Original Research Article

Comparative study of recycling between waste of granules and raw thermoplastics (LDPE, HDPE and PET) 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 theirraw or granulatedforms, for manufacturingpaving stones raisesseveral challenges, including the production of weaker and less durable paving stones, increasedatmospheric pollution, and materialloss. This researchaims to identify the mostadvantageousprocess for employingthermoplasticwaste in paving stone production.

Research Design: The studyisstructuredinto five sections: introduction, methodology, results, discussion, and conclusion.

Location and Duration: The studywasconducted in the city of Kinshasa, and the experimentswerecarried out in July 2021.

Methodology: Raw and granulatedthermoplasticwaste (LDPE, HDPEE and PET) wererespectively mixed with fine grainedsand (] 0.063 – 0.2 mm [).The mixture washeated to obtainhomogeneouspaste. The laterwaspouredintomolds in order to manufacture the paving stones whichweretested for resistance.

Results: On average, the ratio of thermoplastic granules to rawmaterialyielded a recycling time of 17/22 minutes, producing 13/7 pavers. The weightloss of materialswas 5.29±0.98/9.95±1.89 kg, and the strengthwasmeasuredat 12.3±2.19/6.4±1.61 N/mm². The optimal material composition demonstrating the higheststrengthat 22.45 N/mm² comprised 30% LDPE and HDPE, 10% PET, and 60% sand.

Conclusion: Comparingrawthermoplasticwastewithgranulatedthermoplasticwaste, the latter proves more beneficial. Granulatedthermoplasticwasteyields more consolidatedpavers, reducesweightloss of materials, shortensrecycling time, minimizessmokeemission, and provides a superioraveragestrength 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

Utilizinggranulated plastic materials (LDPE, HDPE, and PET) isanticipated to yieldnumerouspaving stones withenhancedresistanceproperties, achieved in less time, whileminimizingatmospheric pollution and materialweightloss.

1.2. Objectives

The primary objective of thisresearchis to contribute to the sanitation efforts in the city of Kinshasa. Specifically, itaims to assess the quality of paving stones resultingfrom the recycling of granulatedthermoplasticmaterials (LDPE, HDPE, and PET) compared to rawmaterials. Additionally, the studyaims to investigate the production levels of flames and smokeduring the plastic meltingprocess and evaluatemateriallosses.

2. METHODOLOGY

2.1. RecyclingProcess

This studyinvolved the separatemanufacturing of paving stones by mixingraw and granulatedthermoplasticwaste (LDPE, HDPE, and PET) with fine-grainedsand. The mixture wasprepared in a metal tank heatedusingcharcoalactivated by an electricblower. The thermoplastics (raw and granules) and sandwereweighedusing a Saco brand scalewith a maximum capacity of 200 kg and a Kern brand pressure balance to achievevariousmaterial proportions. The granules of thermoplasticmaterialswereobtainedthroughgrindingusing the Taiwan Taipe I machine model PG-100 No. 77007, 380V/50Hz, importedfrom China.

The resultinghomogeneouspaste, obtainedaftermelting the thermoplastics mixed with fine sand, waspouredintomoldsplaced on a metal table serving as a support for the molds. Aftercooling, the paving stones weredemoldedusing a hammer. The recyclingprocedurecomprised the followingsteps: the LDPE and HDPE (raw or granulated) wereplaced in a preheated tank withcharcoal and mixed untilahomogeneouspastewasachieved, beforeadding the PET (raw or granulated), followed by the sand.

The homogeneouspastewasthenpouredintopre-lubricatedmoldsusingengine drain oils. To manufacture the paving stones, bothqualities of materials (raw and granulated) weresubjected to the sameparameters and conditions. A set of 30 kg of materials, encompassingvarying proportions of plastics (LDPE, HDPE, and PET), as well as fine sand, wereused, 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

The table 1 shows that in a %/kg ratio, the proportions of the materials combined in the order: LDPE and HDPE, PET and fine sand (] 0.063 – 0.2 mm [) are: 60/18, 20/6 and 20/ 6 for test 1; 20/6, 60/18 and 20/6 for test 2; 30/9, 10/3 and 60/18 for test 3 and the same proportion of materials of 33.3/10 for all in test 4.

2.2. Paving Stone Resistance Test

The resistance test for paving stones wasconductedseparately for bothraw and granulatedpaving stones at the National Public Works Laboratory/Research and DevelopmentDepartment of the Roads Office, locatedat Avenue de la Science No. 482 in Kinshasa/Gombe, following the Dreux method [4].

In general, whetheritwas a raw or granulatedpaving stone, the test involvedsizing the paving stone, weighingit, determiningitsdensity, compressing the paving stone, observingitsreaction (from the initiation of compression to rupture), and recording the maximum loadobservedat 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) wasdetermined by the following formula

$$\text{Total breaking stress (in kg/cm}^{2}) = \frac{\text{Breaking load}}{\text{Total compressed surface}} \quad [4]$$

3. RESULTS

3.1. Aspect relating to the manufacture of paving stones

3.1.1. Comparisonaccording to recycling time and pulpquality

Table 2. Values of parametersrelated to recycling time and pulpquality

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		-	-
Quantityofs PET (kg)		6		18		3		10		-	-
Quantity of fine sand (kg)		6		6		18		10		-	-
Homogeneousdough 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 quiteheavy	Black quiteheavy	Blackish, veryfluid, Solidifyingquickly	Black and heavy, solidifyingslowly	Whitish and quiteheavy	Whitish and heavy	Black and fluid	Black and heavy	-	-

It has been observedthat the fusion of thermoplasticwaste for doughhomogenizationrequiresless time whenutilizinggranulatedmaterials. In terms of doughquality, all tests yielded a homogeneous and dense dough, predominantlyexhibiting a darkcolor.

3.1.2. Comparisonaccording to the number of paving stones and the weightloss of the materials

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		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
Nomber of pavers in molds	9	10	8	17	10	14	9	12	9	13.25
Nomber of paversafterdemolding	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
Averageweight 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
Weightloss 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
Weightloss 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

Table 3. Parametermeasurements: number of blocks produced and loss ofmaterialweight

Comparison of parametersrelated to paving stone manufacturingindicatesthat, on average, usinggranulatedmaterialsyields a higherquantity of paving stones (i.e., 13 paving stones) compared to rawthermoplasticmaterials (i.e., 7 paving stones). Paving stones fromgranulatedmaterialsweighslightlyless (i.e., 1.9±1.22 kg) thanthosefromrawmaterials (i.e., 2.21±0.08 kg). Furthermore, the use of granulatedmaterialsresults in lowermaterialweightloss (5.29±0.98 kg, or 17.63%) compared to paving stones made fromrawmaterials (9.95±1.89 kg, or 24.98%).

3.2. Aspects relating to the strength test of paver

3.2.1. Average values of parameterslinked to the paver resistance test

Table 4. Average values of parameterslinked to the resistance test of the pavers

	Values obtainedfrom the 4 trials								
Variables	Trial 1		Trial 2		Trial 3		Trial 4	Average	
Quality of materials	Raw	Granulated	Raw	Granulated	Raw	Granulated	Raw	Raw	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	275	228	275	228	275	228	275	275	228

usefulsurface (cm^2)									
Breakingload (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 resultsfrom the strength test indicatesthatpaving stones made fromgranulatedmaterialsendured a significantlyhigherbreakingload (i.e., 28000±1609.91 kg), resulting in superioraverageresistance values (i.e., 12.3±2.19 N/mm^2) compared to theircounterparts made fromrawmaterials (i.e., 6.4±1.61 N/mm^2).

3.2.2. Response of Paversunder Stress Test

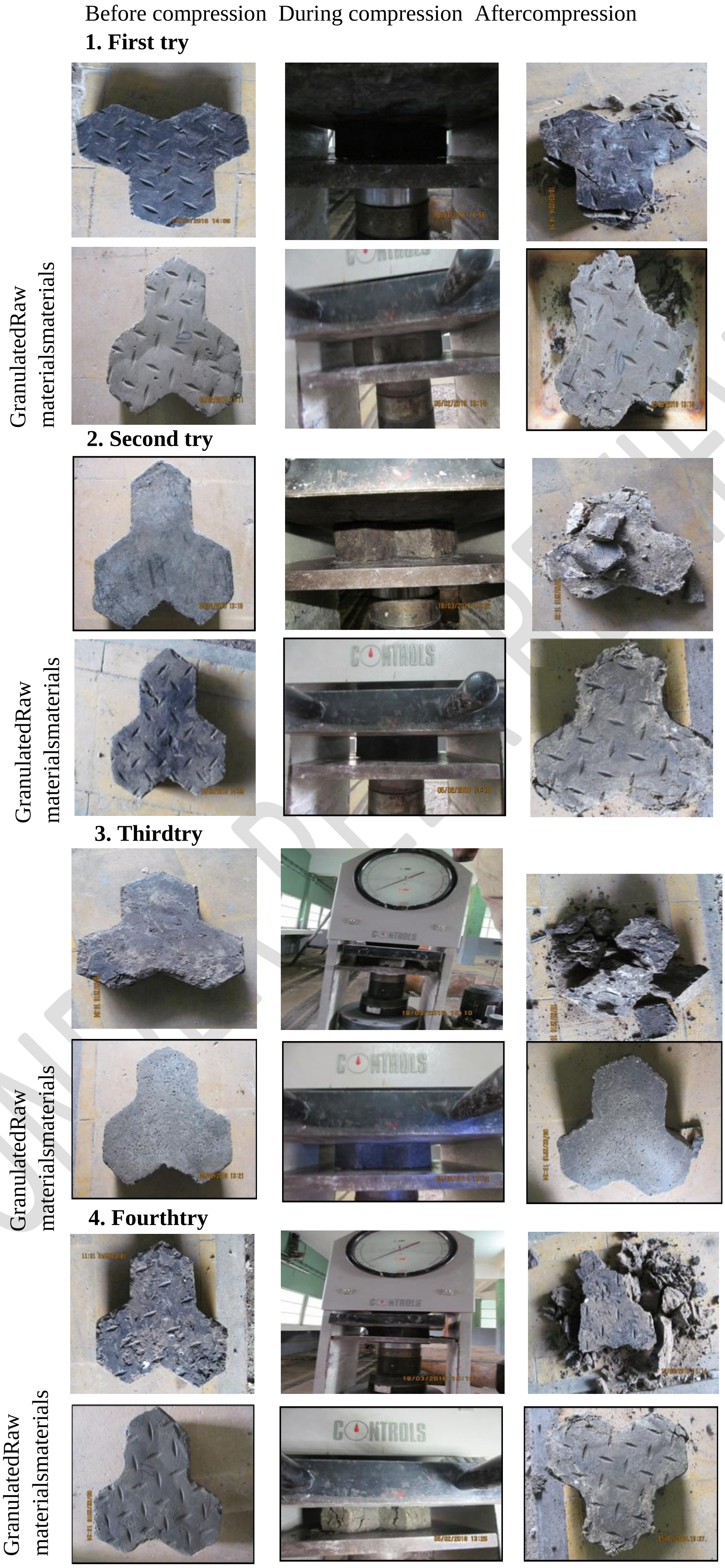

Figure 2. Reaction of paving stones subjected to the resistance test according to the quality of the materials

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 averageresistance values and appropriate uses (Source: [4])

ConcreteQualities	Cement Dosages	AverageResistance (N/mm²)	CharacteristicResistance at 28 Days (Mpa)	Suitable uses

	(kg/m^3)		in compression (Mpa)	in traction (Mpa)	
Low-strength Concrete	150-300	20-25	16	1,6	Small structures: simple house (withoutfloor), 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 resultsobtainedfrom the utilization of granulated and rawthermoplasticmaterials in paving stone production throughrecyclingyields the followingcomprehensive conclusions:

The usage of granulatedthermoplasticspresentsclearadvantages over rawthermoplastics. Specifically, the application of granulated plastics:

- Demonstratessignificantlyreducedweightloss of materials on average, with a ratio of granulatedthermoplastics to rawmaterialsat 17.63±3.32% to 24.98±1.59%, leading to a highernumber of paversproduced (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 upondemolding. In comparison to rawmaterials, thisresultsin 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.
- Yieldssuperioraverageresistance values for the producedpavers (i.e., averagingat 12.3±2.19/6.4±1.61 N/mm²).

The compellingevidencepresenteddemonstratesthat the use of granulatedthermoplasticmaterials in paving stone manufacturing stands as a more efficient and effective approach, showcasingitspotential for widespreadimplementation in the construction industry. Thesefindingscontribute to the ongoing efforts towardssustainable and innovative solutions for paving stone production, emphasizing the importance of recycling and reusingmaterials to achieveenvironmentallyconsciousoutcomes.

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