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Precast lightweight concrete wall panels from plastic waste and household ash as partially sand and cement replacement

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ABSTRACT

Purpose: The present study aims to investigate the properties of precast lightweight concrete wall panels prepared with the addition of plastic powder and household ash as a partial substitution for sand and cement.

Design/methodology/approach: Eight formulations of lightweight concrete wall panels were prepared using a mix. The proportion of sand-to-cement ratio of 3:1 by weight and water-to-cement ratio of 1.85. Subsequently, sand and cement were gradually replaced with plastic powder and household ash. Plastic has water-repellent properties, while household ash is a natural pozzolan with cementitious properties in the presence of water and calcium hydroxide. Therefore, adding both materials in certain proportions should improve the quality of concrete wall panels. The mixture was cast in a fibreglass mould with length, width, and thickness dimensions of 30 x 30 x 3 cm. The evaluations of precast lightweight concrete wall panels include density tests, water absorption, compressive strength, water absorption-desorption capacity, and surface morphology.

Findings: Replacing 20% of sand and 10% of cement with plastic powder and household ash produces lightweight concrete wall panels with a density, water absorption, and compressive strength of 1512.2 kg/m^3, 7.95%, and 3.78 MPa, respectively. These precast concrete wall panels are acceptable for lightweight concrete wall panel requirements according to ASTM C129-06.

Research limitations/implications: In this research, lightweight concrete wall panels were prepared by adding PET plastic powder and household ash to replace the sand and cement partially. In further research, it is necessary to assess the precast lightweight wall panels prepared from other plastic types and natural pozzolans.

Practical implications: Using plastic waste reinforced with household ash as a partial substitute for sand and cement can create eco-friendly precast lightweight concrete wall panels. This is an effort to reduce sand and cement usage in concrete wall panel production and as an innovative way to reduce plastic waste in the environment.

Originality/value: It has been experimentally proven that utilising plastic powder of up to 20% and household ash of up to 10% by weight for partial replacement sand and cement in preparation of precast lightweight concrete wall panels fully meets standard materials for manufacturing according to ASTM C129-06 standard for non-loading-bearing lightweight concrete. The addition of plastic makes the colour of the concrete wall panels' surface more attractive.

Keywords: Household ash, Precast lightweight concrete wall panel, Plastic waste

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PROPERTIES

1. Introduction

Exposure to plastic waste in the environment causes serious problems in the aspects of human health, habitats, and space usage. In water, plastic becomes toxic to aquatic organisms, while on land, plastic blocks air circulation and poisons soil organisms, making soil less productive. Burning plastic releases toxic gases such as vinyl chloride, dioxins, phthalates and bisphenols, disrupting the respiratory and nervous systems [1,2]. The accumulation of plastic in the environment occurs due to careless use, inadequate recycling, and accumulation of plastic in landfills. Thus, converting plastic waste into economically valuable and environmentally friendly products is considered an effective way to minimise the accumulation of plastic waste in the environment. Many economic products are from plastic waste, such as plastic flowers and wallets [3]. In addition, plastic waste has also been widely used as a mixed material in concrete and building materials such as paving blocks, asphalt pavement, bricks, eco-bricks and non-bearing plastic wall panels [4-8].

Currently, wall panels are a very important building material in construction. Wall panels are sheets of patterned material attached to building surfaces as an architectural decoration added to the wall that makes the appearance of the wall look more attractive. Wall panels for interior buildings are generally made from materials such as wood, gypsum, fibreglass-reinforced polymers, and laminated fabrics [9,10]. In contrast, the exterior buildings are made from natural stone or precast concrete and bricks with a thickness of 3 cm [11].

Natural stone has been widely used in exterior wall panels because of its strength, attractive appearance, and low maintenance costs. However, excessive exploitation of natural stone can trigger various problems, such as damage to environmental aesthetics, dug holes that can endanger human safety, and puddles of water during the rainy season, thus acting as a growth medium for dangerous mosquitoes. For this reason, it is necessary to search for potential materials sourced from recycled materials as raw materials for making concrete wall panels without damaging the environment. Some recycled materials that have been used as a mixture in the preparation of concrete wall panels such as limestone waste mixed with polyester resin adhesive [12], iron ore tailings [13], fly ash, granite and marble processing factory waste [14,15], coconut shell [16], rice husk and red clay [17] as well as a mixture of sand, limestone, cement, and recycled rubber [18]. Precast concrete wall panels have the advantage of more flexible construction installation while reducing the exploitation of natural rocks which damage the environment.

The present study investigates the characteristic precast lightweight concrete wall panels prepared from plastic waste-type polyethene terephthalate (PET) reinforced with household ash to partially replace sand and cement. The concrete only functions as non-structural components and not as load receivers. Bringing plastic powder and household ash into play as partial replacements for sand and cement in lightweight concrete wall panels offers many benefits in terms of ecology, energy efficiency and cost [19]. In addition, The addition of plastic in concrete wall panels reduces sand usage and will significantly contribute to the colouring of wall panels to make them seem more attractive. On the other hand, household ash, which is a natural pozzolan, has a high content of silica (SiO_2), alumina (Al_2O_3) and calcium oxide (CaO), which will have cement-like properties when a little water is added. Besides reducing the use of cement, the role of pozzolans is also increasing its durability. Several types of pozzolans are used for mixing precast concrete, including fly ash, volcanic ash, ceramic shards, rice husk ash, sawdust, and biomass ash [20,21]. Adding pozzolan of nano silica at 1%, 2%, and 3% as a partial cement replacement considerably increased the mechanical strength of concrete [22]. The article attempts to investigate the effect of partial substitution of sand and cement with plastic powder and household ash on the properties of precast lightweight concrete wall panels with parameters tested, including microstructure, density, water absorption, compressive strength, and water absorption-desorption behaviour. The water absorption value, density, and compressive strength of lightweight concrete wall panels were compared to the ASTM C129-06 standard for non-loading, lightweight concrete [23].

2. Experimental work

2.1. Materials and methods

The materials used to prepare precast lightweight concrete wall panels comprise plastic powder, sand, household ash, and Portland cement. The household ash was obtained from the combustion of the brick and tile manufacturing industry, while powder plastic was made from polyethylene terephthalate (PET) plastic type. All materials are sieved using a sieve with 1 mm holes. The materials used for lightweight concrete panel preparation are presented in Figure 1.

Fig. 1. Materials for preparing precast lightweight concrete wall panels

Table 1.
Chemical composition of lightweight concrete wall panels materials with XRF test

Materials	Al_2O_3, %	SiO_2, %	CaO, %	Fe_2O_3, %
River sand	13.00	41.10	15.40	24.80
Household ash	5.27	2.90	79.26	2.85
Portland cement	2.10	10.2	76.01	5.07

Physical properties, including specific gravity, water absorption, and metal oxide content, characterise lightweight concrete wall panel materials. The specific gravity was measured using the pycnometer method. In contrast, the water absorption and compressive strength were analysed based on the method according to ASTM C129-06 [23], and the main metal oxide content was determined using X-ray fluorescence. The main content of the oxide metals in raw materials is listed in Table 1, while their physical properties are presented in Table 2.

Table 2.
Physical characteristics of lightweight concrete wall panel materials

Properties	Sand	Plastic powder	Household ash
Specific gravity, kg/m^3	2.30	0.86	1.55
Water absorption, wt. %	1.01	0.22	2.30

2.2. Preparation of plastic powder

Plastic powder can be prepared by heating the chopped plastic using a melting machine. The melted plastic is left to cool and then converted into powder using a grinder machine completed with a filter size of 1 mm.

2.3. Preparation of precast lightweight concrete wall panels

Raw materials used to prepare precast lightweight concrete wall panels were sand, portland cement, and water. The sand-to-cement ratio and the water-to-cement ratio are 3:1 and 0.85, respectively. Eight different concrete wall panel mixtures were prepared for this investigation. Precast lightweight concrete wall panel control was made with a proportion of 3 (sand) to 1 (Portland cement). Then, the sand was replaced gradually with 5, 10, 20, and 30% (by weight) of plastic powder, while the cement was reduced by adding 10, 20, and 30% (by weight) of household ash. The formulation summary of precast concrete wall panels is listed in Table 3.

Table 3.
The mixture proportion was used to prepare one specimen of precast lightweight concrete wall panels, by weight

Speci-mens	Sand (S), kg	Plastic powder (PP), kg	Portland cement (PC), kg	Household ash (HA), kg
1	3.00	0.00	1.00	0.00
2	2.85	0.15	1.00	0.00
3	2.70	0.30	1.00	0.00
4	2.40	0.60	1.00	0.00
5	2.10	0.90	1.00	0.00
6	2.40	0.60	0.90	0.10
7	2.40	0.60	0.80	0.20
8	2.40	0.60	0.70	0.30

The mixture is poured evenly into a mould with dimensions of length, width and thickness of 30×30×3 cm until completely filled. The concrete wall panels were cured for 28 days at room temperature and then investigated for their surface morphology, density, water absorption, compressive strength, and water absorption-desorption behaviour.

2.4. Characterization of precast lightweight concrete wall panels

Precast lightweight concrete wall panels are characterised by their physical properties, including surface morphology, density, compressive strength, water absorption capacity, and water absorption-desorption behaviour. The density, compressive strength, and water absorption values were compared to ASTM C129-06 [23] for lightweight nonloading bearing concrete standard, as presented in Table 4.

Table 4.
Specification of lightweight, non-load-bearing concrete in accordance with ASTM C129-06 [23]

Type II	Average of three units	Individual unit
Compressive strength, MPa	4.14	3.45
Density, kg/m^3	≤ 1.680	
Water absorption, %	≤ 12%	

Surface morphology observation

The surface morphology of precast lightweight concrete wall panels was investigated under scanning electron microscopy with magnification x500.

Determination of dry density

The specimens with a dimension of 5 x 5 x 5 cm are used to determine the dry density of concrete at the age of 28 days. The formula calculates the dry density of each specimen:

$$D_d = M_d/V_d \ (\mathrm{kg/m^3}) \qquad (1)$$

where M_d is the weight of dry concrete (kg), and V_d is the volume of concrete (m^3).

Water absorption test

The water absorption test was conducted to measure the water absorption properties of the lightweight concrete wall panels specimen. The tested samples were used at 28 days, and procedure tests were conducted using methods according to ASTM D6489-99 [24]. The specimens with dimensions of 5 cm x 5 cm x 5 cm were immersed in water at room temperature for 24 hours to be saturated. Subsequently, the surface of the test specimen is dried using a towel and weighed. The specimens were oven-dried at the temperature of 105°C for 24 h and weighed. The formula calculates the water absorption of each specimen:

$$\text{Water absorption} = \frac{M_w - M_d}{M_d} \times 100\ (\%) \qquad (2)$$

where, M_w and M_d are wet and dried specimens weigh, respectively.

Compressive strength test

The compression test was conducted to measure the strength of lightweight concrete wall panels. The specimens with dimensions of 5 x 5 x 5 cm were tested at a cure time of 28 days using the ADR touch compression testing machine, as given in Figure 2.

Fig. 2. Set up the ADR touch compression machine

The tested sample is placed on a compression machine, and the load is applied continuously until the specimen fails. The compressive strength was calculated using the equation:

$$\sigma = P/A \ (N/cm^2) \qquad (3)$$

where σ is compressive strength (N/cm^2), P is compressive load (N), and A is a sectional area (cm^2).

Determination of water absorption-desorption

The gravimetric method, described in research by Zhang et al., 2021 and Li et al., 2014 [25,26], determines the water absorption-desorption. The absorption test specimens were oven-dried at 105°C for 24 hours and then placed in an uncovered container surface at room temperature. The specimen's weight was measured using an analytical balance at 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14 days. For the water desorption test, all tested samples were immersed in water for 3 days to be saturated, and then each tested sample was dried using a towel to remove water bound to the surface of the specimen and weighed. The sample is soaked again in water for 24 hours and weighed. This is repeated until the change in specimen mass is less than 0.5% to obtain a water-saturated sample condition. Then, the specimen was transferred to a glass container at a constant temperature, as shown in Figure 3.

Fig. 3. Glass container for water desorption test

The specimen's weight was periodically measured at 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14 days.

The cumulative percentage increase or decrease in humidity at a certain time as a result of moisture absorption or desorption is calculated using the following formula:

$$M_t = \frac{W_t - W_j}{W_j} \times 100\ (\%) \tag{4}$$

where M_t = water content, W_t absorption = initial weight of the dried specimen, W_t desorption = initial weight of the wet specimen, and W_j = sample weight at a certain time.

3. Results and discussion

The use of precast lightweight concrete wall panels is associated with an increase in the strength and physical attractiveness of the building. In this research, the precast lightweight concrete wall panels were made using plastic waste powder and household ash to substitute sand and cement partially. The physical appearance of precast lightweight concrete wall panels containing plastic powder and household ash is shown in Figure 4.

Fig. 4. The visual appearance of precast concrete wall panels with the addition of plastic powder and household ash as a partial replacement for sand and cement

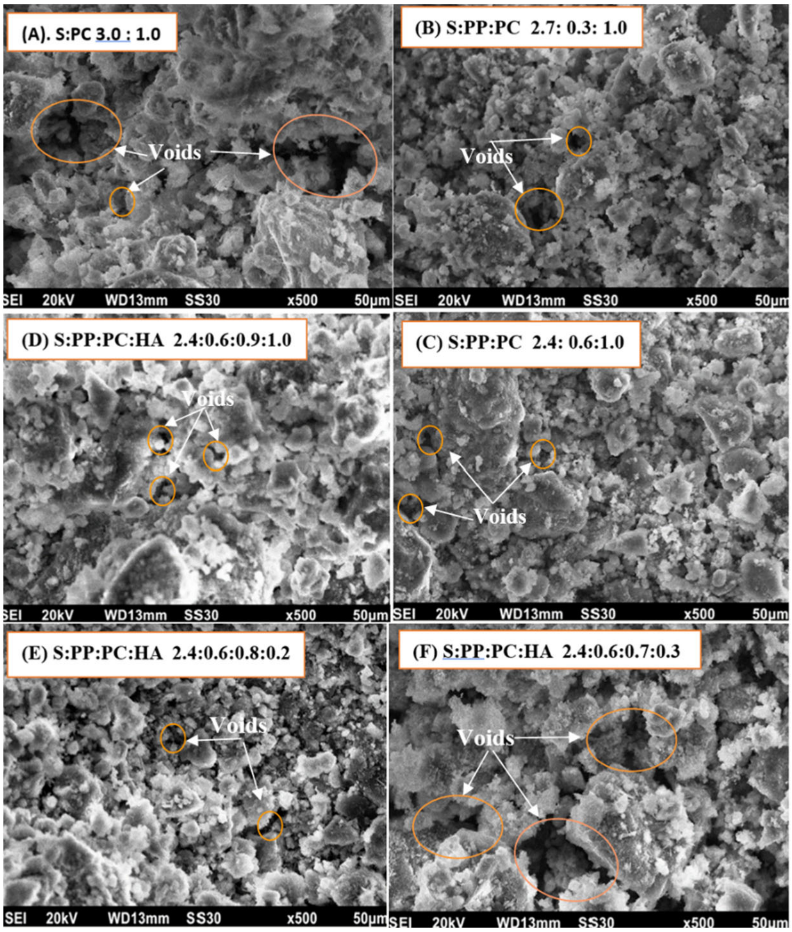

Fig. 5. SEM Micrographs of precast lightweight concrete wall panels with different amounts of plastic and household ash content as a partial replacement of sand and cement at magnification of x 500

3.1. Surface morphology of lightweight concrete wall panels

Scanning electron microscopy (SEM) is widely used to investigate the material's surface morphology. The surface morphology of each lightweight concrete wall panel sample was observed using SEM, and its SEM images are shown in Figure 5. It was observed that there are differences in the surface morphology of lightweight concrete wall panels made with different contents of plastic powders and household ash.

Figure 5 shows that in the precast lightweight concrete wall panel control (without plastic powder), many voids were observed (A). However, the voids tend to decrease as the amount of plastic used to replace the sand increases (B-C) partially. Furthermore, at a constant plastic powder, the addition of 10% household ash to reduce the use of cement causes the pores of the wall panels to become increasingly closed (D). In contrast, more voids appeared when the addition of household ash was increased to 20% and 30% (E-F). Increasing the number of voids in concrete wall panels contributes to increased water absorption of the concrete. As can be seen from Figure 7, the concrete wall panels containing plastic powder of 10% and 20% give a water absorption value of 9.78% and 7.97%, respectively.

3.2. Density studies

Density is one of the significant parameters that should be considered in producing concrete wall panels.

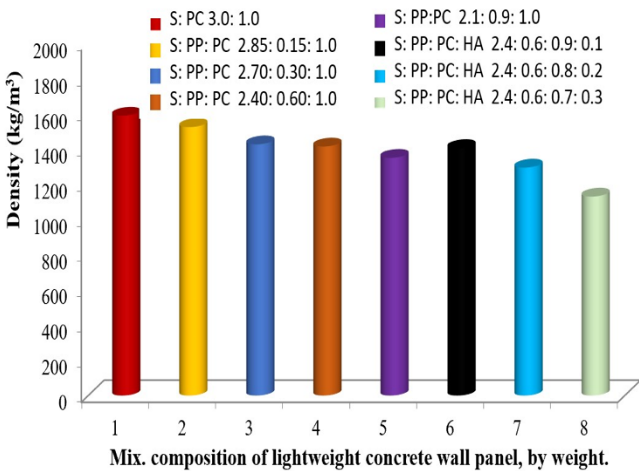

Fig. 6. Dry density of precast concrete wall panels at different mixes. material compositions

Figure 6 shows the density of eight types of concrete wall panels. It can be seen clearly that the density of concrete wall panel samples decreased as the percentage of plastic powder and household ash used for sand and cement replacement increased. Precast concrete wall panel samples have a density range from 1134 to 1521 kg/m^3. According to ASTM C129-06 [23], the density value is less than 1680 kg/m^3 for lightweight concrete, 1680-2000 kg/m^3 for medium weight and more than 2000 kg/m^3 for normal-weight concrete. As compared to the standard value of lightweight non-load-bearing concrete in accordance with ASTM C129-06 [23], the density of precast concrete wall panels was found to be slightly lower. However, these concrete wall panels are still considered lightweight, non-load-bearing concrete.

3.3. Water absorption studies

The ability of materials to absorb water is related to the durability of the material. In general, water absorption in concrete is influenced by pores or cavities, where the more cavities contained in the concrete, the greater its water absorption capacity, decreasing its durability. The water absorption of precast concrete wall panels at different contents of plastic powder (PP) and household ash (HA) used to replace sand (S) partially and Portland cement (PC) for one specimen is shown in Figure 7.

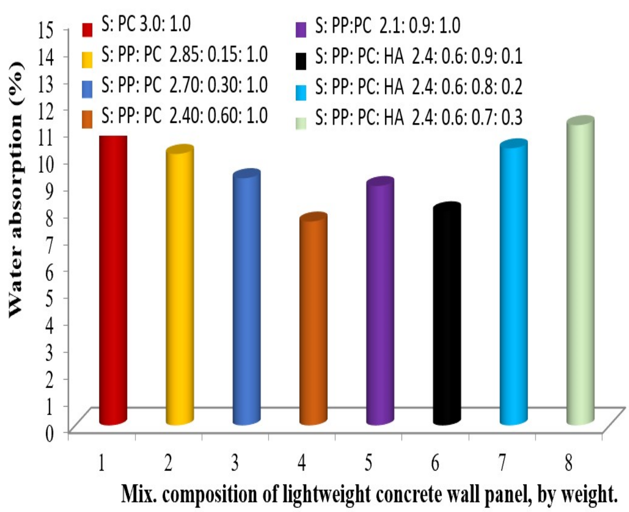

Fig. 7. Water absorption of precast concrete wall panels at different mixed material compositions

As seen in Figure 7, water absorption of precast concrete wall panels tends to decrease slightly with the increase in plastic content. However, water absorption increases as the household ash content in the concrete wall panels increases. The concrete wall panels adding 5%, 10%, 20%, and 30% of powder plastic as a partial sand substitute have a water absorption value of 10.08%, 9.78%, 7.97% and 9.56%, respectively. This may be related to the hydrophobic nature of plastic, which repels water. The water absorption capacity test was also observed to be much lower (0.22%) compared to the water absorption capacity of household ash (2.30%) and sand (1.01%). Adding hydrophobic particles such as plastic to concrete materials provides strong water repellency. Plastic within wall panels tends to fill the voids; the higher the plastic content, the lesser the voids [27-29]. The water absorption capacity also relates to density, where water absorption increases when concrete density is decreased [30]. This finding is in line with Izzati et al., 2018 [31], who states that the water absorption properties of concrete bricks containing polystyrene as a material replacement for sand decrease as the content of EPS increases. Babatunde et al. 2022 [32] reported that the concrete mixture's water absorption capacity decreased with the amount of plastic added. However, the water absorption capacity increased after adding the quarry dust. Research conducted by Kashyap et al. (2023) [33] found that the addition of nano-silica (2%) and marble dust (5%) together was able to reduce water absorption and permeability of concrete up to 26% and 57%, respectively. Based on the water absorption value, precast lightweight concrete wall panels added with plastic powder and household ash up to 20% and 10% are the full requirement according to ASTM-C129-06 [23], in which the water absorption of the non-load bearing should be less than 12%.

3.4. Compressive strength studies

Types and compositions of material mixtures are significant parameters that affect the strength of concrete wall panels. In the study, precast concrete wall panels were made from a mixture of sand and cement with a ratio of 3:1, and then the sand and cement were replaced gradually with plastic powder and household ash. The compressive strength of the specimen was calculated by dividing the maximum load applied to the specimen in cube form during the test by the cross-sectional area, and the result is presented in Figure 8.

Figure 8 shows the compressive strength of precast concrete wall panels for each different plastic powder and household ash content as a partial replacement for sand and Portland cement. The strength gradually decreases when the plastic powder and household content increase. Precast lightweight concrete wall panels without plastic powder and household ash addition give 8.34 MPa of compressive strength. In contrast, replacing 5%, 10%, 20%, and 30% with plastic powder reduces their compressive to 7.48, 6.12, 4.98, and 3.58 MPa. At a constant amount of plastic powder, the compressive strength decreases from 4.98 MPa to 3.78, 2.42 and 2.24 MPa after adding 10%, 20% and 30% household ash as a cement substitute. The minimum strength requirements for non-load-bearing concrete masonry for individual units and the average three-unit test according to ASTM-C129-06 [23] were 3.45 MPa and 4.14 MPa, respectively. In addition, the minimum compressive strength for wall panels in accordance with SNI 03-3122-1992 was 2.82 to 3.12 MPa (class A) and 2.19 to 2.51 MPa [34]. Therefore, to make non-loading precast concrete wall panels, the maximum amount of plastic powder and household ash added to replace sand and cement is 20% and 10% by weight, respectively. The finding is in line with Yaseen (2015) [35], which stated that the strength of precast concrete panels increased with the addition of small pieces of PET waste of 1.0% by volume compared to concrete panels control (without the addition of plastic). Still, the strength decreased after increased plastic content. Another study by Hussain and Yadav (2023) [36] found that the optimum dose of glass fibre added to produce the best mechanical strength of concrete was 1.5% by the weight of cement used.

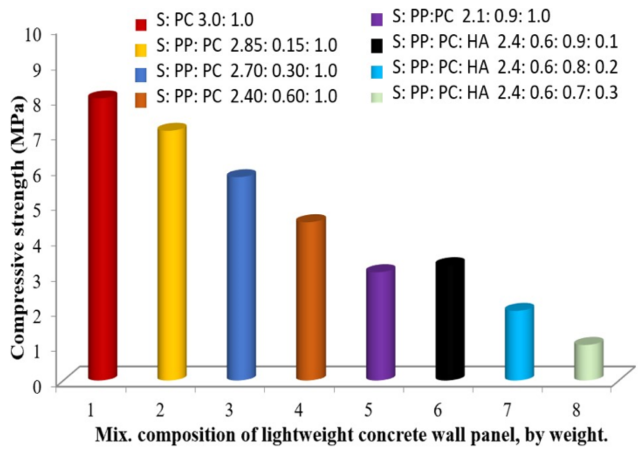

Fig. 8. Compressive strength of precast concrete wall panels at different mixes. material compositions

3.5. Water absorption-desorption behaviour

The water content of precast lightweight concrete wall panels is the free water content bound to the pores of the concrete, which can evaporate at any time. Measuring the water content adsorbed on a test sample involves weighing the test sample after drying and after ageing for a certain time. Changes in water content in concrete wall panels measured at 1 to 14 days are presented in Figure 9.

As shown in Figure 9, all specimens initially showed a high water absorption or desorption rate, then gradually decreased until finally reaching the equilibrium value.

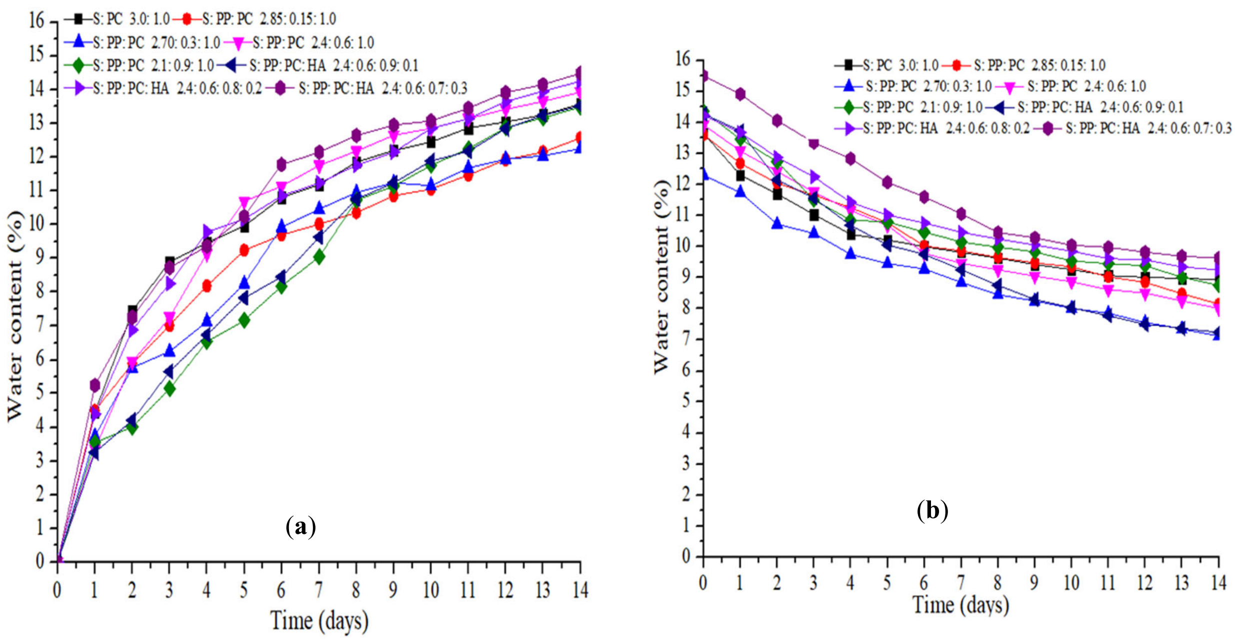

Fig. 9. Water absorption and desorption of precast lightweight concrete wall panels over time: (a) absorption and (b) desorption

The presence of voids in the precast weight-light concrete wall panels containing 20% plastic powder and 30% household ash (S:PP: PC; HA 2.4: 0.6: 0.7: 0.3) allow it to absorb water at a faster rate than precast weight-light concrete wall panels containing 20% plastic powder and 10% household ash. Based on the surface morphology of concrete wall panels (Fig. 5), prepared by replacing up to 20% of sand with plastic powder and 10% of cement with household ash, they have a compact surface morphology with holes sufficiently covered by plastic powder and ash. The density, compressive strength, and water absorption of precast lightweight concrete wall panels containing 20% sand and 10% household ash are 1512.2 kg/m^3, 7.95% and 3.78 MPa, respectively. The concrete wall panels are acceptable to lightweight, non-load-bearing concrete in accordance with ASTM-C129-06 [23].

4. Conclusions

A study has been carried out to evaluate the physical properties of precast lightweight concrete wall panels with the addition of powder plastic and household ash as partial replacements for sand and cement. The physical properties of precast lightweight concrete wall panels were greatly influenced by the percentage of plastic and household ash added. The density, water absorption, and compressive strength of these concrete wall panels containing 20% plastic and 10% household ash were 1512.2 kg/m^3, 7.95%, and 3.78 MPa, respectively. The precast lightweight concrete wall panels are acceptable for lightweight concrete wall panel requirements, according to ASTM-C129-06 [23].

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