J Mater Cycles Waste Manag (2015) 17:33–41
DOI 10.1007/s10163-013-0222-x

ORIGINAL ARTICLE

Recycling scrap automotive heat shield insulation material

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Received: 27 April 2013 / Accepted: 5 December 2013

Abstract Automotive heat shields are usually composed of two metal sheets enclosing an insulating material with a paper-like texture that contains refractory ceramic particles. This article discusses the results achieved by recycling the scrap automotive insulation that is discarded in landfills, using the same concept as paper recycling. For comparison with the original product, tests of thickness, bulk density, weight loss on ignition, tensile strength, compressibility, and recovery were performed on recycled materials produced in a so-called "manual" process (involving little automation and performed in adapted facilities) without pressing, and pressed once, twice, and four times. Materials recycled in a so-called "industrial" process (in a paper recycling plant) without pressing, and pressed once were also tested. The recycled materials can be considered approved with respect to the main requirement, thermal insulation, since they dissipated the underhood temperature by more than 300 °C (like the original product). Like the heat insulation tests, the thermogravimetric analysis suggested that the recycled materials showed higher stability than the original product. Thermogravimetric, microscopy, and energy dispersive spectroscopy analyses indicated that the structural and compositional characteristics of the original product were preserved after recycling.

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Keywords Recycling · Paper · Heat shield · Thermal insulation

Introduction

Heat shields are fundamental components in automotive vehicles because their characteristics prevent the heat generated in parts of the engine that reach high temperatures (up to 1,100 °C), such as the engine block and the exhaust system, from reaching more sensitive parts of the vehicle, such as electric and electronic circuits. Thus, heat shields are important for the thermal stability of engines, helping to keep them working efficiently. Moreover, they reduce exhaust emissions because of their ability to maintain the engine at high temperatures, ensuring the efficient conversion of gases in catalytic converters for vehicles, which also require high temperatures to operate properly [1–3]. Data published by the National Association of Motor Vehicle Manufacturers indicate that Brazil's vehicle production in 2011 was 3.4 million units per year [4]. On average, each vehicle is equipped with three heat shields.

A heat shield may have two layers of metals between which can be sandwiched an insulating material whose workability is similar to that of paper [1]. However, the composition of this "paper" includes an inorganic fraction of about 80 %, which functions as thermal insulation. Typically, 1.2-m wide rolls are produced, which feed systems that cut the material into the proper size for each shield, generating cutting scraps of this type of "paper" (about 30 % of the raw material). The cut out "paper" is placed between the metal sheets and the set is then pressed together to close the "sandwich". A common heat shield weighs about 1 kg, of which approximately 70 g is the insulation material and the remainder is steel.

The physical characteristics of the insulating material differ from one manufacturer to another, but its chemical composition usually involves aluminates, silicates and/or micas, which are typical components of refractory materials that are also used in ceramic furnaces [2, 5, 6].

The objective of this work is to study small- and large-scale recycling of heat shield insulation material. In Brazil, the scraps of this material are discarded in landfills, while at the same time the country imports original material for the production of new insulation. Therefore, the recovery of these scraps for its original application would represent savings of natural and financial resources.

In an optimized cutting system, about 35 % of the insulation material can result in scrap. This means that almost 400 tons of scrap are annually discarded only for the production of heat shields used in the new vehicles manufactured in Brazil. The costs of the wasted raw material, collection, transport and landfilling can reach US$2,600 per ton.

Materials and methods

Given the physical similarity of thermal insulation material to paper, the idea was to test a recycling process similar to that used for scrap paper. Thus, industrial waste consisting of scraps of the original insulating material (Elrotherm® ML) was subjected to two forms of recycling: manual and industrial. The former was called manual because of its strongly artisanal nature, especially in the formation of molded pulp, while the latter was carried out at a paper recycling plant. When not mentioned differently, the equipment used for the manual recycling (item 2.1) and for the tests on the materials (item 2.3) was located at Elring Klinger, in Piracicaba, SP, Brazil.

Figure 1 presents a photograph of the scraps of the insulation material used for the experiments, i.e., after the cutting process.

Fig. 1 Scraps of the insulation material used for the experiments, i.e., after cutting

Manual recycling

Using a paper pulper adapted from a WEG 15 hp motor, the material was shredded in water until its fibers and the ceramic particles in the paper formed a homogeneous paste. This was done by gradually mixing about 50 kg of scrap paper into 100 l of water in a 200-l drum while stirring the mixture at about 180 rpm. After the scrap paper was completely dispersed, which took about 20 min, the drum was topped up with another 50 l of water while stirring for 10 min to homogenize the pulp.

The pulp was placed on a 100 × 40 × 10-cm nylon mesh screen with 10 strands/cm^2, and immersed in a water tank at a depth of 10 cm to help position the cellulose fibers uniformly.

Each screen was carefully removed from the immersion tank to ensure the pulp remained immobile and the paper was formed. The screens were oven-dried at 60 °C for 24 h until the paper reached a moisture content of 12 %, similar to that of the original material.

After drying, the paper sheets were removed from the screens and pressed individually in a 100-ton LAUFFER hydraulic press. One set of sheets was pressed only once, another was pressed twice, and a third set was pressed four times. The purpose of pressing the material more than once was to reach a thickness similar to that of the original insulation material under study, which was 1.0 mm ± 0.1 mm.

Industrial recycling

A partnership was established with a paper recycling plant that manufactures shoe insoles and notebook covers, to use the plant for 1 day to recycle the scrap insulation material.

The industrial recycling process involved the use of a hydrapulper to shred the material, using a proportion of 950 kg of scrap insulation material for each 10,000 l of water, without the addition of any binder.

After dispersing the scrap material in water for about 30 min, the stock (mixture) was transferred to blending and standby tanks, where it was left until it entered the deflaker. Before feeding it into this machine, the entire mixture went through a constant level box, which selected the stock in a concentration range that would enable the pumps to drive the system.

The stock is fed into the machine on a screen mesh with 20 strands/cm^2, which comes into contact with a felt trapping system through pressure. This felt material adheres to the stock spread on the screens and forwards it to a metal roller, which concentrates the fibers into thin layers of "paper."

The metal roller rotates together with the equipment set until the thickness determined by its solenoid valve is formed. When the sheet reaches the required thickness, in this case 2.8 mm (so that it can be removed without breaking), a knife is automatically activated to cut the sheet, which is then removed from the machine by hand.

After producing approximately 300 sheets (five per screen), the pile of sheets was placed in a dewatering press to remove the excess water from the material. The dewatered sheets were then placed in an oven and dried at three consecutive temperatures (90, 80, and 70 °C) for a total of 3 min, until they reached a moisture content of about 12 %. These procedures reduced the thickness of the sheets to about 1.4 mm. After drying, some paper sheets were pressed individually in a 100-ton LAUFFER hydraulic press, in order to obtain a thickness of 1.0 mm ± 0.1 mm.

Tests on the original and recycled materials

The recycled material was subjected to typical quality control tests for heat shield insulation material, since the objective was to use it for its original application.

Measurements were taken of the thickness, bulk density, compressibility and recovery, mass loss on ignition, and tensile strength of the recycled materials. All these tests were performed with the original materials and with the recycled sheets when they were considered ready, except for the tensile test, which was performed after heating the samples to 100 °C for 4 h. The tests and specific standards for each test were those normally applied industrially for heat shields.

The properties of the following materials were measured in these tests: original insulation (from two different lots, for comparison), manually recycled insulation without pressing (MR-0), manually recycled insulation pressed once (MR-1), manually recycled insulation pressed twice (MR-2), manually recycled insulation pressed four times (MR-4), industrially recycled insulation without pressing (IR-0), and industrially recycled and pressed insulation (IR-1). Each test was conducted with seven samples.

The material's compressibility and recovery were determined according to ASTM F-36, item k [7], using a Zwick D-7900 durometer. The bulk density of the material was determined based on DIN 28090-2 [8], which suggests the use of a sample of material with dimensions of 100 mm × 100 mm. The mass of this sample, obtained after drying for 2 h at 60 °C, should be divided by the result of the multiplication of the material dimensions, i.e., thickness, length, and width. Given the importance of thickness as a final property, this parameter was also analyzed separately.

The material's ultimate tensile strength was determined according to ASTM F-152 [9] on samples with dimensions of 25-mm width, 152-mm length and 102-mm effective length, after heating them to 100 °C for 4 h. A Zwick Roell SMART PRO tensile testing machine was used to determine the ultimate tensile strength. This test was performed with two sets of samples: a set prepared for the test in the direction parallel to the fibers of the material and another set prepared for the test in the direction perpendicular to the fibers. For the original and recycled materials, the direction parallel to the fibers was considered the dimension of longest length of the roll and the sheets, respectively.

To determine the property of loss on ignition, the DIN 52911 standard [10] suggests heating a known amount of sample to 600 °C for one hour. The material should then be removed and allowed to cool in a desiccator for approximately 30 min. Samples should be measured beforehand, recording their three dimensions and calculating their volume.

The recycled materials that showed the best results vis-à-vis the original one were subjected to a thermal insulation test, and to thermogravimetry (TGA), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) analyses, along with the original insulation (only one lot, due to the minor differences observed in previous tests).

The thermal insulation test was performed at ElringKlinger (Germany) in a test chamber developed by that company. The sample to be tested, together with an aluminized steel sheet placed adjacent to it (for support) were placed in the chamber, which was heated by infrared radiators to about 800 °C. Thermocouples were attached to measure the exact temperature adjacent to the source of irradiation and behind the heat shield in order to verify the efficiency of the insulation.

The TGA analyses were performed using a Seiko TGA-50 thermobalance in the Department of Materials and Technology of UNESP at Guaratinguetá, SP. This technique consists of measuring the mass of a sample as it heats up; in this study, nitrogen gas was used and the chamber was heated from room temperature to 800 °C, applying a heating rate of 10 °C/min. After reaching this temperature, synthetic air was used to incinerate the sample and thus determine the content of inert materials (ash) of each material.

The samples were gold-coated and their microstructure was analyzed by SEM (INSPECT$^{\mathrm{TM}}$) in the Structural Characterization Laboratory of the Federal University of São Carlos. Some regions of the samples were analyzed by EDS, based on the X-rays generated by the interaction between the electrons in the microscope and the samples, allowing for a qualitative evaluation of the material's chemical composition.

Results and discussion

Table 1 shows the results of the tests on original insulation (from two different lots): manually recycled insulation (without pressing, MR-0, pressed once, MR-1, pressed twice, MR-2, pressed four times, MR-4), and industrially recycled insulation (without pressing, IR-0, and pressed once, IR-1). The following properties were evaluated: thickness, bulk density, mass loss on ignition, tensile strength at break after heating to 100 °C for 4 h, compressibility, and recovery. In Table 1, note that the desired thickness, i.e., that of the original material, was only achieved in the manually recycled material after four pressings. The recycled materials (manual and industrial) showed the expected behavior of decreasing thickness with increasing number of pressings. In the industrial recycling process, even with pressing, the resulting thickness can be considered high compared to that of the original material. This reflects the production system used here, which requires a certain thickness (in this case, 2.8 mm) to ensure that the wet material shows minimal tensile strength, since it will be pulled after the cut is triggered by a valve when this thickness is reached.

Pressing also tends to increase the bulk density of the manually recycled material, as can be observed in Table 1. However, sample MR-4, which yielded the best thickness result, was much denser than the original materials tested here. On the other hand, the bulk density of sample MR-2 was closer to that of the original material, as well as to that of sample IR-1. The considerable difference in the thickness and density of the not-pressed recycled materials and those of the original material demonstrates the necessity for pressing after recycling.

Variations in both thickness and bulk density appear to be more related to differences in pulp concentration (higher or lower cellulose and/or particle content) caused by the material's uneven distribution on the nylon screens during recycling. In this regard, the manually recycled material was expected to show more pronounced standard deviations (SD) due to the intrinsic difficulties of reproducibility, but their SDs were similar to those of the industrially recycled material and the original material.

As it can also be seen in Table 1, the mean values and standard deviations of mass loss on ignition of all the recycled materials were very similar to those of the original product. This suggests that the recycling procedure, including the different numbers of pressings, yielded

Table 1 Mean results and standard deviations (SD) of thickness, bulk density, mass loss on ignition, tensile strength at break, compressibility, and recovery for the original insulation (from two different lots), manually recycled insulation without pressing (MR-0), pressed once (MR-1), pressed twice (MR-2), and pressed four times (MR-4), as well as industrially recycled insulation, without pressing (IR-0) and pressed once (IR-1)

Material	Value	Property						
		Thickness (mm)	Buk density (g/cm^3)	Mass loss on ignition (%)	Tensile strength at break parallel to the fibers (MPa)	Tensile strength at break perpendicular to the fibers (MPa)	Compressibility (%)	Recovery (%)
Original	Mean	1.0	0.95	16.0	5.95	2.52	21	21.0
	SD	0.1	0.05	1.0	0.03	0.15	1.5	1.5
MR-0	Mean	1.6	0.58	16.1	1.40	1.20	46.0	8.0
	SD	0.2	0.02	1.0	0.01	0.00	3.6	0.5
MR-1	Mean	1.3	0.77	16.3	1.43	1.23	37.0	15.0
	SD	0.1	0.03	0.9	0.00	0.01	2.7	1.0
MR-2	Mean	1.1	0.85	15.4	1.50	1.42	28.0	36.0
	SD	0.1	0.04	0.9	0.02	0.01	1.8	2.8
MR-4	Mean	0.8	1.19	16.2	1.70	1.52	12.0	45.0
	SD	0.1	0.06	0.8	0.01	0.01	1.5	2.9
IR-0	Mean	1.7	1.31	18.0	8.40	6.10	23.0	12.0
	SD	0.2	0.06	1.1	0.52	0.54	2.1	0.5
IR-1	Mean	1.2	1.06	17.5	7.00	5.90	12.0	51.0
	SD	0.1	0.05	1.0	0.38	0.47	1.0	3.2
Original (different lot)	Mean	1.0	0.95	15.2	6.5	3.2	28.5	21.0
	SD	0.1	0.04	0.8	0.30	0.22	2.2	1.0

compositions very similar to that of the original one. This is because, in general, the mass loss of around 15–20 % that occurred in all the samples corresponds to the burnable (organic) fraction of the insulation material, confirming that it contains about 80 % of inorganic fillers, which are responsible for the thermal insulation provided by the heat shield.

In Table 1, regarding the tensile strength at break, note that the materials show different results in the two directions, as expected, given the fiber orientation anisotropy of paper [11]. Note, also, that the tensile strength at break of the manually recycled materials is lower (in both directions) than that of the original material and that the industrially recycled materials present superior results of this property. The latter is probably due to the formation of insulation material in several layers during the paper deflaker production process (superposition of as many layers as necessary).

The inevitable breakdown of cellulose fibers during recycling may have contributed to the inferior mechanical properties of the manually recycled material. However, Hubbe et al. [12] argue that the role of the decrease in fiber length during paper recycling and its effect on the mechanical properties of recycled paper is usually overestimated. According to the authors, despite the shear the material is subjected to, merely a new pulping does not necessarily cause a sudden decrease in fiber size that would justify any significant loss of their properties. During its drying, pressing, storage, use, and disposal, paper undergoes a series of chemical and physical changes that, with the decrease in fiber length, help to explain the loss of mechanical properties commonly reported for recycled paper. These changes include the loss of cellulose fines in water (which eventually pass through the nylon screen), the emergence of cracks in the fibers, the closure of pores, decreased surface area and the formation of hydrogen bonds between the surfaces of pressed fibers [12–14]. The loss of fines may have been more intense during manual recycling because a coarser nylon screen was used (10 strands/cm^2) than the one used in industrial recycling (20 strands/cm^2), which helps to explain the inferior mechanical properties of the materials obtained by manual recycling.

Information obtained from industrial sources indicates that a minimum value for the tensile strength at break is 1.5 MPa for samples heated at 100 °C for 4 h. This means that samples MR-2, MR-4, IR-0, and IR-1 show higher than standard tensile strength.

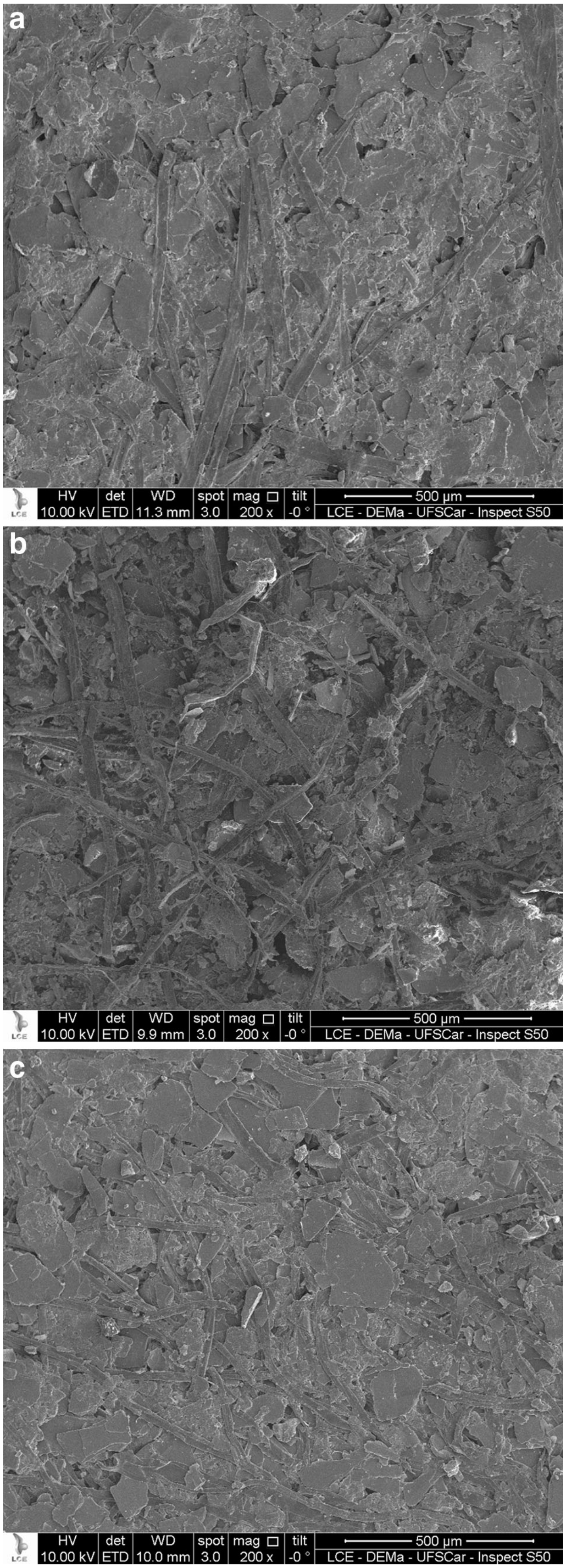
According to Table 1, regarding the materials' compressibility (i.e., how much their thickness decreases after a load is applied for a given length of time), the recycled materials closest to the original material are samples MR-2 and IR-1. With regard to the property of recovery, i.e., how much the material increases in thickness after the compressive load is removed, Table 1 shows that sample MR-1 can be considered the recycled material most closely resembling the original one.

Based on the results depicted in Table 1, it is clearly impossible to establish a rule to help predict a given outcome for the recycled material or even its behavior compared to that of the original material. This was expected due to the intrinsic variability of the manual recycling process and the fact that the industrial recycling equipment was not adapted to the material in question. Moreover, it is not possible to state that the recycling process impaired the properties of the final paper when compared to the original material.

Given the need to choose a recycled material to continue these studies, MR-2 was considered to present the best set of properties compared to those of the original material. Therefore, samples of this material were subjected to SEM, EDS, TGA, and thermal insulation analysis. For purposes of comparison, samples of IR-1 were tested and analyzed likewise. Although the latter did not yield the best results, it was also selected for these tests because it is believed that significant improvements can be achieved by adjusting the process in a plant specifically designed for this material, which would ensure better reproducibility and higher productivity than the manual recycling process.

Figure 2 shows SEM micrographs at 200× magnification of samples of: (a) original, (b) MR-2 and (c) IR-1. As can be seen, these materials are very similar, with long fibers (probably cellulose) interlacing the particles (probably of refractory), apparently comprising most of the composition. Thus, as mentioned earlier, both the original and recycled materials have cellulose fibers that entrap the ceramic particles that will provide the thermal insulation. No noticeable change in the size of the particles, and particularly of the fibers (or in the latter's thickness) is visible; which would have indicated that their dimensions were changed in the recycling process [12]. Even under higher magnification, it was also not possible to detect fiber delamination or cracking, or closing of pores, which could, like decreased average fiber length, negatively impact the properties [12–14].

Figure 3 shows the EDS results from the region presented in Fig. 2c. EDS results of the other materials are not shown here because they were identical in terms of the position and shape of the peaks, as well as the identification of the atom that generated the peaks. Thus, the results in Fig. 3 and the results of the other materials under study presented the same elements (carbon, oxygen, iron, sodium, magnesium, aluminum, silicon, potassium, and titanium). This is an interesting indicator that recycling did not affect the material's composition, and confirms the mass loss on ignition test results (Table 1). While the



◀**Fig. 2** SEM micrographs at x200 of samples of: **a** original, **b** MR-2 and **c** IR-1

presence of carbon indicates cellulosic fibers [15], the presence of the other elements is consistent with the information that the insulating material of heat shields may consist of aluminates, silicates, and/or micas [1, 3, 6]. Mica is a group of complex minerals that may contain, besides silicon and oxygen, all the metals observed in the spectra (iron, sodium, magnesium, aluminum, potassium, and titanium) [16].

Figure 4 shows the curves of the thermal insulation test of the materials: (a) original, (b) MR-2 and (c) IR-1.

In Fig. 4, note that the original material and the recycled materials were extremely effective in insulating a heat source of 800 °C, since the maximum temperatures reaching the thermocouple located behind the insulation were 308 °C for the original material, 315 °C for the manually recycled material, and 306 °C for the industrially recycled material. The variation in the difference in maximum temperature reached by the materials can be considered acceptable, particularly when one considers that the recycled materials, at least graphically, presented a better behavior than the original one at intermediate heating times: the recycled materials took longer to reach the region of maximum temperature.

Table 2 describes some results of TGA, in wide temperature ranges, of 310, 620 and 800 °C, recorded in the thermal insulation test (Fig. 4). It should be noted that no oxygen was allowed to enter in the TGA up to 800 °C, unlike the thermal insulation test, which was performed in ambient atmosphere. Table 2 also shows the ash content of each sample.

Table 2 shows that the recycled materials were consistently more stable (lower mass loss) than the original material at the temperatures recorded in the thermal insulation test. This stability helps explain the good thermal behavior displayed by the recycled materials, which was comparable to that of the original insulation (Fig. 4).

At the end of the test, the materials showed similar ash contents, 81.9–83.6 %, confirming the inference drawn from the analysis of the micrographs (Fig. 2), which suggests that the fraction of refractory ceramic particles (which are inorganic and do not normally pyrolize or combust) was much higher than the fraction of cellulose fibers (organic, i.e., pyrolysable and combustible). These results are in agreement with the test results of mass loss on ignition (Fig. 4) performed in an oxidative atmosphere, which indicated that the original and recycled insulation materials contained a 15–20 % fraction burnable at 600 °C.

The results presented in Fig. 4 show the real possibility of using scraps of original material in the manufacture of

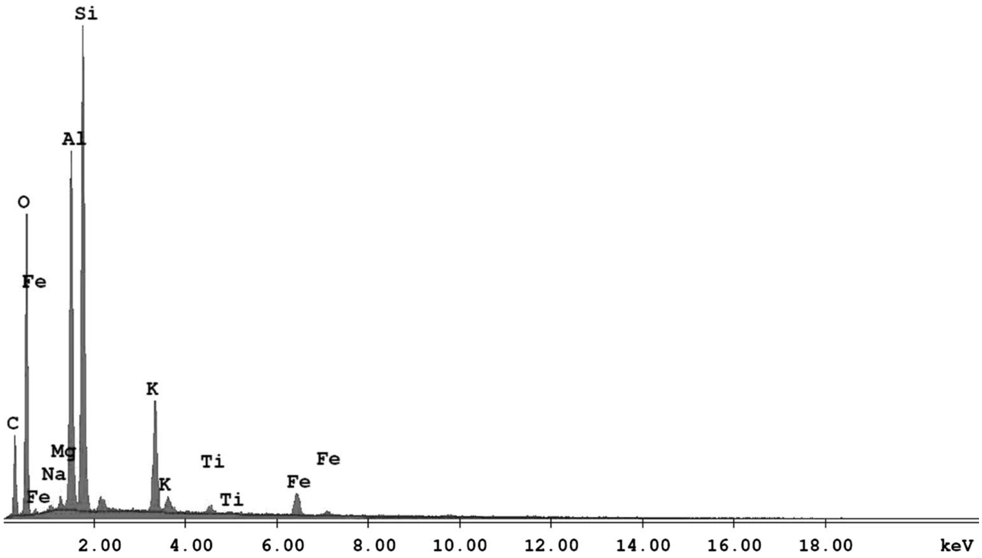


Fig. 3 EDS results of the sample of IR-1

products with the same function. This possibility is the main purpose of any recycling process, given the possibility of maintaining the added value of the original product.

Moreover, the product in question here can be considered noble and its disposal should be avoided, not only due to its potential and cost (of the material and of landfilling), but also due to its final burial in the ground. According to Table 1, at most 17.2 % of the original material is organic, i.e., it may eventually biodegrade. The remainder is inorganic and stable even at temperatures close to 900 °C under the action of oxygen. In other words, in a landfill, unless it reacts with some other component, most of the material is expected to remain intact for a very long time.

Its high inorganic load makes the alternative of incineration impractical, unlike paper in general, which is always aimed at recovery of the energy it contains. For example, paper used in a copy machines has an average ash content of 21.6 % [11]. Its higher organic load means that the idea of burning is a constant in studies of plain paper, including comparisons based on life cycle assessments [17].

Byström and Lönnstedt [18] discuss the advantages and disadvantages of recycling waste paper and of using it to obtain renewable energy for the pulp manufacturing process itself. According to the authors, waste paper pulping offers several advantages, including the absence of wood waste and the fact that it does not involve chemical dissolution. However, when the waste paper is already printed, it may be necessary to remove the ink impregnated in it. Furthermore, the electric power used in the pulp manufacturing process (recycled or original) is generally based on non-renewable sources of energy and the use of scraps is seen as a way to change this situation.

In this context, the recycling of scrap heat insulation used in this work would offer the advantages of pulping waste paper, as well as others. This scrap insulation material can be considered of high quality because it is not printed and, because it is an industrial waste, it contains a minimal amount of impurities and none of the materials associated with ordinary post-consumer waste paper, such as adhesives and staples [19]. In terms of quality, the advantages of these scraps for recycling should be added to the low energy potential of burning this material, which makes this option unattractive, as mentioned earlier.

In the case of a roll manufactured from recycled material, the scrap recycling of this material should be subjected to a new study. If the obtained re-recycled material does not reach the desired quality in terms of mechanical properties (more related to the cellulosic fraction), the original scrap can be mixed with the recycled one. There is still the possibility of refining, a step usually applied to the production of paper from wood and even to its recycling. It is well-known that refining improves mechanical properties, by promoting attraction among the cellulosic fibers [12, 13]. If the insulation properties do not reach those of the original material, then the possibility of using the recycled material in places where the temperature peaks are lower should be verified.

Conclusions

This study demonstrated the possibility of obtaining a product similar to the original from scrap thermal insulation used in automotive heat shields by a simple paper recycling process.

Fig. 4 Heating and thermal insulation curves: **a** original, **b** MR-2, and **c** IR-1. The *line* at the *top* represents heating of the source, the one in the *middle* represents the temperature of the inner surface of the heat shield, and the one at the *bottom* refers to the shield's external surface temperature, i.e., the temperature after heat deflection

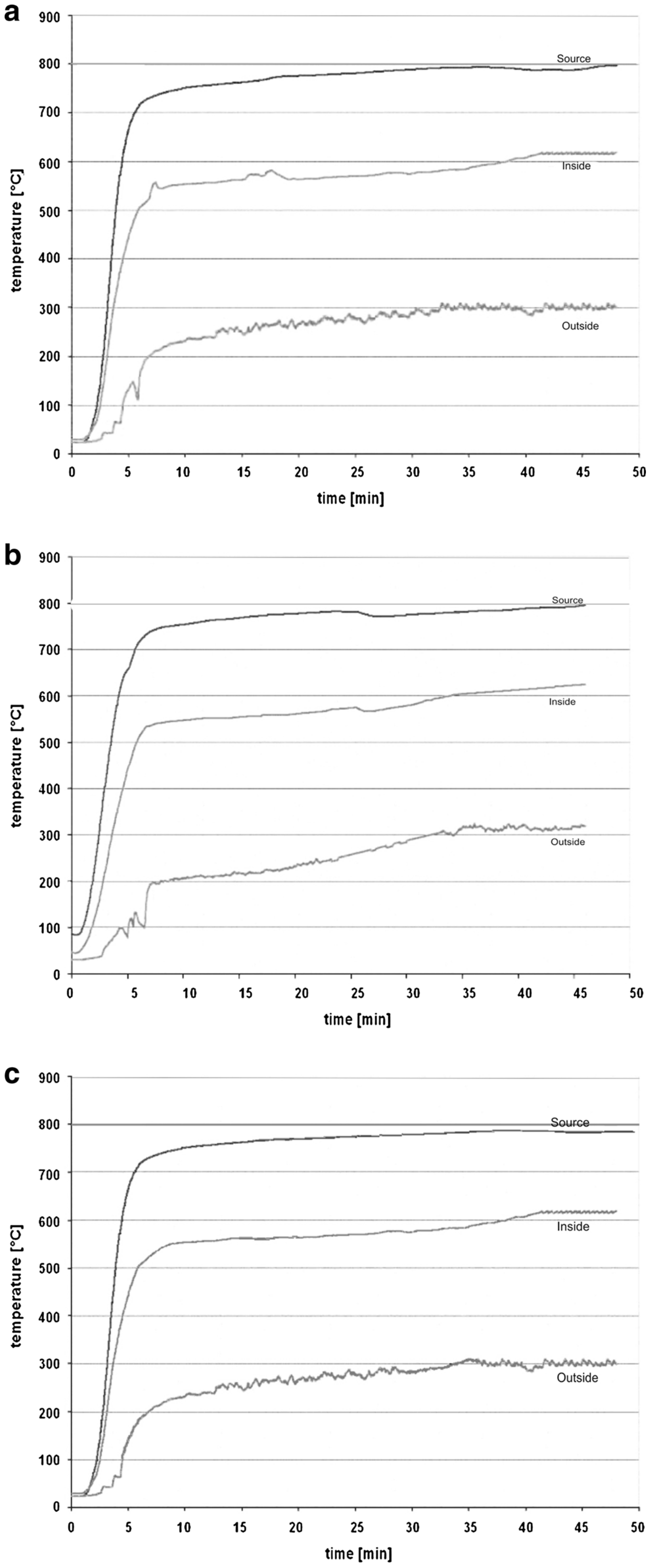


Table 2 Residual mass after 310, 620, and 800 °C, and ash content of the samples

Temperature range (°C)	Residual mass (%)		
	Manually recycled material (MR-2)	Industrially recycled material (IR-1)	Original material
25–310	97.9	98.4	93.5
25–620	85.8	83.9	83.3
25–800	85.1	83.6	82.8
Ash content (25–900)	83.6	81.9	82.8

Moreover, the recycled materials (industrial pressed once and manual pressed twice) were found to satisfy the main requirement, i.e., thermal insulation. After the heat irradiation that heated the environment outside the shield to 800 °C, both the tested recycled insulation and the original material reduced the temperature behind the shield to about 310 °C. This shows the feasibility of this recycling to produce new thermal insulation material. Currently, this scrap material is discarded in landfills.

The SEM, EDS, and TGA analyses led to the conclusion that the recycled materials did not exhibit noticeable differences in their composition, reaching an ash content of 81.9–83.6 % (the ash content of the original material was 82.8 %). TGA also indicated that the recycled materials were even more thermally stable than the original insulation material in most of the evaluated temperature ranges. This was confirmed by the thermal insulation test, since the recycled materials took longer than the original material to reach the region of maximum temperature.

These results were obtained from the material before its consumption. In the case of post-consumer material, such as the ones that are present in an end-of-life vehicle, the recycling is not as interesting. Besides the degradation that can likely occur in the organic fraction of the insulation material during the service life of a heat shield (Table 2), one must consider the labor cost to dismantle the heat shield. Another aspect that makes post-consumer recycling disadvantageous is the small percentage of mass of the insulation material in a heat shield (7 %) and in an ordinary vehicle (0.02 %, considering three heat shields per vehicle of 1 ton).

Acknowledgments The authors are indebted to the ElringKlinger Group and to the professionals who contributed to the data collected for this manuscript, especially to Mr. Hans Eckert for his invaluable assistance in this research, to Prof. Maria Odila Cioffi (UNESP-Guaratinguetá), and to Francisco Xavier da Silva.

References

1. ElringKlinger (2011) Elrotherm^{TM} shielding systems. Elringklinger, Langenzenn. http://www.elringklinger.de/sites/default/files/katalog-abschirmsysteme-201009-en.pdf. Accessed 27 March 2013
2. Poziomyck MM (2009) Master's thesis. Federal University of Rio Grande do Sul, Porto Alegre. http://www.lume.ufrgs.br/handle/10183/21266?show=full. Accessed 27 March 2013
3. Sanwa (2013) Heat shields. Sanwa Packing Industry, Osaka. http://www.sanwa-packing.co.jp/english/html/lineup.html. Accessed 27 March 2013
4. Dana (2013) Protec® Shield systems for thermal and acoustic insulation. Dana, Neu-Ulm. http://dana.com/Automotive_Systems/Products/Sealing%20Products/TAPS/protec.aspx. Accessed 27 March 2013
5. ANFAVEA—National Association of Motor Vehicle Manufacturers (2012) Brazilian motor vehicle industry survey 2011. ANFAVEA, São Paulo. http://www.anfavea.com.br/anuario.html. Accessed 27 March 2013
6. Unifrax (2009) Fiberfrax ceramic fiber paper. Unifrax, Niagara Falls. http://www.fiberfrax.com/files/Fiberfrax-Papers.pdf. Accessed 27 March 2013
7. ASTM International (2003) Standard Test Method for Compressibility and Recovery of Gasket Materials (ASTM F-36-K). ASTM, West Conshohocken
8. DIN—Deustches Institut für Normung (1995) Statisk gaskets for flange connections (DIN 28090-2). DIN, Berlin
9. ASTM International (1995) Standard Test Methods for Tension Testing of Nonmetallic Gasket Materials (ASTM F 152). ASTM, West Conshohocken
10. DIN—Deustches Institut für Normung, (1990) Determination of loss on ignition (DIN 52911). DIN, Berlin
11. Lavrykov AS, Ramarao BV (2012) Thermal properties of copy paper sheets. Dry Technol 30:297–311
12. Hubbe MA, Venditti RA, Rojas OJ (2007) What happens with the cellulosic fibers during the paper making and recycling? A review. Bioresources 2(4):739–788
13. Chevalier-Billosta V, Joseleau JP, Couchaux A, Ruel K (2007) Tying together the ultrastructural modifications of wood fibre induced by pulping processes with the mechanical properties of paper. Cellulose 14:141–152
14. Letková E, Letko M, Vrška M (2011) Influence of recycling and temperature on the swelling ability of paper. Chem Pap 65(6): 822–828
15. Santos ML, Lima OJ, Nassar EJ, Ciuffi KJ, Calefi PS (2011) Study of the storage conditions of the sugarcane bagasse through thermal analysis. Quim Nova 34(3):507–511
16. Anracibia G, Morata D (2005) Compositional variations of syntectonic white-mica in low grade ignimbritic mylonite. J Struct Geol 27:745–767
17. Wang L, Templer R, Murphy RJ (2012) A life cycle assessment (LCA) comparison of three management options for waste papers. Bioresour Technol 120:89–98
18. Byström S, Lönnstedt L (2000) Paper recycling: a discussion of methodological approaches. Resour Conserv Recycl 28:55–65
19. Iosip A, Nicu R, Ciolacu F, Bobu E (2010) Influence of recovered paper quality on recycled pulp properties. Cell Chem Technol 44(10):513–519