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On the Need for a Paradigm Change in the Valuation of Concrete with Waste Materials Based on the Example of Concrete with Crumb Rubber

Julia Nowak [1], Roman Jaskulski [2,*], Wojciech Kubissa [2], Bartłomiej Matusiak [2] and Maciej Banach [2]

[1] Mesilo Engineering sp. z o.o. sp.k., 50-012 Wrocław, Poland
[2] Faculty of Civil Engineering Mechanics and Petrochemistry, Warsaw University of Technology, 09-400 Płock, Poland
[*] Correspondence: roman.jaskulski@pw.edu.pl

Abstract: This paper presents the results of a study of the strength and thermal properties of concrete in which part of the fine and coarse aggregate was replaced with crumb rubber from used tyres up to 2.4% the weight of the concrete. Twelve series of concrete with w/c = 0.45 and w/c = 0.55 were tested. A decrease in compressive strength and a linear dependence of strength in relation to the amount of rubber in the concrete were observed. At the same time, the insulating properties of the material improved, which also depended linearly on the amount of rubber used in the dosage range applied. A thermomechanical index was introduced to evaluate the functionality of the concrete simultaneously on the basis of the two properties mentioned. It was assumed that a decrease in its value of no more than 15% compared to the maximum value obtained allows the concrete to be regarded as meeting the performance requirements. Out of the twelve series tested, including ten with crumb rubber, only three series failed to meet this condition.

Keywords: waste; crumb rubber; concrete; thermal properties; compressive strength

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1. Introduction

Waste car tyres are a troublesome waste, as evidenced, among other things, by the numerous landfills where this waste is dumped, despite the many opportunities for reuse. Among other things, they are used as a highly calorific alternative fuel in cement plants [1–4] and, after shredding, also for other uses.

In order to recycle waste rubber tyres, they are usually subjected to various types of treatment. Most commonly, they are shredded by grinding. Various techniques are used for this, including wet milling and cryogenic grinding. The resulting material, ground tire rubber (GTR), is used, among other things, as a substitute for some of the raw materials used in rubber production [5,6]. The ground rubber can additionally be devulcanized. Microparticles of devulcanized rubber, but also rubber not subjected to such treatment, are used in the production of acrylonitrile butadiene styrene copolymer (ABS) and thermoplastic polyolefins (TPO), which in turn are the basis for the production of materials used in 3D printing [7].

Another way of processing waste tyres is pyrolysis, which offers numerous possibilities for processing tyres and subsequently using the resulting products in various ways. In pyrolysis, the material is subjected to temperatures in the range of 300–900 °C without oxygen. The result is char, liquid hydrocarbon fractions and gases, which can then be combusted for energy [1,5,8].

One of the most common uses of recycled tyre rubber in the construction industry is in the building of asphalt pavements. Such an additive to asphalt concrete improves the performance of the pavement, as well as reduces its cost. Improved performance means, among other things, reduced permanent deformation of flexible pavements and increased resistance to rutting and fatigue damage. On the other hand, cost reduction includes not only pavement construction, but also the subsequent cost of maintenance [9,10].

A different application option being explored for tyre rubber waste is its use in concrete production. This use of such waste is part of a wider trend of using waste materials in concrete technology. The primary motivation for most concrete studies that use waste materials is to reduce the consumption of natural raw materials by partially or completely replacing them with waste materials. This most often applies to aggregates. A parallel or alternative motivation is the need to reduce pressure on the environment by reducing landfill through waste reuse. The situation is no different in the case of waste tyres. In addition, the use of waste crumb rubber in concrete technology produces a material with more favourable thermal properties, which can contribute to lower energy consumption. These three reasons for undertaking research on concrete containing waste crumb rubber are directly in line with the idea of sustainability and sustainable construction.

Concrete with rubber waste has been studied for about 30 years [11,12]. Studies include both the properties of the fresh concrete mixture: flowability, viscosity, passing ability and segregation resistance in the case of SCC [13], workability [14,15], as well as various properties of the hardened concrete. The latter include strength characteristics: compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, ultrasonic pulse velocity [13,14,16,17], dynamic flexural moduli [16], and durability characteristics: water absorption, water sorptivity, fatigue behaviour [13], chloride ions penetration resistance based on electrical resistivity (AASHTO TP 95) and charge passed (ASTM C1202) [14], porosity, wettability—water contact angles (WCAs) test—sorptivity [18], freezing–thawing resistance, and sulphate corrosion resistance [17], as well as other, less frequently studied characteristics, such as electrical resistivity, vibration damping [16], impact resistance, shrinkage, fracture energy [13] or printability test [18].

Rubber waste in concrete is usually used as a replacement for part of the fine or coarse aggregate or both aggregate fractions at the same time. In the case of the former, the replacement may involve up to 100% of the aggregate used. Since aggregate makes up most of the volume in concrete, even its partial replacement with rubber waste significantly affects the properties of the material. Above all, it lowers its compressive and tensile strength [19], which is due, among other things, to the large difference in the elastic modulus of the rubber in relation to the remaining aggregate and the concrete matrix. A rubber particle due to its much higher elasticity behaves to some extent like a void in relation to the much stiffer concrete matrix, leading to local stress concentrations. Another reason pointed out by researchers is the deterioration of the interfacial transition zone (ITZ) situated between the aggregate and the concrete matrix by increasing its porosity [20]. This is a direct result of the hydrophobic properties of the rubber. This decrease in strength can be partly prevented by the use of dispersed reinforcement [19].

As a result of replacing the natural aggregate with crumb rubber waste, the density of the concrete is also reduced due to the low specific density of the rubber being around 0.9 kg/dm^3 with the density of the natural aggregate being usually in the range of 2.5–2.7 kg/dm^3. The reduction in density is also to a small extent the result of an increase in the porosity of the material, which in turn is mainly due to a deterioration in the workability of the concrete mix. A decrease in the density of concrete does not necessarily imply a reduction in the usefulness of the concrete, as long as its strength remains at the level required for specific applications.

Lower density usually goes hand in hand with lower thermal conductivity, and this effect is enhanced when using waste materials with a higher thermal resistance than natural aggregate. The higher thermal resistance is usually due to the amorphous nature of these materials. This applies to crumb rubber, as well as some mineral wastes such as copper slag waste [21].

The lower thermal conductivity of concrete with waste rubber is quite well documented in the literature [20,22,23], but areas of application are still being sought where the use of concrete with part of the aggregate replaced by waste rubber is advantageous due to its better properties. Among other things, rubber has a high vibration damping capacity, hence it is widely used for this purpose. Additionally, concrete made from waste crumb rubber has, in other words, a higher damping coefficient [19,24]. This indicates that elements made from such concrete can be used for building partitions with improved sound insulation.

The compressive strength of concrete made using various waste materials in most cases decreases. This decrease can sometimes be as much as 50% in relation to reference concrete without the waste material [25]. Concrete with crumb rubber is one example. At the same time, the preservation of concrete strength or even an increase in it is a condition for considering a given concrete modification as acceptable or even worthy of study (without the prospect of its application, but in order to increase knowledge), irrespective of its potential possible uses other than as a material for heavily loaded structures. For this reason, along with the use of waste materials that reduce the strength of concrete, solutions are sought to limit this loss of strength. For example, additional dispersed reinforcement is used for this purpose. Alternatively, the amount of waste material is limited to such quantities that the strength loss of the concrete is slight. This sometimes has the consequence that the proportion of waste material used becomes so small that the benefits of a natural resource saving, or waste management become questionable. Thus, the peculiar reluctance to "spoil" concrete resulting from the excessive weight given to the preservation of one of its parameters severely limits the creative modification of this material with a view to improving its other properties (thermal, acoustic, etc.).

However, despite the sometimes significant reduction in concrete strength, it is still sufficient for many applications, including structural engineering. Therefore, when analysing the properties of concrete in which waste materials have been used, resulting in a reduction in the strength of the material, it is necessary to assess the concrete holistically, considering the potential applications of the material thus obtained. Yes, the strength characteristics are sufficiently important that they should not be overlooked in the assessment, but they should also not be given undue weight.

For many decades, the strength characteristics of concrete were almost the only ones subject to standardisation and specific requirements, and in addition to these, in specific situations, certain durability characteristics were added, but these were usually treated as secondary. It took several decades for the durability characteristics of concrete to take on equal importance with the strength characteristics, and this process is still ongoing. Meanwhile, it is the durability properties of concrete that determine how long a structure will retain the required load-bearing capacity. Another change in the analysis and evaluation of concrete characteristics should be the emancipation of those parameters that determine its environmental friendliness. Here, thermal parameters, among others, come to the fore. Thus, the aforementioned holistic evaluation of concrete using waste materials should be based on answering the questions: for which applications do the strength characteristics of the concrete predestine it? Do the durability parameters ensure that the former are maintained at a satisfactory level during the life of the structure? Does concrete made using certain waste materials show characteristics that allow it to be considered a more environmentally friendly material?

The approach postulated above for the investigation of concrete with waste materials has been largely followed in this work. Only the study of durability characteristics has been omitted, but not because it was considered irrelevant, but because it was the authors' intention to present the effect of the addition of rubber waste on the thermal properties of concrete and the extent to which they change as a function of the mass proportion of waste material used and the degree of fineness. Changes in strength properties were also analysed using concrete with different w/c ratios as an example.

In order to study the influence of the amount of crumb rubber in the concrete and the effect of the fraction size of the waste material used, a total of twelve series of concrete were made. Two values of the w/c ratio were adopted in the concrete mix formulations. Four fractions of crumb rubber were used, divided into two groups conventionally referred to as "fine" and "coarse" crumb rubber. Compressive strength and thermal property tests were carried out on each series of concrete. The hot plate method was used to measure the thermal conductivity and volumetric heat capacity of the resulting material when fully saturated with water. Once the density of the concrete was determined, its specific heat was also calculated. In contrast to most studies on concrete with crumb rubber, the amount of waste material used was expressed as a percentage of the weight of the concrete mixture, rather than as a percentage of the weight of the cement or aggregates replaced. The content of fine and coarse fractions of waste crumb rubber was also differentiated to a small extent, so that in cases where the particle size has a negligible effect on the relations obtained, it could be presented in a clearer way.

2. Materials and Methods

2.1. Materials

Portland cement CEM I 42.5 R complying with the requirements of EN 197-1:2011 [26] was used to prepare the concrete. River sand of fraction 0–2 mm was used as fine aggregate, and crushed granite in two fractions as coarse aggregate: 2–8 mm and 8–16 mm. Commercially available crumb rubber of four different fractions was used to prepare the mixes: 0–0.6 mm, 0.6–2 mm, 2–4 mm, and 4–20 mm. Tap water was used as the mixing water. Additionally, a superplasticiser based on modified phosphonates was applied. The composition of the prepared mixes is shown in Table 1.

Table 1. The composition of the tested concrete series (in kg/m^3).

Component/ Parameter	4R	4F1	4F2	4FC	4C1	4C2	5R	5F1	5F2	5FC	5C1	5C2
Cement CEM I 42,5R	325	322	319	329	332	339	325	322	319	329	332	339
River sand 0–2 mm	693	618	544	632	707	721	663	591	520	602	675	688
Crushed granite 2–8 mm	515	510	505	468	473	430	492	487	482	446	451	410
Crushed granite 8–16 mm	772	765	758	702	709	646	738	731	724	670	677	616
Crumb rubber 0–0.6 mm	—	12	24	12	—	—	—	12	24	12	—	—
Crumb rubber 0.6–2 mm	—	17	34	17	—	—	—	17	34	17	—	—
Crumb rubber 2–4 mm	—	—	—	5	5	10	—	—	—	5	5	10
Crumb rubber 4–20 mm	—	—	—	19	19	38	—	—	—	19	19	38
Water	146	145	144	148	149	152	179	177	175	182	186	180
Superplasticiser	0.8	4.0	4.8	4.9	4.2	4.2	—	0.8	1.6	—	1.7	1.6
Total crumb rubber content (as % of concrete mass)	0	1.2	2.4	2.2	1.0	2.0	0	1.2	2.4	2.2	1.0	2.0
w/c ratio			0.45						0.55			

The symbols in the top row of the table are designations for individual concrete series. The first number indicates the value of the w/c ratio ("4" stands for w/c = 0.45 and "5" for w/c = 0.55). The letter F indicates that the fine aggregate has been partially replaced by fine fractions of crumb rubber, and the letter C refers to the coarse aggregate and coarse fractions of crumb rubber. The numbers at the end of the symbol indicate the level of reduction in the natural aggregate: "1"—10% and "2"—20%.

A total of twelve series of mixes were prepared with two w/c ratios of 0.45 and 0.55 (six series each). In addition to the two reference mixes, crumb rubber was used in each of the other series. Four series used only the two finer fractions (0–0.6 mm and 0.6–2 mm), four more series used only the two coarser fractions (2–4 mm and 4–20 mm), and two series used all four fractions. It was assumed that the mass proportion of crumb rubber in the mixes with the finer fraction would be 1.2 and 2.4% (in relation to the mass of all components), and in the mixes with the coarser fraction 1.0 and 2.0%. Mixtures using all four crumb rubber fractions contained 1.0 and 1.2% of the finer and coarser fractions, respectively.

In order to obtain similar amounts of a cement paste in each series, the dosage of crumb rubber was combined with a reduction in the amount of aggregate compared to the reference series. The starting point in designing the composition of the series with crumb rubber was the reference series, i.e., containing only natural aggregate. In the composition of these series, the amount of natural fine or coarse aggregate was first reduced by 10% (if the proportion of rubber was to be 1.0 or 1.2%) or by 20% (for a rubber proportion of 2.0 or 2.4%), respectively. The relevant fractions of crumb rubber were then added in sufficient quantity to achieve the target weight share. In the series in which both coarse and fine fractions of crumb rubber were used, both fine and coarse aggregates were reduced by 10%. Due to the reduction or increase in volume for the series containing the crumb rubber, their compositions were then recalculated so that the total volume of all components amounted to one cubic metre.

For the research reported in this paper, six cubes of 100 mm edge and two cylinders of 150 mm diameter and 300 mm height were used from each series.

2.2. Test Methods

The compressive strength test was conducted on six 100 mm cube specimens on the 28th day of hardening. The specimens were stored in water at ambient temperature until the day of the test. The test was carried out in accordance with EN 12390-3:2019 [27] and performed by using a ToniTechnik instrument having a 3000 kN compression force capacity. The rate of loading was maintained at 0.5 MPa/s as the standard [27] requires for the compressive strength test. The resulting compressive strength was calculated as an average of the six measurements. The standard deviations were also calculated using the six results.

The measurement of thermal properties was carried out using the ISOMET 2114 device used to measure the thermal properties of materials using the non-stationary method. The surface probe IPS 1105 was used with three measurement ranges, giving a total ability to determine the thermal conductivity coefficient in the range of 0.04–6.0 W/m·K, and the volumetric heat capacity in the range 0.04–3.0 MJ/m^3·K. The measurement accuracy declared by the manufacturer is 10% for thermal conductivity coefficient and 15% + 1 kJ/m^3·K for volumetric heat capacity.

Determining the thermal properties with the use of the ISOMET device is based on the "hot plate" method, and involves an analysis of the changes of the surface temperature of the tested specimen in two stages. First when it is heated with a constant power, and then during its cooling. Based on the solution of the inverse problem of non-stationary heat flow, two parameters are determined: the thermal conductivity of the tested material λ and its volumetric heat capacity $C\rho$. If the material density is known, its specific heat Cp can be calculated using Formula (1).

$$C_p = C_\rho / \rho \tag{1}$$

For each of the concrete series, 4 specimens were prepared and tested. They were circular slices 65 mm high with 150 mm diameter cut from cylinder specimens of the same diameter and 300 mm high. The prepared specimens were stored in water before testing. In order to determine the specific density of the material, another 5 circular specimens of 50 mm thickness were weighted. Normal and hydrostatic weighting was performed, and based on the results, the density of each specimen was calculated. The results were then averaged for each series and the average density values were used to calculate the specific heat of the concrete.

The measurements of the thermal properties were carried out on specimens fully saturated with water. In order to prevent the specimens from drying out during the measurements, after being removed from the water for the time of testing, they were covered with foil as tightly as possible. On both sides of the specimen, six subsequent measurements resulting in 48 measurement for each series were performed. The results presented in the paper are medians calculated for each series separately and instead of the standard deviation the median absolute deviation (MAD) was calculated. These two estimators were chosen because of their robustness and significant variation in results because of the heterogeneity of the material.

3. Results

3.1. Compressive Strength

The results of the compressive strength test are shown in Figure 1. In this figure, as in the following figures, the first number, which indicated the value of the w/c ratio, was omitted from the symbols assigned to the individual series. This information was included in a different way in the figures.

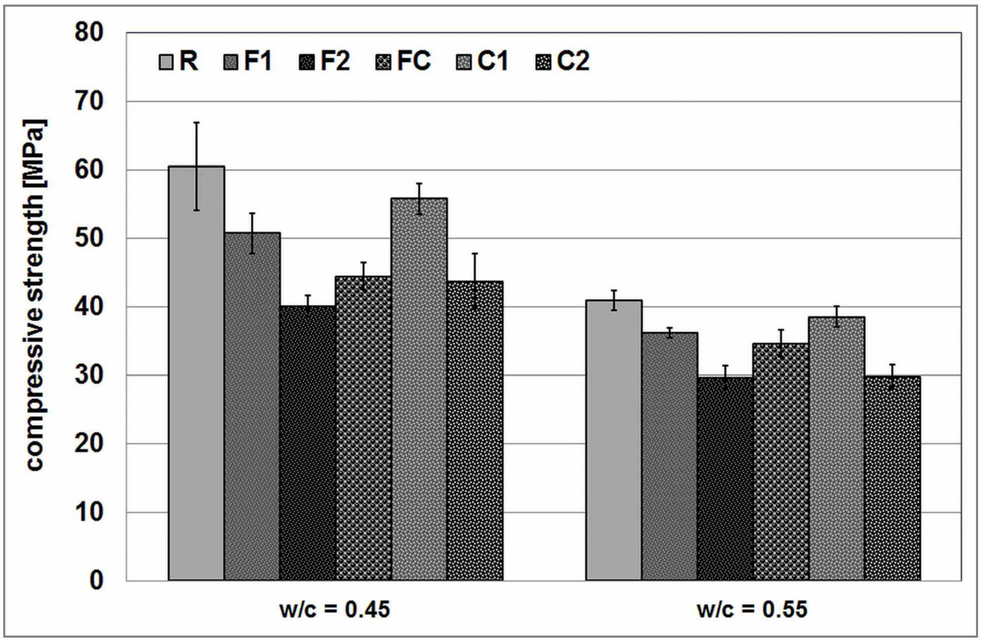

Figure 1. The results of the compressive strength test.

The obtained results of the compressive strength test form three clear trends, according to which this parameter changes depending on: the amount of waste crumb rubber, the fractions of waste crumb rubber used, and the w/c ratio. With regard to the first factor indicated, the strength of the concrete decreases as the mass fraction of crumb rubber in the concrete increases. A slight exception to this rule is the FC series, in which the content of waste rubber is higher than in the C2 series, but the compressive strength of the specimens of these concrete series is higher. This may be due to the beneficial effect of using all fractions of crumb rubber.

With regard to the influence of the particle size of crumb rubber, this is clearly visible in the case of concrete series with w/c = 0.45. Concrete of the C1 and C2 series, where coarse crumb rubber was used, has a higher strength than concrete of the F1 and F2 series with fine crumb rubber, respectively. This relationship also exists for the concrete series with w/c = 0.55, but is far less pronounced. The effect of the w/c value on the compressive strength of the concrete is by far the most pronounced, and it is no surprise that a higher value of w/c results in a decrease in strength. At the same time, a higher w/c value seems to reduce the effects of adding waste crumb rubber to the concrete, at least if the absolute value of the strength difference between the series is taken into account.

3.2. Thermal Properties

The results of the thermal properties test are shown in Figures 2 and 3. Figure 2 shows the results of the thermal conductivity test, and Figure 3 shows the results of the volumetric heat capacity test. Both parameters were measured simultaneously on the same specimens.

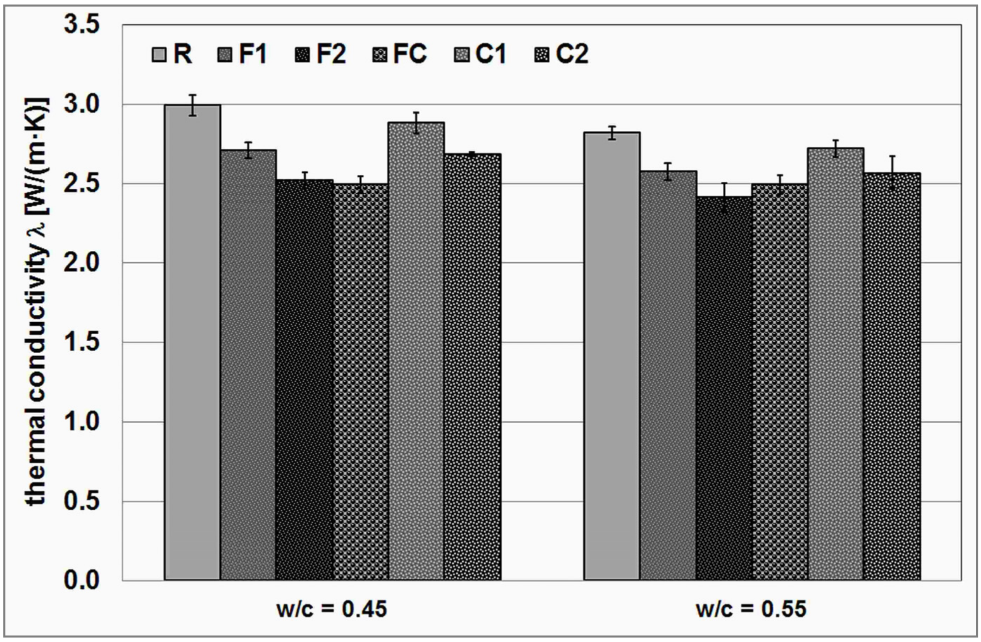

Figure 2. The results of the thermal conductivity measurements.

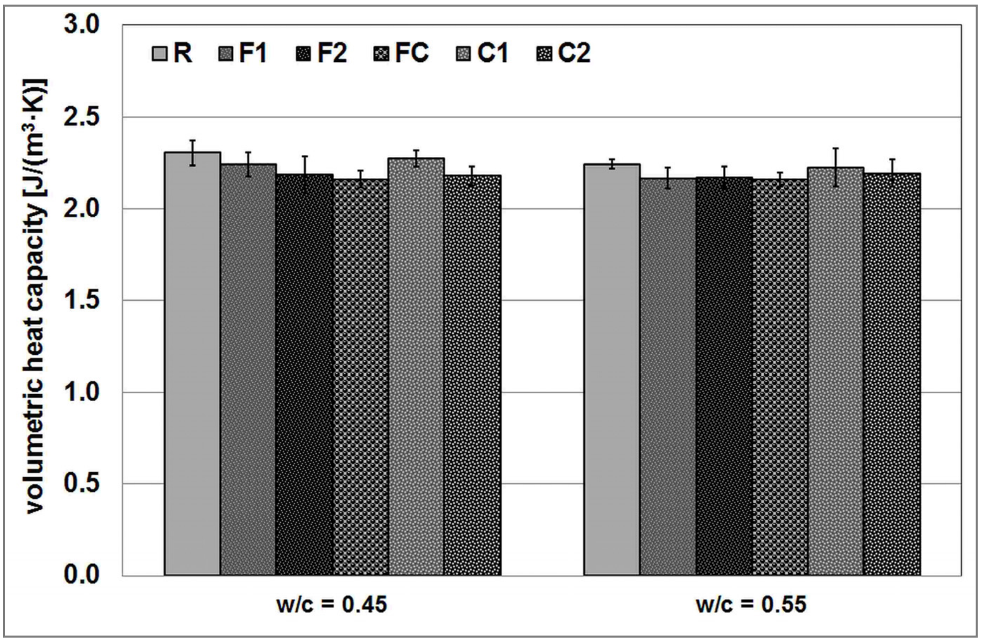

Figure 3. The results of the volumetric heat capacity measurements.

The thermal conductivity of the tested concrete shows a clear diversity of values between the series. A correlation can be seen between the crumb rubber content and the value of this parameter, and it is a negative correlation. An increase in the crumb rubber content corresponds to a decrease in the value of the thermal conductivity coefficient. This effect is pronounced for both concrete series with w/c = 0.45 and w/c = 0.55. At the same time, the concrete series with the higher w/c value have a lower thermal conductivity if we compare materials with the same crumb rubber content of the same fraction group. The effect of crumb rubber content on the development of the thermal conductivity coefficient can be explained by the difference in the value of thermal resistance. The thermal conductivity coefficient of crumb rubber ranges between 0.16 and 0.21 W/m·K [28,29], while for granite it ranges from 2.87 to 3.75 W/m·K [30,31]. On the other hand, concrete with a higher w/c ratio has a higher porosity, which directly translates into the reduction in thermal conductivity. The results obtained clearly indicate that, of the two factors mentioned, the amount of crumb rubber is by far more important.

The negligible influence of the w/c ratio on the thermal conductivity value of the FC series is somewhat surprising. Such a large difference in the w/c ratio usually translates into a difference in the porosity of the concrete, and thus, its thermal conductivity. Such a relationship is clearly visible in the other series. A glance at the density values of the individual concrete series in Table 2 shows that both FC series have very similar densities and the difference between them is significantly smaller than for the other pairs of series. This is probably the reason for the very similar values of the thermal conductivity coefficient obtained in the measurements.

Table 2. Mean values of density of concrete (with the values of its standard deviation).

Series	**Density [kg/cm^3]**
4R	2.43 ± 0.01
4F1	2.37 ± 0.01
4F2	2.32 ± 0.03
4FC	2.32 ± 0.04
4C1	2.39 ± 0.01
4C2	2.35 ± 0.01
5R	2.40 ± 0.02
5F1	2.33 ± 0.03
5F2	2.26 ± 0.03
5FC	2.31 ± 0.04
5C1	2.36 ± 0.02
5C2	2.31 ± 0.04

Since the density of the concrete has been mentioned as a factor influencing the thermal properties of the concrete, it is worth briefly discussing here the results of the investigation of this material characteristic. It was determined in order to calculate the value of the specific heat, as it is this quantity that is used in calculations relating to the thermal balance of buildings and is included in the standards (e.g., ISO 10456:2007 [32]).

The density of the concrete using crumb rubber is, as expected, lower than that of the corresponding reference series. With the exception of the FC series mentioned above, the reduction in material density is strongly correlated with the percentage of waste for series with the same w/c value. The concrete of the C1 and C2 series has a higher density than the concrete of the F1 and F2 series, respectively, which is the result of using different fractions of crumb rubber. This is indicated by the greater differences in density (0.8–1.9%) of the compared series than the differences in the weights of their components (0.2–0.4%).

The calculated values of the specific heat of concrete are presented in Table 3 as median values. This expected value estimator was chosen for its robustness to the presence of outliers. The analysis of the obtained thermal properties test results showed that outliers are quite frequent, and the procedures for sifting them out are labour-intensive and to some extent subjective.

Table 3. Median values of specific heat of concrete (with the values of the median absolute deviation.).

Series	Specific Heat [J/(kg·K)]
4R	949 ± 28
4F1	934 ± 27
4F2	943 ± 42
4FC	931 ± 19
4C1	950 ± 18
4C2	926 ± 22
5R	933 ± 10
5F1	930 ± 24
5F2	960 ± 26
5FC	931 ± 16
5C1	942 ± 44
5C2	952 ± 32

The proportion of crumb rubber in the concrete, on the other hand, correlates to a much lesser extent with the value of the volumetric heat capacity. In the case of the concrete series with w/c = 0.45, there is still some correlation between the two values, but given the magnitude of the variation in the measurement results, it should be concluded that the differences in volumetric heat capacity between the individual series are negligible. In the case of the concrete series with w/c = 0.55, the correlation between the proportion of waste rubber in the mass of the concrete and its volumetric heat capacity is practically non-existent, and the differences between the series are very small and statistically insignificant.

Calculated from the volumetric heat capacity and density of the concrete, the specific heat values are in no way correlated with the crumb rubber content of the material. The best evidence for this is that both the highest and lowest specific heat values characterise the concrete series with crumb rubber rather than the reference concrete and, in the case of the series with w/c = 0.45, the boundary values were obtained for the C1 and C2 series and for the series with w/c = 0.55 for the F1 and F2 series. It is therefore reasonable to conclude that the use of crumb rubber in an amount of up to 2.4% the weight of the concrete has no significant effect on the specific heat of the material thus obtained.

4. Discussion

The strength characteristics of concrete are influenced by numerous factors, ranging from the number and type of ingredients, their type, quality, and mutual proportions, to the method of mix preparation and compaction, to the curing conditions. For this reason, the discussion of the results obtained has been limited to a comparison of the series examined within the framework of the presented research, without comparing the strength values obtained with the results contained in numerous publications devoted to this feature of crumb rubber concrete. This is also a consequence of the paradigm adopted, in which the preservation of the compressive strength of concrete is not a key issue, but neither is the parameter, which is omitted from consideration. The condition to be fulfilled with regard to compressive strength is only that its value should be maintained at a level that allows the anticipated use of the material.

The strength of the reference concrete was 60.6 and 41.0 MPa for the 4R and 5R series, respectively. The concrete with crumb rubber achieved strengths in the range from 40.1 to 55.9 MPa for the series with w/c = 0.45. The strength of the concrete series with w/c = 0.55 was in the range 29.7–38.5 MPa. This means that the difference between the maximum strength and the minimum strength is equal to 15.8 MPa for the crumb rubber concrete with the lower w/c ratio and 8.8 MPa for the concrete with w/c = 0.55.

The highest strength in each group of series with different w/c values was achieved by the series of concrete with the addition of coarse crumb rubber at 1%, namely series 4C1 and 5C1. This was followed by the series with 1.2% fine crumb rubber—series 4F1 and 5F1.

The lowest strength values were recorded for the 4F2 and 5C2 series, while it should be added here that the 5F2 series had only 0.1 MPa higher strength than the 5C2 series, so it is reasonable to conclude that the strength was largely determined by the crumb rubber content. The correlation between the two parameters, divided into two groups of concrete series with identical w/c values, is presented in Figure 4. The reference concrete is also included there.

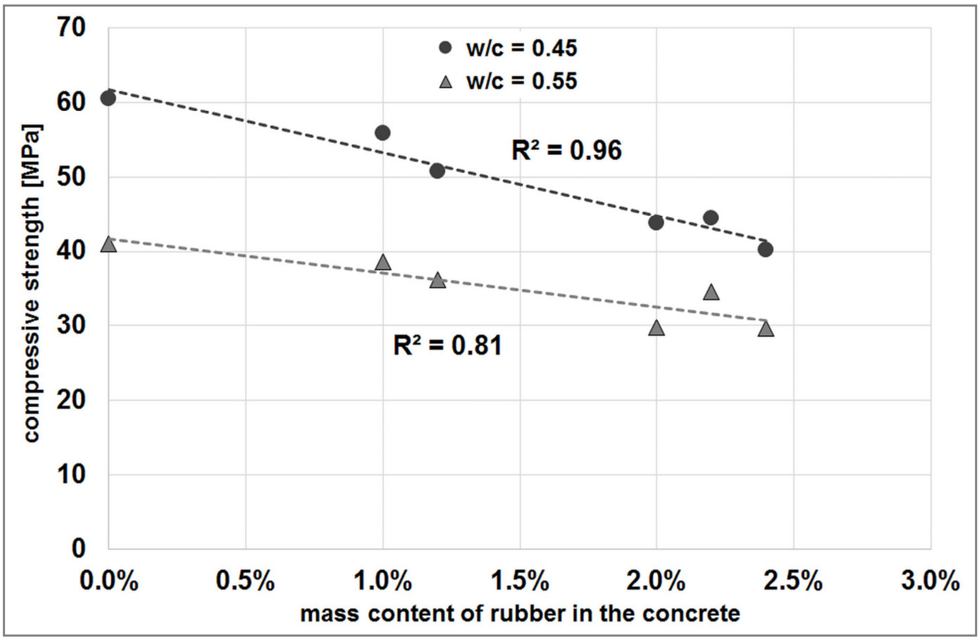

Figure 4. Correlation between the content of crumb rubber and the compressive strength of concrete.

Based on the trend line and the value of the coefficient of determination R^2, the Pearson correlation coefficients can be calculated as r = −0.98 (when w/c = 0.45) and r = −0.90 (when w/c = 0.55). This indicates a high negative correlation. A similarly high correlation exists between the density of the concrete and its compressive strength, as can be seen in Figure 5. In this case, the correlation is positive, and the correlation coefficient values are more closely aligned with r = 0.95 and r = 0.94 for concrete with w/c = 0.45 and w/c = 0.55, respectively.

The results of the concrete thermal conductivity test illustrated earlier in Figure 2 are juxtaposed with the mass proportion of crumb rubber in the concrete. As can be seen from the juxtaposition shown in Figure 6, there is a strong negative correlation between the two parameters at r = −0.94 and r = −0.95, and the relationship between the two parameters can be considered linear over the range tested.

The influence of the size of the crumb rubber particles on the thermal conductivity coefficient can also be assessed indirectly in this figure. The results obtained for the series containing coarse crumb rubber (i.e., those with a mass share of 1% and 2%) are clearly above the defined trend line, while the series using only fine crumb rubber (mass share of 1.2 and 2.4%) are characterised by values below or, in one case, on this line. It can be concluded from this that the thermal conductivity coefficient of concrete with coarse crumb rubber is at a higher level than that of concrete with fine crumb rubber at the same mass proportion.

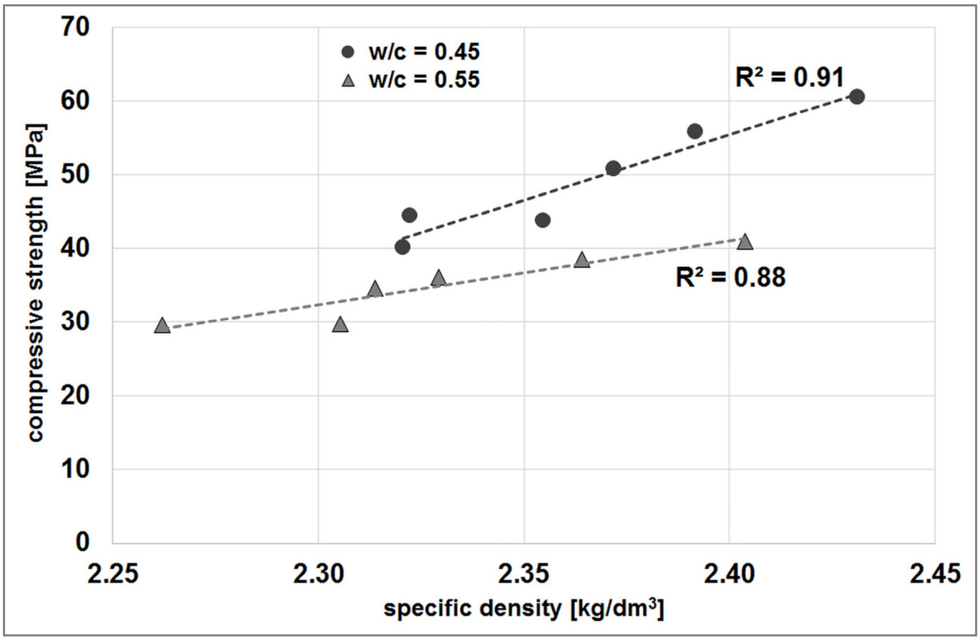

Figure 5. Correlation between the density and the compressive strength of the concrete.

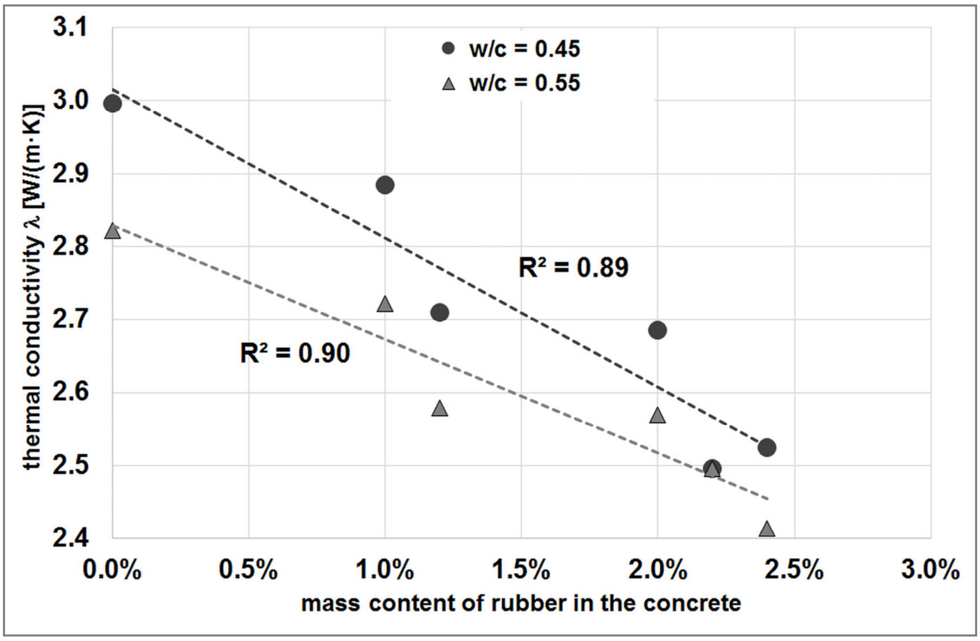

Figure 6. Correlation between the mass content of crumb rubber and the thermal conductivity of the concrete.

This is a different conclusion from that of Fadiel et al. [23], which was based on their test results, but these results cannot be directly compared as they were obtained in tests on mortar that contained crumb rubber in an amount of 7–27% the weight of mortar. In addition, the thermal conductivity values obtained were about five times smaller, and the size of crumb rubber particles was 0–0.6 mm and 0.84–2.00 mm, approximately, corresponding to the sizes used in the concrete with fine crumb rubber in this study. These discrepancies in the obtained trends in the change of thermal conductivity coefficient indicate that the effect of the size of crumb rubber particles on the thermal conductivity of the cement composite may vary, and this should be further investigated.

The correlation between the density of crumb rubber concrete and its thermal conductivity was also investigated and is illustrated in Figure 7, which shows the linear trend lines for both the concrete series with different w/c values separately, as well as collectively for all the series made. In all cases, the correlation is positive and very strong. In the case of the series with w/c = 0.45, the correlation coefficient is r = 0.98, the series with w/c = 0.55 is characterised by a correlation coefficient value of r = 0.97, and a correlation coefficient of r = 0.96 was obtained when all concrete series were considered.

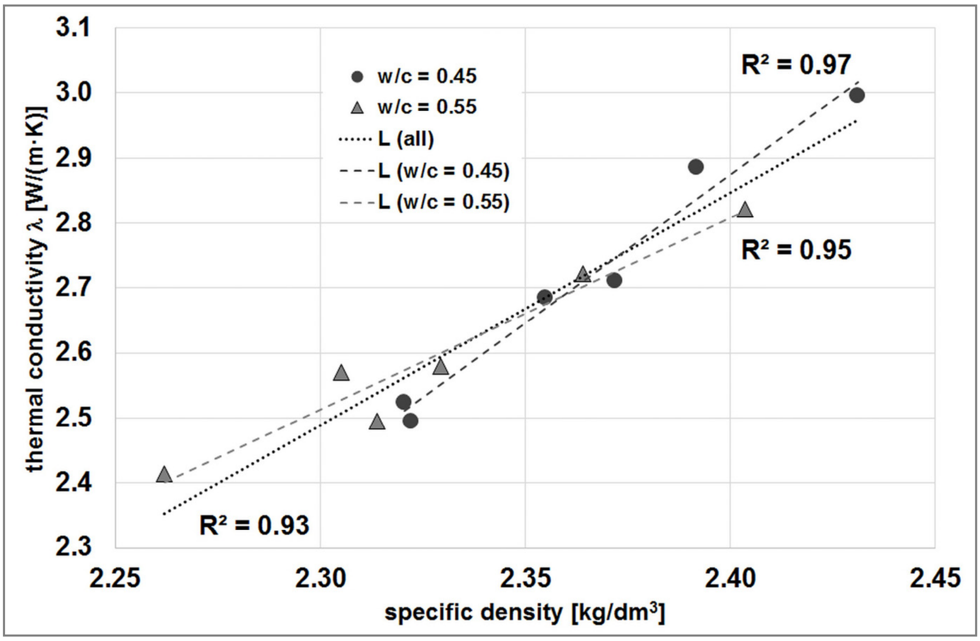

Figure 7. Correlation between the density and the thermal conductivity of the concrete.

The volumetric heat capacity exhibits a slight decrease in value with an increase in the proportion of crumb rubber, as can be seen in the results obtained for concrete with a w/c ratio = 0.45. This trend is in line with the results obtained by Záleská et al. [33]. It is due to the lower value of volumetric heat capacity of crumb rubber compared to that of natural aggregate. This effect is somewhat smaller than would be expected from the difference in this parameter for the two materials, because the decreasing volumetric heat capacity of crumb rubber is partly compensated for by the greater porosity of the material and, therefore, the greater amount of water.

In the case of concrete with w/c = 0.55, the negligible effect of crumb rubber on the value of volumetric heat capacity is most likely due to the greater variation in porosity of the material from series to series. The pore-filling water in concrete has approximately forty times the volumetric heat capacity of rubber, hence even small variations in the water content of concrete have a much greater effect on the measurement of this quantity for a material with significant porosity.

Adopting the paradigm of the equal importance of concrete's strength characteristics and other performance characteristics complicates the assessment of the material's functionality. This is particularly the case when a change in the composition of the concrete mixture translates into favourable changes in some of the concrete's characteristics and worsens other parameters. Formalised assessment methods can be used in such a situation, e.g., the EIPI method [34,35], which additionally allows the ecological performance of the material to be assessed. However, in simple cases where only two parameters form the basis of the assessment, one can limit oneself to defining an index combining the two.

This is the case with the material being evaluated, where one parameter changes in a favourable direction and the other in an unfavourable direction as the proportion of crumb rubber increases. Since the values of both parameters decrease at the same time, an index that is a quotient of the concrete's compressive strength and thermal conductivity coefficient will prove useful in this situation. For the purposes of this study, this was referred to as the thermomechanical index φ and was calculated according to Formula (2),

$$\varphi = f_c/\lambda, \tag{2}$$

where φ is the thermomechanical index, f_c is compressive strength, and λ is the coefficient of thermal conductivity. The results of thermomechanical index calculations are presented in Figure 8. As this index does not make physical sense, but only for practical use, both in the figure and in the discussion of results, its unit has been omitted. The practical sense of calculating this index in a situation where a requirement for a minimum value of concrete strength is imposed is limited to the situation where this requirement is fulfilled.

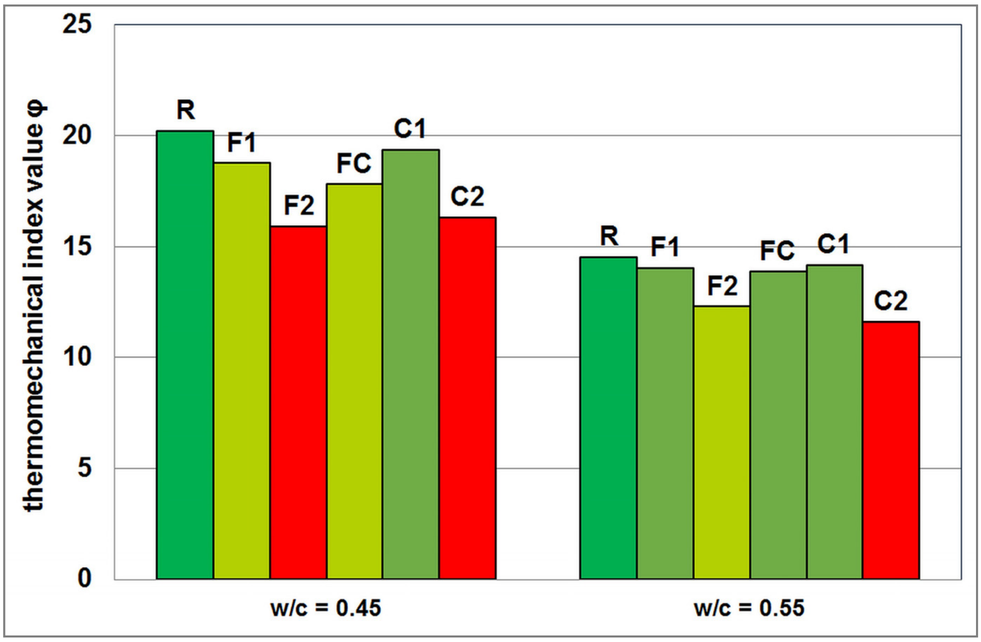

Figure 8. Values of the thermomechanical index.

The reference value of the φ index was assumed to be its highest value at a given w/c value. Values lower by no more than 5% were considered to be of equal quality, and values lower by no more than 15% were considered to be "good enough". The analysis of the thermomechanical index values obtained allows for the conclusion that the use of crumb rubber in concrete in an amount of up to 2.2% of the mass of the material for a concrete series with w/c = 0.55 leads to φ index values of up to 15% lower than the maximum value. Four equivalent concrete series can be identified among these: 5R, 5F1, 5FC, and 5C1, and one "good enough", namely F2. Only the C2 series, with a crumb rubber content of 2.4%, falls outside the specified range.

The results for the concrete series with w/c = 0.45 are considerably more varied and allow dividing them into three groups: 4R and 4C1 as equivalent series, 4F1 and 4FC as "good enough", and 4C2 and 4F2, where the index value was more than 15% below the maximum value among these series. It is worth noting that the crumb rubber content of the 4C2 series is 2.0%, while that of the 4FC series, which has a much better thermomechanical index value, is 2.4%. This indicates that it is not only the amount of crumb rubber that shapes the ratio value. This division is, of course, subjective and conventional. The adoption of other limit values or other criteria may result in a different classification.

5. Conclusions

The use of crumb rubber from waste tyres as a substitute for part of the aggregate did not cause technological difficulties in the preparation of the concrete mixture and the compaction of the specimens. Some recipe modifications were needed due to the strongly different density and water demand of the waste rubber compared to the natural aggregate.

A strong negative correlation was observed between the compressive strength of the concrete and the amount of crumb rubber in the concrete. At the same time, the insulating capacity of the material increased, and the thermal conductivity coefficient also showed a strong negative correlation with the amount of crumb rubber in the concrete. For both parameters tested, their dependence on the amount of crumb rubber in the concrete is linear in the range of dosage used (0 to 2.4 wt.%). The density dependencies of compressive strength and thermal conductivity are also linear in this range.

A thermomechanical index was introduced to simultaneously evaluate the performance of the concrete on the basis of compressive strength and thermal conductivity, the value of which, in most cases, decreased by less than 15% in concrete with waste rubber compared to the results of the reference series. Such a decrease was taken as the limiting acceptable value and was only exceeded in the case of a coarse crumb rubber content of 2.0% and a fine crumb rubber content of 2.4%, but in the latter case only in the series with $w/c = 0.45$.

The volumetric heat capacity in the series with $w/c = 0.45$ is characterised by a slight decrease in value as the proportion of crumb rubber increases. This is due to the lower value of volumetric heat capacity of crumb rubber compared to that of natural aggregate. For concrete with $w/c = 0.55$, the effect of crumb rubber on the value of volumetric heat capacity was negligible.

Despite the deterioration in the summarised performance, it must be concluded that the compressive strength of concrete, even with maximum used crumb rubber content (2.4% of total mass of concrete mix), is sufficient for many applications and the improvement in insulating capacity is large enough that the use of such a material can be beneficial in many cases.

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