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EVALUATION OF THE SUITABILITY OF LOW-DENSITY POLYETHYLENE (LDPE) WASTE AS FINE AGGREGATE IN CONCRETE

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ABSTRACT
This study evaluates an alternative solid waste management option for Low-Density Polyethylene (LDPE) waste commonly called "pure water sachet" as partial replacement of sand in concrete. Three mix ratios of 1:1:2, 1:1.5:3, 1:2:4 were used while the LDPE waste materials were obtained within University of Lagos campus, in Lagos State of Nigeria. The pulverized LDPE plastic waste, with compacted and uncompacted bulk densities of 362.9 kg/m³ and 403.23 kg/m³ respectively, could be classified as an ultra-lightweight fine aggregate in terms of bulk density. The bulk density of the plastic concretes produced using 1:1:2, 1:1.5:3 and 1:2:4 range between 2417.78-2548 kg/m³, 2348.63-2589.63 kg/m³, 2429.63-2424.6 kg/m³ respectively with corresponding compressive strengths range of 22.64-34.26, 20.47-27.32 and 20.21-27.47 N/mm² and could be classified as normal-weight concrete which meets the minimum compressive strength for use as lightweight aggregate in plain concrete (7N/mm²). The optimum and preferable mix is 1:1:2.

Keywords: *concrete, fine aggregate, fire-resistance, LDPE, plastic waste*

1. INTRODUCTION

Plastics have become an integral part of our daily lives. Plastic consumption and generation of plastic wastes continue to pose environmental concerns globally [1]. Its increased usage could be attributed to its low density, strength, long life, and low cost. Other reasons include its resistance to rusting, flexibility of shape, heat conservation [2].Various uses of plastic include packaging, automotive and industrial applications [3]. With such varying applications, the amount of plastic consumption and resulting wastes generated in the developed countries had witnessed sporadic growth in the last two decades. Plastic consumption in the United Kingdom (UK) in 2003 amounted to 4.7 million tonnes, out of which 3.0 million tonnes ended up as wastes. In the United States of America (US), plastic consumption rate for the period was 26.7 million tonnes with 11 million tonnes ending up as wastes [3]. In addition, annual plastic consumption in Western Europe is approximately 60 million tonnes out of which 23 million tonnes end up as plastic wastes [4] while in India, demand for plastic bottles between 2005 and 2006 was approximately 20 trillion [5].

Worldwide, plastic products contribute substantially to an ever increasing volume of municipal solid waste (MSW) streams. Globally, it constitutes 7-9% of MSW, 15-25% in Europe [6], 7% in UK [7] and 2% in Lagos State, Nigeria [8]. In US, the highest tonnage in plastic MSW is containers and plastic packages [9, 10]. In Europe, packaging represents 37.2% of all plastics consumed and 35% worldwide [11].

Recycling of plastic wastes is difficult owing to its commingled nature and the difficulty in identification, separation and classification [12, 13, 14]. The common practice of landfilling is becoming unattractive owing to the inert nature and poor biodegradability of plastic wastes [15, 16], its high volume to weight ratio [12], decreasing landfill space and its increasing cost [17, 3; 18]. Likewise, incineration of plastic wastes in landfills results in environmental concerns such as CO_2, NOx (nitrogen oxides), SOx (sulphur oxides), volatile organic compounds, smoke, heavy metals, polychlorinated dibenzofurans and polycyclic aromatic hydrocarbons which are carcinogenic [1].

Most of the current management approaches to address the problems of plastic wastes are uneconomical and include re-extrusion (primary),

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mechanical treatment (secondary, which includes recycling and re-use), chemical treatment (tertiary) and energy recovery (quartenary) [1; 9; 3]. Diversion of plastic wastes from landfills will lead to reduction in total solid waste collection costs and its recycling in form of new products will help to conserve limited resources, alleviate environmental pollution and create job opportunities [15].

The plastic wastes emanating from poorly disposed pure water sachet, a Low-Density Polyethylene (LDPE), used in packaging water in Nigeria, are found as litters on streets, roads and highways in major cities of Nigeria such as Lagos State, Ibadan, Port Harcourt, [20, 8, 21] and their accumulation contribute to local flooding owing to blocked drainages [22]. The current plastic recycling rate of Lagos Waste Management Authority (LAWMA) in form of waste bins is insignificant to reduce LDPE wastes generated in Lagos metropolis. Hence, this research intends to proffer another alternative to recycle the LDPE plastic wastes in concrete.

2. LITERATURE REVIEW

The paper [23] investigated expanded polystyrene granules as coarse aggregate (CA) in concrete while 24] recycled rubber tyre in concrete and [25, investigated high-density polyethylene (HDPE) in concrete. [2] studied the effect of increase in temperature on glass-reinforced plastics while [26] investigated groundnut shell as fine aggregate (FA) in concrete. [27] highlighted the uses and properties of foamed aerated concrete while [28] used a model to obtain an optimum mix of 1:1:2 for laterized concrete compared to other mix ratios such as 1:2:4, 1:1.5:3, 1:3:6, 1:1.5:3. [29] and [30] studied periwinkle shell and palm kernel shell as aggregate in concrete while [31] investigated pulverized sewage sludge ash in concrete. In [32] structural characteristics of laterized concrete at optimum mix ratio of 1:1:2 was investigated.

3. OBJECTIVES OF STUDY

The objectives of this study are itemized as follows:

i. Highlight the various classifications of lightweight aggregate (LWA) and other aggregates found in literature
ii. Highlight the various classifications of concrete
iii. Classify the pulverized LDPE into the appropriate classification
iv. Evaluate the use of pulverized LDPE plastic wastes in concrete as an alternative solid waste management option viz a viz results obtained for normal compressive strength (CS), normal bulk density (BD), fire-resistant compressive strength (FRCS) and fire-resistant bulk density (FRBD)

3.1 Lightweight Aggregate

There is widespread disparity on the classification of LWA especially for use in concrete. Some literatures are highlighted while an attempt is made to reclassify LWA in order to bridge the observed gaps. [33] defined FA as an aggregate with grain size less than 5mm and CA as aggregate with grain size > 5mm. It classified FA into three groups namely: fine FA, medium FA and coarse FA as shown in Table 1. In addition, it specified the maximum limit of 4% and 10% for the fine content for both coarse and fine natural aggregates respectively as shown in Table 2.

Table 1. Grading of Fine Aggregates [33]

Sieve Size	% by mass passing test sieves			
	Overall limits	Limits for grading		
		Coarse (C)	Medium (M)	Fine (F)
10mm	100	-	-	-
5mm	89-100	-	-	-
2.36mm	60-100	60-100	65-100	80-100
1.18mm	30-100	30-90	45-100	70-100
600 μm	15-100	15-54	25-80	55-100
300 μm	5-70	5-40	5-48	5-70
150μm	0-20	-	-	-

Table 2. Limits for fines content [33]

Aggregate type		Maximum % by mass
Coarse aggregates		4
Fine natural aggregates	Class I	10
	Class II	≤1.4

Article [34] specified that loose bulk density of LWA should be less than 1200 kg/m^3 while the particle density (PD) must be ≤ 2000 kg/m^3. This is in accordance with what was recommended in [35] for LWA. It also recommended that normal-weight aggregate (NWA) should have an oven-dry PD between 2000 kg/m^3 and 3000 kg/m^3.

On the other hand, [36] classified LWA into two groups namely: fine LWA and coarse LWA. Fine LWA are expected to have a dry loose density of ≤ 1120 kg/m^3 and 85-100% passing 5mm test sieve. Coarse LWA are expected to have a dry loose weight of ≤ 880 kg/m^3 with 100% passing designated maximum size sieve. It recommended size ranges of 5-19mm for structural coarse LWA and 2.5-10mm for medium coarse LWA.

Furthermore, [37] recommended that NWA should have a BD of 2300-2400 kg/m^3 while heavyweight aggregate (HWA) should have a BD greater than 3200 kg/m^3.The grading requirement for LWA recommended by [38] is presented in Table 3.

Table 3. Grading requirements for lightweight aggregates for structural concrete [38]

Size Designation	% Mass passing test sieves				
	4.75mm	2.36mm	1.18mm	300μm	150 μm
4.75mm -0	85-100	-	40-80	10-35	5-25

The fineness modulus (FM) of 2.3-3.1 is required of fine aggregate by [39]. In terms of size, [24] classified aggregate as fine when the particle size is less than 6.3mm while [40] specified a size range of 0.063-2mm for FA (sand). According to [41], aggregates in concrete can be classified into five main groups namely: ultra-lightweight (ULW), lightweight (LW), structural lightweight (SL), normal-weight (NW) and heavy-weight (HW) concretes based on density as shown in Table 4.

Furthermore, [42] specified a range of 2.4-2.9 as the bulk specific gravity for NWA while [41] specified a range of 3.4-7.8 for the specific gravity for HWA.

3.2 Classification of Concrete

The paper [36] classified lightweight concrete (LC) into three groups namely: low-density concrete (LDC), moderate-strength concrete (MDC) and structural lightweight concrete (SLWC) as shown in Table 5.

On the other hand, [35] classified concrete into three classes namely: lightweight concrete (LWC), normal concrete (NC), and heavy-weight concrete (HWC) as shown in Table 6.

It further sub-divided LWC into six classes namely: D1.0, D1.2, D1.4, D1.8 and D2.0 as shown in Table 7.

Also, [35] recommended a minimum CS_{28} of 9 N/mm^2 for LWC and a minimum CS_{28} of 10 N/mm^2 for NC and HWC. Minimum CS of 3.5N/mm^2 and 7N/mm^2 are required by [43] and [44] respectively for LWC. [45] required a minimum CS of 15N/mm^2 for concrete to be used as reinforced concrete (RC) and a minimum CS of 7 N/mm^2 for plain concrete (PC). Likewise, a minimum CS of 3.45N/mm^2 is required by [46] for any material to be used for both load-bearing (LB) and non-load bearing (NLB) purposes. [47] specified that NLB concrete should have a density range of 800-1200 kg/m^3.To enhance easy classification of concrete based on BD taking into consideration all the earlier classifications given above and in order to bridge the observed gaps, a new classification is proposed as shown in Table 8 depicting eight types of concrete.

Table 4: Density classification of concrete aggregates [41]

Category	Bulk density of dry-rodded aggregate	Bulk density of Concrete (kg/m^3)	Typical concrete strength (N/mm^2)	Typical applications
Ultra lightweight	< 500	300-1100	< 7	Non-structural
Lightweight	500-800	1100-1600	7-14	Insulating materials
Structural lightweight	650-1100	1450-1900	17-35	Masonry units & structural
Normal weight	1100-1750	2100-2550	20-40	Structural
Heavyweight	>2100	2900-6100	20-40	Radiation shielding

Table 5. Classification of lightweight concrete [36]

Properties	Classes of Lightweight Concrete		
	Low-density	Moderate-strength	Structural concrete
Bulk density (kg/m^3)	320-800	801-1349	1350-1920
Compressive strength (N/mm^2)	0.69-6.89	6.90-17.23	17.24-41.36

Table 6. Classification of concrete by density [35]

Types of concrete	Oven-dry density (kg/m^3)
Lightweight concrete	800-2000
Normal-weight concrete	2001-2600
Heavyweight concrete	>2600

Table 7. Classification of lightweight concrete by density [35]

Density class	Density range
D1.0	800-1000
D1.2	1001-1200
D1.4	1201-1400
D1.6	1401-1600
D1.8	1601-1800
D2.0	1801-2000

Table 8. Proposed classification of concrete based on bulk density

Type of concrete		Bulk density
Ultra-lightweight		300-500
Lightweight		500-800
Moderate –strength lightweight		800-1350
Structural lightweight		1350-2000
Normal-weight		2000-2600
Heavyweight	Moderate-high density	2600-2900
	High-density	2900-6100
	Ultra-high density	>6100

Article [48] gave three classifications for concrete based on CS namely: low-strength concrete (LSC), normal-strength concrete (NSC) and high strength concrete (HSC) as shown in Table 9.

Table 9. Classification of concrete based on compressive strength [48]

Class	Compressive strength (N/mm^2)
Low-strength	<15
Normal-strength	15-20
High-strength	75-115

Article [49] also classified concrete into three groups namely: LSC, moderate-strength concrete (MSC) and HSC as shown in Table 10.

Table 10. Classification of concrete based on compressive strength [49]

Class	Compressive strength
Low-strength	<20
Moderate-strength	20-40
High-strength	>40

In addition, [50] defined ultra-HSC as concrete with CS greater than 150N/mm^2. On the other hand, [51] defined ultra-high performance concrete (UHPC) as concrete with CS greater than 140N/mm^2.

3.3 Classification of Pulverized LDPE plastic wastes

Article [52] gave four classifications for polyethylene based on specific gravity (SG) namely; low-density (LD), moderate density (MD), high density (HD) and ultra-high density (UHD) polyethylene as shown in Table 11. The pulverized LDPE plastic waste had a SG of 0.92 and can be classified as LDPE since its SG falls within the range of 0.91-0.925 for LDPE and is close to the mean SG of 0.9215 specified for LDPE in [53].

Table 11. Classification of Polyethylene [52]

ASTM Test	D792
Property	Specific gravity
Low-density	0.91-0.925
Medium density	0.926-0.940
High density	0.941-0.965
Ultra-high density	0.928-0.941

Therefore, the density of pulverized LDPE is 920 kg/m^3. Since the uncompacted BD and compacted BD of pulverized LDPE are 362.903 kg/m^3 and 403.226 kg/m^3 respectively, it can be classified as ultra-lightweight aggregate (ULWA) based on classification of aggregates shown in Table 4. Likewise, based on [36] classification, it is a fine lightweight aggregate (FLWA) since its bulk densities, both compacted and uncompacted, are less than 1120 kg/m^3 specified for FLWA.

4. MATERIALS

The materials used in this study include cement, sand, granite, water and LDPE in various proportions used to replace sand.

4.1 Cement

Cement used was Ordinary Portland Cement obtained from Bariga market in Lagos State, Nigeria. The cement was produced in accordance with [46].

4.2 Fine aggregate (River Sand)

The sand used as the main FA was river sand obtained from an upland source of Ogun River in Ogun State, Nigeria to ensure that it has low chloride content and organic impurities. 100% of the sand passed 6.3 mm test sieve in accordance with [54].

4.3 Coarse aggregate (Granite)

Crushed granite was obtained from a quarry in Ogun State with a maximum size of 6.3 mm and a nominal size of 5 mm. The grading was done in accordance with [54]. It has a maximum size of 38.1 mm and a nominal size of 25.4 mm.

4.4 Pulverized LDPE Plastic Wastes

The pulverized LDPE plastic wastes (PLDPE) are derived from disposed waste sachets used for packaging water popularly known as "pure water". The sachet wastes were collected from eating and residential joints within University of Lagos campus, Akoka, Lagos State of Nigeria. They were collected in rice and bean sacks, cleaned with clean tap water to remove any form of contaminants and deleterious materials and sun dried for a minimum of three days. The dried wastes were transported in an open van to a milling company where they were pulverized into granules. The PLDPE wastes were sieved with 2 mm test sieve with sieve number 10 to obtain FA. The 2 mm test sieve is within the upper size limits of 4.75mm, 6.3 mm and 2.0 mm specified for FA by [38, 24 and 40] respectively. Laboratory tests were carried out on the granules and the concrete produced at Concrete Laboratory in Department of Civil Engineering, University of Lagos, in Lagos State of Nigeria.

4.5 Water

The tap water obtained from the Concrete Laboratory in Department of Civil Engineering was used to clean the LDPE sachets wastes before pulverization, in mixing and preparing the concrete cubes and in curing the prepared concrete cubes. The water is clean, free of deleterious materials and portable and satisfies the requirement for water according to [55].

5. METHODS

The laboratory tests carried out on the pulverized LDPE plastic wastes, sand, granite, cement and concrete in accordance with respective standards are listed in Table 12.

Table 12. Laboratory tests and respective Standards

S/N	Name of Tests	Material concerned	Standards
1	Concrete proportioning	Pulverized LDPE waste, sand, granite, cement,	ACI 211-2 (1998)
2	Chemical Analysis	Pulverized LDPE plastic waste	API (1998)
3	Grading Analysis	Pulverized LDPE plastic waste, sand, granite	EN 933-1(2009)
4	Compacted and uncompacted Bulk	Pulverized LDPE plastic waste	ASTM C29 (2003)
5	Specific gravity	Cement, sand, granite	ASTM D854 (2000)
6	Specific gravity	Pulverized LDPE plastic waste	ASTM D792 (2008)
7	Bulk density	Concrete	EN 12390-7 (2009)
7	Compressive strength	Concrete	BS 12390-3(2009)
8	Fire-resistant tests	Concrete	EN 1365-2 (1999)

Table 13. Concrete material proportions used in the laboratory experiment

mix ratio	Materials (kg)					water-cement ratio
	Sand	Granite	Cement	Water	PPWSW	
1:1:2	2.24	4.63	2.70	1.60	0.00	0.50
	2.13	4.63	2.70	1.60	0.11	0.60
	2.01	4.63	2.70	1.60	0.22	0.60
	1.90	4.63	2.70	1.60	0.34	0.48
1:1.5:3	2.44	5.04	1.93	1.20	0.00	0.50
	2.32	5.04	1.93	1.20	0.12	0.50
	2.20	5.04	1.93	1.20	0.24	0.50
	2.07	5.04	1.93	1.20	0.37	0.50
1:2:4	2.56	5.29	1.52	0.91	0.00	0.54
	2.43	5.29	1.52	0.91	0.13	0.60
	2.30	5.29	1.52	0.91	0.38	0.74
	2.18	5.29	1.52	0.91	0.40	0.87

5.1 Concrete material proportioning

From survey of some literatures [24-26, 28-32, 56], three concrete mix ratios of 1:1:2, 1:1.5:3 and 1:2:4 were selected because they achieved the highest CS_{28} performance for earlier experiments obtained for other waste products such as rice husk ash, HDPE, periwinkle shells, groundnut shells and laterite. Batch-by-volume approach was adopted in this research to calculate the masses of the various constituents of the concrete in accordance with [57] and is presented in Table 13.

The percentage (%) replacements of sand in the concrete with pulverized LDPE wastes were 0%, 5%, 10% and 15%. Concretes with 0% LDPE served as control for the respective concrete mix ratios. Variable W/C ratios were used ranging between 0.48-0.87. Weighed amount of water was continuously added to obtain a workable concrete using manual method.

5.2 Chemical analysis

Chemical tests on the pulverized LDPE plastic wastes were carried out in accordance to [58] at Environmental Resources Limited, Warri, Delta State of Nigeria using atomic absorption spectrophotometer (AAS).

5.3 Grading analysis

The grading analysis was carried out on sieved pulverized LDPE plastic wastes, sand and granite in accordance to [54] to determine their particle size distribution and their appropriate classification based on available standards. The test sieve arrangements (typically ranging between 60mm and 75μm) covered with a lid was shaken mechanically for a period of 5-10 minutes.

5.4 Compacted and uncompacted bulk density

The compacted and uncompacted bulk densities of the pulverized LDPE plastic wastes were determined in conformity to [59]. Average of three values obtained using different representative samples of the LDPE waste gives the average uncompacted and uncompacted bulk densities of the LDPE waste.

5.5 Specific gravity

The specific gravities of cement, sand, granite and water were determined in accordance to [60] while SG of the pulverized LDPE plastic material was determined in accordance with [53].

5.6 Bulk density

The BD of the concrete cubes was determined in accordance with [61]. The concrete cubes were cast manually using material proportioning given in Table 9. The steel moulds to be used were assembled and lubricated prior to casting for easy removal of the concrete cubes. Each prepared concrete was poured into lubricated steel moulds of size 150mm x 150mm x 150mm in three equal layers, with each layer rodded thirty-five times with 25mm rod to ensure compaction of the concrete constituents and leveled off with a trowel. The concrete cubes were demoulded after twenty-four hours and completely submerged in water in a water tank for curing purposes in accordance with [62]. After the concrete cubes were cured in water for 7, 14, 21, 28 days, they were sun dried and weighed using Avery weighing machine and the respective weights were recorded. The weight of each concrete cube divided by the known volume of the concrete cube, which correspond to the volume of the cube moulds gives the BD at that curing age. Three representative samples were tested for BD at each curing age and the average value gives the average bulk density for the respective curing age. To obtain the FRBD for different % LDPE replacements, three samples were prepared for each % LDPE replacements. They were water-cured for 28 days, sun dried and their bulk density determined prior to fire-testing and after being fire-tested. A total of 144 concrete cubes were tested for normal bulk density (BD) while a total of 72 concrete cubes were tested for 28^{th}-day fire-resistant bulk density ($FRBD_{28}$).

5.7 Compressive strength

The CS for all the concrete cubes was determined in accordance with [63] and each concrete was prepared in accordance to mix proportion in Table 13. Three samples for each curing age and three samples for each % LDPE replacement were tested. A total of 144 concrete cubes were tested for normal compressive strength (CS) while a total of 36 concrete cubes were tested for 28th-day fire-resistant bulk density ($FRCS_{28}$). The CS of each cube was determined on 600KN Avery Denison Universal Testing Machine at a loading rate of 120 KN/min which complies with the requirements of [64]. Three specimens for each of the curing ages and also for each % LDPE replacements were tested to failure by crushing and the maximum load recorded. The maximum load divided by the area of each specimen gives the CS of that sample. The average of the CS for three specimens was taken as the CS at that curing age and also for each % LDPE replacements. A total of three hundred and fifty concrete (350) cubes were cast and tested for BD, CS, $FRBD_{28}$ and $FRCS_{28}$.

5.8 Fire-resistant tests

Fire-resistant tests were carried out in accordance to [48]. At temperature greater than 500^0C, a significant reduction in CS occurs in concrete. Factors influencing such reductions include temperature reached during heat exposure, characteristics of the concrete and the loading conditions during the period of temperature rise. Structural concrete is required to maintain structural action when exposed to heat or fire over a desired length of time known as fire rating. Hence, the respective concrete cubes were burnt in fire at temperature of 500^0C in a gas furnace for one hour at Federal Institute of Industrial Research Oshodi (FIIRO), in Lagos State of Nigeria. The $FRBD_{28}$ and $FRCS_{28}$ were determined for each concrete cube at 0-15% LDPE replacements of sand in concrete after cooling. The ratio of strength after burning to strength before heating gives a measure of the resistance of the concrete to fire.

6. EXPERIMENTAL RESULTS AND DISCUSSION

6.1 Chemical analysis

The chemical analysis indicated that pulverized LDPE plastic wastes do not pose any environmental threat in terms of heavy metals as shown in Table 14.

Table 14. Heavy metals in Pulverized Low-Density Polyethylene (LDPE) Plastic Wastes

Metal	Hg, Fe, Cu, Zn, Al, Ni, V, Cd, As, Co, Mn
Content (ppm)	<0.001

The metals tested were below detection limit of 0.001 ppm of the equipment used as shown in Table 14. On the other hand, total hydrocarbon content (THC) tests revealed that the LDPE wastes contain a high THC of 73.89 ppm using hexane extraction and gave 0.25 ppm (THC) with water extraction. This shows that hexane is a better organic solvent compared to water and that plastic concrete should not be used where there is high exposure to organic solvent to avoid dissolution of the plastic content into the environment.

6.2 Grading analyses

The results of the physical properties for sand, pulverized LDPE plastic waste and granite are presented in Table 15. Figures 1 and 2 showed the particle size distribution for sand and pulverized LDPE plastic waste.

Table 15. Physical properties of sand, pulverized LDPE plastic waste, cement and granite

Property	Cement	Sand	Pulverized LDPE plastic waste	Granite	ASTMC33 (2001)	ACI (1999)	ASTM C330 (1999)
Cu		2.9	2.52	1.34			
Cc		1.0	1.0	1.17			
F.M.		0.605	0.911	19.76	2.3-3.1		
Maximum.size		< 6.3	2	25.4		19	
Bulk Density			363.9-403.23				1120 max.
% Passing 1.18mm		73.7	44.5				40-80
% Passing 5mm		99.4	100				
Specific gravity	3.15	2.65	0.92	2.74			

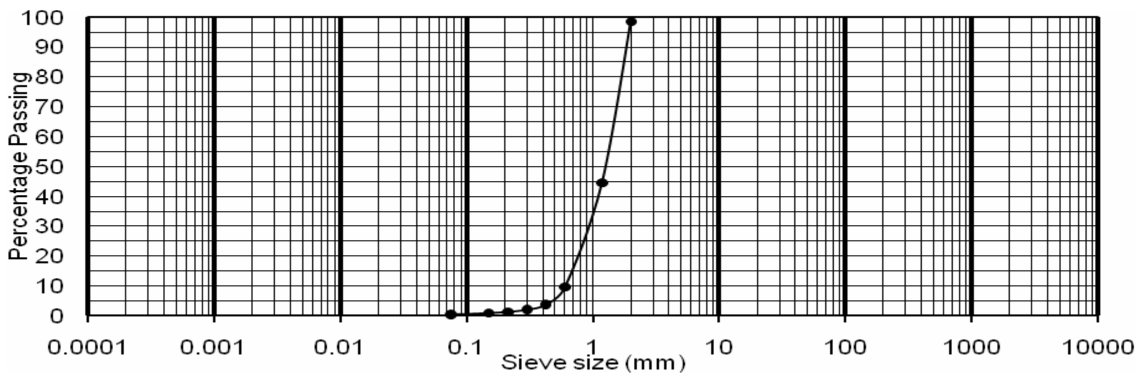

Figure 1. Particle size distribution curve for pulverized LDPE plastic waste

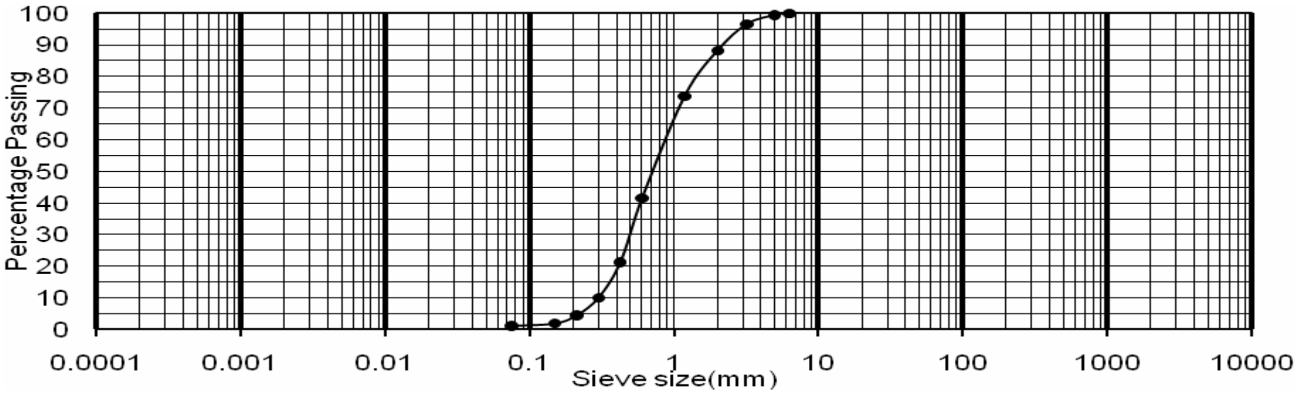

Figure 2. Particle size distribution curve for sand

In line with Table 15, Figure 1 showed that the maximum size of the LDPE granules was approximately 2mm while Figure 2 showed that the river sand was better distributed and had a maximum size less than 7mm.

The river sand had coefficients of uniformity (C_u) and curvature (C_c) of 2.9 and 1.0 respectively as shown in Table 15. The C_c value is within the range of $1 \leq Cc < 3$ recommended for sand but below the Cu value of ≥ 6 recommended for sand by [65]. Hence, it is classified as poorly-graded clean sand according to [65] as shown in Table 16.

The pulverized LDPE also had a C_u of 2.52 and a C_c of 1.0 as shown in Table 15. The C_c value is within the recommended range of $1 \leq Cc < 3$ but below the C_u value of ≥ 6 recommended for sand. Hence, the pulverized LDPE plastic waste can be classified as poorly-graded FA. In terms of FM, sand and pulverized LDPE had FM of 0.605 and 0.911 respectively both of which are below the FM range of 2.3-3.1 recommended by [39] for FA.

However, [42] stated that some natural sands may have FM that is outside the given range. The granite had a C_u of 1.34 and a C_c of 1.17. The C_u is less than the recommended value of ≥ 4 for gravel but within the recommended range of $1 \leq Cc < 3$ for Cc recommended by [65] in Table 16. Hence, it is classified as poorly-graded granite. In the research carried out by [40] on aerated concrete as LWC, river sand was also used. The river sand with specific gravity of 2.59, C_u of 2.0, C_c of 1.2 and FM of 1.89 was used to produce LWC with density range of 1662.78-1714 kg/m^3 and CS ranging from 13.89-17.96 N/mm^2. The % fines for the river sand and pulverized LDPE are 1.1% and 0.5% respectively. Hence, they can be classified as clean poorly-graded sand and clean poorly-graded pulverized LDPE plastic waste since their % fines are less than 5% as specified by [65] in Table 16 and FA of Class II since the % fine is < 1.4 specified by [33] as shown in Table 2. Likewise, the granite used has % fine of $< 1.19\%$ and can be classified as clean, poorly graded granite.

In terms of SG, the specific gravities of sand 2.65 and granite 2.74 are within the range of 2.4 and 2.9 recommended by [42] for natural, NWA and 2.5-3.0 recommended by [66]. Hence, they are suitable for use in concrete work. However, the SG of pulverized LDPE was below the recommended range being an ULW manufactured aggregate with compacted and uncompacted bulk densities of 362.90 and 403.23 kg/m^3, both of which are less than 500 kg/m^3 specified for ULWA by [41] as shown in Table 4.

Table 16. Classification of sand with 50% or more passing 4.75 mm sieve [68]

Sand content	Grading requirements	Symbol	Group Name
Clean sands with < 5% fines	$Cu \geq 6$ & $1 \leq Cc < 3$	SW	Well-graded sand
	$Cu < 6$ &/or $1 \geq Cc > 3$	SP	Poorly-graded sand
Sand with 5-12% clay fines	$Cu \geq 6$ & $1 \leq Cc < 3$	SW-SC	Well-graded sand with clay
	$Cu < 6$ &/or $1 \geq Cc > 3$	SP-SC	Poorly-graded sand with clay
Sand with 5-12% silt fines	$Cu \geq 6$ & $1 \leq Cc < 3$	SW-SM	Well-graded sand with silt
	$Cu < 6$ &/or $1 \geq Cc > 3$	SP-SM	Poorly-graded sand with silt
Sand with > 12% fines	Fines classified as CL or CH	SC	Clayey sand
	Fines classified as ML or MH	SM	Silty sand

This was also experienced by [26] who researched on groundnut shell as FA in concrete. The grounded groundnut shell had a BD of 254.55 kg/m^3 and was used to replace sand from 5% to 75% replacement to produce LWC with corresponding density range from about 910 kg/m^3 to 200 kg/m^3 respectively. Based on the above results, the pulverized LDPE is suitable for use as FA in concrete. However, in order to improve the C_c and C_u parameters to meet the recommended values, a higher sieve size is recommended to be used in sieving the pulverized LDPE plastic waste.

6.3 Evaluation of Plastic LDPE concrete

6.3.1 Normal compressive strength and Fire-resistant compressive strength

Results showed in Figures 3, 4 and 5, revealed that the CS increased with curing age for all the concrete mix ratios 1:1:2, 1:1.5:3 and 1:2:4 but decreased linearly with increasing plastic(LDPE) content. 1:1:2 and 1:1.5:3 showed decrease in CS_{28} with increasing plastic content while 1:2:4 experienced a sharp decrease in CS_{28} at 5% LDPE and then a continuous increase in CS_{28} with increasing plastic content as shown in Figure 6.

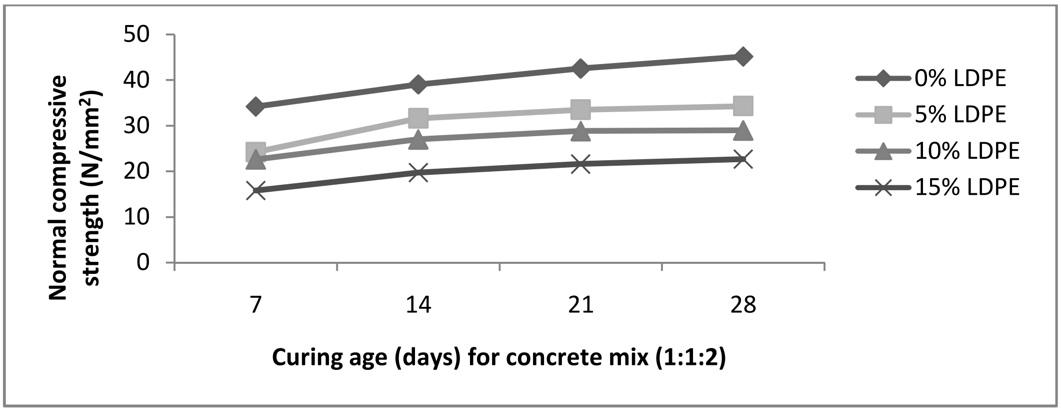

Figure 3. Compressive strength for concrete mix (1:1:2) at different curing ages

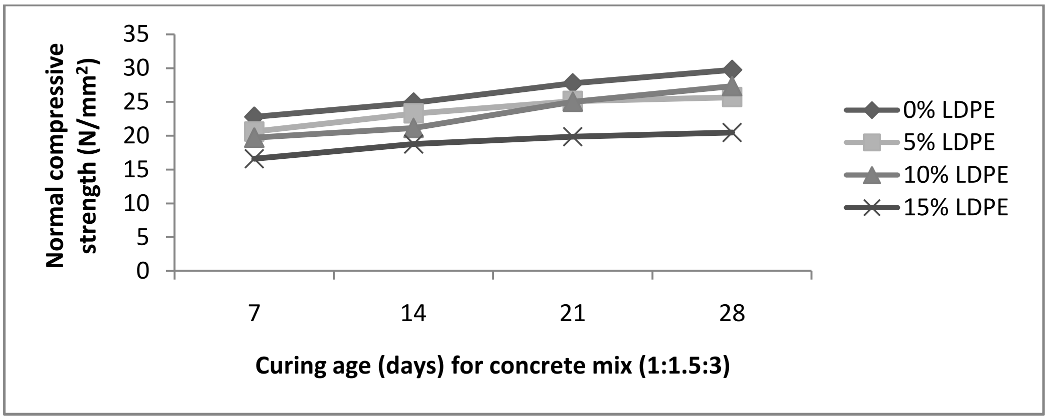

Figure 4. Compressive strength for concrete mix (1:1.5:3) at different curing ages

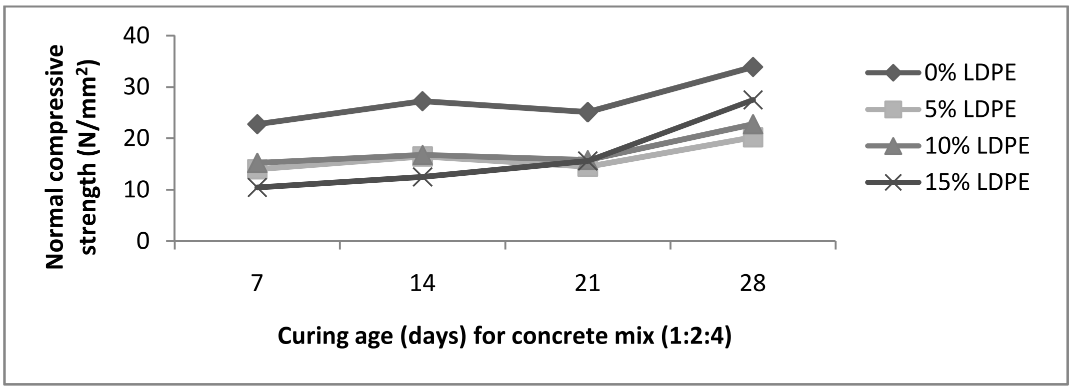

Figure 5. Compressive strength for concrete mix (1:2:4) at different curing ages

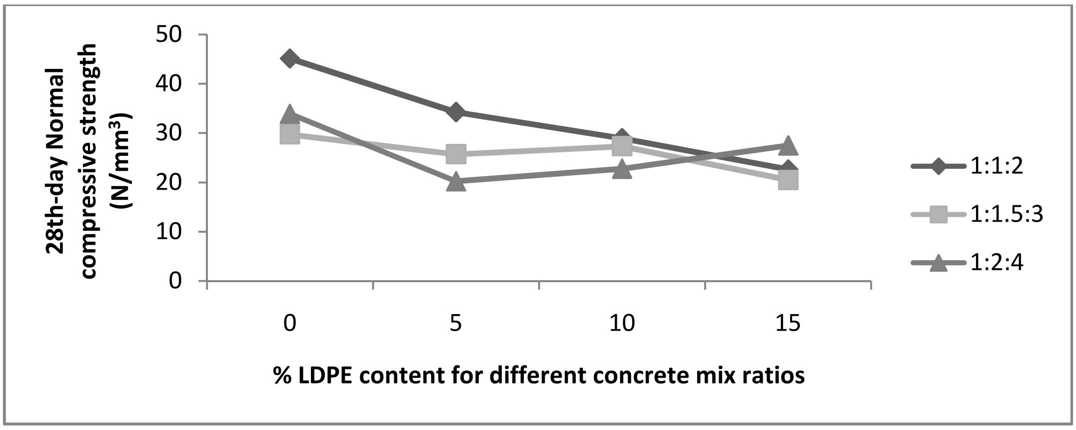

Fig 6. Normal compressive strength at 28 curing days for 0-15% LDPE replacements

The reason for this behaviour is that concrete mix ratio 1:2:4 had the highest coarse aggregate to cement (CA/C) ratio and hence the highest amount of void and porosity, which gives it the capacity to absorb more water and more LDPE to fill up the voids. The results also showed that the CS of the three plastic concrete mix ratios with 0-15% sand replacements with pulverized LDPE plastic wastes far exceeded the minimum required CS of 7 N/mm^2 for normal LWC specified by [45]. Controls (0% LDPE) had the highest CS in all the three mix ratios. For concrete mixes of 1:1:2 and 1:1.5:3, 15% LDPE concrete obtained the lowest CS at all curing ages. The reduction in CS is caused by increase in concrete porosity with increasing plastic content, which increases water absorption (WA) of the concrete leading to decrease in CS. These reductions in CS were corroborated by the results obtained by [5, 23, 26 and 67]. Concrete mix ratio 1:1:2 had the highest CS_{28}, of 45.12, 34.26, 28.94 N/mm^2 corresponding to 0%, 5%, 10% sand replacement with LDPE respectively, for all the three concrete mix ratios while concrete mix ratio 1:2:4 had the highest normal CS_{28} of 27.47 N/mm^2 at 15% LDPE replacement followed by mix ratio 1:1:2 with CS_{28} of 22.64 N/mm^2.

The CS_{28} of 26.55 N/mm^2 obtained by [23] with 5% polystyrene is less than the CS_{28} of 34.26 N/mm^{2}obtained at 5% LDPE for 1:1:2 and CS_{28} of 25.69 N/mm^2) for 1:1.5:3 but greater than CS_{28} of 20.21 N/mm^2 obtained at 5% LDPE for 1:2:4. Also, the CS_{28} of 21.01 N/mm^2 obtained at 10% polystyrene content by [23] was less than the CS_{28} of 28.94 N/mm^{2}obtained at 10% LDPE for 1:1:2 , CS_{28} of 27.32 N/mm^2 obtained for 1:1.5:3 and CS_{28} of 22.76 N/mm2 obtained for 1:2:4. With concrete mix ratio 1:2:3 and 0.5 W/C, the CS_{28} of 40.59 N/mm^2 obtained by [59] at 5% replacement of sand with grinded groundnut shell is greater than the CS_{28} obtained for all the three mix ratios: 34.26 N/mm^2 for 1:1:2, 25.69 N/mm^2 for 1:1.5:3 and 20.21 N/mm^2 for 1:2:4. At 15% replacement, [26] obtained CS_{28} of 21.33 N/mm^2 which is less than CS_{28} of 22.64 N/mm^2 and 27.47 N/mm^2 obtained for 1:1:2 and 1:2:4 respectively at 15% LDPE, but higher than CS_{28} of 20.047 N/mm^2 obtained for 1:1.5:3 at 15% LDPE. The ranges of CS_{28} of 22.64-34.26 N/mm^2 for 1:1:2, 20.47-27.32N/mm^2 for 1:1.5:3 and 20.21-27.47 N/mm^2 for 1:2:4 were higher than the CS_{28} of 13.89 and 15.43 N/mm^2 for water and air-curing respectively obtained by [27] using aerated LWC. The CS_{28} of 21.72 N/mm^2 obtained by [24] using concrete mix ratio of 1:1.5:3 for 10% rubber content was lower compared to the CS_{28} of 28.94, 27.32 and 22.76 N/mm^2 obtained at 10% LDPE for the three concrete mix ratios 1:1:2, 1:1.5:3 and 1:2:4 respectively. The CS_{28} of 21.72N/mm^2 obtained at 5% rubber tyre content was lower compared to the CS_{28} of 34.26 N/mm^2 and 25.69 N/mm^2 obtained for both 1:1:2 and 1:1.5:3 respectively but higher than CS_{28} of 20.21 N/mm^2 obtained for 1:2:4 at 5% LDPE. Similarly, the CS was also found to decrease with increasing rubber content as shown in Figure 6.

The LDPE plastic concrete produced with 5-15% LDPE replacement of sand can be classified as MSC since the range of CS_{28} obtained with the three concrete mix ratios (1:1:2, 1:1.5:3 and 1:2:4) fall within the range of 20-40 N/mm^2 specified by [49] in Table 10. Also, in terms of CS, the LDPE plastic concrete can also be classified as SLWC since the range of CS_{28} obtained fall within the range of 17-41.36 specified for SLWC by [36]. A lower value of bulk density between 1350-1920 kg/m^3 specified for SLWC by [36] would have been obtained at higher % LDPE replacements probably between 50-80% replacements. The pulverized LDPE plastic waste can be used as FA in concrete since the CS_{28} obtained for the mix ratios 1:1:2, 1:1.5:3 and 1:2:4 are above the minimum CS of 9

N/mm² and 10 N/mm² required of LWC, and NC and HWC respectively as specified by [35], the minimum CS of 7 N/mm² required by [44] and [43], 20 N/mm² and 7 N/mm² required by [45] for RC and PC respectively.

The $FRCS_{28}$ for all the three concrete mix ratios: 1:1:2, 1:1.5:3 and 1:2:4 were found to decrease almost linearly with increasing % LDPE replacements as shown in Figure 7.

This was in line with observations for unfire-tested NC produced using mix ratios 1:1:2 and 1:1.5:3. Concrete mix 1:1:2 had the highest FRCS for all % LDPE contents followed by 1:1.5:3 and 1:2:4 as shown in Figure 7. For the plastic LDPE concretes containing 5%-15% LDPE contents, the highest $FRCS_{28}$ of 34.98 N/mm², 30 N/mm² and 27.65 N/mm² were obtained for 1:1:2, 1:1.5:3 and 1:2:4 respectively at 5% LDPE content, 5% LDPE content and 10% LDPE contents respectively. At 0% LDPE content, it was observed that concrete mix ratio 1:1:2 and 1:2:4 experienced strength loss of 7.79% and 20.34% respectively representing a strength retention of 92.21% and 79.66 respectively while concrete mix 1:1.5:3 experienced strength gain of 23.82% at 0% LDPE content.

Furthermore, as shown in Table 17, strength gain was found to decrease with increasing % LDPE content with concrete mix ratios 1:1:2 and 1:1.5:3.

The strength gain obtained for concrete mix ratio 1:1:2 were 21.20%, 6.22% and 6.80% corresponding to 5%, 10% and 15% LDPE replacements respectively. Excluding the control, this gives an average strength gain of 11.37% as shown in Table 17. For concrete mix ratio 1:1.5:3, the strength gained were 16.78%, 5.49% and 3.42% corresponding to 5%, 10% and 15% LDPE respectively and this gives an average strength gain of 8.56% excluding the control. These strength gain were higher than the results obtained by [68] with oven curing of GRP plastics were 5% and 15% glass-reinforced plastic (GRP) concretes achieved a strength gain of 2.21% and 2.99% respectively. For concrete mix ratio, 1:2:4, the strength gain were 4.26% and 21.49% corresponding to 5% and 10% LDPE replacement but a strength loss of 45.83% at 15% LDPE replacement and this gives an average strength loss of 6.69%.

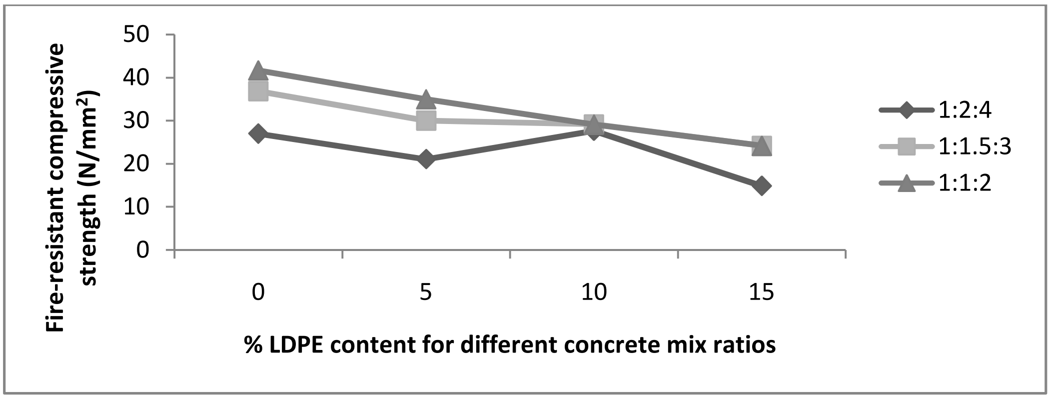

Figure 7. Fire-resistant compressive strength at 28 curing days for 0-15 % LDPE replacements

Table 17. Strength loss or gain for fire-tested concrete cubes

Concrete Mix ratio	% LDPE	Strength loss, SL (CS_{28}-RCS_{28}/CS_{28}) (%)	Average SL or SG	Remark
1:1:2	0	7.69		Strength loss
	5	-21.10	11.37	Strength gain
	10	-6.22	(Strength gain)	Strength gain
	15	-6.80		Strength gain
1:1.5:3	0	-23.82		Strength loss
	5	-16.78	8.56	Strength gain
	10	-5.49	(Strength gain)	Strength gain
	15	-3.42		Strength gain
1:2:4	0	20.34		Strength loss
	5	-4.26	6.69	Strength gain
	10	-21.49	(Strength loss)	Strength gain
	15	45.83		Strength loss

NB: SL = Strength loss; SG = Strength gain

Therefore, in terms of CS retention, concrete mix 1:1:2 is preferable followed by concrete mix 1:1.5:3. The strength retention for all the concrete cubes produced using concrete mix ratios 1:1:2, 1:1.5:3 and 1:2:4 met the requirement of 75% strength retention specified by [44] with the exception of concrete cube produced with mix ratio 1:2:4 using 15% LDPE replacement. In addition, $FRCS_{28}$ for all the plastic concretes exceeded the minimum requirements of 7 N/mm^2 and 20 N/mm^2 specified for normal LWC specified by [45] with the exception of concrete produced with mix ratio 1:2:4 at 15% LDPE with $FRCS_{28}$ of 14.88 N/mm^2. Some of the concrete cubes experienced strength gain. The increase was due to the presence of polymeric film formed from the heating process which intermingled with the cement hydrate resulting in increased $FRCS_{28}$ [69].

Considering the above results, concrete mix ratio 1:1:2 is the optimum mix. This corroborates results obtained by [28] who obtained the highest CS_{28} of 26.6 N/mm^2 at 0.65 W/C ratio, followed by CS_{28} of 23.3 N/mm^2 by 1:1.5:3 at W/C ratio of 0.7 and CS_{28} of 17.6 N/mm^2 for 1:2:4 at 0.875 W/C ratio.

6.3.2 Normal bulk density and fire-resistant bulk density

Concrete mix ratio 1:1:2 showed a decrease in BD with age obtained at 10% and 15% LDPE while an increase was obtained with 0% and 5% LDPE content as shown in Figure 8.

For concrete mix ratio 1:1.5:3, decrease in BD with age was obtained at 0% LDPE, an increase with 5% LDPE and an almost constant value for 10% and 15% LDPE content as shown in Figure 9.

As shown in Figure 10, for concrete mix ratio 1:2:4, an increase in BD was obtained with 10% LDPE, a slight increase with 15% LDPE but a decrease was obtained with 0% (control) and 5% LDPE contents. Concrete mix 1:2:4 showed a fairly stable density for all % LDPE content with increasing curing age compared to concrete mixes 1:1:2 and 1:1.5:3 shown in Figures 8 and 9 respectively.

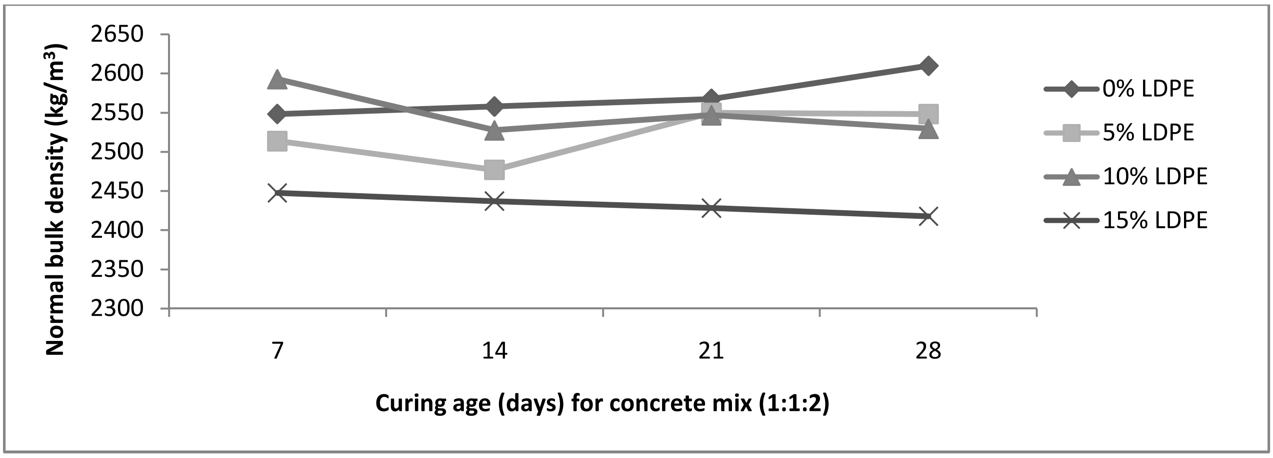

Figure 8. Normal bulk density for concrete mix (1:1:2) at different curing ages

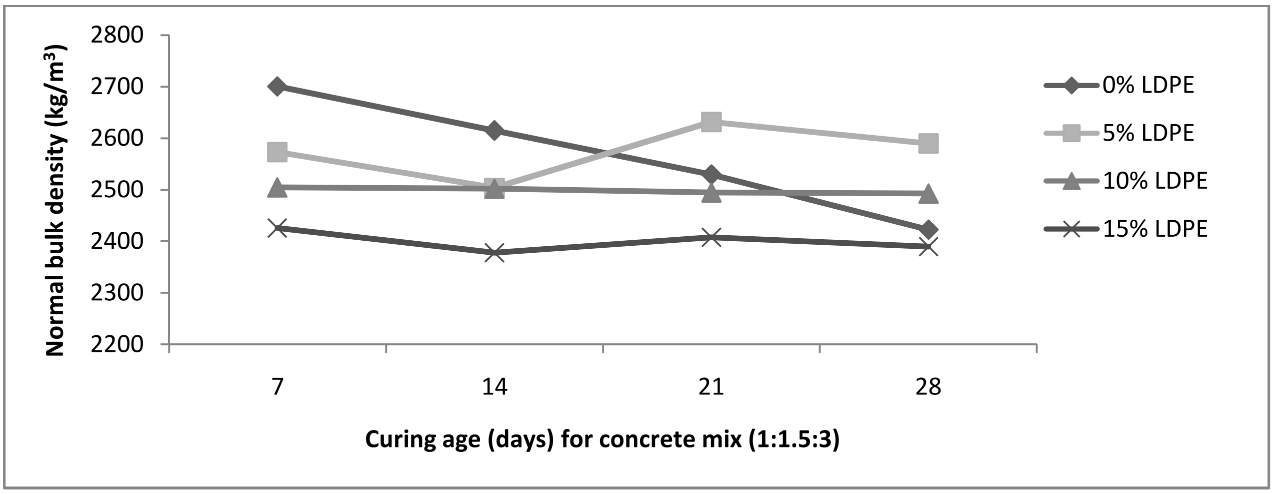

Figure 9. Normal bulk density for concrete mix (1:1.5:3) at different curing ages

Considering Figure 11, concrete mix ratio 1:2:4 had the highest BD_{28} of 2810.38, 2577.78 and 2429.63 kg/m^3 at 0%, 10% and 15% LDPE content respectively while concrete mix ratio 1:1.5:3 had the highest BD_{28} of 2589.63 kg/m^3 at 5% LDPE content.

The reason is that concrete mix ratio has the greatest CA/C ratio, greatest amount of void and porosity, compared to the concrete mix ratios 1:1:2 and 1:1.5:3. These properties allow it to absorb a lot of water, which contributes to its high BD. From Figure 12, it can be observed that concrete mix ratio 1:2:4 had the highest $FRBD_{28}$ of 2820.75 kg/m^3, 2531.86 kg/m^3, 2564.45 kg/m^3 at 0%, 5% and 10% LDPE contents respectively. Concrete mix ratio 1:1:2 had the highest $FRBD_{28}$ of 2340.74 kg/m^3 at 15% LDPE.

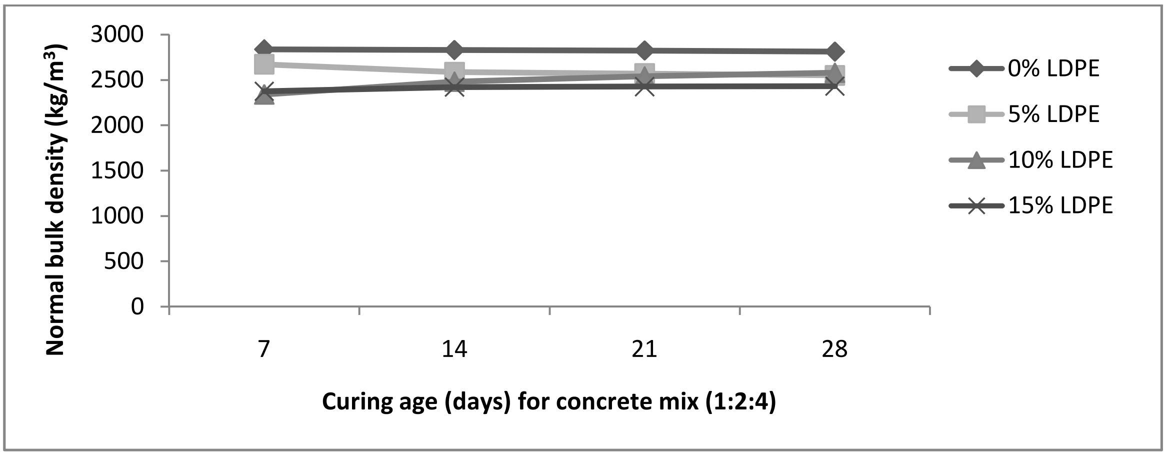

Figure 10. Normal bulk density for concrete mix (1:2:4) at different curing ages

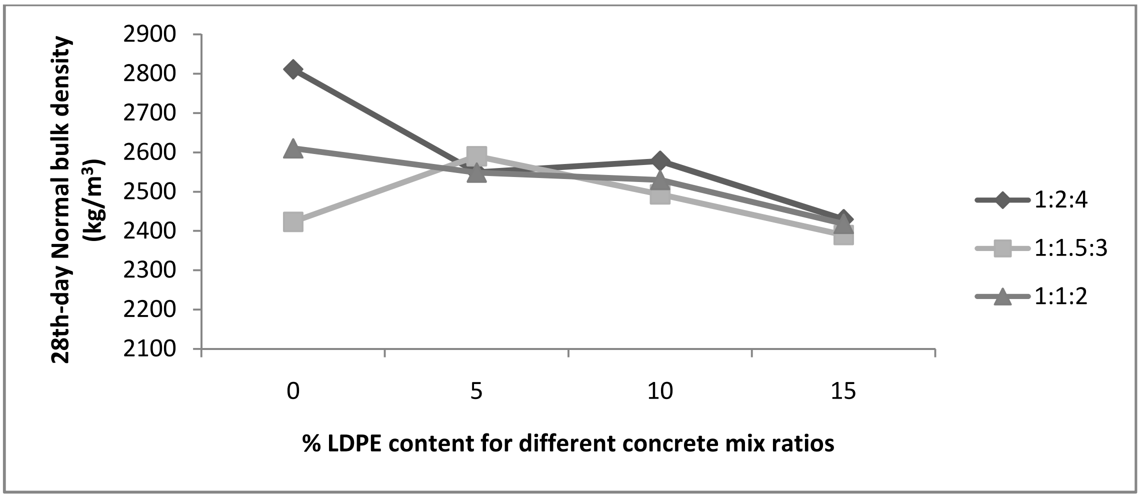

Figure 11. Normal bulk density at 28 curing days (BD28) at 0-15% LDPE replacements

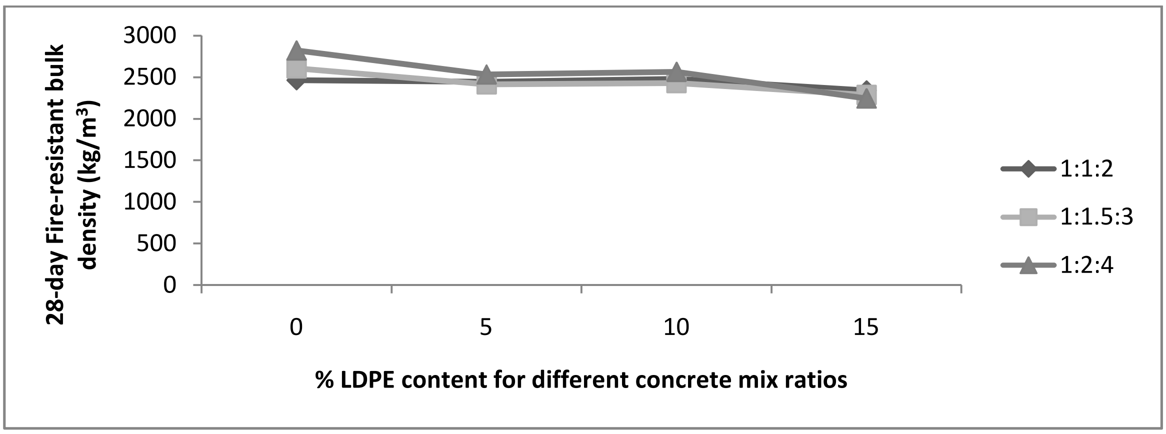

Figure 12. Fire-resistant bulk density at 28 curing days at 0-15 % LDPE replacements

Concrete mix ratio 1:1.5:3 had the least average density loss of 4.58%, followed by 1:2:4 with average density loss of 6.53% and 1:1:2 with average density loss of 9.83%. Considering the controls, concrete mix ratio 1:1:2 had a bulk density loss of 5.59%, while concrete mix ratios 1:1.5:3 and 1:2:4 had density gain of 7.56% and 0.37% respectively. BD_{28} for the plastic concretes produced using 1:1:2, 1:1.5:3 and 1:2:4 range between 2417.78-2548 kg/m^3, 2348.63-2589.63 kg/m^3, 2429.63-2424.6 kg/m^3 while the $FRBD_{28}$ range between 2340.74-2478.52 kg/m^3, 2285.93-2429.63 kg/m^3, 2243.95-2564.45 kg/m^3 respectively. Therefore, the LDPE plastic concretes can be classified as NWC concrete since their bulk densities fall within the range of 2001-2600 kg/m^3 specified by [35] in Table 6 and in the proposed classification in Table 8.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The conclusion of this study can be summarized as follows:

i. In terms of BD, pulverized LDPE plastic waste obtained from "pure water" sachet wastes could be reasonably classified as ULWFA.

ii. In terms of BD, the LDPE plastic concretes produced using 5-15% replacement of sand with pulverized LDPE plastic could be classified as NWC. Higher replacements of sand with pulverized LDPE plastic waste would be required to obtain LDPE concrete within the range specified for LWC.

iv. The optimum concrete mix ratio is 1:1:2 and it is preferable compared to the concrete mix ratios of 1:1.5:3 and 1:2:4. This is because:
   a) It had the highest CS_{28} of 45.12 N/mm^2, 34.26 N/mm^2, and 28.94 N/mm^2 at 0%, 5% and 10% replacements of sand with LDPE.
   b) It had the highest $FRBD_{28}$ of 24.18 N/mm^2 at 15% sand replacement with LDPE.
   c) It had the highest $FRBD_{28}$ of 2340.74 kg/m^3 at 15% sand replacement with LDPE.
   d) It had the highest plastic concrete mean strength gain of 11.37 %.

v. The three concrete mix ratios 1:1:2, 1:1.5:3 and 1:2:4 satisfied the minimum requirements for CS and fire-resistant tests for use in reinforced and plain concrete with the exception of the concrete produced with concrete mix ratio 1:2:4 at 15% sand replacement with LDPE. Hence, beyond 15% replacement of sand with LDPE plastic waste, concrete mix ratio 1:2:4 is not advisable to be used in building elements susceptible to fire due to its potential to lose CS drastically in the presence of fire or heat.

vi. LDPE plastic concrete could be used in production of non-load bearing structural members such as tiles and partitions.

7.2 Recommendations

i. Further research continues to investigate the percentage replacement of sand to obtain structural lightweight concrete.

ii. Recycling of LDPE plastic wastes in concrete is environmentally friendly and should be encouraged.

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