

Original Research Article

Comparative study of recycling between waste of thermoplastics (LDPE, HDPE and PET) raw and granules mixed with sand for the manufacture of paving stones in the city of Kinshasa in DRC.

ABSTRACT

Objectives: The utilization of waste LDPE, HDPE, and PET, either in their raw or granulated forms, for manufacturing paving stones raises several challenges, including the production of weaker and less durable paving stones, increased atmospheric pollution, and material loss. This research aims to identify the most advantageous process for employing thermoplastic waste in paving stone production.

Research Design: The study is structured into five sections: introduction, methodology, results, discussion, and conclusion.

Location and Duration: The study was conducted in the city of Kinshasa, and the experiments were carried out in July 2021.

Methodology: The proportions of thermoplastics and sand were determined through four tests. Subsequently, the thermoplastic waste, in both granulated and raw forms, mixed with sand was recycled, and the resulting paving stones were subjected to resistance testing.

Results: On average, the ratio of thermoplastic granules to raw material yielded a recycling time of 17/22 minutes, producing 13/7 pavers. The weight loss of materials was $5.29 \pm 0.98 / 9.95 \pm 1.89$ kg, and the strength was measured at $12.3 \pm 2.19 / 6.4 \pm 1.61$ N/mm². The optimal material composition demonstrating the highest strength at 22.45 N/mm² comprised 30% LDPE and HDPE, 10% PET, and 60% sand.

Conclusion: Comparing raw thermoplastic waste with granulated thermoplastic waste, the latter proves more beneficial. Granulated thermoplastic waste yields more consolidated pavers, reduces weight loss of materials, shortens recycling time, minimizes smoke emission, and provides a superior average strength of pavers.

Keywords: recycling, waste, thermoplastics, pellets, raw, manufacturing, paving stones and Kinshasa.

1. INTRODUCTION

Currently, the widespread use of low-density (LDPE), high-density (HDPE) thermoplastics, and polyethylene terephthalates (PET) as packaging materials across various sectors has become deeply ingrained in the culture of Kinshasa, particularly

[1]. However, post-use, these materials often lack a proper disposal destination, leading to significant socio-environmental challenges. These include the proliferation of disease vectors, aesthetically unpleasing environments, clogged drainage systems, water pollution due to transformed waterways functioning as dumping sites, and the creation of densely populated soil layers due to accumulated waste. Consequently, these issues hinder water infiltration into the ground, resulting in increased flood occurrences during heavy rains [2]. Plastic pollution in Kinshasa, Democratic Republic of Congo, is a matter of concern for both political-administrative authorities and the population [3]. In light of these challenges, it is crucial to shift the perspective on thermoplastic waste, considering them not as materials to be permanently discarded but as valuable resources capable of generating income, employment, and serving as raw materials for infrastructure items like interlocking paving stones, among other alternative applications. Hence, in the pursuit of a solution, various micro-projects, including the Laboratory of Biotechnology, Technology, and Microbiology Environment (LBTME) within the Faculty of Sciences at the University of Kinshasa, have ventured into hot recycling using raw thermoplastic materials. Positive outcomes have been achieved in the production of different plastic products, notably interlocking paving stones. Regrettably, the use of raw thermoplastic materials presents challenges, notably the significant emission of smoke during the melting process, leading to atmospheric pollution, increased material loss, and reduced durability of the paving stones, among other issues. Given these circumstances, LBTME explored whether recycling LDPE, HDPE, and PET in the form of granules could enhance production efficiency and material quality (pavers) while maintaining environmental quality and human well-being [2].

1.1. Assumption

Utilizing granulated plastic materials (LDPE, HDPE, and PET) is anticipated to yield numerous paving stones with enhanced resistance properties, achieved in less time, while minimizing atmospheric pollution and material weight loss.

1.2. Objectives

The primary objective of this research is to contribute to the sanitation efforts in the city of Kinshasa. Specifically, it aims to assess the quality of paving stones resulting from the recycling of granulated thermoplastic materials (LDPE, HDPE, and PET) compared to raw materials. Additionally, the study aims to investigate the production levels of flames and smoke during the plastic melting process and evaluate material losses.

2. METHODOLOGY

2.1. Recycling Process

This study involved the separate manufacturing of paving stones by mixing raw and granulated thermoplastic waste (LDPE, HDPE, and PET) with fine-grained sand. The mixture was prepared in a metal tank heated using charcoal activated by an electric blower. The thermoplastics (raw and granules) and sand were weighed using a Saco brand scale with a maximum capacity of 200 kg and a Kern brand pressure balance to achieve various material proportions. The granules of thermoplastic materials were obtained through grinding using the Taiwan Taipei I machine model PG-100 No. 77007, 380V/50Hz, imported from China.

The resulting homogeneous paste, obtained after melting the thermoplastics mixed with fine sand, was poured into molds placed on a metal table serving as a support for the molds. After cooling, the paving stones were demolded using a hammer. The recycling procedure comprised the following steps: the LDPE and HDPE (raw or granulated) were placed in a preheated tank with charcoal and mixed until a homogeneous paste was achieved, before adding the PET (raw or granulated), followed by the sand.

The homogeneous paste was then poured into pre-lubricated molds using engine drain oils. To manufacture the paving stones, both qualities of materials (raw and granulated) were subjected to the same parameters and conditions. A set of 30 kg of materials, encompassing varying proportions of plastics (LDPE, HDPE, and PET), as well as fine sand, were used, as presented in Table 1.

Table 1. Proportions of raw and granulated thermoplastic waste in percentages (kg) for the 4 trials

Trials	LDPE & HDPE (%/kg)	PET (%/kg)	Sand (%/kg)
Trial 1	60/18	20/6	20/6
Trial 2	20/6	60/18	20/6
Trial 3	30/9	10/3	60/18
Trial 4	33.3/10	33.3/10	33.3/10

2.2. Paving Stone Resistance Test

The resistance test for paving stones was conducted separately for both raw and granulated paving stones at the National Public Works Laboratory/Research and Development Department of the Roads Office, located at Avenue de la Science No. 482 in Kinshasa/Gombe, following the Dreux method [4].

In general, whether it was a raw or granulated paving stone, the test involved sizing the paving stone, weighing it, determining its density, compressing the paving stone, observing its reaction (from the initiation of compression to rupture), and recording the maximum load observed at the point of break on the pressure gauge of the Controls Milano Italia brand "compression press" device, as illustrated in Figure 1.



Figure 1. Image of the machine « Controls Milano Itali»

The total tensile stress (strength) was determined by the following formula

Breaking load Total breaking stress (in kg/cm^2) = _____ [4] Total compressed surface

3. RESULTS

3.1. Aspect relating to the manufacture of paving stones

3.1.1. Comparison according to recycling time and pulp quality

Table 2. Values of parameters related to recycling time and pulp quality

Variables		Trial 1		Trial 2		Trial 3		Trial 4		Average	
Quality of materials		Raw	Granulated	Raw	Granulated	Raw	Granulated	Raw	Granulated	Raw	Granulated
Quantity of LDPE and HDPE (kg)		18		6		9		10		-	-
Quantity of PET (kg)		6		18		3		10		-	-
Quantity of fine sand (kg)		6		6		18		10		-	-
Homogeneous dough production time (minutes)	LDPE, HDPE	28	19	25	20	30	25	50	29	33.25	23.25
	LDPE, HDPE, PET	13	11	25	21	25	22	30	23	23.25	19.25
	LDPE, HDPE, PET, Sand	9	6	10	7	15	11	5	4	9.75	7
Mean Times (minutes)		17	12	20	16	23	19	28	19	22	17
Quality of the paste		Black and quite heavy	Black quite heavy	Blackish, very fluid, Solidifying quickly	Black and heavy, solidifying slowly	Whitish and quite heavy	Whitish and heavy	Black and fluid	Black and heavy	-	-

It has been observed that the fusion of thermoplastic waste for dough homogenization requires less time when utilizing granulated materials. In terms of dough quality, all tests yielded a homogeneous and dense dough, predominantly exhibiting a dark color.

3.1.2. Comparison according to the number of paving stones and the weight loss of the materials

Table 3. Parameter measurements: number of blocks produced and loss

Variables	Trial 1		Trial 2		Trial 3		Trial 4		Average	
	Raw	Granulated	Raw	Granulated	Raw	Granulated	Raw	Granulated	Raw	Granulated
Quantity of LDPE and HDPE (kg)	18		6		9		10		10.75	10.75
Quantity of PET (kg)	6		18		3		10		9.25	9.25
Quantity of fine sand (kg)	6		6		18		10		10	10
Number of pavers in molds	9	10	8	17	10	14	9	12	9	13.25
Number of pavers after demolding	7	10	7	17	5	14	8	12	6.75	13.25
Total Weight of pavers (Kg)	18.58	22.06	15.19	27.68	26.2	28.8	20.25	20.3	20.06±1.57	24.71±1.99
Average weight of one paver (kg)	2.06	2.21	1.9	1.63	2.62	2.06	2.25	1.69	2.21±0.08	1.9±1.22
Total weight of materials (Kg)	30	30	30	30	30	30	30	30	30	30
Weight loss of materials (kg)	11.42	7.94	14.81	2.32	3.8	1.2	9.75	9.7	9.95±1.89	5.29±0.98
Weight loss of materials (%)	28.7	26.5	37.2	7.7	9.6	4	24.4	32.3	24.98±1.59	17.63±3.32

of material weight

Comparison of parameters related to paving stone manufacturing indicates that, on average, using granulated materials yields a higher quantity of paving stones (i.e., 13 paving stones) compared to raw thermoplastic materials (i.e., 7 paving stones). Paving stones from granulated materials weigh slightly less (i.e., 1.9±1.22 kg) than those from raw materials (i.e., 2.21±0.08 kg). Furthermore, the use of granulated materials results in lower material weight loss (5.29±0.98 kg, or 17.63%) compared to paving stones made from raw materials (9.95±1.89 kg, or 24.98%).

3.2. Aspects relating to the strength test of paver

3.2.1. Average values of parameters linked to the paver resistance test

Table 4. Average values of parameters linked to the resistance test of the pavers

Variables	Values obtained from the 4 trials									
	Trial 1		Trial 2		Trial 3		Trial 4		Average	
Quality of materials	Raw	Granulated	Raw	Granulated	Raw	Granulated	Raw	Raw	Granulated	Granulated
Volume (cm ³)	1375	1028	1375	1028	1375	1028	1375	1375		1028
Weight (gr)	1714	1881	1899	1451	2619	2173	2250	2120.5±7.96		1880.5±3.99
Density (g/cm ³)	1.25	1.83	1.38	1.41	1.90	2.11	1.64	1.5±0.18		1.8±0.94
Compressed useful surface (cm ²)	275	228	275	228	275	228	275	275		228
Breaking load (kg)	24000	19000	17000	21000	14000	51000	15000	17500±1825.46		28000±1609.91
Breaking stress (kg/cm ²)	87.27	83	61.82	92	50.91	224	54.55	63.6±2.11		122.8±4.75
Strength (N/mm ²)	8.7	8.3	6.2	9.2	5.1	22.45	5.5	6.4±1.61		12.3±2.19

The analysis of the results from the strength test indicates that paving stones made from granulated materials endured a significantly higher breaking load (i.e., 28000±1609.91 kg), resulting in superior average resistance values (i.e., 12.3±2.19 N/mm²) compared to their counterparts made from raw materials (i.e., 6.4±1.61 N/mm²).

UNDER PEER REVIEW

3.2.2. Response of Pavers under Stress Test

Before compression During compression After compression

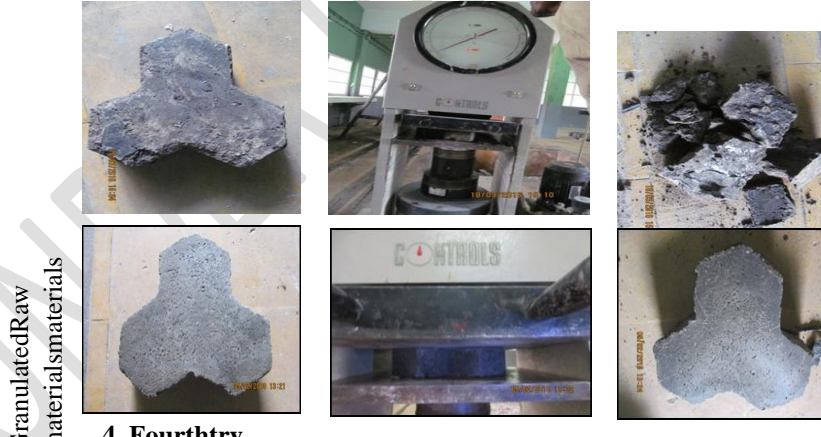
1. First try



2. Second try



3. Third try



4. Fourth try



Figure 2. Reaction of paving stones subjected to the resistance test according to the quality of the materials

Observations of the results across all four tests indicate that pavers made from granulated thermoplastic materials underwent less deformation. This is evident in their well-preserved shape and higher average resistance value (i.e., 22.4 N/mm²) compared to pavers made from raw materials (i.e., 6.4 N/mm²), as shown in Table 4.

4. DISCUSSION

Analyzing the results obtained from the four recycling tests involving various proportions of LDPE, HDPE, and PET materials (granulated and raw) mixed with sand, totaling 30 kg in each test, several important observations can be made. In terms of the time required to achieve a homogeneous mixture paste, it is noted that granulated plastic materials take less time to blend completely in all four tests. This can be attributed to the high porosity of granulated plastic materials, allowing for efficient penetration of the flame for melting [5-6]. The dominant black color of the paste observed in most tests aligns with the findings of Delavelle and De Caevel [7], stating that incineration or fusion of plastic materials generally results in a black color product [8].

Furthermore, the number of blocks obtained in all four tests is consistently higher with the recycling of granulated thermoplastic materials compared to raw thermoplastic materials. Since plastics are petroleum-based, a shorter melting time results in less evaporation of oil and consequently less weight loss of the materials [9]. This is supported by the lower time taken for the melting of granulated plastic materials in all four tests compared to raw plastic materials and the reduced material loss (i.e., 17.63±3.32%) observed with granulated plastic materials compared to raw materials (i.e., 24.98±1.59%). Additionally, the lower average weight of a paving stone made from granulated materials (i.e., 1.9±1.22 kg) is attributed to the fact that, with the same total weight of materials (i.e., 30 kg), granulated plastic materials produce more pavers, averaging 13 pavers, while raw plastic materials produce nearly half (i.e., 6.75 pavers).

Moreover, test 2, using granulated plastics with a higher proportion of plastic bottles (60%), produced more pavers (i.e., 17 pavers) compared to raw plastics (i.e., 7

pavers). This numerical advantage can be attributed to the easy melting of granulated PET materials, resulting in a heavy paste that solidifies slowly and consolidates well in molds, with less loss of dough adhering to the walls of the pot or falling during transport to the molds, in contrast to raw plastics, where achieving a homogeneous pulp presented challenges due to material compaction during melting, mainly determined by the melting temperature [10].

When different types of plastic waste are mixed, recycling encounters compatibility problems due to varying melting temperatures, affecting the homogenization of the pulp and consequently the quality of the final product [11-13]. Mixing several plastics can lead to a decrease in the mechanical characteristics of the final product [14]. The quality of the final product is heavily influenced by the mixing conditions and proportions of the different constituents [17].

In terms of the resistance test, pavers made from granulated plastic materials generally exhibited significantly higher breaking load values with an average of 28000 ± 1609.91 kg, considerably surpassing the resistance of pavers made from raw materials (i.e., 17500 ± 1825.46 kg) and resulting in a higher average resistance value of 12.3 ± 2.19 N/mm² compared to the raw materials (i.e., 6.4 ± 1.61 N/mm²). The superior resistance of pavers made from granulated plastic materials can be attributed to the effective homogenization of the paste and consequent consolidation in molds, heavily dependent on the quality of the paste [18]. Notably, pavers from test 3 achieved the highest average resistance of 22.45 N/mm² with granulated plastic materials, while pavers made from raw materials achieved a lower resistance value (i.e., 5.1 N/mm²). This extreme variation in resistance is influenced by the low breaking load value (i.e., 14,000 kg) presented by raw materials and the high breaking load value (i.e., 51,000 kg) for granulated materials. This phenomenon aligns with the findings of Colin Jacob-Vaillancourt [19], suggesting that an abundance of sand as a raw material can increase the strength of the material produced when recycling plastics mixed with sand for the production of other plastic materials. This information allows for guidelines on the use of different types of paving stones based on their resistance, using the data presented in Table 5.

Table 5. Scale of average resistance values and appropriate uses (Source: [4])

Concrete Qualities	Cement Dosages (kg/m ³)	Average Resistance (N/mm ²)	Characteristic Resistance at 28 Days (Mpa)	Suitable uses
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			in compression (Mpa)	in traction (Mpa)	
Low-strength Concrete	150-300	20-25	16	1,6	Small structures: simple house (without floor), septic tank, ...
Common Concrete	300-350	25-30	20	1,8	
High-strength Concrete	350-400	30-35	25	2,1	Large structures: buildings, multi-story house columns, bridges, abutments (bridge edge),
Exceptionally Strong Concrete	400 and above	35-40	30	2,4	Special structures: skyscrapers, dams, major bridges, ...

He further demonstrated that the pavers from the third test, exhibiting high resistance at 22.45 N/mm², can be utilized in various applications, including small structures like simple houses (without a floor) and septic tanks, as well as in exterior house decoration. Moreover, they can be employed for roadways in metropolitan France [20] and pedestrian/cycle paths within the city or on streets, showcasing the versatility of these paving stones [21-22].

5. CONCLUSION

The comparative analysis of results obtained from the utilization of granulated and raw thermoplastic materials in paving stone production through recycling yields the following comprehensive conclusions:

The usage of granulated thermoplastics presents clear advantages over raw thermoplastics. Specifically, the application of granulated plastics:

- Demonstrates significantly reduced weight loss of materials on average, with a ratio of granulated thermoplastics to raw materials at 17.63±3.32% to 24.98±1.59%, leading to a higher number of pavers produced (13/8 pavers) within a shorter time frame for plastic fusion to achieve a homogeneous mixture (i.e., 16/22 minutes).
- Ensures 100% consolidation of paving stones upon demolding. In comparison to raw materials, this results in 10/10 pavers versus 7/9 pavers on the first trial; 17/17 pavers versus 7/8 pavers on the second trial; 14/14 pavers versus 5/10 on the third trial; and 12/12 pavers versus 8/9 pavers on the fourth trial, averaging to 13/7 pavers.
- Yields superior average resistance values for the produced pavers (i.e., averaging at 12.3±2.19/6.4±1.61 N/mm²).

The compelling evidence presented demonstrates that the use of granulated thermoplastic materials in paving stone manufacturing stands as a more efficient and effective approach, showcasing its potential for

widespread implementation in the construction industry. These findings contribute to the ongoing efforts towards sustainable and innovative solutions for paving stone production, emphasizing the importance of recycling and reusing materials to achieve environmentally conscious outcomes.

6. References

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