

### Research Article

# The Use of Recycled Polyethylene in Water-Oil Emulsion for Lightweight Concrete

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This study was to determine the suitability of recycled waste polyethylene (WPE) processed into water-oil emulsion for lightweight concrete applications. The processed WPE in the form of polyethylene emulsion (PE-e) is to promote physical interaction between the polymeric material and the cementitious matrix. The PE-e used was also to partially replace concrete mix composition by PE-e\_1, PE-e\_2.5, PE-e\_5, and PE-e\_10 percents for reference concrete and to introduce plasticity into the mechanical behaviour of the concrete. The PE was processed into PE-e to promote affinity for water, and this hydrophilicity was prominent in PE-e\_1 and PE-e\_2.5 percent concretes. Concretes with PE-e\_1 and PE-e\_2.5 percent formed good miscibility with the cementitious matrix. The density of the PE-e concrete decreased to 13.68% with 10% PE-e at 28 days. The replacement of mix constituents of PE-e\_1, PE-e\_2.5, and PE-e\_5 percent induced elastic to plastic behaviour in the concrete coupled with low water absorption. The FTIR data showed characteristic peaks of  $3378 \text{ cm}^{-1}$ ,  $1740 \text{ cm}^{-1}$ , and  $1148 \text{ cm}^{-1}$  in the PE-e. Using optical microscopy, it was shown that the PE particles were homogenously dispersed in the concrete matrix. The study shows the feasibility of using PE-e\_1 percent to produce structural lightweight concrete and up to PE-e\_10 percent for nonstructural applications mainly for light non-load-bearing partitions.

#### 1. Introduction

There is growing concern over the use and life cycle impact of polyethylene (PE) on the environment in recent years [1]. In sub-Saharan Africa, as of the year 2019, with a population of around 1 billion, 17 million tonnes of nonbiodegradable plastic waste is generated annually [2]. This solid plastic waste is considered a feedstock for the construction industry which is an alternative for disposal at landfill [3]. Moreover, it is a good substitute for virgin construction materials in masonry concrete [3]. The accumulation and disposal of this plastic create many negative impacts on the land, ocean, aquatic life, and climate change [4]. The recovery and reuse of plastic wastes in concrete through recycling is a proven and effective method to reduce indiscriminate plastic disposal in the environment [2]. The introduction of polyethylene into concrete is not a new study except that there have been issues of bonding challenges with plastic aggregate [5]. Concrete with plastic aggregates is characterized by reduced compressive strength due to the weak adhesive bond between the cement paste and the plastic aggregates [6]. Studies have shown a decrease in compressive strength when replacing natural aggregate with polyethylene terephthalate (PET) aggregates. This reduction can range from 0.4% to 20%, depending on the amount of PET used [7]. Generally, increasing the polypropylene fiber content leads to a higher compressive strength until a certain point, beyond which the strength may decrease. The optimal fiber content for maximum strength typically falls within the range of 0.25% to 1.0% by volume of the concrete [7]. The inclusion of recycled high-density polyethylene (HDPE) plastic in concrete can improve workability making it easier

to mix and pour. It enhances thermal insulation due to the air voids present in the plastic particles. There is a decrease in compressive and tensile strength of concrete with increasing HDPE content. This decrease is attributed to the weaker bond between the plastic and the cement matrix. There is increased drying shrinkage and reduced durability [8]. The hydrophobic nature of the plastics contributes to the bonding challenges. This hinders the diffusion of water into the concrete which is needed by the cement paste for hydration [9]. The intermolecular forces formed on the surface of plastics without chemical treatment are usually nonpolar and are weak van der Waals forces [10]. It has been shown that chemically treated plastics result in a higher polarity on the plastic surface due to oxidation which leads to surface roughening of the plastics. This surface modification due to polarity helps the formation of hydrogen bonds between the cement paste and the plastic aggregates [10]. This helps to improve the bond strength between the plastic aggregates and the cementitious matrix. This results in the reduction of the interfacial gap between the plastic and the fine cementitious constituents due to improved bond properties [10]. Studies have shown that the incorporation of recycled plastic waste into concrete in the form of plastic fiber-reinforced concrete blends well with Portland cement which influences the engineering properties [5-7]. One major advantage of using plastics in concrete is that it takes a long time as the age of the concrete before disposal in the environment thereby reducing the exploitation of natural resources, reduction in water and soil pollution, and reduction in the death of marine life [1, 3]. That is, the added plastic forms part of the concrete lifespan rather than being a nuisance to the environment and serves as an economical way of plastic waste disposal. Through this approach, repurposed and recycled plastics maintain their quality without degradation, serving as a viable alternative to conventional construction materials [11]. Utilizing waste polymers in brick production diverts them from landfills, minimizing environmental pollution and resource waste, reduces carbon footprint, and thereby conserves natural resources. Plastic bricks are significantly lighter than conventional bricks, making them easier to handle and transport and reducing construction costs and environmental impact. It is cost-effectiveness, reducing reliance on virgin resources [12].

There are several methods of processing routes to recycling plastic waste and reuse for construction applications [13]. One such approach is the addition of polyethylene glycol (PEG) by 3% of cement mass resulted in low water absorption, water sorptivity, and carbonation depth [14]. Also, low dry shrinkage was observed compared with other systems for water curing and air curing concretes [15]. Further studies have shown that the incorporation of PE in fiber form into concrete is much more effective than steel fiber in terms of strain hardening, ductility, and crack growth resistance [16]. However, the partial replacement of concrete with emulsified PE (PE-e) processed into lightweight concrete materials constitutes one of the areas where research activities are least to find in the literature, and it is worth studying. Compared to conventional concrete, semilightweight concrete can be 25-30% lighter, leading to benefits like easier handling and installation, reduced structural loads, less material usage, and improved thermal insulation due to air voids, and improved insulation can decrease energy required for heating and cooling buildings.

Lightweight concrete can be 50-75% lighter than conventional concrete, offering even greater benefits in enhanced thermal insulation and significant energy savings due to excellent thermal stability [17].

The purpose of this paper is to study the potential of addition and use of recycled PE processed into water-lipidbased emulsion (PE-e) in the formulation for lightweight concrete production. The second is to investigate the influence of the PE-e on the mechanical, thermal, and wettability behaviour of concrete. Waste PE (WPE) though nonpolar can be processed to produce water-oil emulsion where the hydrophobic nature of the polyethylene (PE) is rendered hydrophilic with the use of an emulsifier. The study uses the technique of melting compounding approach where PE is dissolved in a lipid and dispersed to form an emulsion in aqueous medium using dioctyl sodium sulfosuccinate (DOSS) and saponified fat (SA) as emulsifier. Thus, the DOSS and SA influence the dispersion effectiveness of the PE in the oil-in-water emulsion [18]. The addition of DOSS and SA is expected to also improve workability through the influence of surface texture on the absorption of water [12, 13]. Another advantage of processing and addition of the PE in the emulsion is to improve on the fineness modulus (FM) since it has a direct correlation with the packing density of concrete. Thus, concrete with low proportion of small PE particles is expected to influence the fineness modulus greatly and also enhances the concrete ability to withstand some additional loading after a fracture [3, 14] due to the bridging of cracks by the plastic particles [19].

The study focuses on the design mix for grade 25 concrete, batching formulation, synthesis of the emulsion, characterization, and performance analysis of the concrete. The study also looked for the optimum amount of recycled waste polyethylene emulsion applicable in the concrete.

#### 2. Experimental

2.1. Raw Materials and Mix Designs. The raw materials selected and used were river sand, coarse aggregates in the form of granite pebbles, Portland cement, and shredded waste sachet polyethylene sheets. The design mix for concrete batching is outlined in Table 1 and as detailed in the appendix. The fine sand aggregates used were dredged from Ada, a town in the Greater Accra Region of Ghana. The fine sand was washed to remove all foreign materials and screened to a size diameter of 1 mm maximum. The coarse aggregates were obtained from the Shai Hills in the Greater Accra Region of Ghana. The diameter of the coarse aggregates screened using the sieve method was 5-14 mm. This size range was experimentally chosen to fit well with the mould size to avoid the segregation of aggregates during casting. The cement used was 42.5 R ordinary Portland cement produced by Ghacem Ltd., a subsidiary of Heidelberg cement based in Tema, Ghana. The obtained polyethylene waste was in the form of sachet bags commonly used for

TABLE 1: Theoretical design mix for water-cured reference concretes (REF-WC) and air-cured (REF-AC).

Mixture composition (g)	REF-WC/REF-AC
W/C	0.65
Water	685
OPC	1055
Quartz sand	2784
Coarse aggregated	3360
PE-e	0

the packaging of drinking water. The water used for batching, washing, and for mixing processes was deionized. The PE particle size range from the sieve analysis was 0-850  $\mu$ m. To achieve the objectives of this study, six different groups of concrete with 72 mixture sets were prepared and investigated. For each of the six groups, 12 cubes of 75 mm ×75 mm ×75 mm concrete samples were made. For the twelve cubes, three samples were prepared and tested for 7, 14, 21, and 28 days for bulk density and compressive strength [20], and their mean value was calculated for each test. The concrete batching was formulated for varying amounts of PE-e composition of the reference (REF) concrete of PE-e\_1, PE-e\_2.5, PE-e\_5, and PE-e\_10. Table 1 summarizes the theoretical mix composition for reference concretes.

The dry constituent concrete materials used (river sand, coarse aggregates, cement, and water) were weighed separately according to the mix design proportions. The sand and cement were first mixed thoroughly until a homogenous mixture was obtained. The PE-e was measured and added to the homogenous mixture and stirred until it was evenly distributed. The coarse aggregates were added and mixed. The resulting mixture was thoroughly mixed, and the required water was added to maintain a homogenous mix. The batch was cast into a galvanized aluminium mould to set and dry and demoulded after 24 h. The cast concretes were water cured for 7, 14, 21, and 28 days, respectively, in an open water bath at a temperature between 20 and 27°C. The same batching procedure was repeated for all other compositions. The actual batch compositions are summarized in Table 2. This study focused on percentage replacement of the PE-e on the total mass of the constituent; therefore, the concrete constituents vary for each PE-e replacement.

The formulated and cast concrete pieces were characterized for compressive strength, bulk density, thermal stability using thermogravimetry (TG)/differential thermal analysis (DTA), and the various functional groups present in the concrete using Fourier transform infrared (FTIR) spectroscopy. The TGA was conducted on both polyethylene in emulsion (e-PE) and PE sheets coming from wastewater sachet bags. The modulus of rupture tests was performed on concrete samples (100 mm  $\times$  30 mm  $\times$  15 mm) for the various percentage of e-PE replacements. These characteristics and replacement rates were considered as recorded in some research works on polyethylene concrete [7, 16, 19, 21]. Other variables such as temperature and curing medium were kept constant in order to compare the results with the reference concrete. The curing process for concrete does not begin after 28 days have passed. It is crucial to start curing immediately after the concrete placement and finishing. In fact, the first few days after placement are the most critical for curing, as the cement hydration process is most active during this period [22].

2.2. Synthesis of Polyethylene in Water-Lipid Emulsion. The synthesis process is a first time experimental procedure where material proportions were selected following a series of test-runs and observations. A 2.5 g of dioctyl sodium sulfosuccinate (DOSS, obtained from Sigma-Aldrich Company, USA, with concentration  $\leq 97\%$ ) and 12.5 g of normal saponified coconut oil were added to 50 g of vegetable butter. The mixture was heated up to 80°C with constant stirring for 20 min until no lump or particle was observed. A 200 ml of deionized water was added to the mixture with continuous stirring for another 30 min using a magnetic stirrer at 1100 rpm until complete miscibility was attained to form an emulsifier paste. The emulsifier paste was then left to stand for 24 h to allow the reaction to reach a full completion. A 20 g of waste polyethylene sheet in the form of shredded sachet bags was added to 100 ml of purified hot pressed coconut oil in a 250 ml beaker, and the content was heated to 180°C using a heating mantle. The mixture was stirred continuously till the polyethylene was fully melted to form a light thick yellowish gel. The temperature was gradually reduced until it reached 55°C and at constant vigorous stirring for 10 min. The heating source was turned off to allow the gel mixture to cool to room temperature while still being continuously stirred. A 2ml of 98% sulphuric acid was added to the coconut oil-polyethylene gel mixture and stirred continuously for 5 min. This was followed by the addition of 10 ml of the synthesized emulsifier mixture, which was stirred vigorously and continuously for another 5 min. The emulsifier, which is a surfactant, helps to stabilize the emulsion. The emulsifier molecules have both hydrophilic and hydrophobic regions. The hydrophilic regions interact with the water molecules in the continuous phase, while the hydrophobic regions interact with the polyethylene molecules in the dispersed phase. This helps to prevent the droplets from coalescing and forming a separate layer [23]. A 105 ml of deionized water was added to the mixture to form a polyethylene in water-oil emulsion. The water dissolves the water-soluble components and disperses the oil-soluble components. It mixes the two phases together and controls the temperature. This initiates the polymerization reaction within the monomer droplets [23]. The polyethylene in the water-oil emulsion was then thoroughly mixed and blended with a heavy-duty variable speed blender at 50 Hz and the weight of the emulsion measured. The water acts as the continuous phase in which the monomer droplets are dispersed. This allows for efficient mixing and heat transfer throughout the reaction mixture. The size and stability of the polyethylene droplets depend on the presence of surfactants, which are dissolved in the water phase. The water also facilitates the diffusion of water-soluble initiators and other additives to the reaction sites within the monomer droplets. Water has a high heat capacity, allowing it to efficiently absorb

		Mix	ture composition		
Mixture composition (g)	REF-WC/REF-AC	PE-e_1	PE-e_2.5	PE-e_5	PE-e_10
W/C	0.65	0.61	0.61	0.61	0.61
Water	675	334.12	329.06	295.84	288.56
OPC	1100	544.50	536.25	482.11	470.25
Quartz sand	2780	1376.1	1355.25	1218.42	1188.45
Coarse aggregated	3360	1663.2	1637.10	1472.62	1512.00
PE-e	0	39.58	98.94	197.88	395.75

TABLE 2: Concrete mix compositions with polyethylene emulsion (PE-e).

and dissipate the heat generated during the polymerization reaction. The presence of water helps to maintain the stability of the monomer droplets and prevents them from coalescing, which would interfere with the polymerization process [24, 25]. The water-lipid emulsion interaction creates a hydrophilic layer around the PE which is expected to aid in the effective mixing with the concrete formulation.

The summary procedure for the emulsion preparation is first by preparation of the dispersed phase which is the liquid polyethylene obtained when heated and dissolved in the saponified fat. The resulting mixture is then dissolved in water to form an emulsion and then homogenize the emulsion by continous and aggressive blending. The emulsion is made to cool and store for use.

#### 3. Characterization

3.1. Measurement of Density. Measurement of the bulk density of individual concrete specimens was done by the method of displacement to eliminate possible errors from volume calculations by direct dimension. The same dimensions of sample cubes gave different measurement of displaced water. The volume of water displaced by the masses of each concrete specimen was measured separately in a graduated cylinder. The corresponding masses were measured on Denver analytical electronic balance, and the densities were calculated by dividing each mass by the volume of their corresponding water displaced.

3.2. Compressive Strength Test. The compressive strength measurements on concrete cubes ( $75 \text{ mm} \times 75 \text{ mm} \times 75 \text{ mm}$ ) were conducted according to GS 297-1210. Samples were tested with a control automated compressive testing machine with model number 20063 in accordance with the requirements of ASTM E4. The bearing surface of the testing equipment was aligned centrally on the base plate. The load was applied gently and gradually at an equipment capacity of 1500 kN till the sample fractures. The maximum load at fracture (failure load) was recorded from the equipment graduated scale. Twelve samples each of the REF-WC, REF-AC, and PE-e concrete samples were tested. The compressive strength was then measured.

3.3. Flexural Strength Test (Modulus of Rapture). The concrete samples were characterized for the modulus of rapture to investigate the behaviour of PE-e in the concrete samples when subjected to bending loads. Four samples were characterized at 28-day curing, and the results were compared with REF-WC (reference concrete water cured). The flexural strength measurements were conducted with a force gauge equipment of model number M5-500. The equipment's maximum load capacity was 2.5 kN, integrated with Mark-10 MESUR Lite software, and the strain rate for the measurement was set at 10 mm/min. All samples were tested for flexural strength by applying direct compressive load on the middle of each sample over a support span length (L) of 76.5 mm. The loads P (N) were applied at the center of each sample perpendicular to the width b (30 mm). The load increments were measured with their corresponding time (s) until the sample fractures. The flexural stress, strain, and flexural modulus were calculated according to the following equations [14]:

$$\sigma_{\rm f} = \frac{3PL}{2bd^2},\tag{1}$$

$$\varepsilon_{\rm f} = \frac{6Dd}{L^2},\tag{2}$$

$$E_{\rm f} = \frac{L^3 m}{4bd^2},\tag{3}$$

where *D* (mm) is deflection due to the load *P* (N) applied at the middle of the beam expressed as  $\varepsilon/t$ . Also,  $\sigma_f$  (Pa) is the flexural stress,  $\varepsilon_f$  (mm/mm) is the flexural strain, *L* (mm) is the span length, *b* (mm) is the width of the sample, *d* (mm) is the thickness of sample, *t* (s) is time,  $\varepsilon$  (mm/min) is the strain rate,  $E_f$  (Pa) is the flexural modulus of rapture, and *m* (N/mm) is the gradient of the initial straight-line portion of the load-deflection curve.

3.4. Water Absorption. The water absorption test was done according to ASTM D570. Three of each sample were oven dried with Ascon Tecnologic K39 at  $105^{\circ}$ C for 200 min till a constant mass was attained. The sample sizes were 75 mm × 75 mm × 75 mm. The samples were removed and placed in a desiccator to cool for another 200 min. The samples were weighed right after cooling and then submerged in a deionized water bath at room temperature for 24 hr. The samples were removed from the water bath, and the surface moisture was cleaned and weighed. The mean value of each sample category was calculated. The percentage

absorption of water was calculated according to the following equation [26]:

%water absorption = 
$$\frac{(\text{wet weight-dry weight})}{\text{dry weight}} \times 100.$$
 (4)

3.5. Sieve Analysis. A PE-e contained in a 250 ml beaker was oven heated at 65°C to enhance a free flow of the water-lipid emulsion. The sieves for the analysis were set up according to ASTM/AASHTO USA and clamped firmly on a sieve shaker. The sample was poured into the top sieve (size 850  $\mu$ m). A water spray was placed at the top sieve, and the sample was rinsed while the sieve shaker shook and sieved the sample until the discharge was clear. The residue on each sieve was dried and weighed. The percentage retained on each sieve was calculated according to equation (5) and from which the percent passing was determined [27]. The percent passing was plotted against the sieve size as represented in Figure 1.

$$\% retained = \frac{W_{sieve}}{W_{total}} \times 100\%,$$
(5)

where  $W_{\text{sieve}}$  (g) is the mass of PE aggregates in the sieve and  $W_{\text{total}}$  (g) is the total mass of PE in all sieves.

3.6. Contact Angle Measurement. Two parts of resin to epoxy hardener were mixed thoroughly and cast to mount samples, REF-WC, REF-AC (standard concrete-air cured), and PE-e concretes in 85 mm diameter plastic container. This was done to ensure a thorough polishing of samples with little or no abrasion. The thickness of the composite was 20 mm on average. The samples were removed after hardening. A light-powered model 900 grinder/polisher of South Bay Technology Incorporated was used to grind samples separately with different silicon carbide grit paper sizes of 120, 240, 400, 600, 800, and 1000. Water was sprayed continuously on grit paper for grinding the surface until the desired surface texture was obtained. The measurements were done under room temperature. There were two steps involved in the measurement: recording and calculation. The ground surface was positioned flat and horizontal. A droplet of deionized water was deposited on the surface with a microliter pipette under an illuminated condition. The image of the droplet just as it was deposited by the microliter pipette was imaged and recorded using a Hot 10 lite Infinix 13 megapixel triple camera with a light source. On the recorded image, a horizontal line that serves as the base between the droplet and the sample surface was drawn. A contact angle line was marked from the triple point and a tangent to the surface of the droplet. A perpendicular line is drawn through the center of the droplet. A straight line is then drawn from the triple point through to the top edge of the perpendicular line. At this point, the contact angle was obtained using the Pythagoras theorem [28].

3.7. Thermogravimetric Analysis. Thermal analysis was performed on the waste PE, PE-e, and PE-e concretes for comparative analysis. An SDT Q600 thermometric equipment



FIGURE 1: PE particle gradation curve.

with a crucible diameter of 5 mm was used. The SDT Q600 was integrated with thermal analysis (TA) analyzer explorer software for dynamic measurements. The samples were heated at different times from 25°C to 700°C at a ramp rate of 20.00°C/min. The 700°C was chosen because by this temperature, all the PE would be burnt out and turned into carbon. The dynamic measurements were performed under a nitrogen purge flow rate of 100.0 ml/min. Six of the samples studied were in powdered form, one in emulsion form, and one as shredded waste polyethylene from water sachet bags. A quantity of  $3.5 \pm 0.3$  mg was placed in an open ceramic sample pan. The derivative weight (DW), weight loss (WL), and derivative heat flow (DHF) were recorded as functions of temperature and time. The TG-DTG and DTA-DSC were then plotted. The samples were analyzed using their corresponding plot curves.

3.8. Fourier Transform Infrared. A PerkinElmer Spectrum Two (FTIR spectrometer) was heated for about thirty minutes and test-run to ensure its stability. A total of eight samples were analyzed separately for fine constituents (0-1 mm) taken from all samples, PE-e, and WPE sheet at a wavelength of 4000-4015 nm. The total run-time for each sample was approximately 1-2 min with  $5 \mu g$  mass of the samples.

3.9. *Microscopy*. Two parts of low viscosity resin to epoxy hardener were mixed thoroughly together and cast to mount samples for the samples in a 30 mm diameter plastic container. The samples were removed after hardening. A lightpowered model 900 grinder/polisher of South Bay Technology Incorporated was used to grind samples separately with different silicon carbide grit paper sizes of 120, 240, 400, 600, 800, and 1000. The samples were polished and washed several times with ethanol. The samples were imaged using an AmScope microscope (voltage: 100-240 V; working distance: 53-73 mm) with integrated software for recording the images under various magnifications.

#### 4. Results and Discussions

4.1. The PE-e. From Figure 1 and Table 3, the particle size of the PE in the concrete ranges from 0.106 to 0.85 mm. A vigorous and continuous stirring of the PE-lipid gel prevents early nucleation of the PE. This resulted in the formation of a fine distribution of nucleated PE particles in the gel. The faster the stirring rate, the finer the particles obtained. The formation of larger particles tends to suspend in the emulsion especially at a slow stirring rate. The PE is naturally hydrophobic, but the emulsified allows the acquisition of both polar and nonpolar properties. This property enables the PE emulsion interface to absorb water. By visual observation, the PE particles swelled and agglomerated in the emulsion by the adsorption of the emulsifier leaving approximately 20% of the water on the surface and around swollen PE particles. There is a decrease in the ease of placing freshly mixed concrete, consolidating and finishing with minimal loss of homogeneity. This decreases with increasing weight percent of PE-e. The increase in weight percent PE-e decreases the amount of cementitious material and fines needed to bond with the PE particles. Higher content of PE-e results in poor miscibility. The PE-e probably improved the bonding of the cementitious matrix and the PE particles likely due to an increase in the polarity. However, a higher amount of PE aggregate (up to 10 wt%) leads to a significant increase in the air content of concrete due to particle shape irregularity and poor miscibility of the PE and natural sand.

4.2. Compressive Strength. The compressive strength of the cast concrete samples except with 10 wt% PE-e did follow the normal strength increment with curing age as shown in Figure 2. In all, the highest compressive strength for the samples was observed for the 28-day curing. Curing has an effect on the compressive strength of the concrete. Water curing is the most common and effective method for achieving high compressive strength. It allows for optimal hydration of the cement and leads to a uniform and dense concrete matrix. Air-cured concrete typically has lower compressive strength than wet-cured concrete. This is because air curing allows the water in the concrete to evaporate too quickly, which can prevent the complete hydration of the cement. Hydration is the chemical reaction between cement and water that gives concrete its strength. It has increased shrinkage, cracking, and porosity. Steam curing accelerates the hydration process, leading to rapid strength gain. This method is particularly useful for precast concrete elements where early strength is required. However, steam curing can also lead to reduced long-term strength and cracking if not properly controlled [17, 29]. The highest compressive strength was 29.37 MPa and was less than the expected strength. When smaller particle sizes of coarse aggregate like 2.36 mm, 5.00 mm, and 9.50 mm are required to produce concrete, the cement paste would require a high percentage of water to produce a concrete with good degree of workability due to the low impact resistance of the coarse aggregates [30]. The use of PE-e in the concrete resulted in the loss of compressive strength due to the decrease in density and also the creation of sufficient failure surfaces, as these tend to act

TABLE 3: Sieve analysis results in polyethylene emulsion.

Mass retained	Sieve size (mm)	% mass retained	Cumulative % mass passing	Cumulative % mass retained
101.09	0.85	86.41	13.59	86.41
8.22	0.425	7.03	6.57	93.43
6.185	0.15	5.29	1.28	98.72
1	0.106	0.86	0.43	99.57
0.5	0.053	0.43	0	100
Fine	ness modulı	$\operatorname{is}(\mathrm{FM}) = \frac{4}{2}$	$\frac{78.13}{100} = 4.78$	478.13



FIGURE 2: Compressive strength versus curing age of all studied samples.

as voids in the concrete compared to the work of Thorneycroft et al. on the performance of structural concrete with recycled plastic waste as a partial replacement for sand. Another reason contributing to the low mechanical strength was that there could be weaker interfacial bonding between the binder paste and the PE aggregates [31]. The replacement of concrete aggregates by weight percent of the total mass accounts significantly for the decrease in mechanical strength. This means that strength increment has a moderate inverse relation to an incremental PE-e addition in concrete mixes. There is an increase in strength development with curing age as shown in Figure 2. The cured concrete got hydrated as it gained water in the curing process. There is an inherent micro capillary action in the PE-cementitious paste and the pores leading to differential volume change (DVC) which is a precursor to the generation of strains and stresses within the concrete. The concretes with 1 wt% PE-e and 2.5 wt% PE-e have comparatively good strength whereas those with 5% PE-e and 10% PE-e have low strength. It can be deduced from the data that physical bonding for low workability mixes is weaker since the PE

particles are deprived of much cement paste and fines for bonding. Up to 2.5 wt% of PE-e concrete is workable, beyond which the concrete loses its consistency and workability. The increase in weight percent of PE-e decreases the amount of cementitious material and fines needed to bond with the PE particles. According to Babafemi et al. [32], workability is influenced by the particle roughness, shape, size, and water-cement ratio. The application of the PE-e improved the bond strength of the cementitious matrix and the PE particles in the PE-e due to an increase in the polarity.

The percentage strength enhancement for the REF-WC sample is up to 31.22% at 28-day curing. Weight replacement above 1 wt% PE-e gave reduced compressive strength. Up to 78% strength decrease was observed for 10 wt% PE-e concrete at 28 days as shown in Table 3. The addition of PE-e reduces the compressive strength of the concrete; higher replacement percentages result in greater strength reduction.

4.3. Density. Figure 3 shows the variations in dry density of concrete with different weight percent PE-e in comparison with the standard concrete. The dry densities of REF concrete for both water cured (WC) and air cured (AC) were 2096 kg/m<sup>3</sup> and 2055 kg/m<sup>3</sup> at 28 days, respectively. The standard concrete water cured (SC-WC) is approximately 2% higher in density than the standard concrete air cured (SC-NC). This is probably due to the absorption of water by the standard concrete during the curing period. When various weight percentages of the mix compositions were replaced by PE-e, the densities decreased significantly up to 13.68%. This does not align exactly with the PE-e addition probably due to the increased porosity of hydrated cement paste which decreased the density of the microstructure of the concrete for higher PE-e additions. The dry density values as presented in Table 3 indicate that concrete with PE-e decreases in dry density with increasing PE-e weight percent. The low densities of PE-e concrete are due to the lower density of the PE in comparison with that of the aggregates in the mix composition of fine aggregates, coarse aggregates, and cement.

4.4. Flexural Test Results. The replacement of mix constituents by PE-e 1, PE-e 2.5, and PE-e 5 induces a plasticelastic-plastic behaviour in the concrete as shown in Figure 4. The stress-strain curve showed plastic behaviour which makes it possible to yield before failure, which stands in contrast with standard concrete which undergoes failure in the elastic regime. This behaviour has similarly been reported by Prasad and Jaysawal [33], who observed that concrete composites with PE aggregates undergo several stages of deformation before fracture. From Figure 4, the uniqueness of the stress-strain behaviour of concrete with PE-e 1 is thus represented comparably more in the plastic region before failure. The performance of PE-e\_1, PE-e\_ 2.5, and PE-e\_10 is likened to semicrystalline polymer, flexible concrete, and not as brittle as the REF concretes in Figure 5 and also for PE-e\_10 concrete. Up to the point of failure, when stress is removed, the plastic will usually return

to its former state, but after failure, necking, cold drawing, and fracture, this would not be the case [34]. The behaviour of the stress-strain curve of Figure 4 confirms the conclusions of Kumar and Kumar [35] that plastics in concrete possess characteristic ductility which ensures that concrete significantly deforms in the plastic regime before failure. This makes it indispensable in expansion and contraction, freeze, or thaw weather applications [34].

Also, stress-strain curves for concretes with PE-e\_1, PEe\_2.5, and PE-e\_5 portray a typical S-shaped as shown in Figure 4, which are similar to that of some crystalline rocks. Thus, these curves exhibit plastic-elastic-plastic behaviour similar to typical schist (cored along schistosity) stressstrain curve in uniaxial compression when loaded to failure [36]. Curves for PE-e 1 concrete and PE-e 2.5 concrete from Figure 4 are characterized by what Bell [36] termed as initial "plastic" closing, and this precedes steep-tosteeper linear portion. The curves are generally nonlinear and curve inward at low stresses. As the stress increases, a region of stress is reached where the slope of the stressstrain curves approximates linearly. At this level of stress, the flexural modulus is comparably higher, which suggests that the compaction and closing of cracks before the occurrence of any near-linear deformation. Beyond the linear portion and at near failure, the curves show different degrees of plastic yield for PE-e\_1, PE-e\_2.5, and PE-e\_5 concretes. Up to 5220 MPa flexural modulus was obtained for concrete with PE-e\_2.5 as shown in Table 4. For a PE-e\_10, it does not show any significant yield and failure takes place under the brittle mode. The summary values of  $\sigma_f$ ,  $\varepsilon_f$ , and  $E_f$  for REF-WC and PE-e concretes have been shown in Table 5.

4.5. Water Absorption Test. The water absorption, which indicates how porous a material is given under a specific condition, was measured for all the cast concrete samples. The water absorption of the standard concretes is higher than concretes with PE-e replacement greater than or equal to 4.81% as shown in Figure 6 and Table 6. There is a decrease in water absorption in all percent replacements of PE-e from the standard concretes. Smaller percentages of PE-e replacement showed higher water absorption than higher replacements. As the percentage of PE-e increases, the water absorption decreases. However, the difference in water absorption between PE-e 1 and PE-e 10 is approximately 0.6% indicating that higher PE-e replacement does not enhance a considerable amount of water absorption. The performance of the PE-e in water absorption decreases by 22.76 wt%, 30.34 wt%, and 39.31 wt% for PE-e\_2.5, PEe\_5, and PE-e\_10 concretes, respectively, in comparison with the PE-e\_1. The cementitious material and fine aggregate content needed for proper bonding thus decrease because of the higher weight percentage replacement. This resists the water capillary action and hinders hydration of cement and inhibits the movement of water through the concrete [37, 38]. Concrete is inherently porous, allowing water to penetrate the material. The higher the porosity, the greater the water absorption capacity. A lower w/c ratio results in a denser concrete with less porosity, leading to lower water absorption. Different types of cement have



Mix composition of concrete

FIGURE 3: Density variations of concrete with different weight percent PE-e.



FIGURE 4: Stress-strain plot for concretes with PE-e concretes.

varying hydration rates and pore structures, influencing water absorption. The type and size of aggregates in the concrete mix can also affect water absorption. For example, porous aggregates like crushed stone can increase absorption compared to smoother, denser aggregates like river sand. Higher relative humidity promotes water absorption from the environment into the concrete. Proper curing practices, especially in the early stages, minimize water loss and promote hydration, reducing the potential for subsequent water absorption. Thorough compaction during placement removes air pockets and creates a denser concrete with less water absorption. Smooth finishing techniques can help to



FIGURE 5: Stress-strain plot for REF-AC.

reduce the overall surface area exposed to water and potentially lower absorption [17].

4.6. Contact Angle. The surface hydrophobicity and hydrophilicity are indicated through the measured contact angles as shown in Figure 7. For contact angles less than 90°, the water droplet spread partly increases the interface between the droplet and the sample surface. The surface property is hydrophilic and has a good wetting property. The water droplets remain on a limited surface without spreading for contact angles greater than 90°. The water retains on the surface as the samples are unable to absorb it. Such are considered hydrophobic [20]. This effect is related to the

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Mix composition	Densi	ty (kg/m <sup>3</sup> ) for ages	different water (days)	curing	Compre	ssive strength ( curing ag	MPa) for differe ges (days)	ent water
	7	14	21	28	7	14	21	28
REF-AC				2055				24.64
REF-WC	2025	2033	2037	2096	20.72	22.69	26.21	29.37
PE-e_1	2020	2022	2023	2031	14.29	14.61	14.92	16.80
PE-e_2.5	1976	1976	1992	2003	11.47	11.22	12.43	13.04
PE-e_5	1850	1922	1906	1938	5.83	8.03	7.4	8.65
PE-e_10	1813	1810	1806	1810	7.71	7.4	6.14	6.46

TABLE 4: The density and compressive strength of concrete at different curing ages.

TABLE 5: Summary of  $\sigma_{\rm f}$ ,  $\varepsilon_{\rm f}$ , and  $E_{\rm f}$  for various compositions of REF-WC.

Composition	Gradient	$\sigma_{\rm f}$ (MPa)	$\varepsilon_{\rm f}$ (MPa)	E <sub>f</sub> (MPa)
REF-WC	197.769	5.436	0.027	3913
PE-e_1	205.060	3.740	0.020	5220
PE-e_2.5	79.909	2.823	0.036	1907
PE-e_5	42.592	0.706	0.018	935
PE-e_10	9.958	0.148	0.014	197

nonabsorptive characteristics and the hydrophobic nature of plastic grains, which lead to concrete mixes with more free water [5]. The contact angles indicate that droplets show wetting for REF-AC, REF-WC, PE-e\_1, PE-e\_2.5, and nonwetting for PE-e\_5 and PE-e\_10 concretes. The smooth texture and the light glassy surface of the REF-AC sample probably account for its contact angle higher than the REF-WC. The processed PE adsorbed the emulsifier leading to the formation of a micelle with both hydrophilic and hydrophobic properties. During batching, the micelle loses all the hydrophilic heads into the mixture for bond formation thereby leaving the hydrophobic heads surrounding the polyethylene particles. Higher percentages of 5 and 10 PE-e in concrete tend to introduce comparatively many hydrophobic heads, which decreased the samples' surface affinity for water due to low interfacial surface energy. This confirms the results of the water absorption test and as also confirmed by Li et al. [39, 40].

4.7. Thermal Test Results. Figures 8(a) and 8(b) show the TGA thermograms of PE-e, WPE, and sample concretes fired at 300°C-700°C. The first weight loss in the temperature range 0°C-300°C is probably attributed to the dehydration of C-S-H, ettringite, and calcium aluminate hydrates. The temperature at which these compounds lose water depends upon the CaO/SiO<sub>2</sub> ratio in the hydrated cement matrix. Whereas above 450°C, the percentage of portlandite sharply diminishes but does not fall to zero value in cement pastes that were fired at 600°C-700°C due to the partial rehydration of lime [41]. The decomposition rate for PE-e in Figure 8(a) is more rapid within than the WPE, and this can be attributed to the degradation of the absorbed emulsifier and water molecules in the PE particles. The decomposition curves in

Figure 8(a) for both PE-e and WPE are less multistage showing relative stability beyond 400°C. At the onset of mass change or loss, the weight difference between the PE-e and the shredded PE sheet is 3.6 mg. Significant detectable decomposition occurred in the PE-e up to 300°C. There is a fast decomposition between temperatures 300 and 400°C due to extensive degradation of polymer chains resulting from the evolution of unstable volatile products in the PEe contributing to the mass change [42]. With rising temperature up to 300°C, the percentage of portlandite slightly increases due to hydration of the OPC grains which was encouraged under the hydrothermal condition. Above 300°C, the percentage of portlandite slightly diminishes due to dehydration of portlandite to lime. At approximately 400°C, the percentage degradation and corresponding decomposed masses of the PE-e and WPE in Figure 8 are 85.69% (4.44 mg) and 29.15 (0.48 mg), respectively. The second weight loss in the temperature ranges 300°C-550°C is attributed to the dehydration of portlandite [41]. The DTG for PE-e shows initial mass increases from 28 to 80°C due to oxygen uptake to form compounds that are unstable towards higher temperatures. These compounds rapidly converted into labile forms and became endothermic. There is a repetition of this between temperatures 260 and 380°C. The DTG behaviour of WPE is different with no observed differential weight loss but rather showing an alternating insignificant weight gain and loss between 380 and 500°C. This is attributed to the inactivity of the polymer chains to undergo oxidation under nitrogen flow. Complete decomposition is observed between temperatures 550 and 700°C. The third weight loss in the temperature ranges 550°C-700°C is attributed to the decarbonation of calcite. A significant amount of calcite was detected in all of the hydrated samples which is attributed to the limestone filler commonly added to OPC [41].

In Figure 9(a), the thermal stability of REF-AC and REF-WC and concretes with PE-e are presented. The differential loss in mass concerning temperature generally follows a similar pattern. The REF-AC and REF-WC show a much closer resemblance that confirms the absence of PE-e in the concretes. Under a nitrogen purge flow rate of 100 ml min<sup>-1</sup>, all concrete shows a sharp decrease in mass loss between the temperatures of 80 and 200°C. There is a general increase in mass loss between the temperatures of 200 and 480°C. The concrete with PE-e\_2.5 shows a strong increase in mass



FIGURE 6: Water absorption with various concrete compositions.

TABLE 6: Water absorption for various compositions of concrete.

Composition	Mass after oven drying (g)	Mass after 24 hr water curing (g)	Water absorption (%)
REF-AC	956.3	1010.7	5.69
REF-WC	969.3	1024.5	5.69
PE-e_1	862.4	874.9	1.45
PE-e_2.5	822.6	831.8	1.12
PE-e_5	894.4	903.4	1.01
PE-e_10	783.9	790.8	0.88

loss with the optimum loss of  $0.146 \text{ mg min}^{-1}$  at  $444^{\circ}$ C. At temperatures of  $422^{\circ}$ C and  $460^{\circ}$ C, there was a differential mass loss of  $0.09 \text{ mg min}^{-1}$  for both PE-e\_1 and PE-e\_10. The differences in differential mass losses can be attributed to compositional differences in concrete during the sampling process. An almost steady mass loss was observed between temperatures 500 and  $600^{\circ}$ C and a gradual sharp increase observed from  $640^{\circ}$ C to  $692^{\circ}$ C.

There is depolymerization which occurred during the heating of the PE in the samples until equilibrium was obtained at the ceiling temperature and beyond which there was a shift of equilibrium of polymerization to depolymerization. At this point, the monomers become volatile and therefore burned off and evaporated. This leads to the observed significant mass loss, particularly between 200 and 480°C. The first peak observed for all PE-e concretes from 36 to 82°C is supposed to be the emission of the emulsifier used for the synthesis of the PE [43].

From the TG plot in Figure 9(a), for the REF concretes, PE-e\_1, PE-e\_2.5, PE-e\_5, and PE-e\_10 concretes, there were differences in the initial mass of each sample because of volume measurement of samples. This disparity was probably due to the different compositions of the concrete and

the nonuniformity of the particle sizes. There was an approximate 1.10 mg mass loss of the PE-e\_10 concrete sample between 234.35 and 425.55°C beyond which no further loss was observed even at the last and highest temperature of 693.54°C.

The DTA curves in Figure 9(b) which represent material characteristics for identification which indicate different endothermic peaks for the PE-e and the WPE, where the WPE has a single and higher endothermic peak at 327°C [44]. From Figure 9(b), the curves for PE-e show three endothermic peaks at 390°C, 403°C, and 470°C. The melting points of the PE-e were higher than the ones observed with the WPE. It is worth noting that the DTA peaks are not a true reflection of the sample temperature, and in this case, the samples have higher temperatures because they undergo endothermic reactions.

In Figure 9(b), the comparative DTA curves in Figure 9(b) show concretes for PE-e\_1, PE-e\_2.5, PE-e\_5, and PE-e\_10. The PE in PE-e\_2.5 and PE-e\_10 concretes were observed to show an increased melting temperature, which shows a noticeable decline in weight loss which may be attributed to volatile materials in the PE-e evaporating [23]. The melting of the PE in the concrete general was observed between 260 and 450°C, which does not differ significantly from the pure sample. The postmelting decline is linear and similar for all samples including the standard concretes between the temperatures of 500-700°C. Also, it can be deduced from Figure 9(b) that the heat capacity of PE-e is higher than that of the WPE when it is synthesized as a lipid-polyethylene emulsion.

The plot of heat flow against temperature in Figure 10 shows different peaks for the WPE and PE-e for the entire plot. The highest peaks, which correspond to the melting points, were observed at 55.10 mW at 391.55°C for PE-e and 32.61 mW at 391.21°C for WPE. The plot indicates a similar behaviour pattern in both samples showing different heating temperatures. Qualitatively, there is no change in the



FIGURE 7: Contact angles for the various concrete composition.



FIGURE 8: (a) Plot of DTG and TG against temperature for PE-e and WPE and (b) plot of TG against temperature for all studied samples.

chemical composition of the PE-e. The addition of the emulsifier and  $H_2SO_4$  to the mix increases the surface area of the emulsion thereby enhancing a steady endothermic process between 309 and 391.55°C.

Figure 10 shows the crystallization peak (exothermic) between the temperatures of 0 and 120°C for all concretes with PE-e except the standard concretes. This regime represents a C-S-H ettringite. Generally, glass transition temperature ( $T_g$ ) was at 157°C with unhindered segmental motions from the interactions of neighbouring chains [24]. The PE in the concrete undergoes melting at 250-450°C (endothermic process). Between the temperatures of 450 and 500°C,

there is thermal decomposition of calcium hydroxide. The DSC plot in Figure 10 does not indicate glass transition in the reference concretes confirming the methodology and experimental work that there was no PE-e in the concrete batch composition. Figure 10 shows different  $T_{\rm g}$  for PE-e concrete and PE-e only, with the PE-e showing  $T_{\rm g}$  at comparably high temperature at 205°C. At 570°C, quartz begins to decompose. Calcium carbonate begins to decompose at 700°C.

4.8. FTIR Test Results. The IR spectra in Figure 11 indicate a similar behaviour pattern in the REF concretes, PE-e\_1, PE-



FIGURE 9: (a) A plot of DTG against temperature for all studied samples. (b) DTA against temperature for all studied samples.



FIGURE 10: Plot of DSC versus temperature for all studied samples.

e\_2.5, PE-e\_5, and PE-e\_10 concrete samples but with the spectra for the WPE and PE-e showing characteristic trends and peaks of polyethylene at certain wave numbers. The IR shows equal peak band for both the PE and the PE-e. The IR spectra show several conspicuous humps at elevated percentage transmittance between 87.73 and 99.93 with corresponding wavelengths of 450-1744 cm<sup>-1</sup>. Lower values of % transmittance mean that some of the energy is absorbed by the compound and gives downward spikes. There are minimal humps or vibratory strings between 1744-2849 cm<sup>-1</sup> and 2920-4000 cm<sup>-1</sup>. The PE-e spectrum contains higher absorption bands at 719 cm<sup>-1</sup>, 1154 cm<sup>-1</sup>, 1466 cm<sup>-1</sup>,

1744 cm<sup>-1</sup>, 2849 cm<sup>-1</sup>, 2917 cm<sup>-1</sup>, and 3750 cm<sup>-1</sup>. There is a region of strong absorption between 2800 and 3000 cm<sup>-1</sup> due to the methyl asymmetrical stretching of the C-H atoms. Typical of PE is the methyl symmetrical stretching at 2876 cm<sup>-1</sup>. There are weak absorptions in the regions of 1800-2900 cm<sup>-1</sup> and 2920-4000 cm<sup>-1</sup> due to the rocking together of the CH<sub>2</sub> moieties. The spectra show alkane bands which typically stretch at 3100-3030 cm<sup>-1</sup>, aromatic stretching of C=C at 1480-1600, and bending of CH at 1660-2000 cm<sup>-1</sup> [45]. The medium absorptions observed between 500 and 1800 cm<sup>-1</sup> can be attributed to the bending of C-H and the stretching of C-C [46]. The summary of the absorption bands is presented in Table 7. The PE bands from this experimental work compare with typical characteristic IR bands of PE [28] shown in Table 8. The higher variations in absorbance of the PE-e can be attributed to the differences in surface free energy at different wavelength [28] incident on uptake of oxygen during the synthesis of the lipidpolyethylene emulsion causing an increase in the polarity of surface free energy thereby enhancing absorption of CH ions. The presence of the polar groups increases the hydrophilicity [47] of the PE-e compared to the WPE, and this property aids in batching of the concrete.

4.9. Microscopy Results. The microscopic images of the various concretes are shown in Figures 12(a)-12(f). The PE particles in the composite show distinct morphology, granular, and predominantly regular. The microscopic microstructures reveal the homogenous distribution of the PE particles in a nonemulsified state. This confirms the research goal that when PE is emulsified in water-oil, it makes it easier to mix with the concrete. Once mixed in concrete, the hydrophilic heads of micelles take part in the hydration process leaving the pure PE particles. The cement paste is homogeneous



FIGURE 11: Plot of FTIR for WPE, PE-e, and all studied samples.

TABLE 7: FTIR absorption bands of WPE, PE-e, and PE-e concretes per percentage weight replacement.

WPE	PE-e	REF-AC	REF-WA	PE-e_1	PE-e_2.5	PE-e_5	PE-e_10
		_		3449	3422	3401	3420
2917	2917	_	_	2925	2921	2919	2919
2847	2849	_	—	—	2852	2849	2849
_	1744	_	1720	—	—		—
_		_	_	_	_	1538	1538
1461	1461	1400	1410	1423	1422	1417	—
_	1154	_	—	—	_		—
_	—	1000			1012	1079	1086
_	—	_	845.5	981	_		—
719	719	_	—	—	_		—
	—	385	—	—	—	—	—

TABLE 8: Characteristic FTIR absorption bands for polyethylene [48].

Band (cm <sup>-1</sup> )	Assignment	Intensity
2919	CH <sub>2</sub> asymmetric stretching	Strong
2851	CH <sub>2</sub> symmetric stretching	Strong
1473 and 1463	Bending	Strong
1377	CH <sub>3</sub> symmetric deformation	Weak
1366 and 1351	Wagging deformation	Medium
1306	Twisting deformation	Weak
1176	Wagging deformation	Very weak
731-720	Rocking deformation	Medium

on both macro- and microscale. Generally, low reliefs were observed in all micrographs indicating the bonding of aggregates and the PE particles with the cement paste. There was a general absence of microcracks, air voids, and pasteaggregate porosity in the matrix. An improved packing even up to 10% PE-e replacement was observed. Therefore, the formulation of concrete for various percentages of PE-e is identical. Inherently, it indicates the normal trajectory of density and compressive strength for various percentage replacements of PE-e except for the 21 and 28 days of 10 wt% PE-e. The drop in compressive strength may be due to a deficiency in shear resistance around the cement paste. The light and few corrugations observed at the top right half of Figure 12(d), most probably, are artifacts caused by the grinding process as also reported by Zinin et al. and Roy et al. [49, 50].



FIGURE 12: (a-f) Concrete showing the dispersion of PE particles for various percentages of PE-e concrete and REF concretes.

#### 5. Conclusion

The concretes with recycled PE in water-oil emulsion for percentage replacement of 1% PE-e and 2.5% PE-e, 5% PE-e, and 10% PE-e were comprehensively studied. Based on the present results, the following conclusions can be drawn:

- (i) Polymeric material such as WPE can be synthesized for concrete formulation. The hydrophobic nature of the PE was rendered to have an affinity for water making it possible to bond with the cementitious material
- (ii) Hydrophilicity was observed in concrete with PE-e\_1 and PE-e\_2.5. Concretes with PE-e\_1 and PE-e\_2.5 have good workability whereas those with PE-e\_5 and PE-e\_10 have low workability
- (iii) Concretes with PE-e\_5 and PE-e\_10 do not form good miscibility when the PE is in the fresh mix but releases all the water to the cement paste and fine aggregates
- (iv) The density and compressive strength of the PE-e concrete decreased up to 13.68% and 78%, respectively, with PE-e\_10 at 28 days compared to REF-WC

- (v) The introduction of PE-e\_1 introduces plastic deformation in the concrete, and this is good in enhancing the yield strength of the concrete. There was a significant increase in the flexural modulus up to 33.4% of 3.913 GPa of the REF-WC to 5.220 GPa
- (vi) There were additional peaks of  $2917 \text{ cm}^{-1}$ ,  $2849 \text{ cm}^{-1}$ ,  $1744 \text{ cm}^{-1}$ ,  $1461 \text{ cm}^{-1}$ ,  $1154 \text{ cm}^{-1}$ , and  $719 \text{ cm}^{-1}$  observed in the PE-e, which confirms the absorption of CH<sub>2</sub> ions. This is attributed to the synthesis of the PE-e
- (vii) The microscopy showed the homogenous distribution of polyethylene particles in the concrete mix

From the study, it is feasible to use PE-e\_1 and PE-e\_ 2.5 to produce nonstructural lightweight concrete of 10-20 MPa [51].

#### Appendix

#### A. Concrete Mix Design (CMD)

- A.1. Design Calculations (Using IS 10262:2009, [51-53])
  - (a) Strength class: grade 25 (25 N/mm<sup>2</sup>)

- (b) Type of cement: ordinary Portland cement
- (c) Maximum nominal size of aggregates: 14 mm
- (d) Minimum cement content: 206 kg/m<sup>3</sup> (Table 18.3 of [49])
- (e) Maximum water/cement ratio for severe exposure condition: 0.65 (Table 18.3 of [49])
- (f) Workability of freshly batched concrete: 75 mm (slump)
- (g) Coarse aggregate type: crushed granite aggregate with no fines
- (h) Chemical admixture: no admixture/concrete retardant used
- A.2. Data for Materials
  - (i) Cement used: OPC 42.5R grade
  - (ii) Specific gravity of cement: 3.15
  - (iii) Specific gravity of coarse aggregate: 2.68
  - (iv) Specific gravity of fine aggregate: 2.65
  - (v) Aggregates have free surface moisture
  - (vi) Coarse aggregate: conforming to Table 2 of IS 383
  - (vii) Fine aggregate: conforming to zone III of IS 383

A.3. Target Strength for Mix Proportioning.

$$f_{\rm cm} = f_{\rm ck} + 1.65s,$$
 (A.1)

where  $f_{\rm cm}$  is mean compressive strength of concrete,  $f_{\rm ck}$  is the characteristic compressive strength, and *s* is the standard deviation.

From Table 1 of IS 10262:2009 standard deviation,  $s = 4 \text{ N/mm}^2$ .

Therefore, target strength =  $25 + (1.65 \times 4) = 31.60 \text{ N/mm}^2$ .

A.4. Selection of Water-Cement (W/C) Ratio. From Table 18.3 of [49], maximum water-cement ratio is 0.65 for mild exposure.

A.5. Selection of Water Content. By interpolation from Table 2 of IS 10262:2009, maximum water content per cubic meter of concrete for 14 mm nominal maximum aggregate size of aggregate is 200 kg (for 25 mm–50 mm slump range). Estimated water content for 75 mm slump = 200 + (3% of 200) = 206 kg.

A.6. Calculation of Cement Content.

$$W/C = 0.65.$$
 (A.2)

Cement content =  $206/0.65 = 316.92 \text{ kg/m}^3 > 260 \text{ kg/m}^3$ from Table 18.3 of [49].

A.7. Proportion of Volume of Coarse Aggregate and Fine Aggregate Content. By interpolation from Table 3 of IS 10262:2009, volume of coarse aggregate per unit volume of total aggregates corresponding to 14 mm size aggregates for zone III (fine sand) is 0.544; hence, the volume of fine aggregates per unit volume of total aggregates is 0.456.

A.8. Mix Calculations for  $1 m^3$  Concrete.

Volume of cement = 
$$\frac{\text{mass of cement}}{\text{specific gravity of cement}}$$
  
  $\times \frac{1}{1000} = \left(\frac{316.92}{3.15}\right) \times \left(\frac{1}{1000}\right) = 0.101 \text{ m}^3,$ 

Volume of water =  $\times = 0.206 \text{ m}^3$ , Volume of all in aggregates =  $1 - (0.101 + 0.206) = 0.693 \text{ m}^3$ , Volume of coarse aggregates =  $0.693 \times 0.544 = 0.377 \text{ m}^3$   $\cdot (\text{check } 3.2.1.7 \text{ for zone III ratio})$ , Mass of coarse aggregates (CA) = volume of coarse aggregates  $\times \text{specific gravity of CA}$   $\times 1000 = 0.377 \times 2.68$   $\times 1000 = 1010.36 \text{ kg}$ , Volume of fine aggregates (FA) = volume of all in aggregates  $\times 0.496 = 0.693 \times 0.456$   $= 0.316 \text{ m}^3$ , Mass of FA = volume of FA  $\times$  specific gravity  $\times 1000$  $= 0.316 \times 2.65 \times 1000 = 837.40 \text{ kg}$ .

(A.3)

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Mix proportions in mass per 1 m<sup>3</sup> are as follows:
Cement = 316.92 kg.
Water = 206 kg.
Fine aggregate = 837.40 kg.
Coarse aggregates = 1010.40 kg.
Volume of 6 specimen moulds = 2.53 \times 10^{-3} m<sup>3</sup>. Add 33% for bulking.
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Total dry volume to batch =  $3.325 \times 10^{-3}$  m<sup>3</sup>. Therefore, mix proportions in mass per dry volume for concrete REF-AC and REF-WC are as follows:

Cement = 1055 gWater = 685 g (685 ml)Fine aggregate = 2784 gCoarse aggregates = 3360 g

#### **Data Availability**

The data used to support the findings of this study are included within the article.

#### **Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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