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Composites Containing Felt Wastes from the Automotive Industry

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Abstract: (One) Background: Using textile waste materials in composites is a well-known problem and is frequently addressed by various scientific teams. Most of this work concerns textile waste introduced into composites as yarn strands. The present work focuses on adding textile wastes prepared in the form of single filaments of yarn spun to fluff, which was produced from waste felt materials from the automotive industry. (Two) Methods: The material was extracted from the bulkheads of worn-out vehicles, serving as thermal and acoustic insulation. The waste was shredded to form single yarn fibres with a fibre diameter of 0.08–0.3 mm and a 2–8 cm length. The shredded waste was used as a filler and modifier for composites. Four test batches were produced with different recyclate contents. A traditional cementitious composite without additives was used as a comparison material. (Three) Results: Composites filled with 3% felt waste have 23.31% lower density (1.71 g/cm^3), 71.03% higher absorbability (21.58%), 49.58% lower tensile strength (19.86 MPa), and 53.55% lower compressive strength (3.64 MPa) than traditional composites. Partitions made of these composites had much higher thermal insulation than traditional composites. Composite made of 1% waste was resistant to the phenomena of thermal spalling. Moreover, the spot flame loading did not damage the composite, and there were no scratches or defects. (Four) Conclusions: The tests proved that the waste felt materials could potentially be used as fillers and modifiers in lightweight composites with higher thermal insulation. The addition of felt fibres improves the resistance of the composite to local spalling.

Keywords: felt wastes; automotive wastes; waste fillers; lightweight composites; thermal insulation; thermal spalling

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1. Introduction

One of the priorities of current scientific efforts is the development of effective waste management systems [1] that aim to ensure ecological safety, understood as an ecological state that safeguards the peaceful and healthy existence of all ecosystem components. Although techniques for effective recycling have already been developed for most types of unwanted matter, such as steel products, glass products, selected plastics, etc. [2], in many cases, for economic or logistical reasons, they are abandoned or carried out in an extensive form. Felt products from used vehicles are an example of such matter.

Felt is one of the oldest textile products [3]. It is obtained by felting the fibres, i.e., pressing them in a moist state, which combines them into a single compact mass [4]. Products were initially made from natural fibres such as sheep's wool, alpaca, silk and flax. Today, most products are made from synthetic fibres such as polyesters (elan and torlen), elastane (spandex and lycra), and polyamide [5–7]. According to their properties, technical felts are divided into some types [8]. In the automotive industry, upholstery felt is mainly used [9] and as a soundproofing layer against ambient noise and engine vibration, as well as to improve the acoustic environment inside a vehicle. According to various manufacturers, automotive felts are often recycled as they are made from polyester, elastane, and polyamide waste. Due to this fact, they are often nonhomogeneous in terms of colour and technical fibre parameters. Therefore, they have a low material value and suitability for subsequent recycling processes. Surveys conducted among entrepreneurs operating vehicle disassembly stations have shown that felt waste is difficult to manage. There is a low interest in recycling them. Therefore, they are mainly deposited in landfills and neutralized by landfilling or, after drying, collected and incinerated by waste incinerators, which are extremely inefficient and do not fulfil the potential of this material.

One of the ideas currently being promoted for innovative recycling of unwanted waste is to use it as an ingredient in building materials [10–13]. The policy presented by the European Union, already cited in the 2008 Raw Materials Initiative document, envisions the intensified production of recycled materials with properties at least not inferior to those produced from virgin raw materials. This trend, i.e., in Poland, is reflected in the guidelines presented by the Ministry of Economy in the National Strategy for Innovation and Efficiency of the Economy [14] (Annex to Resolution No. 7 of the Council of Ministers of 15 January 2013 on the Strategy for Innovation and Efficiency of the Economy 'Dynamic Poland 2020').

The scientific community's response to the above [15–18] issues has been numerous research works devoted to analyzing the possibility of using recyclates as fillers in concrete composites [19–25]. Most of the works carried out, unfortunately, do not focus on obtaining the specific properties of recycled concretes. The main aim is the utilization of waste [26]. The authors present the problem of waste generation [27] and the reasons for the difficulty of reuse [28]. The researchers also point out the impossibility of spontaneous biodegradation of waste [29–37]. On the other hand, many scientific papers prove that, despite waste, composites with characteristics superior to those obtained from traditional composites can be obtained from recyclate. Among these are high abrasion resistance [38], ultrahigh strength [39], high chemical resistance [40], heat storage capacity [41], resistance to high temperatures [42], or resistance to sewage effluent environments [43]. All of these, and other articles [44–47], prove that with the right composition of components, even recycled ones [48–51], it is possible to obtain final composites with nonstandard technical parameters that surpass some of the technical parameters of traditional composites.

Another problem with concrete composites that research teams are working on solving is their sensitivity to high temperatures [52–58].

A challenging issue is composing concretes that are resistant to sudden temperature changes. An exceptionally unfavourable phenomenon here is the thermal spalling of concretes [59]. According to various studies [60], the water vapours contained in the capillaries of concrete at 100 °C begin to boil, thereby increasing their volume [61]. This induces tensile stresses in the walls of the closed capillaries [62]. Exceeding the tensile strength of the concrete causes an explosive bursting of the capillary walls and the tearing off of concrete fragments [63]. This phenomenon is destructive in a particular way for compact and airtight concretes with high strength [64]. For this type of concrete, the possibility of free vapour migration outside the concrete element does not exist [65]. The most commonly proposed solution here is the use of polypropylene fibres [66]. For ordinary composites, fibres are a type of dispersed reinforcement [67]. The fibres melt in elements subjected to high temperatures, and the resulting channels allow the water vapour contained in the capillaries to escape [68]. However, it is now thought that spalling may also have other following mechanisms of the formation, such as temperature differences between the surface and interior of the concrete element, differences in thermal expansion of aggregate and grout, differences in thermal expansion of concrete and reinforcement, and transformations of the minerals forming the concrete. Analysis of these phenomena showed that the more destructive they are, the tighter, denser, and less absorbent the cement composite is.

Taking into account the above-mentioned technical and ecological considerations, the authors of this paper concluded that the use of synthetic fibres derived from waste felt materials could positively affect selected parameters of concrete composites that will be produced with their participation. In addition, it was hypothesized that a strong filling of the concrete composite with this type of recyclate would increase its thermal insulation and that adding fibres would increase the resistance of the composites to thermal spalling. Here, special consideration was given to using very fine textile fibres that would allow them to be evenly distributed as a filler and modifier in the cement matrix.

In the literature, work has been encountered on filling cementitious composites with lightweight waste materials to increase their thermal insulation [69]. Even in industrial production, so-called polystyrene-based concretes are popular [70]. For example, the study by [71] shows the possibilities of producing lightweight concretes using EPS polystyrene granulate. Similarly, papers [72,73] demonstrate that recycled material can be used successfully in these applications. Paper [74] presents the mechanical properties of hybrid composite materials containing pineapple fibre, polystyrene particles, and paper tissue. In the earlier publications, certain regularities can be observed regarding the technical parameters of lightweight composites. All the papers indicate that as the lightweight fillers increase, the volume density of the composites decreases, and their absorbability increases. Similarly, both compressive and tensile strengths decrease [70,71]. In a way, composites take on the characteristics of the filler, which is usually a lightweight, absorbent material with low strength parameters. However, these composites usually have applications other than load bearing, which is why research into them continues.

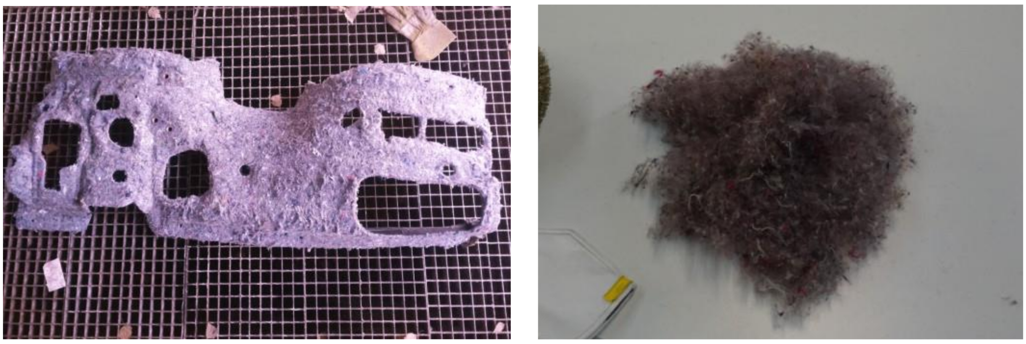
There are also many articles in the literature on the reinforcement of building composites with waste textiles [46,75]. The study by [76] investigated the mechanical behaviour of polymer concrete reinforced with textile waste. It was observed that the textile fibre content alleviated cracking during loading, in contrast to the brittle cracking of the composite without fibres. Similar observations were made by the authors of the paper, whose research focused on the use of waste fibres from carpets [77], the use of nylon textiles [78], or textile packaging bags [79]. The use of textile fibres up to 0.5% by volume of the composite usually led to a slight reduction in the density of the composite [80] and an increase in the compressive [81] and tensile [82]. An interesting study looked at the resistance of this type of composite to high temperatures. In a paper [83], the authors demonstrated that at temperatures of 800 °C, adding fibres had a beneficial effect in reducing the effects of destructive spallation. Similar observations were made by the authors of the paper [84] in which composites containing 0.5% nylon fibres showed no signs of spalling after exposure to 450 °C, while the same concrete without fibre additives spalled at temperatures as low as 150 °C. In addition, in the paper [85], the authors proved that composites containing textiles have a lower thermal conductivity. A decrease in the weight of the composites was also expected due to the melting of the synthetic fibres [86].

Considering all the aspects mentioned above, and the fact that no studies on cementitious composites modified to a high degree with felt waste from used vehicles have been found in the literature, the research presented in this paper was undertaken. This material was extracted from the bulkheads of used vehicles, acting as thermal and acoustic insulation. The shredded waste was used as a modifier for cementitious composites. Four test batches with different recyclate contents were produced, and a traditional cementitious composite without additives was used as a comparison material. Specific density, absorption, flexural strength, and compressive strength were tested for all the composites produced. Considering the expected unique properties of the composites, i.e., insulation in contact with high temperatures and resistance to spalling, additional original insulation and thermal resistance tests were carried out.

1.1. Materials

This study's primary research material was waste felt from the automotive industry. The material was collected from the bulkheads of a worn-out vehicle—a Jeep Cherokee

WK2, where it performed thermal and acoustic insulation functions. Moreover, the material was collected from vehicle disassembly stations in the form of soundproofing mats. Plastic mats were covered on the passenger compartment side to protect the felt from damage and dust. The protective coating was removed, and the material was then shredded using a wire brush mounted on a contour grinder to form felt fluff. Figure 1 shows the waste in matted form and as fluff after shredding. Shredding was carried out until individual yarn fibres could be separated up to the size quoted by felt manufacturers of 0.08–0.3 mm. The length of the fibres used was approximately 4–8 cm.



(**a**) (**b**)

Figure 1. Waste felt materials from the automotive industry, (**a**) in the form of soundproofing boards, (**b**) after shredding.

According to the manufacturer's sheet, the felt had the properties presented in Table 1 below. The table also gives the types of fibres and the parameters of the yarn from which the felt is made.

Table 1. Properties of felt based on manufacturer's data.

Lp.	Parameter	Standards	Value
1	Density [g/cm^3]	0.35+/−0.02	0.360
2	Breaking strength	≤50 kg/cm^2	≤55 kg/cm^2
3	Tensile strength at break	≤110%	90%
4	Free sulphuric acid content	≤0.30%	0.25%
5	Botanical impurities content	≤0.35%	0.18%
6	Mineral impurities content	≤0.12%	0.01%
7	Fire protection properties	≤70 mm/min	≤10 mm/min
8	Thermal resistance	max. up to 150 °C	150 °C
9	Yarn fibre thickness	-	0.08–0.3 mm
10	Fibre material	-	Polyesters, elastane, polyamide

Portland cement CEM I 42.5N—SR 3/NA from Cemex companies was used as the cement for the concrete. According to the manufacturer's sheet, this cement is characterized by stable physical and chemical parameters with an appropriate setting time, high early and final strength parameters, low alkali content, and high resistance to aggressive chemical agents. Thanks to these advantages, it is popularly used in the production of concrete commodity mixtures. Table 2 shows the physical and chemical parameters of the cement used.

Concrete plasticizer Qplast from the Simeplast company was used as a plasticizing admixture. According to the manufacturer's sheet, it is a highly potent plasticizing plasticizer that distributes the cement particles in the concrete mix. It is used to improve the working and service properties of the concrete mix while reducing the amount of batch water. According to the technical data, which are based on [87], it significantly improves the workability and cohesiveness of the mix, thus facilitating the concreting, improving the cohesion and coherence of the mix, counteracting the segregation of components and the separation of water, allowing a reduction in the amount of water by approximately 10%, while maintaining high workability, and simultaneously increasing the strength, water and frost resistance, durability, and density of the concrete. Due to the fact that the composite is filled with high water-content waste, it was decided to use it. The primary technical parameters of the admixture, based on its technical sheet, are shown in Table 3.

Table 2. Physical and chemical parameters of the cement used were taken from the manufacturer's product sheet.

Feature	Unit.	Average Score	Requirements
Start of binding	min	233	>60
End of bond	min	291	
Water efficiency	%	27.5	
Constant volume	mm	1.1	<10
Specific surface area	cm^2/g	3688	
Compressive strength: after 2 days	MPa	23.9	<10
Compressive strength: after 28 days	MPa	55.9	42.5–62.5
Chemical analysis: SO_3	%	2.77	<3.0
Chemical analysis: Cl	%	0.070	<0.10
Chemical analysis: $Na_2Oeq.$	%	0.53	<0.6

Table 3. Basic properties of Simeplast's Qplast admixture based on the manufacturer's technical sheet.

Property	Description
Form	Liquid
Chloride content	<0.1%
Alkali content	<2.0%
Compressive strength	After 7 days, concrete tested $\geq$ 110% control concrete After 28 days, concrete tested $\geq$ 110% control concrete
Air content	Test mixture $\leq$ 2% by volume above the content in the mixture control
Water reduction earnings	In the test mixture $\geq$ 5% w compared to the control mixture
Density (20 °C):	1.075+/−0.02 kg/dm^3
pH:	5+/−1
Grain size	0.15 um

Silica dust from the SLIMIC Poland company was used as a concrete additive. According to the manufacturer's description, microsilica originated as a byproduct obtained during the production of silicon metal and ferrosilicon alloys in arc furnaces. It consists of fine dust particles, the diameter of which was estimated to be, on average, 100 times smaller than the average grain size of cement. For technical reasons, the silica dust was supplied in a compacted form as microbeads representing agglomerates of individual particles. As described, microsilica is a critical additive for watertight concretes. Replacing 15% of the cement with microsilica increases the impermeability of the concrete several times, which is difficult to achieve by other methods. The primary characteristics of microsilica from the technical sheet are given in Table 4.

Table 4. Basic properties of microsilica based on the product data sheet.

Parameter	Unit	Value	Evaluation Method
Form	-	fine powder	Visual
Colour	-	grey	Visual
Fragrance	-	odourless	-
Density	g/cm^3	2.05	EN 1097-6
Bulk density	g/cm^3	1.1	EN 1097-3
Alkalinity	pH	less than 11.5	PN-EN-ISO 10523

The composition of the initial concrete mix was developed using an experimental method based on the recipes used to produce ready-mix concrete C30/37. During the initial analysis of the composite's partial products, special attention was paid to the compressibility of the felt material. The initial assumptions were to carry out six trials with a percentage distribution of felt between 0 and 5% by weight of the entire composite. It was also assumed that the composite would have no pores or voids between the filler fibres. A slurry of a liquid consistency was therefore designed first, which was able to fill the spaces between the felt fibres. Experiments with different water/cement ratios starting from 0.3 to 0.5 proved that a w/c ratio of 0.46 met this criterion. This was the lowest ratio of water to cement to ensure the highest parameters of the composite and allowed free mixing with the fibres. However, experiments in successive approximations of adding recyclate to the slurry showed that it was impossible to obtain a tight composite with a mass content of recyclate equal to 5% of the total weight of the composite without special technological treatments such as compression and vibration. A higher content than 3% of felt started to cause the inhomogeneity of the material and the formation of free spaces between the fibres of recyclate. It was therefore considered that a value of 3% by weight of the composite filled by recyclate would be the final value tested. The composition of this mixture was used to design the subsequent series of tests. In subsequent series, the volume occupied by the felt waste was gradually replaced by a traditional sand and gravel aggregate. Successive test series containing waste were designated by the letter F (from the word felt) combined with a numerical value expressed as a percentage to indicate the waste content by weight of the composite. Finally, felt mixtures were developed as F0.1 (for the series with 1% of waste), F1.6 (for the series with 1.6% of waste), and F3.0 (for the series with 3% of waste). As a control mix, samples were made in which all the filler was sand and gravel aggregate (CONTR).

Table 5a presents the weight values of the ingredients used during the experimental design of the composite fully filled with felt and after converting them into a recipe for 1 m^3 of the mixture. Table 5b summarises the ingredient quantities of all concrete mixtures for which experimental work was carried out in relation to 1 m^3.

Table 5. (**a**). The weight values of the components used during the experimental design of the F3.0 composite fully filled with felt and after converting them into a recipe for 1 m^3 of the mixture. (**b**). Summary of ingredient quantities of all concrete mixtures for which experimental work was carried out in relation to 1 m^3.

(**a**)

Component	Quantity of Substrate [kg] in the Test Mixture	Substrate Density [kg/m^3]	Volume of Test Mixture [m^3]	Conversion Rate of Ingredient per 1 m^3 of Concrete Mix	Amount of Substrate [kg/m^3] Concrete Mix	Component Volume [m^3]
Cement CEM I 42.5N—SR 3/NA	9.270	3100.00	0.002990	109.52	1015.28	0.3275
Felt	0.455	360.00	0.001264	109.52	49.83	0.1384
Water	4.323	1000.00	0.004323	109.52	473.47	0.4735
Qplastplasticiser	0.138	1050.00	0.000131	109.52	15.11	0.0144
Microsilica	0.928	2200.00	0.000422	109.52	101.64	0.0464
SUMA	15.114		0.009130		1655.34	1.0002

(**b**)

Component	Substrate Density kg/m^3	For F3.0 Mix (3% Recycled)		For F1.6 Mix (1.6% Recycled)		For F1.0 Mix (1% Recycled)		For CONTR (0% Recycled)	
		Amount of Substrate in kg/m^3 Concrete Mix	Component Volume [m^3] in 1 m^3 Concrete Mixture	Amount of Substrate in kg/m^3 of Concrete Mix	Component Volume [m^3] in 1 m^3 Concrete Mixture	Amount of Substrate in kg/m^3 of Concrete Mix	Component Volume [m^3] in 1 m^3 Concrete Mixture	Amount of Substrate in kg/m^3 of Concrete Mix	Component Volume [m^3] in 1 m^3 Concrete Mixture
Cement CEM I 42.5N—SR 3/NA	3100.00	1015.28	0.3275	1015.28	0.3275	1015.28	0.3275	1015.28	0.3275
Sand 0–2 mm	2480.00	-	-	38.69	0.0156	73.38	0.0296	114.43	0.0461
Gravel 2–4 mm	2650.00	-	-	114.48	0.0432	156.85	0.0592	244.55	0.0923
Felt	360.00	49.83	0.1384	28.44	0.0790	18.53	0.0515	-	-
Water	1000.00	473.47	0.4735	473.47	0.4735	473.47	0.4735	473.47	0.4735
Qplastplasticiser	1050.00	15.11	0.0144	15.11	0.0144	15.11	0.0144	15.11	0.0144
Microsilica	2200.00	101.64	0.0462	101.64	0.0462	101.64	0.0462	101.64	0.0462
SUMA		1655.34	1.0000	1787.11	0.9994	1854.27	1.0018	1964.49	1.0000

1.2. Testing Procedures

The program of planned research work involved, in the first phase, was to carry out basic tests to which structural materials used in construction are subjected.

All samples were prepared in the same way. In the first phase, cement slurry and felt fluff were prepared in separate containers. Successive portions of the waste material were added to the slurry, mixing the mixture with a rotary mixer. Eleven samples of each test series were made. After two days of forming, the samples were transferred to a container with water and conditioned for 28 days.

All prepared concrete mixtures were subjected to an evaluation of consistency, which was referred to as the standard test according to PN-EN 12350-2:2011 [88], testing of the concrete mixture. Part 2. Consistency testing used the cone drop method.

Volumetric density was tested on cubic samples measuring 4 × 4 × 16 cm. The samples were measured by an OWL meter HT-14-100 and weighed on the Ohows Nawigator scale in accordance with EN 12390-7:2011 [89]. The volumetric density was calculated as the ratio of the volume of the tested samples to their weight.

Water absorption was tested on identical samples and equipment as volumetric density. The samples were immersed and remained in the water until their weight was established. The water absorption was calculated according to [90] as the ratio of the amount of water the composite was able to absorb to the weight of the dry composite expressed as a percentage.

The flexural strength of the three-point scheme was tested according to the method given by [91]. Moreover, specimens measuring 4 × 4 × 16 cm were prepared for the test, and the compressive strength of the specimens was tested according to the method given by [92]. The 4 × 4 × 4 cm specimens were tested after the specimens were broken during the flexural strength test. The strength test was conducted on a MATEST 2000 testing machine, with a 0–300 kN strain gauge attachment also from MATEST, model: C089PN468, factory number: C089PN468/AA/0001.

Tests of the insulating properties and resistance of the composites to direct fire were carried out based on the authors' comparative methods. The first test consisted in checking the insulating properties of the samples. On the test stand, the composite samples in the form of insulation boards with dimensions of 30 × 30 × 4 cm were heated on one side with a YATO YT-82293 technical heater with a power of 2000 W. The air stream generated by the heater at 550 °C from a distance of 8 cm acted on the surface of the sample for 15 min, where the highest temperature dictated this distance declared from the device. On the other side of the sample, a temperature reading was taken every minute using an electronic thermometer TM-902C with a type K thermocouple with a temperature measurement range of −50 °C to 1300 °C with a resolution of 1 °C. The readings over time were compared for successive test runs.

The second test was to check resistance to fire and thermal spalling. For this purpose, a burner Tirros TM-706, fuelled by a mixture of propane-butane gas, was used. The test specimens were rectangular in shape, measuring 30 × 30 × 4 cm. The torch's flame was applied to the centre of the specimen. During the test, the temperatures on the other side of the specimen were also monitored, and the value reached by the opposite side of the specimen after 8 min of flame action was recorded. In addition, the point of direct flame action was assessed. The highest temperature dictated the distance of 4 cm from the device.

Point-loading partitions and concrete samples with high temperatures is not a normalized technique. However, it is used as a comparative method by many research teams. For example, the analyses in [93] compared the fire resistance of three different types of slabs made of reinforced concretes (RC), which were prestressed, and polypropylene fibres. The plates were loaded with the direct action of the fire from gas burners. The same testing device was used to check the impact of fire on the mechanical properties of slurry-infiltrated fibre concrete (SIFCON) [94]. In [95], a similar scheme was used to investigate reinforced concrete structural walls. The research techniques presented in this paper refer indirectly to the experiments presented in [95], in which the test of resistance to the thermal chipping of composites was carried out on concrete samples with dimensions of 30 × 30 × 10 cm.

Samples were locally subjected to high temperatures, and the destruction effects were analyzed using precise digital photography methods.

The test stands for insulating properties, and fire resistance tests, are presented in Figure 2a,b.

(a) (b)

Figure 2. Temperature tests. (**a**) Test stand for the insulation test of the samples. (**b**) Test stand for the author's fire resistance test.

2. Research Results and Analysis

In terms of consistency testing, all samples during the test showed a semifluid consistency, which corresponded to a cone drop (S3) of between 100 and 150 mm and were, respectively, for CONTR—150 mm, F1.0—110 mm, F1.6—100 mm, F3.0—100 mm. It is worth noting here, however, that the mixture became less workable with an increasing felt content for two reasons. First, mechanical mixing was hampered by the waste fibres coming together. The second reason for less workability was water absorption by the absorbent recyclate. Relating the results of this study to those reported in the literature only confirms the regularity noted. The addition of nylon fibres [85] or carpet fibres [86], even amounts as low as 0.5% resulted in a marked decrease in workability. The differences between the workability of the control concrete and the addition remained insignificant at an addition of just 0.1%. Here, the difficulties described were overcome by using an experimental composite design system. This study has shown that using this type of recyclate will require similar operations each time concrete is designed using different quantities of fibres.

Figure 3 shows the results of the specific density of the composites.

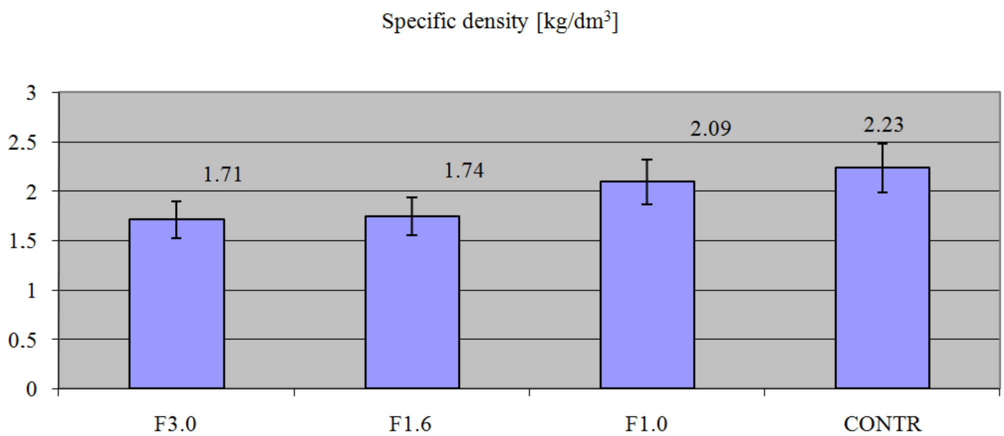


Figure 3. Results of specific density testing of composites.

As expected, the assessed specific density of the composite was the highest for the control composite (Figure 3). It amounted to 2.23 g/cm^3 and was 6.69% higher than that of the composite filled with 1% recyclate (2.09 g/cm^3), 21.97% higher (2.09 g/cm^3) than that of the F1.6 composite (1.74 g/cm^3), and 23.31% higher (1.71 g/cm^3) than that of the F3.0

composite, respectively. The specific density value was recorded for the F3.0 composite (1.71 g/cm^3). The value of 1.71 g/cm^3 qualified it as a lightweight concrete and made it possible to assume that it would be a composite with improved thermal insulating properties due to its lightweight filler content.

Relating these results to those reported in similar works [76–78] only confirmed the apparent relationship. In the works cited, the values of the composites with the addition of felt ranged from 2.15 to 2.32 g/cm^3, which was only due to the lower recyclate content and the higher value recorded for the control composites.

Figure 4 shows the results of the saturation test on the composites.

The highest absorbency was recorded for the composite containing 3% recyclate and was as high as 21.58%. Subsequently, the absorbency tested for composites with decreasing recyclate content—decreased. It was 41.61% lower for the F1.6 composite (12.6%), 53.38% lower for the F0.1 composite (10.06%), and 71.03% lower for the CONTR composite at 6.25%. Similar results were observed in all cases initially reported in the literature [76–86]. The differences in the absorbability of the composites depended significantly on the type of fibre and its content as an additive. None of the studies reported such a high content of waste fibre (maximum of 2%). The value of 3% represented the maximum saturation of the composite with waste, which was dictated by the desire to produce an insulating composite. This translated into a high increase in saturation. In the literature, the values were closer to those reported for composites with a fibre content of 1%, with a maximum value of 15%.

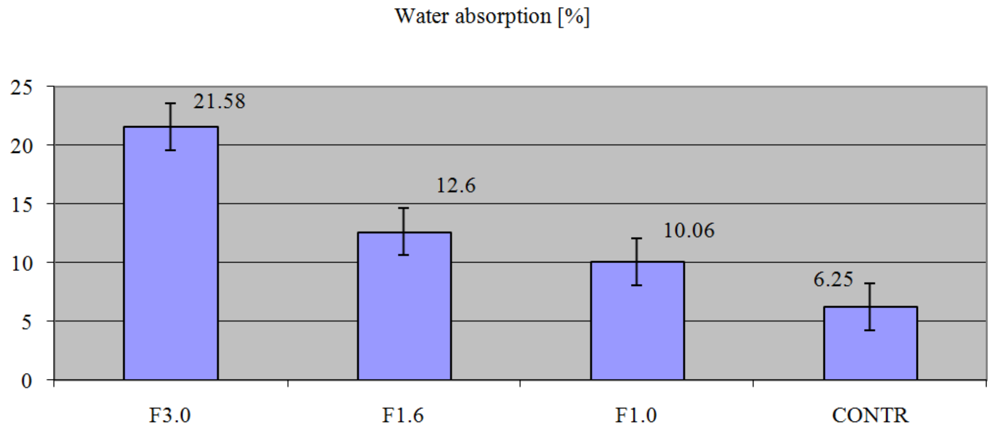


Figure 4. Results of the saturation test of the composites.

Figure 5 presents the results of compression strength tests on the composites.

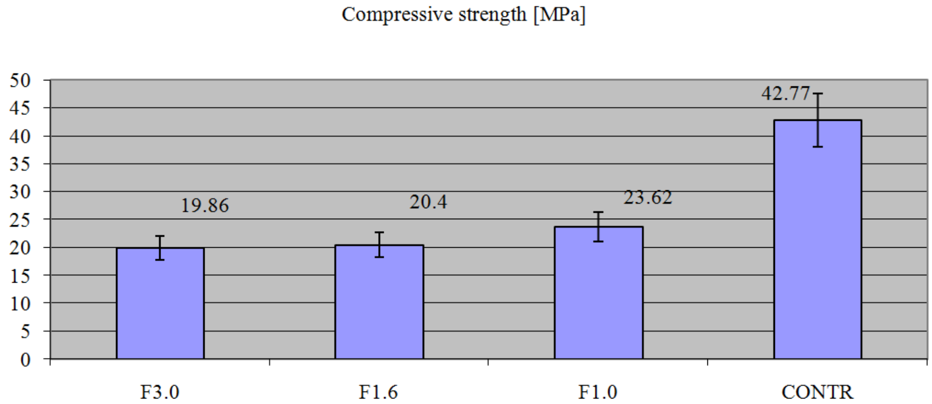


Figure 5. Compressive strength results of the composites.

The composite without the addition of the CONTR recyclate had the highest recorded value in terms of compressive strength, 68.43 MPa. The other composites had a lower strength the higher the recyclate addition. Successively for the F0.1 composite, the value was 44.77% (23.62 Mpa) lower. For the F1.6 composite, the value was 52.30% lower (20.4 Mpa). For the F0.3 composite, it was 53.55% lower (19.86 Mpa).

Relating the present results to those presented in the literature, some inconsistency was noted. In the literature, for example, Wang et al. [80], using a nylon fibre addition of 1 to 2%, obtained an increase in compressive strength from 40.7 to 61.8 Mpa. Similarly, Mohammadhosseini [83,86] found 25.5 to 34.1 MPa with 0.5–1.5% carpet waste. Similar trends with marked increases of up to 20% in strength parameters have been observed in other works [78–81]. Relating test results with felt to those presented in similar works, it was found that composites with recyclates behaved differently from others with textile waste. The reason for this was probably the use of very fine fibres. Carpet waste fibres, for example, can be up to 5 mm in diameter, whereas the individual felt fibres used here were between 0.08 and 0.3 mm in diameter. Although they may have been made of the same material in terms of transferring local loads in the composite samples, they performed quite differently. It is known that the failure pattern of a dozen or so individual yarn fibres is different from the failure of the same number of fibres connected in a weave. Fibres in weaves working together can carry greater loads. However, a fact that coincides with observations reported in the literature of the failure course of the tested composite samples containing recyclates is worth noting. In their case, in contrast to the typical brittle fracture, the composite, especially with a 3% fibre content, showed some plasticity during failure. Despite the pronounced fracture and failure of the specimens, the damaged fragments of the specimens did not detach, as is the case with conventional concretes.

Figure 6 shows the results of the composite tensile strength by bending in a three-point scheme.

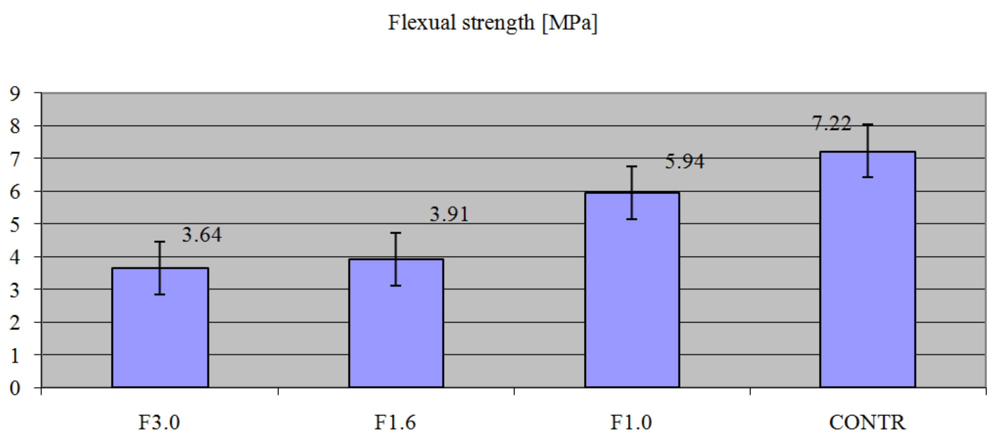
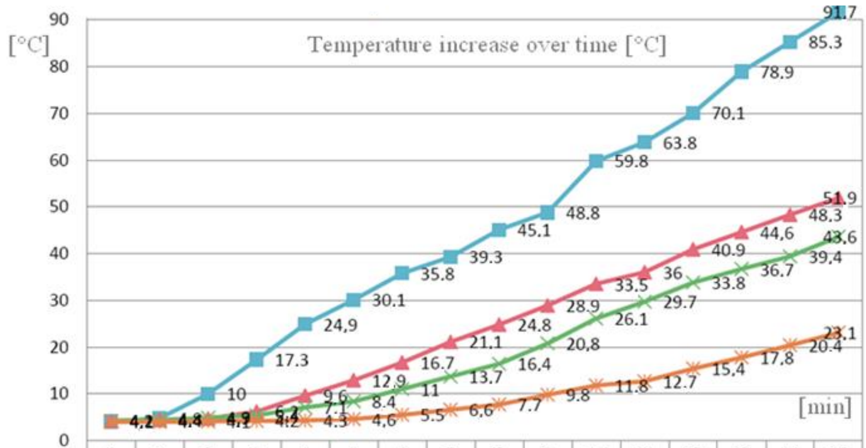


Figure 6. Results of tests on the tensile strength of composites by bending in a three-point scheme.

The results of the bending strength test are presented in Figure 6. The composite without the addition of the CONTR recyclate had the highest recorded value of 7.22 MPa. The other composites had a lower strength the higher the recyclate addition. Successively for the F1.0 recyclate, the value was 21.54% lower (5.94 MPa); for the F1.6 composite, it was 45.84% lower (3.91 MPa); and for the F0.3 composite, it was 49.58% lower (3.64 MPa).

Some inconsistency was also noted by relating the present test results to those presented above. Wang et al. [80] used 1 to 2% nylon fibre to increase tensile strength from 4.2 to 4.35 MPa. Similarly, Hosseini [83,86], with 0.5–1.5% carpet waste, proved an improvement in this parameter and changes of 3.0–3.5 MPa. Therefore, this study concluded that carpet fibres have a higher tensile strength than cement stone, so their addition could be considered a microreinforcement of the composite. The results of the own tests only confirmed the hypotheses raised in the paragraph on felt waste. Individual thin felt fibres uniformly distributed in the cement matrix broke during stretching, and their tensile strength appeared lower than that of the cement stone alone. This was the reason for the strength decreases observed in the subsequent test series.

The data obtained when the hot air flow was applied to the composite insulation panels are presented in Figure 7.



Time [min]	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CONTR 0%	4.1	4.8	10	17.3	24.9	30.1	35.8	39.3	45.1	48.8	59.8	63.8	70.1	78.9	85,3	91.7
F1.0 1%	4.2	4.4	4.7	6,2	9.6	12.9	16.7	21.1	24.8	28.9	33.5	36	40.9	44.6	48.3	51.9
F1.6 1.6%	4.2	4.4	4.9	5.4	7,1	8.4	11	13,7	16.4	20.8	26.1	29.7	33.8	36.7	39.4	43,6
F3.0 3%	4	4	4.1	4.2	4.3	4.6	5.5	6.6	7.7	9.8	11.8	12.7	15.4	17.8	20.4	23.1

Figure 7. Data obtained during the exposure of the hot air jet to insulation boards made of composites.

As is not difficult to see, despite the relatively short exposure, the temperature increases in all cases were relatively uniform, with successive temperature increases over time being smaller the higher the recyclate content of the composite. In the study, as would be expected, the sample with a felt content of 3% showed the highest insulating properties. As mentioned in the literature section, this was related to the insulating properties of the recyclate fibres and was evidence of the transfer of technical properties from the recyclate to the composite. The sample without felt material, CONTR, had the lowest insulating capacity. After 15 min, the temperature on the opposite side of the partition from which it was made was 91.7 °C. After the same period of time, the value read for the F3.0 composite was 23.1 °C, which was 74.8% lower. Therefore, this study proved the validity of filling the composites with recycled felt when composing thermally insulating composites.

During the follow-up test, only the final temperature was assessed, measured on the opposite side of the partition, which was heated with a gas burner. This test lasted 8 min. The temperatures established for the subsequent test runs were: 100 °C for the control composite, for the F1.0 composite: 90.3 °C, for the F1.6 composite: 78.9 °C and finally, for the F3.0 composite: 52.1 °C. Here again, the results of the temperature tests proved that the thesis of increased insulation of the recycled composite with felt waste was correct, and the waste-filled composite showed greater insulation in this higher temperature range.

Relatively unexpected phenomena were damage to the insulation boards, which occurred during the temperature analyses (Figure 8a,b).

The first phenomenon analyzed gave the fracture of the composite control slab without CONTR fibres (Figure 8a). This was expected, as thermal spalling of the top layers of the composite due to burning was anticipated rather than the failure of the whole panel. The destructive cause here was presumed to be the point heating of the component and the phenomenon of thermal expansion of the material. The effects of their interaction are shown in the hypothetical diagram, Figure 9.

(a) (b)

Figure 8. Damage to insulation boards that occurred during the temperature analyses carried out. (**a**) cracking of CONTR board, (**b**) peeling of F3.0 composite.

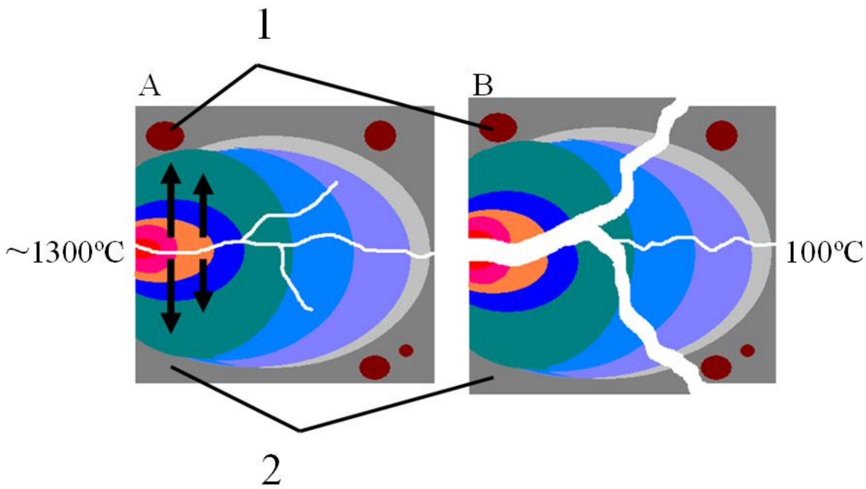
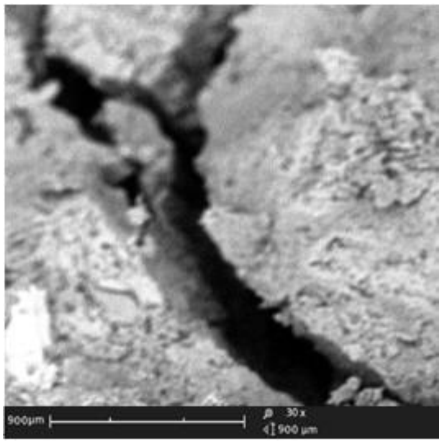


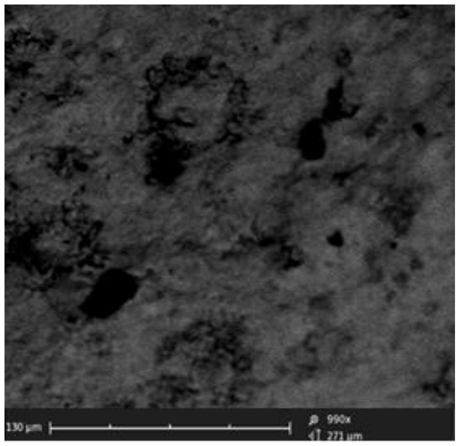
Figure 9. Hypothetical failure pattern of CONTROL composite insulation boards. 1—aggregate in the composite, 2—cement stone. The colours indicate the temperature propagation inside the composite. At the point of heating, there was an increase in the material volume due to the materials' thermal deformation. The volume increase resulted in stresses symbolised by the arrows shown in the figure. At the point of application of the thermal load, tensile stresses are generated, causing scratching of the composite (A—appearance of a crack. B—destruction of the composite).

It Is likely that there was an increase in the volume of the material at the point where the effect of the high temperature was greatest, which caused the local tensile stresses indicated by the arrows. Once the material's tensile strength was exceeded, the composite structure was breached, and fracture occurred.

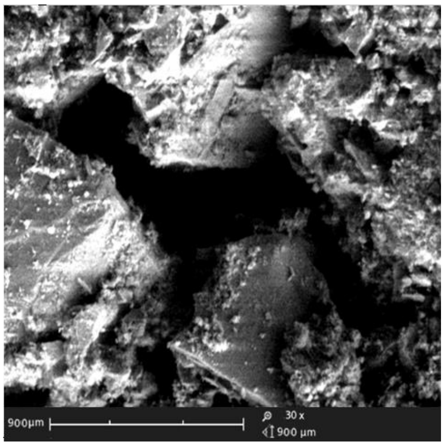
The structure of the felt composite, which was subjected to fire, also looked quite unexpected (Figure 9). Already during annealing, a large mass loss of the sample appeared. Here, the fibres filling the composite, which were in direct contact with the fire, were burned. Artefacts were found in the deeper layers of the test sample, showing that the fibres that had not been burnt spontaneously decomposed due to the high temperature instead of the fire. These areas were visualized in the scanning microscope images (Figure 10a,b).



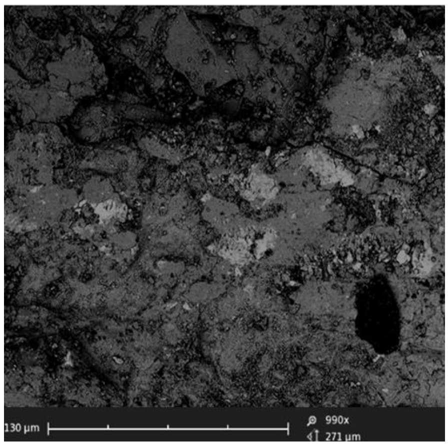
(**a**)



(**b**)



(**c**)



(**d**)

Figure 10. Damage to the structure of the F3.0 composite as a result of fire, (**a**,**c**)—pronounced cracks in the structure, (**b**,**d**)—void after fibre melting.

Figure 11 presents the hypothetical temperature distribution and surface failure pattern of the F3.0 composite samples.

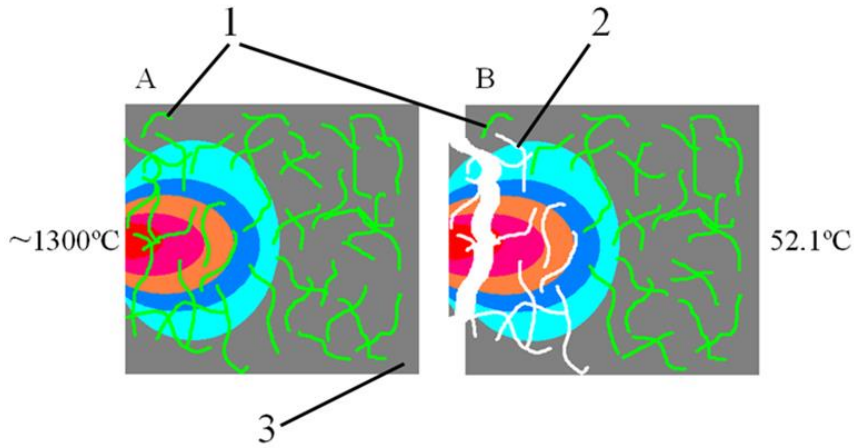


Figure 11. Hypothetical temperature distribution and surface failure pattern of F3.0 composite specimens. 1—recycled fibres in the composite, 2—voids formed after melting of fibres due to high temperature, 3—cement stone. The colours indicate the temperature propagation within the composite (A—high temperature interaction phase. B—superficial destruction of the composite).

It symbolically signalled that the impact of the high temperature was more localised due to the use of an insulating filler. The melting or burning of fibres in direct contact with the fire resulted in voids in the composite. Despite the superficial damage, the felt-containing composite samples were not entirely destroyed, as happened to the CONTR control composite sample.

The analysis of the temperature test results proved to be similar to what was observed in work presented by other research teams [83–86]. Composites with recycled felt content had higher thermal insulation in all fire temperature ranges, which was higher in the composite's degree of recycled felt filling. All insulating panels at a point application temperature of 550 °C retained their integrity without weight loss or scratching, and the insulating capacity recorded on a comparative basis was greatest for the F3.0 composite. Based on the author's fire resistance testing, it can be concluded that point-applied fire is destructive to compact and airtight composites, as damage to the entire panels was likely to have occurred due to the different thermal expansions of the heated and unheated zones. Similarly, extensive damage was observed for the F3.0 composite, where losses of both burnt fibres and cement spalling due to fibre burning were recorded. In contrast, negligible damage was recorded for composites with recyclate contents of 1 and 1.6%. In this case, there was neither cracking of the panels nor pronounced external peeling of the composite. This observation allowed the conclusion to be drawn that a uniform distribution of very fine fibres can improve the resistance to spalling even for very small amounts by weight of waste used. The failure of the F1.0 specimens with 1% recycled content during exposure to fire consisted only of the melting of fibres that were in superficial contact with the fire. It can also be assumed here that, through the resulting air voids, there was a more uniform temperature distribution in the composite, which compensated for the stresses caused by the uneven heating of parts of the partition, as was the case with the control composite. Therefore, the experiments' main conclusion allowed us to recommend waste felt fibres, not only as a filler in composites with improved thermal insulation but also as an additive to modify the chipping resistance of the composite, which was effective even when used in very small quantities.

3. Conclusions

Along with end-of-life vehicles, vehicle dismantlers obtain felt waste, used in cars as thermal and acoustic insulation. Due to their heterogeneity, waste felt materials are disposed of by dumping them in landfills, which is an extremely inefficient disposal method.

The results shown in this study have proven that such waste can be reused as a component of building composites. The novelty of the work presented was using textile waste which was shredded to single yarn fibres with diameters of 0.08–0.3 mm.

Composites modified with this type of recyclate had a 23.31% lower density (1.71 g/cm^3), 71.03% higher absorbability (21.58%), 49.58% lower tensile strength (19.86 MPa) and 53.55% lower compressive strength (3.64 MPa) than conventional composites. Partitions made of these composites had much higher thermal insulation than traditional composites.

Experimental work has shown that waste-modified composites containing 3% evenly distributed fine waste fibres in the cement matrix have significantly higher thermal isolation than composites without the additive.

Similarly, using a modifier in the form of fine yarn fibres results in increased resistance to thermal spalling. A flame-treated composite with 1% fibre did not damage the samples, and no scratches or cavities occurred.

Based on the experiments carried out, it was recommended that felt fibres from waste could be used both as a filler in composites to improve thermal insulation and as an additive—a modifier to improve the spalling resistance of the composite use of which is effective even with very small amounts of recyclate.

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