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Influence of andesite as a supplementary cementitious material on the properties of Portland limestone cement-based products

Parinya CHAKARTNARODOM[1], Sureerat POLSILAPA[1], Wichit PRAKAYPAN[2], Passakorn SONPRASARN[3], Edward A. LAITILA[4], and Nuntaporn KONGKAJUN[5,6,*]

[1] *Department of Materials Engineering, Faculty of Engineering, Kasetsart University, Bangkok, 10900, Thailand*
[2] *Source Runner Enterprise Co. Ltd., Bangkok, 10220, Thailand*
[3] *Sun Cement Process Co. Ltd., Ratchaburi, 70120, Thailand*
[4] *Department of Materials Science and Engineering, Michigan Technological University, Houghton, MI, 49931, USA*
[5] *Department of Materials and Textile Technology, Faculty of Science and Technology, Thammasat University, Pathumthani,12121, Thailand*
[6] *Thammasat University Research Unit in Sustainable Materials and Circular Economy, Thammasat University, Pathumthani,12121, Thailand*

***Corresponding author e-mail**: n-kongkj@tu.ac.th

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Abstract

Andesite, a dark volcanic rock, was investigated as a supplementary cementitious material (SCM) in four Portland limestone cement (PLC)-based products—(1) cement for structural applications, (2) blended cement for bricklaying and plastering, (3) general-purpose plastering mortar, and (4) plastering mortar for lightweight block applications—with the aim of improving visual appearance, reducing carbon footprint, and lowering raw material cost. Laboratory tests identified 10% PLC replacement with andesite as the optimal level, which was then applied across all mixes. In paste and mortar testing, the incorporation of andesite increased initial and final setting times by 14.06% to 50.78% and 5.13% to 11.43%, respectively, compared to mixes without andesite, while still meeting industrial standards. Compressive strength results showed an 8.42% to 20.06% reduction at 28 days; however, all products continued to comply with the required performance criteria. At the industrial scale, products were produced and field-tested, and their color was evaluated using digital image analysis. Results showed that grayscale values were 13.12% to 32.03% lower than those of control products, indicating a consistently darker shade and enhanced visual appearance. Economically, substituting PLC with andesite reduced raw material costs by 2.64% to 7.44%, depending on the product, demonstrating that andesite can improve aesthetics and sustainability while maintaining compliance with industry standards.

1. Introduction

The cement industry is responsible for approximately 5% to 8% of global anthropogenic CO_2 emissions annually, primarily due to the clinker production process, where significant emissions result from both limestone calcination (0.5 ton to 0.7 ton of CO_2 per ton of clinker produced) and fuel combustion. To mitigate these emissions, a widely adopted strategy is the partial replacement of clinker with alternative cementitious materials such as fly ash, slag, and pozzolans [1,2].

Portland limestone cement (PLC), a blended hydraulic cement defined by ASTM C595 [3], is widely used in general concrete construction in many countries, including Thailand. It contains 5% to 15% limestone by weight. During production, limestone is ground together with clinker. Because limestone is softer than clinker, the total energy required for grinding is reduced. Compared to ordinary Portland cement (OPC), PLC results in lower carbon emissions due to its reduced clinker content and lower energy consumption during the grinding process. [4–6] PLC can reduce CO_2 emissions by approximately 10% when 12% of the clinker is replaced with limestone [6]. In terms of performance, many properties of concrete made with PLC are comparable to those of concrete made with OPC, including compressive strength and setting time [7–9].

Consumer perception plays a crucial role in the market adoption of any product. In the cement and concrete industry, shade is often linked to material strength, with many consumers believing that darker cement indicates higher strength. Since PLC contains less clinker than OPC, it generally has a lighter shade, which can influence purchasing decisions, even though concrete made with PLC and OPC demonstrates comparable performance [7–9]. Rosa *et al.* [10] showed that this issue can be addressed through the use of mineral-based pigments, which not only enhance the appearance but also improve the mechanical properties of self-compacting concrete, yielding satisfactory results.

Andesite is a volcanic rock found in several provinces across Thailand, including Nakhon Ratchasima, Saraburi, Phetchabun, Lopburi, Nakhon Nayok, Phrae, Uttaradit, Lampang, Prachinburi, and Trat [11]. It typically ranges in color from gray to black [12] and can exhibit a uniaxial compressive strength of up to 270.79 MPa, making it suitable for use as aggregate in concrete [13]. In construction, andesite is commonly used for paving, curbstones, stair steps, and windowsills [14]. Khamput [11,15] evaluated the use of andesite as coarse aggregate in concrete, as well as in concrete blocks, interlocking blocks, and paving blocks. Although a slight reduction in compressive strength was reported, the resulting products still met the relevant performance standards.

Davraz *et al.* [16] examined the utilization of andesite waste powder—produced during mining, processing, and polishing—as a mineral additive in concrete. Their results demonstrated that the powder meets the physical, chemical, and pozzolanic criteria specified for pozzolans in industrial standards. Lahmar *et al.* [17] investigated andesite as a supplementary cementitious material (SCM) in high-performance concrete, reporting improved durability along with reduced porosity and water absorption. From an environmental perspective, Hamidi *et al.* [18] demonstrated that the total energy required for cement production decreases when andesite is incorporated.

In this study, andesite—owing to its high abundance in Thailand and its naturally dark color—was utilized as a SCM in various PLC-based products to enhance their visual appearance. The applications included cement for structural use, blended cement for bricklaying and plastering, general-purpose plastering mortar, and plastering mortar for lightweight block construction. For each product, key properties, including compressive strength and setting time, were evaluated and compared against the relevant industrial standards.

2. Experimental

The raw materials used in this study include PLC, andesite, coal fly ash, crushed limestone, sand, water, and chemical admixtures including hydroxypropyl methyl cellulose (HPMC) and tallol diethanolamide (TD).

Coal fly ash is a by-product generated from coal combustion in power plants [19,20]. In the construction materials industry, it is widely used as a partial substitute for cement in concrete and other cement-based products. This substitution not only reduces raw material costs but also lowers the carbon footprint of the final products [21,22]. According to Flower and Sanjayan [23], greenhouse gas emissions from coal fly ash production are only 0.027 t CO_{2-e} per ton of ash produced—primarily from collection and transportation—compared to 0.7 t CO_{2-e} to 1.0 t CO_{2-e} per ton of cement produced. In addition to cost and emission reductions, the use of coal fly ash can enhance certain properties of cement-based materials, such as durability [24-29].

HPMC is widely used to improve the water retention of cement paste [30], while TD acts as a surfactant and functions as an air-entraining admixture [31,32]. Both HPMC and TD are proprietary commercial additives provided in powder form.

The andesite, sourced from a mine in Saraburi, Thailand, was ground to a fine powder with a particle size smaller than 74 µm (passing a 200 mesh sieve), as shown in Figure 1.

The chemical compositions of PLC, andesite, and fly ash were determined using an X-ray fluorescence (XRF) spectrometer (Bruker S2 PUMA Series II), and the results are presented in oxide form in Table 1.

This study investigates the effects of incorporating andesite as a SCM on the setting time, compressive strength, and shade of four PLC-based products:

Product A: Cement for structural applications

Product B: Blended cement for bricklaying and plastering applications

Product C: General-purpose plastering mortar

Product D: Plastering mortar for lightweight block applications

The replacement level of PLC in each product was determined based on the heat of hydration test, following ASTM C186-98 [33]. Figure 2 illustrates the apparatus used for this part of the experiment, which includes a temperature data logger connected to sealed containers via thermocouple wires

Figure 1. Andesite powder.

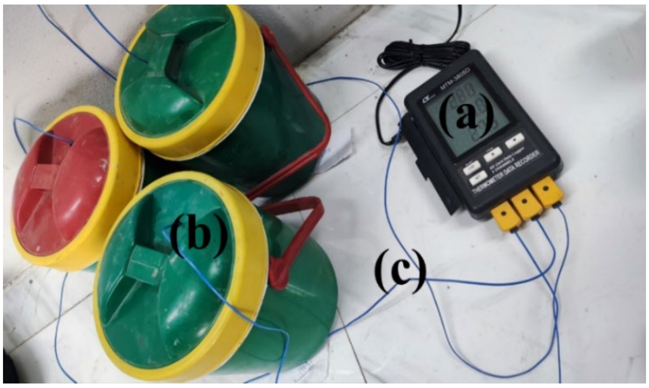

Figure 2. Apparatus used for the heat of hydration test: (a) temperature data logger; (b) containers for storing the cement paste; and (c) thermocouple wires.

Table 1. Andesite chemical composition.

Material	Composition [wt%]						
	CaO	SiO_2	Al_2O_3	SO_3	Fe_2O_3	MgO	Others
PLC	70.98	16.77	3.22	4.21	3.28	0.78	0.76
Andesite	53.77	23.74	8.30	5.96	4.90	1.41	1.92
Fly ash	27.59	35.35	17.92	6.60	7.24	1.33	3.97

Cement pastes were prepared by mixing PLC, andesite, coal fly ash, and water according to the proportions shown in Table 2. The reference mix, labeled as Formula Ref, served as the control. In formulas H1 through H3, PLC was partially replaced with andesite at replacement levels of 5%, 10%, and 15% by weight, respectively. After mixing, the cement pastes were placed into sealed containers. The temperature increase resulting from the exothermic hydration reaction was monitored using thermocouple wires and recorded by a temperature data logger at 30 s intervals. Based on the results of the heat of hydration test, the optimal replacement level of PLC with andesite was determined.

Table 3-6 present the mix proportions used to prepare samples of Products A, B, C, and D. The formulas Ref1 through Ref4 serve as control mixes for Products A through D, respectively. These control formulations are representative of typical commercial products available on the market. Formulas AN1 through AN4 correspond to mixes in which a portion of the PLC is replaced with andesite. The variable x denotes the fraction of PLC replaced by andesite, as determined from the heat of hydration test.

Figure 3. Vicat apparatus for setting time measurement.

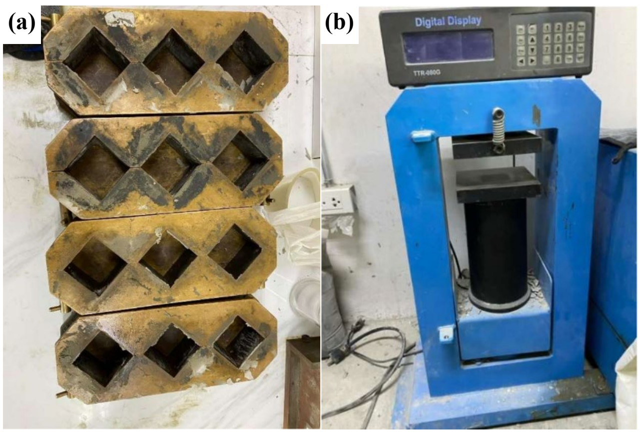

Figure 4. (a) Cube molds used for cement sample casting; and (b) compression testing machine.

The initial and final setting times of samples from each product were determined in accordance with ASTM C191-13 [34], using a Vicat apparatus as shown in Figure 3. The minimum requirements for initial and final setting times for each product, based on industrial standards, are summarized in Table 7.

The compressive strength of Products A through D, with and without andesite, was evaluated using a compression testing machine. Cube specimens measuring 5 cm × 5 cm × 5 cm were cast from mixtures prepared according to the mix proportions shown in Table 3-6. Figure 4(a) shows the brass cube mold used for casting samples, while Figure 4(b) depicts the compression testing machine employed in this study. The machine, model STS-C901 D, has a maximum capacity of 300 kN with a resolution of 0.01 kN. The loading rate applied in this work was 12.5 $kN \cdot s^{-1}$. Additionally, the minimum required compressive strength for each product, as specified by the relevant industrial standards, is presented in Table 8.

Table 2. Mix proportions used for the heat of hydration test.

Material	Formula [g]			
	Ref	**H1**	**H2**	**H3**
PLC	400	380	360	340
Andesite	0	20	40	60
Coal fly ash	100	100	100	100
Water	150	150	150	150

Table 3. Mix proportions of Product A.

Material	Formula [g]	
	Ref1	**AN1**
PLC	400	400(1-x)
Andesite	0	400x
Coal fly ash	100	100
Water	150	150

Table 4. Mix proportions of Product B.

Material	Formula [g]	
	Ref2	**AN2**
PLC	200	200(1-x)
Andesite	0	200x
Coal fly ash	25	25
Limestone	275	275
HPMC	0.2	0.2
Water	175	175
PLC	200	200(1-x)
Andesite	0	200x

Table 4. Mix proportions of Product C.

Material	Formula [g]	
	Ref3	**AN3**
PLC	140	140(1-x)
Andesite	0	140x
Coal fly ash	15	15
Limestone	230	230
Sand	615	615
HPMC	0.50	0.50
TD	0.02	0.02
Water	250	250

Table 5. Mix proportions of Product D.

Material	Formula [g]	
	Ref4	AN4
PLC	130	130(1-x)
Andesite	0	130x
Limestone	260	260
Sand	610	610
HPMC	0.68	0.68
TD	0.04	0.04
Water	300	300

Table 6. Minimum required initial and final setting times for each PLC-based product according to industrial standards.

Product	Requirement [min]		Related industrial standard
	Initial setting time	Final setting time	
A	> 45	< 420	TIS 2594-2567 [35]
B	> 45	-	TIS 80-2550 [36]
C	> 60	-	TIS 1776-2566 [37]
D	> 60	-	TIS 2735-2559 [38]

Table 7. Minimum required compressive strength for each PLC-based product according to industrial standards.

Product	Requirement	Related industrial standard
A	> 28 MPa after 28 days of curing	TIS 2594-2567 [35]
B	> 11.8 MPa after 7 days of curing	TIS 80-2550 [36]
C	> 2.5 MPa after 28 days of curing	TIS 1776-2566 [37]
D	> 2.5 MPa after 28 days of curing	TIS 1776-2566 [37]

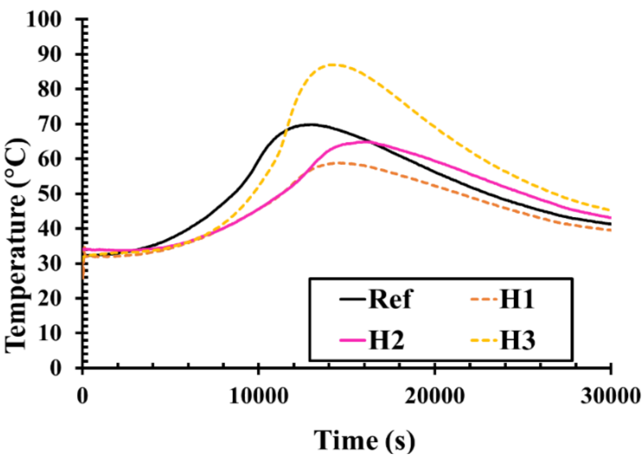

Figure 5. Temperature variation resulting from heat release during the heat of hydration test.

3. Results and discussion

The effects of replacing PLC with andesite on the hydration reaction are shown in Figure 5. As previously mentioned, the heat of hydration test was performed in accordance with ASTM C186-98 [33]. The temperature rise recorded inside the instrument chamber (Figure 2) reflects the heat released during the hydration process [39,40]. As seen in Figure 5, all mix proportions display a similar temperature profile, with an initial increase to a peak temperature followed by a gradual decline. As noted in previous studies [41], this temperature rise is primarily due to the exothermic hydration of tricalcium silicate ($3CaO{\cdot}SiO_2$), which forms calcium silicate hydrate (C–S–H, $3CaO{\cdot}2SiO_2{\cdot}3H_2O$) and calcium hydroxide ($Ca(OH)_2$), as expressed by the following Equation:

$$2(3CaO{\cdot}SiO_2) + 6H_2O \rightarrow 3CaO{\cdot}2SiO_2{\cdot}3H_2O + 3Ca(OH)_2 \quad (1)$$

At a replacement level of 5% (Formula H1), both the peak temperature and the time at which it occurs are lower and more delayed compared to the control mix (Formula Ref). This behavior is likely due to the dilution effect, where reactive PLC is partially replaced with andesite, resulting in reduced heat release and slower hydration kinetics [39,40, 42,43]. Although fly ash was also incorporated, its retarding effect was observed, which may arise from the dilution effect, as noted by Wongkeo *et al.* [44] , and from the possible absorption of calcium ions on the fly ash surface, as reported by Sereewatthanawut *et al.* [45].

For Formula H2, the peak temperature increases relative to H1 but remains slightly below that of the control. In contrast, Formula H3 exhibits a significantly higher peak temperature than the control mix, along with a faster rate of temperature rise compared to H1 and H2. This increasing trend is likely attributable to the nucleation effect [39–41], where andesite particles act as heterogeneous nucleation sites for C–S–H, the main product of the hydration reaction.

In this study, the optimal replacement level was determined by comparing the time–temperature profiles of the mixes to that of the control, aiming to identify the level that most closely matched the control's hydration behavior. Although Formula H3 exhibited a higher peak temperature than the control, excessive heat generation during curing can adversely affect the performance and long-term durability of cement-based products. Since Formula H2 achieved a peak temperature most similar to the control, a 10% replacement of PLC with andesite ($x = 0.1$) was selected as the optimal level. This proportion was then applied in the mix designs for Formulas AN1, AN2, AN3, and AN4, as shown in Table 3–6, respectively.

The initial and final setting times of samples from all PLC-based products are presented in Figure 6. In Figure 6(a), AN1 records times of 99.38 min and 117.00 min, representing increases of 15.22% and 11.43% over Ref1, respectively. In Figure 6(b), AN2 shows initial and final setting times of 125.00 min and 146.79 min, which are 15.38% and 10.09% higher than Ref2. In Figure 6(c), AN3 has times of 273.75 min and 305.00 min, exceeding Ref3 by 14.06% and 8.16%. In Figure 6(d), AN4 reaches 361.88 min and 410.00 min, representing increases of 50.78% and 5.13% over Ref4, respectively. According to the requirements specified in the relevant industrial standards listed in Table 7, both the control formulas and those incorporating andesite meet the required criteria, although the andesite-containing formulas exhibit longer initial and final setting times.

Figure 7 shows SEM micrographs of the microstructure of (a) Ref1 and (b) AN1 samples after 28 days of air curing. In Figure 7 (a), the C–S–H phase is observed along with residual ettringite, whereas in Figure 7(b), the identified phases are C–S–H and portlandite ($Ca(OH)_2$, CH)

Figure 8 presents the compressive strength of samples from all cement-based products. The dashed lines in Figure 8(a-d) indicate the minimum compressive strength requirements specified by the corresponding industrial standards, as outlined in Table 8. As expected, the compressive strength of all products increases over time due to the ongoing curing of PLC [14]. However, in each case, the formulas incorporating andesite show lower compressive strength than their respective control mixes.

In Figure 8(a), the compressive strengths of AN1 at 1, 3, 7, and 28 days of curing are 28.61 MPa, 39.82 MPa, 47.02 MPa, and 50.62 MPa, representing decreases of 10.54%, 12.19%, 7.84%, and 8.42% compared to Ref1, respectively. In Figure 8(b), AN2 records strengths of 10.62 MPa, 19.47 MPa, 23.46 MPa, and 27.06 MPa, which are 17.50%, 19.03%, 16.91%, and 13.96% lower than Ref2. In Figure 8(c), AN3 achieves strengths of 1.81 MPa, 3.84 MPa, 4.24 MPa, and 4.68 MPa, corresponding to reductions of 16.06%, 10.71%, 16.59%, and 14.01% compared to Ref3. In Figure 8(d), AN4 reaches 1.02 MPa, 2.19 MPa, 2.76 MPa, and 3.40 MPa, which are 42.34%, 17.99%, 26.51%, and 20.06% lower than Ref4, respectively. Despite these reductions, all andesite-containing samples meet the minimum compressive strength requirements specified in the relevant industrial standards (Table 8).

These results are consistent with previous findings, which attribute strength reduction to the inherent properties of andesite. Karataş *et al.* [47] reported that its lower active CaO content, combined with a greater tendency to form voids [45,47,48], weakens the cement matrix. Similarly, Hamidi *et al.* [18] observed that although andesite exhibits pozzolanic activity, it is insufficient to offset the effects of cement replacement, thereby limiting strength development. In this study, fly ash was also incorporated; however, as noted by Win *et al.* [49] and Moghaddam *et al.* [50], mortars containing fly ash still showed reduced strength at 28 days, indicating that the pozzolanic contributions of fly ash become more effective only at later curing ages.

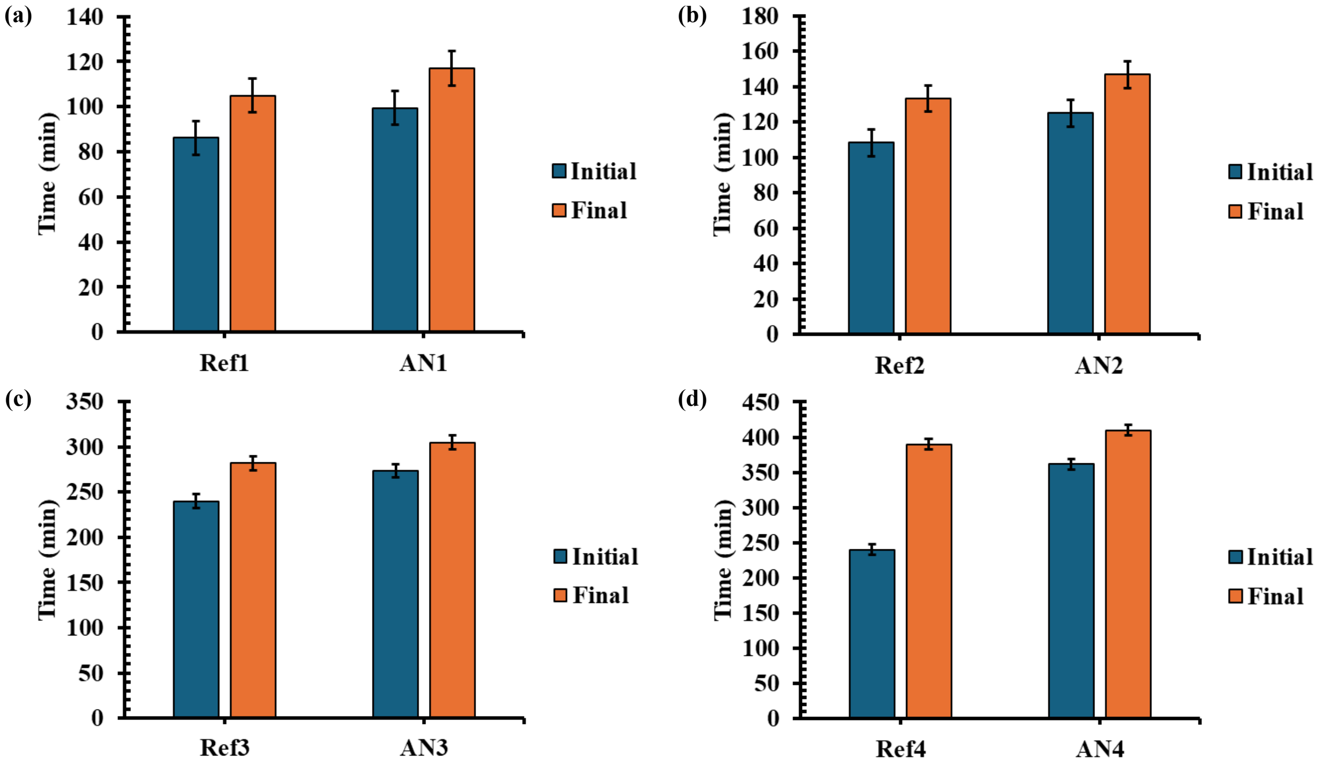

Figure 6. Initial and final setting times of: (a) Product A; (b) Product B; (c) Product C; and (d) Product D.

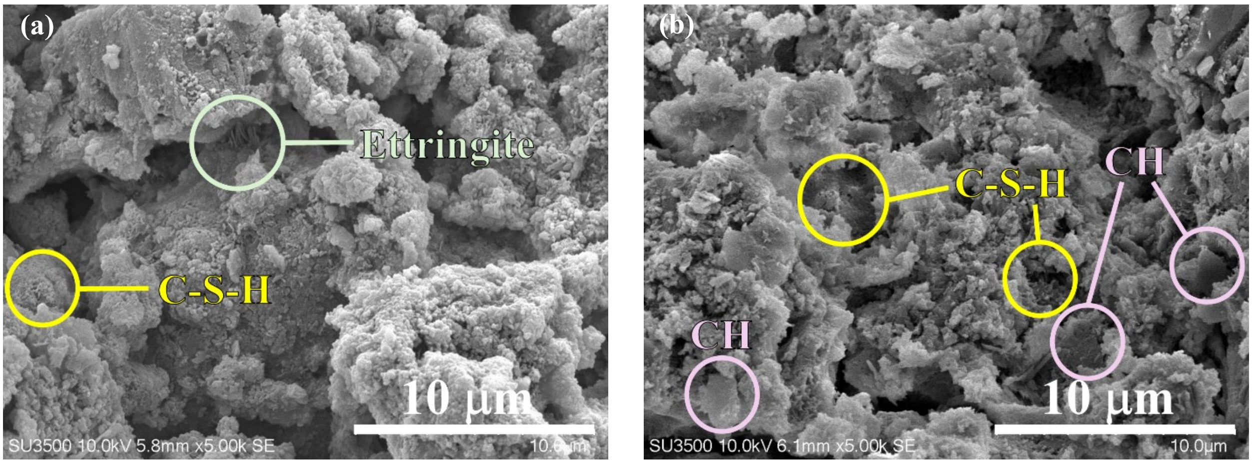

Figure 7. SEM micrographs showing the microstructure of (a) Ref1 and (b) AN1 samples after 28 days of air curing.

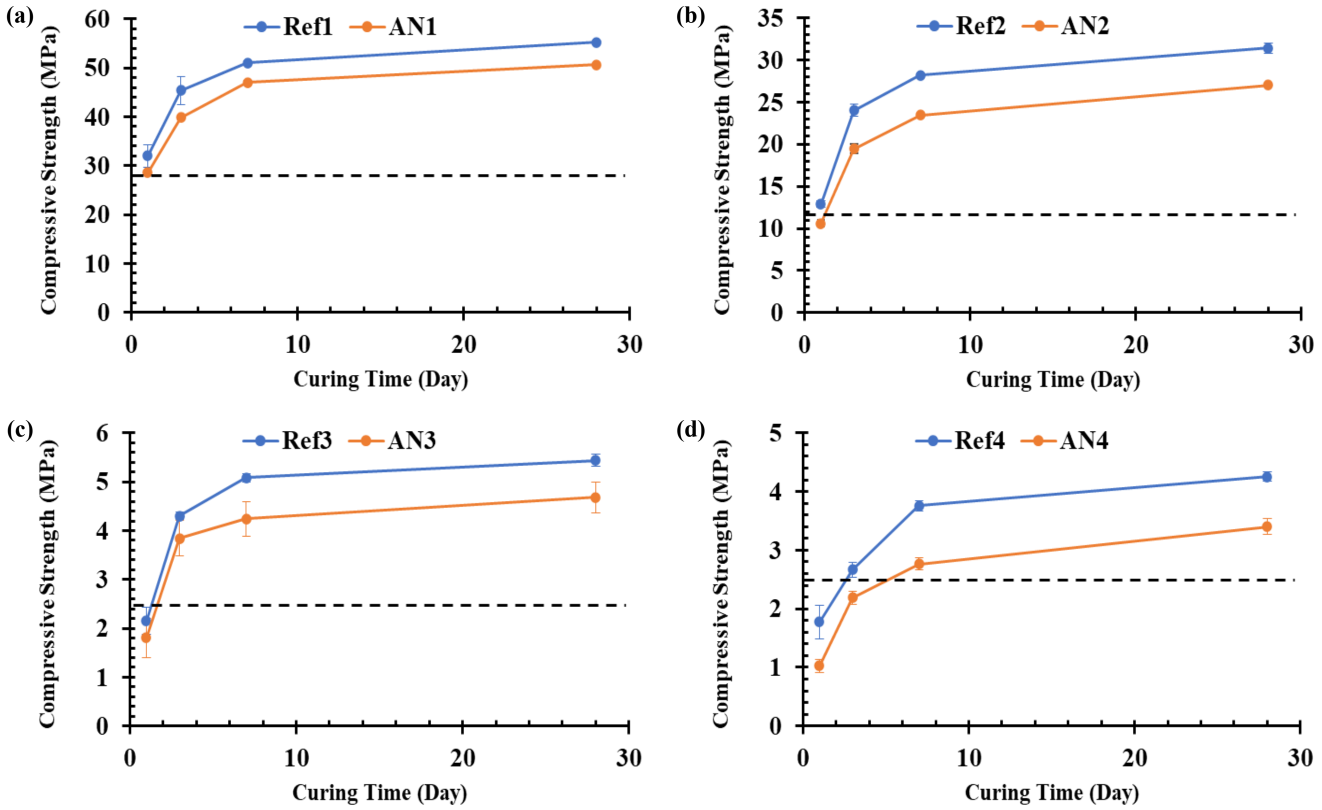

Figure 8. Compressive strength of: (a) Product A; (b) Product B; (c) Product C; and (d) Product D. Dashed lines indicate the minimum requirements specified by relevant industrial standards.

Figure 9. Concrete pipes manufactured using Product A.

Figure 11. Wall surface plastered with Product C.

Figure 10. Wall surface plastered with Product B.

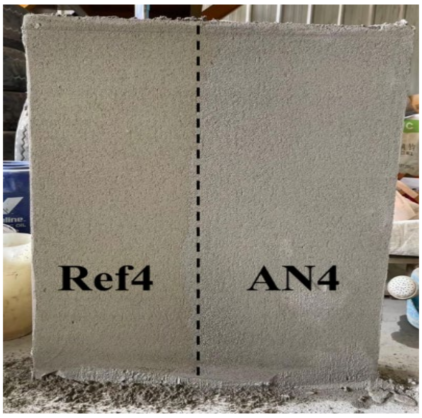

Figure 12. Wall surface plastered with Product D.

Since all four cement-based products, both with and without andesite addition, meet the required properties specified by industrial standards, they were subsequently implemented on an industrial scale. For Product A, cement from both Formula Ref1 and Formula AN1 was successfully used to manufacture concrete pipes, as shown in Figure 9. Products B, C, and D were mixed on an industrial scale and successfully applied to brick walls, as illustrated in Figure 10–12. As previously mentioned, one of the objectives of incorporating andesite was to enhance the shade of Products A to D.

With the aid of modern image processing tools, color values can be extracted directly from images [51]. The RGB values obtained from Figure 9 to Figure 12 using Adobe Express are presented in Table 9. According to Chang *et al.* [52], differences in color can be quantified through changes in RGB codes. In this study, the RGB values of andesite-incorporated samples (AN1 to AN4) were consistently lower than those of their corresponding control samples (Ref1 to Ref4), indicating a darker appearance.

Grayscale intensity, which ranges from 0 (black) to 255 (white), provides a further measure of shade [53]. Using the method described by Ullah *et al.* [54], grayscale values (Y) were calculated from RGB values as:

$$Y = (0.2989 \times R) + (0.5870 \times G) + (0.1140 \times B) \qquad (2)$$

Based on Table 9, the grayscale values of Products A to D with andesite incorporation are 182, 126, 107, and 131, respectively, representing reductions of 13.12%, 25.46%, 32.03%, and 15.81% compared with their corresponding control samples. These reductions confirm that the andesite-incorporated samples appear darker than the controls. Overall, these findings demonstrate that andesite effectively enhanced the visual appearance of Products A to D by producing a darker shade while maintaining compliance with industrial performance standards.

A cost analysis was conducted to compare the raw material costs for the dry mixtures of Products A to D, with and without andesite. The prices of the raw materials are listed in Table 10. Notably, the price of PLC is approximately 400% higher than that of andesite. Therefore, replacing PLC with andesite can have a significant impact on reducing raw material costs.

Table 8. RGB color codes and grayscale values of control samples (Ref1 to Ref4) and andesite-incorporated samples (AN1 to AN4) extracted from Figure 9–12.

Product	Control sample		Andesite-incorporated sample	
	RGB code	Grayscale value	RGB code	Grayscale value
A	213, 209, 205	210	182, 182, 184	182
B	179, 168, 146	169	138, 125, 98	126
C	156, 158, 157	157	107, 108, 101	107
D	166, 154, 136	156	135, 131, 120	131

Table 9. The price of raw materials.

Material	Price [$/ton]
PLC	62.00
Andesite	12.40
Coal fly ash	18.60
Lime stone	18.60
Sand	14.26
HPMC	3720
TD	7440

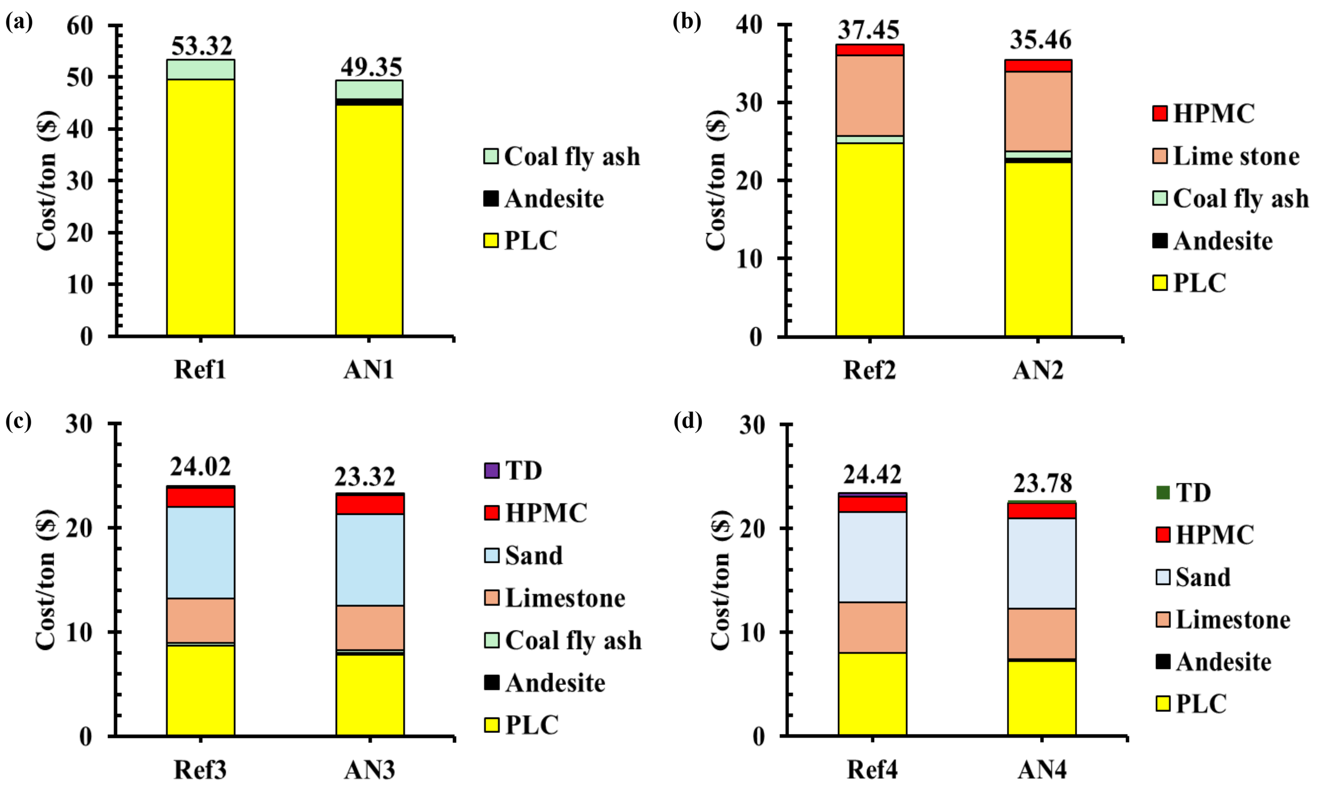

Figure 13. Total raw material costs for the dry mixtures of (a) Product A, (b) Product B, (c) Product C, and (d) Product D, with and without andesite incorporation.

Figure 13 compares the dry mixture costs of each product with and without andesite incorporation. For Product A, the total cost without andesite is $53.32 per ton, while with andesite it decreases to $49.35 per ton, representing a 7.44% cost reduction. For Product B, the cost drops from $37.45 per ton to $35.46 per ton, a 5.30% reduction. For Product C, the cost decreases from $24.02 per ton to $23.32 per ton, a 2.89% reduction. For Product D, the cost declines from $24.42 per ton to $23.78t per ton, representing a 2.64% reduction. These results demonstrate that andesite not only enhances the shade of Products A through D but also contributes to lowering raw material costs, as illustrated in Figure 13.

4. Conclusions

Andesite was investigated as a supplementary cementitious material (SCM) in four PLC-based products: (1) cement for structural applications, (2) blended cement for bricklaying and plastering, (3) general-purpose plastering mortar, and (4) plastering mortar for lightweight block applications. Heat of hydration tests identified 10% PLC replacement with andesite as the optimal level, which was adopted in all mix designs. Laboratory results showed that andesite incorporation extended the initial and final setting times by 14.06% to 50.78% and 5.13% to 11.43%, respectively, and reduced compressive strength by 8.42% to 20.06% at 28 days compared to control mixes; however, all samples still satisfied the relevant industrial standards. At the industrial scale, digital image analysis of field-tested products confirmed that andesite produced a consistently darker shade, with grayscale values reduced by 13.12% to 32.03% compared to controls, thereby improving visual appearance. Economically, replacing PLC with andesite lowered raw material costs by 2.64% to 7.44% depending on the product. Overall, andesite was shown to enhance aesthetics and sustainability while maintaining compliance with performance requirements. Importantly, this approach supports the United Nations Sustainable Development Goals by promoting resource efficiency (SDG 12), lowering carbon impact (SDG 13), and contributing to sustainable construction practices (SDG 9 and SDG 11).

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.

Data availability

Data will be made available on request.

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