Curtailing the Environmental Impact of Waste Plastics through Re-use for Sustainable Paving Stone Manufacture in Kinshasa City

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In Kinshasa, attacks on the environment and human well-being continue to increase with the accumulation of thermoplastic waste (LDPE, HDPE and PET) mainly produced. Collected in unsanitary landfills, this waste pollutes the environment with all the consequences on health. This study makes it possible to reduce the socio-environmental impacts of thermoplastic waste by reusing them for the manufacture of paving stones for the sanitation of Kinshasa. Specifically, it initiates the collection of thermoplastic waste, recycling techniques for the production of paving stones and raising awareness among Citizens and Decision-Makers of the importance of their management. Thus, a survey questionnaire was administered to a sample of 1276 households. The proportions of materials used to obtain the resistant paving stones are: 60% fine sand, 35% LDPE and HDPE and 5% PET. Melted at 200°C, the thermoplastics are mixed with sand until a homogeneous paste is obtained to be poured into moulds prearranged on a metal table. The consolidated pavers are removed from the mould after 45 minutes using a hammer. The results obtained show that 4% of households manage their waste better and that 96% contribute to plastic pollution. 87.1% of households denounce the harmful effects of thermoplastics on the environment and point out the clogging of gutters (28.4%), the pollution of space (25%) and the pollution of rivers (16.5%). Twenty-two pavers with an average weight of 1953.33 ± 6.22 gr are manufactured. The weight loss of the materials is 14.2% (7.1 kg). The compressive strength of the pavers is 32.74 ± 0.94 N/mm². In short, reducing the socio-environmental impacts of thermoplastic waste in Kinshasa is complex and requires a multidimensional approach with the efforts of all stakeholders.

Keywords: Kinshasa, impacts, waste, thermoplastics, pollution, sanitation, paving stones

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INTRODUCTION

Over the last four decades, the city of Kinshasa has experienced a demographic surge resulting from the rural exodus and displaced people fleeing the war in the east of the country (OCHA, 2022; Ngoie and Lelu, 2009). This increase in population is not without consequences on the living environment which is mainly occupied by spontaneous neighbourhoods (Kibala, 2020) and therefore the production of solid household waste is enormous, and their management poses great difficulties. Indeed, nowadays, out of the estimated 10,000 tonnes of solid household waste generated per day in Kinshasa, thermoplastic waste represents 15% (Holenu *et al*., 2020). Studies conducted by Weya *et al*. (2013) showed that without a real destination, this thermoplastic waste used as packaging and thrown away without standards or control in micro-ecosystems, pollutes the soil (such as in a certain place in the city in the commune of Lingwala, the layer of thermoplastics buried under the ground reached a depth of 2 meters as shown in Figure 1) and waterways, harm biodiversity, contribute to climate change and pose public health problems.

This production is extremely dangerous when we know that it takes at least 100 years for a thermoplastic to completely degrade (Kassay, 2015). De Bock *et al*. (2020) noted that, of the three main classes of plastics (thermosets, elastomers and thermoplastics), the last class with low density polyethylene (LDPE), high density polyethylene (HDPE) and polyethylene terephthalates (PET) is the one that combines the properties of recyclability and does not pose the major problem of incompatibility when they are mixed for the production of other plastic or semi-plastic materials such as paving stones. Despite this recycling potential, the revaluation of thermoplastic waste for the manufacture of paving stones is not yet well applied in Kinshasa (Epusaka, 2019) due to the absence of waste collection and recycling infrastructure in this city, lack of awareness of the importance of recycling thermoplastic waste, difficulties in sorting waste according to their composition and quality, lack of precision on the types of plastic waste to be recycled between thermoplastics, thermosets and elastomers, lack of partnership between public, private and academic actors to promote cooperation and synergy in this area and the lack of definition of the formula leading to the determination of the proportions of materials for the production of paving stones with better resistance to simple compression.

This study therefore, seeks to understand how thermoplastic waste can be efficiently collected, sorted and recycled to produce paving stones with better compressive strength values. It also aims to raise awareness among citizens and decision-makers of the importance of thermoplastic waste management and to promote the adoption of environmentally and health-friendly recycling practices. Finally, it seeks to evaluate the socio-environmental impacts of this waste, in order to present the advantages of this approach which demonstrates that in Kinshasa, thermoplastic waste which causes serious pollution and health problems are raw materials that are potentially recyclable for the production of other plastic materials with a high compressive strength value, such as paving stones (32.74 ± 0.94 N/mm²).

Figure 1. View of a 2 m profile of the ground occupied by thermoplastic waste in Kinshasa/Lingwala

MATERIALS AND METHODS

Four neighbourhoods were selected. The choice of municipalities was made based on their average which is 6 municipalities. Taking into account the fact that the districts of Mont-Amba and Tshangu only have 5 communes, we selected 4 communes per district with a view to subjecting all the districts to the same exercise. An exception for the Tshangu district of which 3 urban communes (Kimbanseke, Masina and N'djili) were retained while excluding the 2 rural communes (Maluku and N'sele) whose extent of plastic pollution is not accentuated. For the choice of neighbourhoods, one neighbourhood per municipality was selected, with the exception of the municipalities of Masina and Kimbanseke where 2 neighbourhoods were selected per municipality given the extent of poor waste management collected. This gives a total of 17 sample neighbourhoods for the entire city. The selection of neighbourhoods was done randomly by drawing lots and the surveys were carried out using a survey questionnaire administered to 1276 households according to Table 1 and the counting was carried out using statistical computer software: Epi-info, Epi-data, Stata 12 and Excel.

The size and choice of households to be surveyed followed the following approach:

Sample size of households at the municipal and neighbourhood level

Sample size at the municipal level

When the total number of households (population) is greater than 10000

$n = \frac{z^2 dpq}{\alpha^2}$ (1) (Ngondo, 2001; Andrew & Coll, 1983)

With: n = The desired sample size when the number of households (population) is greater than 10000 households;

z: The difference generally set at 1.96 (or more simply at 2.0) which corresponds to a confidence level of 95%;

d: Correlative factor whose value is equal to 1;

$p = \frac{pc}{pt}$ (2) $\frac{\text{(Target population)}}{\text{(Total population)}}$ (Andrew & Coll, 1983): proportion of target households (population) having a given characteristic. If no estimate exists, we can use 50% or 0.50. With p = 0.50; the value of n (sample size) is significant at a confidence level (Z) of 95%;

q = 1,0 – p : is the difference in population proportions;

α = desired degree of precision, usually 0.05 or sometimes 0.01 to increase precision.

When the total number of households (population) is less than 10000

$nt = \frac{n}{1+\frac{n}{N}}$ (3) (Rau, 2017; Crépon & Latif, 2017) ;

nt = the desired sample size (when the population size is less than 10,000 households (individuals);

$n = \frac{z^2 dpq}{\alpha^2}$;

N = household size (population) less than 10000 individuals.

Sample size at neighbourhood level

$n_x = \frac{n.n1}{N}$ (4) (Andrew & Coll, 1983)

With: n_x = number of sample households per neighbourhood ;

n_l = number of residential households per neighbourhood;

n = total number of sample households for the municipality (found using the two formulas (N > or < 10000 households;

N = number of residential plots (households) in the municipality of the district concerned.

Interval (I) or "no survey" or even "reason"

To give all households (plots) the chance to be surveyed, stratification was used by calculating the interval I.

$I = \frac{ni}{nf}$ (5) (Kiye, 1997)

With : ni = number of residential plots per district;

nf = total sample of households to be surveyed;

I = interval between two households (plots) to be surveyed.

In order to ensure good representation of the sample, the plot was retained as the sampling unit, the household was used as the unit of analysis (survey); in this case, only one household was considered per plot. This process is scientifically authorized within the framework of priority investigations in a given population (Grotoiert & Marchout, 1992; Verma, 2009). Thus, the municipalities and neighbourhoods selected, the number of households per municipality and per neighbourhood, the size of the sample per municipality and per neighbourhood, the proportion (%) retained, the size of the sample retained per neighbourhood and the stratification by interval are presented in Table 1.

Table 1: Sample size at the level of: municipality (N) and neighbourhood (nx) and interval (I)

Districts	Number of municipalities selected (15)	Number of districts selected (17)	Number of plots by		Size of the sample by		Percentage (%) retained	Retained sample size per neighbourhood (nx) sd	Interval (I)
			Municipality	Neighbourhood	Municipality (n, nt)	Neighbourhood (nx)			
Funa	1. Selembao	1. Nfafani	48111	1134	10.000	236	20%	47 ≈ 50	23
	2. Ngiri-ngiri	2. 24 Novembre	5286	593	3458	388	15%	58 ≈ 60	10
	3. Makala	3. Mfidi	24087	757	10.000	314	10%	31 ≈50	15
	4. Bandalungwa	4. Lingwala	22184	3420	10.000	1542	5%	77 ≈ 80	43
Lukunga	5. Ngaliema	5. Joli-Parc	67887	2595	10.000	382	20%	73	36
	6. Gombe	6. Gare	48019	1084	10.000	226	15%	41 ≈40	27
	7. Mont-Ngafula	7. Kindele	82077	3243	10.000	395	20%	79	41
	8. Kinshasa	8. Mongala	4257	690	2986	484	17%	81	9
Mont-Amba	9. Matete	9. Totaka	12027	1554	10.000	1292	10%	129	12
	10. Limete	10. Industriel	21899	3370	10.000	1539	5%	76 ≈ 80	42
	11. Ngaba	11. Bula-Mbemba	18022	1639	10.000	1640	10%	164	10
	12. Lemba	12. Mbanza-Lemba	21761	2885	10.000	1326	5%	66 ≈ 70	41
Tshangu	13. N'djili	13. 8/Ubangi	34551	5749	10.000	1664	10%	166	35
	14. Masina	14. 3-Congo	64.373	3476	10.000	540	10%	54	64
		15. Imbali/Petro-C.	64.373	7081	10.000	1100	10%	110	64
	15. Kimbanseke	16. Kingasani1(ya suka)	96222	3268	10.000	339	15%	51 ≈ 50	65
		17. Maviokele	96222	2447	10.000	254	50%	127 ≈ 120	20
		Total			6444	13661	-	1276	-

Recycling Process of Thermoplastics for the Manufacture of Paving Stones

The materials (thermoplastic waste (LDPE, HDPE and PET) and fine sand) proportioned by a Saco brand scale with a maximum weight of 200kg were mixed in a metal tank heated with the charcoal which was fanned by an electric blower. The homogeneous paste obtained after melting at 200°C, the thermoplastics mixed with fine sand using a casting ladle was poured into moulds lubricated with engine drain oils (SAE 40) and placed on a table metal serving as a support. After cooling, the pavers were removed from the mould using a plastic hammer. The proportions of materials used are those predefined by previous studies carried out by Weya *et al*. (2013) which gives the best resistance value, 60% (i.e. 30 kg) of fine sand, 35% (i.e. 17.5 kg) of LDPE and HDPE and 5% (i.e. 2.5 kg) of PET.

Compressive strength test of paving stones

The compressive strength test of the paving stones was carried out at the National Public Works Laboratory/Research and Development Directorate of the Roads Office located at No. 482 Avenue de la Science in Kinshasa/Gombe using the Dreux method. It consists of sizing the block, weighing it, determining its density, compressing it, observing its reaction from the start of its compression until rupture and reading the maximum load observed at rupture in the pressure gauge of the block.

RESULTS AND DISCUSSION

Impacts of Thermoplastic Waste on the Environment and Health

According to the results presented in Tables 2 and 3 and Figure 4 which respectively deal with the aspects relating to the use or not of plastics, the socio-environmental impacts of thermoplastic waste in the city of Kinshasa and the future of thermoplastics post-use, it is observed that 93.2% of households compared to 6.8% use thermoplastics, of which 41.2% represent the large proportion of those who use them for packaging. They are followed by those who use it to buy food (i.e. 28.7%), sales (i.e. 16%), domestic use (10.2%) and lighting a fire (4%). According to the impacts, it shows that 87.1% of the households questioned recognize the harmful effects of thermoplastic waste on the environment and health: this concerns clogging of gutters (28.4%), space pollution. urban (25%), the birth of disease vectors (36.2%), followed by bad odours (33%), the tasting of sachets by herbivores (goats and cattle) leading to their death (20.8%) and pollution of the aquatic living environment (10.1%). The future of post-consumer waste shows that 4% of households made up of sale (1%), recovery (1%) and reuse (2%) recycle thermoplastic waste and therefore, 96% contribute to plastic pollution.

Indeed, majority of households (93.2%) use thermoplastics, while there is only a small proportion (4%) of households which recycle their waste thermoplastics. This means that 96% of households contribute to plastic pollution due to the absence of "urban culture" linked to bad habits rooted in the culture of "everything is ready to throw away, everything down the drain, in spaces public or in waterways", the lack of initiative for the recovery of waste and the absence of an urban sanitation service thus constituting a serious waste management problem in the city of Kinshasa (Vuni *et al*., 2020). This is why a majority of households (87.1%) recognize that thermoplastic waste has negative impacts on the micro-ecosystems of Kinshasa and on public health. These observations are also made by UEMOA (2013) which found that in the majority of cities in developing countries, there are multiple attacks on the environment and human life due to the absence of urban culture and the lack of importance given to waste, always considered as utilities or negative externalities.

Table 2: Distribution of respondents according to whether or not they use plastics

Variable	Modality	Absolute frequency	Relative frequency
Do you use thermoplastics?	Yes	1189	93,2
	No	87	6,8
	Total	**1276**	**100,0**
If yes? for what use?	Packing	490	41.2
	Sale	190	16.0
	Domestic use	121	10.2
	Purchase food	341	28.7
	Fire lighting	47	4.0
	Total	**1189**	**100.0**
If not, why?	Not important	16	18.4
	Prohibited use	32	36.8
	Make the city dirty	33	37.9
	Damages the ground	6	6.9
	Total	**87**	**100.0**

Table 3: Distribution of respondents according to the impacts of thermoplastic waste in the Kinshasa environment and on life (health)

Variable	Modality	absolute fréqu.	relative fréqu.
In your opinion, does thermoplastic waste cause harm to the environment and to life (health)?	Yes	1112	87.1
	No	164	12.9
	Total	**1276**	**100.0**
If yes, which ones in the environment?	Blockage of gutters	316	28.4
	Pollution of urban space	278	25
	Water impermeability in the ground	153	13.8
	Floods	109	9.8
	River pollution	184	16.5
	Atmospheric pollution	72	6.5
	Total	**1112**	**100.0**
If yes, which ones affect life (health) ? é	Birth of disease vectors	402	36.2
	Creation of bad odours	367	33.0
	Harm to aquatic life	112	10.1
	Attack on herbivorous life	231	20.8
	Total	1112	100.0

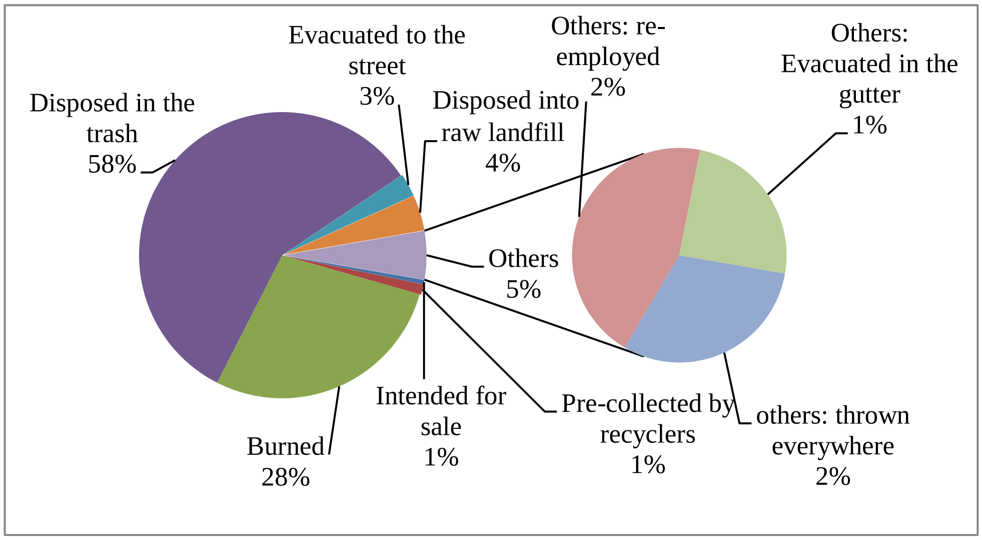

Figure 4. Distribution of respondents according to the fate of post-use thermoplastics

Recycling of Thermoplastics (pavers manufacturing)

Table 4 shows that the mixture of 17.5 kg of sachets, 2.5 kg of bottles and 30 kg of fine sand produced a fairly heavy homogeneous black paste after 95 minutes of mixing. 22 consolidated paving stones measuring 240 mm in diameter and 5 cm thick were manufactured. Of the 42.97 kg total weight of the 22 pavers, the average weight of the pavers is 1.95 kg and the weight loss of the materials is equal to 14.2% (i.e. 7.1 kg).

It was noted for the manufacture of the paving stones that it took 95 minutes to homogenize the mixture of bags, bottles and sand. This time, greater than that of the experiments of Indjeku (2017) which only used bags mixed with fine sand (i.e. 65 minutes), is a function of the difference in the melting temperature of each type of thermoplastic and their chemical composition (Glotin, 2021).

These two factors (melting temperature and chemical composition) influence the homogenization time of the paste and the cooling of the paving stones (Racine, 2009). The above is corroborated by the observations of Sadoun (2018) who indicated that temperature influences the degree of melting of plastics. This is the reason why Levesque (2002) states that thermoplastics (polyethylene, polypropene, polyvinyl chloride and polystyrene), made up of linear or branched polymers, melt by simple heating, while Lakhdar (2015) emphasised that the range of melting temperature of 100 to 200 °C of plastics depends on the physical and chemical composition; a property also used for their formatting.

The difference test was carried out to find out whether or not there is a significant difference between the average weight of the pavers resulting from the mixture: LDPE, HDPE, PET and fine sand (i.e., 1953.33 ± 6.22 gr) and those paving stones resulting from the simple mixture of LDPE and fine sand (i.e., 1872 ± 4.51 gr) found by Indjeku (2017). It implies that at the threshold of $\alpha = 5\%$, with standard deviations of 3.02 and 3.46 respectively, the critical value read in the student table at 21 dof is $t\alpha = 2.08$ and tc (calculated) = 0.21. As $tc < t\alpha$, the null hypothesis is accepted.

This means that there is no significant statistical difference between the average weight of two types of paving stones and two types of materials used; therefore, the mixture resulting from the use of different types of thermoplastics for the manufacture of paving stones does not influence the weight of the different types of paving stones, since it depends on the amount of homogeneous paste contained in the moulds (Rasoatahinjanahary, 2014), although mixing simple sachets with fine sand homogenizes quickly.

The pavers resulting from the mixture of sachets, bottles and fine sand gave an average resistance of 32.74 ± 0.94 (≈ 33) N/mm² greater than that of the pavers resulting from the mixture of sachets with fine sand (i.e. 24 N/mm²) found by Indjeku (2017). It means that, whatever the composition of the two types of mixtures, the resistance values are higher, compared to other materials used for the manufacture of paving stones (see table 6), simply because the thermoplastics are endowed properties of being good for recycling and having better resistance to compression, due to their very high density (Aucher, 2011). They also have other properties including good resistance to acids, bases and solvents (St-Charles, 2015).

Table 4: Aspect relating to the manufacture of paving stones

Variables	Values
Quantity of bag (LDPE and HDPE): 35% (in kg)	17.5
Quantity of bottles (PET): 5% (in kg)	2.5
Quantity of fine sand: 60% (in kg)	30
Homogenization time for bags + bottles + sand (in minutes)	95
Quality of the paste (bags + sand)	Black, quite heavy
Number of pavers produced	22
Diameter of a paver (in mm)	240
Thickness of a paving stone (in cm)	5
Total weight (in kg)	42.97
Average weight of a paving stone (in kg)	1.95
Weight loss of materials (in kg)	7.1 (i.e., 14.2%)

Resistance Test by Compression of the Paving Stones

It was observed that at an average of 4 minutes of compression, the blocks which have 1125 cm^3 of average volume, 1953.33 ± 6.22 gr of average weight, 1.74 ± 0.14 of average density, 225 cm² of surface average total compressed stress and 73666.67 ± 161.56 kg average total breaking load gave 327.4 ± 1.73 kg/cm² average total stress at break and therefore an average compressive strength of 32.74 ± 0.94 (≈ 33) N/mm².

Table 5: Aspects relating to paving stone strength testing (high and low density)

Variables	Average per block
Average volume (in cm^3)	1125
Average weight (in gr)	1953.33 ± 6.22
Average medium density	1.74 ± 0.14
Average total compressed surface (in cm^2)	225
Average compression time (in minutes)	4 ± 0.67
Average total breaking load (in kg)	73666.67 ± 161.56
Average total breaking stress (in kg/cm^2)	327.4 ± 1.73
Average useful breaking stress at 28 days of age: Strength (in N/mm^2)	32.74 ± 0.94 ≈ 33

This value (33 N/mm²) is higher compared to other mixtures as presented in table 6. This can be explained by the fact that the mixture of several thermoplastics with almost the same recycling properties has in most cases leads to an increase in the compressive strength of the material produced (Besson, 2014).

Table 6: Resistance values of paving stones obtained from different materials

Matter	Resistance (in N/mm²)
Paver made from bags, bottles and find sand	33
Paver made from bags and fine sand	24
Paver concrete paver	18
Paver made from bags and slag	11
Paver made from pure clay	7

According to Table 7, the paving stones resulting from this study having a resistance of 33 N/mm² included in the value scale of concrete with high compressive strength are useful for large works and present a novelty and deserve attention particular in the city of Kinshasa.

Table 7: Scale of average resistance values and appropriate uses

Quality of concrete	Cement dosage (in Kg/m³)	Average resistance (in N/mm²)	Proper use
Low strength concrete	150-300	20-25	Small works: simple house (without floor), septic tank
Common concrete	300-350	25-30	Small works: simple house (without floor), septic tank
High strength concrete	350-400	30-35	Major works: building, powder column of house on floor, bridge, abutment (bridge edge), …
Exceptional strength concrete	400 and more	35-40	Special works: skyscrapers, dams, major bridges

Source: Dreux (1981)

CONCLUSION

The goal assigned to this study "reduction of the socio-environmental impacts of thermoplastic waste (low density (LDPE), high density (HDPE) and polyethylene terephthalate (PET)) in the city of Kinshasa thanks to their revaluation for the manufacture of paving stones sustainable" was verified. In short, thanks to the recycling of thermoplastic waste (LDPE, HDPE and PET) for the manufacture of sustainable paving stones with a view to enhancing circular economy, this study, has just demonstrated that the reduction socio-environmental impacts of thermoplastic waste which is mainly produced and without real destinations in the city of Kinshasa is possible. It is therefore necessary to popularize and support this technology which confirms the possibility of recycling thermoplastic waste (LDPE, HDPE and PET) in the city of Kinshasa, and which provides a sustainable solution to the sanitation of the city in the face of the impasse caused by this type of waste.

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