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THE EFFECT OF RECYCLED WASTE POLYSTYRENE PLASTIC AGGREGATE ON THE ENGINEERING PROPERTIES OF LIGHTWEIGHT COMPOSITES

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Abstract

The substantial generation of polystyrene waste from the food industry poses significant environmental and human health challenges. This study addresses these issues by using recycled lightweight aggregates (RLWA) from waste polystyrene plastic as an alternative for coal bottom ash in the production of lightweight composites (LWC) incorporating ternary binder materials of cement, fly ash, and ground granulated blast-furnace slag. To assess the impact of RLWA on LWC's engineering performance, various proportions of RLWA were incorporated into the LWC mixtures as a fine aggregate. Results show that RLWA content significantly influenced the mechanical and durability properties of LWC. Specifically, increasing RLWA content reduced the dry density and mechanical strength, while increasing the water absorption and drying shrinkage of the LWC. The correlations among these LWC's properties were also examined. Notably, the LWC specimen with 50% RLWA content achieved the highest 28-day flexural strength of 11.06 MPa and compressive strength of 63.8 MPa, alongside the lowest water absorption rate of 5.34% with a dry density of 1896 kg/m^3. These results underscore the potential of utilizing RLWA as a fine aggregate in LWC production, highlighting its feasibility for practical applications and providing information for more sustainable construction practices. By turning wastes into useful construction materials, the study not only addresses waste management issues but also contributes to the development of greener materials for sustainable growth.

Keywords: engineering properties; lightweight composites; recycled lightweight aggregate; waste polystyrene plastic.

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1. Introduction

Nowadays, environmental pollution caused by plastic has become a significant issue due to its widespread use and improper disposal. It is estimated that plastic accounts for 12% of municipal solid waste and Asian countries discharge most of the plastic waste [1, 2]. In 2021, there were 8.4 ± 1.4 Mt of plastic waste discharged from 193 countries [1], in which, it is predicted that global microplastic emissions could reach 0.749 Mt by 2060 [3]. Plastic waste plays a key role in air, soil, and water pollution. For example, the availability of plastic fragments in the air may cause lung diseases [4]. Besides, inadequate landfills or the burning of plastic waste may cause soil pollution. Indeed, microplastic can permeate into the soil and prevent nutrient absorption of trees, lowering food production and causing health issues [5]. In terms of water pollution, microplastic in marine environments can cause intestinal damage including cracking of villi and splitting of enterocytes in fish [6].

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The primary types of plastic waste are polyethylene, polypropylene, polyvinyl chloride, polystyrene, polyethylene terephthalate, and polycarbonate [7]. Polystyrene is petroleum-based plastic, made from styrene (vinyl benzene) monomer [8], which contains trapped air in over 96% of the total volume and is used in various major industries, especially in industrial food fields [9]. It is estimated that a significant amount of polystyrene waste, roughly 20 Mt, is released annually [10]. The high amount of this waste can create various problems related to the environment, animals, and humans as mentioned above. Therefore, turning plastic waste into valuable material may be a good choice for sustainable development to address existing waste plastic and environmental challenges.

The use of plastic waste like polystyrene plastic in building materials has been studied for many years. Indeed, Kharun and Svintsov [11] used expanded polystyrene (EPS) and crushed polystyrene for structural thermal concrete production, highlighting the compressive strength and the thermal conductivity ranging from 0.28 to 4.22 MPa, and from 0.073 to 0.3 W/(m.°C). This type of concrete could be used for thermal insulating and structural thermal insulating material. Sayil and Gurdal [12] incorporated polystyrene waste and gypsum to create blocks and panels, resulting in sufficient mechanical strength, good heat insulation, and fire retardant. The produced specimens had a density from 200 to 800 kg/m^3 and can be used for block production. Demirboga and Kan [13] investigated the impact of an artificial aggregate made of polystyrene waste to replace natural sand in concrete manufacture, showing lower thermal conductivity and higher shrinkage. Besides, the increase in polystyrene aggregate (PA) content made the mixture rubbery, harsh, and difficult to place and compact. In Vietnam, several studies regarding the preparation of lightweight concrete with EPS in combination with industrial by-products. For instance, Van et al. [14] investigated the combined effects of EPS (0-40% by volume of concrete) and bottom ash (BA, 0-30% by mass of natural aggregate) on the properties of lightweight concrete. The results showed that increasing EPS and BA contents declined the strength of lightweight concrete. In particular, the 28-day-old concrete specimens with 40% EPS and 30% BA showed a roughly 26% reduction in strength when compared to the control concrete. Therefore, the authors recommended using this kind of concrete in lightweight concrete blocks for Vietnam's high-rise buildings. Thang et al. [15] produced lightweight concrete using various recycled EPS contents (25-50% by volume of concrete). The authors reported that the lightweight concrete containing 25% EPS registered the maximum dry density and compressive strength of 1550 kg/m^3 and 21 MPa, respectively. Further increasing the EPS content reduced the density, compressive strength, and thermal conductivity of concrete. Hoang et al. [16] studied the fabrication of EPS lightweight concrete panels based on increasing the strength of the mortar matrix and optimizing the porous structure of the system (by using various EPS contents) to make EPS lightweight concrete with a respective density and compressive strength of 875-1150 kg/m^3 and 7.5-15 MPa for manufacturing wall panels while making the EPS lightweight concrete with and a density of 1275 kg/m^3 and compressive strength of 20 MPa for producing floor and roof panels.

Due to the lightweight and low thermal conductivity properties mentioned above, the polystyrene waste was applied for lightweight concrete production. Previous studies have evaluated the performance and properties of lightweight concrete using PA. For instance, Xu et al. [17] used Taguchi's method to study the density, strength, and stress-strain behavior of lightweight concrete for lightweight hollow brick manufacture, demonstrating the density and compressive strength ranged from 1760 to 2060 kg/m^3 and 7 to 20 MPa, respectively. Apart from showing the relationship between the mechanical strength and the density of lightweight concrete, Xu et al.'s study also reported that the impact of PA dosage was most significant, followed by water-to-binder ratio, cement content, and sand content. Babu et al. [18] studied the impact of expanded and un-expanded PA size on the strength and moisture migration properties of lightweight concrete (with density ranging from 1000 to 1900 kg/m^3), resulting in higher moisture migration in un-expanded PA. The concrete made of un-expanded PA exhibited brittle failure similar to normal-weight concrete and higher in mechanical strength than that of expanded PA. Sabaa and Ravindrarajah [19] explored the effects of replacing chemically coated crushed polystyrene granules with coarse aggregate on the properties of lightweight concrete, highlighting the increase of drying shrinkage and creep, whereas compressive strength, modulus of elasticity, and density decreased. Notably, a maximum drying shrinkage value of 1000 microstrain was observed after 240 days. Šeputytė and Sinica [20] created lightweight concrete using expanded glass and PA, revealing that the concrete exhibited a low thermal conductivity coefficient (from 0.070 to 0.098 W/m·K), density, and compressive strength. Besides, a strong relationship between the density and thermal conduction was also established. Herki et al. [21] explored the impact of stabilized PA on the engineering properties of lightweight concrete. The PA in this investigation was made of 70% polystyrene, 10% natural aggregates, and 20% cement. The results showed that the density, mechanical strength, and ultrasonic pulse velocity decreased after increasing PA. Moreover, the direct proportional relationship between ultrasonic pulse velocity and compressive strength was established. Another study by Herki and Khatib [22] found that the stabilized PA had a significant impact on the mechanical and durable characteristics of lightweight concrete. Particularly, the density and the compressive strength were 42% and 67% lower whereas the water absorption increased remarkably (over 20%).

On the other hand, to promote the sustainability and eco-friendly of lightweight composites (LWC), various industrial by-products (i.e., fly ash (FA), ground granulated blast-furnace slag (GGBFS), and BA) have been incorporated in the LWC mixtures. Akçaözoğlu and Atiş [23] studied the impact of adding GGBFS and FA on the strength of lightweight mortars that contained waste polyethylene terephthalate bottle aggregates. They found that replacing 50% of the cement with GGBFS improved compressive strength and reduced drying shrinkage. However, replacing 50% of the cement with FA decreased the mechanical strength of the mortar. Jang et al. [24] studied the resistance of various mortar types (i.e., conventional cement mortar, lightweight mortars containing expanded shale or BA, FA-cement mortar, and GGBFS-cement mortar) against the coupled deterioration of chloride penetration and carbonation. The results show that the lightweight mortar containing BA exhibited greater resistance to chloride compared to the other types. It was also noted that the type of binder used significantly impacted the rate of chloride penetration. In the study conducted by Lee et al. [25], they evaluated the effect of using FA and GGBFS as cement substitutes on the engineering properties of mortar, which was made with artificial lightweight aggregate produced by calcining coal ash and dredged soil. The results demonstrated that the lightweight mortar with 5% FA and 5% GGBFS exhibited the best performance in terms of strength improvement and carbonation resistance. Tang et al. [26] evaluated the influence of replacing fine aggregate and cement with coarse and ground BA on mortar performance. The authors found that using 25% coarse BA as a fine aggregate and 10% or 20% ground BA as a cement replacement significantly increased mortar strength, leading to reduced landfill waste and CO_2 emissions, thus promoting sustainability.

Although previous investigations in the performance of LWC using PA have been carried out, these studies mostly concentrated on the effect of polystyrene aggregate on mechanical strength and the application of polystyrene aggregate as sand replacement. So far, the investigation of polystyrene waste as an alternative to BA in LWC with FA and GGBFS has been relatively limited. This study aims to address these gaps by utilizing recycled lightweight aggregates (RLWA) made from waste polystyrene plastic to substitute for BA at different proportions. The study will investigate the impact of RLWA on the mechanical and durable properties of LWC and establish the correlation between strength and other properties of the resulting LWC. The ultimate goal is to encourage the practical application of these findings for sustainable development.

2. Materials and experimental methods

2.1. Materials

In this study, the LWC was prepared by using blended Portland cement (PC), FA, and GGBFS as binder materials due to their positive effects on the mechanical strength of the composites. The major chemical compositions of these binder materials are given in Table 1, showing that the primary compositions of FA and GGBFS were SiO_2, Al_2O_3, and CaO, while silicon dioxide and calcium oxide accounted for over 80% of the main ingredients of PC. During cement hydration processes, SiO_2 and CaO played a key role in the formation of calcium-silicate-hydrate (C-S-H), which was attributed to the mechanical strength enhancement of LWC [27]. Indeed, the main silicate phases in cement, tricalcium silicate (C_3S) and dicalcium silicate (C_2S) react with water to form C-S-H and calcium hydroxide (CH) based on Eqs. (1) and (2) [28]:

$$2\,C_3S + 6\,H_2O \longrightarrow 3\,CaO \cdot 2\,SiO_2 \cdot 3\,H_2O + 3\,Ca(OH)_2 \tag{1}$$

$$2\,C_2S + 4\,H_2O \longrightarrow 3\,CaO \cdot 2\,SiO_2 \cdot 3\,H_2O + Ca(OH)_2 \tag{2}$$

Besides, previous studies also reported that FA and GGBFS were pozzolanic materials, and the main chemicals present in FA and GGBFS also contributed to improving the mechanical strength and durability of concrete through the mechanism of forming C-S-H and calcium-aluminum-silicate-hydrate (C-A-S-H) gels by Eq. (3) [27–30] and Eq. (4) [31]:

$$x\,Ca(OH)_2 + SiO_2 + (x{-}y)\,H_2O \longrightarrow C_xSH_y \tag{3}$$

$$A + C\bar{S}H_2 + 3\,CH + 7\,H \longrightarrow C_4A\bar{S}H_{12} \tag{4}$$

Table 1. Primary chemical compositions of binders

Composition (%)	PC	FA	GGBFS
SiO_2	19.90	50.27	33.87
Al_2O_3	4.48	35.61	14.41
Fe_2O_3	3.24	5.22	0.01
CaO	61.56	1.20	40.84
MgO	3.32	0.78	6.74
SO_3	2.76	0.20	1.20
K_2O	0.65	1.87	0.47
Na_2O	0.17	0.29	0.39
Others	3.92	4.56	2.08

Moreover, using industrial by-products such as BA as fine aggregate replacement in concrete production could help to prevent the depletion of natural resources, reduce environmental problems, save costs [32], and still reach the required strength [33, 34]. Thus, BA with a density of 2145 kg/m^3, water absorption of 8.2%, and fineness modulus of 2.63 was used as the aggregate in this investigation and collected at a thermal power plant with the particle size distribution and scanning electron microscope (SEM) images shown in Figs. 1 and 2, respectively. It could be observed that the surface of BA particles was rough and irregular, and its microstructure was porous, which was consistent with Arun et al.'s finding [34].

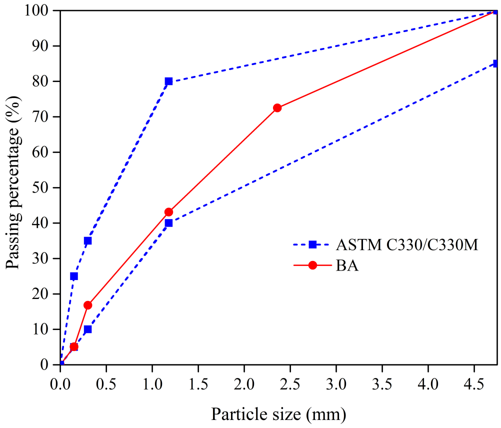

Figure 1. Particle size distribution of BA

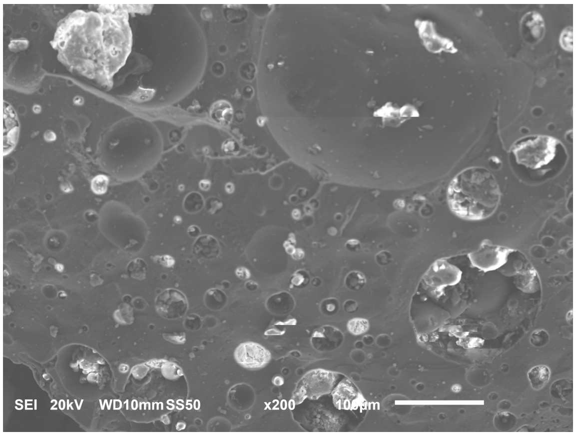

Figure 2. SEM image of BA particles

Figure 3. Recycling procedures of RLWA from waste polystyrene plastic

The process of preparing RLWA used for this investigation involves five main stages, as illustrated in Fig. 3. Initially, waste polystyrene plastic (PP), mostly from food containers, was collected from food stores, sidewalks, and landfills. The PP waste was then treated to remove contaminants such as oil, grease, and organic waste. Step 3 involved naturally drying the treated PP waste to ensure it was free of water, making the next processing steps easier. The dry PP waste was then divided into sheets no larger than 100 mm in step 4 to prepare for the crushing stage. In the final step, the PP waste processed in step 4 was placed into a crusher, producing RLWA with particle sizes in the ranges of 0.3-2.36 mm. These aggregates were then packed in plastic bags and stored at room temperature until being used. It is noted that the RLWA had a density of 36 kg/m^3.

In this study, the mixing water used was local tap water. A superplasticizer (SP) was also used to adjust the workability of fresh LWC mixtures.

2.2. *Mixture proportions*

The mixture proportions of LWC samples (see Table 2) were designed based on the author's experience, laboratory trials, and adjustments. In the first mixture group, BA was fixed at 65% of the binder weight. RLWA was then used to replace BA at levels of 0% (PS00-0.65 mix), 50% (PS50-0.65 mix), 70% (PS70-0.65 mix), and 100% by volume (PS100-0.65 mix). Furthermore, the second mixture group was designed to maximize the use of RLWA by increasing the BA/binder ratio from 0.65 to 1.0 (PS100-1.0 mix), 1.5 (PS100-1.5 mix), and 2.0 (PS100-2.0 mix) while fully replacing BA with RLWA in all of these mixtures. Based on the previous findings [35], the FA and GGBFS contents were fixed at 25% and 35% of PC weight for all LWC mixtures. A constant water-to-binder ratio of 0.27 was used and SP dosage was adjustable to obtain a slump value of LWC mixtures in the ranges of 18 ± 2 cm.

Table 2. Quantity of each material for producing 1 m^3 of LWC mixtures

Mixtures	PS00-0.65	PS50-0.65	PS70-0.65	PS100-0.65	PS100-1.0	PS100-1.5	PS100-2.0
PC (kg)	426	426	426	426	363	300	255
FA (kg)	266	266	266	266	227	187	159
GGBFS (kg)	372	373	373	373	318	262	223
BA (kg)	692	346	208	0	0	0	0
RLWA (kg)	0	5.8	8.1	11.6	15.2	18.8	21.4
SP (kg)	2.1	1.2	0.9	0.5	0.4	0.9	1
Water (kg)	287	287	288	288	245	202	172

2.3. *Sample preparation and test methods*

To cast the LWC samples for experimental tests, all materials were first prepared based on the designed proportions as given in Table 2. All binder materials and BA were dry mixed for 2 min to prevent local segregation and ensure uniform distribution. Next, 3/4 of the SP-water solution was gradually added to the dry mixture and mixed for another 2 min to adequately moisten the materials. Following the moistening step, RLWA and the remaining solution were introduced, and the mixture was mixed for an additional 2 min to achieve a homogeneous mix. During this stage, it is important to gradually and uniformly add the RLWA to the wet mixture to ensure its uniform distribution in the LWC mixture. Subsequently, the slump of the LWC was measured to ensure the designed range of 18 ± 2 cm. After slump measurement, the LWC mixture was poured into molds with different dimensions for various tests. The samples were de-molded after 24 hours and then cured in water until testing.

The engineering performance of LWC was evaluated at 7 and 28 days by using various test methods (Fig. 4). Indeed, the hardened LWC was tested for dry density and water absorption using cubic specimens of 50×50×50 mm according to ASTM C642. Besides, the flexural and compressive strength tests were conducted using prismatic specimens of 40×40×160 mm following ASTM C348 and ASTM C349, respectively. The length changes as an indicator for drying shrinkage of LWC were recorded at 0, 3, 7, 14, and 28 days following ASTM C596. It is noted that each test method was repeated on three specimens, and the average value was reported as the final result.

(a) Dry density and water absorption

(b) Flexural strength

(c) Compressive strength

(d) Drying shrinkage

Figure 4. Test methods used to determine the LWC's properties

3. Results and discussion

3.1. Dry density

Dry density is a crucial parameter in determining the classification and suitability of LWC for various applications, particularly where weight reduction is a critical factor for high-rise buildings, long-span bridges, precast products, etc. In this study, the dry density values at 7 and 28 days of LWC are presented in Fig. 5. Overall, the dry density values measured for all specimens were in the ranges of 1350-1996 kg/m^3. The results also revealed that the dry density slightly increased during the curing time and significantly reduced with the RLWA content. It could be explained that the higher dry density with time was majorly attributed to both the hydration of PC and the pozzolanic reactions of FA and GGBFS, creating a denser structure and increasing the dry density. Whereas, the significantly lower density of RLWA in comparison with other LWC components was the major reason for the lower dry density value of the LWC specimens containing higher RLWA content.

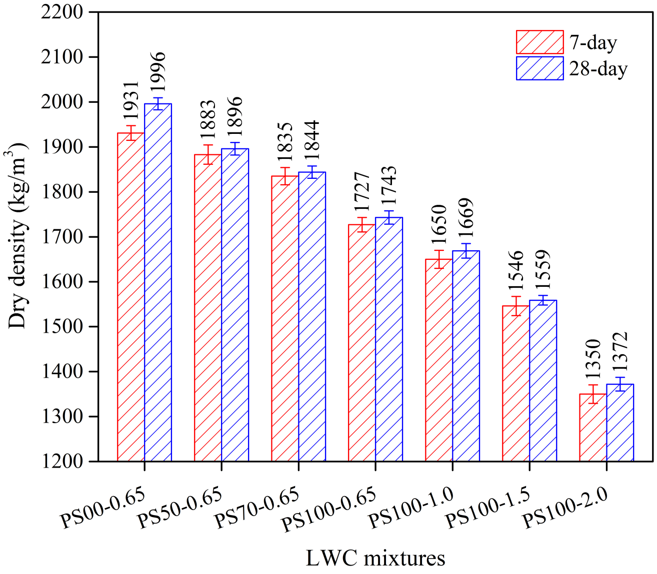

Figure 5. Dry density of LWC

3.2. *Flexural strength*

Fig. 6 shows the development in flexural strength of LWC at 7 and 28 days. As a result, all of the RLWA-incorporated specimens exhibited smaller flexural strength values than those of the control one. After 28 days of curing, the flexural strength of all samples rose thanks to the chemical reactions of binder materials as discussed in Section 4.1 [27, 36]. At this moment, the flexural strength of the no RLWA specimens was 12.56 MPa, which was higher than those of LWC specimens. In detail,

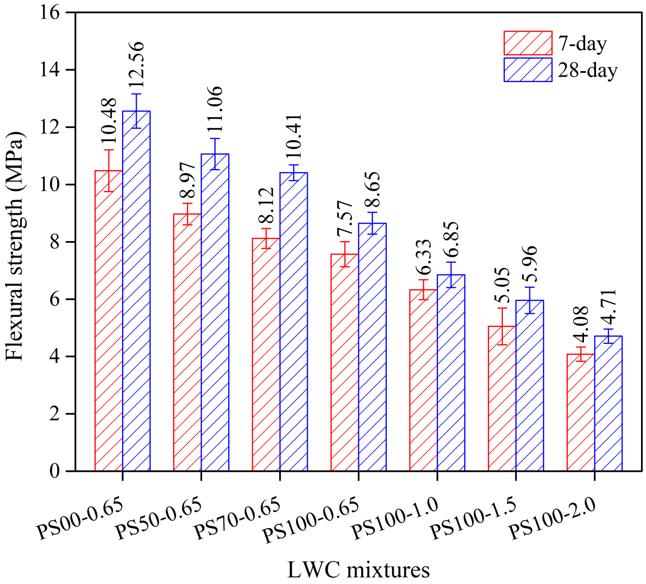

Figure 6. Flexural strength of LWC

the PS50-0.65, PS70-0.65, and PS100-0.65 specimens earned flexural strength values of about 12%, 17%, and 31% lower than that of the PS00-0.65, respectively. Following this trend, the flexural strength values of the PS100-1.0, PS100-1.5, and PS100-2.0 specimens decreased by approximately 46%, 53%, and 63% as compared to that of the PS00-0.65 specimen, respectively. The reduction in flexural strength after adding RLWA was reported by a previous study [9] and might result from several aspects related to the porosity and mechanical strength of RLWA, which will be discussed in Section 4.3.

3.3. Compressive strength

Compressive strength is crucial for LWC performance, demonstrating its ability to bear loads. The compressive strength of LWC specimens is presented in Fig. 7. Generally, the compressive strength of LWC showed an upward trend after 28 days and the specimens containing the highest RLWA content earned the lowest compressive strength. Comparing the RLWA and control specimens at 7 days yielded different results. For instance, the control samples showed a compressive strength of 66.3 MPa, while the PS50-0.65 specimen showed a reduced strength of 52.4 MPa, a 21% reduction. The PS70-0.65 and PS100-0.65 samples also exhibited reductions in compressive strength, measuring 47.7 MPa and 39.2 MPa, which represented decreases of 28% and 40.8%, respectively. On the other hand, the compressive strength values of the PS100-1.0, PS100-1.5, and PS100-2.0 specimens were 52.3%, 67.3%, and 80.7% lower than that of the control specimen. At 28 days, while the PS00-0.65's compressive strength was significantly increased to 79.5 MPa, the compressive strength values of the PS50-0.65, PS70-0.65, and PS100-0.65 slightly increased to 63.8 MPa, 52.1 MPa, and 47.5 MPa, respectively. For the PS100-1.0, PS100-1.5, and PS100-2.0 specimens, the strength enhancement trend over time was also witnessed. Indeed, these specimens' strength increased to 35.2, 30.6, and 18.1 MPa, which was about 55.7%, 61.5%, and 77.2% lower than that of the PS00-0.65 specimen. These results stressed the importance of RLWA content to the performance of LWC and the reduction in compressive strength after adding RLWA was also reported by a previous study [9]. Additionally, the relatively high strength of the LWC obtained in this study was in good agreement with the findings reported by Kim and Lee [37] and Cheah et al. [38].

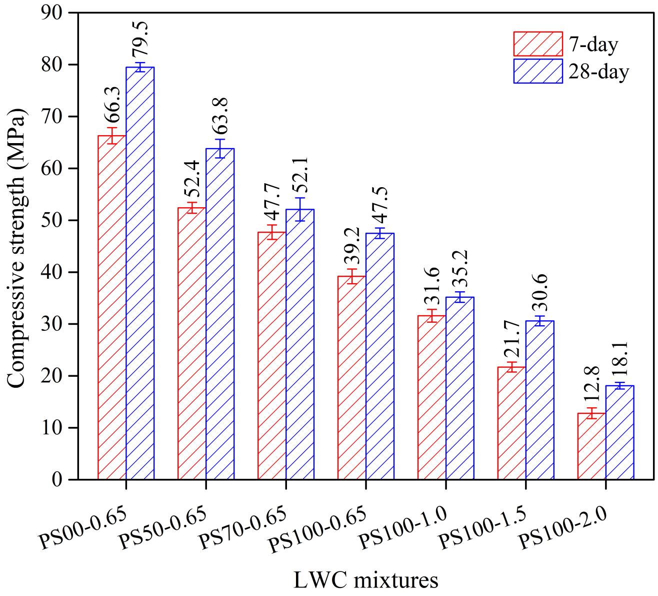

Figure 7. Compressive strength of LWC

Analyzing the compressive strength changes over 7 and 28 days for LWC cured in water revealed the effective impact of the pozzolanic reaction and the hydration of binder materials [27, 39]. Besides, previous studies also found that adding RLWA made from polystyrene led to a reduction of aggregates and increased the surface area of fine particles, weakening the interfacial zone between the aggregates and the paste and thus resulting in a decrease in compressive strength [14, 21]. The lower mechanical strength of RLWA compared to its substitutes could contribute to the reduction in mechanical strength [17]. Moreover, the porosity within the RLWA makes it vulnerable, leading to failure at the interface between the RLWA and the paste [40].

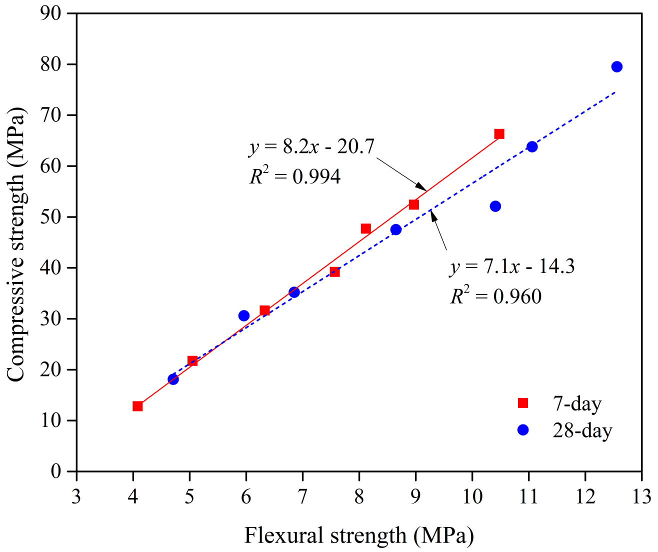

Figure 8. Relationship between compressive and flexural strengths of LWC

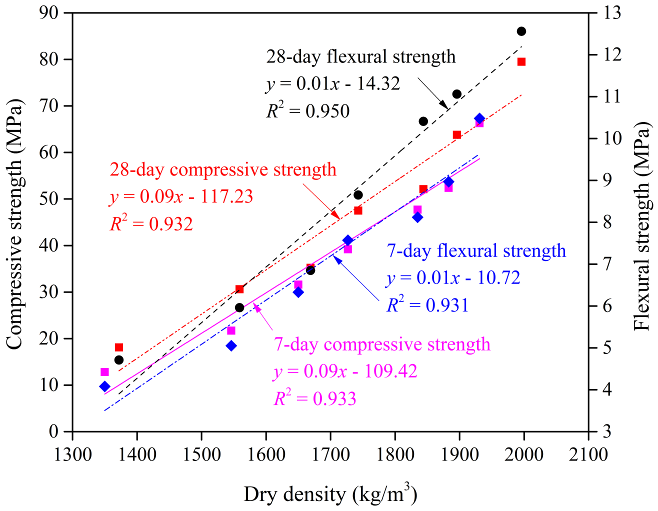

Figure 9. Relationship between dry density and mechanical strength of LWC

The linear relationship between compressive strength and flexural strength was established as shown in Fig. 8. This trend demonstrated the strong association between compressive and flexural strength. With $R^2 > 96\%$, the formula of $y = 7.1x - 14.3$ could be used to estimate either compressive strength or flexural strength at 28 days when one of the two factors was known. Moreover, the relationship between mechanical strength and dry density of the LWC was also presented in Fig. 9. It could be observed that the dry density was proportional to mechanical strength, this finding aligns with the discussed trend above. This positive correlation underscores the critical importance of optimizing the mixture design to modify the properties of LWC for specific applications.

3.4. Drying shrinkage

The drying shrinkage of LWC specimens with various RLWA contents is presented in Fig. 10, showing distinctive trends in dimensional changes over various time intervals. In general, the length change of all specimens ranged approximately from −0.108% to −0.372%. In detail, the control specimen exhibited the smallest change in length of −0.108%, which was lower than those of PS50-0.65 (−0.164%), PS70-0.65 (-0.195%), and PS100-0.65 (−0.284%) specimens. Moreover, it was found that the higher the RLWA incorporation, the higher the drying shrinkage of the LWC specimens. For example, the length change values recorded for the PS100-1.0, PS100-1.5, and PS100-2.0 specimens were −0.299%, −0.367%, and −0.372%, respectively.

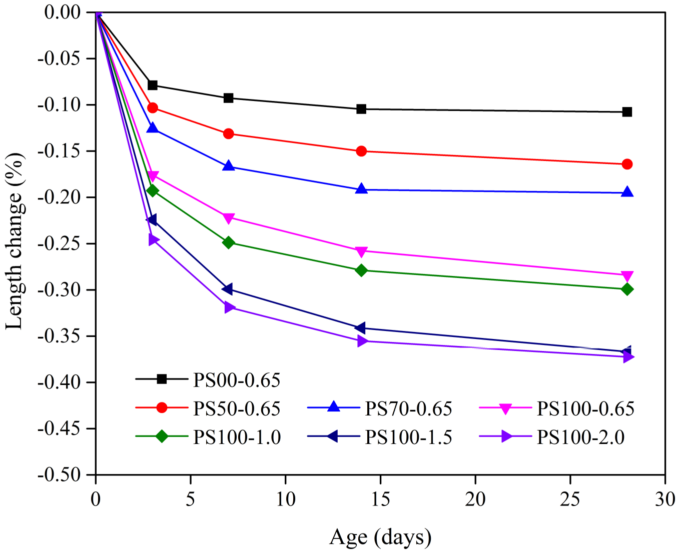

Figure 10. Drying shrinkage of LWC

The different length changes revealed the strong influence of RLWA on the drying shrinkage behavior of LWC. It is well known that the drying shrinkage mainly depends on the evaporation of pore water in the structure. In the LWC samples, the addition of RLWA led to the increment of imperfection in the structure, resulting in higher humidity evaporation and increasing drying shrinkage [34]. Sabaa and Ravindrarajah [16] found that the PA exhibited lower stiffness and compressibility, leading to a reduction in the amount of rigid aggregate particles and increasing drying shrinkage. Besides, the low mechanical strength and higher surface smoothness in PA resulted in little restraint to the shrinkage [38].

3.5. Water absorption

Water absorption is also an important property of LWC, which is used to evaluate its durability, particularly when the LWC is exposed to an aggressive environment. The water absorption of all LWC specimens is shown in Fig. 11. Notably, the water absorption of the LWC was significantly higher than that of the control specimen. As a result, the water absorption values of all specimens ranged from 4.76% to 16.82% at 7 days and from 3.94% to 15.23% at 28 days. In detail, the PS00-0.65, PS50-0.65, PS70-0.65, and PS100-0.65 specimens absorbed between 4.76% and 8.31% of water at 7 days. These absorption levels decreased slightly to between 3.94% and 7.74% at 28 days. A similar trend was observed for the PS100-1.0, PS100-1.5, and PS100-2.0 specimens, as the amounts of water absorbed in these specimens were in the ranges of 9.39%-16.82% at 7 days and 8.39%-15.23% at 28 days. This trend might be attributed to the reason that the porosity of LWC specimens was higher due to the greater porosity of RLWA in comparison with the BA particles, leading to the increase in the water absorbed. Lermen et al. [40] previously reported that RLWA could float in the liquid mortar mixture because of the closed cell structure.

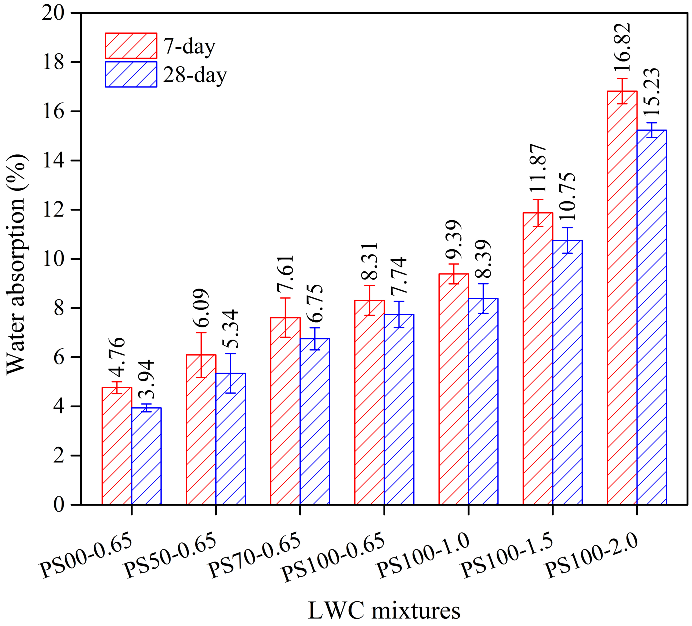

Figure 11. Water absorption of LWC

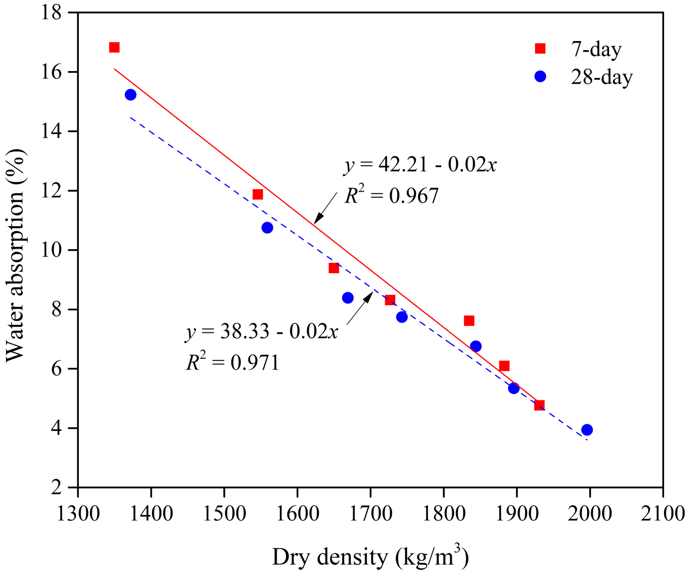

Figure 12. Relationship between water absorption and dry density of LWC

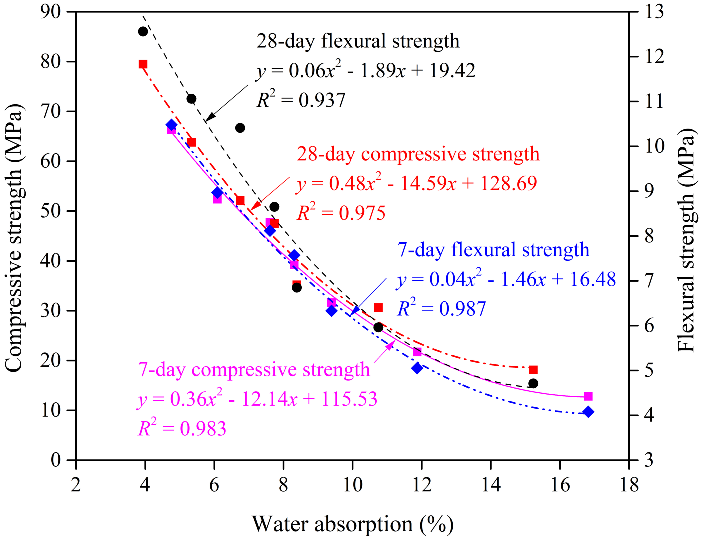

Figure 13. Relationship between water absorption and mechanical strength of LWC

The relationship between water absorption and dry density of LWC is displayed in Fig. 12. Generally, the negative correlation was witnessed at 7 and 28 days, which aligned with the discussed trend above. It is recognized that the dry density and water absorption are related to the void content of LWC. The greater the porosity, the higher the water absorption and the lower the dry density. This relationship was presented by the linear equation of $y = 38.33 - 0.02x$ ($R^2 = 97\%$), which could be used to determine either water absorption or dry density at 28 days when one of the two factors was known. Similarly, the correlation between water absorption and mechanical strength of the LWC was established (Fig. 13), indicating that higher water absorption capacity was closely associated with lower mechanical strength in the LWC specimens. With a relatively high coefficient of determination ($R^2 > 93\%$) at all ages, it was easier to estimate the strength and absorption capacity of LWC using the appropriate regression equations as shown in Fig. 13.

4. Conclusion

Based on the obtained results, the following conclusions can be drawn:

- Incorporating higher RLWA contents resulted in lower dry density and greater water absorption capacity of the LWC specimens. The dry density and water absorption of the 28-day-old specimens were in the respective ranges of 1372-1996 kg/m^3 and 3.94-15.23%. The PS100-2.0 specimen registered the smallest dry density of 1372 kg/m^3 and the highest water absorption of 15.23% while these values were recorded at 1996 kg/m^3 and 3.94% for the control specimen, respectively.

- The mechanical strength of LWC generally decreased with the increment of RLWA content in the mixtures. The specimen containing less RLWA (i.e., PS50-0.65) exhibited the highest compressive and flexural strength values at 28 days of 63.8 MPa and 11.06 MPa, while the specimen incorporating the highest RLWA content (i.e., PS100-2.0) earned the lowest compressive and flexural strength values of 18.1 MPa and 4.71 MPa, respectively.

- The inclusion of more RLWA increased the drying shrinkage of LWC and all of the LWC specimens showed remarkably higher drying shrinkage than that of the control specimen. As a result, the length change recorded for all 28-day-old specimens was relatively low, ranging from −0.107% to −0.372%.

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