tires is a global problem due to the lack of recycling options [12]. Recycling crumb rubber waste from tires in civil engineering as concrete aggregates can be environmentally and economically efficient [10,13–19]. Crumb rubber, produced from used tires, is one of the material wastes that can be used in concrete to partially or entirely replace coarse or fine aggregates [20]. Fine rubber particles are efficient in thermal insulation due to the large surface area preventing significant heat flux transitions [21]. The rubber goes through a tire-cutting process to produce rubber chips between 70 mm and 100 mm. Subsequently, the size of these chips is reduced in a granulator. Finally, the material is introduced into a mill to make fine particles. The rubber granules are graded during each processing level, and steel fibers and wires are separated using magnetic separators.

The studies presented in the literature performed on concrete with the addition of crumb rubber had varied results: the differences given by the materials and the mixture compositions used in concrete preparations [22–30]. All the studies identified the high potential of using tire rubber in concrete, highlighting the role of increasing the energy absorption capacity of concrete significantly [31–34].

Taking into account all the above-mentioned studies, the goal of the present paper is to highlight the behavior of concrete mixed with crumb rubber. An experimental program was developed to evolve the overall behavior of this material as a part of the thermal envelope. In order to achieve a complex and complete analysis of crumb rubber concrete, the density, the determination of the compressive strength, the thermal conductivity, and microscope analyses were pursued.

The significance of the article is to research a solution for integrating crumb rubber, a clean energy and efficient material, and waste in a concrete-based material. The results of this research will help to better understand the influence of various percentages of crumb rubber in concrete mixtures, offering calibration of the compositions for further experiments and tests. In practice, crumb rubber concrete may be suitable for structural elements requiring an improved thermal performance but with a lower compressive strength class. The results of this study will contribute to a greater understanding of the potential for using crumb rubber as a sustainable alternative in the construction industry with the ultimate goal of promoting more environmentally friendly building practices.

2. Materials and Methods

The rubber granules used in this research study were obtained from tire waste (Figure 1). The granules were not treated, and the aggregate replacement with rubber granules was conducted according to the volume of the materials.



Figure 1. Crumb rubber granules.

The concrete used in the tests had an A/C ratio of 0.55, strength class C 20/25, exposure class XC3 XA1, and consistency class S3. For 1 m^2 of concrete, the mixture composition included 330 kg of cement CEM I/A-LL 42.5R, 180 l of water, 764 kg of aggregates of 0–4 mm, 317 kg of aggregates of 4–8 mm, and 782 kg of aggregates of 8–16 mm.

The incorporation of tire rubber at levels of 10%, 20%, and 30% yielded the optimal combination of heat resistance and mechanical properties in concrete [35–37]. To study the influence of crumb rubber, three different mixture compositions were used in which 10%, 20%, and 30% of the 4–8 mm aggregate volume was replaced. The quantities of the component materials used in the concrete mixture are presented in Table 1. A standard case of the mixture composition was needed to compare and highlight the differences between conventional and crumb rubber concrete.

Table 1. Component materials for normal and crumb rubber concrete.

Case Studies	Water (l/m^3)	Cement (CEM I42.5R) (kg/m^3)	Aggregate 0–4 mm (kg/m^3)	Aggregate 4–8 mm (kg/m^3)	Aggregate 8–16 mm (kg/m^3)	Rubber (kg/m^3)
C 20/25	180	330	764	317	783	0.0
S1—10% rubber	180	330	764	285	783	9.2
S2—20% rubber	180	330	764	253	783	18.4
S3—30% rubber	180	330	764	221	783	27.6

Each case study considered nine cubic samples of 150 mm in all side lengths. The crumb rubber granules were evenly distributed during the concrete mixing process. The samples were made, vibrated, and handled considering the specifications of European standards in order to avoid segregation and bleeding phenomena. All tests were carried out under constant laboratory conditions to avoid influencing the results due to changes in temperature and humidity.

The compositions were subjected to thermal conductivity measurements after 28 days using ISOMET 2114, a portable device for measuring thermomechanical characteristics, equipped with a surface sensor for hard materials (Figure 2). The measurements using this device were performed by applying a dynamic investigation method, which allowed for a reduction in the test time compared to steady-state assay methods. Thermal conductivity measurements are based on temperature records taken periodically as a function of time.

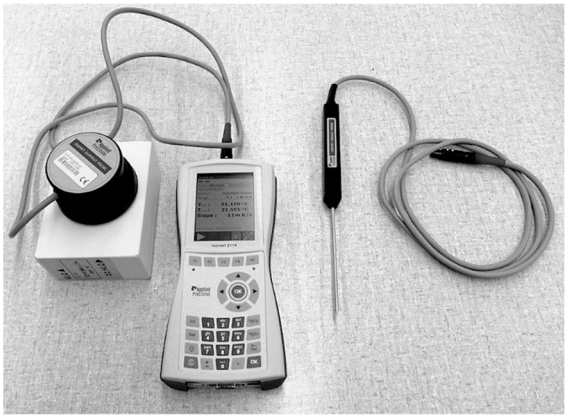


Figure 2. ISOMET 2114—portable device for measuring thermomechanical characteristics.

In order to determine the compressive strength, after 28 days, the compositions were subjected to compression using ZwickRoell SP1000 hydraulic equipment (Figure 3) with a force accuracy of less than 1%. A compressive force was applied perpendicular to the casting direction, and the loading speed was 0.2 MPa/s. The standard EN 12390-3:2009 requirements were followed in the testing procedures.



Figure 3. ZwickRoell SP1000 hydraulic equipment.

To examine the bonding between the crumb rubber and the other components in the concrete mixture, a series of analyses were conducted using a microscope LFD (large-field detector in low-vacuum working mode) on 1 cm samples of each of the four compositions (Figure 4).

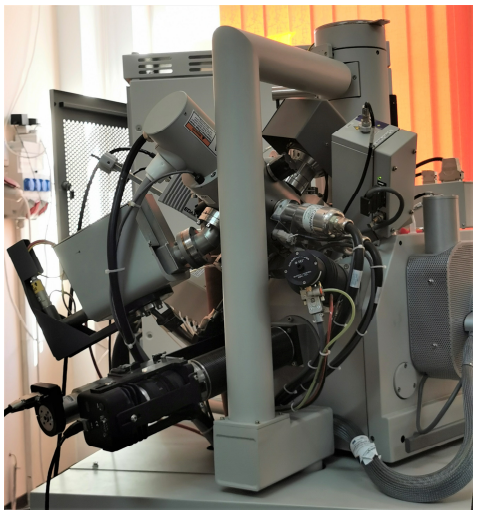


Figure 4. The microscope large-field detector.

3. Results

3.1. Density

In the first stage, the density of the four compositions was determined after completely hardening the cubic specimens by weighing them and calculating the volume of the samples. Figure 5 presents the values that describe the density of the considered concrete mixtures. By analyzing the results, it can be observed that the crumb rubber concrete has a lower density by approximately 2.04% in the case of 10% rubber granules and by 2.48% and 3.13% in the case of the 20% and 30% rubber mixtures (Table 2).

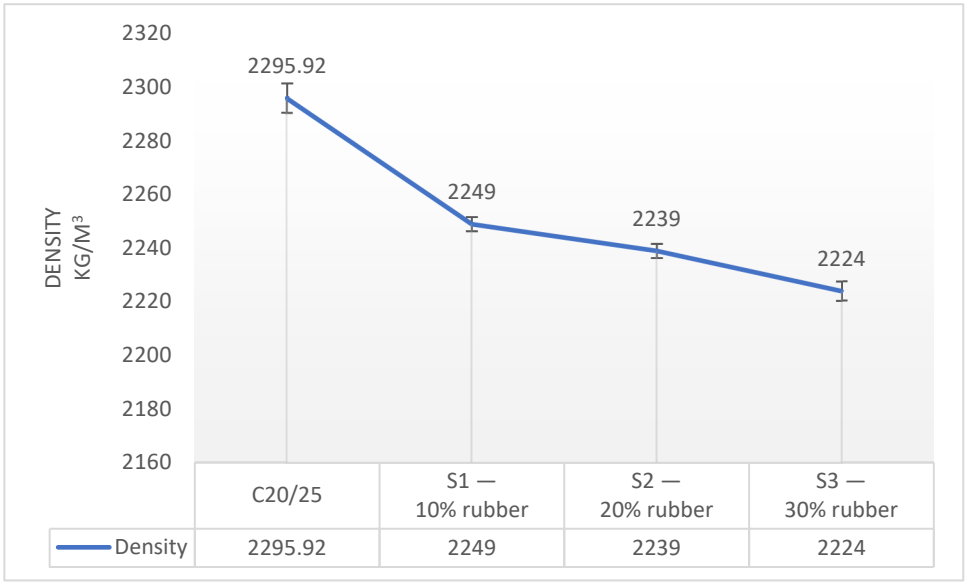


Figure 5. The average density of the proposed mixtures.

Table 2. The density of the proposed mixtures.

Case Studies	Density (kg/m^3)	Decreasing (%)
C 20/25	2296.92 2290.04 2300.80	
average	**2295.92**	
S1—10% rubber	2248.00 2247.00 2252.00	
average	**2249.00**	**2.04**
S2—20% rubber	2238.00 2237.00 2242.00	
average	**2239.00**	**2.47**
S3—30% rubber	2223.00 2221.00 2228.00	
average	**2224.00**	**3.13**

3.2. Thermal Conductivity

Regarding thermal insulation properties, the thermal conductivity of concrete mixed with crumb rubber is lower than that of plain concrete. Studies have reported that the thermal conductivity of concrete mixed with crumb rubber decreased significantly with an increasing amount of crumb rubber due to the low conductivity of rubber and air trapped in this mixture [35]. The low thermal conductivity values were attributed to the increase in the porosity of the concrete due to the incorporation of the crumb rubber. In addition to the thermal insulating property of rubber, the crumb rubber concrete has a large amount of air due to the air bubbles attached to the rubber particles [21].

However, decreases in the compressive strength of the crumb rubber concrete mixture have been reported [36]. To maintain the best possible compressive strength values, reduced percentages of aggregates were replaced with crumb rubber particles. In most studies, 10%, 20%, and 30% percentages were used [37] to obtain the best results in heat and resistance.

The four compositions were studied from the point of view of thermal conductivity. The compositions were poured into 15 × 15 × 15 cm cubic molds, stripped from hardening, and subjected to measurements after 28 days using ISOMET 2114. Complete characteristic thermomechanical measurement reports were provided, which include the results of the thermal conductivity coefficient. For each sample, the thermal conductivity was measured on each side of the cube for further verification and mediation of the results obtained (Figure 6).



Figure 6. Measurement of thermal conductivity on each side of the cubes.

The thermal conductivity values for the control samples ranged from 2.05 W/mK to 2.26 W/mK for the surfaces perpendicular to casting and from 2.48 W/mK to 2.58 W/mK for the casting surfaces. It was observed that the thermal conductivity on the casting surfaces was 13–20% higher than the average of the thermal conductivity values measured perpendicular to casting (Table 3). These values may lead to a further study of thermal bridges with different values for the ground floor slab, whose thermal conductivity is the value of the casting surface, and the concrete base, whose thermal conductivity is the value perpendicular to casting.

Table 3. Thermal conductivity of the control mixture composition.

Measuring Point	On the Casting Surface (W/mK)	Perpendicular to the Casting Surface (W/mK)			
C 20/25—sample 1	2.58	2.14	2.07	2.11	2.18
C 20/25—sample 2	2.61	2.26	2.16	2.05	2.20
C 20/25—sample 3	2.48	2.21	2.25	2.13	2.17
average	**2.55**	**2.16**			

The tests were also performed for the concrete mixture with a replacement of 10% of the aggregates with crumb rubber (Table 4). The thermal conductivity values ranged from 1.73 W/mK to 2.34 W/mK for surfaces perpendicular to casting and values of 2.59 W/mK for the casting surface. It was observed that the thermal conductivity on the casting surface was 20% higher than the average of the thermal conductivity values perpendicular to casting. A minor improvement was observed compared to the control samples of less than 1% (from 2.16 W/mK to 2.14 W/mK) (Figure 7).

Table 4. Thermal conductivity of crumb rubber concrete mixtures.

Measuring Point	On the Casting Surface (W/mK)	Perpendicular to the Casting Surface (W/mK)			
S1—10% rubber	2.59	2.26	1.73	2.24	2.34
S2—20% rubber	2.24	2.17	1.95	2.14	1.93
S3—30% rubber	2.22	2.06	1.97	1.96	1.85

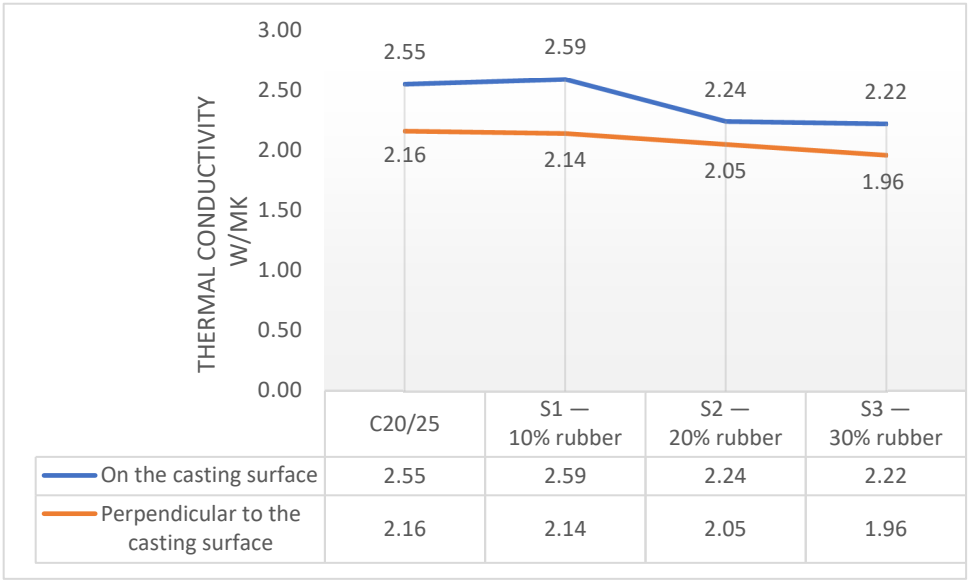


Figure 7. Variation in the thermal conductivity of crumb rubber concrete compared to C20/25.

Measurements for the concrete mixture with the replacement of 20% of the aggregates with crumb rubber were performed (Table 4). The values of the thermal conductivity ranged from 1.93 W/mK to 2.17 W/mK for surfaces perpendicular to casting and a value of 2.24 W/mK for the casting surface. It was observed that the thermal conductivity on the casting surface was 9% higher than the average of the thermal conductivity values perpendicular to casting. Compared to the control samples, there was an improvement of 12% in the thermal conductivity on the casting surface (from 2.55 W/mK to 2.24 W/mK) and 5% perpendicular to casting (from 2.16 W/mK to 2.04 W/mK) (Figure 7).

Tests were also carried out for the third set of samples, replacing 30% of the aggregates with crumb rubber. The thermal conductivity values ranged from 1.85 W/mK to 2.06 W/mK for surfaces perpendicular to casting and 2.22 W/mK for the casting surface (Table 4). The thermal conductivity on the casting surface was 13% higher than the average thermal conductivity values perpendicular to casting. The 30% crumb rubber samples showed an improvement of 13% in the thermal conductivity on the casting surface (from 2.55 W/mK to 2.22 W/mK) and 9% perpendicular to the casting direction (from 2.16 W/mK to 1.96 W/mK) compared to the control samples (Figure 7).

The measurement methodology highlighted the effect of the casting procedure on the thermal conductivity because it was observed that the application of compaction produces a preferential orientation of the particles in the planes perpendicular to the compaction force [38], and this orientation determines an orthotropic behavior of the samples, even with an anisotropic one in general.

There was a median decrease of 4% in the thermal conductivity with an increase in the percentage of crumb rubber (10%, 20%, and 30%).

3.3. Compressive Strength

Compressive strength is the main mechanical characteristic of concrete, an essential value for classifying concrete into strength classes. Under these conditions, determining the resistance to uniaxial compression is an essential element of the experimental program.

In order to determine the compressive strength of the four compositions (Figure 8), the previously made compositions were subjected to compression using ZwickRoell SP1000 hydraulic equipment.

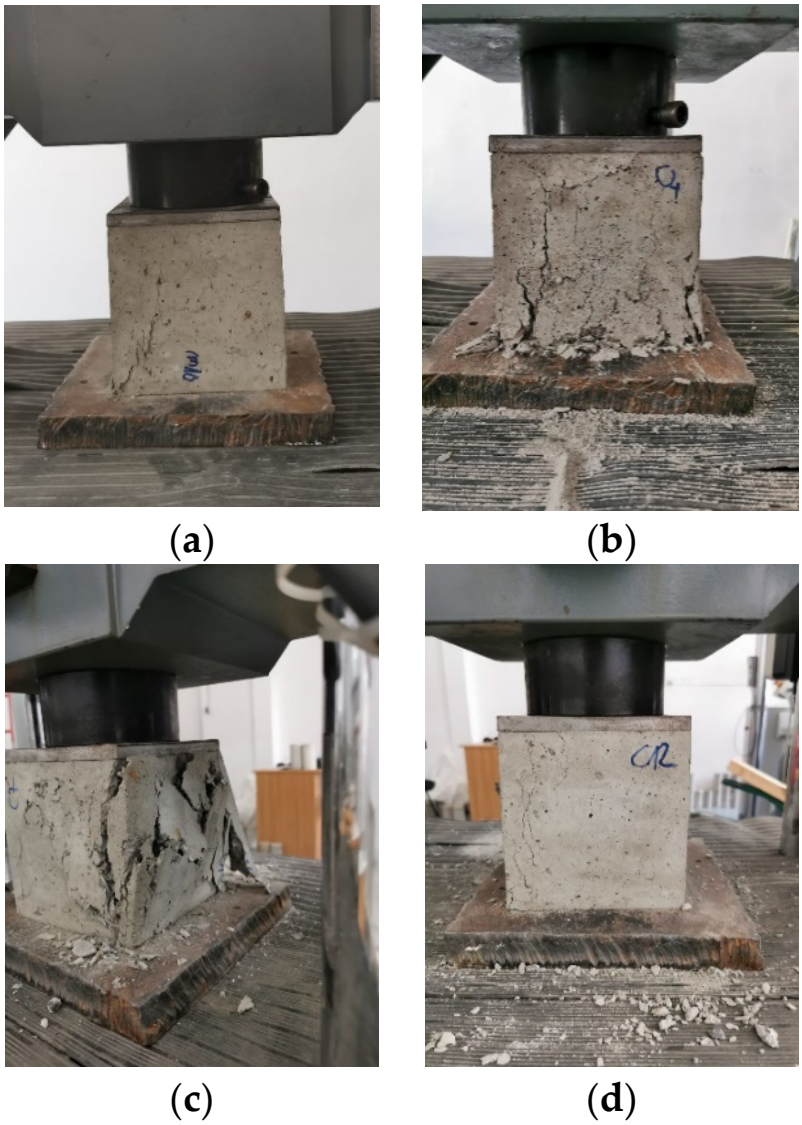


Figure 8. Determination of compressive strength: (**a**) C20/25, (**b**) S1—10% rubber, (**c**) S2—20% rubber, and (**d**) S3—30% rubber.

The average compressive strength value of the control concrete was around 25.98 MPa, and the values of the concrete mixed with crumb rubber were 24.29 MPa (10%), 20.35 MPa (20%), and 18.60 MPa (30%) (Table 5). The reduction in the compressive strength was not substantial enough for the 10% replacement, being 6.5%. With the increase in the percentage of crumb rubber, there was a more pronounced decrease: 20.35% for the 20% replacement and 28.41% for the 30% replacement.

Table 5. Compression strength of crumb rubber concrete compared to C20/25.

Case Studies	Compression Strength (MPa)	Decreasing in Percentage (%)
C 20/25	25.98	0
S1—10% rubber	24.29	6.5
S2—20% rubber	20.35	21.70
S3—30% rubber	18.60	28.41

The results were similar to those in the specialized literature [19,39,40]. The variation in the compressive strength depending on the percentage of rubber used is shown in

Figure 9. This conclusion was expected, given that all previous studies indicated a decrease in compressive strength [41]. The results of one study [39] show that this substitution leads to a decrease in the physical–mechanical properties of the resulting concrete, including a lower density (10.5%), a higher porosity (18%), and increased water absorption (2–4%) compared to reference concretes. It was determined that the reuse of tire rubber without any pretreatment does not significantly affect the physical–mechanical properties of the resulting concrete.

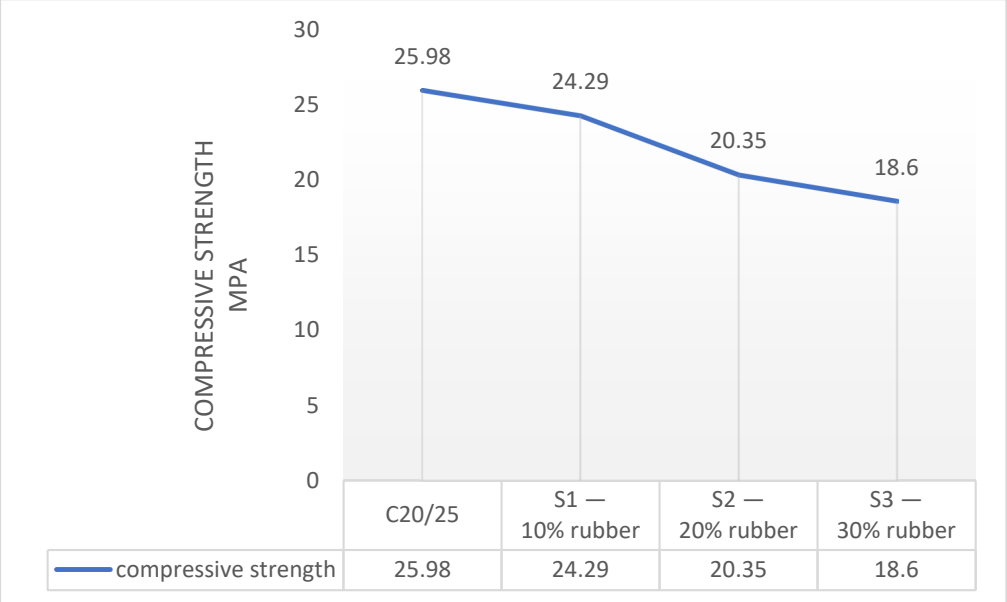


Figure 9. Variation in the compressive strength of crumb rubber concrete compared to the C20/25.

Incorporating crushed rubber into concrete can significantly contribute to environmental protection by solving used tires' storage, transport, and disposal problems. Incorporating a limited amount of crushed rubber into the concrete improves thermal–mechanical properties but decreases compressive strength. The decrease in the mechanical properties of the concrete mixtures with crushed rubber is due to the low density of the material, the trapped air, and the low adhesion of the rubber to the other elements in the concrete composition.

3.4. The Adhesion of Rubber in the Concrete Composition

Due to the careful distribution of the crumb rubber, while mixing the concrete in the concrete mixer, the crumb rubber particles were mostly uniform in the cubic samples. During the tests to determine the compressive strength, cracks were observed in the joint areas between the rubber particles and the concrete mixture. In order to study the adhesion of the crumb rubber to the other elements in the concrete composition, a set of analyses using a microscope LFD (large-field detector in low-vacuum working mode) for 1 cm pieces of each of the four compositions (control sample, S1—10% rubber, S2—20% rubber, and S3—rubber 30%) were conducted. Figure 10 shows the adhesion between the areas with crumb rubber particles with the rest of the aggregates. Compared to conventional concrete, where a uniform adhesion is observed, the samples with crumb rubber show a lower adhesion to the conventional aggregates due to the smoother surface of the recycled rubber.

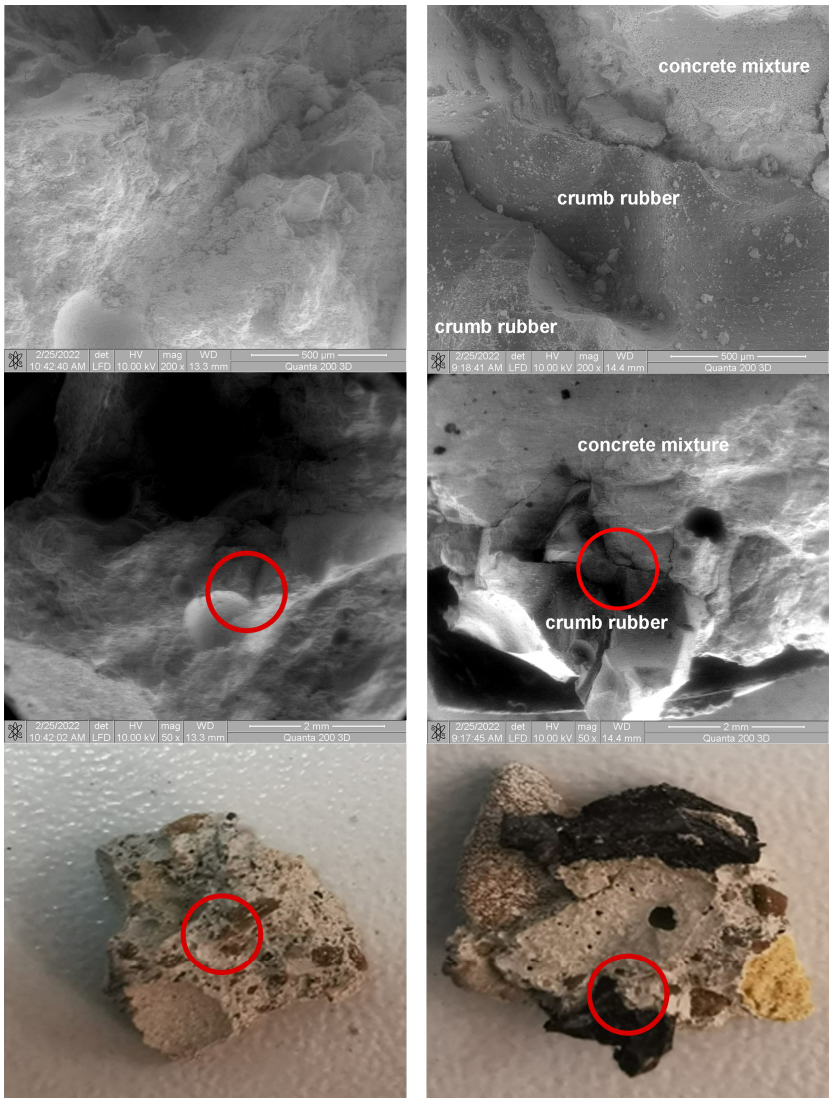


Figure 10. Pictures from the microscope analysis of: (**a**) C20/25 and (**b**) crumb rubber concrete.

4. Discussion

The measurements showed a decrease in density by a maximum of 3.13% when 30% of the 4–8 mm aggregate was replaced by crumb rubber. This decrease can be attributed to the low density of crumb rubber compared to the density of the aggregates and the presence of air trapped within the mixture compositions [21,40]. This reduction in density has significant consequences for the strength and overall performance of the concrete.

From the thermal performance perspective, there was a minimal improvement in the concrete when 10% of the aggregate was replaced with crumb rubber. The effects of crumb rubber on the thermal conductivity of the concrete were more apparent when the proportion of this replacement component was increased by 20% or higher. The third set of samples, which contained 30% crumb rubber, demonstrated approximately a 13% improvement in thermal conductivity when measured on the casting surface and a 9% improvement when measured perpendicular to casting. These findings suggest that the incorporation of crumb rubber in the concrete mixture increases the thermal conductivity, influencing the overall performance of the concrete as a thermal envelope component.

In order to select an appropriate mix that offers improved thermal resistance while maintaining the structural role of concrete in the building envelope, it is necessary to consider also the compressive strength.

The results of the concrete mixture composition measurements indicate the inclusion of the control samples in the C20/25 strength class, as defined by the minimum characteristic compressive resistance of the control samples. In the analysis of the compressive strength, replacing rubber by up to 20% changed the class of the compressive strength to C16/C20 (with compressive strengths of 24.29 MPa and 20.35 MPa, for 10% and 20%, respectively), but replacing it with 30%, changed the class of the compressive strength to C12/15 (with a compressive strength of 18.60 MPa).

C20/C25 concrete is suitable for high-loaded vertical elements (such as pillars), beams with high transversal loads and large spans, and complex foundations. C16/20 class concrete is commonly used for casting foundation blocks, floors, low-loaded structural columns, or resistance wall beams. In contrast, C12/15 class concrete is often used to construct foundations of small buildings with low structural loads, such as houses with timber frame-strength structures. As can be observed, even if there is a depreciation in the resistance class of the concrete by adding rubber, the obtained crumb rubber concrete can be used in the construction of buildings. However, these laboratory research results suggest that the proportion of rubber in the concrete mixture can significantly impact the compressive strength of the resulting material and should be carefully considered when selecting the appropriate mix for a specific application.

Microscopic analysis indicates that utilizing smaller rubber particles may help to mitigate the negative effects of reduced adhesion between the component elements of the mixture. This finding suggests that the size of the rubber particles may play a role in the overall performance of the concrete mixture and may be an essential consideration when selecting the appropriate mix for a specific application.

5. Conclusions

To summarize, the results indicate that by adding rubber, the thermal performance of the concrete is enhanced, while its compressive strength is reduced. These findings suggest that crumb rubber mixtures may be suitable for structural elements requiring an improved thermal performance but with a lower compressive strength class. It is essential to undertake further research to gain a more thorough understanding of the impact of crumb rubber on the properties of concrete and to determine whether the effects are linearly proportional to the amount of crumb rubber used. By conducting additional studies using a diversity of proportions of crumb rubber, a more comprehensive understanding of the impact of these materials on the density, strength, and overall performance of the concrete can be attained. In addition, investigating the influence of other variables, such as the type and size of the aggregates used, the mix design, and the pouring conditions, can provide insight into the mechanisms behind these effects and the conditions under which they occur.

The practical implementation of the developed and tested samples can contribute to creating effective and sustainable stratifications of thermal envelope elements that meet the requirements of an energy-efficient building. This could be achieved by considering the findings of this experimental research and using them for further studies. Furthermore, more measurements will calibrate the percentage of compositions for crumb rubber concrete as an energy-efficient cement-based material.

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