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Agricultural and High-Density Polyethylene (HDPE) Waste Recycling to Produce High Voltage Insulator for Covered Conductor (CC) Distribution Systems

D. I. Moubarak[1], Mohamed E. Ibrahim[1,2], Amr M. Abd-Elhady[1,2], Djamal Hissein Didane[3], Abdelazeem Abdelrahman Amin[1*]

[1] *Faculty of Technological Industry and Energy, Delta Technological University (DTU), Quwaysna, 32631, EGYPT*
[2] *High Voltage and Dielectric Materials Lab, Electrical Engineering Department, Faculty of Engineering, Menoufia University, Shebin El_Kom, 32511, EGYPT*
[3] *Center for Energy and Industrial Environment Studies (CEIES), Universiti Tun Hussein Onn Malaysia 86400, Parit Raja, Batu Pahat, Johor, MALAYSIA*

*Corresponding Author: Dr.Abdelazeim.ismaeil@dtu.edu.eg
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Abstract

Waste manufacturing represents a crucial technological field that finds a great interest all over the world. Therefore, recycling of agricultural and HDPE waste is carried out to produce high voltage insulator suitable for use in CC based electric distribution systems. The insulator manufacturing processes from the adopted waste are presented. To verify the suitability of the manufactured material to be used in producing high voltage insulator, the properties of the manufactured material are measured. These properties are material permittivity, dielectric loss, resistivity, tensile strength and water absorbance. The measured properties of the recycled material are found to be suitable to be used in manufacturing high voltage insulators. The measured dielectric properties of the manufactured material are used to simulate an insulator with real dimensions to be compared with another traditional porcelain insulator with the same real dimensions. The comparison is carried out from the electric field distribution point of view using finite element (FEM) analysis method using FEMM 4.2 software. Also, the comparison is experimentally carried out using a cap and pin porcelain insulator with real dimensions and a manufactured insulator sample having the same creepage length. The experimental comparison is carried out though leakage current measurements considering wet polluted condition at different equivalent salt deposit densities (ESDDs) of 0.1, 0.3 and 0.6 mg/cm^2 according to IEC 60815 standrad. Finally, the obtained results either theoretical or experimental show the validity of the manufactured insulator to be used efficiently in CC based electric distribution systems.

1. Introduction

In fact, waste recycling represents a crucial technological topic that finds a great interest all over the world. This comes as waste recycling contributes to economic benefits as waste is transformed to useful products. Also, waste recycling limits the occurrence of environmental pollution and of course climatic changes [1]-[8]. Agricultural and plastic waste such as rice husk and HDPE are among the common types of waste. For example, in Egypt, the agricultural waste reaches 35 million tons per year [9], however, plastic waste represents about 5.4 million metric ton annually [10]. The traditional way to get rid of some agricultural waste such as rice husk and thin tree branches is to burn it or to throw it in water drains that contribute to environmental pollution and climatic changes. Also, plastic waste is considered very dangerous especially if it is burnt as it produces toxic gases that have an adverse effect on environment and general health. Also, presence of plastic waste such as HDPE in water drains represents a big hazard on general health due to its dangerous components as well as they are not easy disposable materials which represents an additional hazard on environment. So, recycling agricultural waste such as rice husk and thin tree branches as well as plastic waste such as HDPE to manufacture useful products is of great importance [11]-[13].

On the other hand, CC based electric distribution systems are commonly used in many countries such as Africa (e.g. Ghana), Europe (e.g. Finland and Spain), Australia, Asia (e.g. Japan), North and South America [14]. These systems are preferred in forested countries due to its high reliability compared to traditional systems that depends on bare wire [15],[16]. CC based electric distribution systems have several types [17],[18]. The system that uses CC fitted with transmission towers through insulators is one of these systems. This system uses mainly two types of high voltage insulators (HVI) made from porcelain or polyethylene. In [19],[20], it is found that the electric field strength at CC/HVI interface is lower with the use of LDPE insulator if compared to porcelain as the relative permittivity of LDPE is closer in value to the sheath material of CC. So, LDPE insulator is manufactured to reduce the electric field strength at CC/HVI interface to avoid quick surface tracking of the CC insulation sheath material due to partial discharge activity at this region. Another solution to avoid quick surface tracking is to coat the traditional porcelain insulator with room temperature vulcanized (RTV) silicone rubber [21]. Using RTV silicone rubber coating with porcelain prevents the formation of continuous water films at the insulator surface due to its hydrophobicity. Therefore, its performance is improved when used with CC/HVI systems due to the lower activity of partial discharges as well as lower leakage current. Manufacturing CC with outer semi-conductive sheath can also improve the performance of CC/porcelain HVI as it reduces the formation of high electric field strength at CC/HVI interface as illustrated in [20]. However, in [22], it is suggested to use insulated ties to provide fitting of CC with HVI instead of non-insulated ties. In the same research, the reason behind the improved performance when using insulated ties comes also as it reduces the electric field strength at CC/HVI interface. Considering this crucial point, the present paper focuses on using a material manufactured from agricultural and HDPE waste to produce HVI as an alternative to the traditional porcelain insulator to achieve a better performance of CC/HVI systems.

Therefore, in this paper, manufacturing of high voltage insulator for CC based electric distribution system from waste recycling is carried out. The manufacturing is carried out from recycling of rice husk, fine tree branches powder as agricultural waste and HDPE of pre-used refills. The manufacturing technique is explained with the required details. Measurements of the manufactured material permittivity, dielectric loss, resistivity, tensile strength and water absorbance are carried out to prove the suitability of the material to be used as high voltage insulator. The measured dielectric properties of the manufactured material are used to simulate an insulator with real dimensions to be compared with another traditional porcelain insulator with the same dimensions. The comparison is carried out from the electric field distribution point of view using finite element (FEM) analysis method. Also, the comparison is experimentally carried out using a real porcelain insulator and a manufactured insulator sample having the same creepage length. The experimental comparison is carried out though leakage current measurements considering clean and wet polluted conditions. Finally, the present paper is organized as follows:

- Section 1: is the present section that introduces an introduction about the importance of the waste recycling and a review for different techniques used to improve the performance of CC/HVI system.
- Section 2: presents the manufacturing technique of high voltage insulator for CC/HVI system from waste recycling.
- Section 3: presents the measurements of the manufactured material permittivity, dielectric loss, resistivity, tensile strength and water absorbance.
- Section 4: presents the calculation of electric field intensity using FEM is carried out considering a traditional porcelain insulator as well as a suggested one made from the waste recycled material with the same dimensions at the same conditions.
- Section 5: presents the experimental measurements of leakage current adopting the conventional porcelain insulator as well as a manufactured insulator sample from the produced material having the same creepage length.
- Section 6: presents the leakage current results followed by discussion; and
- Section 7: presents the main conclusions achieved from this research.

2. Manufacturing of HVI from Waste Recycling

In this section, manufacturing of HVI from recycling of agricultural and HDPE waste is presented. The manufacturing process is carried out in Egyptian factory called Poly Smart. The manufacturing process is shown schematically in Fig. 1. Firstly, rice husk and fine tree branches as agricultural waste are grinded and transformed to fine powder with an average particle size of 150 μm. The obtained powder is dried using a drier to extract the humidity from it. HDPE of old refills is transformed to small pieces by a grinder. HDPE is mixed with the agricultural waste powder with other additives such as Calcium Carbonate (CaCo3), polyethylene wax, pigments, coupling agent and anti-ultraviolet compound. Table 1 shows the percentage of the used concentrations during the manufacturing process. In fact, CaCo3 (75 μm) is added and used as a filler during the recycling process to increase the tensile strength of the obtained recycled material. Polyethylene wax is added to the mixture to achieve a smooth surface of the manufactured material. Coupling agent is used with the manufacturing process to achieve good binding between HDPE and all additives. Anti-ultraviolet compound is added to the mixture to achieve higher ageing time for the designed material. However, pigment with the desired colour is added during the manufacturing process to obtain the required colour. In this study, a brown colour pigment is used.

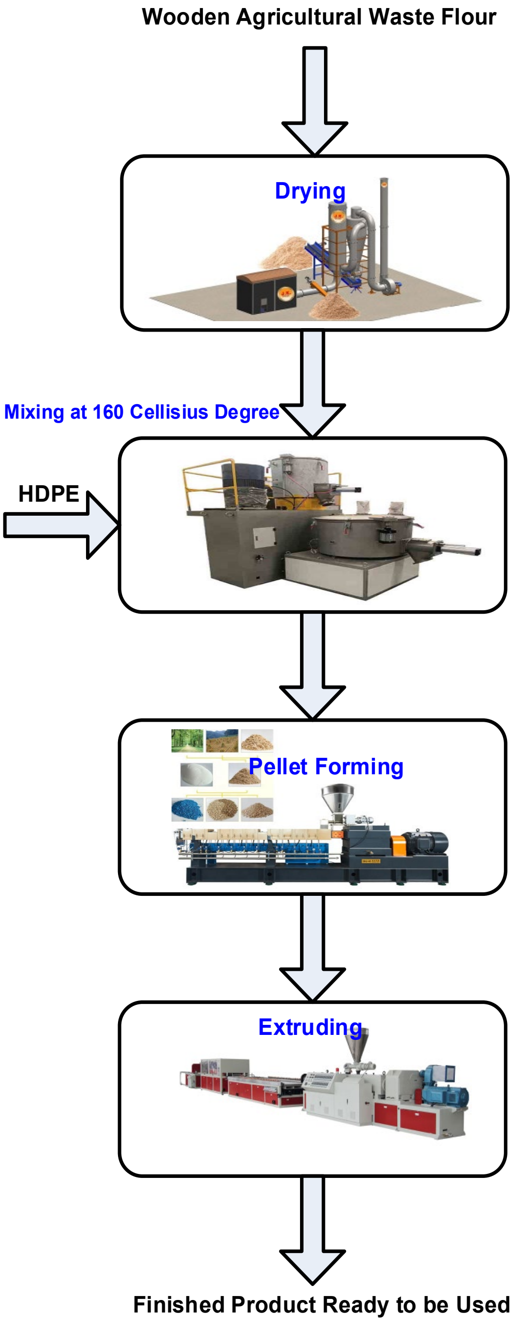


Fig. 1 *Manufacturing process of the recycled material*

Secondly, all materials shown in Table 1 are well mixed in a mixer. Then, the obtained mixture is mixed under heat (160°C) to obtain a molten compound. This molten compound is transformed to small pellets. These pellets are shaped in a mould using an extruder. In this paper, a mould having square cross-section is used. Finally, the produced material is ready to be tested and used.

Table 1 *Percentages of the materials used during the manufacturing process*

Composition	Percentage
Agricultural powder	54.3 % wt
HDPE	29.6 % wt
$CaCo_3$	10.86 % wt
Polyethylene wax	1.18 % wt
Coupling agent	1.97 % wt
Anti-ultraviolet	0.5 % wt
Pigment	1.48 % wt

3. Measurement of Material Permittivity, Dielectric Loss, Resistivity, Tensile Strength and Water Absorbance

In this section, measurement of material permittivity, dielectric loss factor, volume resistivity, tensile strength and water absorbance is carried out. Material permittivity, dielectric loss factor and volume resistivity are measured using an accurate LCR meter model Keysight E4980A that shown in Fig. 2a which has an accuracy of 0.05%. The used cell in these measurements (model 16451B) has a standard three electrodes shown in Fig. 2b and the measurements are carried out according to ASTM D150-22 standard. A piece of the manufactured material with dimensions of 2 cm × 2 cm × 4 mm is tested. Fig. 3 shows the measured relative permittivity of the manufactured material with frequency. From this figure, the relative permittivity of the manufactured composite is found to be 3.75 at lower frequencies. Of course, this value decreases with the increase in frequency due to polarization effect in the same manner as well known for solid dielectrics. The value of the dielectric loss tangent of the manufactured material is found to be 0.074 at lower frequencies as declared from Fig. 4. However, the measured volume resistivity at lower frequencies is found to be 2 MΩ.m and it decreases with the increase in frequency as presented in Fig. 5. The decrease in volume resistivity with the increase in frequency comes due to the change in dipole movements as well known for solid dielectric materials. In fact, the measured values of the recycled material are considered reasonable and give an indication for its suitability to be used as an insulating one. Tensile strength of the manufactured material is measured using a universal testing machine. Dumbbell shaped piece of the material is used to measure its tensile strength to be suitable to be fitted with the testing machine. Tensile strength measurements are carried out for three samples of the material. The tensile strength at break is recorded for each sample. It is found that the average tensile strength for the manufactured material is about 34.8 MPa. So, it can withstand mechanical stresses when used as high voltage insulator. One of the important properties needed to be measured for dielectric materials is its water absorbance. Hence, the increased water absorbance of the material gives adverse effects on its dielectric properties. Therefore, water absorbance of the manufactured material is carried out. A piece of the manufactured material having dimensions of 2 cm × 2 cm × 4 mm is completely immersed in water. The piece is weighed before and after immersion in water. The difference in its weights after and before its immersion is divided by its weight before immersion to compute the percentage of its water absorbance. It is worth to mention that the material is dried using soft tissue paper before weighing after its removal from water directly to avoid weighing of stuck in water on its surface. Measurement of water absorbance is carried out until water absorbance becomes approximately constant. It is found that the maximum recorded water absorbance is about 0.005%. This value means low water absorbance of the material. This comes due to the good surrounding and binding of wooden floor of the agricultural waste with HDPE. Also, the obtained low water absorbance of the manufactured material gives another evidence for its suitability to be used as an insulator.

(a)

(b)

Fig. 2 *(a) LCR meter; and (b) the test cell used in permittivity and dielectric loss factor measurement*

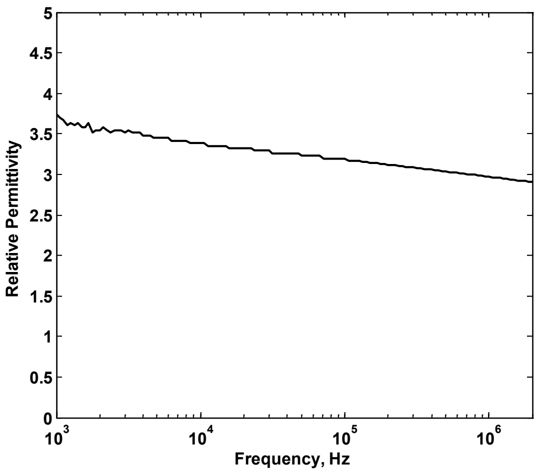


Fig. 3 *Measured relative permittivity of the manufactured material*

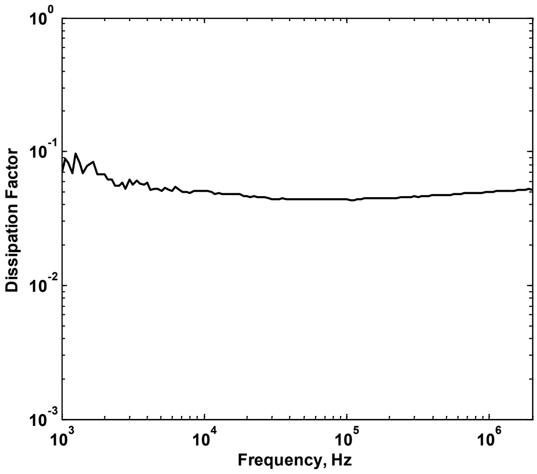


Fig. 4 *Measured dielectric loss factor of the manufactured material*

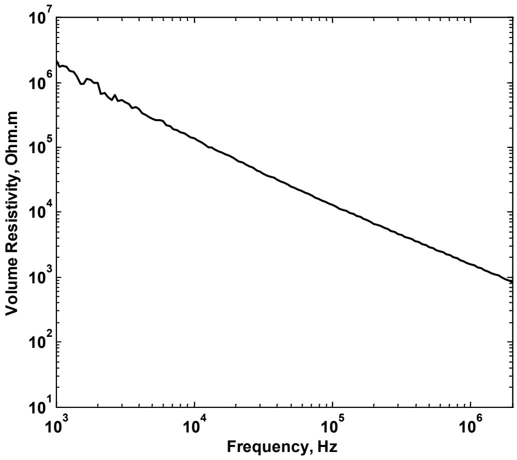


Fig. 5 *Measured volume resistivity of the manufactured material*

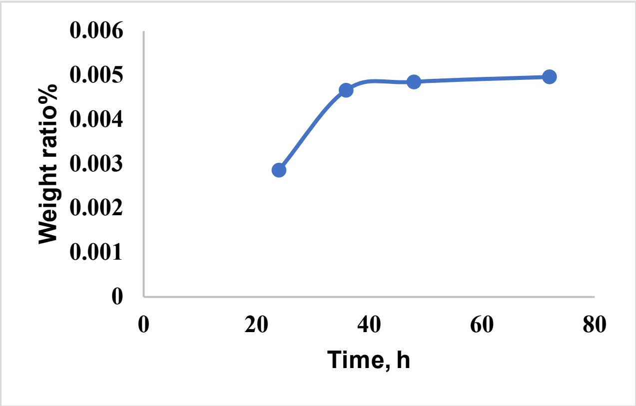


Fig. 6 *Measured water absorbance of the manufactured material*

4. Calculation of Electric Field Using Finite Element Analysis

To validate the efficacy of the recycled material in manufacturing high voltage insulator for covered conductor based electric distribution systems, finite element (FEM) analysis is used to calculate the electric field distribution. Electric field distribution is carried out considering real dimensions of a standard high voltage insulator. The adopted dimensions of the standard insulator are shown in Table 2. These dimensions are used to simulate two systems; the first system uses an insulator made of porcelain (relative permittivity = 5.9), but the other insulator is made of the recycled material (relative permittivity = 3.75). The dimensions of the adopted CC for the two systems are conductor cross section area 240 mm2 made of aluminium and the conductor has a single XLPE layer (relative permittivity = 2.3) having a thickness of 0.4 cm. The two systems are simulated using FEMM 4.2 software considering an applied voltage of 22 kV on the conductor.

Fig. 7 shows the obtained electric field strength distribution (considering porcelain and recycled materials) over the insulator surface from the conductor outer surface to a distance of 63 cm from this point. The computation is limited to this distance as it is the electric field is expected to be sharp at this region. From this figure, maximum electric field strength occurs at the conductor/insulator interface. This comes due to change of relative permittivity of relative permittivity of conductor insulation and insulator material. Also, it is found that the maximum electric field strength reaches 2.82×10^6 V/m considering porcelain insulator. However, this value is reduced to 3.75×10^5 V/m when recycled material insulator is used. This means that there is a reduction in the maximum field strength by 86.7% when the recycled material insulator is used. This means that a lower partial discharge activity is predicted when using the recycled material to be used as a high voltage insulator for CC systems.

Fig. 8 shows the electric field distribution through the CC insulation material (made from XLPE) considering porcelain and the recycled material insulators. Also, a small void (0.15 mm radius) through XLPE insulation is simulated at this case. This void is used to simulate the presence of any cavities that may occur during the manufacturing of CC or due to use for long periods in service. The figure shows that the maximum electric field strengths in the voids considering porcelain and recycled material insulators are 2.91×10^6 V/m and 9.47×10^3 V/m, respectively. This means a reduction in maximum field strength in the void by 99.6% with recycled material compared to porcelain. Also, this leads to lower partial discharges in CC and of course in the system that leads to a better system performance and an expected increased lifetime.

Table 2 *Main dimensions of a standard high voltage insulator*

No. of sheds	4
Creepage distance, mm	432
Overall height, mm	185

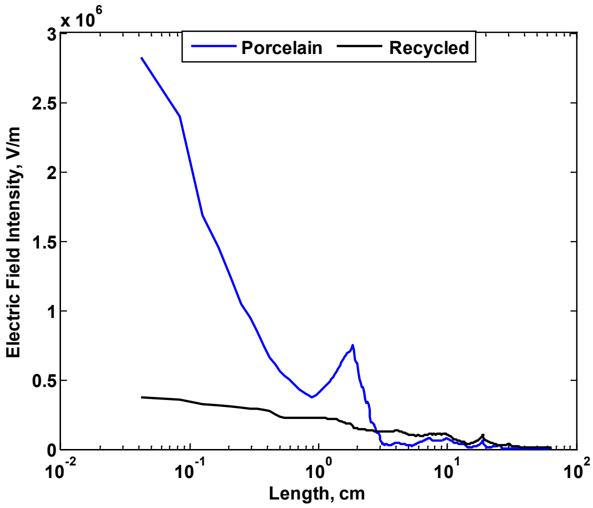


Fig. 7 Electric field strength distribution over high voltage insulator surface

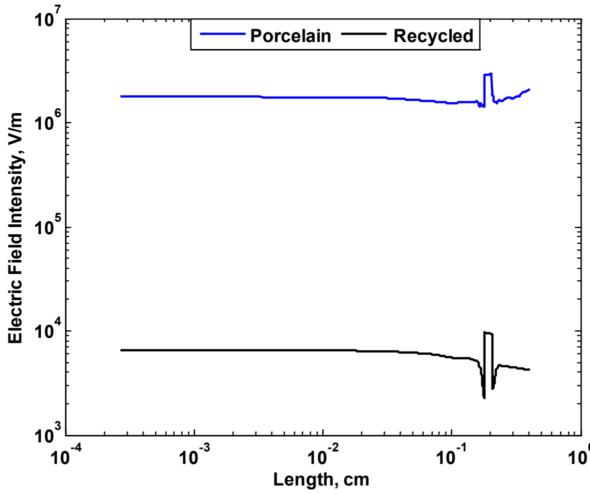


Fig. 8 Electric field strength distribution through cc insulation

5. Leakage Current Measurements Considering Porcelain and Recycled Material Insulators

Leakage currents considering two systems are measured. The first system uses a standard high voltage porcelain insulator with the data given before in Table 2. However, the second system used a specimen of the recycled material. The specimen of the recycled material is used in this section instead of a real high voltage insulator due to the difficulties in manufacturing a mould having the shape of a real insulator at our laboratory. The specimen is manufactured to have a square cross-section having dimensions of 15 cm × 15 cm. However, its height is chosen to equal the creepage path of the standard porcelain insulator (43.2 cm). This selection is carried out to make the comparison very close in physical conditions as possible. Leakage current measurements are carried out using a high band width current transducer (100 MHz). The output of this transducer is recorded using an oscilloscope having 200 MHz band width. The measured data are plotted using MATLAB software.

Fig. 9 shows the schematic diagram of the experimental setup used to measure leakage currents for both systems. 22 kV at 50 Hz voltage is applied to both systems considering wet polluted conditions. The adopted pollution conditions are carried out according to IEC 60815 standard [23] at equivalent salt deposit densities (ESDDs) of 0.1, 0.3 and 0.6 mg/cm2 to simulate different pollution conditions. Wet pollution conditions are carried out by spraying the insulator with saline solution of 30 mg/litre salinity with the suitable amount to obtain the required ESDD value. It is worth to mention that three reading shots for leakage current are recorded for each condition to provide suitable judging on insulator performance.

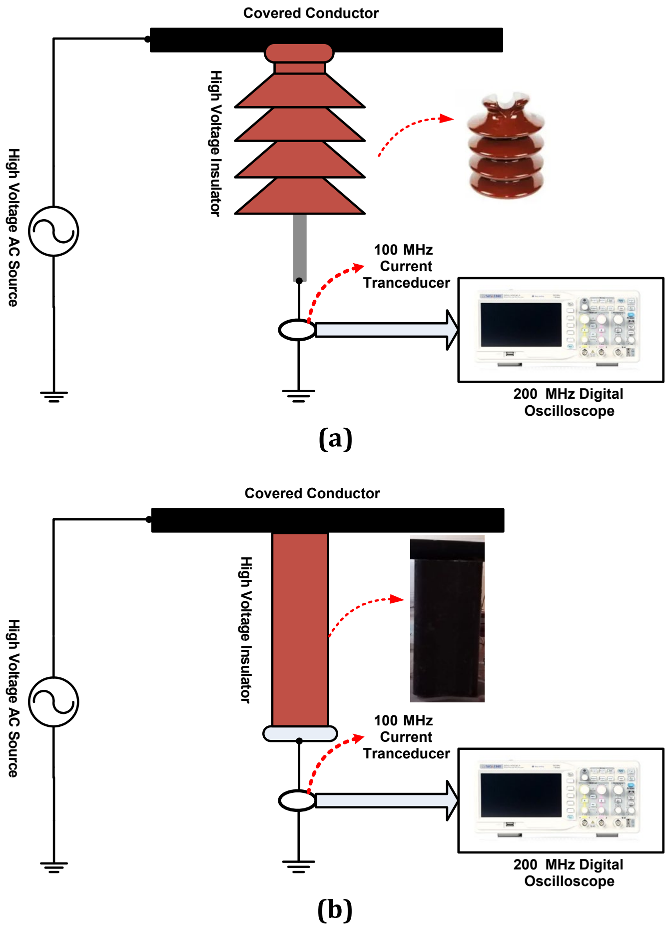


Fig. 9 *Leakage current measurement (a) Standard porcelain insulator; and (b) Recycled material insulator*

6. Leakage Current Results

Figs. 10 to 12 show the waveforms of the measured leakage currents for the both types of insulators at the adopted ESDDs. Fig. 10 shows three shots of the measured leakage current waveforms at an ESDD of 0.1 mg/cm2 considering the conventional porcelain as well as the insulator manufactured from the recycled material. From this figure, it can be shown that the maximum recorded current with porcelain insulator is found to be 3.19 mA. However, it is found to be 1.11 mA with the insulator manufactured from the recycled material. Also, a higher number of current pulses is noticed with porcelain insulator if compared to the insulator manufactured from recycling. This means that lower dry band arcing occurs with the insulator manufactured from recycling if compared to the porcelain insulator.

At the ESDDs of 0.3 mg/cm^2, it is found that the maximum recorded current is 3.39 mA with porcelain insulator and 2.45 mA with the insulator manufactured from the recycled material. However, the maximum current is found to have a value of 3.51mA with porcelain insulator and 2.45 mA with the insulator manufactured from the recycled material at ESDD of 0.6 mg/cm^2. Also, the number of current pulses occur with porcelain insulator is higher compared to the insulator manufactured from the recycled material. This gives another validation that lower dry band arcs occur with the insulator manufactured from the recycled material compared to the insulator manufactured from porcelain.

Fig. 13 shows the average value of the maximum recorded leakage currents at the three adopted ESDDs to summarize the obtained leakage current results. Again, maximum recorded leakage currents with porcelain insulator are found to be lower than it for the insulator manufactured from the recycled material at all the adopted

ESDDs. In fact, this comes due to two reasons. The first one; is the lower difference in relative permittivity's of the covered conductor insulation and the insulator material as demonstrated in Section 3. This results in reduced sharp points (points with higher electric fields) as previously validated in Section 4. The second reason; is the lower tendency of the recycled material to form continuous water paths if compared to porcelain. In other words, the recycled material is found to have a higher hydrophobicity than porcelain.

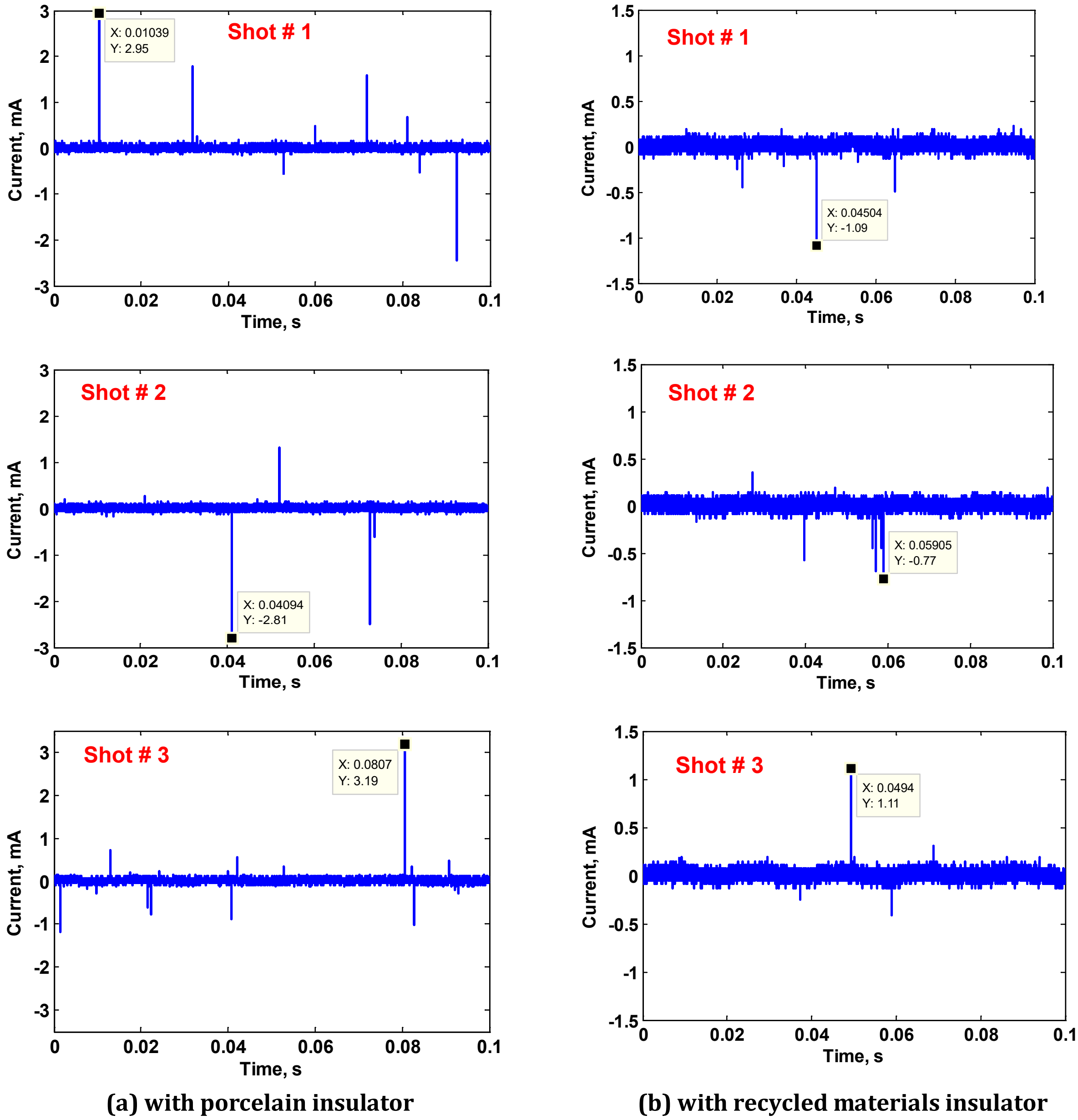
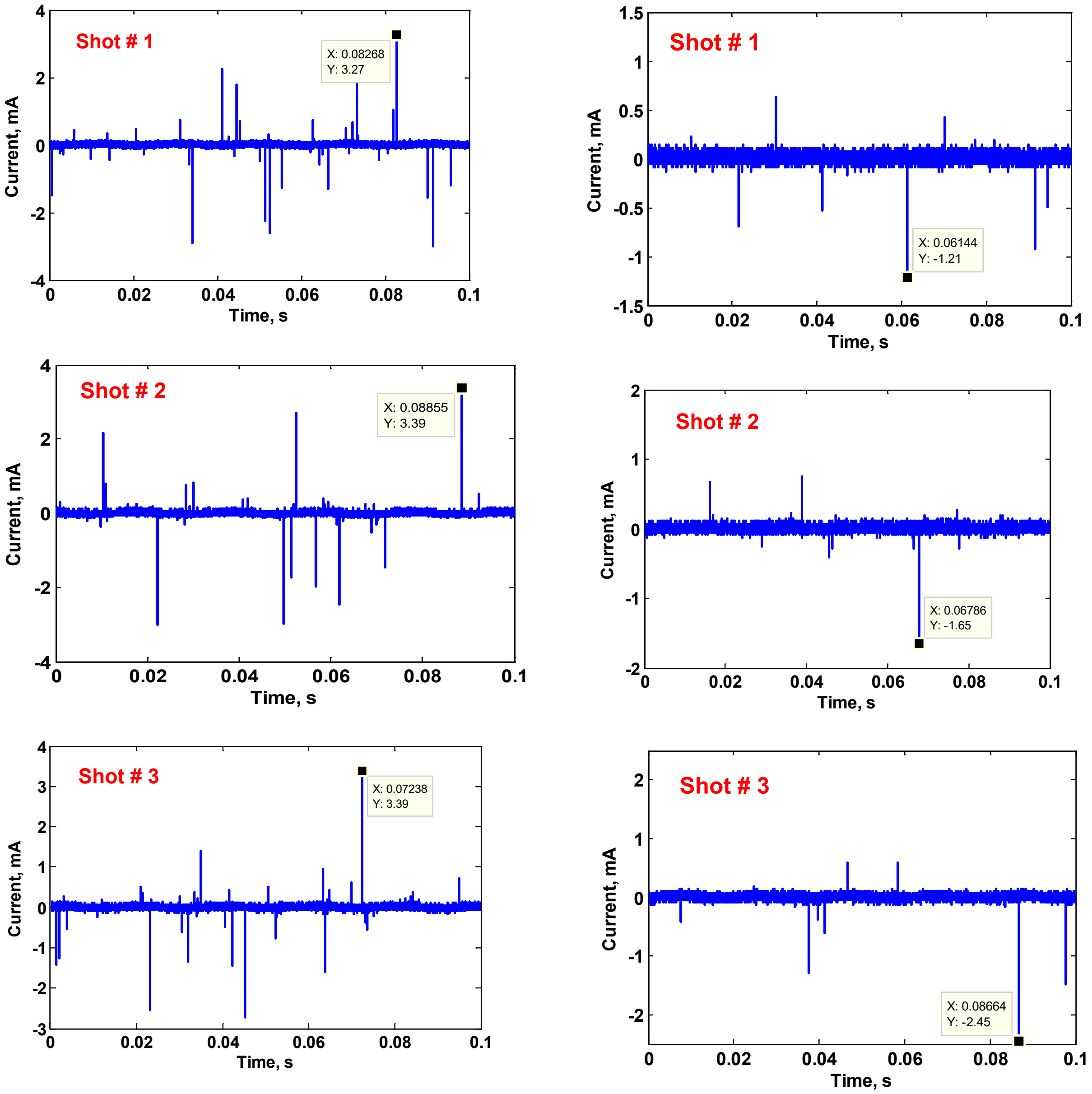
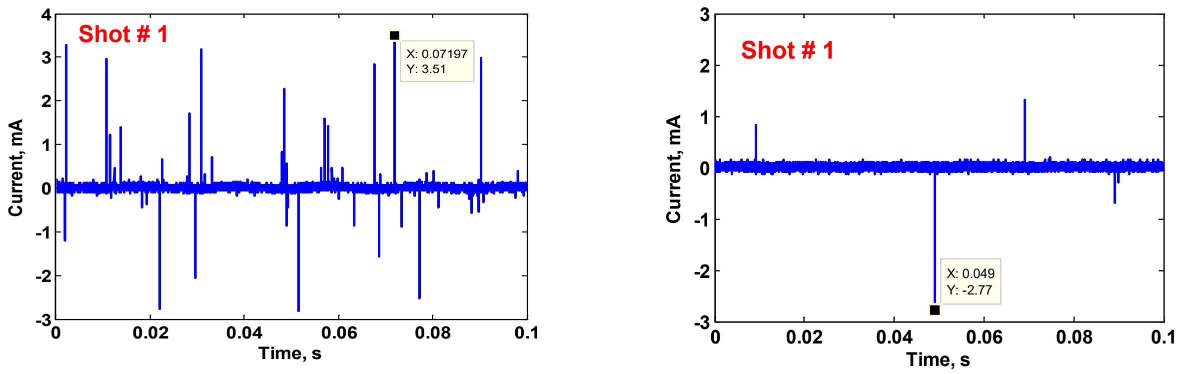


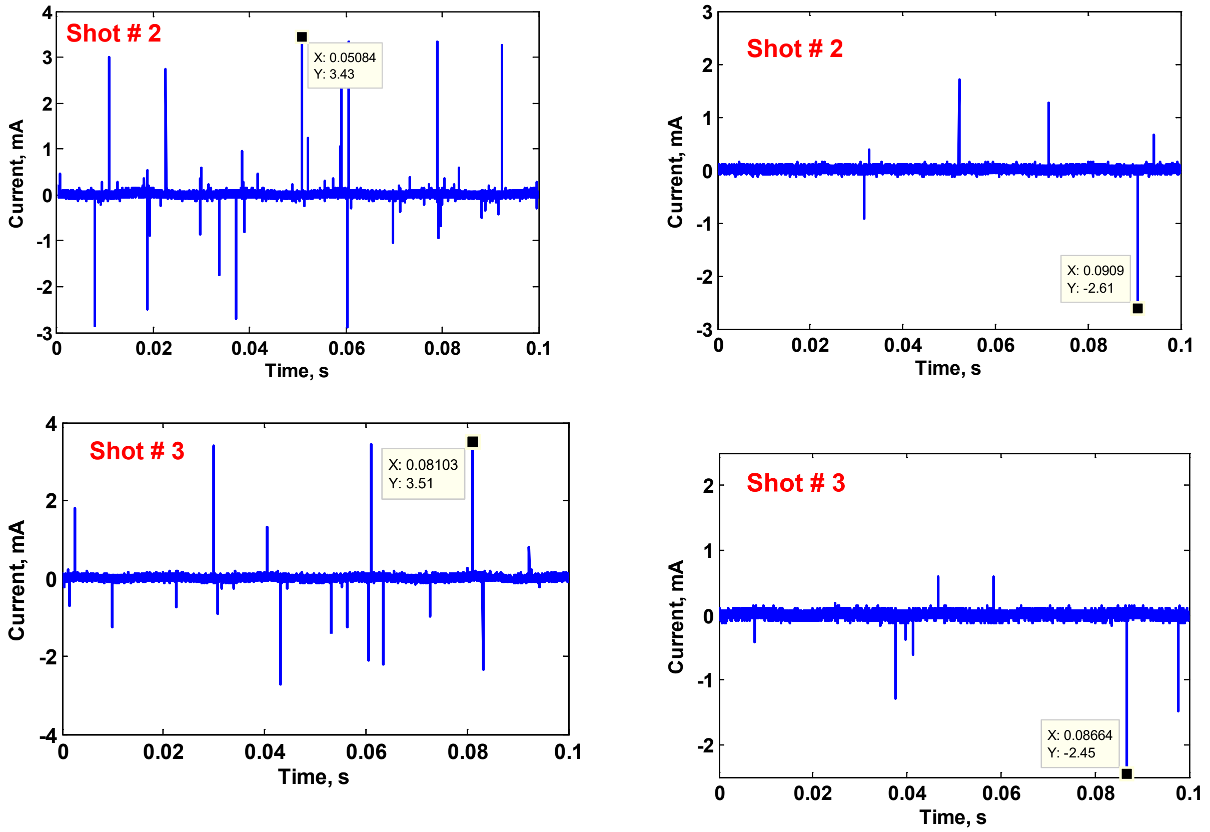
Fig. 10 *Leakage current versus time, ESDD = 0.1 mg/cm² for (a) Porcelain insulator; and (b) The insulator manufactured from the recycled material*



(a) With porcelain insulator **(b) With recycled materials insulator**

Fig. 11 *Leakage current versus time, ESDD = 0.3 mg/cm² for (a) Porcelain insulator; and (b) The insulator manufactured from the recycled material*





(a) With porcelain insulator **(b) With recycled materials insulator**

Fig. 12 *Leakage current versus time, ESDD = 0.6 mg/cm² for (a) Porcelain insulator; and (b) The insulator manufactured from the recycled material*

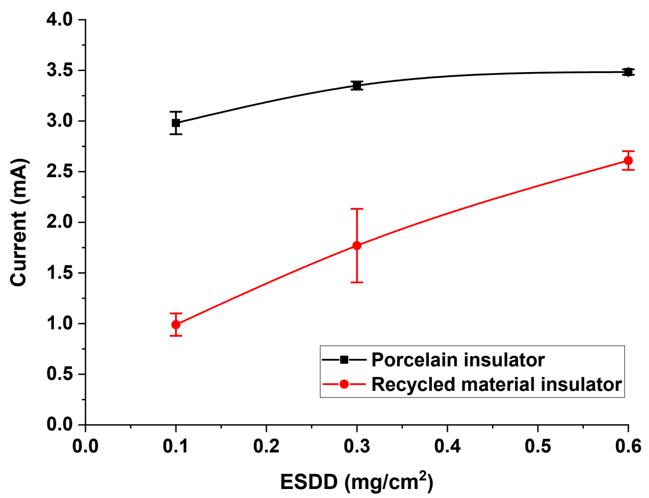


Fig. 13 *Average values of maximum recorded leakage currents in ma at ESDDS of 0.1, 0.3 and 0.6 mg/cm² for both insulators*

7. Conclusion

High voltage insulator for covered conductor based electrical distribution systems has been manufactured from waste recycling. The adopted waste contains HDPE and agricultural waste. The manufactured material has been evaluated through permittivity, dielectric loss, resistivity, tensile strength and water absorbance measurements. The obtained recycled material properties have proven its suitability to be used as a high voltage insulator. Finite element analysis using high voltage insulator with real dimensions has been carried out considering the traditional porcelain as well as the insulator manufactured from the recycled material. It has been found that lower sharp points (points with higher electric field intensities) have been formed with the insulator manufactured from the recycled material compared to the traditional porcelain one. Also, leakage current measurements have been carried out for the two adopted insulators considering the same creepage distances at three ESDD values; 0.1, 0.3 and 0.6 mg/cm^2 to simulate different pollution conditions according to IEC 60815 standard. At all ESDD values, the maximum recorded leakage current value as well as the number of current pulses have been found to be lower for the insulator manufactured from the recycled material compared to the traditional insulator made from porcelain. Finally, the obtained results have proven a better performance of the proposed insulator manufactured from waste recycling compared to the conventional porcelain one which gives a promise for the possibility for its manufacturing in the future.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *D. I. Moubarak;* ***data collection:*** *Mohamed E. Ibrahim;* ***analysis and interpretation of results:*** *Amr M. Abd-Elhady;* ***draft manuscript preparation:*** *Abdelazeem Abdelrahman Amin and Djamal Hissein Didane. All authors reviewed the results and approved the final version of the manuscript.*

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