Eng. Sci., 2022, **18**, 329–336

Engineered Science
DOI: https://dx.doi.org/10.30919/es8d696

Repurposing Plastic Wastes in Non-conventional Engineered Wood Building Bricks for Constructional Application – A Mechanical Characterization using Experimental and Statistical Analysis

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Abstract

Plastic waste is accumulating at an alarming rate, polluting the environment due to various industrial activities. Plastic waste is also non-biodegradable, making global accumulation deteriorate. Moreover, it is observed that using sustainable building materials encourages the efficient use of wood industry waste. The study uses polyethylene terephthalate (PET) waste combined with wood fibers to make non-conventional bricks. In the present study, two distinct types of bricks were evaluated, one containing 25% weight of PET waste and the other containing 40%. All samples were subjected to compressive strength and hardness tests in accordance with the applicable American Society for Testing and Materials (ASTM) standards. Since a perfect brick composition should include both the mechanical properties on the higher sides, in the current work, Data Envelopment Analysis (DEA) was utilized to conduct a multi-response analysis and determine the optimal combination of plastic waste and wood fibers for manufacturing non-conventional bricks. The brick containing 25% by weight of plastic waste proved to be the best of the two types of wood plastic composites (WPCs) created in this study, with a grey relational grade value ranging between 2.384 and 3.045.

Keywords: Non-conventional building materials; Recycled materials; Solid waste reuse, Plastic waste, Wood fiber.
Received: 14 March 2022; Revised: 06 April 2022; Accepted: 11 April 2022.
Article type: Research article.

1. Introduction

The production of clay bricks uses many non-renewable materials that contribute to releasing greenhouse gases such as carbon dioxide, carbon monoxide, and other chemical pollutants. The production process includes firing the bricks to achieve strength which requires 24 million tons of coal every year, known for being one of the most polluting commodities on the planet.[1–3]

Rapid urbanization and changing human lifestyles contribute significantly to the large volume of waste generated and disposed of each year. Plastic waste is a type of solid waste generated in large quantities possessing a serious threat to the planet's sustainability.[4] Plastic pollution is a global problem of high concern[5] since plastic (synthetic or semi-synthetic materials created by the polymerization process) is a non-biodegradable material capable of damaging land, waterways, and air.[6–8] Global plastic manufacturing has increased to an annual average of more than 300 million metric tons, a stunning leap from the 1.5 million metric tons produced in 1950.[9–11] Plastic waste contaminates the natural environment in rural and urban areas in developing countries, posing a serious threat to waste management. Due to the non-biodegradability of synthetic plastic materials, they are either burned openly or dumped in land and water bodies, posing serious environmental problems.[12] A few researchers have also anticipated that plastic waste generally takes 500 years to degrade completely[13] and thus requires it to be recycled instead. Among the several options for recycling plastic waste, construction material made from recycled plastic has attracted considerable interest. The addition of plastic waste to construction materials has a twofold purpose: it decreases the

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quantity of plastic trash that ends up in landfills or as litter and reduces the usage of mined construction materials, minimizing the construction industry's negative impact on the environment.[14] Thus, several engineers and researchers in recent times have begun developing lightweight, cost-effective, and low thermal-conductive blocks that may be used to construct buildings out of plastic waste.[1,3] For example, Kognole *et al*.[15] created plastic waste-sand bricks and examined the mechanical properties as sand and plastic waste mix changed.

Based on mechanical strength tests, Madghe *et al.*[16] determined the optimal composition of plastic bricks, in which shredded plastic in powder form was mixed with cement and fly ash. Islam and Shahjalal[17] assessed the concrete performance when polypropylene (PP) plastic, generated from waste plastic products, was used as a partial substitute for natural stone aggregate (SA) and fired-clay brick aggregate (BA). Akinyele and Oyelakin[18] used molten plastic to substitute cement in sand Crete bricks and evaluated mechanical characteristics for applicability as construction bricks for building and pedestrian pavement. Aneke and Shabangu[2] studied the use of plastic scrap waste (SPW) and foundry sand (FS) in the manufacturing of efficient green bricks for masonry buildings. Alaloul *et al*.[19] recycled plastic bottles containing plastic waste and created an interlocking brick. Bhat *et al*.[20] developed and tested the mechanical characteristics of lightweight unconventional plastic waste-sand bricks to see if they may be used as building materials.

Aside from recycling plastic waste, researchers and the construction industry have recently focused on increasing the use of eco-friendly, sustainable construction materials.[21–24] The use of engineered wood, particularly derived from wood industries and agricultural residues, to create eco-friendly construction materials has garnered increased global attention.[25] Engineered wood products, also known as composite wood products, are constructed from wood particles or fibers that have been changed from the original log, mixed, or coated with an adhesive, and then recombined to make the desired result.[26] The use of engineered wood enables the products to be formed into structurally efficient shapes that are not possible with sawing, allowing for greater productivity with less wood usage.[27] As per recorded research works, including wood particles in clay bricks has improved compressive strength and porosity.[28] Furthermore, research has shown that the addition of wood-particle to conventional brick improves its flexural strength.[29] Wood particles have been found as the optimum low-cost adsorbing additive employed in bricks for property enhancement from a wide range of available materials.[30] Farazela *et al*.[31] combined waste wood fibers with sand and proved the feasibility of fabricating engineered wood bricks exhibiting a wide range of compressive strength ranging between 1.75 and 20.61 MPa, depending on the percentage by weight of wood fibers added.

Garcez *et al*.[32] fabricated engineered wood-based bricks using wood fibers and cement as the elements. The bricks formed were tested mechanically and found to be of suitable use as an alternative to masonry clay bricks used as a traditional building material. Plotnikov *et al*.[33] their documented research work proved that engineered wood-based construction materials can be used as a right substitute for metals, expensive plastics, bricks, and concrete used in the construction industry. The properties of the engineered wood bricks fabricated by Turgut and Algin[34] indicated their suitable applications in the construction industry as a good alternative replacement to concrete blocks, ceiling panels, and sound barrier panels. Though several works have been recorded to showcase the implementation of engineered wood as a potential construction material, combining wood and plastic to create engineered wood or wood-polymer composites (WPCs) is a relatively recent innovation in the engineered product business.[33,35] Like the usage of thermoplastic recycled materials, WPCs also have demonstrated the technological and economic requirements to become new mass-produced materials.[36] WPCs are marketed as low-maintenance, high-durability products. However, after a decade of outside use in the building sector, concerns about durability have surfaced.[37,38] Given the continued importance of WPC durability concerning their use in building construction and other related industries, it necessitates a rigorous examination of the end products' mechanical qualities.[37] Thus, focusing on the need for truly sustainable alternatives to conventional clay bricks, increased utilization of wood particles in the manufacture of eco-friendly construction materials, and recycling plastic waste to mitigate its escalating environmental impact, the current work intends to provide a concise summary of the results of laboratory tests conducted to determine the feasibility of implementing the process of producing engineered wood building bricks from plastic waste. The evaluation is based on the compressive strength and hardness of manufactured samples. All the samples were tested as per ASTM D7031-11(2019) *Standard Guide for Evaluating Mechanical and Physical Properties of Wood-Plastic Composite Products*.[39] The Data Envelopment Analysis (DEA) approach was used to conduct a multi-response study and discover the optimal raw material combination for brick manufacturing.

2. Materials and methods

2.1 Brick preparation

The materials employed in this work were chopped wood fiber and shredded polyethylene terephthalate (PET). PET garbage was collected from designated bins positioned at

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various collection stations. The PET waste was fully cleaned, dried, and shredded to a maximum particle size of 4 mm using a slow-speed granulator. The wood fibers and PET waste granules were blended in different proportions by weight to create two separate types of brick prototypes, WPC 1 and WPC 2. Table 1 has the composition details for each type of brick. The plastic waste and wood fiber mixture was preheated for a while, then heated in the laboratory furnace at 300°C for 15 min. The mixture was then poured into the prepared wooden mold, which was lined with parchment paper on the inside, and cooled at room temperature. The bricks made were 150 × 50 × 50 mm in size as per the requirement of the ASTM standards.[39] The brick prototypes were left to cure for 28 days before conducting any tests

Table 1. Types of wood-plastic composite bricks and composition.

Sl. No.	Brick Type	Percentage by weight of wood particles	Percentage by weight of plastic waste
1	WPC 1	75	25
2	WPC 2	60	40

The burnt plastic fused the wood fiber to form a solid brick, giving the WPC 1 and WPC 2 brick prototypes dark textures. Fig. 1(a) and Fig. 1(b) show the surface of WPC 1 and WPC 2 samples, respectively, photographed using a CANON digital single-lens reflex (DSLR) camera with a 50 mm focus lens. The WPC 1 bricks exhibited a smoother surface than the WPC 2 bricks. The brick surface was perforated with cracks and bulges. Furthermore, warpage was greater in the case of WPC 2 bricks than in the case of WPC 1 bricks. In other words, the increase in the percentage of the plastic component increased the irregularity in the shape of the formed bricks.

2.2 Compressive strength testing

The ASTM D7031-11(2019) *Standard Guide for Evaluating Mechanical and Physical Properties of Wood-Plastic Composite Products*[39] suggests the usage of section 12 of ASTM D143-21 *Standard Test Methods for Small Clear Specimens of Timber*[40] for the compression-perpendicular-to-grain tests of wood plastic composites. The load was applied through a 50 mm wide metal bearing plate positioned across the specimen's upper surface at equal distances from the ends and perpendicular to the length. The bearing plate surface that contacted the wood specimens was flat, with no rounded or chamfered corners. The load was delivered continuously during the test at a rate of 0.305 mm/min using a UTM established in the laboratory with a loading capacity of 100 tons. A total of ten specimens (five for each composition) were tested for compressive strength. Fig. 2(a) and Fig. 2(b) illustrate the specimen prepared as per the ASTM standards, and Fig. 2(c) represents the compression strength testing equipment used in the present study.

2.3 Hardness testing

The ASTM D7031-11(2019) *Standard Guide for Evaluating Mechanical and Physical Properties of Wood-Plastic Composite Products*[39] suggests the usage of section 13 of ASTM D143-21 *Standard Test Methods for Small Clear Specimens of Timber*[40] for the hardness tests of wood plastic composites. The brick samples are assessed using the Rockwell R scale (used for soft materials and thermoplastics) with a steel ball 12.70 mm in diameter fitted in the Rockwell Tester.[41] The test specimens were put on a steel anvil and subjected to a mild load (10 kg). This surface showed a shallow indentation. The dial was set to zero while under mild load, and a major load (60 kg) was applied, causing the ball to indent into the plastic test specimen, generating a deeper indented surface. The significant load was lifted within 15 seconds. After another 15 seconds, the hardness was read on the instrument's gauge with the slight load still applied while the surface recovered to a predetermined point. Two penetrations were conducted on each face of a specimen to provide a fair representative average of the brick. A total of ten specimens (five in each composition) were tested for hardness. Fig. 2(d) illustrates the Rockwell hardness tester setup used in the present study.

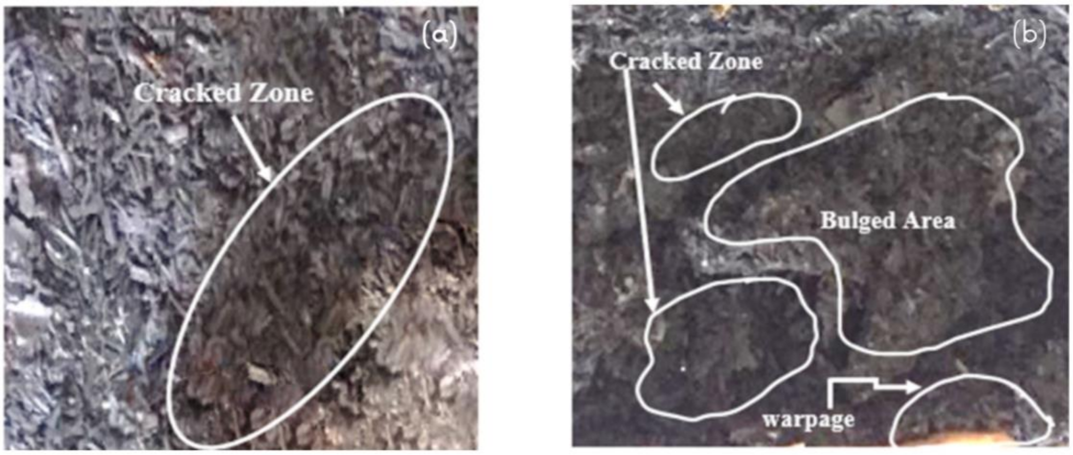

Fig. 1 Photograph of the Surface of the fabricated engineered wood building bricks: (a) WPC 1; (b) WPC 2 captured using CANON digital single-lens reflex (DSLR) camera with a 50 mm focus lens.

Fig. 2 Wood-plastic specimen and equipment used in the present experimental study: (a) wood plastic composite bricks with 25 wt.% plastic wastes; (b) wood plastic composite bricks with 40 wt.% plastic wastes; (c) Compressive strength testing machine; (d) Steel ball indenter of Rockwell hardness tester with a calibrating specimen of wood plastic composite.

2.4 Statistical analysis

Initially, analysis of variance (ANOVA) is used since it is a conceptually simple, powerful, and widely used method of statistical testing on studies with two or more groups.[42] The ANOVA test determines if the averages of various independent groups of continuous data differ significantly on a single factor.[43] Therefore, one-way ANOVA tests are conducted for the experimental results to determine if there is a significant difference in the mechanical strengths of both the types of engineered wood building (wood plastic composite) bricks made for the study purpose.

The Games-Howell test is used for the post-hoc test because it gives good control of what is known as "family-wise error", also known as Type I error, in circumstances where the variances are unequal. It's also quite effective in non-normality situations.[44,45] Besides, the current study focuses on two responses for prepared engineered wood building bricks: compression strength and Rockwell hardness. An ideal brick composition must have both responses on the higher sides.

Thus, Data Envelopment Analysis (DEA), a proven statistical approach where multiple inputs and multiple outputs, regardless of how many they are, can simultaneously be optimized,[46–50] is used in the current work to do a multi-response study and discover the ideal combination of plastic waste and wood fiber to manufacture the wood plastic bricks. DEA methodology for the current work involves the following steps:[51]

Step 1: Using Equations (1) and (2), compute the weights (w) for compression strength (CS) and Rockwell R scale hardness (HRR) for all the respective obtained values.[51]

$$W_{CS} = \frac{CS_i}{\sum_{i=1}^{10} CS} \tag{1}$$

$$W_{HRR} = \frac{H_i}{\sum_{i=1}^{10} HRR} \tag{2}$$

Step 2: By multiplying the observed data by its weight, convert the response data to weighted data using Equations (3) and (4).[51]

$$A = CS \times W_{CS} \tag{3}$$

$$B = HRR \times W_{HRR} \tag{4}$$

Step 3: Divide larger-the-better data by smaller-the-better to calculate the multi-response performance index (MRPI). In the present work, both the response data represent larger-the-better; therefore, Equation (5) represents the mathematical form of calculating the MRPI.[51]

$$MRPI_i = A_i + B_i \tag{5}$$

3. Results and discussion

Table 2 shows the compressive strength and R-scale Rockwell hardness results. Table 3 represents the Games-Howell (GH) comparison for the conducted one-way ANOVA tests for compressive strength and R-scale Rockwell hardness concerning the engineered wood building (wood plastic composite) bricks. Each of the parameter levels (brick type in this study) is assigned a grouping letter (A, B, C, D, *etc.*) in the GH comparison. If all parametric conditions have the same letter, the multiple comparison method does not reveal a statistically significant difference in mean response.[52] A significant mean difference is confirmed for any factor level that does not share a letter. Since the averages do not share a common letter concerning both compressive strength and R-scale Rockwell Hardness results, it is concluded that there is a significant difference in the mechanical properties.

Table 2. Results of compression strength (MPa) test and R-scale Rockwell hardness (HRR) for the engineered wood building (wood plastic composite) bricks.

Mechanical property	Brick type	Sample number				
		1	2	3	4	5
Compressive strength (MPa)	WPC 1	2.463	2.499	2.486	2.487	2.496
	WPC 2	3.319	3.358	3.375	3.349	3.316
R-Scale Rockwell hardness number (HRR)	WPC 1	21.8	22.65	19.84	21.25	20.81
	WPC 2	15.3	15.2	14.3	14.75	15.35

Table 3. Grouping Information using the Games-Howell method and 95% confidence for compressive strength and R-scale Rockwell hardness of the engineered wood building (wood plastic composite) bricks.

Mechanical property	Brick type	Sample size (N)	Mean	Grouping letters
Compressive strength (MPa)	WPC 1	5	2.48620	A
	WPC 2		3.3434	B
R-Scale Rockwell hardness number (HRR)	WPC 1		21.270	A
	WPC 2		14.980	B

Moreover, from Fig. 3(a) and Fig. 3(b), representing the interval plots for compressive strength and Rockwell hardness of the engineered wood building (wood plastic composite) bricks, it could be inferred that the compressive strength is at a higher side for WPC 2 and Rockwell hardness is high for WPC 1 type. The compressive strength increases as the percentage of PET increases in the WPC bricks. The increment is the result of the increment in the strong bonding between wood fibers and matrix material (plastic waste). At a lower percentage of plastic, the adhesion required to transfer the stress from matrix to fiber is reduced. The obtained result agrees with prior research conducted by Ramesh *et al.*[53]

The hardness of the WPC 1 demonstrates the highest hardness value because it includes a lower amount of PET (soft component) and a higher amount of engineered wood fibers (hard component). The hardness is always determined to improve with the WPC's wood percentage increment, as evident from the previous studies.[54,55] WPC materials absorb moisture in varying degrees, some more than others. When immersed in water for 24 hours, WPCs are shown to absorb between 0.7 and 3% by weight. Water absorption by WPC materials can result in various undesirable effects, including board deformation, swelling, buckling, and mold growth, which may have further effects on the investigated mechanical properties. Nonetheless, the current study is limited to assessing mechanical strength in unaged conditions.

Thus, water absorption and mechanical testing of water-absorbed WPCs could be regarded as the future scope of this investigation. Also, the addition of various other plastic components from wastes with higher compressive modulus such as polystyrene, polyimide, and polypropylene, while maintaining the wood fiber wt.% like the presented study may have a different effect on the mechanical properties of the engineered wood bricks and the use of sand as a filler may cause an increase in mechanical property. However, these combinations are outside the scope of the current work and could also constitute a prospective extension. Since compressive strength and Rockwell hardness results showcase two different opinions on choosing the optimum brick composition, Data Envelopment Analysis (DEA) is further applied to select the best option. The weights assigned to the individual performance measures for various combinations of process parameters, determined using the DEA methodology, are shown in Table 4.

The results obtained from the DEA methodology depict that the maximum value of MRPI is obtained for experiment number 2, about WPC 1 bricks comprising 25 wt.% of plastic waste and 75 wt.% of wood fiber. Moreover, if the top 5 values of MRPI are considered, all pertain to WPC 1 bricks. Thus, it can be said that hardness outperforms compressive strength while conducting the multi-response optimization using the DEA method. Thus WPC 1 is the best of the two when considering both the response variables as a single response. Moreover, the mean compressive strength for the selected WPC 1 bricks is 2.486 MPa which is very close to the minimum compressive strength of 3.5 MPa, required for a Burnt Clay Brick as per IS code.

Thus, with slight modification, sustainable engineered wood (wood-plastic composite) bricks can be made to replace the traditional fired clay bricks. The replacement can reduce plastic waste, enhance wood waste utilization, and promote a more ecologically friendly construction sector.

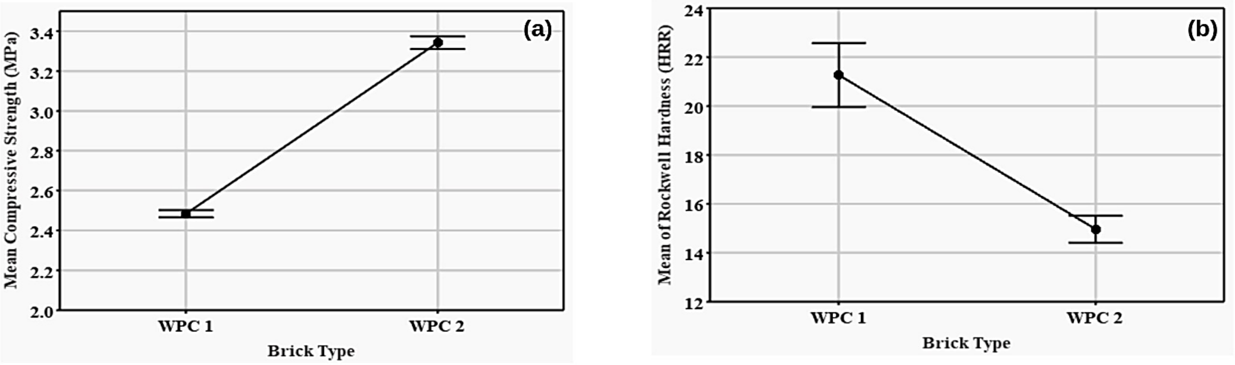

Fig. 3 Interval Plots for wood plastic composite bricks: (a) Mean compressive strength; (b) Mean R-scale Rockwell hardness.

Table 4. Multi-response performance indicator values for the experimental data.

Exp. No.	Weights of responses		Multi-response performance index (MRPI)
	Compressive strength (MPa)	R-scale Rockwell Hardness (HRR)	
1	0.0845	0.1203	2.830
2	0.0857	0.1250	3.045
3	0.0853	0.1095	2.384
4	0.0853	0.1172	2.704
5	0.0856	0.1148	2.603
6	0.1139	0.0844	1.669
7	0.1152	0.0839	1.662
8	0.1158	0.0789	1.519
9	0.1149	0.0814	1.585
10	0.1138	0.0847	1.677

4. Conclusion

The current study is concentrated on the possibility of fabricating and testing lightweight bricks from plastic (PET) waste gathered from municipal waste and wood fiber. The compression strength and Rockwell R-scale hardness test are tested as an indicator of the mechanical properties of the non-conventional bricks. The DEA approach is used to conduct the multi-response study and determine the best combination. The engineered wood building (wood plastic composite) bricks containing 25 wt.% of plastic waste and 75 wt.% of wood fiber produce the best results in terms of hardness with a mean value of 21.270 HRR, whereas the bricks containing 40 wt.% of plastic waste prove best in compressive strength test with a mean value of 3.343 MPa. Moreover, the wood fiber plastic bricks comprising 40 wt.% plastic waste and 60 wt.% wood fibers exhibit severe warpage, inconsistencies in the shape of the bricks, and breakages. The DEA method of multi-response (compression strength and hardness) study utilized in the present work to determine the best composition for making the wood plastic composite bricks indicates that the bricks containing 25 wt.% plastic waste and 75 wt.% wood fiber are the best of the two types of WPCs created in this study.

Conflict of Interest

The authors declare no conflict of interest.

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