Nigerian Research Journal of Engineering and Environmental Sciences 11(1) 2026 pp. 123-132
p ISSN: 2635-3342; e ISSN: 2635-3350

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

RJEES

Original Research Article

Effect of Water-Cement Ratio and Superplasticizer Dosages on Autogenous Deformation of Mortar Containing Burnt Clay Waste

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http://doi.org/10.5281/zenodo.21046736

ARTICLE INFORMATION

Article history:
Received 14 Apr. 2026
Revised 26 May 2026
Accepted 29 May 2026
Available online 30 Jun. 2026

Keywords:
Deformation
Water-cement ratio
Super plasticizer
Mortar
Burnt clay waste

ABSTRACT

This study examines the effects of water–cement ratio (0.4 and 0.6), superplasticizer dosage (1% and 2%), and partial replacement of cement with burnt clay waste powder (BCWP) at 5%, 10%, and 25% on autogenous deformation, compressive strength, and setting time of cement mortar. Experimental procedures followed relevant ASTM and BS EN standards. Results indicate that autogenous deformation increases rapidly within the first seven days before stabilizing. Lower water–cement ratio (0.4) produced higher shrinkage due to self-desiccation, while 0.6 reduced shrinkage but also lowered strength. BCWP showed a dual effect: 5–10% replacement slightly increased shrinkage, whereas 25% reduced it due to cement dilution and slower hydration. Superplasticizer dosage had a moderate influence, with 2% slightly increasing autogenous deformation while improving workability and strength development. Compressive strength increased with lower water–cement ratio, while higher BCWP content reduced strength. Optimal performance was achieved at 0.4 water–cement ratio, 2% superplasticizer, and up to 10% BCWP, yielding 28-day strengths above 15 N/mm², suitable for structural masonry applications. Setting time results showed that BCWP accelerated both initial and final setting, whereas superplasticizer slightly delayed setting due to improved workability retention. The study concludes that BCWP can be effectively utilized as a partial cement replacement up to 10% for sustainable mortar production without significantly compromising performance. Optimization of water–cement ratio, superplasticizer dosage, and BCWP content provides a balanced approach to improving strength, shrinkage behavior, and setting characteristics.

1. INTRODUCTION

The rapid expansion of the global construction industry has spurred a surge in research and development aimed at tackling real-world challenges and enhancing the quality of life (Backes and Traverso, 2021). Investigating innovative materials, testing their limitations, and exploring alternatives to traditional materials are crucial endeavors. Improving existing materials or discovering new ones with superior physical and chemical properties is essential for driving progress in the field.

A wide range of construction materials, including concrete, mortar, reinforcement steel, soils, and water, continue to be the focus of extensive research and development aimed at improving their performance and durability. One critical area of focus is the cement mortar, a fundamental component in the production of concrete, mortar, and grout. Over time, challenges have arisen due to its physical and chemical properties, prompting ongoing efforts to enhance its performance. These advancements consider multiple factors, such as environmental and chemical aspects, leading to the development of new and improved materials (Scrivener *et al.,* 2018).

Cementitious materials, such as cement mortar, are prone to defects due to their inherent properties and interactions with environmental factors like temperature and relative humidity. These interactions cause the material to undergo volume changes, resulting in autogenous deformation, also known as self-generated shrinkage. This self-induced deformation can lead to cracking in structures where the cement mortar is used, compromising their integrity (Lothenbach *et al.,* 2008).

In modern sustainable construction, attention has shifted toward reducing cement consumption and incorporating industrial and agricultural wastes as supplementary cementitious materials (SCMs). Burnt clay waste powder (BCWP), a by-product of the ceramic and brick industries, is rich in silica and alumina, offering pozzolanic properties that can partially replace cement (Jimoh *et al.,* 2025). Utilizing BCWP not only diverts waste from landfills but also reduces the carbon footprint associated with cement production (Ramarao and Sitharam, 2012; Kumar et al., 2019). Despite these benefits, its influence on autogenous deformation, especially when combined with varying water–cement ratios (W/C) and superplasticizer dosages, remains insufficiently understood.

The incorporation of SCMs such as fly ash, silica fume, and rice husk ash has been widely reported to improve durability and reduce permeability, though often at the cost of increased autogenous (Wyrzykowski and Lura, 2022; Wu et al., 2018). Previous studies confirmed that BCWP exhibits pozzolanic activity capable of improving strength and reducing permeability. However, their works did not examine the interaction between BCWP, W/C ratio, and chemical admixtures on autogenous deformation (Singh and Singh, 2017; Ramarao and Sitharam, 2012).

Therefore, this study aims to fill this gap by experimentally investigating the effect of water–cement ratio and superplasticizer dosage on the autogenous deformation of mortar containing burnt clay waste**,** providing new insights into sustainable, shrinkage-resistant mortar design.

2. MATERIALS AND METHODS

2.1. Material Collection

The materials and methods to be inculcated in the course of this research were locally sourced and the methods used were done according to standard specifications and procedures using various standard codes of practice. The materials to be used include Dangote Portland Limestone Cement conforming to ASTM C150 (2009) was obtained from a local cement store. Burnt clay waste was sourced from the Concrete and Materials Laboratory at the University of Lagos and processed to achieve a particle size distribution similar to that of cement, as shown in Figure 1. A polycarboxylic ether-based superplasticizer conforming to ASTM C494 (2008) was obtained from COSTAR Building Product System.

2.2. Material Processing

The dried material was subsequently ground using a laboratory ball mill until its fineness approximated that of Portland cement. The powdered form was then sieved through a 75 µm sieve to ensure uniformity.

Figure 1: Pile of broken bricks at a manufacturing site

2.3. Design Mix

The study adopted a factorial experimental design to evaluate the effects of water–cement ratio, superplasticizer dosage, and BCWP replacement level on autogenous deformation. The superplasticizer dosages were set at 1% and 2% by weight of cement. The BCWP levels (5%, 10%, and 25%) and W/C ratios (0.4 and 0.6) were combined to create multiple mix variations, allowing a comprehensive assessment of parameter interactions. Cement mortar was prepared using a 1:3 mix ratio (cement to sand) in accordance with ACI 211.1-91 recommendations. The materials were mixed in a mechanical mixer at 140 ± 5 rpm for approximately five minutes to achieve uniformity. Cement was partially replaced with BCWP at 5%, 10%, and 25% by weight in successive mixes.

The experimental program consisted of sixteen mortar mix combinations classified into control and modified mixes. The control mixes included 1A (0.6 water cement ratio, 1% superplasticizer, 0% burnt clay waste), 2A (0.6 W/C, 2% SP, 0% BCW), 1B (0.4 W/C, 1% SP, 0% BCW), and 2B (0.4 W/C, 2% SP, 0% BCW), while the modified mixes incorporated burnt clay waste at different replacement levels. Mixes 1C, 2C, 1D, and 2D contained 5% BCW with varying water–cement ratios and superplasticizer dosages; mixes 1E, 2E, 1F, and 2F contained 10% BCW under similar proportions; and mixes 1G, 2G, 1H, and 2H contained 25% BCW with corresponding variations in water–cement ratio and superplasticizer content.

2.4. Tests on Mortar

2.4.1. Autogenous deformation test

Autogenous deformation tests were performed according to *ASTM C1698* and *ISO 1920-3*. The corrugated-tube method was adopted, whereby fresh mortar was poured into a sealed corrugated tube and placed in a water bath maintained at 20 ± 1°C. Deformation readings were taken at predetermined intervals using a dial gauge. Due to limited access to specialized equipment, an improvised test setup was developed using rectangular moulds (160 × 40 × 40 mm). The specimens were demoulded after 24 hours, wrapped in foil to prevent moisture exchange, and mounted on the apparatus to measure deformation over time. Although improvised, the setup maintained precision adequate for comparative analysis.

2.4.2. Compressive strength test

The compressive strength of the mortar specimens was determined following *BS EN 1015-11* (British and European standard for hardened mortar testing). Specimens were cured and tested using a hydraulic testing machine, with load applied uniformly until failure. The compressive strength was calculated as the ratio of the maximum load to the cross-sectional area of the specimen.

2.4.3. Setting time test

The setting times of the mixes were evaluated using the Vicat apparatus, in accordance with *BS EN 196-3:2016*. The procedure involved determining the time required for the cement paste to achieve standard consistency and the interval between initial and final setting. This test provided insights into the influence of BCWP and superplasticizer on the hydration kinetics of the mortar.

3. RESULTS AND DISCUSSION

3.1. Autogenous Deformation Test

Table 1 displays the shrinkage data for various mix samples. From Figure 2, the autogenous deformation tends to increase with BCWP content up to a certain level. For instance, sample 1F recorded the highest deformation value of approximately 0.053 mm, indicating that BCWP replacement levels in the range of about 10 % to 25 % can significantly influence shrinkage behavior. In contrast, the control samples 1A and 1B, containing 0 % BCWP, exhibited much lower deformation values of approximately 0.018 mm and 0.040 mm, respectively, demonstrating reduced autogenous shrinkage in the absence of BCWP. This observation confirms that the incorporation of BCWP alters the internal structure of the mortar and intensifies shrinkage when compared to conventional mixes without BCWP.

Table 1: Shrinkage data for various mix samples

Label	Mix composition	Shrinkage				
		1d (mm)	3d (mm)	7d (mm)	14d (mm)	28d (mm)
1A(control)	0.6W/C, 1%SP, 0%BCW	0.004	0.010	0.015	0.018	0.018
2A(control)	0.6W/C, 2%SP, 0%BCW	0.007	0.018	0.027	0.027	0.027
1B(control)	0.4W/C, 1%SP, 0%BCW	0.010	0.024	0.035	0.040	0.040
2B(control)	0.4W/C, 2%SP, 0%BCW	0.015	0.035	0.045	0.047	0.047
1C	0.6W/C, 1%SP, 5%BCW	0.020	0.038	0.046	0.048	0.048
2C	0.6W/C, 2%SP, 5%BCW	0.025	0.046	0.055	0.062	0.062
1D	0.4W/C, 1%SP, 5%BCW	0.022	0.040	0.050	0.054	0.055
2D	0.4W/C, 2%SP, 5%BCW	0.030	0.055	0.060	0.064	0.065
1E	0.6W/C, 1%SP, 10%BCW	0.015	0.032	0.038	0.042	0.042
2E	0.6W/C, 2%SP, 10%BCW	0.020	0.038	0.042	0.044	0.044
1F	0.4W/C, 1%SP, 10%BCW	0.025	0.044	0.050	0.051	0.051
2F	0.4W/C, 2%SP, 10%BCW	0.030	0.055	0.060	0.060	0.060
1G	0.6W/C, 1%SP, 25%BCW	0.006	0.012	0.019	0.022	0.022
2G	0.6W/C,2%SP, 25%BCW	0.009	0.019	0.025	0.029	0.029
1H	0.4W/C, 1%SP, 25%BCW	0.009	0.017	0.022	0.025	0.026
2H	0.4W/C, 2%SP, 25%BCW	0.012	0.022	0.028	0.031	0.032

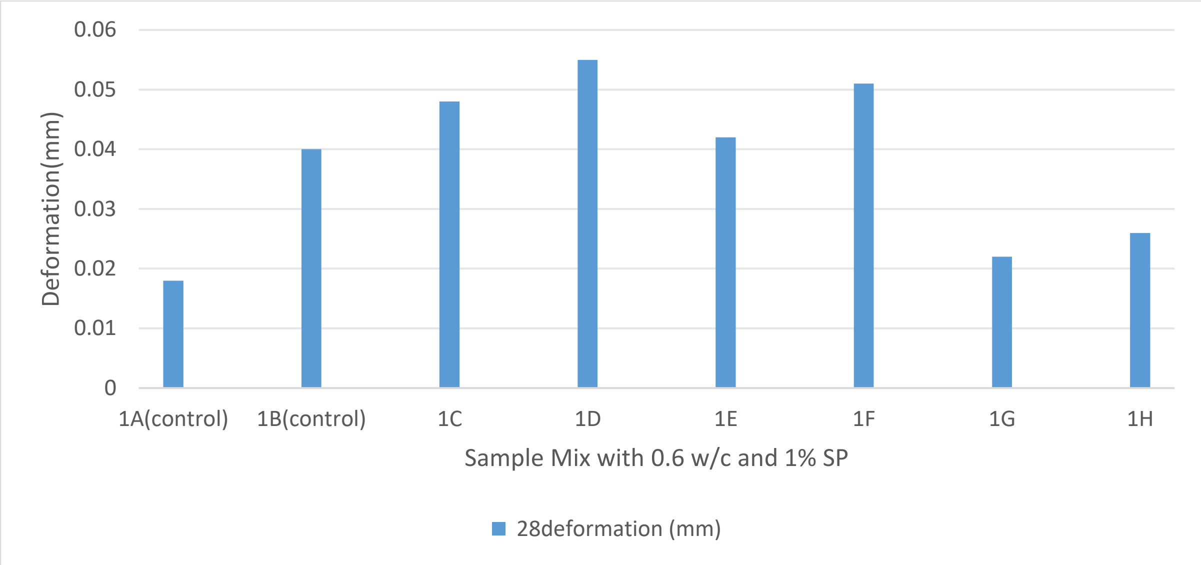

Figure 2: Deformation of samples having 1% SP

According to Table 1, autogenous deformation increased steadily with curing age for all mixes, with the most rapid increase occurring between Day 1 and Day 3. Beyond this early age, deformation continued to develop at a slower rate up to Day 28. This trend suggests that the majority of autogenous shrinkage occurs during early hydration, while continued hydration and internal moisture redistribution contribute to gradual deformation at later ages. Similar early-age shrinkage behavior has been reported by Abdul Razak et al. (2020), who observed that most autogenous deformation in modified mortars develops within the first few days of hydration due to self-desiccation effects. The observed influence of water–cement ratio on deformation is also consistent with previous findings. Mortars with a lower water–cement ratio (0.4) generally exhibited higher autogenous deformation than those with a higher ratio (0.6), regardless of BCWP content. This agrees with the findings of Chen et al. (2016), who reported that lower water–binder ratios produce finer pore structures, resulting in higher capillary stresses and increased autogenous shrinkage. Therefore, the results of this study align well with existing literature, confirming that both mix composition and curing age play critical roles in the development of autogenous deformation in cementitious materials.

3.2. Results Compressive Strength Test

Table 2 presents the average compressive strength results for 7 and 28 days. From Table 2, the data shows cement replacement with BCW (which is a pozzolanic material), two water-cement ratios: 0.6 and 0.4, two dosages of superplasticizer (SP): 1% and 2%, and compressive strengths at 7 days and 28 days.

The relationship between the compressive strength for 7 and 28 days and varying water cement ratio for the control samples is presented in Figure 3. Increasing BCW as a partial replacement for cement reduces the 28-day compressive strength. Small replacements (5–10%) cause a moderate decrease, while high replacement (25%) leads to a significant drop due to insufficient cement for proper hydration. Lower W/C ratios or higher superplasticizer dosages slightly improve strength, but the overall trend clearly shows that higher BCW content weakens the concrete.

According to Figure 4, the results show that mixes with a lower water cement ratio (0.4) consistently achieved higher 28-day compressive strengths than those with a higher ratio (0.6) at all BCW replacement levels. This confirms the well-established inverse relationship between the water cement ratio and strength, as the water content decreases, concrete becomes denser and less porous, leading to improved strength.

Table 2: Average compressive strength results for 7 and 28 days

Label	Average compressive strength (N/mm^2) for 7days	Average compressive strength (N/mm^2) for 28days
1A (Control)	10.8	12.0
2A (Control)	11.5	13
1B (Control)	13	15
2B (Control)	14	16.5
1C	9.5	11
2C	10	11.8
1D	11	12.8
2D	11.8	13.5
1E	8.5	10.2
2E	9	11
1F	9.8	11.5
2F	10.4	12.3
1G	6	7
2G	6.5	7.5
1H	6.8	8
2H	7.2	8.5

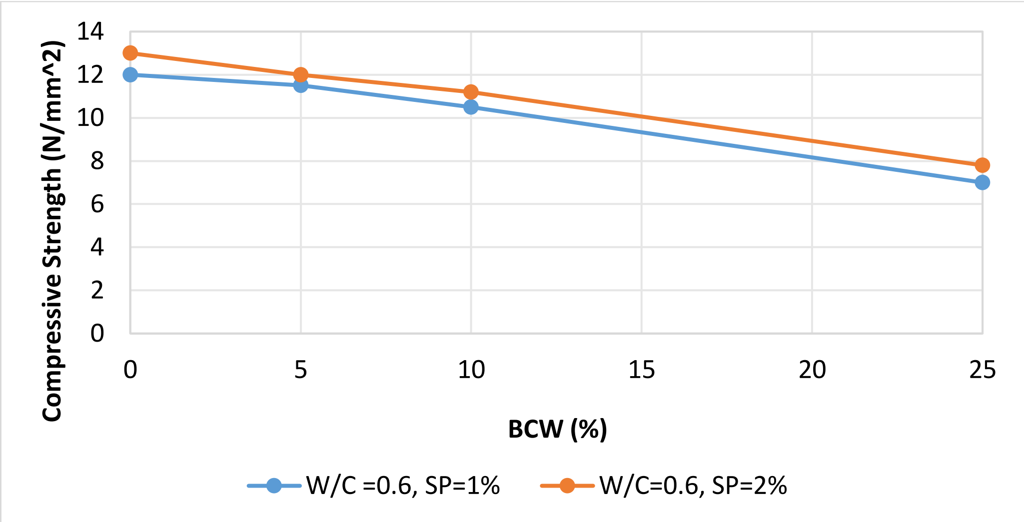

Figure 3: Relationship between the compressive strength for 7 and 28 days and varying water cement ratio for the control samples

The results further show that mixes with a lower water–cement ratio (0.4) consistently achieved higher 28-day compressive strength than those with a higher ratio (0.6), regardless of BCW content. For instance, at 0% BCW, compressive strength increased from approximately 12 N/mm² at W/C = 0.6 to 15 N/mm² at W/C = 0.4.

This trend confirms the inverse relationship between water–cement ratio and compressive strength, which has long been established in cementitious materials research. According to Abrams' water–cement ratio law (Abram 1998), reducing the water content leads to a denser microstructure with fewer capillary pores, thereby improving strength development. The consistency of your findings with this fundamental principle validates the reliability of the experimental results. Overall, the Figure 4 demonstrates that reducing the water-cement ratio enhances strength regardless of BCW content, but excessive BCW substitution still weakens the concrete because of limited cement hydration and binder formation.

Figure 5 shows that increasing the superplasticizer dosage from 1% to 2% slightly increases the 28-day compressive strength of concrete at all levels of BCW replacement. For both SP dosages, strength decreases progressively as the percentage of BCW increases, but the mixes containing 2% SP consistently exhibit higher strengths than those with 1%.

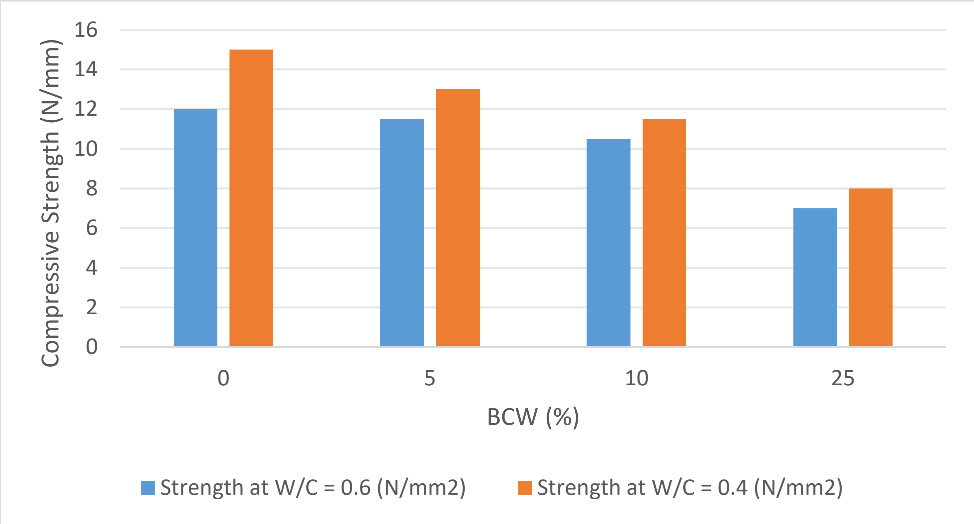

Figure 4: Various mix samples with their 7 and 28-day strengths

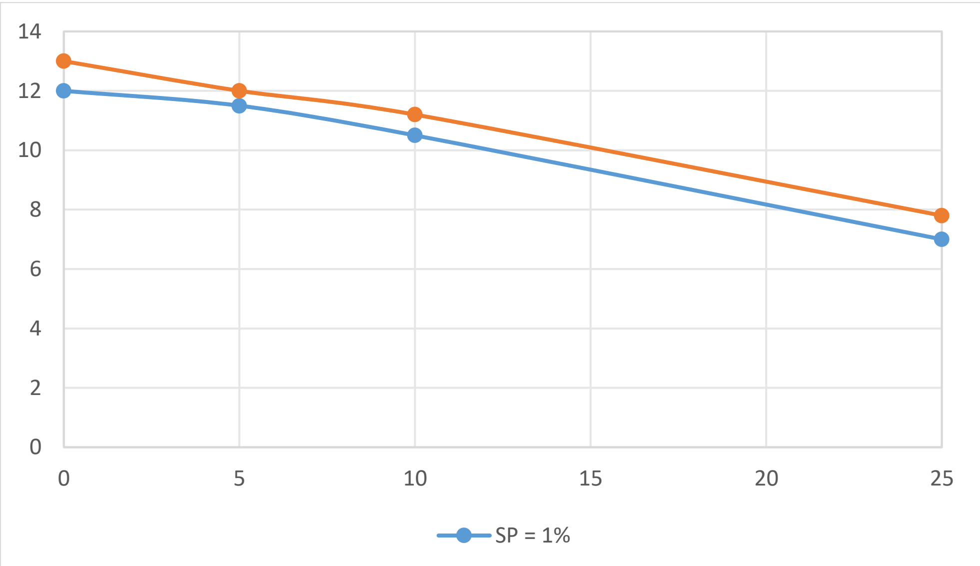

Figure 5: Effect of the Introduction of BCW in the mortar mix

Additionally, the increase in superplasticizer dosage from 1% to 2% resulted in a slight improvement in compressive strength at all BCW replacement levels. This improvement is attributed to enhanced workability and improved particle dispersion, which allow better compaction and more efficient hydration. However, the marginal difference between the two SP dosages indicates that beyond an optimal level, additional superplasticizer offers limited strength enhancement. Similar observations were reported in previous studies, where superplasticizers improved strength indirectly by enabling lower water–cement ratios rather than directly contributing to strength gain (Malhotra and Mehta, 1996). Overall, the compressive strength results align well with existing literature. Strength development is enhanced by lower water–cement ratios, increased curing age, and adequate superplasticizer dosage, while excessive replacement of cement with BCW adversely affects strength. Optimal performance in this study was achieved with a water–cement ratio of 0.4, 2% superplasticizer, and no or minimal (≤5%) BCW replacement, producing 28-day compressive strengths exceeding 15 N/mm² (Class M15), confirming suitability for structural masonry applications.

3.3. Setting Time Test Results

The setting time test was conducted to determine the initial and final setting times of the cement paste, both for cement only and for cement with 15% Burnt Clay Powder (BCP) substitution, following determination of the standard consistency. Tests were also performed with the addition of 1% of Costamix 600 (PCE) superplasticizer to evaluate its effect on setting time as shown in Table 3.

Table 1: Setting time result

Mix	Consistency(W/C)	Initial Setting Time (mins)	Final Setting Time (mins)
Cement Only	0.28	164	440
Cement + 15%BCW	0.32	133	235
Cement + 1% SP	0.250	177	465
Cement + 25%BCP+ 1% SP	0.3	140	230

The setting time test was conducted to determine the initial and final setting times of cement paste with and without Burnt Clay Waste (BCW) substitution, as well as the effect of superplasticizer addition. As shown in Table 3, replacing 15% of cement with BCW increased the water–cement ratio required to achieve standard consistency from 0.28 for the cement-only mix to 0.32. This increase can be attributed to the higher surface area and water demand of BCW particles.

The incorporation of BCW significantly accelerated the setting process. The initial setting time reduced from 164 minutes for the cement-only paste to 133 minutes for the BCW-blended paste, while the final setting time decreased sharply from 440 minutes to 235 minutes. This acceleration is attributed to the presence of reactive aluminosilicate phases in burnt clay, which promote early hydration reactions. Similar findings were reported by Scrivener et al. (2018), who observed that calcined clay additions accelerate early hydration and reduce setting times due to enhanced nucleation effects and increased availability of reactive alumina. When 1% Costamix 600 (PCE) superplasticizer was introduced, the water–cement ratio required for standard consistency decreased for both mixes, reducing to approximately 0.250 for the cement-only mix and 0.30 for the BCW-blended mix. The addition of the superplasticizer resulted in a slight delay in both initial and final setting times. For the cement-only mix, the initial and final setting times increased to 177 minutes and 465 minutes, respectively, while the BCW-blended mix recorded 140 minutes and 230 minutes. This retardation effect is due to the adsorption of PCE molecules on cement particle surfaces, which slows down the early hydration process. Similar retardation behavior associated with polycarboxylate-based superplasticizers has been reported by Plank and Hirsch (2007) who noted that PCE admixtures delay setting by dispersing cement particles and reducing early hydration rates.

Overall, the results demonstrate that BCW substitution accelerates the setting of cement paste, while the addition of superplasticizer counteracts this effect by retarding hydration. These findings are consistent with published literature and confirm that the combined use of BCW and PCE superplasticizer allows control of setting characteristics to suit practical mortar and concrete applications.

4. CONCLUSION

This study examined the effects of water-cement ratio, superplasticizer dosage, and burnt clay waste powder (BCWP) on the autogenous deformation, compressive strength, and setting behavior of cement mortar. The research aimed to promote sustainable construction by reducing cement consumption and utilizing waste materials while maintaining satisfactory strength and durability.

Results showed that autogenous deformation increased with curing age in all mixes, with the greatest changes occurring within the first three days. Mortars with a lower water-cement ratio of 0.4 exhibited greater deformation due to limited water available for hydration. Incorporation of BCWP up to 10%, increased shrinkage slightly because of its fine particles and high surface area, while higher replacements reduced deformation due to dilution of the cementitious material. The use of superplasticizer produced a minor increase in deformation but its effect was less significant compared to the water-cement ratio and BCWP content.

Compressive strength increased with curing age for all mixtures. Mortars with a lower water-cement ratio consistently achieved higher strengths than those with a higher ratio, confirming the inverse relationship between water content and strength. Partial replacement of cement with BCWP led to a gradual reduction in strength, but mixes containing up to 10 percent BCWP maintained acceptable performance levels. The inclusion of 2 percent superplasticizer improved workability and slightly enhanced strength due to better compaction and cement dispersion. The optimal combination was found to be 0.4 water-cement ratio, 2 percent superplasticizer, and 10 percent BCWP replacement, which provided a balance between mechanical strength and sustainability.

Setting time tests revealed that BCWP increased water demand and accelerated setting, while superplasticizer reduced water requirement and delayed setting. The combination of BCWP and superplasticizer resulted in moderate consistency and acceptable setting times, indicating that they can work effectively together to produce workable and durable mortar.

Overall, the findings demonstrate that burnt clay waste powder can serve as a sustainable supplementary cementitious material in mortar production when used in moderate amounts. It contributes to later-age strength gain and reduces environmental impact through waste utilization. However, excessive replacement beyond 10 percent negatively affects strength and early-age shrinkage. Therefore, controlled proportions and proper mix optimization are essential. Future studies should focus on long-term durability and microstructural analysis to further enhance the performance of BCWP blended mortar.

5. ACKNOWLEDGMENT

The authors wish to acknowledge the assistance and contributions of the laboratory staff of Department of Civil and Environmental Engineering, University of Lagos, Akoka, Lagos State toward the success of this work.

6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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