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Durability And Resilience Of Mortar Incorporating Pulverised Burnt Clay Waste Under Freshwater And Saline Exposure

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ABSTRACT: *Flooding significantly affects the performance of cement-based materials, particularly in tropical environments. This study evaluates the durability and resilience of mortar incorporating Pulverised Burnt Clay Waste (PBCW) under prolonged freshwater and saline exposure. Mortar mixes containing 0–20% PBCW were prepared at binder–sand ratios of 1:6 and 1:8 with a constant water–binder ratio of 0.60. After 28 days curing, specimens were immersed for 120 days and followed by 120-day air-drying recovery. Control mixes experienced strength losses of up to 47.78%, whereas PBCW-modified mixes showed lower deterioration (28–36%) and improved recovery. The highest resilience index of 173.52% was obtained at 10% PBCW replacement under saline conditions. XRD analysis indicated reduced portlandite and formation of chloride-binding phases. Results show that 5–10% PBCW provides optimal performance. PBCW is therefore a viable supplementary cementitious material for durable and resilient mortar in flood-prone environments.*

KEYWORDS: *Pulverised burnt clay waste (PBCW), mortar durability, flood exposure, resilience index, saline exposure, pozzolanic materials*

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I. INTRODUCTION

Flooding poses a significant threat to the durability of cementitious materials, particularly mortar and sandcrete blocks widely used in tropical regions. Prolonged exposure to water and subsequent drying cycles accelerate deterioration through leaching, increased porosity, and strength loss (Babafemi et al., 2021; Olofinnade et al., 2021).

Beyond durability, the ability of materials to recover strength after exposure—termed *resilience*—is an important performance indicator. Quantitative assessment using indices such as Damage Index (DI), Strength Recovery Index (SRI), and Resilience Index (RI) provides insight into material performance under environmental stress (Hosseini et al., 2021; Sun & Chen, 2022).

Supplementary cementitious materials (SCMs) derived from waste products have gained attention due to their environmental and performance benefits. Pulverised Burnt Clay Waste (PBCW), a silica-rich material obtained from fired brick waste, exhibits pozzolanic characteristics and has potential for enhancing durability (Kareem & Raheem, 2022; Scrivener et al., 2021).

However, limited studies have examined the performance of PBCW-modified mortar under prolonged immersion and recovery conditions. This study therefore evaluates the durability and resilience of mortar incorporating PBCW under freshwater and saline exposure.

II. MATERIALS AND METHODS

2.1 Materials

Ordinary Portland Cement (CEM I 42.5R) conforming to *BS EN 197-1 (2011)* and river sand (fine aggregate) were sourced from the open market. The potable water conforming to *NIS 554:2015* was used.

Pulverised Burnt Clay Waste (PBCW) was obtained from factory-fired brick waste, crushed, and ground into fine powder. The chemical compositions (percentage oxides) of PBCW were determined using XRF as presented in Table 1.

Table 1: Chemical composition of PBCW determined by XRF

Sample	SiO_2	Al_2O_3	$Fe2O_3$	CaO	K_2O	Na_2O	TiO2	MnO	P_2O_5	SO_3	LOI
PBCW	62.53	20.5	8.15	2.25	1.6	0.21	0.09	0.01	0.01	0.01	4.6

The high silica and alumina content indicates strong pozzolanic potential (Kareem & Raheem, 2022).

2.2 Mix Proportion

Mortar mixes were prepared at binder–sand ratios of 1:6 and 1:8 with PBCW replacement levels of 0–20% and a constant water–binder (w/b) ratio of 0.60. The detailed mix proportions used in this study are presented in Table 2.

Table 2: Mix proportions of mortar incorporating varying percentages of PBCW

M1 (1:6)	PBCW (%)	Cement (%)	w/b	M2 (1:8)	PBCW (%)	Cement (%)	w/b
M1 (1:6)-0	0	100	0.60	M2 (1:8)-0	0	100	0.60
M1 (1:6)-5	5	95	0.60	M2 (1:8)-5	5	95	0.60
M1 (1:6)-10	10	90	0.60	M2 (1:8)-10	10	90	0.60
M1 (1:6)-15	15	85	0.60	M2 (1:8)-15	15	85	0.60
M1 (1:6)-20	20	80	0.60	M2 (1:8)-20	20	80	0.60

2.3 Specimen Preparation

Mortar of 50 cube sizes were cast following ASTM C109/C109M (2024). Specimens were cured under moist conditions at 20 ± 2°C with regular water application to maintain continuous hydration.

2.4 Immersion Exposure

Specimens were immersed for 120 days in freshwater and 4 wt.% NaCl. The solutions were periodically monitored and replenished to maintain consistent concentration. After exposure, specimens were air-dried under laboratory conditions for 120 days.

2.5 Tests Conducted

The tests conducted included compressive strength testing, XRF (material characterization), XRD (phase analysis), and evaluation of durability indices (DI, SRI, and RI).

2.6 Resilience Indices

Three performance-based indicators were adopted from recent durability and resilience literature: Damage Index (DI), Strength Recovery Index (SRI), and Resilience Index (RI) (Zhang et al., 2021; Hosseini et al., 2021; Sun & Chen, 2022). These indices enable quantitative assessment of strength deterioration, recovery capacity, and overall post-disturbance performance of cementitious materials:

The Damage Index (DI) expresses the percentage loss in compressive strength due to flood exposure. DI is represented by equation 1. A positive DI indicates strength degradation, while a negative value indicates strength gain beyond the control due to continued hydration or pozzolanic reaction. Lower DI values signify improved resistance to flood-induced deterioration.

The Strength Recovery Index (SRI) evaluates the ability of the mortar to regain strength after a post-exposure curing (recovery) period. SRI is represented by equation 2. An SRI value of 100% indicates full recovery to control strength. Values greater than 100% indicate enhanced post-disturbance strength performance.

The Resilience Index (RI) represents the overall retained structural performance after exposure and recovery. RI is represented by equation 4. An RI equal to or greater than 100%

indicates complete resilience or performance enhancement.

This index provides a simplified measure of post-flood structural robustness. These indices collectively quantify degradation, recovery capacity, and overall structural resilience under flood exposure:

$$DI\ (\%) = \frac{(F_c - F_e)}{F_c} \times 100 \quad (1)$$

$$SRI\ (\%) = \frac{F_r - F_e}{F_c - F_e} \times 100 \quad (2)$$

$$RI\ (\%) = \frac{F_r}{F_c} \times 100 \quad (3)$$

Where:

F_c= compressive strength before exposure

F_e = compressive strength after exposure

F_T = compressive strength after recovery

Lower DI values indicate reduced deterioration, while higher SRI and RI values indicate better recovery and improved resilience of the mortar after environmental exposure.

III. RESULTS

3.1 Chemical Composition

PBCW exhibited high SiO_2 and Al_2O_3 content, confirming its pozzolanic nature.

3.2 Microstructure (XRD)

The mineralogical phases identified are summarized in Table 3.

Table 3: Mineralogical phases identified by XRD in mortar specimens (15% PBCW for Mix 1/2) after 120-day exposure and recovery

Specimen	Exposure	Dominant Phases	Key Secondary Phases	Crystallinity
PBCW	—	Quartz, Mullite	Cristobalite, Minor Feldspar, Amorphous phase	Moderate
Control (0%)	Freshwater	Portlandite, Calcite	Ettringite	High
Control (0%)	4 wt.% NaCl	Amorphous C–S–H	Halite, Gypsum	Low
Mix 1 (15%)	Freshwater	Quartz, Calcite, Reduced Portlandite	Stratlingite	Moderate
Mix 1 (15%)	4 wt.% NaCl	C–S–H, Aluminosilicates	Friedel's Salt	Low–Moderate
Mix 2 (15%)	Freshwater	Secondary C–S–H, Calcite	Stratlingite, Residual Portlandite	Moderate–High
Mix 2 (15%)	4 wt.% NaCl	Friedel's Salt, C–S–H	Minor Halite	Moderate

The XRD results revealed that the control sample contained prominent phases such as portlandite and calcite. In contrast, the PBCW-modified mixes showed a reduction in portlandite content and an increase in calcium silicate hydrate (C–S–H), indicating improved pozzolanic activity. Also, samples exposed to saline conditions exhibited the formation of Friedel's salt, reflecting the interaction between chloride ions and the cementitious matrix.

3.3 Strength before exposure

The 28-day compressive strength results are presented in Fig. 1.

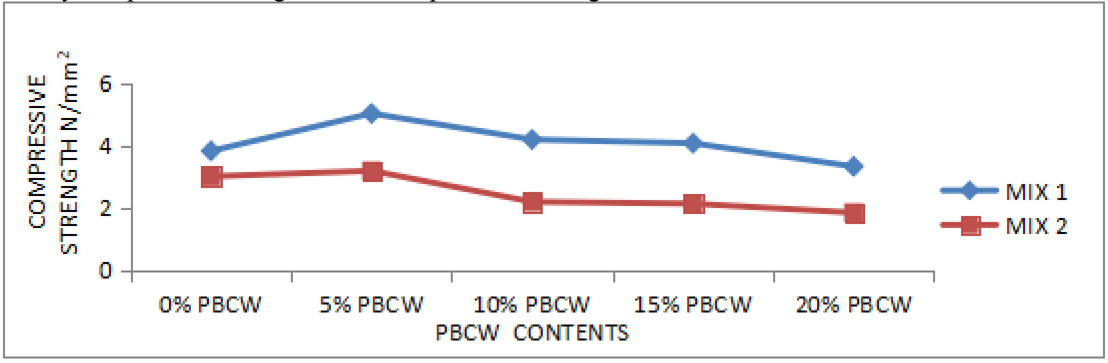

Fig. 1: 28-day compressive strength of mortar mixes with varying PBCW replacement levels

Compressive strength decreases at higher PBCW replacement levels (>10%) for both Mix 1 (1:6) and Mix 2 (1:8). Mixes containing 5–10% PBCW exhibit compressive strength values comparable to the control mixes.

3.4 Freshwater Exposure

The compressive strength results after freshwater immersion and recovery are presented in Fig.s 2 and 3 for Mix 1 (1:6) and Mix 2 (1:8), respectively.

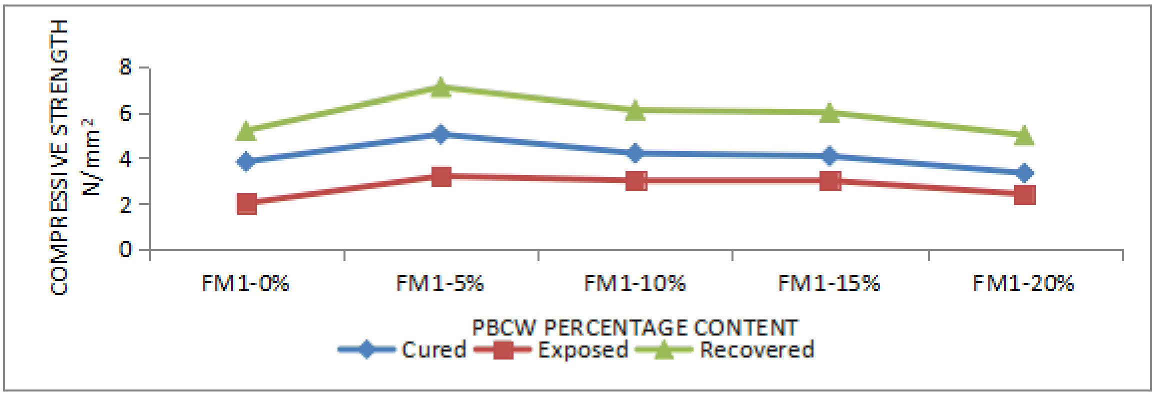

Fig 2: Compressive strength of Mix 1 (1:6) mortar under freshwater exposure and recovery conditions

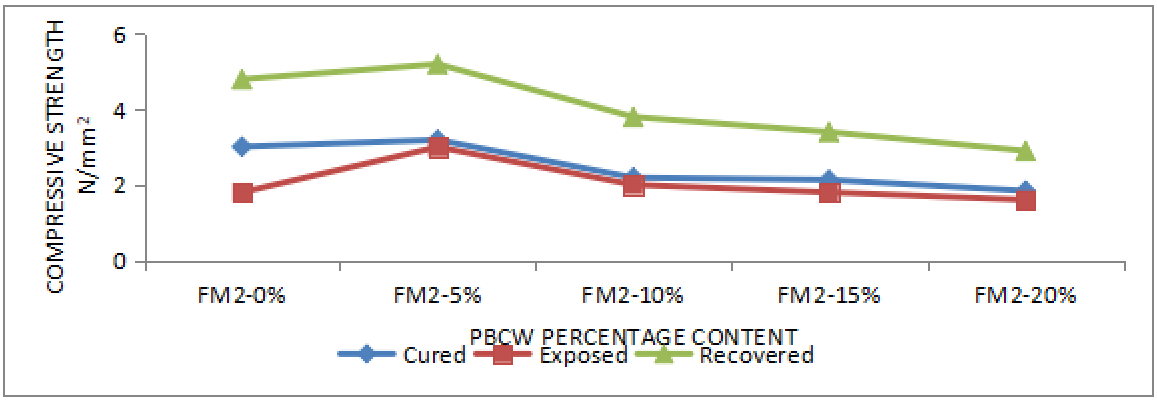

Fig. 3: Compressive strength of Mix 2 (1:8) mortar under freshwater exposure and recovery conditions

All mixes show a reduction in compressive strength after immersion compared to pre-exposure values. The control mixes record the highest strength loss, while PBCW-modified mixes show lower reductions, particularly at 5–10% replacement levels. All mixes show a reduction in compressive strength after immersion compared to pre-exposure values. The control mixes record the highest strength loss, while PBCW-modified mixes show lower reductions, particularly at 5–10% replacement levels.

3.5 Saline Exposure

The compressive strength results after saline immersion and recovery are shown in Fig.s 4 and 5 for Mix 1 (1:6) and Mix 2 (1:8), respectively.

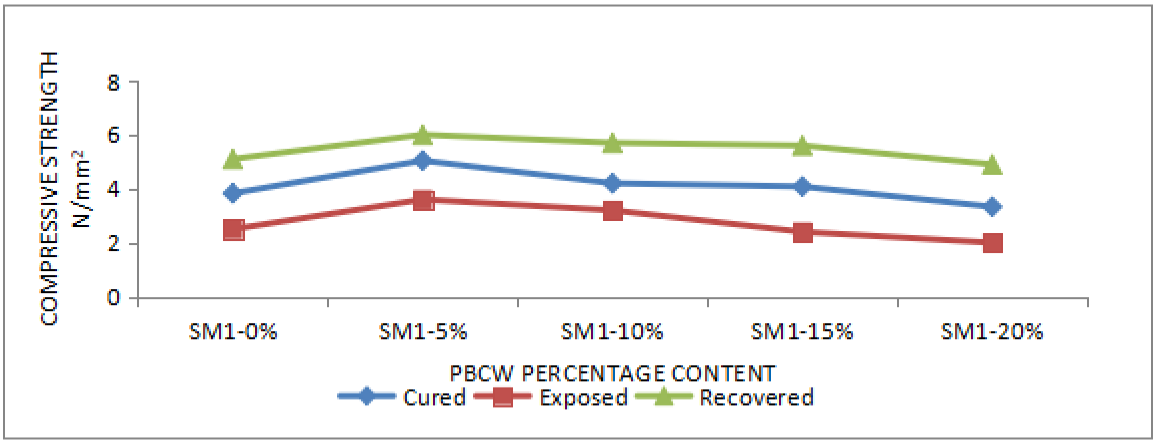

Fig. 4: Compressive strength of Mix 1 (1:6) mortar under saline exposure and recovery conditions

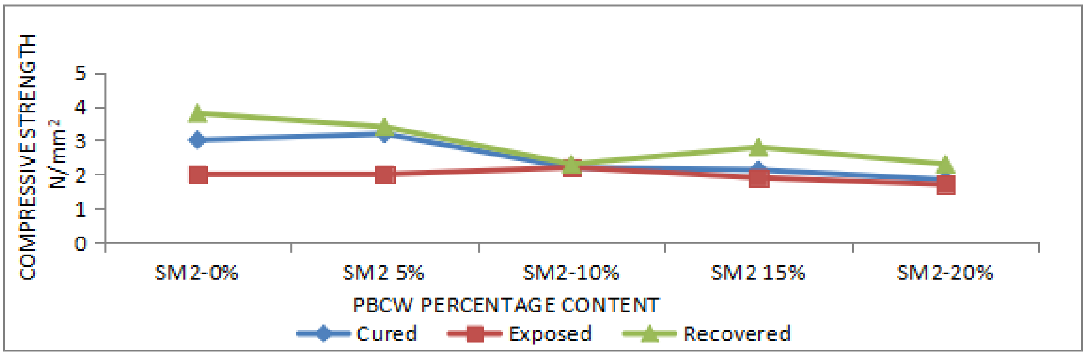

Fig. 5: Compressive Strength Of Mix 2 (1:8) Mortar Under Saline Exposure And Recovery Conditions

All mixes exhibit strength reduction after saline exposure. The reduction is generally higher than that observed under freshwater conditions. PBCW-modified mixes show lower strength loss compared to the control mixes.

3.6 STRENGTH RECOVERY

The compressive strength values after the recovery period are presented in Table 4.

Table 4: Compressive strength (MPa) of PBCW-modified mortar mixes at 28 days, after 120 days immersion (freshwater and saline), and after 120 days recovery

Mix / PBCW (%)	**Pre-Exposure**	**Freshwater Environment**		**Saline Environment**	
	28 Days Curing (MPa)	120 Days Exposure (MPa)	120 Days Recovery (MPa)	120 Days Exposure (MPa)	120 Days Recovery (MPa)
M1(1:6)–0%	3.83	2.0	5.2	2.5	5.1
M1 (1:6)–5%	5.04	3.2	7.1	3.6	6.0
M1 (1:6)–10%	4.20	3.0	6.1	3.2	5.7
M1 (1:6)–15%	4.08	3.0	6.0	2.4	5.6
M1 (1:6)–20%	3.33	2.4	5.0	2.0	4.9
M2 (1:8)–0%	3.01	1.8	4.8	2.0	4.6
M2 (1:8)–5%	3.19	3.0	5.2	2.0	4.8
M2 (1:8)–10%	2.19	2.0	3.8	2.1	3.8
M2 (1:8)–15%	2.13	1.8	3.4	1.9	3.5
M2 (1:8)–20%	1.84	1.6	2.9	1.7	3.1

All mixes exhibit an increase in compressive strength after the recovery period compared to their post-immersion values. PBCW-modified mixes show higher recovery levels than the control mixes.

3.7 Resilience Indices

The calculated Damage Index (DI), Strength Recovery Index (SRI), and Resilience Index (RI) are presented in Table 5. Fig.s 6 and 7 show the resilience Index for Mix 1 (1:6) and Mix 2 (1:8) respectively.

Table 5: Damage Index (DI), Strength Recovery Index (SRI), and Resilience Index (RI) of mortar mixes under freshwater and saline exposure

Mix– PBCW (%)	Freshwater Environment			Saline Environment		
	DI (%)	SRI (%)	RI (%)	DI (%)	SRI (%)	RI (%)
M1 (1:6)–0%	47.78	172.29	135.77	34.73	178.48	133.16
M1 (1:6)–5%	36.51	177.42	140.87	28.57	166.67	119.05
M1 (1:6)–10%	28.57	172.00	145.24	23.81	178.13	135.71
M1 (1:6)–15%	26.47	166.18	147.06	41.18	173.81	137.25
M1 (1:6)–20%	27.93	170.11	150.15	39.94	173.08	147.15
M2 (1:8)–0%	40.20	200.83	159.47	33.55	192.16	152.82
M2 (1:8)–5%	5.96	191.30	163.01	37.30	186.21	150.47
M2 (1:8)–10%	8.68	188.89	173.52	4.11	190.91	173.52
M2 (1:8)–15%	15.49	181.82	159.62	10.80	187.50	164.32
M2 (1:8)–20%	13.04	185.71	157.61	7.61	192.59	168.48

PBCW-modified mixes generally exhibit lower DI values and higher SRI and RI values compared to control mixes. Mixes containing 5–10% PBCW recorded higher resilience index values compared to other mixes. The maximum RI value of 173.52% is recorded for Mix 2 (1:8) with 10% PBCW under both freshwater and saline conditions.

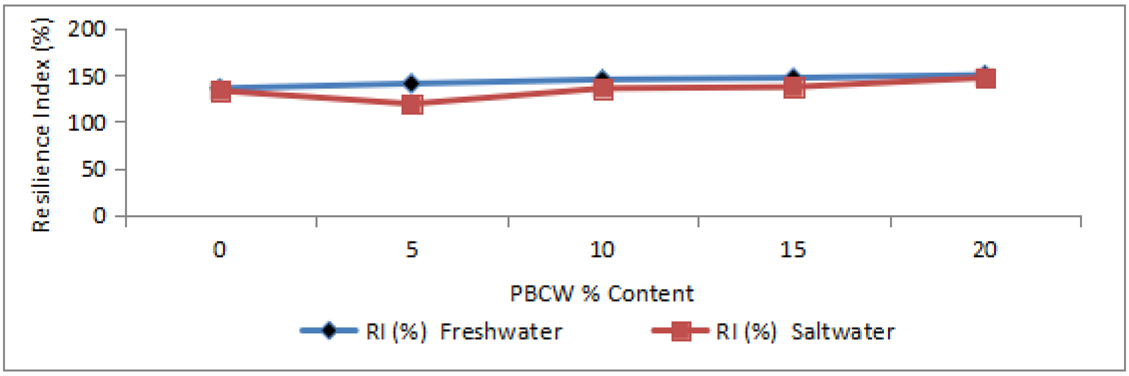

Fig. 6: Resilience index (RI) of PBCW-modified mortar for Mix 1 (1:6) under freshwater and saline conditions.

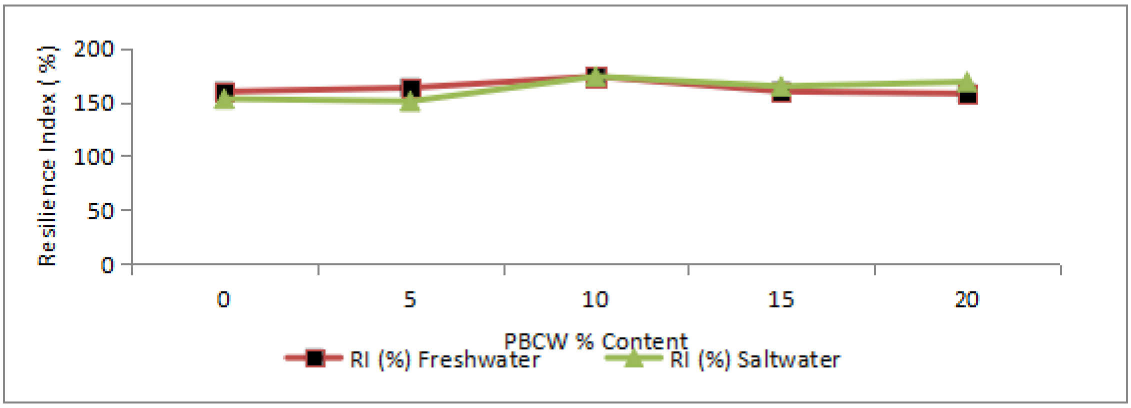

Fig. 7: Resilience index (RI) of PBCW-modified mortar for Mix 2 (1:8) under freshwater and saline conditions

Table 6: Summary of performance of PBCW-modified mortar

Parameter	Control	5% PBCW	10% PBCW	Observation
Strength loss	High	Moderate	Low	Improved durability
Recovery	Moderate	High	Very High	Better resilience
RI (%)	~130	~150	~173	Optimal at 10%

IV. DISCUSSION

The high silica and alumina content of PBCW contributes to pozzolanic reactions, leading to reduced portlandite and formation of additional C–S–H (Kareem & Raheem, 2022; Olofinnade et al., 2021).

Under saline conditions, the formation of Friedel's salt indicates chloride binding, which enhances resistance to chloride ingress (Salman & Akinpelu, 2023).

The improved durability of PBCW-modified mixes is attributed to pore refinement and reduced permeability (Babafemi et al., 2021; Adegbemileke et al., 2024).

Strength recovery is linked to continued hydration and delayed pozzolanic reactions, contributing to enhanced resilience (Hosseini et al., 2021; Sun & Chen, 2022).

V. CONCLUSION

Prolonged exposure reduces mortar strength, with saline environments causing more severe deterioration than freshwater.

Incorporation of PBCW significantly improves durability and post-exposure recovery.

Mixes containing 5–10% PBCW demonstrated optimal performance with lower damage and higher resilience.

PBCW is therefore a sustainable and effective supplementary cementitious material for mortar in flood-prone environments.

This study demonstrates that PBCW can serve as a cost-effective and sustainable alternative to conventional cement in enhancing mortar performance under aggressive environmental conditions.

VI. RECOMMENDATIONS

The study recommends the use of 5–10% pulverised burnt clay waste (PBCW) as a partial replacement material in mortar, as this range provides an effective balance between durability and resilience under varying environmental conditions. This proportion demonstrated improved performance compared to higher replacement levels, making it suitable for practical applications in flood-prone areas. Furthermore, future research should focus on investigating the behaviour of PBCW-modified mortar under long-term exposure conditions to better understand its durability over extended periods. Also, advanced microstructural analyses are recommended to further validate the observed performance and provide deeper insight into the mechanisms responsible for the enhanced properties of the modified mortar.

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