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Improving Insulation of Rigid Polyurethane Foam Using Corn Stems and Cotton Stalks

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ABSTRACT

Nowadays there is increasing activity in the development of materials from residual materials. Semi-structural materials made from waste materials are usually composites. Current use of these materials is minimal, but future economics can provide these materials with a competitive advantage. Polyurethane foam is an excellent material for various uses. It is made by foaming a liquid mixture of isocyanato -polyols in the presence of a blowing agent. This article contains an experimental study of improving the insulation of rigid polyurethane foam by the means of incorporating various amounts of each cotton stalks and corn stems. Four ratios (0.0, 10, 20, and 30 % by volume) of cotton stalks or corn stems were used with rigid urethane foam. The produced composite mad from rigid urethane foam and cotton stalks or corn stems were tested to measure bulk density, thermal conductivity and thermal resistivity. The results indicated that the thermal conductivity and thermal resistivity affected by the replacement ratios (%). The thermal conductivity was decreased with increasing replacement ratios. On the other hand, the thermal resistivity was increased with increasing replacement ratio (%). The results showed that the thermal properties of rigid urethane foam were improved with adding cotton stalks or corn stems. Corn stems showed the best, lowest, thermal conductivity values than cotton stalks. The lowest thermal conductivity was 0.01692 W/m.ºC at corn stems with replacement ratio of 30 (%) as well as, the highest thermal resistivity of 59.09 m.ºC/W at the same previous replacement ratio.

Keywords: Insulation, Rigid Polyurethane foam, Cotton stalks, Corn stems, Thermal conductivity, Improving, Agricultural residues.

INTRODUCTION

Historically, because of its high quality, cotton cultivation is considered one of the most important strategic crops in Egypt and is harvested at the end of September each year, leaving a large amount of cotton stalk remains as a renewable and sustainable source of biomass. Around 80 Mt of cotton stalks are produced worldwide every year (Al Afif *et al.,* 2020). In Egypt, according to the Agricultural Economics Bulletin, the amount of waste from cotton stalks was estimated at 0.5 million tons, as reported in ref., (El-Atty *et al.,* 2016). Corn stems are agricultural by-products and currently have no economic value. The disposal of agricultural residues is currently a major economic and ecological problem; however, the abundance and availability of corn stems as an agricultural by-product make them a good source of raw materials for a wide variety of agricultural products. It used and converted into adsorbents such as activated carbon is a possible way out. Egypt produces 3.12 million tons of corn stems by-products annually (Husseien *et al.,* 2009). Indeed, before the 1990s, farmers stored and consumed these residues by incineration in home stoves until gas stoves became widespread, thus relying on the in-situ incineration of these massive amounts of residues by burning them in the open air in their fields in ridiculous and illegal ways. This behavior leaves a repeated catastrophic situation in air pollution every year during this period (Rabea *et al.,* 2021). As the population increases, agricultural residues from grain growing increases every year, a large part of the residue is directly incinerated and returned to the field, and a small part is used, among other things, for the production of paper, cardboard and animal feed. These high-yielding, renewable agricultural residues have the advantages of energy saving and great advantages (Lu *et al*., 2016 ; Naik and Kiran, 2018). The construction industry must take full advantage of industrial by-products and renewable materials in order to achieve sustainable development of building materials (Hassan *et al.,* 2019; Onuaguluchi and Banthia, 2016). Inexpensive and renewable plant strains are available and accessible in abundance. Plant fibers are characterized by abundant sources, low cost, low density, renewable, safety and biodegradability (Ismail and Jaeel, 2014; Xie *et al*., 2015). Insulation materials in buildings have been widespread since the beginning of the 20th century. The new construction and building systems offer many advantages and have some disadvantages in terms of building physics and the comfort conditions that arise over time and slim to avoid load carrier system (Thorsnes and Bishop, 2013; Binici *et al*., 2014). Polyurethane foams (PUFs) are flexible substances broadly used for numerous fields together with medical, car parts, and constructing programs because of their low thermal conductivity and extraordinary mechanical properties (Wiyono *et al.*, 2016*).* Polymer foams comprise a multiplicity of cells in a polymer matrix. The foam can have an open, partially open or closed cell structure. Polymer foam requires less

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material than a solid polymer of the same volume, so that the material costs are reduced in many applications (Niaounakis, 2015). Polyurethane foams are widely used in industry because of their mechanical, electrical, thermal and acoustic properties (Verdejo *et al*., 2009). Rigid polyurethane foam is currently one of the best thermal insulation materials available. Thermal insulation is therefore an essential feature of most building materials. The combination of rigid polyurethane foam with different lining materials results in composite building materials with important applications (Kapps and Buschkamp, 2004). Agricultural and fabric residues are usually used with inside the manufacturing of insulation substances. A study by (Zhou *et al.,* 2010*)* tested the thermal behavior of an innovative material made from cotton stalks, a residue from cotton production. Particle board was obtained by converting the stalks into fibers without the use of chemical binders and testing the thermal conductivity of the sample, it was between 0.0585 and 0.0815 W /m.°K; the results indicated that the denser material gave lower thermal insulation. Agricultural residues of biological origin are residues such as maize, sunflower or wheat straw, they are thin fiber materials and, due to their voids, have insulating properties when they are recycled, they make indisputable contributions to the economy.

The main goal of the present research was using some agricultural residues to improve the insulation of rigid polyurethane foam. Also, to test the improved thermal performance of rigid polyurethane foam with different proportions of agricultural residues in its matrix if they are used for isolation purposes.

MATERIALS AND METHODS

The experimental part of the present work was carried out in the summer of 2020 at the Faculty of Agricultural Engineering, Al-azhar Univ. Cairo, Egypt.

Raw materials

Cotton stalks (TS) and corn stems (CS) were collected from a farm in El-Gharbia Governorate,Egypt, and prepared for the experiment by cutting (TS) and (CS) into small pieces of 200 mm long for each and 11 mm and 19 mm in diameter as the average values for (TS) and (CS) respectively. There were naturally dried by spreading it outdoors during the day's intense sun hours. After drying, the moisture content on a wet basis was found about ± 8.80% and ± 7.33 respectively.

Rigid Polyurethane Foam

The materials used for making the rigid urethane foam were obtained from commercial sources. The rigid polyurethane foam (RUF) has the chemical characteristics: (A) Polyol component: a mixture of polyol, flame retardant, catalyst, stabilizer, and HFC blowing agent (Polyol: true density = 1.21 g / cm^3 at 20 ° C, viscosity = 200 mPa at 20 ° C)**.** (B) Isocyanate component: contains a polymeric diphenylmethane MDI (methylenediphenyl diisocyanate, IsoPMDI 92140) (true density = 1.24 g / cm^3 at 20 ° C**,** viscosity = 220 mPa at 20 ° C)**.**

Specimen's preparation mold

A plywood rectangular mold with internal dimensions of (300 × 200 ×50 mm) was used in this study to form specimens for testing. The plywood used to fabricate the mold was residues obtained from furniture industry workshop in the El-Gharbia Governorate, Egypt. The plywood mold made in such a way that it can be removed and installed by connecting the wooden sides together with screws. Its top side which was (300 x 50 mm) was opened, in order to put the stems or stalks and pour the foam through it. The lower side facing the open side had many metal nails (1.0 mm) in diameter to help regularize the placement of the stems or stalks in a homogeneous manner while pouring the foam. After the process of pouring the foam and leaving it for a sufficient period to complete solidification, then the mold was removed, and the reinforced foam is taken out, then it was cut by an electric saw into specimens with dimensions appropriate to the conduct of the tests.

Thermal conductivity apparatus

In order to study the thermal conductivity of the produced specimens, a device according to the Lee method was developed by Noakes *et al.,* (1953). The apparatus was constructed, by ElBessoumy, (2005) which consists of: (1) an electrical heater of 1 kW. (2) Steam unit made from stainless-steel. (3) A hose to transport the steam to the steam chamber. (4) Steam chamber of 100 mm height and 105 mm diameter (5) Brass disk attached with the steam chamber, its diameter is 105 mm and its thickness is 10 mm. (6) Lower brass disk, its mass is 740 g. (7) Thermometer. (8) Supported chains.

Test procedures

Three ratios of cotton stalks and corn stems (TS and CS) by volume were used with rigid urethane foam (RUF) , in order to study bulk density (kg/m^3) ,thermal conductivity (W/m. °C) and thermal resistivity (m.ºC/W) of the produced composite that had affected by the following variable: percent volume of reinforcement. The experiments were carried out at the research center of Agricultural Engineering Faculty, Al-Azhar University, Nasr city, Cairo, Egypt.

Percent volume of replacement (%)

The rigid urethane foam (RUF) ratios by volume were added to three ratios of (TS) and (CS) by volume. The cotton and corn stalks ratios were 10, 20 and 30 (%) by volume, in addition that ratio of (0 %) was without adding (TS) and (CS) as a control specimen. Samples of 200 mm in length for each were taken from 100 (CS) and (TS), the average diameter of each of them was 19 and 11 mm, respectively. Depending on its average length and diameter, the volume of one sample was calculated for both (CS) and (TS), which the average volume of sample for each (CS) and (TS), were 56,677 and 18,997 cm^3, respectively. Three volumes of 10, 20 and 30% from the total mold volume used in the samples preparation were calculated. The volumes of 300, 600 and 900 cm^3 of (TS) and (CS) were required to achieve the ratios of 10, 20, and 30 % by volume respectively. To achieve these previous volumetric ratios, the total required number of stems or stalks were calculated to be used with each volumetric ratio. And it turned out that, the number of corn stems were 5, 11 and 16 required. While, the number of cotton stalks were 16, 32 and 47.

Preparations for testing

The plywood rectangular mold lined with aluminum foil was used to prepare test specimens. About 10, 20 and 30 % of (TS and CS) by volume respectively, were arranged inside and placed vertically in the mold. Rigid urethane foam (RUF) was produced between and around (TS and CS) by placing a 50-50 (A-Polyol and B-isocyanate components) by volume in the bottom of the mold immediately after mixing. After about 30 min, the composite of rigid urethane foam (RUF) and (TS and CS) was removed from mold. the composite of rigid urethane foam (RUF) and stalks was cut into circular specimens of fixed diameter of 105 mm and thickness of 50 mm for thermal conductivity test.

Experimental design

A combination of each of two types of (TS and CS) and three ratios of it to be added to rigid urethane foam resulting, in six treatments. Each treatment was repeated three times to give three replicates resulting in 18 specimens.

Measurements

The following measurements were carried out at ambient room temperature of 21 °C and relative humidity of 65 %. The following testes were carried out for each specimen:

Bulk density (Bd)

A mass of each specimen "M" was recorded with thickness "L" of 50 mm and diameter "d" of 105 mm used to calculate the bulk density "Bd" at previous different ratios according to the following equation:

$$\boldsymbol{Bulk\ density\ (Bd)} = \frac{\boldsymbol{4\,M}}{\boldsymbol{\pi d^2 L}} \dots\dots\dots\ \mathbf{(1)}$$

Thermal conductivity (K)

Insulation materials are supposed to conduct heat badly in order to prevent large heat losses. The lower the heat conduction in a material, the less heat flows through it. Thermal conductivity is the time rate of steady-state heat flow through a unit area of a homogeneous material in a direction perpendicular to its isothermal planes, induced by a unit temperature difference across the sample. Thermal conductivity is the measure of the flow rate of thermal energy transferred through a unit thickness of a material under a specified temperature gradient (Hassanin *et al.,* 2018). Thermal resistivity indicates the thermal insulation of a material. The Lee's method (Noakes *et al.,* 1953) for the thermal conductivity determination of a bad conductor was used with all specimens. A specimen (B) of thickness (x) and radius (r) was placed between two brass discs (S, C). The steam generated from the hot water passes through a hose to the steam chamber (A). After a period of time, the readings (T_1, T_2) of each of the two thermometers (1) and (2) were fixed until they reached the steady state. These two readings were recorded, which were the degrees of the upper surface and the lower surface of the specimen (B) respectively, because the brass very good conductor of heat. Then the thermal gradient was calculated as follows (T_1-T_2) / x. The rate of heat flow into the specimen was calculated when the degree of (B) was fixed. In the second case, it means that the specimen acquired heat from (S) at the same rate that heat loses to the surroundings from (C). To calculate the rate of heat loss from (C), the mass of disc (C) is set, let it be (m) and let it be the specific heat of brass (s). The disc (C) alone was slowly heated until the thermometer sets a temperature slightly greater than (T_2), let it be (T_3), then the specimen was placed alone on top of (C), the time (t) in seconds was recorded that elapses until the temperature becomes less than T_2 and as much as (T_3) is greater than it, let this temperature be (T_4). The average rate of heat loss is m.s (T_3-T_4 /t) and this is the rate of heat flow from (S) to the specimen (B). The thermal conductivity for the specimen was calculated from the following equation:

$$K = \frac{m.s\,(T_3 - T_4)\,x}{t\,(T_1 - T_2)\,\pi\,r^2} \qquad (2)$$

Where:

***K*: Thermalconductivity for sample (W/m.°C).**
***m*: Mass of brass disk (C) 0.74 (kg).**
***S*: Specific heat for brass, (380 J/kg.°C).**
***x*: Thickness of specimen (m).**
T_1 and T_2: The specimen's surfaces temperatures
***t* : Cooling time from (T_3 to T_4) (sec.).**
***r* : The radius of specimen (m).**

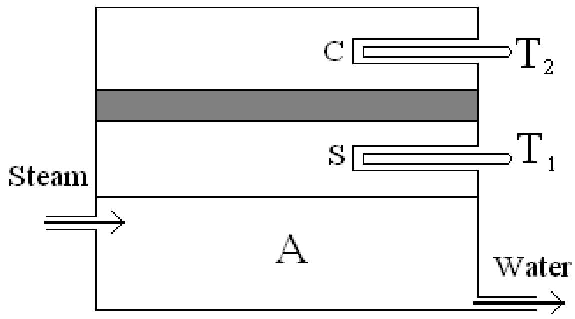

Fig. 1. A schematic diagram for steam unit and specimen of thermal conductivity Apparatus (C,S) Brass disks, (B) Specimen, (T_1, T_2) Thermometers, ElBessoumy,2005).

RESULTS AND DISCUSSION

Replacement volume percentage "RV, %" via mass "M" and bulk density "Bd":

Figures (2 and 3) shows, the relation between "RV, %", mass "M, kg" and bulk density "Bd, kg/m^3" for "TS and CS". It shows that mass and bulk density is affected by percent volume of replacement (%). The mass and bulk density increases with percent volume of replacement (%) increasing for "TS and CS". The obtained data indicated that, the mass is increased from 0.047 to 0.103 kg and from 0.020 to 0.061 kg at increased percent volume of replacement (%) from 10 to 30 % for used "TS and CS" respectively. As the bulk density is depending on the mass, the bulk density is increased as well from 118.65 to 262.19 kg/m^3 and from 51.21 to 155.67 kg/m^3 at increased percent volume of replacement (%) from 10 to 30 % for used "TS and CS" respectively. The percentages of increase in the mass and bulk density of specimens made of rigid urethane foam and cotton stalks were about 68, 77, and 85 % at replacements ratios of 10, 20 and 30 % respectively. While, the percentages of increase in the mass and bulk density of specimens made of rigid urethane foam and corn stems were about 26, 52, and 75 % at replacements ratios of 10, 20 and 30 % respectively. The values of mass and bulk density for cotton stalk are higher than the values of mass and bulk density for corn stems at different percent volume of replacement (%).

Replacement volume percentage "RV, %" via thermal conductivity (W/m.ºC) and thermal resistivity (m.ºC/W)

Figures (4 and 5) illustrate the relation between "RV, %", thermal conductivity (W/m.ºC) and thermal resistivity (m.ºC/W) for "TS and CS". The obtained data showed that thermal conductivity and thermal resistivity are affected "RV, %".The thermal conductivity decreases by increasing "RV, %" for each "TS and CS". The thermal conductivity is decreased from 0.04000 to 0.02881 W/m.ºC and from 0.02663 to 0.01692 W/m.ºC at increased "RV, %" from 10 to 30 % during using each of "TS and CS" respectively as showing in Fig. (4).

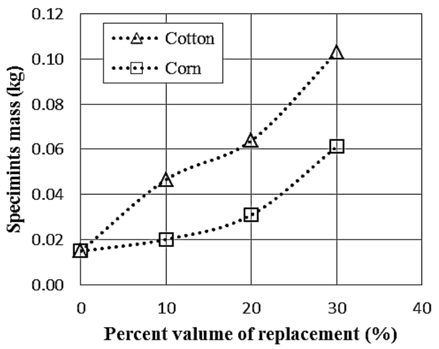

Fig. (2): Effect of material percentage on sample mass for (TS and CS)

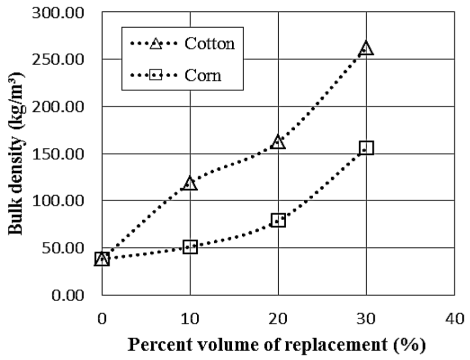

Fig. (3): Effect of material percentage on bulk density at for (TS and CS).

The percentages of decrease in the thermal conductivity of specimens made from rigid urethane foam and cotton stalks were about 64, 70, and 74 % at replacements ratios of 10, 20 and 30 % respectively. While, the percentages of decrease in the thermal conductivity for specimens made from rigid urethane foam and corn stems were about 76, 82, and 85 % at replacements ratios of 10, 20 and 30 % respectively. The obtained data indicated that the thermal resistivity increases with increasing "RV, %"for "TS and CS". Figure (5) indicates that, the thermal resistivity is increased from 25.00 to 34.71m.ºC/W and from 37.55 to 59.09 m.ºC/W by increasing "RV, %" from 10 to 30 % for used "TS and CS" respectively. The percentages of increase in the thermal resistant of specimens made from rigid urethane foam and cotton stalks were about 64, 70, and 74 % "RV, %" of 10, 20 and 30 % respectively. While, the percentages of decrease in the thermal conductivity for specimens made from rigid urethane foam and corn stems were about 76, 82, and 85 % at "RV, %" of 10, 20 and 30 % respectively. The values of thermal conductivity for corn stems are lower than the values of thermal conductivity for cotton stalks at different "RV, %" and vice versa for the thermal resistivity. It means that the "CS and TS" improved the thermal properties of the rigid urethane foam. Finally, the corn stems have the lower thermal and higher resistant than the cotton stalks.

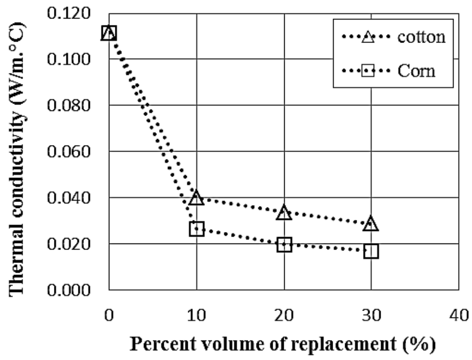

Fig (4): Effect of material percentage on thermal conductivity for (TS and CS).

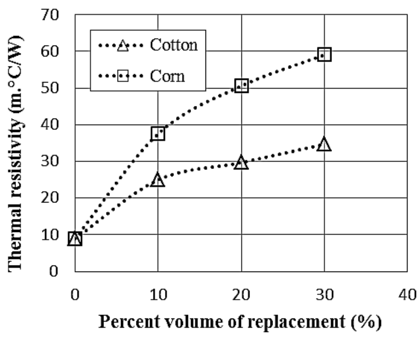

Fig. (5): Effect of material percentage on the intrinsic thermal resistivity for (TS and CS).

CONCLUSION

In this work, cotton stalks and corn stems replacement ratios (%) by volume were mixed with rigid urethane foam. Bulk density, thermal conductivity and thermal resistivity were identified as output parameters. Generally for the all the produced specimens, by increasing cotton stalks and corn stems replacement ratios (%), the thermal conductivity was decreased while, the bulk density and thermal resistivity were increased. The thermal conductivity and thermal resistivity were affected by the bulk density. As a result, the cotton stalks and corn stems were improved the thermal properties of rigid urethane foam. While, corn stems improved the thermal properties more than cotton stalks. Also, there were lowest values of thermal conductivity, bulk density and have the highest values of thermal resistivity.

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تحسين عزل الفــــوم بإستخـــدام حطب القطن والذرة

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ساعدت مشكلة تراكم الفضلات الزراعية في الحقول فى مصر إلى العديد من مشكلات التوازن البيئي. وقد أدى عدم تدبير كيفية استخدام هذه البقايا بطريقة تطبيقية مفيدة إلى تفاقم المشكلة مما جعلها في صدارة المشكلات البيئية. وحالياً يوجد مستويات عالية لتحويل الفضلات الزراعية بطرق مفيدة للمحافظة على البيئة والصحة العامة. وقد وجد فى مصر، استخدام ألواح الفوم فى عزل الحوائط. إلا أنه يعيبه ضعفه وقلة مقاومته للصدمات وايضا انخفاض قيم العزل الخاص به. وقد يمكن التغلب على هذه العيوب بزيادة تدعيم الألواح ببعض الفضلات الزراعية مثل حطب القطن وحطب الذرة. مما يجعلها أكثر مقاومة للصدمات وايضا قد يعمل على تحسين خواصها الحرارية . ولقد أجرى هذا البحث فى قسم هندسة المنشآت الزراعية والتحكم البيئى – كلية الهندسة الزراعية - جامعة الأزهر - القاهرة. لمعرفة مدى إمكانية استخدام حطب القطن وحطب الذرة لتحسين بعض خواص الفوم الحرارية والحصول على منتج من الفوم مقاوم للكسر. وقد أنتج هذا المركب عن طريق وضع نسب حجمية ٣٠،٢٠،١٠ ٪ من حطب القطن وحطب الذرة مع الفوم في قالب سهل الفك والتركيب مصنوع من خشب الابلاكاش بأبعاد ٥٠×٢٠٠×٣٠٠مم.وقد أجريت في هذا البحث ثلاث اختبارات هي:حساب الكثافه الظاهرية. قياس الموصلية الحرارية. قياس العزل الحرارى . كانت افضل النتائج كما يلى: كانت أقل وأعلى قيمة للموصلية الحرارية هى ٠،٠٢٨٨١ و ٠،١١١٥٢ عند عينات بها نسب احلال حجمية لحطب القطن (٣٠ , صفر٪) على الترتيب بانخفاض مقداره حوالي ٧٤٪. كانت أقل وأعلى قيمة للعزل الحرارى هى ٨،٩٧ و ٣٤،٧١عند عينات بها نسب احلال حجمية لحطب القطن (٣٠ , صفر٪) على الترتيب بانخفاض مقداره حوالي ٧٤٪. كانت أقل وأعلى قيمة للموصلية الحرارية هى ٠،٠١٦٩٢ و ٠،١١١٥٢ واط/م.م عند عينات بها نسب احلال حجمية لحطب الذرة (٣٠ , صفر٪) على الترتيب بانخفاض مقداره حوالي ٨٥٪. كانت أقل وأعلى قيمة للعزل الحرارى هى ٨،٩٧ و ٥٩،٠٩ واط/م.م عند عينات بها نسب احلال حجمية لحطب الذرة (صفر، ٣٠٪) على الترتيب بزيادة مقدارها حوالي ٨٥٪.ومن خلال هذه االنتائج يمكن استخدام حطب القطن وحطب الذرة (الفضلات زراعية) فى تحسين بعض خواص الفوم الحراريه ولكن يفضل حطب الذرة عن حطب القطن مما يساعد فى استخدامه فى مجال أوسع. ونوصى باستكمال هذه الدراسة واستخدام فضلات زراعية اخرى باحجام مختلفة (نسب أعلى) وترتيبات مختلفة مستقبلا واجراء قياسات اخرى.