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DEVELOPMENT OF AESTHETIC PAVING BLOCK TECHNOLOGY CEMENT-LESS BASED ON SUSTAINABLE PLASTIC BOTTLE WASTE

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A B S T R A C T

PET plastic waste that is difficult to decompose is one of the main challenges in environmental management. This research aims to develop a paving block production technology made from PET plastic waste with a more efficient mixing method, using a mixing machine with a temperature control system and mechanical stirring. The paving block sample is made with a composition of 25% PET plastic and 75% fine aggregate. The conventional mixing method, which uses manual stirring and heating with a stove, is compared to the machine method which is equipped with automatic control to maintain the homogeneity of the mixture and temperature stability. Next, the paving block is tested for compressive strength to evaluate the quality of the production result. The results showed that the machine method produced paving blocks with an average compressive strength of 20.10 MPa, higher than the conventional method which only reached 15.6 MPa. The standard deviation in the engine method is lower (1.71) than in the conventional method (5.15), indicating more consistent quality. In terms of efficiency, the machine method reduces production time by up to 48%, although the cost per paving block is slightly higher, which is Rp 4,840.5 compared to Rp 4,166 in the conventional method. This research shows that the innovation of mixing machines not only improves the quality and efficiency of paving block production, but also supports environmental sustainability by utilizing plastic waste as construction materials. The main contribution of this research is the development of more reliable, time-saving, and high-quality production methods for recycling-based material applications in the large-scale construction industry.

1. INTRODUCTION

The increasing demand for environmentally friendly and sustainable building materials has driven innovation in the use of recycled materials, such as plastics, in the construction industry. The use of recycled plastic in the manufacture of paving blocks is one of the innovative solutions to overcome environmental problems, especially in reducing the volume of plastic waste which continues to increase every year. Plastic, which is known to be difficult to decompose naturally, can be recycled and utilized as a primary binder in paving block mixes. Utilizing recycled plastic in construction helps reduce the impact of plastic waste on the environment by reducing landfill discharge and pollution. It also reduces the need for natural aggregates, thus conserving natural resources (Minde et al., 2024). In addition to helping reduce pollution due to plastic waste, this material also has the potential to increase the durability and strength of paving blocks, making it an effective eco-material alternative for construction purposes. Previous research revealed that the use of PET in construction materials can increase thermal inertia, which contributes to energy savings of up to 50-

57% in certain environments. This can be used to highlight the potential of PET-based paving blocks in supporting the reduction of energy consumption in infrastructure (Limami et al., 2020). The researchers focused on the right proportions, as well as the selection of the optimal material to ensure that the resulting paving blocks have the same or better mechanical strength and durability compared to conventional paving blocks (Loganayagan et al., 2021; Kadam et al., 2024).

The results of previous studies show that the use of plastic waste as a partial or total substitute material in the manufacture of paving blocks provides several significant advantages (Aneke et al., 2021; Aneke & Shabangu, 2021; Thiam et al., 2021). Research has shown that paving blocks with plastic waste can achieve strong pressure for a variety of applications. For example, blocks with 10% melted LDPE plastic reach a compressive strength of 9.39 MPa, suitable for garden use (Desyani et al., 2023). Other studies reported compressive strength ranged from 12.78 MPa to 18.06 MPa with partial replacement of sand with plastic powder, meeting the requirements for pedestrian applications (Mashudi et al., 2020; Arnandha et al., 2020; Sastrawidana et al., 2022; Fauzan et al., 2023). Based on observations, PET and LDPE plastics mixed with sand at high temperatures act as strong binders, which allows for a reduction in cement use. Research has found that plastics can improve the moisture resistance and durability of paving blocks, although compressive strength varies depending on the proportion of plastic and sand used. The study using a 50:50 ratio between plastic and quarry sand resulted in the highest compressive strength of 6.32 MPa, although this material began to melt at temperatures of more than 140°C (Babatunde et al., 2022). Another study showed that a proportion of 30% plastic and 70% sand provides a compressive strength of 22.82 MPa when combined with basalt fibers (Iftikhar et al., 2024).

In developing this paving block technology, the researchers used a simple method by using plastic waste as a substitute for binder and sand as aggregate. This method involves heating the sand to a certain temperature, then mixing it with recycled plastics such as PET or LDPE (Ryu et al., 2020). This heating process is done manually or with a simple tool, such as a furnace or stove, to melt the plastic so that it can envelop the sand particles and serve as a binder (Chauhan et al., 2019).

By looking at the quality achieved using a simple method, the potential to improve the quality of paving blocks is still very large. Previously, researchers tended to focus on the proportions of materials such as recycled plastic and sand, as well as the types of plastics used to improve the mechanical strength and durability of paving blocks. However, the influence of production process variables such as heating temperature, stirring time, and mixing speed has not been observed in depth. These variables play an important role in ensuring that the plastic and sand mixture is evenly mixed and results in paving blocks with optimal homogeneity.

Without good control over these factors, the results obtained can vary significantly, even if the proportions of the materials used are appropriate. Therefore, it is necessary to make further observations on aspects of the production process, including more precise temperature regulation, optimal stirring time, and mixing speed to achieve a more consistent and uniform quality of paving blocks.

This research aims to develop paving block technology by utilizing heating devices equipped with integrated temperature control and automatic stirring systems. This technology is designed to produce more optimal heat distribution during the mixing process, resulting in paving blocks with consistent mechanical strength and durability. Through this approach, innovation is expected to overcome challenges in more environmentally friendly and sustainable manufacturing, especially in the use of recycled materials such as plastics, which can also reduce plastic waste. Thus, the quality of the paving blocks produced is maintained, and the production process can be carried out more efficiently.

2. RESEARCH METHOD

This research was carried out experimentally by producing a sample of PET plastic-based paving blocks using two methods: the conventional method and the machine method with a control system. In the conventional method, PET plastic is melted using a pan stove, then mixed manually with fine aggregate until it is homogeneous. Meanwhile, in the machine method, mixing is carried out using a specially designed tool with a temperature control system and mechanical stirring to ensure the stability of process parameters. After the mixing process, the mixture is molded using a standard paving block mold and allowed to cool until it hardens. The observed parameters include temperature and time stability during the process, mixture homogeneity, and compressive strength of the paving block which is tested according to SNI standards. The results data from both methods were compared to evaluate the effectiveness of the tool and its impact on product quality.

2.1 Machine Design

The machine, as shown in Figure 1, is designed by using the principle of thermal mixing, where PET plastic is melted and mixed with fine aggregate in a closed tank. The temperature control system maintains heat stability during the process, while mechanical stirring ensures an even distribution of the aggregate in the plastic matrix. The main components of the machine are described as follows:

Mixing Tank, The mixing tank is designed with a capacity of 50 liters for laboratory scale needs, allowing the mixing of materials in the amount of 10 Paving Blocks for the trial and development of paving block products. The tank is made of stainless steel material that is resistant to high temperatures, ensuring the ability to withstand the melting process of PET plastics at temperatures up to 300°C. The tank is designed with a tight lid to reduce heat loss and protect the operator from direct exposure to high temperatures.

Heating System, The heat source in the mixing machine comes from the gas stove located at the bottom of the mixing tank. This heating system is equipped with a thermocouple connected to a digital temperature controller, ensuring temperature stability during the mixing process.

Stirring System, The stirring system uses an electric motor with adjustable variable speed. This feature allows the stirring speed to be adjusted according to the characteristics of the material being processed, thus ensuring the homogeneity of the mixture. The stirring blade is designed in a spiral shape to provide optimal movement in mixing the melted PET plastic with fine aggregate.

Control System, the automatic temperature controller is equipped with a digital display that allows the operator to monitor and adjust the temperature in real-time. The integrated thermocouple detects temperature changes in the tank and sends the data to the controller. Meanwhile, the inverter is used to regulate the speed of the stirring motor .

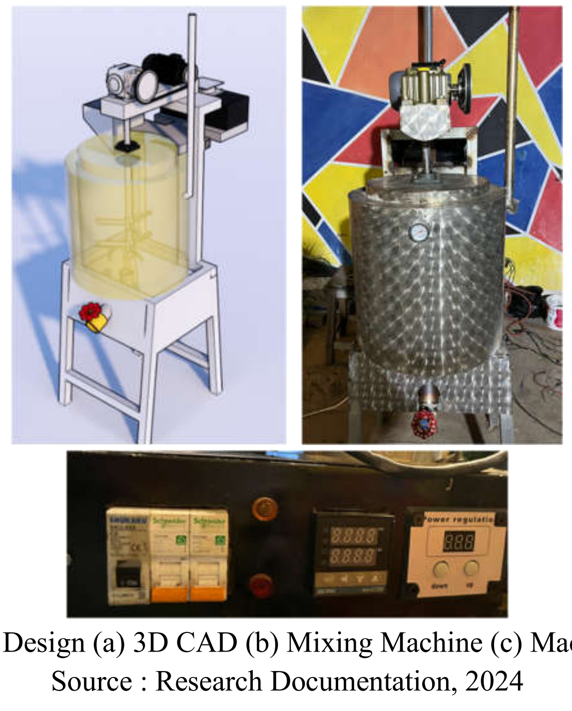

Figure 1. Machine Design (a) 3D CAD (b) Mixing Machine (c) Machine Control Panel
Source : Research Documentation, 2024

2.2 Sample Making

The paving block sample is made with a mixed proportion of 25% PET plastic and 75% fine aggregate by weight. . The aggregate prepared is sand that has passed the feasibility test with a size that has passed the filter no 8 (Karisma et al., 2023), PET waste consisting of post-consumption soft drink bottles is collected from the environment. The collected PET is cleaned of contaminants such as PVC, labels and cut by shredder into small pieces as flakes with a 10 mm strainer (Gürü et al., 2014). Sample making was carried out through two methods, namely the conventional method and the method using a mixing machine, with a total of 9 samples each. In conventional methods, each sample is produced from a single mixing process separately. In contrast, in the method using a mixing machine, each mixing process produces 3 samples. This approach was carried out to evaluate the consistency of results between samples as well as the process efficiency of both methods. The mixing process is carried out with the same procedure, which is to melt the plastic to a temperature of 250°C, then add sand and stir the mixture for 20 minutes to ensure homogeneity. In addition, phosphorus and resin are used to produce aesthetics with the concept of "glow in the dark" (Karisma et al., 2023). Figure 2 shows sampling flow.

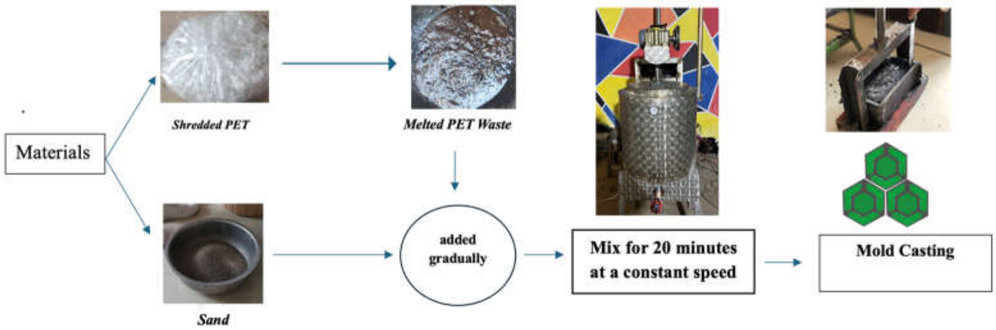

Figure 2. Sampling Flow
Source : Research Documentation, 2024

2.3 Sample Testing and Analysis

Samples of paving blocks are tested to evaluate their quality and consistency based on several parameters. Tests are performed on samples from both methods (conventional and using mixing machines) to analyze the difference in yield and process efficiency. The compressive strength test is carried out to evaluate the ability of the paving block to withstand compressive loads in accordance with the SNI 03-0691-1996 standard (Badan Standarisasi Nasional, 1996). This test uses the Universal Testing Machine (UTM) tool, where each sample is subjected to a gradual compressive load until it reaches the point of failure. Maximum compressive strength data (kg/cm²) is recorded for each sample from both conventional methods and methods using mixing machines. The results of the compressive strength test are used to compare the quality of the products produced by the two methods, with additional analysis in the form of average compressive strength values and standard deviations to evaluate the consistency of the results.

3. RESULT AND DISCUSSION

3.1 Temperature and Homogeneity Analysis

Temperature control during the paving block production process is essential to ensure the homogeneity of the mixture and the quality of the final result. This analysis aims to evaluate the temperature fluctuations that occur at each stage of the process using a simple method. Table 1 presents temperature fluctuation data based on observations of several samples at the heating, melting, and mixing stages.

Table 1. Temperature Fluctuations Simple Method

Condition	Time (Minutes)	Sample										
		1	2	3	4	5	6	7	8	9	Average	ST DEV
		Temperature (°C)										
Warming	0	35	36	38	37	39	35	38	38	36	36.9	1.453
Warming	1	54	54	64	63	80	55	67	65	60	62.5	8.206
Melting	3	141	149	196	180	172	153	201	175	190	172.9	21.475
Melting	5	176	178	190	195	203	184	194	187	188	188.4	8.425
Melting	7	186	189	219	220	251	193	222	214	217	212.4	20.353
Melting	8	191	194	216	215	254	196	210	220	212	212.1	18.869
Melting	10	201	205	222	230	268	207	225	233	229	224.5	20.084
Melting	12	211	217	230	235	288	215	232	241	238	234.1	22.869
Mixing	13	216	222	236	238	290	223	239	245	243	239.1	21.57
Mixing	14	221	228	222	228	157	225	225	234	227	218.5	23.376
Mixing	16	231	239	221	223	152	236	224	228	229	220.3	26.276
Mixing	18	226	239	238	240	175	244	239	243	241	231.7	21.861
Mixing	20	220	238	250	257	244	240	253	259	255	246.2	12.235
Mixing	22	214	237	280	289	257	238	273	292	285	262.8	27.631
Mixing	24	208	236	273	275	283	230	267	280	278	258.9	27.046
Mixing	26	202	234	281	280	291	234	283	284	290	264.4	32.194
Mixing	27	199	234	310	296	286	229	305	297	312	274.2	41.949

Source: Research Results, 2024

Based on Table 1, the analysis showed that at the heating stage (0–3 min), the average temperature increased from 36.9°C to 62.5°C with a low standard deviation at the beginning (1.453) but increased sharply to 8.206 at minute 1, indicating significant variation between samples due to uneven heat distribution. In the melting stage (3–12 minutes), the average temperature gradually increases from 172.9°C to 234.1°C, but the temperature fluctuation remains high with a standard deviation reaching 22.869 at the 12th minute. This variation indicates that the temperature control system is not yet optimal, which can affect the melting quality of PET plastics and the homogeneity of the mixture. In the mixing stage (13–27 min), the average temperature peaked at 274.2°C with greater fluctuations in the final mixing stage (ST DEV 41.949 at 27 min), indicating an inconsistent heat distribution during material mixing.

Inconsistent heat distribution can lead to an uneven drying process and potential weaknesses in the structure (Quoc et al., 2021). This condition has the potential to cause inhomogeneity in the mixture, which can affect the compressive strength of the paving block. Overall, the simple method shows significant temperature fluctuations at each stage, especially at the final mixing, so a more precise temperature control system is needed to improve process stability and product quality. This is in line with research (Prist et al., 2017), which reveals that in the production of plastic components, maintaining consistent temperature control is essential to maintain product quality and improve time performance.

The process using the machine method shows well-controlled temperature stability at each stage. Table 2 shows that, in the heating phase (0–3 minutes), the average temperature increases from 53°C to 92°C with a low standard deviation (0.58–1.53), indicating the efficiency of the heating system in achieving an even initial temperature. In the melting stage (5–20 minutes), the temperature increases steadily from 129°C to 235°C, with the standard deviation remaining low (1.00–1.53). This stage indicates optimal temperature control, which is essential for obtaining a homogeneous plastic matrix.

Furthermore, at the mixing stage (22–40 min), the temperature peaks at 250°C with a standard deviation of 1.00, indicating consistent heat distribution during the addition and mixing of the aggregate. which is close to the melting point of PET (260°C), supporting the formation of a uniform plastic matrix. Previous research has also emphasized the importance of temperatures around 300°C, which is 46°C above the melting point of the crystal, to ensure total melting and the formation of a more stable thermal structure (Hsu et al., 2006).

Table 2. Temperature Fluctuation Machine Method

Condition	Time (Minutes)	Batch 1	Batch 2	Batch 3	Average	ST DEV
		Temperature (°C)				
Warming	0	53	53	53	53	0.00
Warming	1	66	65	66	66	0.58
Warming	2	80	79	77	79	1.53
Warming	3	93	93	91	92	1.15
Melting	5	130	127	129	129	1.53
Melting	7	135	132	134	134	1.53
Melting	8	136	134	135	135	1.00
Melting	10	143	143	141	142	1.15
Melting	12	159	160	158	159	1.00
Melting	14	176	173	174	174	1.53
Melting	16	194	192	191	192	1.53
Melting	18	215	214	213	214	1.00
Melting	20	236	235	234	235	1.00
Mixing	22	250	249	251	250	1.00
Mixing	24	210	207	209	209	1.53
Mixing	26	199	196	200	198	2.08
Mixing	28	201	200	202	201	1.00
Mixing	30	211	209	210	210	1.00
Mixing	32	226	224	225	225	1.00
Mixing	34	237	234	235	235	1.53
Mixing	36	256	251	252	253	2.65
Mixing	38	271	268	269	269	1.53
Mixing	40	282	280	279	280	1.53
Mold	42	289	285	284	286	2.65

Source: Research Results, 2024

However, towards the final stage of mixing to printing (42 min), the temperature showed greater fluctuations (ST DEV 2.65) due to material movement, which could affect the homogeneity of the mixture (Badan Standarisasi Nasional, 1996). Overall, the temperature stability at the initial stage to mixing is excellent, but small fluctuations in the printing stage indicate opportunities for further optimization to improve product consistency.

Based on a comparison of the two methods, the machine method showed much better temperature stability at each stage of the process, with low standard deviations at the heating (0.58–1.53) and melting (1.00–1.53) stages, as well as small fluctuations in the final mixing (2.65). In contrast, simple methods show large temperature fluctuations, especially at the melting stage (22.869) and final mixing (41.949), signaling uneven heat distribution. Temperature stability in the machine method supports the homogeneity of the mixture and consistent product quality, while fluctuations in the simple method have the potential to cause inhomogeneity and decrease the compressive strength of the paving block.

Figure 3 shows that the machine method produces a more homogeneous mixture (a) than the conventional method (b), with a more uniform distribution of materials. This is reflected in the results of the paving block, where the sample of the machine method (c) has a smoother and more consistent surface, while the sample of the conventional method (d) shows inhomogeneity with a rougher surface. Better homogeneity in the machining method ensures higher compressive strength and more consistent product quality, while conventional methods tend to produce products with varying quality due to lack of process control.

In conventional methods, temperature fluctuations during the mixing process and inhomogeneity of the aggregate distribution in the plastic matrix contribute to greater yield variation. The standard deviation of 5.15 MPa reflects a lack of process stability, which causes compressive strength results to vary significantly between samples. Certain samples, such as the 9th sample with a value of 8.098 Mpa as shown in Table 3, indicate that these inconsistencies can negatively impact the quality of the final product. In contrast, the machine method equipped with a temperature control system and mechanical stirring results in paving blocks with an average higher compressive strength and a much smaller standard deviation (1.71 MPa). This reflects the stability of the mixing process, including a consistent temperature at 250°C and uniform stirring at a constant speed, which allows for a more homogeneous distribution of fine aggregates in the PET plastic matrix. This consistency contributes to the overall improvement of the quality of the paving blocks.

(c)

(a) **(b)** **(d)**

Figure 3. (a) homogeneity of the machine method **(b)** mixed homogeneity of the conventional method **(c)** sample of the machine method **(d)** sample of the conventional method
Source : Research Documentation, 2024

Table 3. Compressive Strength Test Results

Sample	Conventional	Machine
1	15.8	18.65
2	13.52	18.45
3	12.22	17.70
4	10.41	19.02
5	15.77	20.27
6	16.65	19.96
7	25.31	22.51
8	22.23	22.12
9	8.098	22.23
Average (Mpa)	15.6	20.10
ST Dev	5.15	1.71

Source: Research Results, 2024

Based on Figure 4, it can be seen that the distribution of compressive strength data generated by the conventional method (blue) shows quite high variability, with some samples at low compressive strength values, such as the 9th sample (8.098 MPa), while others, such as the 7th sample (25.31 MPa), achieve much higher values. This reflects that conventional methods do not have consistent process control, thus causing significant fluctuations in the compressive strength of the paving block.

On the contrary, the distribution of compressive force data produced by the machine method (orange) looks more uniform and consistent. Almost all of the values are in a relatively narrow range of around 19–22 MPa, which indicates that the machine method is able to maintain temperature stability and homogeneity of the mixture during the production process. This is supported by a much lower standard deviation in the machine method (1.71) compared to the conventional method (5.15).

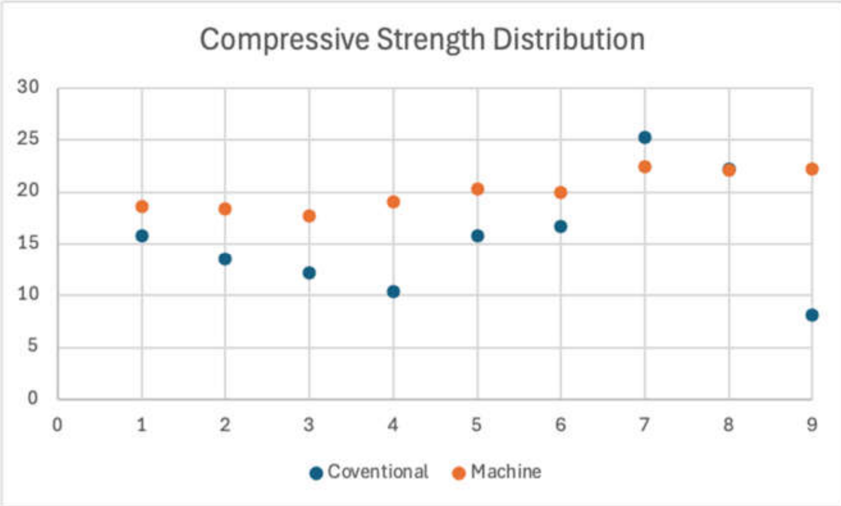

Figure 4. Compressive Strength Distribution
Source: Research Documentation, 2024

3.2 Production Efficiency

To evaluate the production performance of conventional methods and machine methods, an analysis is carried out on the time and cost required to produce paving blocks.

Table 4. Production efficiency

Parameter	Conventional	Machine
Mixing Time per Batch (minutes)	27	42
Number of Paving per Batch	1	3
Total Gas Cost per Batch (Rp)	4166	12500
Electricity Cost per Batch (Rp)	-	2021.60
Total Cost per Batch (Rp)	4166	14521.60
Cost per Paving Block (Rp)	4166	4840.50
Total Time for 9 Paving (minutes)	27 × **9 = 243 minutes**	42 × 3 = **126 minutes**
Total Cost for 9 Paving (Rp)	4166 × 9 = **37494**	4840.5 × 9 = **43565**
Time Efficiency (%)	-	((243 - 126) ÷ 243) × 100 = **48% faster**
Cost Efficiency (%)	-	((43565 - 37494) ÷ 37494) × 100 = **16.2% more expensive**

Source: Research Results, 2024

Based on Table 4, the machine method shows a significant advantage in time efficiency, with a time saving of 48% compared to the conventional method. The machine method is able to produce 9 paving blocks in just 126 minutes, while the conventional method takes 243 minutes. This makes it more suitable for large-scale production, where time efficiency is a top priority. In terms of cost, the conventional method is more economical with a production cost of Rp. 4166 per paving block, while the machine method requires a cost of Rp. 4840.5 per paving block, or about 16.2% more expensive. The increase in costs on the machine method is mainly due to the use of electricity and automatic control systems that support product quality. Although more expensive, the machine method produces paving blocks with higher quality consistency, thanks to homogeneous mixing and better temperature control.

4. CONCLUSION

Based on the results of the study, the use of a mixing machine with a temperature control system and mechanical stirring provides a significant advantage over conventional methods in making paving blocks made from PET plastic waste. The mixing machine is able to produce paving blocks with higher average compressive strength (20.10 MPa compared to 15.6 MPa in conventional methods) and better consistency (standard deviation of 1.71 compared to 5.15 in conventional methods). In addition, the machine also increases production time efficiency by up to 48%, although the cost per paving block is slightly more expensive by 16.2%. With stable temperature control and homogeneous mixing, these machines support the achievement of more consistent product quality, making them a more reliable solution for large-scale production. This innovation not only supports environmental sustainability through the use of plastic waste, but also offers a more efficient and high-quality alternative to construction materials.

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