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Sustainable Cement Paste Incorporating Andesite Waste Powder: Mechanical Performance and Feasibility for Ornamental Elements

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Abstract. Utilising industrial waste as a partial solution for Portland cement has become more common as the need for environmentally friendly building materials grows. The potential of using andesite waste powder (AWP), a byproduct of the stone-processing industry, as a cementitious material for ornamental cement-based products is examined in this study. The flowability, dry unit weight, and compression strength tests were done on cement paste samples with 0%, 50%, and 75% AWP replacement levels at water-to-binder ratios of 0.30, 0.35, and 0.40. As the AWP content increased, the workability and compressive strength decreased. This is because AWP has a lower hydraulic response and higher water demand. After 28 days, the mixture with 50% AWP and a water-to-binder ratio of 0.30 had the best performance, with a compression strength of 22.56 MPa and a dry unit weight of 1738.28 kg/m^3. The economic analysis demonstrated that the strength-to-cost ratio of AWP-based paste was more favourable than that of conventional ornamental materials. This research demonstrates the potential of AWP as a sustainable and cost-effective alternative material for ornamental applications.

Keywords: Andesite waste powder, cement replacement, ornamental materials, compressive strength, economic feasibility.

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1. Introduction

Ornamental materials are used in both structural and decorative applications to improve the appearance, durability, service life, and performance of buildings, landscapes, and architectural elements. The quality of ornamental materials depends on the characteristics of the stone. The mineralogical composition, degree of cementation, and particle size of stone influence their physical properties and mechanical behavior [1]. In the stone industry, raw rock blocks obtained from quarries are transformed into slabs, tiles, and various decorative goods. Throughout the cutting procedure, water is consistently utilized to cool the cutting instruments, diminish dust emissions, and enhance cutting effectiveness. Although these techniques yield high-quality ornamental stone products, they concurrently produce significant quantities of trash, including stone fragments, fine powders, and sludge consisting of water combined with stone particles. The by-products generated during the cutting and finishing phases provide a considerable environmental issue for the stone industry [2,3]. Recent research has highlighted the recovery and reutilization of stone-cutting waste as a secondary raw material in sustainable building, namely as a partial substitute for cement in cementitious composites[4,5].

Andesite is an extrusive igneous rock distinguished by a fine-grained texture and a mineral composition mostly comprising plagioclase feldspar, pyroxene, and amphibole, along with a relatively high silica (SiO_2) content that enhances its potential pozzolanic capabilities [6,7]. Andesite is frequently used as a construction and decorative stone for paving, wall cladding, monuments, and architectural features due to its durability, aesthetic appeal, and mechanical strength. The extraction, cutting, polishing, and finishing procedures in the stone business produce significant amounts of andesite waste, including dust, sludge, and fine powder. An excessive amount of this waste presents environmental difficulties since it necessitates extensive disposal locations and may lead to air and soil pollution [8,9]. Recent investigations indicate that waste andesite dust possesses considerable quantities of reactive silica and alumina, rendering it appropriate as a supplementary cementitious material and a partial substitute for Portland cement [10–12]. Ozkan and Ceylan [6] Examine the mechanical characteristics of cementitious composites utilizing waste andesite dust. The replacement of cement with waste andesite dust at lower replacement rates of up to 15% produced more desirable findings. The utilization of waste andesite powder as a mineral additive enhanced the high-temperature resistance [13] and improved performance in acidic and sulfate conditions compared to other mortars [14]. During cement hydration, andesite waste powder effects on particle filling and reactivity in the latter phases. It engaged in the process, efficiently occupying structural gaps with powder particles and hydration products such as C-S-H gel. This resulted in the enhancement of the cement slurry's pore structure and increased density[15]. Additionally, geopolymer synthesis with andesite waste powder offers a solution for sustainable mortar manufacturing and waste reduction [16–18].

Previous research concentrated on assessing the chemical composition, pozzolanic activity, mechanical performance, and durability attributes of mortar, concrete, or geopolymer containing andesite waste powder. The results consistently demonstrate that andesite waste contains considerable silica and can partially substitute cement at low replacement rates without significantly impairing performance. This study examines the feasibility of utilizing andesite waste generated from the stone-processing industry as a partial cement replacement in ornamental construction materials. Unlike previous studies that mainly focused on structural applications, this research will evaluate both the engineering performance and ornamental characteristics of the resulting products. Thus, the study provides more scientific information concerning the sustainable value of andesite waste, while supporting circular economy practices and enlarging the use of supplemental cementitious materials in ornamental construction products.

2. Methods

2.1. Characterization of Material

Portland cement was used as a primary cement binder, which conforms to SNI 15-7064-2004 [19]. Portland cement has a specific gravity of 3.10 and a bulk density of 1250 kg/m^3. Andesite waste powder (AWP) was used as a secondary cement binder, which replaced cement by weight. The AWP was taken from the stone industry in Yogyakarta. AWP was oven-dried at 100 °C for 24 h before use. AWP has a specific gravity of 2.59 and a bulk density of 1312 kg/m^3. The X-ray Fluorescence (XRF) is used to determine the chemical composition of materials. The results of XRF analysis are listed in Table 1. The total major oxides of AWP (SiO_2 + Al_2O_3 + Fe_2O_3)≥ 70% meet class F of ASTM C618 [22], which has pozzolanic properties only. Although AWP has a lower CaO content than Portland cement, it has a higher SiO2 content. The Scanning Electron Microscopy (SEM) using the Quanta 650 Scanning Electron Microscope of the materials is shown in Figure 1. Portland cement particles often display angular to sub-angular geometries with finer and more uniform particle distributions, while their surfaces appear denser and smoother as a result of the clinker grinding process. On the other hand, andesite waste powder obtained through stone-cutting processes typically displays irregular, porous, abrasive, and heterogeneous particle morphologies, accompanied by a broader particle size variety. Fig 2 shows the particle size distributions obtained by the laser diffraction method using the HORIBA SZ-100 machine.

Table 1. Chemical composition and standard values of Portland cement and AWP

Chemical Composition (%)	Portland cement	AWP	ASTM C618
SiO_2	16.9	47.7	
Al_2O_3	5.10	18.6	
Fe_2O_3	3.36	10.2	
CaO	67.5	12.0	
SO_3	2.43	0.0485	<5
Na_2O	1.19	3.97	
MgO	2.54	3.46	<5
P_2O_5	0.132	0.307	
K_2O	0.697	1.99	
MnO	0.0535	0.244	
SiO_2 +Al_2O_3+Fe_2O_3	25.36	76.5	>70

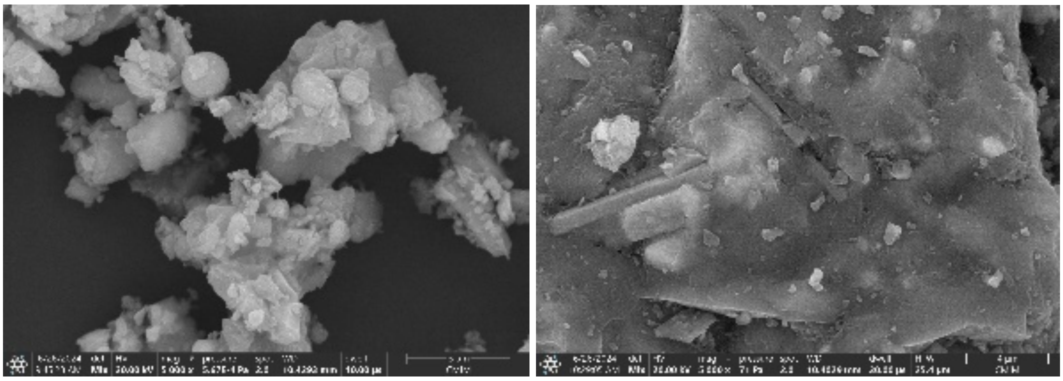

Figure 1. Portland cement (right) and AWP (left) SEM result

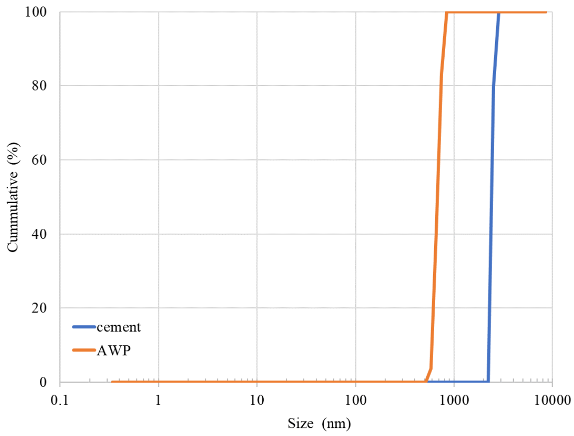

Figure 2. Particle size distribution curves of materials

2.2. Design of the mixture

This study examines the feasibility of utilizing AWP as a partial cement replacement in ornamental construction materials. AWP was used by replacing cement at various ratios of 0%, 50%, and 75%. The water/binder material (BM) ratio was determined as 0.30, 0.35, and 0.40. The mixture composition was determined using the absolute volume method, assuming that the mixture was compact. The total component per unit volume of the admixture may be calculated from Eq. 1. Table 2 presents the weight ratios of the mixtures utilized in the manufacturing of ornamental materials.

$$\frac{W_{AWP}}{G_{AWP}+\gamma_{AWP}}+\frac{W_{cement}}{G_{cement}+\gamma_{cement}}+\frac{W_w}{G_w+\gamma_w}=1\,m^3 \tag{1}$$

where in 1 m^3 AWP-cement paste, W_{AWP}: weight of andesite waste (kg); W_{cement}: weight of cement (kg); W_w: weight of water; G_{AWP}: specific gravity of andesite waste; G_{cement}: specific gravity of cement; G_w: specific gravity of water; γ_w: unit weight of water: 1000 kg per m^3.

Table 2. Detail mix proportion of cement composites.

Mix code	WAD Ratio	Water/BM	Portland cement (kg/m^3)	AWP (kg/m^3)	Water (kg/m^3)

A0%	0%	0.3	770.94	-	231.28
		0.35	742.35	-	259.82
		0.4	715.8	-	286.32
A50%	50%	0.3	385.55	385.55	231.33
		0.35	371.25	371.25	259.87
		0.4	357.97	357.97	286.38
A75%	75%	0.3	289.15	481.91	231.32
		0.35	278.42	464.04	259.86
		0.4	268.47	447.44	286.36

2.3. Mixing and Curing

The mixing was performed following the procedure in ASTM C305 [20]. Cement binder, Portland cement, and AWP were dry-mixed for one minute before water was added. The mixture was further mixed for five minutes until it became homogeneous. The resulting mixture was tested for workability before it was cast into the molds. After 24 hours, the samples were extracted from the molds and preserved in water curing at 23 ± 2 ◦C until the time of testing.

2.4. Experimental Procedure

The workability was tested using the flow table test method. The flow test was performed immediately after the mixing was finished. The flow was determined by measuring the diameter of the mixture on the flow table along the four lines inscribed on the tabletop using a caliper after 25 jolts were applied, as specified in the standard ASTM C 1437-01 [21].

The dry unit weight of the specimens was determined before compressive strength testing. The dry mass of each specimen was measured with a calibrated digital balance, and its volume was determined from the specimen dimensions. The dry unit weight was calculated by dividing the dry mass by the corresponding volume and was represented in kg/m^3.

The compressive strength of the cement paste was measured in accordance with ASTM C109 [25] using cube specimens measuring 50 mm × 50 mm × 50 mm. The tests were conducted at ages of 7, 14, and 28 days. Three samples were analyzed for each mixture, and the mean of the results was calculated. As a comparison, other ornamental materials were prepared by cutting them into cubes of 50 mm × 50 mm × 50 mm. Three samples were created for each material.

The economic feasibility of AWP cementitious ornamental products was compared to that of other natural stones product. The product is constructed with dimensions of 70 x 90 cm and a height of 2 m. The calculation involves combining the material and labor needs that are required for production. A field survey was conducted to compare the pricing of ornamental products of equivalent size to the created ornamental product. The survey was executed at three locations, and the mean value was calculated.

2.5. Statistical Analysis

All experimental measurements were performed utilizing three replicate specimens for each mixture. The test findings, comprising dry unit weight and compressive strength, are displayed as the mean value with the standard deviation (mean ± SD). A descriptive statistical analysis was conducted to assess the variability and consistency of the experimental results across the various mixtures. No inferential statistical tests were conducted, as the study concentrated on the comparative evaluation of material characteristics and performance patterns related to varying quantities of andesite waste substitution.

3. Results and Discussion

3.1. The workability

The flowability results from Fig 3 show a clear reduction in the workability of the cement paste as the andesite waste powder (AWP) replacement level increased. For the control mixtures (A0%), the flowability increased slightly from 91.91 cm at w/b = 0.30 to 93.91 cm at w/b = 0.40, indicating that higher water content improved the fluidity of the paste. However, when 50% of the cement was replaced with AWP (A50%), the flowability decreased to 82.17–82.97 cm, corresponding to reductions of approximately 10.6%, 10.6%, and 11.6% compared with the respective control mixtures. A further decrease was observed for the A75% mixtures, where flowability values ranged from 73.01 to 73.81 cm, representing reductions of approximately 20.6%, 20.6%, and 21.4% relative to A0%. Compared with A50%, the A75% mixtures exhibited an additional decrease of approximately 11%, demonstrating that increasing AWP content consistently reduced the workability of the cement paste. The reduction in flowability can be attributed to the physical characteristics of AWP. Although AWP contains significant amounts of silica and may contribute to long-term pozzolanic activity, its fresh-state behavior is primarily governed by its filler characteristics and water absorption capacity. Similar findings were reported that increasing waste andesite dust content reduced the workability of cementitious composites because of the porous nature and irregular morphology of the particles [6,22].

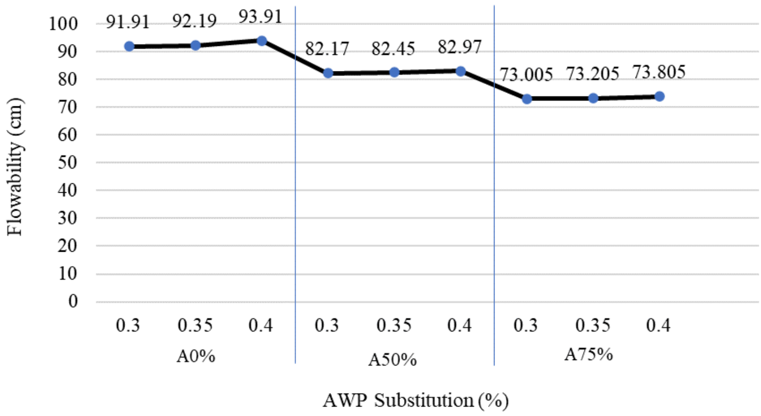

Figure 3. The workability of AWP cementitious material

3.2. The dry unit weight

The dry unit weight results of the AWP cementitious material are shown in Fig 4. The dry unit weight ranged from approximately 1738 to 1998 kg/m³ and was influenced by both the curing age and the level of andesite waste powder (AWP) substitution. In the control mixtures (A0%), the dry unit weight generally decreased as the water-to-binder ratio increased from 0.30 to 0.40, which can be attributed to the formation of a more porous microstructure caused by excess mixing water. The incorporation of AWP at 50% and 75% replacement levels produced variable dry unit weight values; however, several mixtures, particularly A75%-0.30, exhibited the highest dry unit weight (1998.19 kg/m³ at 7 days). This behavior is related to the physical characteristics of AWP, which possesses a specific gravity typically ranging from 2.60 to 2.75, slightly lower than that of Portland cement (approximately 3.10 to 3.15), but contains fine particles capable of filling voids between cement grains and improving particle packing [6]. The increase in dry unit weight observed in some AWP mixtures indicates that the filler effect contributed to a denser matrix despite the lower density of the waste material itself. Moreover, curing age influenced density development through the progression of hydration reactions and pore refinement. Several mixtures exhibited higher dry unit weights at 28 days than at earlier ages, suggesting continued formation of hydration products and microstructural densification. Nevertheless, excessive AWP replacement combined with higher water-to-binder ratios resulted in lower dry unit weights because the reduced cement content limited calcium-silicate-hydrate (C-S-H) formation, while the porous and angular morphology of AWP particles increased void content within the hardened matrix. Similar relationships between dry density, particle packing, specific gravity, and hydration development have been reported for andesite waste and other siliceous supplementary cementitious materials, where density is governed by the balance between filler effects, cement dilution, particle characteristics, and curing conditions [8,22,23]

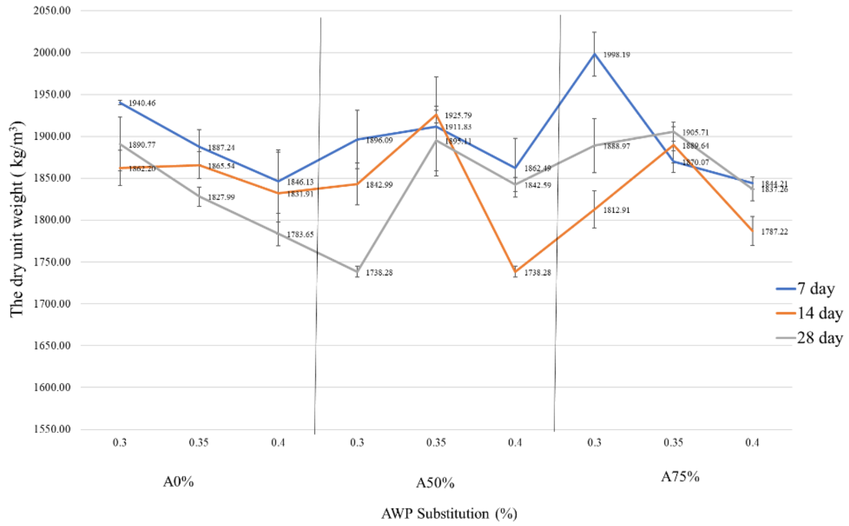

Figure 4. The dry unit of the AWP cementitious material

3.3. The compressive strength

The compressive strength of AWP as a secondary cementitious material is presented in Fig. 5. The strength development of the cement paste was strongly influenced by both the water-to-binder ratio (W/BM = 0.30, 0.35, and 0.40) and the andesite waste powder (AWP) replacement level (0%, 50%, and 75%). The control specimens without AWP (A0%) exhibited the highest compressive strengths at all curing ages, with the maximum value of 32.06 MPa recorded at a w/b ratio of 0.30 after 7 days of curing. The incorporation of AWP significantly reduced compressive strength compared with the control mixtures. At 50% cement replacement (A50%), the 28-day compressive strength ranged from 14.46 to 22.56 MPa, while at 75% replacement (A75%), the 28-day strength further decreased to 6.30–9.45 MPa. The control mixtures had the greatest compressive strengths due to the substantial presence of calcium oxide (CaO) in Portland cement, which facilitates the development of calcium-silicate-hydrate (C-S-H) gel during hydration. XRF examination of AWP generally reveals elevated levels of silica (SiO_2) and alumina (Al_2O_3), while exhibiting reduced amounts of CaO, leading to diminished hydraulic reactivity and a diluting effect upon cement substitution [6,13]. Besides that, elevated AWP content diminished workability due to increased water absorption and heightened interparticle friction, resulting in lower free water for hydration and compaction. Thus, although the silica-rich composition and filler properties of AWP may facilitate limited pozzolanic reactions and microstructural densification at later curing stages, the interplay of diminished CaO content, porous particle morphology, coarser particle attributes compared to cement, and decreased workability elucidates the reduced compressive strengths noted in mixtures with elevated AWP proportions. Studies examining andesite waste and other siliceous rock powders as supplemental cementitious materials have revealed analogous connections among chemical composition, particle shape, workability, and strength development [24–26].

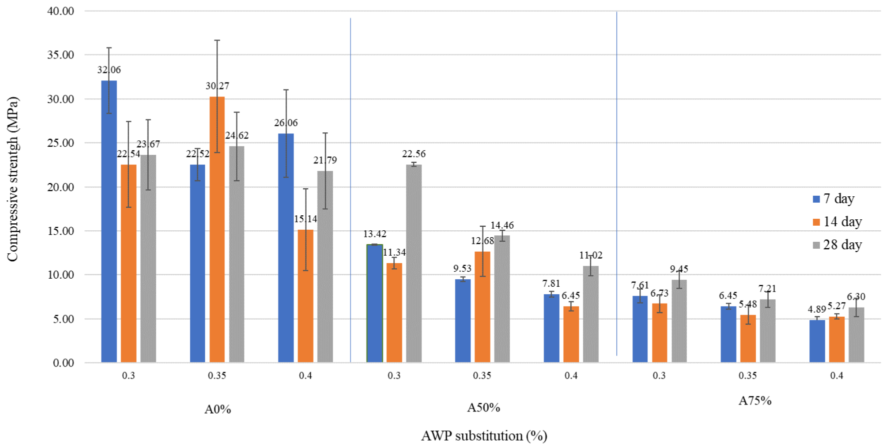

Figure 5. The compressive strength of the AWP cementitious material

3.4. The economic feasibility

Among the investigated mixtures, A50%-0.30 was identified as the optimum formulation because it provided the best balance between workability (82.17 cm), dry unit weight (1738.28 kg/m³), and compressive strength (22.56 MPa at 28 days), while achieving a 50% reduction in cement consumption. The economic feasibility was done by comparing the cost, compressive strength, and also the dry unit weight of the ornamental product from AWP cementitious material with other ornamental product materials. Fig 6 shows an example of an ornamental product from AWP cementitious material (left) and the comparison with other materials (right).

The economic feasibility analysis presented in Figure 6 indicates that the AWP–cementitious material offers a highly competitive balance between material cost, density, and mechanical performance compared with conventional ornamental materials. Although basalt stone exhibited the highest market price (IDR 9,500,000/item), its compressive strength (19.42 MPa) was lower than that of the AWP–cement paste (22.56 MPa). Similarly, andesite stone had a higher cost (IDR 5,500,000/item) and only slightly higher strength (24.81 MPa) than the AWP-based material. Although the fly ash–cement paste achieved the highest compressive strength (35.23 MPa), its production cost was still higher than that of the AWP-based material [26]. In contrast, the AWP–cement paste achieved a comparable compressive strength while requiring only approximately 50% of the cost of andesite stone (IDR 2,750,000/item), demonstrating a favorable strength-to-cost ratio. Similar conclusions have been reported in studies on sustainable ornamental materials, where mineral waste-based cementitious composites demonstrated lower production costs while maintaining adequate mechanical performance for architectural applications [27]

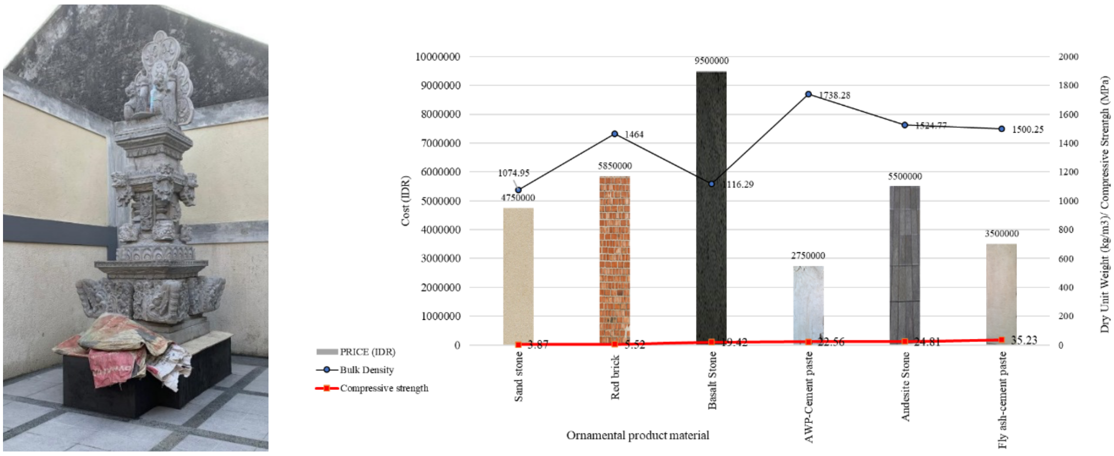

Figure 6. The ornament product made with AWP (left) and the comparison with other material

4. Conclusion

This study revealed that andesite waste powder (AWP) is suitable as a sustainable substitute for cement in ornamental cement-based products. Nevertheless, an increase in AWP content diminished the workability and compressive strength of the combinations. The flowability was reduced by nearly 11% and 21% at 50% and 75% AWP replacement levels, respectively, due to the increased water demand and angular particle shape of AWP. Compressive strength decreased with higher replacement levels due to the lower hydraulic reactivity of AWP relative to Portland cement. Despite this, the blend with 50% AWP and a water-to-binder ratio of 0.30 demonstrated optimal performance, achieving a compressive strength of 22.56 MPa while continuing to maintain acceptable workability and density. The economic feasibility analysis indicated that the AWP–cementitious material exhibited a superior strength-to-cost ratio relative to traditional ornamental materials, positioning it as an acceptable alternative for ornamental applications. This study focused solely on workability, dry unit weight, compressive strength, and economic performance. Thus, subsequent research should examine durability-related properties, including permeability, water absorption, drying shrinkage, dimensional stability, and long-term durability to enhance engineering applications and service-life evaluations.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work, the author(s) used Jenni.AI to assist with language refinement, grammar checking, and improving the clarity and readability of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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