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Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies

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ABSTRACT

This paper reports a study on thermal and sound insulation samples developed from waste wool and recycled polyester fibers (RPET) for building industry applications. Waste wool fiber is a potential source of raw material for thermal and sound insulation applications, but its quantities are limited. In order to overcome the above problems, waste wool fibers were mixed with RPET fibers in 50/50 proportions in the form of a two layer mat. Another set of three samples from 100% waste wool and 100% RPET fibers were also prepared. All samples were tested for thermal insulation, acoustic, moisture absorption and fire properties. Also, behavior of the samples under high humidity conditions was evaluated. An extensive biodegradability study was conducted to analyze the conversion of organic carbon into carbon dioxide by composting method for 50 days. Two layer 50% waste wool and 50% RPET mat provided the best insulation, acoustic, moisture absorption and fire properties. The RPET/waste wool mats were absorbing more than 70% incident noise in the frequency range of 50–5700 Hz. The RPET/waste wool mats have adequate moisture resistance at high humidity conditions without affecting the insulation and acoustic properties. 65–70% biodegradation was achieved for wool/RPET mats for 50 days composting period.

1. Introduction

The growing environmental awareness throughout the world has triggered a shift towards developing environmentally friendly materials from renewable resources. Thermal insulation plays an important role in contributing to the energy savings in the building by heat gains and losses through the building envelope [1]. A study reported that effective building insulation alone will save over one hundred times the impacts of carbon foot print from material usage and disposal, irrespectively of the materials used [2]. At the same time, noise pollution is increasingly getting more attention amongst the construction industry as it is a major health concern [3] and demand for better noise insulating materials is increasing. The widely used insulation material in the construction industry is the glass fiber based which is derived from the silica sources and other synthetic fibers used are derived from the petroleum based resources. Glass fiber based materials known to have carcinogenic effects [4]. With new regulations and increasing demand for alternative materials, development of materials which can provide both thermal and sound insulation will become a sustainable alternative. A study has been reported on the development of insulation materials from sheep wool fibers with comparable properties as that of conventional materials [3]. In another recent study, authors highlighted the quantity issues of alterative sheep wool materials available in the market to meet the demand for the building sector, although sheep wool materials are very good insulators [5]. One of the problems associated with the sheep wool insulation materials is their susceptibility to higher moisture content and resultant drop in their performance [6,7].

Wool is a natural fiber obtained from shearing the sheep, known to have many outstanding properties including excellent insulation and low flammability characteristics [8]. Wool fibers are found mainly in Australia, New Zealand, China, United Kingdom, South Africa and other places around Europe and Asia. Short wool fibers obtained by shearing the sheep-hair are not suitable for apparel/clothing purpose; and therefore generally discarded as a waste material. These wool fibers are also obtained from the sheep's nurtured for meat production. These non-standard fibers are known as waste wool fibers. Plenty of such waste wool fibers are available in South Africa without any value addition to the

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wool farmers. The price of this waste wool is less than $0.3 US dollar per kilogram [9]. In terms of environmental profiles of materials, wool fiber based materials consume lowest amount of energy during material use and disposal stage than any other existing natural materials [10]. Since the quantity of waste wool fibers are not enough to meet the alternative material demand, it must be combined with another material to develop value based products like insulation materials. At the same time, this new material must contribute to green material development with a low carbon foot print.

Recycled polyester (RPET) fibers are derived from the post-consumer waste of plastic bottles which are potential source of raw material for reducing environmental pollution [11]. It uses less energy in fiber manufacturing than the conventional virgin polyester fibers and also helps in reducing carbon foot print by recycling the plastic bottles which otherwise goes into the landfill sites and remain there for ages as they are not biodegradable. There are some papers available in the literature covering the biodegradation of wool as well as polyester [12,13] fiber based materials. There is no published information available in using the waste wool fibers as raw materials in developing value based dual insulator (thermal and sound insulation) materials. Furthermore, there are no studies available on the biodegradation behavior of the waste wool based product in order to examine its carbon foot print as an alternative source of raw material.

The objective of this work is to develop cost effective waste wool based materials/samples for building industries with both thermal and sound insulation properties besides other important properties such as moisture absorption and fire resistance. Furthermore, to study the biodegradation behavior of the developed samples as well as to study their behavior during high humidity conditions. This type of alterative materials must contribute to development of green building materials and conserve environment, in which sample layers are recyclable and biodegradable. It will also help to minimize the carbon foot print, during disposing-off the samples after their service life.

Two types of waste wool fibers, coring wool (CW) and dorper wool (DW) were used. These names were derived from the sheep breed. Two nonwoven mats were produced from these fibers. Another mat was produced from RPET fibers. Waste wool fibers were then combined with RPET in 50/50 proportions in the form of a two layer mat and named as coring wool product (CWP) and dorper wool product (DWP) as shown in Table 1. In total, five samples were produced and their performances have been evaluated including the biodegradation behavior. Needle-punching mat making process was used to prepare the samples.

2. Materials and methods

2.1. Nonwoven mat preparation

For preparing the nonwoven mat, individual fibers were first opened on a bale opener. Then, the fiber web was cross-lapped on a cross lapper and needle-punched on a needle-punching machine to bond a fiber web. Specifications of the fibers used were, RPET-linear density 6.7 dtex, staple length 32 mm, siliconized; CW-fiber diameter 20.7 μm, staple length 22 mm; DW-fiber diameter 28.6 μm, staple length 38 mm. Five samples were prepared by needle-punching process (Table 1). Three samples were prepared from the 100% fibers without mixing with RPET fiber and final sample was a single layer sample. For preparing CWP and DWP, RPET and waste wool fibers were used in 50/50 proportions in the form of a two layer mat, one side was either CW or DW, whereas other side was RPET. The needle-punching parameters were kept same for all samples. The nominal area weight of the samples (mats) was 1000 g/m^2. Thicknesses of the samples were in between 15 and 17 mm. A triplicate of each sample was produced and average values of the triplicate were used to characterize each sample.

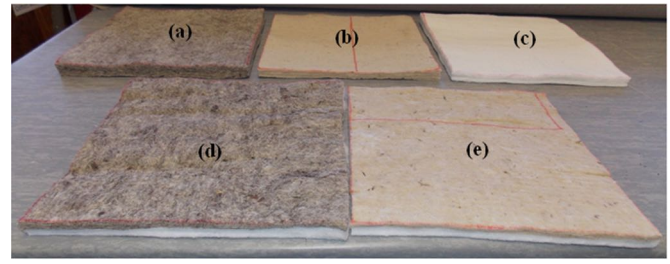

Fig. 1. Photograph of the samples: (a) DW 100%, (b) CW 100%, (c) RPET 100%, (d) DWP, (e) CWP.

Since material requirements for building industries are stringent in terms of fire properties, waste wool and RPET fibers were sprayed with a low level of fire retardant (5% by weight, comprising a mixture of di-ammonium phosphate and sodium tetraborate) to impart fire retardancy properties. This treatment also assists in eliminating fungus and moth problems associated with the waste wool fibers. Furthermore, 1% silicon (by weight) was sprayed on the waste wool fibers in order to improve their moisture resistance. All spraying was carried out on the surface layers only in order to maintain the recyclability and biodegradability of the sample. At the end of service life, the surface layer sprayed with chemicals can be easily peeled off by hand, without using any mechanical action and the remaining sample can be subjected to biodegradability and recyclability. The surface layers approximately contribute to 10% of sample composition.

Photographs of the samples are shown in Fig. 1. All samples were conditioned for 24 h prior to testing in a standard testing atmosphere maintained at 65 ± 5% humidity and 20 ± 2 °C temperature.

2.2. Thermal conductivity

Laser Comp Fox 314 heat flow meter was used for measuring the thermal conductivity as per the ASTM C518-10 standard [14]. Sample size used for measurement was 300 mm × 300 mm × (samples thickness). In this test, the sample was placed in between two solid plates. The temperatures of the plates were kept at three levels during the testing. These levels were set points 1, 2 and 3. The test temperature for set point 1 was −5 °C. Similarly, the test temperatures for set points 2 and 3 were 15 °C and 35 °C, respectively.

Table 1
Sample compositions and their physical properties.

Sample code	Sample composition	Number of layers	Thickness [mm]	Bulk density [kg m^{-3}]
Coring wool (CW)	100%	Single	15	66.66
Dorper wool (DW)	100%	Single	17	58.82
Recycled polyester (RPET)	100%	Single	16	62.50
Coring wool product (CWP)	50% (CW)50% (RPET)	Double	16	62.50
Dorper wool product (DWP)	50% (DW)50% (RPET)	Double	17	58.82

Note: the number shows the % of fibers by weight.

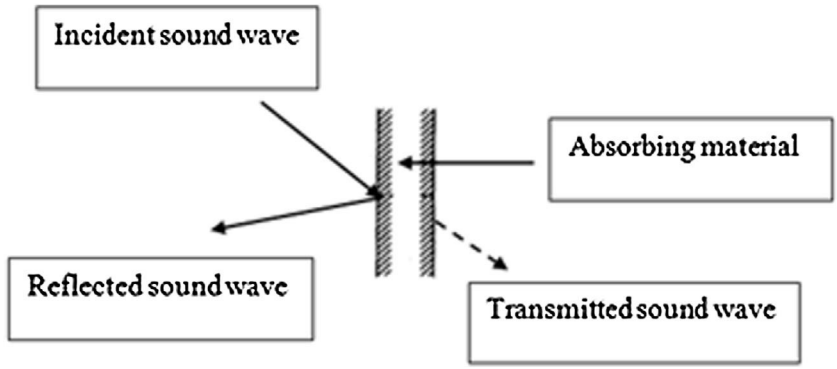

Fig. 2. Sound wave propagation in a material.

For each temperature, the thermal conductivity was measured and the average value was reported. Direction of heat flow was upward during the testing. Five readings were recorded for each sample.

2.3. Acoustic property

When a sound wave is incident on a material, it can be absorbed, reflected and transmitted by the material. All three phenomena are possible depending upon the types of material (Fig. 2). Absorbing the incident sound wave is an effective way to control the noise.

Sound absorption coefficient (α) was measured according to ASTM E 1050-10 standard test method by using an impedance tube, two microphones and a digital frequency analyzer [15]. This method is used to determine the sound absorption capacity of a material in response to the normal incidence sound wave. The LMS acoustic testing instrument from LMS International, Belgium was used for this purpose. The frequency range used for the measurement was 50–5700 Hz. The frequency range was divided into three different classes, low (50–1000 Hz), medium (1000–2000 Hz) and high (2000–5700 Hz) ranges. Five readings were taken randomly from each sample for evaluating acoustic properties.

2.4. Moisture absorption and humidity testing

Moisture absorption of a material plays a significant role in its performance behavior. It is particularly important for the insulation materials. Moisture absorption of the insulation samples were measured according to the SANS 1381-1:2007 standard [16]. Binder climatic chamber KMF 115 E5.2 from Binder Inc, Bohemia, USA was used for this testing. In this method, samples were dried for 30 min initially at 135 °C in an oven and then weighed. Subsequently, it was dried further in oven at 135 °C for another 30 min and weighed, followed by another 15 min of drying and then weighing. The purpose of several drying cycles was to get a constant dry mass, W_d (complete dry), before placing the samples in the climatic chamber. This chamber was maintained at 90 ± 5% relative humidity (RH) and 23 ± 2 °C temperature. The dry samples were kept in the chamber for 72 h and again weighed (wet sample, W_w). Five readings were taken randomly from each sample for the estimation of moisture absorption of the sample, which is given by:

$$\frac{W_w - W_d}{W_d} \times 100$$

The moisture conditioned samples (wet samples) obtained from 72 h of conditioning was again used to evaluate the behavior of the sample under high humidity conditions (90 ± 5% RH and 23 ± 2 °C temperature).

2.5. Fire properties

Fire testing of the samples was carried out on a Dual Cone Calorimeter according to the SANS 10177-5:2007 standard [17]. Pre-conditioned samples kept in a standard testing atmosphere (maintained at 65 ± 2% humidity and 20 ± 2 °C) were tested within 3 min of removal from the controlled atmosphere. Initially, the temperature of the cone element was maintained at 400 ± 5 °C in the testing chamber for the first 5 min, and then the temperature was raised to 750 °C. The burning behavior of the samples was observed in terms of melting of samples, smoke generation, ignition and continuous burning time. Two readings were taken randomly from each sample for fire testing.

2.6. Thickness and area weight

The thicknesses of the mats were measured according to the European Disposables and Nonwoven Association (EDANA) standard, WSP 120.6 (05) [18]. The area weights of the mats were measured according to ASTM D 3776 by using an electronic balance [19]. It is defined as the mass per unit area and usually measured in g/m^2 (or gsm). Five random readings were taken from each sample for measuring thickness and areal weight.

2.7. Material structure

The longitudinal views of the mats were determined by scanning electron microscope (SEM), FEI Quanta 200 after sputter coating the samples. The applied voltage was kept at 20 KV and small spot size setting was used in capturing the SEM images. Samples were observed initially in its original form and then after 50 days of degradation. Five random samples were selected from each specimen for observation purpose.

2.8. Biodegradation

In order to study the biodegradability of the samples, the surface layers sprayed with chemicals (fire retardant and silicon coating) was peeled off by hand and the remaining sample (90%) was subjected to biodegradability testing. In this study, biodegradation test was carried out in three months old well aerated compost, derived from mushroom farm consisting of straw/hay/mulch and chicken manure. Further, the compost was sieved to a size below 0.8 mm to obtain uniform size of compost for testing biodegradability of samples as per ASTM D6400 standard [20].

The biodegradability of the test samples were carried out in biometer respirometric flasks (Fig. 3). The test sample was mixed with compost in a ratio of 1:6 (w/w sample to dry solids of compost). The mixture was then placed in a cylindrical glass vessel as

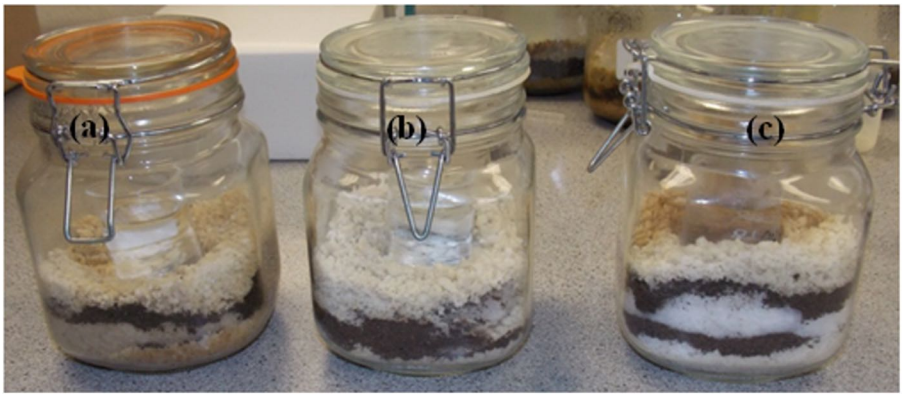

Fig. 3. Biodegradation test set up images of some of the samples, (a) CW 100%, (b) CWP, (c) RPET 100%.

shown in Fig. 4. A beaker containing 50 ml of potassium hydroxide solution (0.5 N KOH) was placed on the upper layer to trap carbon dioxide emitted during composting. During the compostability tests, the flasks were kept in air ventilated oven at a temperature of 58 ± 2 °C, which simulates actual industrial composting conditions. The moisture content of each flask was maintained at 50–55% throughout the test by measuring the weight loss due to evaporation, and adding deionized water to counterbalance such losses.

The biodegradation of the sample was tracked by trapping all the emitted carbon dioxide (CO_2) in the KOH solution. CO_2 is emitted by organic metabolization of the sample through the action of microorganisms and is representative of the total degradation due to biological factors. As gaseous CO_2 is emitted, it reacts with the KOH in the beaker as shown in Eq. (1) below.

$$2KOH + CO_2 \rightarrow K_2CO_3 + H_2O \quad (1)$$

The beaker containing KOH is removed from the biodegradation flask and barium chloride (1 N $BaCl_2$) is added to its contents as shown in Eq. (2).

$$K_2CO_3 + BaCl_2 \rightarrow BaCO_3 + 2KCl \quad (2)$$

The barium carbonate ($BaCO_3$) formed (Eq. (2)) appears as a cloudy white precipitate. The remaining amount of KOH in the solution can now be determined by titrating with 0.5 N HCl, using phenolphthalein as an endpoint indicator. This titration reaction is shown below.

$$KOH + HCL \rightarrow KCl + H_2O \quad (3)$$

The theoretical amount of carbon dioxide (CO_2(t) in g per vessel) produced by total oxidation of incubated samples in each flask can be calculated by the following expression (Eq. (4)):

$$CO_2\,(t) = M_t \times C_t \times \frac{44}{12} \quad (4)$$

where, M_t is the total dry amount of constituent or plastic sample (g) added to the compost, C_t is the relative amount of total organic carbon (g) in the total dry plastic sample. A biodegradation curve was obtained by plotting percentage carbon dioxide released versus incubation time. Biodegradation was calculated as the percentage of carbon in the polymer mineralized as CO_2 according to the expression (Eq. (5)):

$$\text{Biodegradation}\,(\%) = (CO_2)\,s - \frac{(CO_2)\,c}{(CO_2)\,t} \times 100 \quad (5)$$

where, (CO_2)s and (CO_2)c are the amount of CO_2 produced in the sample and in the control, respectively.

3. Results and discussion

3.1. Thermal insulation property

The thermal insulation properties of the samples were measured in terms of the thermal conductivity. The thermal conductivities of various samples are shown in Table 2. Lower the thermal conductivity better is the insulation property. Low values of the thermal conductivity imply higher resistance to conduction of the heat through the material. It creates a barrier between the surrounding environment and the samples. No significant

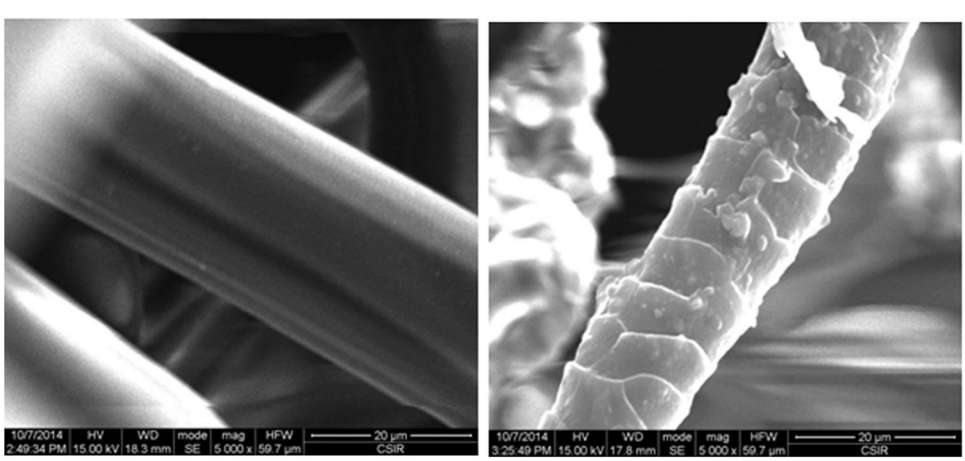

Fig. 4. SEM images of the RPET and DWP samples.

Table 2
Thermal conductivity of various samples.

Sample code	Thermal conductivity at various temperatures [W/mK]			Average thermal conductivity [W/mK]
	−5 °C	15 °C	35 °C	
CW	0.030 (0.004)	0.032 (0.004)	0.034 (0.003)	0.032 (0.004)
DW	0.031 (0.004)	0.032 (0.005)	0.034 (0.005)	0.032 (0.005)
RPET	0.033 (0.004)	0.035 (0.004)	0.038 (0.003)	0.035 (0.003)
CWP	0.030 (0.003)	0.032 (0.004)	0.035 (0.004)	0.032 (0.004)
DWP	0.030 (0.004)	0.033 (0.004)	0.035 (0.004)	0.033 (0.004)

Values in the parenthesis indicate the standard deviation.

differences were observed between the samples (Table 3). Waste wool fibers have inherent insulation properties. While comparing wool samples with RPET, a slight increase in the thermal conductivities was observed.

With the increase in temperature, thermal conductivity increases for all samples. This may be due to the fact that with the increase in temperature, the rate of heat conduction through the sample increases, which increases the thermal conductivity. CWP and DWP were showing the similar thermal conductivity values as that of 100% CW and DW samples. Two layer mats with 50% of waste wool fibers along with 50% RPET fibers provided one of the best insulation properties. These results showed that it is possible to develop samples which show similar thermal conductivity as that of 100% waste wool fibers. In order to meet the supply/demand cycle of waste wool samples, it is one of the possible ways to derive value out of waste wool fibers by mixing with RPET. These samples were suitable for roof ceiling insulation application in a building. In another paper, authors reported that the thermal insulation materials made from natural raw materials are suitable alternatives to the conventional materials [21].

3.2. Acoustic property

One of the objectives was to obtain good sound absorption property in the samples in addition to the thermal insulation property. All developed samples showed good sound absorption properties in overall frequency range (50–5700 Hz). Sound absorption coefficients (α) of the samples in various frequency ranges are shown in Table 4. The sound absorption was lower at low frequencies (50–1000 Hz) and increased from medium (1000–2000 Hz) to high frequency range (200–5700 Hz) for all the samples.

The lowest value of α was 0.61 for RPET and highest was 0.75 for DWP and this difference was significant (50–5700 Hz). Sound absorption depends upon thickness of the material amongst other factors [22,23]. Higher the α value, better was the sound absorption property. The reason can be attributed to the fact that the kinetic energy of the incident sound wave gets converted to low level of heat energy when it passes through a thicker structure. Thicker structure absorbs sound wave by causing frictional loss between sound wave and fibers, thereby dampening the effects of the propagating sound wave. Another factor was the tortuosity

Table 3
Analysis of variance (ANOVA) between various samples for average thermal conductivities.

Summary						
Groups	*Count*	*Sum*	*Average*	*Variance*		
CW	5	0.16	0.032	1.75E-05		
DW	5	0.162	0.032	2.53E-05		
RPET	5	0.175	0.035	9.5E-06		
CWP	5	0.16	0.032	0.000016		
DWP	5	0.165	0.033	0.000018		
ANOVA						
Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between groups	0.00003144	4	7.86E-06	0.455388	0.767397	2.866081
Within groups	0.0003452	20	1.73E-05			
Total	0.00037664	24				

Table 4
Acoustic coefficients (α) in various frequency ranges.

Sample code	50–1000 [Hz]	1000–2000 [Hz]	2000–5700 [Hz]	50–5700 [Hz]
CW	0.10 (0.050)	0.42 (0.050)	0.85 (0.057)	0.69 (0.058)
DW	0.16 (0.064)	0.55 (0.062)	0.94 (0.062)	0.74 (0.063)
RPET	0.09 (0.012)	0.34 (0.015)	0.81 (0.025)	0.61 (0.029)
CWP	0.13 (0.032)	0.48 (0.031)	0.89 (0.030)	0.71 (0.032)
DWP	0.18 (0.036)	0.58 (0.034)	0.95 (0.033)	0.75 (0.035)

Values in the parenthesis indicate the standard deviation.

Table 5
Moisture absorption properties of various samples.

Sample Code	Dry weight, W_d [gm]	Wet weight, W_w [gm]	Moisture absorption, $\frac{W_w - W_d}{W_d} \times 100$ [%]
CW	16.45	17.38	5.65 (0.847)
DW	17.04	18.02	5.75 (0.805)
RPET	15.40	16.08	4.44 (0.666)
CWP	16.83	17.77	5.58 (0.781)
DWP	16.95	17.80	5.01 (0.751)

Values in the parenthesis indicate the standard deviation.

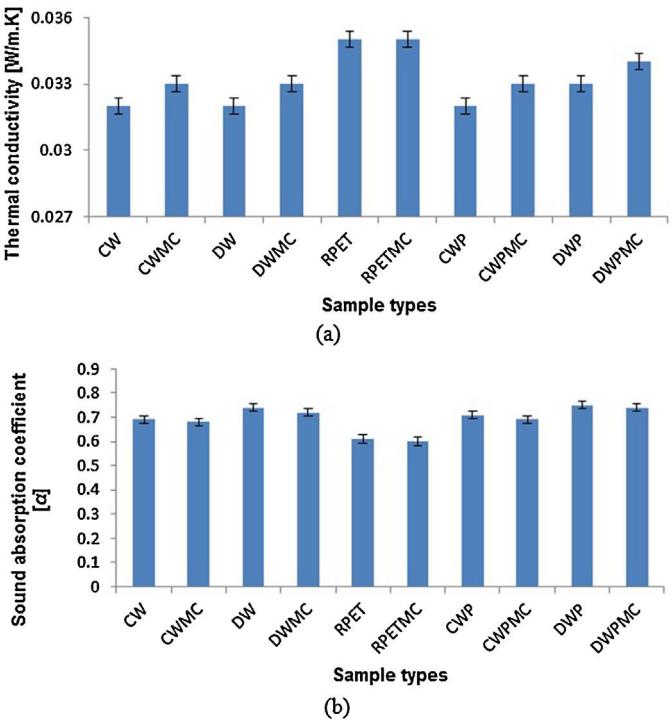

Fig. 5. (a) Thermal conductivity and (b) Sound absorption (50–5700 Hz) properties of the samples after subjecting to high moisture content. CW—Coring wool, CWMC—Coring wool after moisture conditioning, DW—Dorper wool, DWMC–Dorper wool after moisture conditioning, RPET–Recycled polyester, RPETMC–Recycled polyester after moisture conditioning, CWP–Coring wool sample, CWPMC –Coring wool sample after moisture conditioning, DWP–Dorper wool sample, DWPMC - Dorper wool sample after moisture conditioning.

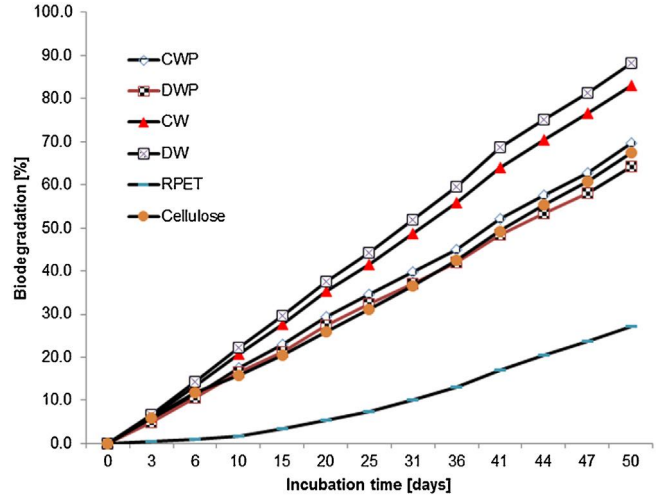

Fig. 6. Biodegradation results of test samples under compost conditions.

of the nonwoven mats, which is a ratio of the length of the open pores (i.e. the length of the interconnected through pores) to the material thickness. Higher thickness of the sample allows the sound wave to be channeled through the tortuous path of the through pores, thereby creating more frictional losses and thereby increasing the α value. In the case of lower thickness, path lengths available for the propagation of the sound wave were not enough to cause sufficient amount of frictional loss. Also, DWP was a two layer structure, designed to entrap the sound wave within the structure. Two layer structure with air gap between them assists in dampening the sound wave within the sample.

SEM images of the RPET and DWP (Fig. 4) samples showed the presence of very tiny scales in case of the DWP's wool fiber component. These scales were effective in creating additional obstruction to the passage of sound, thereby improving the sound absorption by the sample. Also, in the medium (1000–2000 Hz) and high frequency range (2000–5700 Hz), these scales further assisted in dampening the sound wave. In the case of RPET, as it is a smooth fiber without presence of any scales, sound absorption in the similar frequency range was lower. Waste wool based samples like CW, DW, CWP and DWP showed comparable α values. DWP showed higher α values than CWP in overall (50–5700 Hz) as well as individual frequency ranges, due to the presence of longer fiber length of DW in DWP samples, which may result in creating a more uniform pore structure for the passage of sound. The RPET/waste wool mats (CWP and DWP) can absorb more than 70% of the incident noise in the overall frequency range of 50–5700 Hz. In another study's authors reported very good sound insulation properties of sheep-wool as compared to polystyrene or rock wool for wall insulation application [24,25].

3.3. Moisture absorption property

All natural fibers (including fibers from animal origin) absorb moisture when they are exposed to the environment, especially during high humidity conditions [8]. If the insulation sample absorbs the moisture to a considerable extent, it significantly affects the thermal insulation property and its ability to perform the intended function of providing insulation. In order to preserve

Table 6
Fire properties of various samples.

Sample code	Melting characteristics	Smoke generation (Second)	Ignition time (Second)	Continuous burning time (Seconds)
CW	Shrink and melt	5	20	135
DW	Shrink and melt	5	20	140
RPET	Shrink and melt	8	15	170
CWP	Shrink and melt	7	18	150
DWP	Shrink and melt	7	18	150

Table 7
Elemental analysis results of test samples.

Sample code	N [%]	C [%]	H [%]	S [%]
CW	16.34	43.42	3.59	1.08
DW	13.37	46.28	8.52	2.29
RPET	2.06	63.09	2.74	0
CWP	10.54	52.06	5.78	0.86
DWP	11.79	49.58	6.89	1.64

Note: All the results are average of two test samples.

the insulation properties of the mats, the waste wool components were sprayed with silicon and tested for moisture absorption at 90 ± 5% RH and 23 ± 2 °C for three days in the climatic chamber. The RPET sample was tested without any silicon spraying. The results are shown in Table 5. All samples absorbed 4–6% of moisture, little higher than the specific requirement of 2% [16]. One of the important issues regarding sample behavior under high humidity conditions was to understand if there were any significant reductions in main performance properties, i.e. thermal insulation and acoustic after moisture absorption.

The same moisture conditioned samples obtained after 72 h of conditioning were used to evaluate the behavior of the absorption in high humidity condition. No significant changes in the acoustic absorption as well as thermal insulation values of the sample after performing the above test were observed (Fig. 5a and b). The spraying of silicon acts as barrier to moisture penetration and it assists in maintaining performance properties of the samples. These results showed that the RPET/waste wool mats have adequate moisture resistance under high humidity conditions without changing the insulation and acoustic properties.

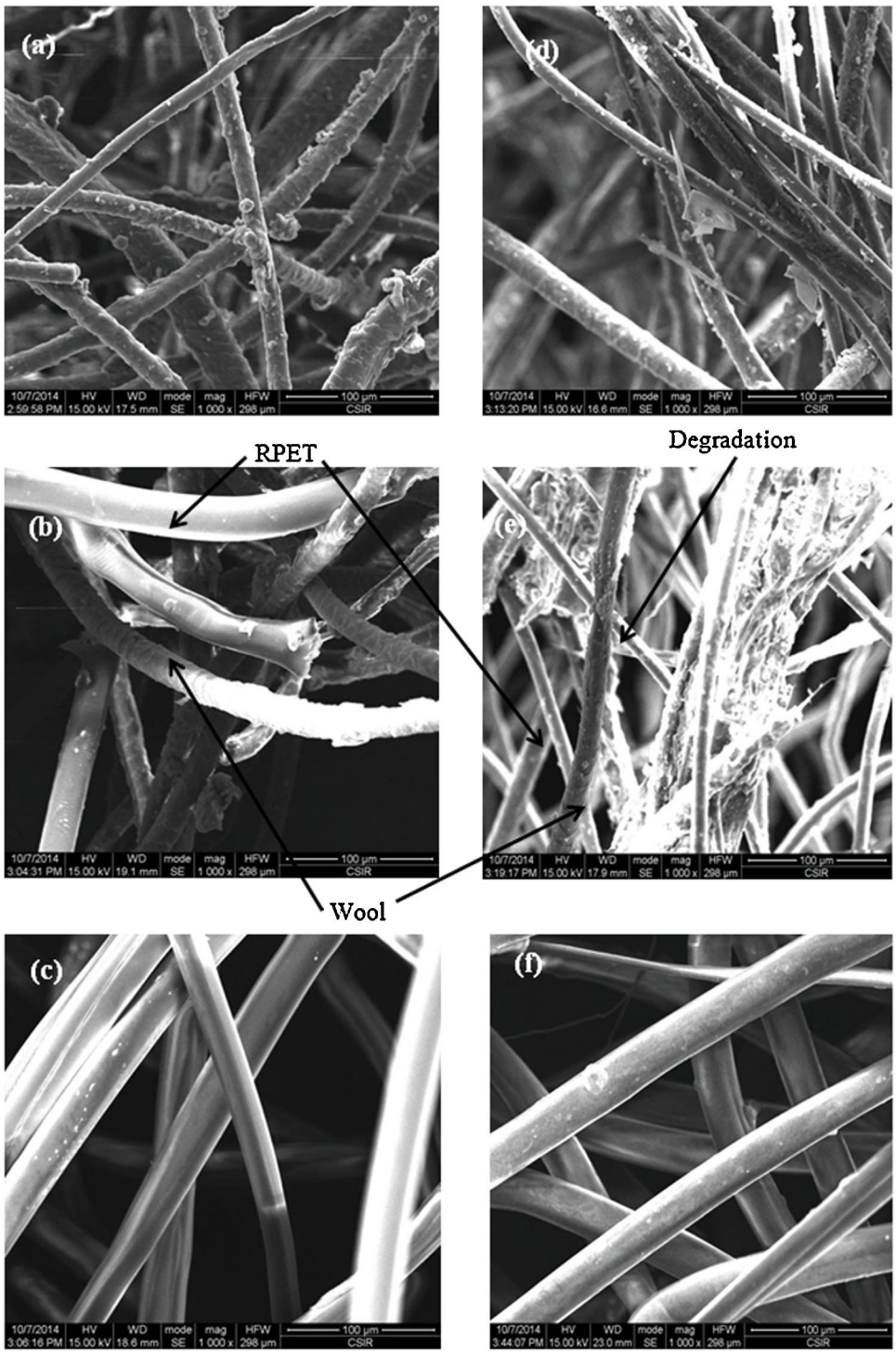

Fig. 7. SEM images of the original sample – 0 day of degradation (a) CW, (b) CWP, (c) RPET; – after 50 days of degradation (d) CW, (e) CWP, (f) RPET.

Table 8
Organic carbon content and theoretical carbon dioxide (CO_2)t of test samples and reference sample analyzed in the compost respirometric test.

Run	Sample code	Amount [mg]	C [%]	C [mg]	(CO_2)t [mg]	Biodegradation (%) in 50 days
1	CW	4601	43.42	1997.75	7325.10	83.0
2	DW	4050	46.28	1874.34	6872.58	88.3
3	RPET	5230	63.09	3299.61	12098.56	27.2
4	CWP	4173	52.06	2172.46	7965.70	69.7
5	DWP	4802	49.58	2380.83	8729.72	64.3
6	Cellulose (Reference)	5092.1	42.3	2153.96	7897.85	67.4

3.4. Fire properties

The results of fire properties of various samples are shown in Table 6. All samples shrink first and then melt.

The CW and DW samples showed better fire properties than that of RPET sample. The CW and DW samples took bit longer time to ignite in comparison to that of RPET. This was due to inherent fire retardant properties of waste wool fibers in the CW and DW samples, which delayed the burning. CWP and DWP showed similar fire properties as that of CW and DW, expect bit longer burning time which may be because of the presence of RPET in the sample. All samples were not combustible at the onset of fire (temperature was approximately 400 °C), first they melted, generated smoke and then burnt at higher temperatures (approximately 750 °C). These samples can prevent, to certain extent, an immediate fire hazards (temperature resistance up to 400 °C).

3.5. Biodegradation results

The elemental analysis of the samples used for biodegradation studies is shown in Table 7. CW and DW samples mainly consist of carbon, followed by nitrogen, hydrogen and sulfur, whereas RPET mainly consists of carbon.

4. Compostability tests

A maximum level of biodegradation of 83% and 88% in 50 days was observed for DW and CW, respectively (Fig. 6 and Table 8). However, an acceleration phase was carried out for the DWP and CWP samples after 10 days of incubations and they were approaching similar biodegradation behavior to that of micro-crystalline cellulose powder, i.e. reference samples (Fig. 6). Comparing with other test samples, the observed biodegradation behavior for RPET sample was slow. Biodegradation results of the samples under compost conditions in terms of carbon conversion into CO_2 emissions indicate about 60–70% biodegradation in the case of RPET/waste wool mats in 50 days incubation time. Whereas, during the same time period, the observed biodegradation was about 80–85% in 100% waste wool mats and 30% in case of 100% RPET mat (Fig. 6 and Table 8).

Morphological studies on some of the mats in its original condition (0 day) and after degradation (50 days) is shown in Fig. 7. In its original condition, CW mat showed the presence of scales on fiber surface, whereas CWP mat showed the presence of scales as well as smooth fiber surface of RPET (Fig. 7a and b). RPET mat showed outer smooth fiber surface (Fig. 7c). After 50 days of degradation, most of the scales in CW mat were degraded (Fig. 7d). These results also support previous biodegradation studies reported in the case of 100% waste wool mats, where maximum biodegradation was observed for the CW and DW mats. CWP mat showed the presence of degraded CW fiber component, whereas RPET component remained mostly intact (Fig. 7e). It also supports the previous finding of 60–70% biodegradation in CWP and DWP mats. There was not much change in the morphology of RPET mat after degradation (Fig. 7f).

The insulation materials developed from RPET/waste wool blend contribute towards green building materials, where the layers were recyclable (RPET) and biodegradable (CW and DW fiber components). A life cycle assessment (LCA) will be conducted in the next step to confirm the contribution or reduction in carbon foot print. Even after the service life, the waste wool fiber layers can be used in agricultural land for nitrogen fixation of the plants, so that use of chemical fertilizer can be minimized to a certain extent. Furthermore, the combination of RPET/waste wool was an easy way to meet the supply and demand cycle of materials in the context of South Africa as well as the rest of the world.

A durability test in a wall condition is necessary to lead this product to build materials market, particularly for wall insulation application. Furthermore, volatile organic compound (VOC) emission test is also necessary to confirm the safety of the materials in use.

5. Conclusion

Five different nonwoven mats (CW, DW, RPET, CWP and DWP) were produced and tested for thermal insulation, acoustic absorption, moisture absorption, fire retardancy and biodegradation behavior. RPET/waste wool mats (CWP and DWP) showed the best thermal insulation, acoustic absorption, moisture absorption and good fire properties. CWP and DWP mats were absorbing more than 70% of the incident noise (50–5700 Hz). There were no significant changes in the thermal insulation and acoustic properties of the mats when evaluated under high humidity conditions. The observed biodegradation was about 60–70% for CWP and DWP mats in compost incubation for 50 days. During the same time period, the observed biodegradation was 80-85% for CW and DW mats and 30% for RPET mats. SEM images showed that some of the scales present in the wool fibers of CW and CWP mats were degraded, whereas as expected no changes in the morphology of RPET fiber mat was noticed. These alternative materials will contribute to the cost benefit as well as green building initiative through the development of materials from natural and recycled resources. LCA will be conducted in the next step to confirm contribution to the carbon foot print, as well as the VOC emission test to confirm the safety of the materials in use.

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