UTILIZING COAL BOTTOM ASH AS A FINE AGGREGATE IN MORTAR: THE EFFECTIVENESS OF PRE-TREATMENT METHODS

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Abstract - The increasing demand for sustainable construction materials has encouraged the use of industrial by-products as sand replacements in mortar. Coal bottom ash (CBA), a by-product of thermal power plants, shows potential as a fine aggregate but has high porosity and weak bonding. This study examines Na_2CO_3 pre-treatment (0.1 M and 0.25 M) to enhance performance of CBA a full sand replacement in mortars. Mechanical strength, ultrasonic pulse velocity (UPV), drying shrinkage, water absorption, and rapid chloride ion penetration (RCPT) were tested. At 28 days, 0.25 M-treated CBA increased flexural and compressive strengths by 44.5% and 29.9%, respectively, and UPV by 6.6%. Drying shrinkage and water absorption decreased by 18.2% and 13.6%, while RCPT dropped 20.1%. These findings confirm that Na_2CO_3 pre-treatment, particularly at 0.25 M, markedly improves strength and durability, making CBA a viable and sustainable fine aggregate alternative.

Keywords - Coal bottom ash; pre-treatment method; flexural strength; compressive strength; durability.

1. Introduction

The global construction industry faces increasing pressure to reduce its environmental footprint and transition toward sustainable and circular material practices [1]. Cement-based materials, particularly mortar and concrete, are among the most widely used construction materials worldwide, yet their production contributes significantly to natural resource depletion and carbon dioxide (CO_2) emissions [2]. To address these challenges, the incorporation of industrial by-products into cementitious systems has become a pivotal strategy for developing eco-efficient and cost-effective alternatives to conventional aggregates.

CBA, a by-product of coal combustion in thermal power plants, is generated in substantial quantities and is often landfilled, posing environmental and logistical concerns [3]. Characterized by its granular texture and moderate pozzolanic potential, CBA has attracted attention as a partial replacement for fine aggregate in mortar and concrete. However, untreated CBA typically exhibits high porosity, low bulk density, and poor surface bonding characteristics, which can adversely affect the strength and durability of the resulting composites. These shortcomings limit its widespread application in structural-grade materials.

Several recent studies have focused on incorporating different forms of bottom ash into the mortar as a sustainable alternative to natural fine aggregates or binders. Kim et al. [4] explored the efficacy of chloride washing treatments on municipal solid waste incineration bottom ash, demonstrating enhancements in mechanical performance and environmental safety due to the removal of harmful residues. Schlupp et al. [5] and Velardo et al. [6] assessed the viability of biomass-derived bottom ash as a full or partial replacement for sand or cement, reporting improved later-age strength yet identifying drawbacks such as high water demand and irregular particle morphology. Prabakaran and Ramadoss [7] observed that incorporating graphene oxide nanosheets into bottom ash-based mortars significantly improved both flowability and structural performance, indicating the benefits of nanomaterial reinforcement. Similarly, Raghavendher et al. [8] confirmed that incinerator ash could function effectively as a supplementary binder in eco-concretes, provided its particle size and reactivity are optimized. Meanwhile, Markpiban et al. [9] highlighted that using bottom ash for internal curing enhanced tensile behavior and reduced drying shrinkage through sustained moisture release. While these contributions affirm the potential of CBA in construction materials, limited research has addressed the impact of alkali activation-specifically sodium carbonate (Na_2CO_3) treatment of CBA when used directly as a fine aggregate. This study fills that knowledge gap by investigating the influence of Na_2CO_3 pretreatment on the mechanical and durability performance of CBA-based mortars, offering a practical and scalable method for improving CBA utilization in green construction applications

Recent research has shown that chemical pre-treatment methods, particularly using Na_2CO_3, can significantly enhance the performance of industrial by-products. Alkali treatment can dissolve amorphous aluminosilicate phases in CBA, promote pozzolanic reactions, remove residual unburnt carbon, and improve particle surface morphology-thereby enhancing both the interfacial bond with the cement paste and the overall microstructure of the matrix. While several studies have explored the use of CBA as a cementitious filler or supplementary cementitious material, there is a lack of systematic investigation into its role as a fine aggregate, especially when subjected to pre-treatment to optimize its physical and chemical characteristics.

Therefore, this study aims to evaluate the mechanical and durability performance of mortars incorporating alkali-treated CBA as a full replacement for natural sand. Two concentrations of Na_2CO_3 solution (0.1 M and 0.25 M) were selected to pre-treat the CBA and examine the influence of activation level on mortar properties. Key performance indicators, including flexural strength (FS), compressive strength (CS), ultrasonic pulse velocity (UPV), drying shrinkage (DS), water absorption (WA), and rapid chloride ion penetration (RCPT), were assessed at 28 and 56 days. This work contributes to the field by proposing a material recycling strategy that not only diverts waste from landfills but also enhances mortar performance through simple, scalable pre-treatment processes. The findings are expected to inform sustainable material design for infrastructure applications where durability, resource efficiency, and environmental responsibility are paramount.

2. Materials and experimental details

2.1. Materials

Portland cement of grade 40 conforming to Vietnamese standard TCVN 2682:2020 [10] and ground granulated blast-furnace slag (GGBFS) of grade S95 conforming to TCVN 11586:2016 [11] were used as the primary binders in all mortar mixes. The cement had a specific gravity of 3.12 and a mean 28-day compressive strength of 53.6 MPa, while GGBFS had a specific gravity of 2.95. CBA was sourced from a thermal power plant in the North of Vietnam, with a range size of 0.14–1.25 mm. To ensure material representativeness, three 50-kg batches were collected over a month, air-dried, and homogenized. Quality control included visual inspection, bulk density, and water absorption measurements. As a result, the material was characterized by angular particles, high surface porosity (see Figure 1), and low bulk density (1040 kg/m^3). CBA had a density of approximately 2000 kg/m^3 and a high water absorption rate of 32%.

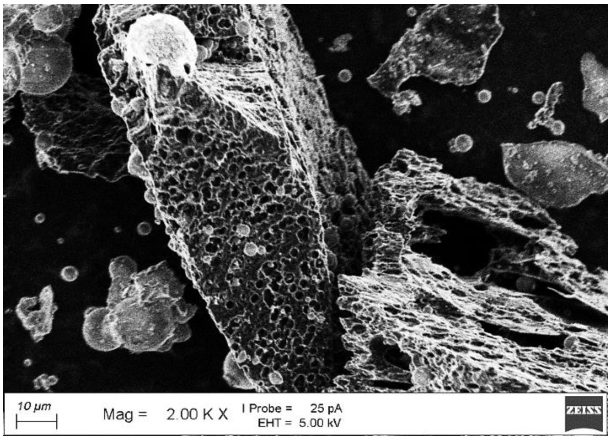

Figure 1. *SEM image of CBA particles at scale x2000*

Na_2CO_3 powder (99.2% purity) was dissolved in distilled water to prepare 0.1 M and 0.25 M solutions. CBA was soaked in these solutions for 24 hours, then rinsed with distilled water until the final rinse reached pH < 9.0, ensuring minimal residual alkalis. The treated ash was oven-dried at 105 ± 2 °C for 24 hours. This process aimed to remove impurities, reduce alkali-silica reaction risk, and improve the reactivity and surface quality of CBA for mortar use.

Type G superplasticizer (SP) in accordance with TCVN 8826:2024 [12] with a pH of 8.65 and density of 1.09 g/cm^3 was used to ensure the workability of mortar mixtures. Potable tap water complying with TCVN 4506:2012 [13] was used for both mixing and curing processes.

2.2. Mix proportioning

All mortar mixes were prepared with a fixed water-to-binder (w/b) ratio of 0.4 and a fine aggregate-to-binder ratio of 2.8. Binder materials comprised 85% cement and 15% GGBFS. A 15% replacement of cement with GGBFS was used to enhance durability, promote late-age strength, and reduce clinker content for sustainability. As a latent hydraulic material, GGBFS reacts more readily in alkaline environments, such as those created by Na_2CO_3 treatment. While not specifically isolated in this study, the combined effects of GGBFS and Na_2CO_3 likely contributed to the improved strength and durability observed. CBA under three different pre-treatment methods of water-treated (WT), and Na_2CO_3-treated at 0.1 M (NC-0.1) and 0.25 M (NC-0.25) concentrations were used as fine aggregate in mortar. Despite the CBA's high water absorption rate (32%), workability was effectively maintained using a 1% superplasticizer dosage across all mixes. The pre-soaking also acted as pre-saturation, lowering the immediate water demand. Informal slump flow checks showed consistent workability with no segregation, indicating that the high absorption issue was well-managed through pre-soaking and admixture control.

2.3. Sample preparation and test programs

Mortar specimens were prepared using a laboratory mixer in accordance with TCVN 3121-2:2022 [14], ensuring consistent mixing, casting, and curing procedures. After mixing, the mortar was cast into molds specific to each test, compacted in two layers, and demolded after 24 hours. Specimens were then cured in lime-saturated water at 23 ± 2 °C until testing at 28 and 56 days. A comprehensive test program (see Table 1) was conducted to evaluate the mechanical and durability properties of the mortar. Tests were performed in triplicate to ensure reliability, and results were averaged for analysis.

Table 1. *Test methods used to evaluate the mortar's properties*

Test name	Age (day)	Sample size (mm)	Reference
FS	28, 56	40×40×160	TCVN 3121-11:2022 [15]
CS	28, 56	Using portions of prisms broken in flexure	TCVN 3121-11:2022 [15]
UPV	28, 56	Ø100×200	TCVN 9357:2012 [16]
DS	0, 3, 7, 14, 28, 56	25×25×285	TCVN 8824:2011 [17]
WA	28, 56	50×50×50	TCVN 3121-18:2003 [18]
RCPT	28, 56	Ø100×50	TCVN 9337:2012 [19]

3. Result and discussion

3.1. Flexural strength

The FS results presented in Figure 2 demonstrate a significant enhancement in the mechanical behavior of mortars incorporating CBA as fine aggregate when subjected to alkaline pre-treatment. At 28 days, the reference mix using water-treated CBA (WT) recorded an FS of 2.11 MPa, while the mixes with 0.1 M and 0.25 M Na_2CO_3 pre-treatment (NC-0.1 and NC-0.25) attained strengths of 2.58 MPa and 3.05 MPa, respectively. These values represent a 22.3% increase for NC-0.1 and a 44.5% increase for NC-0.25 compared to the WT mix. The trend continued at 56 days, with WT reaching 2.81 MPa, while NC-0.1 and NC-0.25 achieved 3.52 MPa and 3.98 MPa, respectively-translating to improvements of 25.3% and 41.6% over the control.

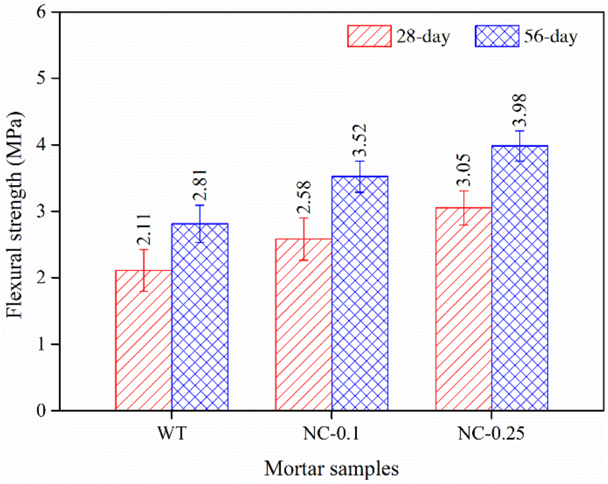

Figure 2. *FS of mortar*

These results confirm the effectiveness of alkali pre-treatment in enhancing the mortar's resistance to tensile stress and crack propagation under bending loads. The superior performance of alkali-treated CBA can be attributed to several interrelated mechanisms. Firstly, Na_2CO_3 pre-treatment likely removes loosely bonded surface impurities such as residual carbon, and partially dissolves the amorphous silica and alumina phases on the ash surface. This increases the surface reactivity of CBA, facilitating pozzolanic reactions that produce additional calcium silicate hydrate (C–S–H) gel, which is the principal binding phase in cementitious matrices. The formation of this secondary C–S–H phase improves the bond strength between the CBA particles and the cement paste, resulting in a denser and more cohesive matrix. Secondly, the pre-treatment may alter the surface morphology of the CBA, leading to better mechanical interlocking and improved stress transfer across the CBA's interface. The continued strength development between 28 and 56 days, particularly in the NC-0.25 group, further suggests ongoing secondary hydration and pozzolanic activity. The increment of 30.6% in the WT mix between 28 and 56 days is comparable to the 36.4% and 30.5% gains observed in NC-0.1 and NC-0.25, respectively, indicating that the alkali treatment accelerates early-age strength while maintaining long-term gain potential.

3.2. Compressive strength

The CS results depicted in Figure 3 further validate the effectiveness of alkali pre-treatment in enhancing the structural performance of mortar incorporating CBA as fine aggregate. At 28 days, the reference mix reached a CS of 12.74 MPa, while the mixes treated with 0.1 M and 0.25 M Na_2CO_3 solutions demonstrated significantly higher CS values of 14.92 MPa and 16.55 MPa, respectively. This represents a 17.1% increase for NC-0.1 and a substantial 29.9% enhancement for NC-0.25 compared to the WT. At 56 days, the trend remained consistent: WT increased to 14.31 MPa, while NC-0.1 and NC-0.25 recorded strengths of 16.28 MPa and 18.52 MPa, corresponding to gains of 13.7% and 29.4%, respectively, over the untreated mix. The increase in compressive strength with higher Na_2CO_3 concentration is attributed to enhanced pozzolanic activity and improved microstructure. Alkali activation dissolves reactive silica and alumina in CBA, forming additional C–S–H gel. It also refines the particle surface and improves packing density, strengthening the paste–aggregate bond and reducing porosity-consistent with findings by Alanazi [20].

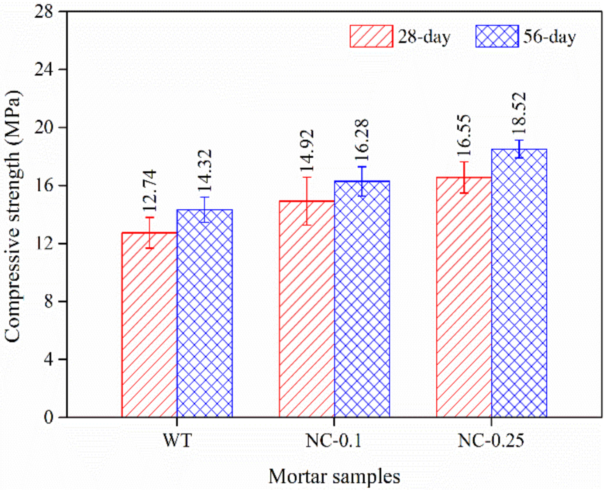

Figure 3. *CS of mortar*

Notably, the strength gain from 28 to 56 days reflects the sustained pozzolanic activity. WT showed a 12.3% increase over this period, whereas NC-0.1 and NC-0.25 exhibited 9.1% and 11.9% increases, respectively. Although the percentage growth is slightly lower in the treated mixes due to their already elevated early-age strength, the absolute 56-day values remain considerably higher, indicating that the chemical activation not only accelerates hydration but also sustains long-term strength development. The consistently superior performance of the NC-0.25 group suggests that higher Na_2CO_3 concentrations offer greater activation of reactive phases, though optimization is essential to avoid possible issues such as efflorescence or alkali-silica reaction under field conditions. These findings collectively underscore that alkali-pretreated CBA can serve as a high-performance, eco-efficient alternative to conventional fine aggregates in mortar formulations.

3.3. Ultrasonic pulse velocity

The UPV values presented in Figure 4 reveal the influence of alkali-treated CBA on the internal quality and compactness of mortar. At 28 days, the control mix with WT exhibited a UPV value of 3077 m/s, whereas mortars incorporating CBA treated with 0.1 M and 0.25 M Na_2CO_3 (NC-0.1 and NC-0.25) reached 3150 m/s and 3279 m/s, respectively. This corresponds to an increase of 2.4% for NC-0.1 and 6.6% for NC-0.25 compared to the control. At

56 days, UPV values improved across all mixes: WT increased to 3252 m/s, while NC-0.1 and NC-0.25 achieved 3306 m/s and 3456 m/s, marking respective gains of 1.7% and 6.3% over the control. These UPV enhancements suggest an improvement in the microstructural integrity and density of the hardened mortar as a result of alkali pre-treatment. Higher UPV values typically correlate with reduced porosity, better matrix continuity, and fewer internal flaws or microcracks. Na_2CO_3 treatment enhances pozzolanic reactivity in CBA's amorphous phases, increasing C–S–H formation, which fills voids and strengthens the paste–aggregate bond. It also refines particle surfaces, improving packing density and contributing to a denser, more uniform microstructure-reflected in higher UPV values. This aligns with Fang et al. [21], who noted improved solid volume and reduced pore continuity in alkali-activated by-products. While UPV gains between 28 and 56 days were modest, the overall trend confirms that alkali-modified CBA improves homogeneity and internal quality-beneficial for both strength and long-term durability.

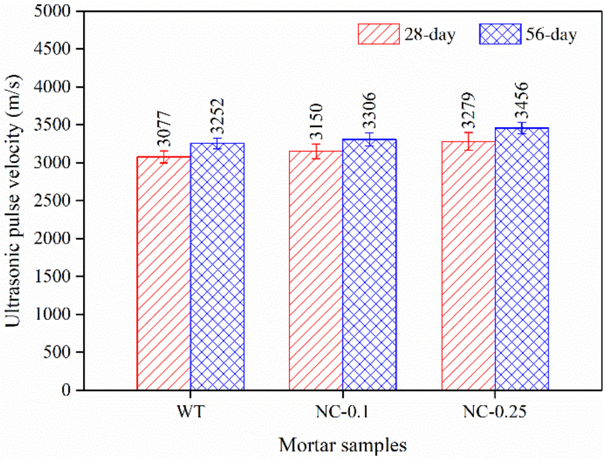

Figure 4. *UPV of mortar*

3.4. Drying shrinkage

The development of DS in mortars incorporating CBA is illustrated in Figure 5. As expected, all mixes exhibited progressive shrinkage with time due to moisture loss from the cement matrix; however, mortars incorporating alkali-treated CBA showed consistently lower DS compared to the water-treated control (WT), particularly in the early stages. At 3 days, the WT mix exhibited a DS of -0.044%, whereas NC-0.1 and NC-0.25 recorded -0.039% and -0.036%, representing reductions of 11.4% and 18.2%, respectively. This early improvement is likely due to the denser microstructure induced by the alkali-activated pozzolanic reaction, which reduces the rate of initial DS. By 7 days, the WT specimen reached -0.067%, while NC-0.1 and NC-0.25 achieved lower shrinkage values of -0.060% and -0.055%, showing respective reductions of 10.4% and 17.9%. This continued reduction highlights the role of pore refinement and improved particle bonding, which slows the internal moisture migration responsible for DS. At 14 days, the difference becomes more stable: WT showed -0.090%, while NC-0.1 and NC-0.25 recorded -0.080% and -0.072%, corresponding to reductions of 11.1% and 20.0%, respectively. The sustained trend suggests that Na_2CO_3 treatment not only accelerates early C–S–H formation but also enhances long-term internal cohesion within the matrix. By 28 days, DS in WT reached -0.112%, compared to -0.106% in NC-0.1 and -0.102% in NC-0.25. Though the rate of change slowed, reductions of 5.4% and 8.9% were still observed, indicating the continued effectiveness of alkali treatment in minimizing volume change during prolonged drying. At 56 days, WT reached -0.125%, while NC-0.1 and NC-0.25 maintained lower DS values of -0.120% and -0.116%, yielding final reductions of 4.0% and 7.2%. These differences, though smaller at later ages, confirm that alkali pre-treatment contributes to long-term dimensional stability, likely through enhanced microstructural densification and reduced capillary stress.

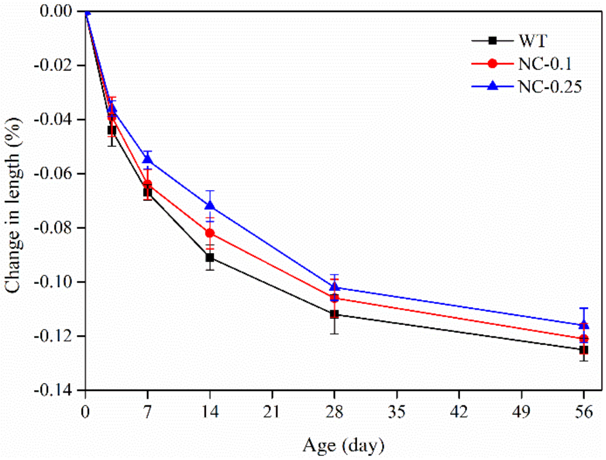

Figure 5. *DS of mortar*

3.5. Water absorption

WA is a critical indicator of mortar porosity and permeability, directly influencing its durability and resistance to aggressive environmental agents. As shown in Figure 6, mortars incorporating alkali-treated CBA demonstrated consistently lower WA values compared to the water-treated reference mix, confirming the positive influence of Na_2CO_3 pre-treatment on microstructural refinement. At 28 days, the WT mix exhibited a WA value of 11.32%, while NC-0.1 and NC-0.25 recorded reduced values of 10.96% and 9.78%, respectively. These values represent reductions of 3.2% for NC-0.1 and a significant 13.6% for NC-0.25 relative to WT.

The lower WA rates in the alkali-treated mixes indicate a denser pore structure, likely due to enhanced pozzolanic reactivity triggered by Na_2CO_3. This results in the formation of additional C–S–H, which fills voids and reduces capillary porosity. By 56 days, a similar trend was observed with overall reductions in all groups as hydration progressed. WT reached 10.49%, while NC-0.1 and NC-0.25 further declined to 9.74% and 8.51%, respectively. The reductions at this stage amounted to 7.2% for NC-0.1 and 18.9% for NC-0.25 compared to WT. The greater drop in the NC-0.25 group supports the hypothesis that higher alkaline concentration leads to more pronounced microstructural densification, reducing the connectivity of pores and the ability of the matrix to absorb water. These findings are consistent with the work of Ismail et al. [22], who reported improved impermeability in mortars containing alkali-activated fly ash and CBA due to pore-blocking effects and refined gel structure. Furthermore, the drop in WA over time for all groups reflects the ongoing hydration process, though the superior performance of treated samples highlights the accelerated and enhanced hydration kinetics induced by chemical activation.

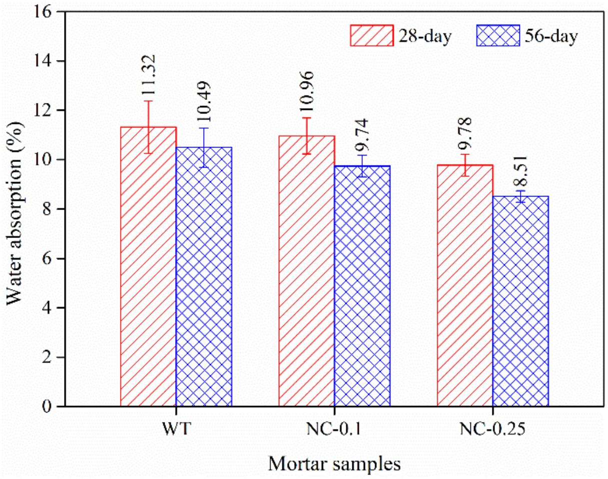

Figure 6. *WA of mortar*

3.6. Rapid chloride ion penetration

The resistance of mortar to chloride ion ingress, assessed through the RCPT, is a key indicator of long-term durability, especially for structures exposed to marine or de-icing environments. As shown in Figure 7, the incorporation of Na_2CO_3-treated CBA significantly improved chloride resistance by reducing the total charge passed, indicating a denser, less permeable pore system. At 28 days, the control mix exhibited a charge passage of 3770 Coulombs, categorizing it within the moderate permeability range based on TCVN 9337:2012 [19]. In contrast, the NC-0.1 and NC-0.25 mixes recorded substantially lower values of 3479 Coulombs and 3010 Coulombs, reflecting 7.7% and 20.1% reductions, respectively. These reductions suggest that alkali pre-treatment enhances the densification of the microstructure, likely due to improved pozzolanic reactivity and more abundant formation of secondary C–S–H, which refines the pore structure and reduces ionic mobility. By 56 days, all mixes demonstrated improved performance due to continued hydration and pore structure refinement. The WT mix decreased to 2726 Coulombs, while NC-0.1 and NC-0.25 further declined to 2574 Coulombs and 2372 Coulombs, respectively. These values correspond to 5.6% and 13.0% reductions compared to WT, moving closer to the low permeability threshold. The sustained lower RCPT values in alkali-treated mixes suggest long-term improvements in the durability and corrosion resistance of reinforced systems. Mechanistically, Na_2CO_3 pre-treatment enhances chloride resistance by promoting physical densification and chemical binding, potentially through increased Friedel's salt formation and aluminate interaction. The NC-0.25 mix showed the best performance, reflecting stronger alkali activation, reduced pore connectivity, and improved interfacial zones. This treatment reduced chloride permeability by over 20% at an early age and 13% at 56 days, supporting its use in durable, sustainable mortar production.

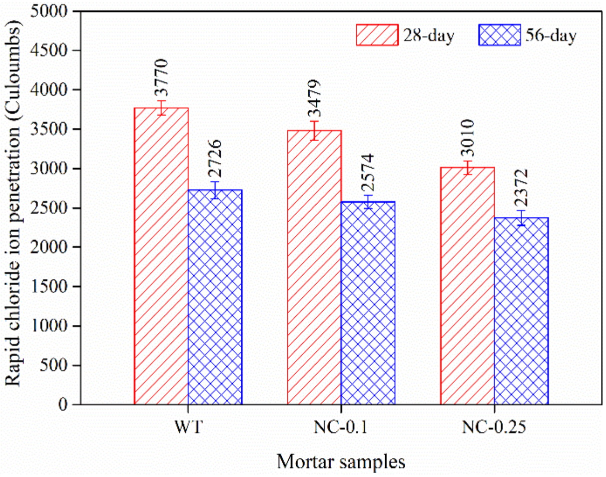

Figure 7. *RCPT of mortar*

3.7. Discussions on the scalability and economic viability of using Na_2CO_3 solution for industrial processing

In this study, the 0.25 M Na_2CO_3 concentration yielded the highest improvements in strength and durability. Na_2CO_3 pre-treatment provides both surface cleaning and chemical activation, enhancing pozzolanic reactions and improving particle packing. Several other methods have been used to improve CBA properties, such as water washing, thermal activation, and chemical admixtures. While water washing removes soluble salts, it has a limited impact on reactivity. Thermal treatment lowers loss on ignition but is energy-intensive, and chemical admixtures can increase costs and require careful compatibility control. Based on the authors' experience and input data from local suppliers, Na_2CO_3 pre-treatment is considered a low-cost, scalable process using an abundant chemical commonly applied in industrial settings. Treating 1 ton of CBA with 0.25 M Na_2CO_3 costs approximately $5, depending on local prices. The soaking, rinsing, and drying steps can be integrated into existing aggregate processing systems. Due to its mild nature, Na_2CO_3 poses minimal health or environmental risks, making this method both economically and technically viable for large-scale use in sustainable mortar production.

4. Conclusion

This study presents a novel and practical strategy for enhancing the performance of mortar by chemically activating CBA through Na_2CO_3 pre-treatment. By transforming CBA from an underutilized industrial by-product into a fine aggregate, the research bridges sustainability goals with engineering functionality in cementitious materials. Based on the experimental findings, the following conclusions can be drawn:

- Both FS and CS were significantly enhanced by Na_2CO_3 pre-treatment. At 28 days, NC-0.1 and NC-0.25 mortars achieved FS increases of 22.3% and 44.5%, respectively, compared to the WT. At 56 days, these improvements reached 25.3% and 41.6%, indicating sustained benefits from chemical activation. Similarly, the NC-0.1 and NC-0.25 showed CS increases of 17.1% and 29.9% at 28 days, respectively, while the 56-day strength gains were 13.7% and 29.4% higher than the control.

- UPV increased by up to 6.6% at 28 days and 6.3% at 56 days for the NC-0.25 mix. This suggests a denser and more homogeneous microstructure in alkali-treated mortars. Whereas, DS was reduced across all ages. At 56 days, NC-0.1 and NC-0.25 exhibited total DS reductions of 4.0% and 7.2%, respectively, compared to the WT mix. The most notable early-age DS reduction was 18.2% at 3 days for NC-0.25.

- WA decreased as a result of the denser pore structure. At 28 days, absorption dropped by 3.2% and 13.6% for NC-0.1 and NC-0.25, respectively. These improvements increased to 7.2% and 18.9% at 56 days, confirming enhanced durability.

- RCPT was substantially lowered. At 28 days, NC-0.1 and NC-0.25 showed reductions of 7.7% and 20.1%, while the 56-day RCPT reductions were 5.6% and 13.0%, respectively. These findings indicate better resistance to chloride ingress and improved long-term durability.

The data collectively confirm that Na_2CO_3 pre-treatment of CBA, particularly at 0.25 M concentration, effectively improves both the mechanical performance and durability properties of mortar. The approach enhances pozzolanic reactivity, refines microstructure, and promotes sustainability by utilizing industrial by-products, making it a promising solution for eco-efficient cementitious materials.

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