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Engineering Properties of Concrete produced using Aggregates from Polyethylene Terephthalate Plastic Waste

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Abstract: *Plastic is a globally accepted material for a wide variety of applications. Plastic waste materials contribute to pollution of the environment due to improper disposal methods. An ideal method of disposal of plastic waste is its incorporation into the construction industry. The objective of this study is to evaluate the engineering properties of concrete produced with aggregates from polyethylene terephthalate plastic waste. Fine and coarse aggregates were obtained from polyethylene terephthalate plastic waste and used to produce concrete. The engineering properties of focus were: slump of fresh concrete, the density of hardened concrete and compressive strength of hardened concrete. These properties were evaluated using the relevant British Standard European Norm equipment and procedures. The values obtained are as follows: slump – 10mm, the maximum density of hardened concrete (14 days curing) – 1500 kg/m^3 and maximum compressive strength (28 days curing) – 12.16 N/mm^2. The slump value indicates a very dry mix suitable for the production of interlocking blocks and kerb stones. The density value is of lightweight concrete suitable for use as roof fascia, slabs and tiles. The value of compressive strength indicates that the concrete can find application in the design of concrete structures, specifically, low load-bearing precast partitions/sections.*

Keywords— Plastic, Polyethylene Terephthalate, Waste, Concrete, Slump, Density, Compressive Strength

1. INTRODUCTION

Waste is produced from all kinds of human activity. The use of plastic in various productive activities is globally accepted as it is cheap, lightweight and durable. This acceptance and use results in the huge generation of plastic waste. The accumulation of various forms of plastic waste materials in the environment adversely affects the earth's flora and fauna, even humans, [1], [2]. The annual global production of plastics was about 380 million tons of plastic globally for the year 2018, while 6.3 billion tons of plastic have been produced from 1950 to 2018. The percentage of this quantity that has been recycled or incinerated is estimated at 9% and 12% respectively [3].

Globally generated plastic waste stood at 242 million tonnes in 2016, this being 12 per cent of all municipal solid waste. Three regions of the world were responsible for the bulk of this generated waste. The breakdown is as follows: 57 million tonnes from East Asia and the Pacific, Europe and Central Asia generated 45 million tonnes while 35 million tonnes came from North America. Sub – Saharan Africa contributes 17 million tonnes to the global total [4], [5]. Nigeria is the seventh-highest generator of plastic waste in the world at 2.5 million tonnes of plastic waste annually, while 219,000 tonnes of plastic waste is generated in Uganda every year, [6], [7].

Plastic is non – biodegradable and degrades very slowly with exposure to normal atmospheric weathering conditions. As such they persist in the environment for a very long time. This property poses challenges in the area of safe disposal of plastic waste. Stomach contents of various organisms have been found to contain particles of plastic. These organisms include: earthworms, birds, turtles, dolphins and whales. Smaller particles may be of even more consequence, as organisms who may ingest them are at the basis of different food webs. Smaller plastic particles can provide surface area for the adsorption of other contaminants and promote contamination in organisms [8].

Most of the plastic produced globally is not properly disposed of by recycling, incineration or in landfills. Fifty percent of all plastics produced are mostly lightweight plastic products and packaging materials; which are mostly for one time use. Often, they are not properly disposed of within the vicinity of their final use to the consumer. They are usually thrown to the ground, out of a car window, onto an already full refuse heap or blown about by wind; this contributes to the pollution of the environment [1]. This pollution manifests in the form of aesthetic nuisance, the foul smell emanating from liquids trapped in the plastic containers, clogging of drains and waterways, providing habitat for insects and rodents etc.

Polyethylene terephthalate (PET or PETE), is a strong, stiff synthetic fibre and resin and a member of the polyester family of polymers. PET can be used as fibres for permanent-press fabrics and disposable bottles for beverages [9]. PET is clear, strong, and lightweight plastic that has wide application as a packaging material in the food and beverage industry. Its use is greatly enhanced when the convenience of the end-user is essential in packaging food, water soft drinks/juices etc. [10]. In 2016, global production of plastic drinking bottles stood at 480 billion, [11].

Resource recycling is a recurring theme in environmental management. It is the process of collecting and processing items that could be discarded as waste and converting them into new products is known as recycling, [12]. It is the third option in the waste hierarchy which classifies waste management strategies according to their ability to minimize and reduce the negative impact of waste. There is no degradation in the quality of recycled plastics during the service cycle, and more importantly, the use of virgin construction materials can be reduced with recycled plastics as a substitute [13].

Among the various types of recycling management approaches, the reuse of waste and recycled plastic material in the construction and allied industry is considered an ideal method for disposing of plastic waste, [14]. Recycled plastic has found wide application in the contemporary construction industry. Recycled plastics do not exhibit any degradation in quality within their period of service and can be used as a substitute for virgin construction materials. [13]. It has found use in damp proof membranes, bitumen adjustments and full or partial replacement of aggregates. It has given great benefits in its resilience and weight [14].

In general, there are two forms of plastics used in concrete viz, PET aggregates (PETA); which replaced natural aggregates and PET fibres (PETF) which are used in fibre-reinforced concrete (FRC) [13]. Properties of concrete can be significantly improved with the introduction of PET aggregates. This is due to certain characteristics of concrete viz: good resistance to abrasion, poor water absorption, high heat capacity, poor thermal conductivity and high ultimate tensile strength. PET aggregates (PETA) have significantly less density compared to natural aggregate (NA), therefore it can be used to develop concrete of relatively lower density (lightweight concrete), [15]. Reference [16], observed that the water proliferating capacity is influenced by the introduction of PET fibres in concrete in addition to reduction in sorptivity. High ductility performance and fibre adhesion to concrete were results of tests carried out by [17] on PET fibre–reinforced concrete.

Plastic aggregates have been produced using various procedures. Reference [18], patented a procedure of producing plastic aggregates for use in concrete. This procedure involves soaking high density plastic strips in strong alkali and exposing the mixture to ultraviolet radiation. The reaction alters the texture and the chemical make-up of the surface of the surface of the plastic strips. This creates a better affinity for common cement binders. The procedure utilized by [19] and [20] involved mechanically grinding/shredding the plastic waste to pre – determined sizes. A combination of mechanical and thermal procedure was used by [21] and [22]. The plastic waste went through grinding/shredding and was fed into a plastic granulator machine where melting and extrusion was done to produce uniform pellets of required diameter and length. Reference [23], patented a thermal procedure for producing construction aggregates from plastic waste. Plastic waste was mixed with a filler, typically red sand, fly ash and quarry fines. The mixture was compressed and melted to form a composite sheet or slab, which was then crushed to form either fine or coarse aggregates.

The objective of this study is to produce concrete using aggregates from polyethylene terephthalate plastic waste and evaluate the following engineering properties viz slump, density of hardened concrete and compressive strength.

2. MATERIALS AND MATERIALS

2.1 Materials for the study

The materials required for this study are outlined as follows:

2.1.1 P.E.T. Plastic Waste

Waste P.E.T. plastic waste bottles were obtained from residential and commercial waste receptacles, in Ishaka Town, Western Uganda.

2.1.2 Cement

Multipurpose 32.5 Portland Pozzolona Cement was used. This cement is produced by Tororo Cement at its Plant in Tororo, Uganda. It conforms to [24] and [25].

2.1.3 Water

Clean water was obtained from the Construction Materials Laboratory, Department of Civil Engineering, Kampala International University (Western Campus), Ishaka, Uganda.

2.2 Methods for the Study

The following methods were adopted to carry out the study:

2.2.1 Production of plastic aggregates

The polyethylene terephthalate waste bottles were shredded using a utility knife and a pair of scissors. Afterwards they were washed to remove all impurities and dried in open space at room temperature to remove all moisture. A mould is prepared using wood of 5cm thickness. The interior of the mould is lined with thin steel sheets. The shredded plastic is placed in an aluminium pan and put in an oven. The shredded plastic is heated to a minimum temperature of 300^0C for a period of 10 minutes. The aluminium pan is then removed from the oven and the melted plastic is quickly poured into the mould and allowed to cool at room temperature for 6 hours. The melted plastic contracts while cooling and the cooled plastic block is then knocked off the mould. The plastic block is crushed manually to obtain plastic aggregates.

2.2.2 Size classification of aggregates

The plastic aggregates are classified into fine and coarse aggregate in accordance with [26] using a MATEST A060 – 01 auto sieve shaker. The sieve sizes used are: 20mm, 5mm and 0.063mm. The aggregates that pass through the 20mm sieve but are retained on the 5mm sieve are classified as coarse aggregates. Likewise, the aggregates that pass through the

5mm sieve but are retained on the 0.063mm sieve are classified as fine aggregates.

2.2.3 Concrete mix ratio and casting of concrete cubes

The concrete mix ratio adopted for this study is designed to produce M25 concrete in accordance with [27]. This mix ratio is one part by mass of cement, one part by mass of fine aggregates and two parts by mass of coarse aggregates (1:1:2). It is suitable for domestic and commercial applications. The water to cement ratio used is one part by mass of water to two parts by mass of cement.

Twelve (12) concrete cubes were cast using the mixture in 100mm x 100mm x 100mm cube-shaped moulds. The cubes were de – moulded after 24 hours and placed in a water tank for curing.

2.2.4 Slump test

This test was carried out in accordance with [28]. The fresh concrete mix was compacted into a mould in the shape of a frustum of a cone, having 300 mm height, 200 mm bottom diameter, and 100 mm top diameter. The concrete mixture was poured into the cone immediately after mixing in three layers, with each layer compacted 25 times using a tamping rod. When the cone is withdrawn upwards, the distance the concrete has slumped provides a measure of the slump of the concrete.

2.2.5 Density of hardened concrete

The density of hardened concrete was determined following [29] and [30]. The procedure is based on the simple mathematical premise as follows:

$$D = \frac{M}{V} \qquad (1)$$

Where,

D is the density (Kg/m^3)

M is the mass of the specimen (Kg)

V is the volume (m^3)

The mass of the hardened concrete cubes was determined using a CITIZEN SSH 93L weighing scale and the volume was determined by multiplying the length, breadth and height measurements of the concrete cube specimen.

2.2.6 Compressive Strength test

Compressive strength test was carried out in accordance with [31]. The tests were carried out on three (3) cubes at intervals of 7, 14, 21 and 28 days of curing. The concrete specimen was placed in a MATEST CO89PN140 compressive test machine. Load was applied on the concrete specimens at the rate of $0.25Nmm^{-2}s^{-1}$ until failure occurred. The maximum load sustained by the specimen and the compressive strength of the concrete was read off from the liquid crystal display (L.C.D.) screen on the machine. The average value of the compressive strength of the specimens per curing interval was determined and recorded.

3. Results and Discussion

3.1 Plastic Aggregates

The plastic aggregates were produced in the Construction Materials Laboratory, Civil Engineering Department, Kampala International University, Western Campus, Ishaka, Uganda.

Figure 1 shows the waste plastic bottles collected from waste receptacles.

Fig. 1. *Waste plastic bottles*

The washed and shredded waste plastic bottles are shown in Fig. 2.

Fig. 2. *Washed and shredded waste plastic bottles*

Figure 3 shows the wooden mould used to receive the molten plastic. The molten plastic is poured into the mould and allowed to cool (fig. 4).

Fig. 3. *Wooden mould*

Fig. 4. *Wooden mould containing molten plastic left to cool*

The cooled plastic block is removed from the mould (Fig. 5) and subjected to manual crushing in the lab.

Fig. 5. *Cooled plastic blocks*

3.2 Aggregates Sizes

The mechanical vibration array used for size classification of the aggregates is shown in Fig. 6.

Fig. 6. *MATEST A060 - 01 Auto Sieve Shaker*

The outcome of the size classification is as follows:

a) The fine aggregates are displayed in Fig. 7. These are aggregates that pass through the 5mm sieve and are retained on the 0.63mm sieve.

Fig. 7. *Fine aggregates*

b) Figure 8 shows the coarse aggregates. These are the aggregates that pass through the 20mm sieve and are retained on the 5mm sieve.

Fig. 8. *Coarse aggregates*

3.3 Mixing of concrete

The cement, fine aggregates and coarse aggregates were mixed following a mass ratio of 1:1:2. The water to cement ratio is 1:2 by mass. The mass of the constituents was measured using a CITIZEN SSH 93L weighing scale. Figure 9 shows the measurement of concrete constituents.

Fig. 9. *Coarse aggregates*

3.4 Slump of fresh concrete mixture

The size, shape and surface texture of the aggregates affects the ease of flow of the fresh concrete. The fresh concrete mixture has a slump of 10mm, which falls into S1 slump class [32]. The slump test set-up is shown in fig. 10.

Fig. 10. *Slump test set – up*

The aggregates produced are angular and have non - uniform shape, resulting in less fluidity and consequent low slump value. This behavior was also reported by [20]. Reference [16], reported that increased surface area and rough texture of aggregates causes them to adhere to other concrete ingredients making the mix less workable. Reference [21], observed a reduction in slump value with an increase in the quantity of plastic pellets added to the concrete mixture.

According to [33], the recorded slump result is categorised as very low and the concrete mixture is described as very dry mix used in paving machines with high-powered vibration. It can be used to produce interlocking blocks and kerb stones for construction of pavements and walkways.

3.5 Density of hardened concrete

The hardened cubic concrete specimen is shown in fig. 11. Table 1 shows the density of hardened concrete determined for the concrete samples at 1, 7, 14, 21 and 28 days curing time. From the results below, the highest density of hardened concrete was recorded as 1500 kg/m^3 after 14 days of curing time. The density of hardened concrete increased from day 1 to day 14, reduced on day 21 and increased slightly on day 28. Figure 12 is a graph of average density of hardened concrete with respect to curing time

Fig. 11. *Hardened cubic concrete specimen*

Table 1: *Density of hardened concrete with respect to curing time*

Curing time (days)	Density of hardened concrete (Kg/m^3)				
	Sample 1	Sample 2	Sample 3	Average	Standard deviation
1	1410	1420	1410	1413	4.73
7	1420	1470	1420	1437	23.57
14	1440	1450	1500	1463	26.24
21	1440	1430	1440	1437	4.73
28	1450	1440	1450	1447	4.73

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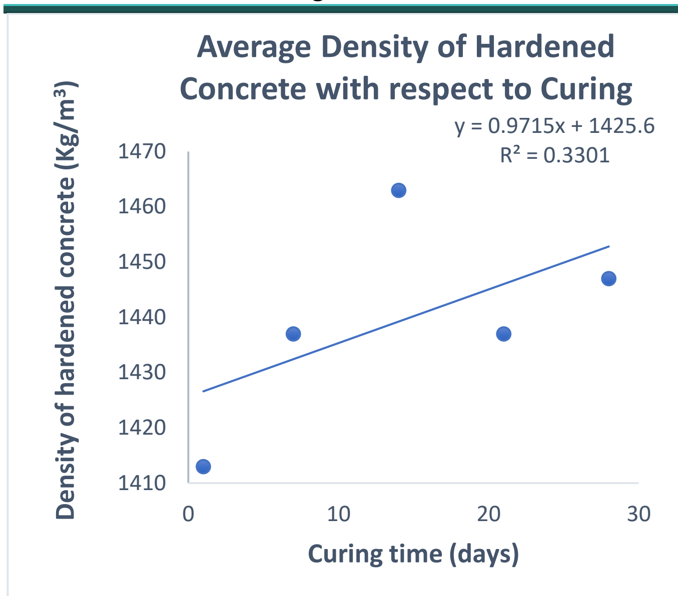

Fig. 12. *Average density of hardened concrete with respect to curing time*

The progress of cement hydration within the concrete matrix, leads to a reduction in the volume of voids thus an increase in density of concrete specimens with respect to time. According to [34], the mechanical properties of concrete are highly influenced by its density. A denser concrete generally provides higher strength, less porosity and fewer amount of voids. This is an indication of greater durability of concrete.

The concrete produced can be classified as lightweight aggregate concrete. Reference [32] describes lightweight concrete as having an oven-dry density of not less than 800 kg/m^3 and not more than 2000 kg/m^3. Specifically, the concrete produced is of density class D 1,6 which has a density range of 1400 to 1600 Kg/m^3. This concrete can be used for roof fascia, roof tiles and roof slabs. Lightweight aggregate concrete blocks also find application in both internal and external walls where loading is minimal.

3.6 Compressive Strength of Hardened Concrete

The compressive strength test was carried out using the compressive test machine as shown in fig. 13. The results of compressive strength tests carried out on the concrete samples at 7, 14, 21 and 28 days curing time are shown in table 2. Figure 14 shows the cubic concrete specimen after failure during the determination of compressive strength. The compressive strength increased significantly with each curing interval across all the samples tested. The maximum compressive strength attained was 12.16 N/mm^2 on the 28th day of curing. This was approximately 50% less than the target compressive strength of the concrete mix ratio. The result is similar to that obtained by [35]. Figure 15 is a graph showing average compressive strength with respect to curing time.

Fig. 13. *MATEST CO89PN140 compressive test machine*

Fig. 14. *Cubic concrete specimen after failure*

Table 2: *Compressive strength of hardened concrete with respect to curing time*

Curing time (days)	Compressive strength (N/mm^2)				
	Sample 1	Sample 2	Sample 3	Average	Standard Deviation
7	8.21	8.59	8.89	8.56	0.2783
14	9.21	9.19	8.95	9.12	0.1182
21	9.91	11.36	10.21	10.49	0.625
28	12.16	11.85	11.49	11.83	0.2738

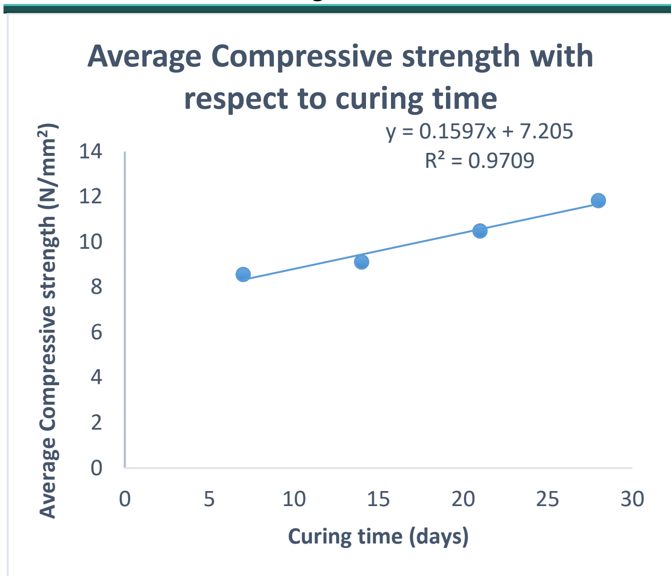

Fig. 15. *Average compressive strength with respect to curing time.*

Reference [36], [13] and [19], observed that compressive strength of concrete containing plastic aggregate decreases with an increase in plastic content due to plastic exhibiting hydrophobic properties. This contributes to the reduced cement hydration reaction near the surface of plastic preventing development of greater bond strength between the smooth plastic surface and the cement paste. Compressive strength of concrete is adversely affected by the addition of plastic in any form, as observed by [15], [37] and [38].

The concrete mix produced is light-weight concrete which satisfies the requirements of LC 8/9 compressive strength class, for low load bearing pre – cast sections and partitions [32]. It can also be marginally suitable for application as LC 12/13 light – weight concrete in design of concrete structures [39].

3.7 Relationship between average compressive strength and average density of hardened concrete

The relationship between average compressive strength and average density of hardened concrete is shown in fig 16.

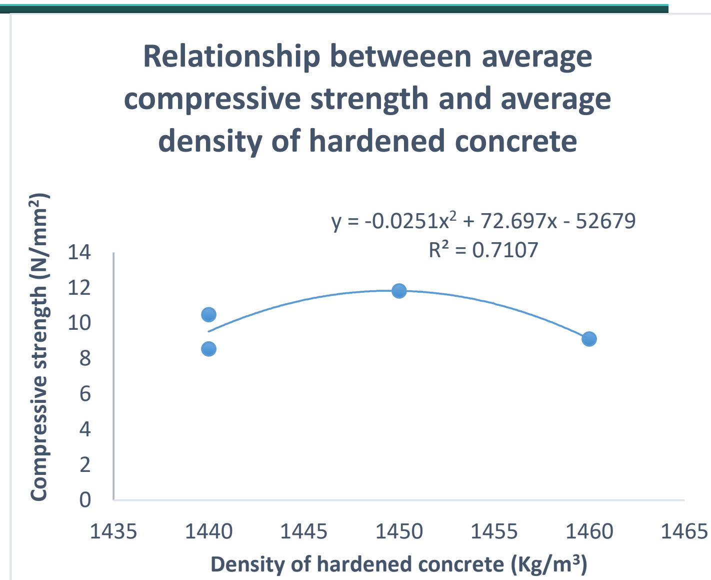

Fig. 16. *Relationship between compressive strength and density of hardened concrete*

The relationship between average compressive strength and average density of hardened concrete is not linear. It can be best described using a second order polynomial equation.

4. CONCLUSIONS

Engineering properties of concrete produced with aggregates from polyethylene terephthalate plastic waste were evaluated. Specifically, values for slump, density of hardened concrete and compressive strength properties were determined. Aggregates obtained from polyethylene terephthalate waste were used to produce concrete following a mix ratio of 1:1:2, with a target strength of 25N/mm^2. Engineering properties were evaluated using the relevant British Standard European Norm equipment and procedures. The values of the engineering properties are as follows: slump = 10mm, maximum density of hardened concrete (14 days curing) = 1500kg/m^3 and maximum compressive strength (28 days curing) = 12.16N/mm^2. The slump value indicates a very dry mix suitable for the production of interlocking blocks and kerb stones for construction of pavements and walkways. The density value recorded falls into the category of lightweight concrete suitable for use as roof fascia, slabs and tiles. The value of compressive strength indicates that the concrete can find application in design of concrete structures, specifically low load bearing pre – cast partitions/sections and in – fill blocks in beam and block flooring.

Further studies should be carried out to evaluate other engineering properties of the concrete. This will fully describe the behavior of the concrete and other possible applications in Civil Engineering.

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