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The acoustic insulation of rigid polyurethane foam composite with some agricultural residues

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ABSTRACT

The rapid growth of agricultural production has generated several environmental impacts with an important contribution from agricultural residues. Significant agricultural residues come from cultivation of cotton and corns, particularly its stalks, which were used in this work to produce a renewable composite of rigid polyurethane foam (RPUF) with soundprofing property. This work aimed to improve acoustic insulation performance of rigid polyurethane foam by adding agricultural residues (cotton or corn stalks, TS or CS) to produce a composite of rigid polyurethane foam with some agricultural residues. Four volumes ratios (5, 10, 15 and 20 %) of cotton or corn stalks were replaced with rigid polyurethane foam, beside a control replacement ratio, pure polyurethane foam, (0 %). The produced composite mad from rigid polyurethane foam (RPUF) and (TS or CS) were tested to measure bulk density "Bd, kg/m^3" and acoustic insulation "Ai, %". The results cleared that bulk density and acoustic insulation percentage were affected by previous replacement ratios (%) thus; bulk density and acoustic insulation percentage were increased with increasing the previous replacement ratios of each cotton or corn stalks. The data illustrated that acoustic insulation property of rigid polyurethane foam was improved with incorporated each TS or CS. Corn stalks showed the best, highest, acoustic insulation percentage values than cotton stalks. The highest acoustic insulation percentage were 28.07 and 20.18 (%) for corn and cotton stalks respectively, at replacement ratio of 20 (%).

1. Introduction

During the last decade, the world production of agricultural residues has steadily increased. That being said, cotton stalks (TS), the agricultural byproduct of cotton production that remains in the field after harvest (Mythili and Venkatachalam, 2013), is an abundant waste at a global estimate of 79.5 million tons per year in 2019–20 (Johnson et al., 2020). Cotton is one of the main cash crops grown in Egypt, covering an area of approximately 375,000 fad., and producing 330,300 Mg of cotton seed. According to (A.E.B., 2016), the yield and the amount of cotton waste were determined to be around 500,000 Mg/year. Corn stalks (CS) 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 stalks as an agricultural by-product makes them a good source of raw materials for many purposes. Egypt produces 3.12 million tons of cornstalk by-products per year (Husseien et al., 2009). As agricultural waste continues to accumulate, it becomes a major environmental and public health concern. Noise pollution is another environmental issue that is gaining increasing attention because of its negative impact on human health (Arenas et al., 2013). The development of efficient and environmentally friendly sound absorbing materials is important (Jiang et al., 2012). Noise is an unwanted sound

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perceived by humans. Noise comes from many sources, such as public traffic, factories or even at home. To reduce noise pollution, sound absorption should be taken as a measure. Sound absorption is a physical phenomenon in which the energy of sound waves is attenuated within a material, resulting in a reduction in wave energy (Chanlert and Ruamcharoen, 2021). Stacy (1959) defined sound absorption as a part of the sound wave that hits the surface and is not reflected. There are many ways to dampen the sound wave, by increasing the air resistance (Tang et al., 2018) or even by destructive interference between the incident wave and the reflected wave (Shao et al., 2019). Building design and construction require high-performance acoustic insulation materials to create a healthy and comfortable environment at home and at work, beside to reduce energy consumption and achieve sustainability (Aly et al., 2021). Acoustic comfort requires the reduction of disruptive noise, such as noises caused by footsteps, falling objects and moving furniture, which are considered to be significant sources of annoyance for building residents (Warnock, 1999; Buratti and Moretti, 2006). The term "acoustic material" is used broadly and applied to materials that exhibit a high level of sound absorption. In order to produce an acceptable sound absorbing material, several factors that influence the sound absorbing property of the acoustic material, such as porosity, hardness, elasticity or even surface morphology, must be considered (Eijk et al., 1950) etc. The investigation of acoustically absorbing materials in a specific or broad range has become increasingly important over the decades. The application of these materials in various sectors of industry, such as aeronautics and road transport, poses a major technical challenge due to the ability to be reduced with the least possible amount of insulation applied, thus reducing the cost and additional weight to be minimum (Da Silva et al., 2016). Polyurethane (PU) is one of the most commonly used polymers in various industries. The properties of polyurethane depend on the starting materials and the manufacturing processes. With isocyanate and polyol as typical reagents, catalysts, surfactants and water as a blowing agent, it would turn out to be polyurethanes with outstanding properties. One of the important commercial polyurethane products is foam, which is widely used for many versatile purposes. According to mechanical properties, it can be classified as rigid or soft. The sound absorption capacity of polyurethane foam is exceptional (Gwon et al., 2016). As a result of the increasing demand for better insulation materials and sound absorbers, Pathnaik et al. (2015) reported that the majority of sound insulation used in the construction industry is based on glass fibers and other derivatives, silica and synthetic fibers. Papadopoulos (2005) add that these materials need to improve their performance, be adaptable and cost-effective. It is therefore advisable to reduce the use of conventional acoustic absorbers obtained from fossil sources, which require large amounts of primary energy to produce them. In this sense, Mati-Baouche et al. (2016) studied the acoustic properties of a mixture of crushed sunflower stalk particles bound by chitosan, where a good absorption coefficient was obtained. There are several studies on the sound absorption capacity of natural products. Bamboo fibers have proven to be good sound absorbers (Koizumi et al., 2002). Even at low densities, rice straw particleboards can absorb sound in the range of 900 to 8000 Hz (Yang et al., 2003). Sugar cane bagasse in the form of chipboard has good performance in soundproofing, especially in the 500 to 2000 Hz range (Carvalho et al., 2015). One of the benefits of natural products is that they are safe for the earth's environment. Most of the natural products used as acoustic material are agricultural waste. In recent decades, growing environmental concerns have increased the interest of the scientific community in developing natural fiber biocomposites (Mathias et al., 2015). The use of natural fibers to reinforce polyurethane has become increasingly attractive due to the desire to produce composite materials that are renewable and biodegradable (Kuranchie et al., 2021). The use of these environmentally friendly sustainable materials effectively contributes to the reduction of greenhouse gas emissions, promotes environmental protection and sustainability, and provides a cost-effective means of manufacturing composites (Mokhothu and John, 2017). Another interesting aspect of natural fibers is that they also help improve other properties such as insulation and sound absorption of rigid polyurethane foams. Another interesting aspect of natural fibers is that they also help improve other properties such as insulation and sound absorption of rigid polyurethane foams. The work of (Sair et al., 2019) investigated how the introduction of alkalized alfa fibers could reinforce rigid polyurethane foam and improve its insulating properties. The normal sound absorption of pure PU foams generally shoots up steadily from 0.1 at 50 Hz to around 0.19 at 2 kHz. However, they observed that at low frequencies (up to 350 Hz), both pure and reinforced foams had the same sound absorption coefficient. Beyond 350 Hz, the fiber-reinforced composite foams had a higher degree of sound absorption due to the fillers. This observation was due to a reduction in vibration transmission due to the numerous small holes found in the hollow tubular structures of the alfa fibers (Berardi and Iannace, 2015). Another study, Ekici et al. (2012) investigated how to improve the sound absorption capacity of PU foams by adding natural tea leaf fibers. His motivation was based on the fact that sound absorption is an important requirement for human comfort, especially in automobiles and production environments where higher sound pressure levels are generated. They found that to produce low-cost insulation materials, the versatility of polyurethane could be explored by introducing tea leaf fibers into the formulation of rigid PU foams. After creating several formulations, they concluded that sound absorption increased steadily with increasing filler content with a final sound absorption value of 0.39 at 6.3 kHz. At 8% filler concentration, an 80% increase in sound absorption was observed. Tao and Cai (2016) also studied the influence of rice straw fibers and wheat straw fibers on the sound absorption properties of rigid polyurethane foams (RPUF). After producing the foam masses, they measured their sound absorption at different frequencies. They found that at 10% fiber content (both rice and wheat straw fibers) the maximum sound absorption coefficient was measured. However, the average sound absorption coefficient of the wheat fiber filled composite foams was higher than that of the rice fiber filled composite foam at 5% and 10% filler content. Using SEM images, they found that the addition of straw fibers damaged the closed cell structure of the Polyurethane foam resulting in an open cell structure which could have explained the improvement in absorption properties. Chen and Jiang (2018) also studied how the addition of bamboo leaf particles affects the acoustic properties of polyurethane foams. In this study, they reported that PU composite foam with 6% bamboo fiber provided the highest noise reduction coefficient. And the maximum sound absorption level at 6.3 kHz. In addition, they found that 8% bamboo chips with a particle size of 2-3mm provided the best soundproofing. Due to the above reasons, there is an increasing demand for using ecological, biodegradable and sustainable materials to produce polyurethane compounds for some applications. In this regard, natural fibers derived from agricultural wastes are preferred over their synthetic counterparts because of their ready availability, lightness, profitability, strength and biodegradability. In addition to their renewable nature, the use of natural fibers in polyurethane foams results in composite foams with better properties than pure polyurethane foams (Kuranchie et al., 2021). The main aim of present work was using some agricultural wastes (TS and CS) to improve acoustic insulation of rigid polyurethane foam. Beside, testing improved acoustic insulation performance of rigid polyurethane foam with different replacement volumes of agricultural wastes, if they are used for isolation purposes.

2. Materials and methods

All the experiments of present research were carried out in winter of 2021 at faculty of agricultural engineering, Al-azhar univ., Cairo, Egypt.

2.1. Raw materials

Cotton and corn stalks (TS and CS) were collected from a field in El-Gharbia Governorate, Egypt, and prepared for the experiments by cutting them into small pieces, each 200 mm in length. The mean values of its diameter were recorded at 11 and 19 mm, respectively. They were dried naturally before being prepared by being placed outside during the day's intense hours of sunshine. After drying, the moisture content was approximately ± 10.65% and ± 9.42 % on a wet basis, respectively.

2.2. Raw materials preparation

Cotton and corn stalks were washed in boiling water at 100°C for 60 minutes and dried naturally in the sun for 7 hours, then mercerized by immersion in an aqueous solution of sodium hydroxide (NaOH) 1.5 wt% at room temperature for 48 Hours. After that, the excess NaOH were removed from cotton and corn stalks with water. Finally, cotton and corn stalks were naturally dried in the sun for 6 hours and stored.

2.3. Rigid Polyurethane Foam

The materials used to prepare rigid polyurethane foam (RPUF) were obtained from a commercial source. Rigid polyurethane foam (RPUF) has following chemical properties: (A) Polyol component: a mixture of polyol, flame retardant, catalyst, stabilizer and HFC blowing agent (polyol: density = 1.13 g/cm^3 at 25 °C, viscosity = 396 mPa at 25 °C) (B) isocyanate component: contains a polymeric diphenylmethane-MDI (methylenediphenyl diisocyanate, IsoPMDI 92140) (density = 1.23 g/cm^3 at 25 °C,viscosity = 270 mPa at 25 °C).

2.4. Specimen's preparation mold

In this work to form specimens, a rectangular plywood mold with inner dimensions of (300 × 200 × 50 mm) was used. The plywood used to manufacture the mold was wooden residues received from a furniture workshop within side El-Gharbia Governorate, Egypt. Mold made to be removed and installed by connecting the wooden sides with screws. Its top (300 x 50 mm) was opened to place stalks and pour foam through. The underside facing open side had many metal pins (1.0 mm) in diameter to help even out placement of stalks while pouring foam. After pouring foam and allowing sufficient time to fully set, the mold was removed and the produced composite was cut with a power saw into circular specimens of appropriate dimensions for testing.

2.5. Digital sound level meter

To study effect of cotton and corn stalks replacement with the pure rigid polyurethane foam on acoustic insulation percentage "AI, %" of the obtained composite, a sound level meter was used, to measure sound level by decibel "dB". The used device technical specifications, according to manufactured catalogue, are as follow:

- Model No.: 33-2055a.
- country: China.
- Battery: 9- volt Alkaline.
- Microphone: Electret Condenser.
- Range: 50 dB to 126 dB.
- Accuracy: ±2 dB at 114 dB SPL.
- Reference: 0 dB = 0.0002 Micro Bar.
- Display Response: Fast and Slow.
- Operating Temperature: 273 to 323 °K.
- Storage Temperature: 233 to 338 °K.
- Dimensions (H×W×D): 159x 64x 44 mm.
- Weight: 165 g Approx.

2.6. Cubic foam

A cubic foam box was used with a digital sound level meter to record acoustic insulation percentage of produced specimens without any effect of surroundings sounds, because tests were done in isolated room. The cubic foam box dimensions were 300 × 190 × 190 mm. It made from rigid foam with a hollow shape to put specimens inside. The first side diameter was 122 mm, side of sound source while, the other side was 112 mm, side of sound level meter microphone, to insure that specimens are stick in the middle distance of cubic foam box as in Fig. (1). the other side was locked with a foam disk with small hole in its center to put the measuring device microphone inside.

2.7. Test procedures

Four volumetric ratios of TS and CS were replaced with the pure rigid polyurethane foam (RPUF), to study bulk density "Bd, kg/m^3" and acoustic insulation "Ai, %" of the obtained composite, which were influenced by following variable: percent volume of replacement "PVR, %". The tests were conducted at Research Center of the Faculty of Agricultural Engineering, Al- azhar University, Nasr City, Cairo, Egypt.

2.8. Percent volume of replacement "PVR, %"

The pure rigid polyurethane foam (RPUF) were replaced with four ratios of each (TS) and (CS) by volume. Corn and cotton stalks replacement ratios were 5, 10, 15 and 20 (%) by volume, in addition that ratio of (0 %) was without adding (TS) or (CS) as a control specimen. one hundred samples of 200 mm in length for each, were collected from (CS) and (TS), the average diameter of each was 19 and 11 mm, respectively. Depending on its average diameter and length, volume of one sample was calculated for both (CS) and (TS), which average volume of sample for each (CS) and (TS), were 56,677 and 18,997 cm^3, respectively. Four volumes of 5, 10, 15 and 20% from total mold volume of 3000 cm^3 used in samples preparation were calculated. The volumes of 150, 300, 450 and 600 cm^3 of (TS) and (CS) were required to achieve the previous ratios of 5, 10, 15, and 20 % by volume respectively. To achieve these previous volumetric ratios, the total required number of stalks was calculated to be used with each volumetric ratio. And it turned out that, number of cotton stalks required of 8, 16, 24 and 32. While, number of corn stalks required of 3, 5, 8 and 11.

2.9. Preparations for testing

Aluminum foil was used to line a plywood rectangular mold to prepare specimens for testing. About 5, 10, 15 and 20 % by volume of TS or CS respectively, were arranged and placed vertically into the mold. The foam of Rigid polyurethane (RPU) was produced between and around (TS or CS) when placing a 50-50 (A-Polyol and B-isocyanate components) by volume onto bottom of the mold immediately after mixing. After about 30 min, composite of rigid polyurethane foam (RPUF) and (TS or CS) was removed from mold. The obtained composite of rigid polyurethane foam (RPUF) and stalks was cut into circular specimens of fixed diameter of 105 mm and thickness of 50 mm for acoustic insulation test.

2.10. An experimental design

A combination of each of two types of cotton and corn stalks (TS and CS) and four volumetric ratios from them which to be replaced to rigid polyurethane foam resulting, in eight treatments. Each treatment was repeated three times to give three replicates, resulting in 24 specimens.

2.11. Measurements

The following tests were carried out at ambient room temperature of 27 °C and relative humidity of 62 %. The following measurements were carried out on each specimen:

2.12. Bulk density "Bd, kg/m^3"

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, kg/m^3" at previous different ratios according to the following equation:

$$\text{Bulk density (Bd)} = \frac{4\,\text{M}}{\pi \text{d}^2 \text{L}} \qquad [1]$$

2.13. Acoustic insulation percentage "AI, %"

To calculate acoustic insulation percentage "AI, %", value of sound source was recorded first by a digital sound level meter and it was 114 dB. A circular specimen of obtained composite was put in middle of the distance inside a cubic foam box. The value of sound behind specimen was recorded. By subtraction 114 dB from that recorded value after putting specimen, the resultant was divided by 114 dB. The resultant was multiplied by 100 to give the acoustic insulation percentage "AI, %" and so on for all other specimens, as in Fig. 1.

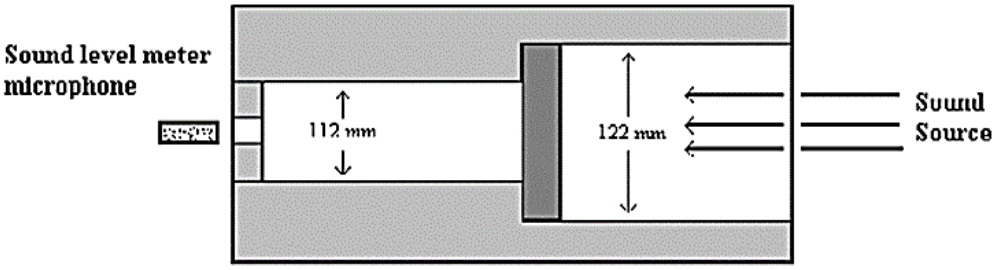

Fig. 1. Schematic diagram of cubic foam with specimen, (ElBessoumy, 2005).

3. Results and discussions

Percent volume of replacement "PVR, %" via mass "M" and bulk density "Bd"

Figs 2 and 3 illustrate, 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 increased with increasing percent volume of replacement (%) for (TS and CS). The obtained data indicated that, the mass is increased from 0.030 to 0.067 kg and from 0.020 to 0.038 kg at increased percent volume of replacement (%) from 5 to 20 % for used (TS and CS), respectively. As the bulk density is depending on the mass, the bulk density is increased as well from 77.56 to 171.23 kg/m^3 and from 51.03 to 96.54 kg/m^3 at increased percent volume of replacement (%) from 5 to 20 % for used (TS and CS), respectively. The percentages of increase in mass and bulk density of specimens made of rigid polyurethane foam and cotton stalks were about 48, 67, 74 and 76 % at replacements ratios of 5, 10, 15 and 20 %, respectively. While, the percentages of increase in mass and bulk density of specimens made of rigid polyurethane foam and corn stalks were about 20, 32, 46 and 58 % at replacements ratios of 5, 10, 15 and 20 %, respectively. The values of mass and bulk density for cotton stalk are higher than the values of mass and bulk density for corn stalks at different percent volume of replacement (%) and it is agreed with Chris-Okafor et al. (2017).

Acoustic insulation "Ai, %" via percent volume of replacement "PVR, %" and bulk density "Bd, kg/m^3"

Figs. 4 and 5 indicate relation between acoustic insulation "Ai, %", "RV, %" and bulk density "Bd, kg/m3" for (TS and CS). The obtained data showed that acoustic insulation is affected by "RV, %" and bulk density "Bd, kg/m3". The acoustic insulation increases with increasing "RV, %" and bulk density for each (TS and CS). The acoustic insulation is increased from 7.89 to 20.18 % and from 7.89 to 28.07 % at increased "RV, %" from 5 to 20 % and bulk density from 40.69 to 171.23 kg/m3 and 40.69 to 96.54 kg/m3 for each of (TS and CS), respectively. The percentages of acoustic insulation for corn stalks are higher than percentages of cotton stalks at different "RV, %" and bulk density. It means that (CS and TS) improved acoustical properties of rigid polyurethane foam. Finally, corn stalks (CS) have higher acoustic insulation than cotton stalks (TS). This may be due to that the addition of corn stalks damaged close cell structure of polyurethane foam resulting in an open cell structure, which might have contributed for improvement in sound absorption property and lead to a high ratio of acoustic insulation; it is agreed with Tao and Cai, (2016).

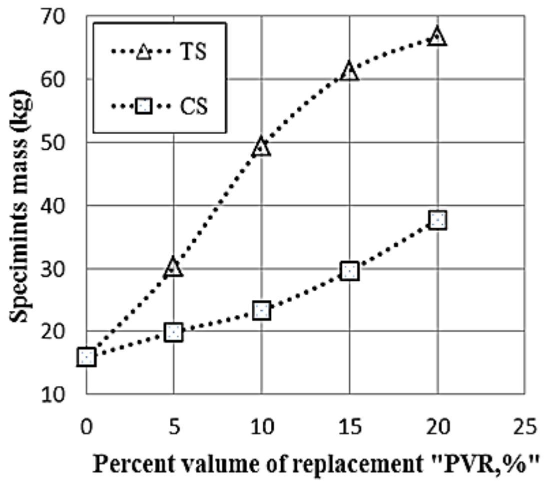

Fig. 2. Effect of "PVR, %" on specimens mass for (TS and CS).

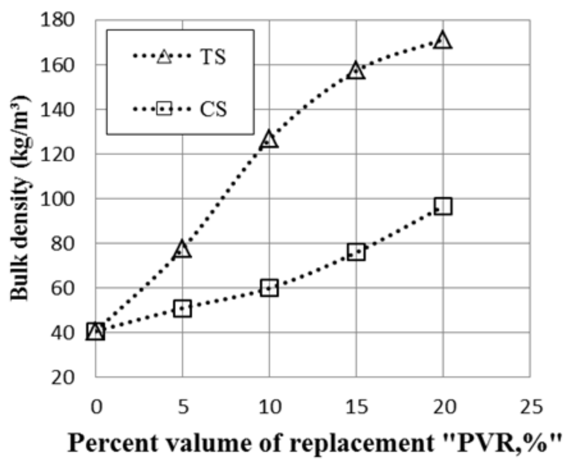

Fig. 3. Effect of "PVR, %" on bulk density "Bd, kg/m^3" for (TS and CS).

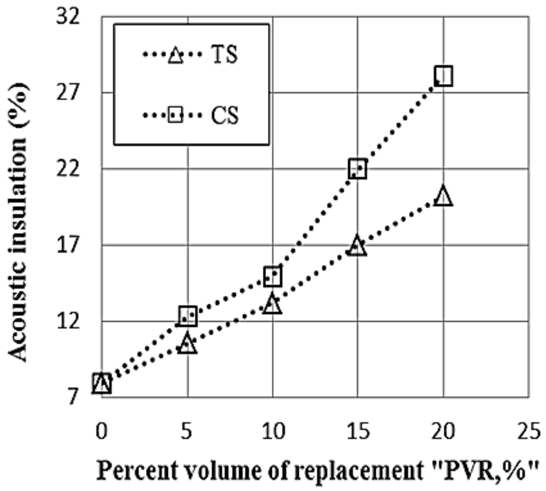

Fig. 4. Effect of "PVR, %" on acoustic insulation "Ai, %" for (TS and CS).

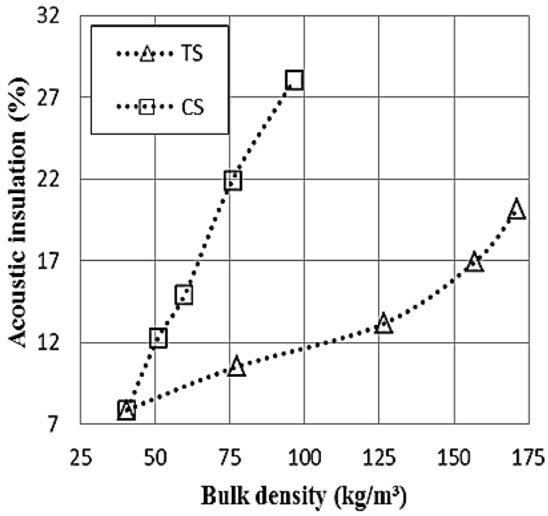

Fig. 5. The relation between acoustic insulation and bulk density for (TS and CS).

4. Conclusions

In this research, cotton and corn stalks ratios (%) by volume were replaced with rigid polyurethane foam. Bulk density and acoustic insulation were identified as output parameters. Generally for all produced specimens, by increasing cotton or corn stalks replacement ratios (%), the acoustic insulation and bulk density were increased. The acoustic insulation was affected by percent volume of replacement and bulk density. As a result, cotton and corn stalks helped to improve sound properties of rigid polyurethane foam. On the other hand corn stalks were improving sound properties of the obtained composite, more than cotton stalks.

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العزل الصوتي لمركب رغوة البولي يوريثان الصلب مع بعض المخلفات الزراعية

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الملخص العربي

أدى النمو السريع للإنتاج الزراعي إلى العديد من الآثار البيئية مع مساهمة مهمة من المخلفات الزراعية. تأتي المخلفات الزراعية الهامة من زراعة القطن والذرة، وخاصة سيقانها، والتي تم استخدامها في هذا العمل لإنتاج مركب متجدد من رغوة البولي يوريثان الصلبة مع خاصية عزل الصوت. ويهدف هذا العمل إلى تحسين آداء العزل الصوتي لرغوة البولي يوريثان الصلبة عن طريق إضافة المخلفات الزراعية المقطعة يدوياً (سيقان القطن والذرة كل على حدة) لإنتاج مركب من رغوة البولي يوريثان الصلبة. مما يجعلها أكثر مقاومة للصدمات وأيضاً قد يعمل على تحسين خاصية العزل الصوتي. ولقد أجرى هذا البحث في قسم هندسة المنشآت الزراعية والتحكم البيئي - كلية الهندسة الزراعية - جامعة الأزهر - القاهرة، لمعرفة مدى إمكانية استخدام حطب القطن أو الذرة لتحسين بعض خواص العزل الصوتي والحصول على منتج من الفوم مقاوم للكسر. وقد أنتج هذا المركب عن طريق وضع نسب حجمية ٥ و ١٠ و ١٥ و ٢٠ % من حطب القطن والذرة كل على حدة والمقطع يدوياً بأطوال ٢٠ سم مع الفوم في قالب سهل الفك والتركيب مصنوع من خشب الأبلاكاش بأبعاد ٥٠×٢٠٠×٣٠٠مم ومقارنته بمعاملة بدون إحلال (فوم فقط). وقد أجري في هذا البحث حساب كلا من: الكثافة الظاهرية وقياس عزل الصوت وكانت النتائج كما يلي:

- كانت أقل وأعلى قيمة لعزل الصوت هي ٧,٨٩ و ٢٠,١٨ ٪ وأقل وأعلى كثافه ظاهرية هي ٤٠,٦٩ و ١٧١,٢٣ كجم/م^{3} عند عينات بها نسب إحلال حجمية لحطب القطن (صفر , ٢٠ ٪) على الترتيب.
- كانت أقل وأعلى قيمة للعزل الصـــوتي هي ٧,٨٩ و ٢٨,٠٧ ٪ وأقل وأعلى كثافه ظاهرية هي ٤٠,٦٩ و ٩٦,٥ كجم/م^{3} عند عينات بها نسب إحلال حجمية لحطب الذرة (صفر، ٢٠ ٪) على الترتيب.

ومن خلال هذه النتائج يمكن استخدام حطب القطن أو الذرة في تحسين خاصية العزل الصوتي للفوم، ولكن يفضل حطب الذرة عن حطب القطن مما يساعد في استخدامه في مجال أوسع. ويُوصى باستكمال هذه الدراسة واستخدام مخلفات أخرى بأحجام مختلفة مستقبلا وإجراء قياسات أخرى.