

Effect of Elevated Temperature on Mechanical Properties of Waste Polymers Polyethylene Terephthalate and Low Density Polyethylene Filled Normal Concrete Blocks

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To cite this article:

Kevin Ibe Ejiogu, Paul Andrew Mamza, Peter Obinna Nkeonye, Shehu Aliyu Yaro. Effect of Elevated Temperature on Mechanical Properties of Waste Polymers Polyethylene Terephthalate and Low Density Polyethylene Filled Normal Concrete Blocks. *American Journal of Polymer Science and Technology*. Vol. 4, No. 1, 2018, pp. 28-35. doi: 10.11648/j.ajpst.20180401.12

Received: April 22, 2018; **Accepted:** May 7, 2018; **Published:** June 2, 2018

Abstract: Thermal properties of M30 normal concrete block (NC) were compared with concrete filled with waste polyethylene terephthalate and waste low density polyethylene aggregates which were used as partial replacement of sand in the production of concrete blocks (plast-cretes). Tests were carried out using 100mm×100mm Cubes and 100mm×200mm Cylinder for Compressive and Split tensile Test respectively. The mechanical properties of normal concrete and plast-crete were studied and compared over two temperature regimes at 100°C-400°C and 400°C-800°C. The compressive and Split Tensile strength of normal concrete increased slightly from 100°C-400°C, and reduced from 400°C-800°C. However, the compressive and split tensile strength of the plast-crete showed a gradual reduction from 100°C-400°C and this continued from 400°C-800°C, and became more pronounced as the percentage of waste plastics in the plast-crete increased. The percentage of weight loss for the normal concrete increased from 100°C-400°C, this increase continued from 400°C-800°C. The plast-crete also showed an increase in the percentage weight loss for both temperature regimes and the percent weight loss became more pronounced as the percentage of waste plastics in the plast-crete increased. The normal concrete showed greater spalling than the plat-cretes. Even with the slight reduction in strength with increasing temperature, Plast-cretes can still be applied in areas where low temperature and minimal load bearing applications are needed such as fancy blocks, pedestrian walk ways, slabs, partition walls, fences, houses and light traffic structures.

Keywords: Concrete, Plast-Crete, Elevated Temperature, Compressive Strength, Percent Weight Loss, Waste Polymers, Waste Plastics Polyethylene Terephthalate, Waste Plastics Low Density Polyethylene

1. Introduction

Waste plastic Polyethylene Terephthalate and Low Density Polyethylene are a menace to environmental waste managers [1, 2] in the World most especially in Nigeria [3], the various problems caused by these waste plastics include flooding, environmental degradation, destruction of marine life, and depletion of valuable land assets utilized as land filled sites [3]. Recycling of these waste plastics is the only viable

alternative in tackling this menace. One of the ways of disposing of these waste plastics is by utilizing them as aggregates in concrete mixes, especially in the production of normal concrete structures [4].

The benefits of these methods are enumerable particularly in the effective protection of the environment and conservation of scarce natural resources [5]. Several work have been done in utilizing waste plastics in the production of various categories of concrete blocks and several authors have confirmed the viability of utilizing waste plastics as aggregates in the production of

concrete blocks[6]. While this concrete produced with waste plastics aggregates are applied for various end use applications [7]. Under normal environmental conditions, many concrete is subjected to various temperature ranges and regimes, in the environment, the concretes are only subjected to mere ambient environmental conditions [8]. However, there are very serious consequences when these concrete materials are subjected to elevated temperatures. The effect of elevated temperature on concrete materials cannot be over-emphasized [9]. When concrete is exposed to elevated temperatures, the mechanical properties are significantly compromised, the concrete may fail in different ways [10], and the extent of strength loss is highly dependent on the range of the temperatures the concrete was exposed to and the duration [11]. Other contributory factor (s) to the strength lost are the type of aggregate utilized in the mix proportion, the water- cent ratio utilized and the strength of the concrete after 28 days at room temperature [12]. The thermal coefficient of expansivity of concrete materials (sand, gravel and cement gel) is different, resulting in differential volume variations of the materials at elevated temperatures which can lead to cracking and failure [13].

At temperatures above 430°C, concrete with siliceous aggregates usually has a significant loss in strength compared with those of lightweight aggregates [14]. It has been observed that normal concrete can lose half of its strength at a temperature of 600°C and above [15]. The properties of high strength concrete (HSC) are different from those of normal strength concrete at elevated temperatures [16]. The difference in mechanical properties may be due to porosity, moisture content, quantity of silica fume and heating rate. The information available on properties of concrete at normal environmental conditions and at ambient temperatures can never be applied to concrete that will be exposed to elevated temperatures, thus there is need therefore to carry out detailed study on the impact of elevated temperatures on concrete, so that proactive steps can be taken to eliminate fire induced spalling in concrete that compromises the integrity of concrete structures [17].

This work seeks to study the effect of elevated temperature on M30 Normal Concrete Block (NC) and concrete that is filled with waste plastic aggregates (Plast-crete).

2. Experimental

2.1. Materials

2.1.1. Cement

Dangote Ordinary Portland cement 44.5 grade was utilized in the study. The cement had a specific gravity of 3.15. The cement had a percent weight of lime, silicate, iron oxide, aluminium oxide and a loss on Ignition of 60.20%, 20.40%, and 3.48%, 7.89% and 0.75% respectively. The cement conformed to ASTM C 150-07, Standard Specification for Ordinary Portland cement.

2.1.2. Fine Aggregate (FA)

Natural river sand was used for the production of the concrete; it was collected and stored according to ASTM C

75-03. The sand had a specific gravity of 2.65. It passed through the 5.00mm sieve and retained on the 150 μ m sieve. The sand had a fineness modulus, water absorption, loose bulk density, compacted bulk density, compaction factor, Percent Void and Percent moisture content of 3.14, 1.10%, 1630Kgm³, 1750Kgm³, 0.931, 38% and 2.0% respectively. The fine aggregate conformed to ASTM C33-97, and fell under the Zone 2 on the gradation graph.

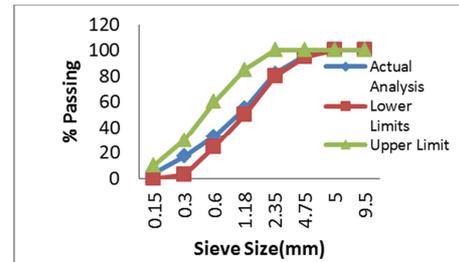


Figure 1. Gradation of Fine Aggregate.

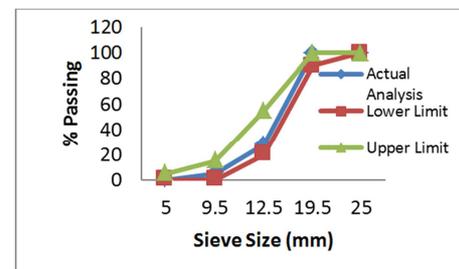


Figure 2. Gradation of Coarse Aggregate.

2.1.3. Coarse Aggregate (Gravel)

The coarse aggregate was collected and stored according to ASTM C 75-03. The gravel has a specific gravity of 2.52. The gravel passed through the 20mm sieve and retained on the 5mm sieve. The gravel had a fineness modulus, percent water absorption, loose bulk density, compacted bulk density, compaction factor, percent void and moisture content of 6.95, 0.50%, 1542Kgm³, 1647Kgm³, 0.94, 40% and 0.95% respectively. The gravel conformed to ASTM C33-97.

2.1.4. Waste Polyethylene Terephthalate (WPET)

The WPET had a specific gravity of 1.36. The WPET passed through the 5.0mm sieve and was retained on the 75 μ m sieve. The fineness modulus, water absorption, loose bulk density, compacted bulk density, compaction factor, percent void, moisture content and maximum size of 3.59, 0.1, 520.34Kgm³, 6.38.98%Kgm³, 0.81, 62.29%, 0% and 2.36mm respectively. WPET was washed and crushed before it was utilized in the production of plast-crete. The WPET aggregates showed good gradation, lesser voids, good particle size distribution and also fell within Zone 2 class of aggregates within the gradation curve (Figure 3).

2.1.5. Waste Low Density Polyethylene (WLDPE)

The WLDPE had a specific gravity of 0.92. The WLDPE passed through the 5.0mm sieve and was retained on the 150 μ m sieve. The WLDPE had a fineness modulus, water

absorption, loose bulk density, compacted bulk density, compaction factor, percent void, moisture content and maximum size of 4.17, 0.005%, 237.82Kg/m³, 291.60Kg/m³, 0.86, 74.15%, 0% and 4.75 respectively. WLDPE was washed and crushed before it was utilized in the production of plast-crete. WLDPE showed poor gradation, poor particle size distribution, more voids and fell outside the upper and lower limit in its gradation curve (Figure 4).

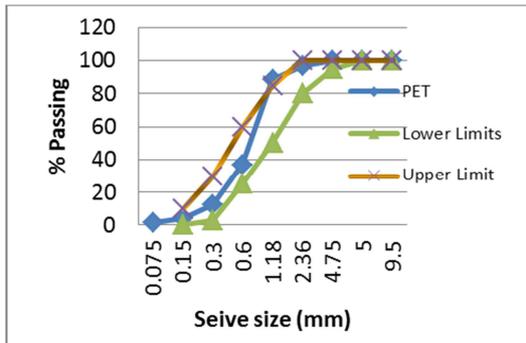


Figure 3. Gradation of WPET

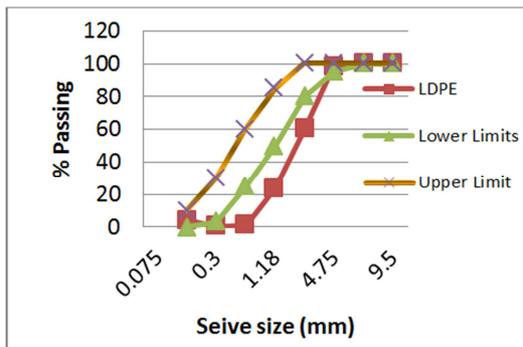


Figure 4. Gradation of WLDPE.

2.1.6. Water

Ordinary Portable water was used for the proportioning of the concrete and met the ASTM C 1602-04 standard. It had a density of 1g/cm³.

2.2. Scope of the Work

The scope of this work was to study the effect (s) of elevated temperature on the mechanical properties of concrete produced by utilizing WPET and WLDPE as partial replacement of sand in the production of concrete blocks. These categories of concrete were categorized as plast-crete.

2.3. Methods

2.3.1. Mix Design Method

The mix design ACI-211.1-91 was utilized the mix design method for the production of the M30 Normal concrete (NC) grade. The water to cement ratio (W/C) was 3.89 and the proportion was 1:1.50:2.58, cement: sand: gravel. The mix design proportion methods are shown in Tables 1 and 2 below. The concrete produced were for mild exposure and the Targeted Mean Compressive Strength (TMCS) was

37.50, targeted air content was about 35% and slump was between 30-75mm to ensure good workability. All materials used in the proportioning of the concrete were utilized in their Surface Saturated Dry (SSD) condition.

Table 1. Mix Design Proportion for WPET Filled Plast-crete.

S/N	% Plastics	Kg/m ³				
		CMT	Water	Sand	PET (×10 ⁻³)	Gravel
1	0	420	163.54	627.93	0.00	1085.80
2	5	420	163.54	616.53	11.30	1085.80
3	10	420	163.54	565.14	22.60	1085.80
4	15	420	163.54	533.73	33.91	1085.80
5	20	420	163.54	502.34	45.21	1085.80
6	25	420	163.54	471.18	56.43	1085.80
7	30	420	163.54	439.55	67.82	1085.80
8	35	420	163.54	408.15	79.10	1085.80
9	40	420	163.54	376.73	90.42	1085.80
10	45	420	163.54	345.36	101.72	1085.80
11	50	420	163.54	313.97	113.02	1085.80

Compacted bulk density WPET=638.98Kg/m³, Compacted bulk density sand=1750kg/m³, Conversion factor=638.98/1750=0.365

Table 2. Mix Design Proportion for WLDPE Filled Plast-crete

S/N	% Plastics	Kg/m ³				
		CMT	Water	Sand	LDPE (×10 ⁻³)	Gravel
1	0	420	163.54	627.93	0.00	1085.80
2	5	420	163.54	616.53	5.24	1085.80
3	10	420	163.54	565.14	10.48	1085.80
4	15	420	163.54	533.73	15.73	1085.80
5	20	420	163.54	502.34	20.97	1085.80
6	25	420	163.54	471.18	27.20	1085.80
7	30	420	163.54	439.55	31.45	1085.80
8	35	420	163.54	408.15	36.70	1085.80
9	40	420	163.54	376.73	41.95	1085.80
10	45	420	163.54	345.36	47.19	1085.80
11	50	420	163.54	313.97	52.43	1085.80

Compacted bulk density WLDPE=291.6Kg/m³, Compacted bulk density sand=1750kg/m³, Conversion factor=291.6/1750=0.167

2.3.2. Casting and Curing

100 mm cubes were casted and utilized for the test elevated temperatures on the compressive strength of the concrete blocks. The concrete with zero plastics served as the control sample while the plast-crete (s) were produced by replacing sand with 10%, 20%, 30%, 40% and 50% waste plastics. The samples were kept in the mould for 24hrs in the laboratory at ambient temperature; the samples were demoulded and cured in water for 28days. The samples were then removed in water and allowed to dry for 24hrs in the laboratory before testing (ASTM C 192).

2.3.3 Heating of the Samples

The samples were then placed in an electric furnace at 100°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, and 800°C. The temperature for each sample was maintained for 3 hours to maintain thermal stability. The heating rate was set at 3.0°C/ min conformed to ASTM C 119-14. The plast-crete was then left to cool at ambient temperature to allow for easy and safe handling.

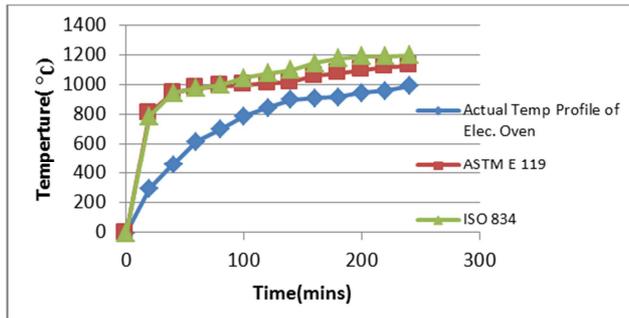


Figure 5. Time-Temperature Curve of the Electric Oven.

2.3.4. Compression Strength (CS) Test

The compression test was then carried out on the 100mm cube using the 3000KN compression testing machine according to ASTM C 39-05 at the rate of 0.30mm/min. Five samples per batch were tested for each temperature range and the average compressive strength was recorded.

$$F_C = P_{\max} / A \quad (1)$$

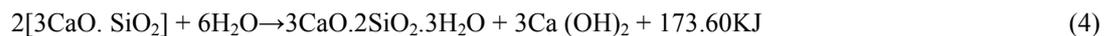
In Equation (1), F_C = compressive strength, P_{\max} = fracture Load applied on cube, A = area of cube

2.3.5. Split Tensile Strength (STS) Test

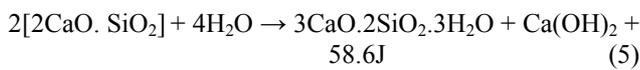
The Split Tensile Strength was carried out on the 100mm×200mm cylinders using the 3000KN compressive testing machine according to ASTM C 496-04 at the rate of 0.30mm/min. five samples per batch were tested for each temperature range and the average split tensile strength was recorded.

$$F_{STS} = 2P_{\max} / \pi DL \quad (2)$$

In Equation (2), F_{STS} = Split tensile strength, P_{\max} = fracture load applied on cylinder, D = Diameter of concrete cylinder,



Dicalcium Silicate + Water → Dicalcium Silicate Hydrate + Calcium Hydroxide Heat



However, there was a sharp decrease in the CS of NC from 400°C – 800°C as a result of the thermal degradation of the aggregate within the concrete as temperature increased [17, 18], due to thermal expansion, these negative effects were complicated by other factors such as additional volume changes caused by variation in moisture content, dehydration, drastic change in chemical composition, disintegration of the (-C-H-S-) structure of the cement gelled paste and spalling in the concrete which contributed to the propagation of micro - cracks and loss of integrity in the NC [14]. There was a sharp decrease of CS of NC from 400°C – 800°C of 10.18%, 24.00%, 65.38%, 79.01% respectively.

There was a gradual decrease in CS of the plast-crete (s) from 100 °C – 400 °C, unlike the NC. The plast-crete (s) showed a continuous decrease in CS in the

L = Length of concrete cylinder.

2.3.6. Percent Weight Loss with Temperature

The percent weight loss with temperature was carried out on the batches for each temperature range and results were recorded.

$$\text{Percent Weight Loss} = (W_1 - W_2) / W_1 \times 100 \quad (3)$$

In Equation (3), W_1 = initial weight before thermal treatment, W_2 = final weight after thermal treatment.

(Note: The average value was recorded after testing all the samples in each of the batches)

3. Results and Discussions

3.1. Compressive Strength

The effects of elevated temperature on the CS of plast-crete are shown in Figure 6 and Figure 7 comparatively with the NC. For the purpose of effective analysis of the study of the temperature profiles were divided into two regimes, 100 °C – 400 °C and 400 °C – 800 °C. The NC showed a gradual increase in CS from 100 °C – 400 °C and a sharp decrease in CS from 400 °C – 800 °C. The increase in CS from 100 °C – 400 °C was as a result of the production of hydration materials such as Tricalcium silicate (C_3S) and Dicalcium Silicate (C_2S) due to an increased rate of hydration reaction between water vapour and unhydrated cement as a result of autoclaving effects. There was an increase in CS from 100 °C – 400 °C of 0.13%, 2.72%, 2.72%, 0.13% respectively.

3.1.1. Chemical Equation for the Production of Hydration Materials in the Concrete

Tricalcium Silicate + Water → Tricalcium Silicate Hydrate + Calcium Hydroxide + Heat

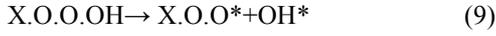
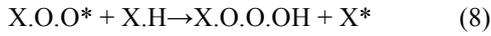
100 °C – 400 °C even though the hydration and autoclave effect took place because the subsequent gain in CS that would have been achieved was nullified as a result of a large amount of voids within the plast-cretes [15]. The CS of the plast -crete decreased further from the 400°C – 800°C. This could also be attributed to the poor interfacial bonding between the plastics and hydrated cement gel, uneven expansion of various components within the concrete which lead to the propagation of microcracks. These reductions in CS was even more pronounced as the quantities of waste plastics increased in the plast-crete (s) from 10% to 50% as shown in Figure 6 and Figure 7. Reduction in CS in the plast-crete from the 400°C – 800°C can also be attributed to the complete melting and thermal degradation of the waste plastic in the plast-crete and also drastic changes in chemical composition as temperature increased [16, 17, 18].

3.1.2. Equation Showing Proposed Thermal Degradation of WPET and WLDPE Utilized in the Plast-Crete

Initiation

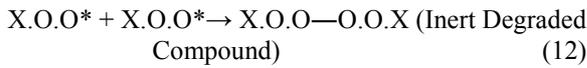
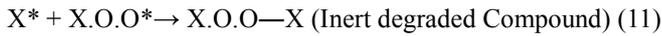
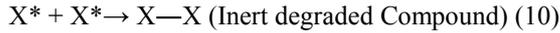


Propagation



Note: X*= Free Radical, any route stated above can initiate thermal degradation of the plastic.

Termination



The WPET plast-crete had a higher CS than WLDPE plast-crete as a result of its higher specific gravity, better thermal stability, and better gradation of WPET aggregate over that of WLDPE aggregate [19, 20]. In addition, WPET plast-crete had lesser voids compared to WLDPE plast-crete. At 10% Waste plastics content, the CS of WPET plast-crete was higher than that of WLDPE plast-crete at the 200°C, 400°C, 600°C and 800°C by 3.71%, 14.29%, 42.29% and 85.71% respectively. The CS of NC was higher than the 10% filled WPET plast-crete at the 200°C, 400°C, 600°C, and 800°C by 11.62%, 1.43%, 14.56% and 25.00% respectively. Similarly, the CS of NC was higher than that of the 10% filled WLDPE plast-crete at the 200°C, 400°C, 600°C, and 800°C by 16.67%, 21.91%, 31.65% and 37.50% respectively.

3.2. Split Tensile Strength

STS is dependent almost on the same factors as CS and are considerably much lower than the CS, however it remains an important factor in the deformation of concrete at elevated temperatures because deformation in concrete is mainly due to tensile deformation and stresses and structural damage to the concrete member in tension influenced by the promotion of microcracks. The STS in Figure 8 and Figure 9 showed that the CS of NC gradually increased from 100°C – 400°C and there was a sharp reduction in the STS from 400°C – 800°C. In the 100°C – 400°C the NC recorded a slight increase in STS of 3.17%, 4.76%, 5.80%, 9.52% respectively. However, from 400°C – 800°C, the NC recorded a sharp reduction in STS of 28.57%, 52.38%, 58.73%, 59.52% respectively. The WPET and WLDPE plast crete (s) showed a gradual decline in STS from 100°C – 400°C, this decrease in STS continued from 400°C – 800°C [21, 22] This decrease in STS in the plast-cretes became more pronounced as the percentage of waste plastics introduced into the plast-crete increased [20]. At 10% waste plastics content, the STS of WPET plast-crete was higher than that of WLDPE plast-crete at the 200°C, 400°C, 600°C, and 800°C by 4.67%, 2.08%, 37.93% and 25% respectively. The STS of NC was higher than the 10% filled WPET plat-crete at the 200°C, 400°C, 600°C, and 800°C by 16.67%, 20.37%, 12.50%,

27.50% respectively. Similarly, the STS of NC was higher than that of the 10% filled WLDPE plast-crete at the 200°C, 400°C, 600°C, and 800°C by 21.50%, 22.87%, 40% and 27.50% respectively [22, 23].

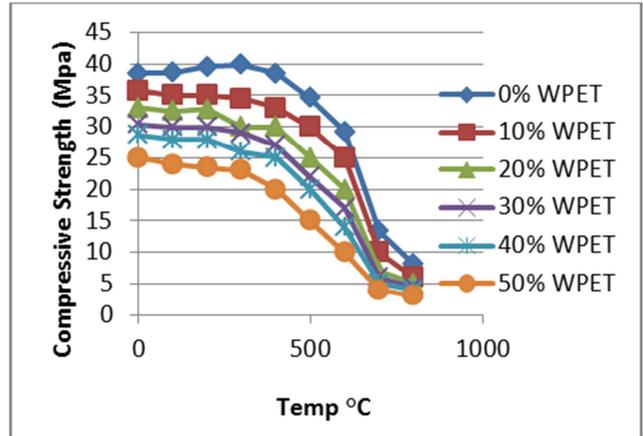


Figure 6. The Effect of Elevated Temperature on the CS of WPET Filled Concrete

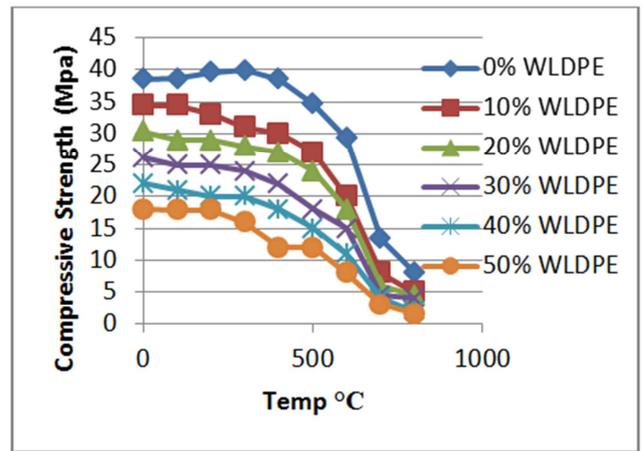


Figure 7. The Effect of Elevated Temperature on the CS of WLDPE.Filled Concrete.

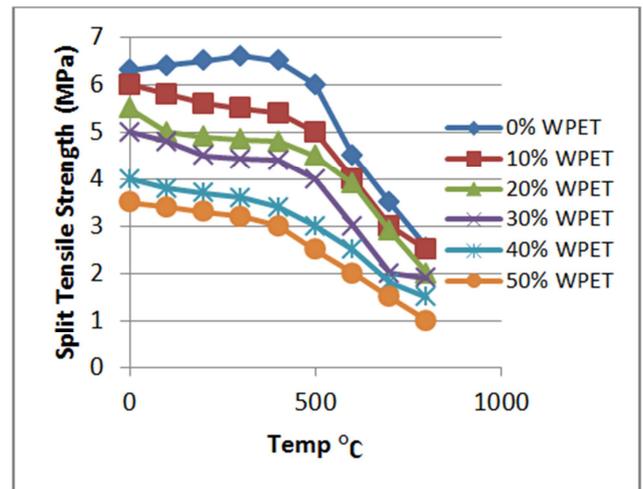


Figure 8. The Effect of Elevated Temperature on the STS of WPET filled Concrete.

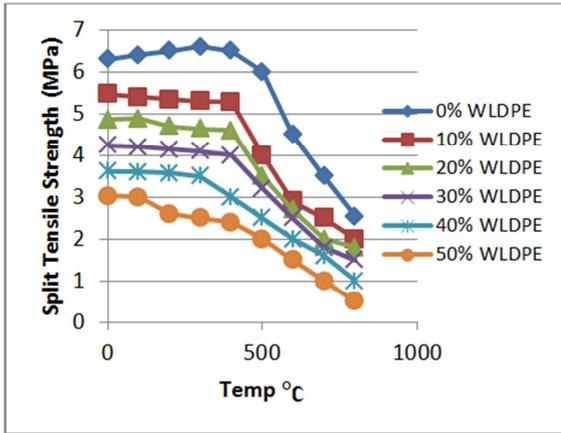


Figure 9. The Effect of Elevated Temperature on the STS of WLDPE filled Concrete.

3.3. Percent Weight Loss

The effect elevated temperature on the percent weight loss of WPET and WLDPE plast-cretes are shown in Figure 10 and Figure 11. There was a gradual percent weight loss of NC from 100 °C – 400 °C. This percent weight loss increased further from 400 °C – 800 °C, (Chitvoranund, Winnefeld, Hargis, Sinthupinyo, & Lothenbach, 2017) There was an increase in percent weight loss for the NC in the 200°C, 400°C, 600°C and 800°C by 0.3%, 0.4%, 1.5% and 2.0% respectively. The increase in percent weight loss of NC as temperature increased was as a result of the following reasons:

3.3.1. Loss of Water

Water evaporates from 100°C; evaporation is faster at the surface due to atmospheric vapour pressure. At 150°C, water in the cement pores and water that are chemically bound are expelled. At about 450°C – 500°C, gelled and capillary water were totally eliminated

3.3.2. Decomposition of Portlandite (Calcium Hydroxide)

This occurred between 450°C – 550°C.



3.3.3. Decomposition of Hardened Cement Paste Gel

The calcium silicate hydrate (-C-S-H-) gel structure of the hydrated cement at temperatures of 500 °C – 600 °C decomposed to produce C₂S [24, 25]

3.3.4. Decarbonization of Lime Stone at Temperature of Between 600°C – 800°C



The WPET and WLDPE plast-crete showed a gradual decrease in percentage weight loss as temperature increased from 100°C – 400°C and from 400°C – 800°C. The weight loss became more pronounced as the percentage of waste plastic content in the Plast-crete increased from 10-50%. Apart from the reasons enumerated above the weight loss of the plast-crete (s) were further enlarged by the melting of the waste plastics causing chain scission, reduced chain length,

and molecular weight. The NC showed a lower percent weight loss than the plast-crete (s). The weight loss of the NC was lower than the 10% filled WPET plast-crete in the 200°C, 400°C, 600°C, and 800°C by 0.67%, 0.63%, 1.33% and 1% respectively. The weight loss of the NC was lower than the 10% filled WLDPE plast-crete in the 200°C, 400°C, 600 °C , and 800 °C by 8.33%, 7.75%, 4.0% and 3% respectively. At the 10% filled waste plastic content, the WPET Plast-crete showed a lower percent weight loss than the WLDPE plast-crete in the 200°C, 400°C, 600°C, and 800°C by 4.6%, 4.38%, 1.14%, and 1% respectively [26, 27].

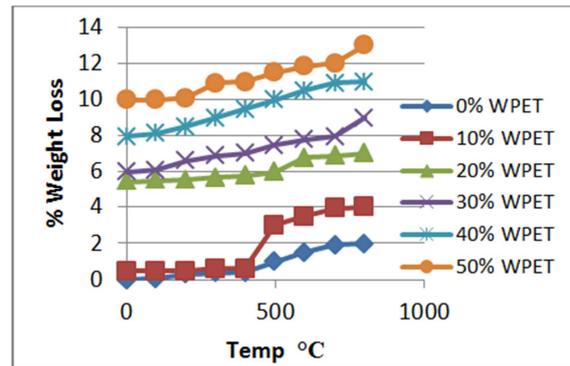


Figure 10. Effect of Elevated Temperature on the Percent weight of WPET Filled Concrete.

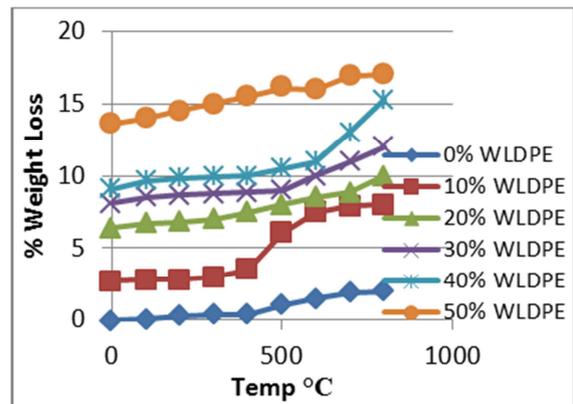


Figure 11. Effect of Elevated Temperature on the Percent Weight of WLDPE Filled Concrete.

3.4. Spalling of Concrete

The amount of spalling noticed in NC was more substantial compared to the plast- cretes, this was because spalling usually began at 190 °C and continued as the temperature increased. In the NC spalling at high temperatures caused internal pressure to build up due to the evaporation of both free and bound water which caused propagation of micro cracks leading to spalling of the NC surface. However, in the plast-cretes; the melted plastics absorbed within the matrix of the plast-crete created a path way where gases (water vapour) that were generated due to heating can easily be released; this reduced the effect of spalling in the plast-cretes [23, 28, 29].



Figure 12. Higher Rate of Spalling in NC at Elevated Temperatures.



Figure 13. Lower Rate of Spalling in Plast-crete at Elevated Temperatures.

4. Conclusion

There was a slight increase in CS and STS of the NC from 100°C – 400°C, but these reduced sharply from 400°C – 800°C. The plast-cretes showed a gradual decrease in CS and STS as the temperature increased from 100°C – 400°C and this trend continued from 400°C – 800°C. WPET filled plast-cretes had the higher compressive strength and split tensile strength than WLDPE filled plast-cretes from 100 °C – 400 °C and 400°C – 800°C. NC had higher CS and STS than the plast-cretes. There was a gradual increase in weight loss of NC as the temperature increased from 100 °C – 400 °C and from 400 °C – 800 °C. The plast-cretes also showed a gradual increase in weight loss as the temperature increased from 100°C – 400°C and from 400°C – 800°C. WPET filled plast-cretes had a lower weight loss than the WLDPE filled plast-cretes from 100 °C – 400 °C and 400 °C – 800 °C. The NC showed a lower weight loss than the plast-cretes from 100°C – 400°C and from 400°C – 800°C [30, 31].

The plast-cretes showed a higher level of resistance to spalling than the NC at elevated temperatures because the melted plastics absorbed into the matrix of the concrete created a pathway for explosive gases to escape through the pores of the concrete rapidly, preventing spalling [32-34].

Despite the reduction in CS, STS and weight loss at elevated temperatures, the plast-cretes still showed a high level of integrity within some practicable temperature limits and can thus, still be utilized in low temperature and moderately high temperature environment such as low cost buildings, pedestrian walkways, slabs, fences, fancy blocks

and light traffic applications. This will go a long way to help recycle waste plastics in the environment.

Authors' Contributions

Engr. Ejiogu Ibe Kevin and Prof. Paul Andrew Mamza; conceived the ideological concepts and designed the methodology, and discussed the results of the work. Prof. Nkeonye. O. Peter; analyzed the data and directed the course for discussion (s) and postulated reasons why the results followed a particular trend. Prof. Yaro. S. A; as Chairman of the professorial shell chair in the University, provided and assisted in the laboratory facilities utilized for the work.

Conflicts of Interest

The authors declared no conflict of interest in this research work.

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