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ARTICLE

Compressive Strength–Water Absorption Behaviour of Concrete with Coal Bottom Ash as Sand Replacement across Water–Cement Ratios

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ABSTRACT

Coal bottom ash (CBA) is produced in large quantities by coal-fired power plants. It offers a viable opportunity for sustainable utilisation as a partial replacement, especially for fine aggregate in concrete. However, its porous morphology and surface characteristics complicate controlling water demand and optimising concrete performance. In this research, the synergistic effects of water–cement (WC) ratio (0.40, 0.45, and 0.50) with CBA contents (0%, 10%, and 20% from mass of sand) on compressive strength and water absorption of concrete at 28 and 56 curing ages. Increasing the WC ratio and CBA content generally reduced compressive strength and increased water absorption, whereas extended curing improved strength while lowering absorption. Target performance was achieved with up to 20% CBA when the WC ratio was maintained within 0.40–0.45, defining a practical mix-design window. A strong inverse correlation was observed between compressive strength and water absorption at WC = 0.40–0.45 ($R^2 \approx 0.92$–0.95), whereas the relationship weakened at WC = 0.50 ($R^2 \approx 0.82$–0.83) due to increased pore connectivity and variability associated with excess mixing water. The reliability of these correlations was further confirmed through statistical error analysis, with low RMSE, RAE, and RRMSE values, particularly at WC = 0.45, indicating high predictive accuracy and minimal deviation between measured and predicted

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strengths. In contrast, higher error metrics at WC = 0.50 reflect reduced model robustness. These findings establish design boundaries that can be adopted in practice to valorise CBA while safeguarding performance, thereby informing greener specifications and guiding future standards for the use of industrial by-products in concrete.
Keywords: Coal Bottom Ash; River Sand Replacement; Compressive Strength; Water Absorption; Water-Cement Ratio

1. Introduction

Coal remains a principal feedstock for electricity generation worldwide because it is comparatively inexpensive and abundant relative to oil and natural gas [1]. Environmental risks are non-trivial: hazardous constituents associated with carcinogenicity, reproductive toxicity and developmental effects and leachable species can contaminate soils and groundwater [2,3]. More broadly, escalating consumption of goods and services amplifies waste and pollution, underscoring the need to maximise energy and resource efficiency across the whole production–use–disposal chain [4]. Coal bottom ash (CBA), collected at the base of the boiler, is generated at scale, with annual outputs of ~25 million tonnes (Mt) in India, 15 Mt in the United States, 4 Mt in Europe and 1.6 Mt in Malaysia [5]. Coal wastes exhibit low recycling rates worldwide, and open dumping of CBA from industrial facilities and thermal power stations can lead to accidental releases and widespread dispersal [6]. Experimental evidence shows that heavy metals such as Barium (Ba), Manganese (Mn), Zinc (Zn), Arsenic (As), and Nickel (Ni) may occur at levels up to several times regulatory limits, with mobility enhanced under acidic conditions typical of ash deposits [7]. The coal incineration generates both airborne pollutants and solid residues that are partially controlled by staged filtration of NO_x, particulate matter (PM) and sulphur-bearing species before release through stack systems [8]. Regional outlooks indicate that sustained demand from total electricity consumption in Thailand and some of Southeast Asia is projected to increase power requirements by almost 80% by the end of 2036, and coal still provides roughly 40% of global electricity [9]. In Peninsular Malaysia, coal and gas are expected to supply approximately 58% and 25% of electricity in 2024, supported by large coal-fired stations such as Kampar, Manjung, Sejingkat, Jimah and Tanjung Bin [10]. This reliance inevitably produces substantial amounts of coal ash, the non-combustible residue of combustion. Owing to limited beneficial uses, CBA is frequently stockpiled on open land, intensifying land-take and long-term stewardship burdens [11]. Within this context, recycling and the responsible use of coal wastes have become priorities for environmental protection. CBA is a readily available raw material that can be collected from coal plants, warehouses, manufacturing facilities and energy plants [12].

Growing constraints on natural river sand, driven by resource depletion and the need to protect riverine ecosystems, have led to a shift toward alternative fine aggregates in concrete. Sand extraction removes a finite geomaterial, destabilises channels, and degrades water quality; in parallel, escalating concrete demand amplifies pressure on limited deposits and exposes supply to volatility. Within this context, CBA presents a technically and environmentally credible substitute because its particle-size envelope overlaps that of fine aggregate, and it is generated at scale as an energy-sector by-product that would otherwise require landfilling. The literature indicates that, at appropriate replacement levels and with a sound mix design, CBA can deliver acceptable mechanical and durability performance through filler and pozzolanic effects, while simultaneously reducing waste burdens and conserving primary aggregates [13]. However, its porous structure and variable chemical composition raise concerns regarding its influence on the mechanical and durability performance of concrete [14]. Recent investigations into waste-derived cementitious composites, such as those incorporating degraded cellulosic fibres, liquefied polystyrene, or cement kiln dust, have demonstrated that proper optimisation of mix proportions and binder interactions can mitigate the inherent limitations of such wastes, yielding lightweight concretes with acceptable strength and absorption characteristics [15]. Crucially, using CBA contributes to a circular-economy pathway: it diverts a voluminous industrial residue from disposal, curbs the need for river sand mining. It can lower life-cycle impacts when transport and processing are rationalised [16]. Practical adoption still requires attention to source variability, porosity-driven water demand, and optimisation of the water–cement ratio to control strength and transport properties; however, these are engineering challenges amenable to specification, pre-treatment, and proportioning strategies. In short, the limitations and externalities of river sand extraction, together with the proven feasibility of CBA as a partial sand replacement, motivate research to quantify performance envelopes across curing ages and mix parameters, enabling reliable design windows for sustainable, sand-lean concrete [17].

Construction materials are a prime target, particularly natural sand, which is increasingly scarce due to the growth in concrete production [18]. The partial substitution of sand with CBA has therefore attracted attention as a measure capable of mitigating both resource depletion and waste accumulation within a circular economy. Numerous studies report technically acceptable performance when CBA is used as a fine aggregate (specifically as sand replacement), with encouraging strength outcomes under specific conditions [19–21]. The effect of CBA as a partial sand replacement on compressive strength is strongly mix-design dependent but broadly follows a consistent pattern: low-to-moderate dosages, appropriate particle grading, and proper water control can preserve or even enhance strength, whereas excessive replacement or poor rheology management leads to losses [22].

Recent research has highlighted the growing interest in utilising CBA as a sustainable material in concrete technology, not only for its mechanical implications but also for its contribution to microstructural refinement and improved environmental performance. Microstructural investigations have revealed that finely graded and thermally treated CBA can participate in secondary hydration reactions, forming additional Calcium-Silicate-Hydrate (C–S–H) gel that enhances the matrix densification. Studies have shown that improved interfacial transition zones (ITZs) occur when CBA is optimally dosed, particularly under extended curing conditions. However, its inherently porous nature may increase initial water demand and early-age permeability. On the other hand, regarding durability-wise, multiple studies have examined the influence of CBA on properties such as chloride penetration, carbonation depth, and freeze–thaw resistance. While untreated CBA may compromise resistance at high replacement levels due to increased porosity, pre-treatment techniques and the addition of pozzolanic materials have demonstrated considerable mitigation of these effects. Additionally, life-cycle assessments (LCAs) indicate that partial substitution of river sand with CBA significantly reduces the carbon footprint of concrete, especially when combined with fly ash or other supplementary cementitious materials.

Strength gains are repeatedly reported when CBA is incorporated at approximately 5–20%, with several studies identifying 10% as a practical optimum in both conventional and self-compacting concretes [23]. Finer fractions (e.g., material passing 600 μm) tend to be more beneficial due to improved filler packing and a modest pozzolanic contribution. At later ages, many systems exhibit additional strength development as reactive silica and alumina in the ash consume portlandite and generate secondary C–S–H, thereby narrowing pores and strengthening the interfacial transition zone. Mixes that underperform at 28 days can equal or surpass controls by 90–180 days when curing is adequate. Higher replacement levels can still perform well if workability is kept constant through the use of high-range water-reducing admixtures, Saturated Surface Dry (SSD) of CBA, or synergy with highly reactive fines (e.g., silica fume); in such cases, reports include parity or improvements at 20–50% replacement, and even total fine-aggregate substitution has been demonstrated in specially engineered systems (e.g., steel fibre or ternary blends) when a low water–cement ratio and strong dispersion are maintained [24]. Conversely, performance declines are common when oven-dry ash is substituted at fixed water content (leading to water uptake by the porous ash, slump loss, poor compaction and elevated voids), when washing removes beneficial fines, or when replacement is pushed to very high levels without admixture support; excessive ash increases total porosity, weakens the aggregate skeleton, and degrades the load path [25]. Nevertheless, limitations have been observed, most notably strength penalties at higher replacement levels, and the literature contains inconsistencies that complicate generalisation [26]. Additionally, previous work focused on two regressions that examined the relationship between increases in compressive strength and both dry density and ultrasonic pulse velocity (UPV) [27]. The strength–density fit is robust ($R^2 = 0.9385$), indicating that denser mixtures, characterised by lower capillary porosity and a tighter interfacial transition zone, can carry higher loads. An increase of 100 kg/m^3 in dry density corresponds to a strength gain of about 6.4 MPa. The compressive strength–UPV relationship is also positive, albeit slightly weaker ($R^2 = 0.8299$), consistent with UPV tracking the stiffness and continuity of the solid skeleton; an increase of 500 m/s in UPV implies a 5.8 MPa higher strength.

On the other hand, water absorption is a key durability indicator because it reflects capillary porosity, the quality of the interfacial transition zone, and the ease with which fluids can penetrate hardened concrete. For mixes incorporating CBA as a sand or cement replacement, water absorption at 28 days typically rises with increasing CBA content owing to the ash's porous particles, higher specific surface area and the associated slump loss and compaction difficulty when water demand is not compensated [28]. This trend is reported whether CBA replaces fine aggregate or a portion of binder, and it is accentuated when oven-dry ash is used at fixed mixing water, when coarser fractions predominate, or when grinding increases surface area without parallel rheology control [29]. Conversely, several investigations show that with adequate curing and an appropriate water–cement ratio, absorption declines between 28 and 90/180 days as secondary pozzolanic reactions consume portlandite and form additional C–S–H, progressively densifying the matrix and reducing pore connectivity [30]. As a practical rule, modest CBA dosages (5–20%) at low WC and with proper fresh-state control tend to keep absorption within commonly accepted thresholds, while higher dosages increase absorption unless mitigated by high-range water reducers, mix re-proportioning, or hybridisation with highly reactive fines [31]. Compounding this, CBA properties vary with source and combustion conditions, introducing further uncertainty into the mix design [32].

Compared to river sand, CBA has irregular particle geometry, internal pores, and surface roughness that differ from those of inert natural sand when used as a fine aggregate. These characteristics often lead to increased water demand during mixing. It was found that CBA interferes with the distribution of cement paste and the interlock of aggregates, ultimately affecting the microstructural integrity of the hardened concrete. Simultaneously, the water–cement (WC) ratio is a primary parameter governing both mechanical strength and durability-related transport properties. Lower WC ratios tend to enhance strength by reducing capillary porosity and increasing hydration under proper curing conditions. In contrast, higher WC ratios introduce more free water, which can evaporate or remain trapped in the microstructure as interconnected pores, thereby increasing the matrix's permeability and water absorption.

When CBA is incorporated into the mix, these mechanisms become coupled. The porous nature of CBA can absorb part of the mix water, potentially altering the effective WC ratio locally and leading to heterogeneous hydration. Inadequate compensation for this effect may reduce early-age strength and increase surface absorption. Conversely, the latent pozzolanic reactivity of the siliceous components in CBA, activated under suitable curing and WC conditions, may contribute to later-age strength gain. Thus, understanding the interaction between WC ratio and CBA content is essential for tailoring mix designs that balance strength and durability. Establishing correlations between compressive cube strength and water absorption of cube specimens under varying WC ratios and CBA proportions enables the identification of design windows that optimise performance while incorporating industrial by-products sustainably.

Despite extensive work on CBA as a fine-aggregate substitute, a gap remains in systematically isolating the combined effects of water–cement ratio (WC) and CBA content (%) on both compressive strength and water absorption, and in quantifying their co-variation over realistic curing periods. The porous, highly absorptive nature of CBA elevates water demand and perturbs paste–aggregate interactions, while higher WC increases capillary porosity. Furthermore, only a limited body of work has examined paired measurements at 28 and 56 days across practical sand replacement, and even fewer studies have translated the data into correlations (R^2) for compressive strength and water absorption that can guide design. Accordingly, this study undertakes a controlled experiment with WC 0.40, 0.45, and 0.50, and CBA contents from 0%, 10%, and 20%, to quantify their effects on strength and absorption at 28 and 56 days. Subsequently, the relationship between the two responses is established at each WC level using correlation analysis (R^2). The results are synthesised into a practical design window that balances compressive strength requirements with transport property, providing mechanistically informed guidance for the proportioning of CBA concretes in practice.

2. Experimental Investigation

This section outlines the experimental programme. Firstly, describe the constituent materials and their key properties, including the particle-size characteristics of CBA relative to those of river sand. Then, details the specimen casting and curing procedures for the selected WC ratios and CBA replacement levels. After that, it presents the test methods used to determine compressive strength and water absorption.

2.1. Materials and Material Properties

Ordinary Portland Cement (OPC) 42.5 was employed with natural river sand as the fine aggregate and crushed stone (maximum size 20 mm) as the coarse fraction. The CBA sourced from the Manjung Power Plant served as a substitute for sand. It should be noted that the present study utilised CBA obtained from a single source; therefore, the findings may not fully capture the variability in physical and chemical characteristics arising from different coal combustion systems. Particle-size analysis indicates that CBA meets the grading requirements for fine aggregate and is broadly comparable to river sand, as depicted in **Figure 1**[33]. However, its cumulative passing curve is smoother, and its gradation is wider, indicating a combination of finer and coarser particles. In contrast, the distribution of river sand is more uniform and steeper, with a predominance of medium-sized particles. Since both materials fall within the specified upper and lower boundaries, both materials were used for further studies. The increased specific surface area of the finer fraction and the broader CBA gradation may increase water demand and absorption, potentially affecting workability if the water–cement ratio is left unchanged. River sand with more uniform grading generally promotes consistent workability and strength, providing a predictable baseline for comparison.

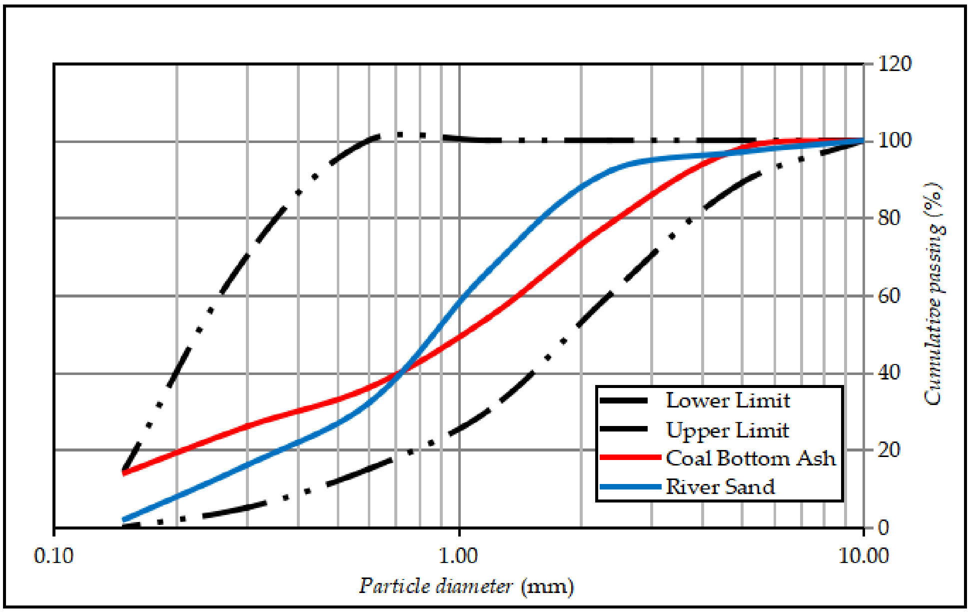
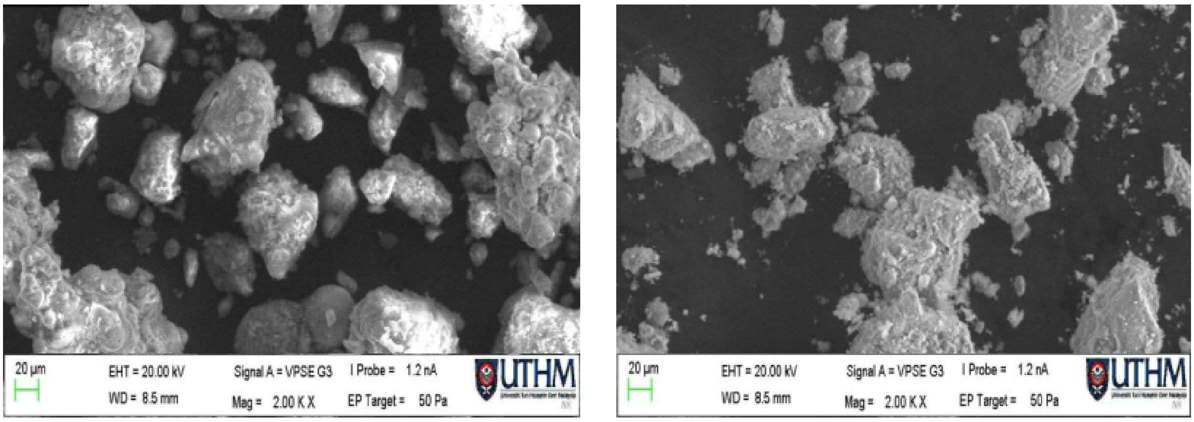


Figure 1. Gradation profiles of CBA and river sand.

The Scanning Electron Micrographs (SEM) show clear morphological contrasts between the aggregates. **Figure 2a** reveals CBA with a rough, highly porous surface comprising a blend of rounded and angular particles. In contrast, **Figure 2b** shows river sand with smoother surfaces and predominantly rounded to subangular forms. These textural differences are reflected in the measured properties listed in **Table 1**. CBA exhibits a lower specific gravity (2.32 vs. 2.63 for river sand), consistent with its lower density and internal voids, and a markedly higher water absorption (26.38% vs. 1.66%), indicative of greater open porosity. The prominent roughness and porosity of CBA are likely to increase water demand, elevate absorption, and influence the interfacial transition zone, factors that can affect workability and potentially depress strength, even though the fineness modulus values (2.93 and 2.94 for CBA and river sand, respectively) suggest equivalent overall particle size distributions. On the other hand, more constant rheology and mix performance are supported by the smoother, more rounded river sand[34].



(**a**) (**b**)

Figure 2. Surface morphology under SEM for (**a**) CBA and (**b**) river sand.

Table 1. Comparative physical parameters of CBA and river sand.

Physical Properties	CBA	River Sand
Specific gravity	2.32	2.63
Water absorption (%)	26.38	1.66
Fineness modulus	2.93	2.94

Table 2 summarises the oxide compositions of OPC, river sand, and CBA. It highlights significant chemical contrasts directly relevant to concrete behaviour, as determined in accordance with ISO 9516-1:2003 [35]. River sand contains a high silica fraction, SiO_2 (54.30%), supporting inert filler performance and durability, whereas CBA shows a lower SiO_2 content (≈26.40%), suggesting limited intrinsic pozzolanic reactivity relative to siliceous ashes. CBA is richer in alumina (Al_2O_3 ≈ 10.83%) than both OPC and river sand by 3.50% and 6.14%, respectively. It may influence early hydration through aluminate phases, and it contains markedly higher ferric oxide (Fe_2O_3 ≈ 18.30% vs. ≈ 0.21% in river sand), potentially affecting colour and density [36]. As anticipated, calcium oxide (CaO) prevails in OPC (about 58.6%). It is only partially present in CBA (about 11.18%), suggesting that although CBA can supply some calcium to hydration products, OPC plays a more significant role. Minor oxides (K_2O, TiO_2, MgO, Na_2O, SO_3) occur in varying amounts and collectively tune setting, durability and potential alkali-related responses. Based on $SiO_2 + Al_2O_3 + Fe_2O_3$ = 55.53% and compliance with sulphate and loss-on-ignition limits, the CBA qualifies as a Class C material under ASTM C618 [37], reflecting the presence of pozzolanic constituents alongside appreciable calcium, which can foster additional C–S–H formation when properly proportioned.

Table 2. Oxide composition of OPC, river sand, and CBA.

Oxides	Percentage (%)		
	OPC	River Sand	CBA
SiO_2	15.8	54.30	26.4
Al_2O_3	3.50	6.14	10.83
Fe_2O_3	3.10	0.21	18.30
CaO	58.6	0.83	11.18
K_2O	0.32	0.28	0.48
TiO_2	0.12	0.32	0.81
MgO	1.16	—	2.84
Na_2O	—	—	0.23
SO_3	3.30	—	0.41

2.2. Casting and Curing of Specimens

The mix proportions for the CBA-modified and normal concrete (NC) are shown in **Table 3**. The control mix produced an actual mean strength of 43.12 MPa after being proportioned to attain a designated compressive cube strength of 30 MPa at 28 days [38]. Three WC ratios (0.40, 0.45, and 0.50) and three CBA replacement amounts by mass of sand (0%, 10%, and 20%) made up the experimental variables. This factorial variation enables a direct comparison of material reactions across the specimen sets, allowing a controlled evaluation of the combined effects of water content and CBA dose on fresh and hardened behaviour. The purpose of the experiment was to correlate concrete's compressive strength and water absorption were affected by the WC ratio and CBA concentration. The selection of 10% and 20% CBA as partial sand replacements was based on previous literature identifying this range as optimal for balancing strength retention and material sustainability [23]. The WC ratios of 0.40, 0.45, and 0.50 were chosen to simulate low to moderate water availability conditions, offering insight into pore development and strength evolution. For all mixes, a control group with 0% CBA was included for comparison.

All reported results represent the mean of three cube specimens per mix condition. In total, 54 cubes (100 × 100 × 100 mm) were cast to evaluate compressive strength and water absorption for both normal and CBA concretes at 28 and 56 days. Materials were batched to the prescribed mix proportions and mixed mechanically to ensure uniformity. Specimens were labelled, demoulded after 24 h, and subsequently water-cured to the designated test ages, following the procedures outlined in [39].

Table 3. Concrete batch proportions for 1 m^3 of CBA concrete.

Design Mix	WC Ratio	Amount (kg/m^3)				
		Cement	Coarse Aggregate	Fine Aggregate	CBA	Water
NC-0.40WC	0.40	475	1070	655	0	190
NC-0.45WC	0.45	427.5	1062.5	710	0	190
NC-0.50WC	0.50	380	1055	765	0	190
CBAC10%-0.40WC	0.40	475	1070	589.50	65.5	190
CBAC10%-0.45WC	0.45	427.5	1062.5	639	71	190
CBAC10%-0.50WC	0.50	380	1055	688.5	76.5	190
CBAC20%-0.40WC	0.40	475	1070	524	131	190
CBAC20%-0.45WC	0.45	427.5	1062.5	568	142	190
CBAC20%-0.50WC	0.50	380	1055	612	153	190

2.3. Testing Methods

The two main responses were water absorption and compressive strength. Concrete cubes were subjected to a compression test at 28 and 56 days, in accordance with BS EN 12390-3:2019 [40]. The specimen was loaded at a steady rate of 0.6 ± 0.2 $MPa\cdot s^{-1}$ without shock after being centred beneath the platen (**Figure 3a**). To counter any tendency for the rate to decline on manually operated machines, the force was continuously raised at the chosen rate (±10%) after an initial seating load that did not exceed ≈30% of the projected failure load. As shown in **Figure 3b**, loading was continued until no higher load could be maintained, and the failure mode was verified to be satisfactory.

(**a**) (**b**)

Figure 3. Compressive strength procedure illustrating (**a**) specimen placement and (**b**) post-failure condition.

Water absorption was determined on companion cubes in accordance with BS 1881-122:2011+A1:2020 [41]. Specimens were oven-dried at 105 ± 5 °C to constant mass (successive 24 h mass loss < 0.5%), cooled to room temperature in a desiccator, and weighed to obtain the dry mass, W_{dried}. All specimens were then fully immersed in water at 20 ± 2 °C for 24 h, removed, and surface-dried with a damp cloth to a saturated-surface-dry condition. All specimens were then weighed to record as the saturated mass, $W_{sat.water}$. Water absorption was calculated using Equation (1) and reported to the nearest 0.01% as the mean of three specimens per mix.

$$\text{Water Absorption} = \frac{W_{sat.water} - W_{dried}}{W_{dried}} \times 100\% \quad (1)$$

3. Results

This section starts with the compressive strengths for all combinations at 28 and 56 days, and then it reports the water-absorption results. The suggested mix-design guidelines are supported by the outcome, which summarises these data through correlation analysis and shows an explicit inverse, almost linear correlation between compressive strength and water absorption.

3.1. Compressive Strength

Figure 4 summarises the compressive strengths for the mixes with varying water–cement ratios. Strength decreased systematically with both increasing CBA content and a higher WC ratio, whereas curing from 28 to 56 days produced clear gains for all mixes, mirroring the trends of the control (**Figure 4**). All mixes exceeded the required 30 MPa, and both the control and CBA achieved the target strength of 43.12 MPa (28 days) at WC = 0.40 and 0.45, respectively. The most favourable replacement level at 28 days was 10% CBA, yielding strengths comparable to the control at WC = 0.40 and 0.45 (52.8 MPa and 46.8 MPa), corresponding to reductions of approximately 3.4% and 1.92%, respectively. Raising the WC ratio to 0.50 reduced strength by 11.3% relative to the control, and, at this high-water content, varying CBA from 10% to 20% produced little additional effect (i.e., the replacement level had no evident influence). For 20% CBA, the highest 28-day strength occurred at WC = 0.45 (45.4 MPa); at WC = 0.40, it was 43.3 MPa (4.85% lower). By 56 days, the strengths for 20% CBA at WC = 0.40 and 0.45 converged to 49.6 MPa in both cases. Relative to the control, the corresponding reductions were 26.1% and 5.1% at 28 days, and 22.4% and 5.8% at 56 days, highlighting the comparatively lower strength penalty at WC = 0.45 within this replacement range.

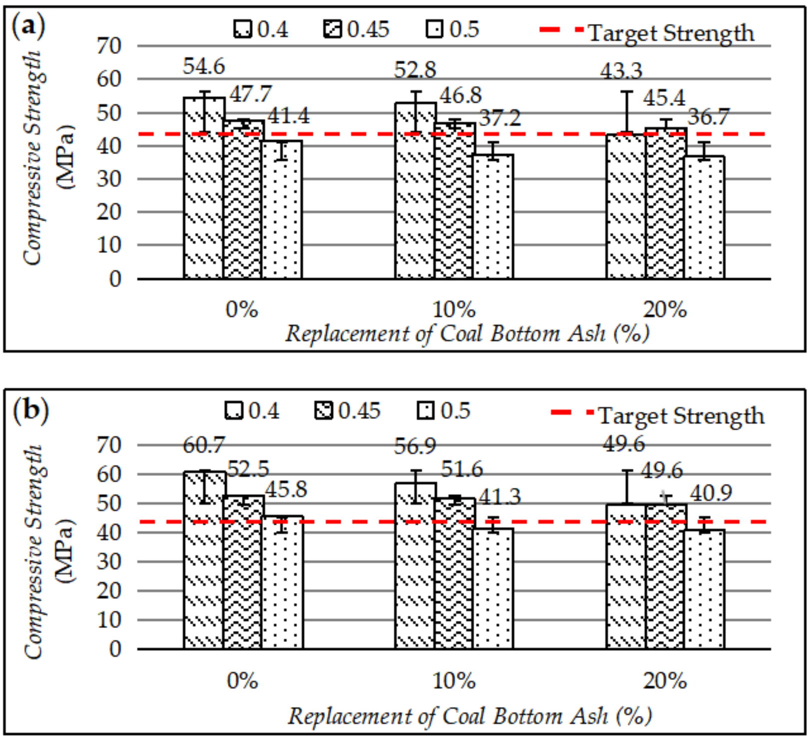


Figure 4. Effect of CBA content and WC ratio on compressive strength at (**a**) 28 days and (**b**) 56 days.

This study found that mixes with 10% CBA at WC = 0.40–0.45 delivered compressive strengths comparable to the control, consistent with prior reports that ~10% sand replacement can match a 28-day control strength of about 50 MPa[19]. Another finding, likewise identified 10% CBA (at WC = 0.55) as sufficient to meet a 35 MPa target, with longer curing producing strengths that eventually exceeded the control (e.g., 15% CBA = 58.3 MPa at 56 days)[21]. In the present work, increasing the WC ratio from 0.40 to 0.45 still permitted 10–20% CBA to achieve acceptable strength, whereas at WC = 0.50 the influence of CBA level became negligible—mirroring the typical penalty of excess mixing water. More broadly, the literature indicates that CBA incorporation can depress early strength (≤28 days) but that parity with the control is often achieved at extended ages (up to 365 days) through ongoing reactions[42]. From a practical perspective, 10–20% CBA within WC = 0.40–0.50 is a reasonable window when workability (without superplasticiser) is a primary constraint; this aligns with findings that ≤30% CBA can be acceptable for both workability and strength in conventional mixes, as suggested by Faisal et al.[43].

The strength trajectories observed here are also consistent with the ash's chemistry. The CBA used qualifies as Class C (SiO_2 + Al_2O_3 + Fe_2O_3 = 55.53%), implying relatively lower silica than typical Class F ashes and, hence, somewhat reduced long-term pozzolanic potential—a factor that helps explain why strengths in this study did not surpass the control by 56 days, unlike the trend reported by Ghadzali et al.[21]. Strong calcium–silicate–hydrate (C–S–H) gels with greater compressive strength were formed because of the high pozzolanic reaction in CBA, which happened late in the curing phase. The chemical composition of the CBA employed in this investigation is to blame. Because the proportion of SiO2 + Al2O3 + Fe_2O_3 was 55.53%, the CBA employed in this investigation was categorised as Class C. Because of this, the silica oxide concentration was lower than that of Class F, which led to a somewhat slower development of long-term characteristic strength[44]. Experimental studies comparing CBA sources of classes (Class F and Class C) were carried out by Thi et al.[11]. A higher silica oxide level was shown to affect concrete's strength properties. As shown in **Table 2**, the CBA utilised in this study also has a high calcium oxide (CaO) content. Conversely, the higher CaO content measured for this CBA can accelerate early hydration by supplying additional calcium hydroxide, which in turn supports C–S–H formation, an effect also noted for Class C ashes utilised CBA in Class C and discovered that a CBA substitution of up to 30% increased the early strength of CBA concrete, which surpassed the control at 7 days[19]. Ultimately, the water–cement ratio remains the dominant lever: lower WC increases binder concentration and reduces capillary porosity, while higher WC enlarges the pore network and suppresses strength[45]. Thus, WC ratio and porosity are intrinsically linked, and their control is essential to realise the benefits of low-level CBA incorporation.

3.2. Water Absorption

Figure 5 presents the water absorption results at 28 and 56 days, respectively. As expected, absorption increased with both higher CBA replacement and higher WC ratio, while curing reduced absorption for all mixes. For the control concrete at 28 days, the values were 5.33%, 5.96% and 6.11% for 0.40, 0.45 and 0.50, respectively. Then, these decreased to 5.22%, 5.81% and 6.03% at 56 days, representing reductions of approximately 2.10%, 2.61% and 1.32%, respectively. Although the most pronounced absorption occurred at high CBA and high WC, replacing sand with ~10–20% CBA at WC values of 0.40–0.50 resulted in no marked penalty relative to the control. Notably, all mixtures remained below 10%, consistent with an acceptable durability grade[19].

These trends align with published findings for CBA-modified concretes, including self-compacting concrete: absorption tends to rise with CBA dosage yet commonly remains in the **~6.0–6.8%** range for **10–30%** replacement at 28 days, and mixes with up to **~40% CBA** have been reported as suitable in terms of absorption[46]. Additionally, other studies concur that concrete mixtures containing up to 40% CBA are considered suitable for good concrete production due to their low water absorption rates. However, concrete's water absorption often depends on the aggregate used[47]. As shown in **Figure 2a**, the root cause is the porous morphology of CBA, which increases initial water absorption and is eventually offset by pozzolanic reactions that produce more C–S–H and gradually consolidate the matrix composition[5]. C–S–H gels are formed in part by the pozzolanic components in CBA, especially those with calcium-silicate bases. By filling the gaps between cement grains, these gels reduce concrete's overall porosity and water permeability. This slow densification of the concrete matrix can explain the observed decline in water absorption with age. As noted by Jaber et al.[48], enhanced C–S–H formation reduces pore volume and connectivity, thereby lowering absorption with age. Consequently, while CBA's porosity can raise early-age absorption, the time-dependent refinement of the microstructure mitigates this effect and supports the longer-term durability of CBA concrete.

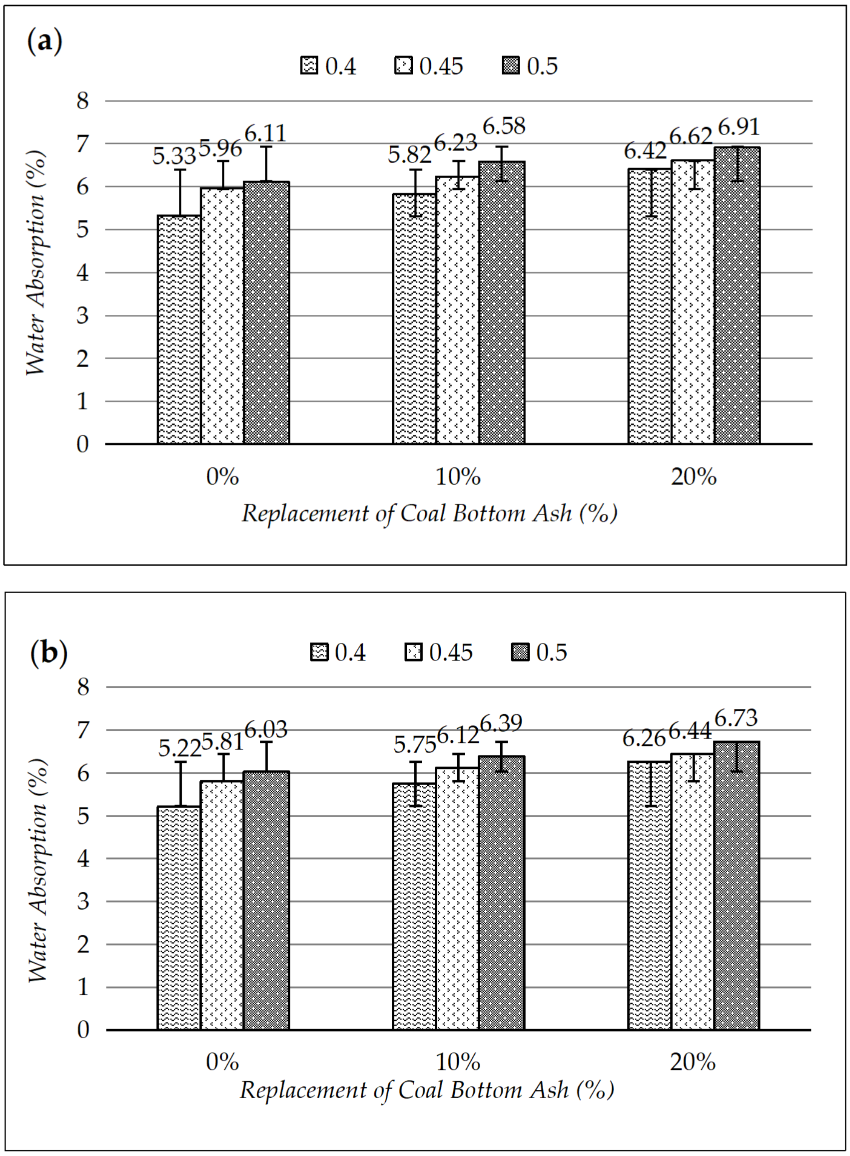


Figure 5. Effect of CBA content and WC ratio on water absorption at (**a**) 28 days and (**b**) 56 days.

3.3. Statistical Evaluation of the Strength–Water Absorption Relationship

Although CBA is a highly absorbent, relatively weak aggregate, sand replacement at 10–20% produced acceptable mixes provided the WC ratio was appropriately controlled. To quantify the interplay between mechanical and transport behaviour, the relationship between compressive strength and water absorption was examined at each WC ratio using linear regression. The coefficient of determination (R^2) was employed to assess the strength of association, with values approaching 1 indicating a strong correlation. Average values from mixes containing 0%, 10%, and 20% CBA were plotted as scatter points with best-fit lines (**Figure 6**). As a result, the findings show a significant negative interaction, suggesting that decreases in compressive strength are linked to improvements in water absorption. This inverse interaction is essential to understanding the effects of CBA on concrete morphology. Additionally, longer cure times reduced water absorption while increasing compressive strength.

The R^2 values were relatively high at a WC ratio of 0.40, reaching 0.92 after 28 days and 0.93 at 56 days, as shown in **Figure 6a**, suggesting a substantial negative association between compressive strength and water absorption. This implies that, even with up to 20% CBA replacement, concrete mixtures with this WC ratio exhibit steady, predictable structural performance. Higher compressive strengths result from this ratio's comparatively low water absorption, underscoring the need to manage the WC ratio for the best possible concrete performance. As seen in **Figure 6b**, the R^2 values for WC = 0.45 were somewhat higher, at 0.94 for 28 days and 0.95 for 56 days, indicating a stronger association. This ratio works well for CBA concrete because it combines high strength with ease of mixing, which may be explained by an ideal balance between workability and decreased porosity. The consistent R^2 values further support this mix's dependability for structural applications throughout time. On the other hand, at WC = 0.50, the R^2 values dropped to 0.82 at 28 days and 0.83 at 56 days (**Figure 6c**), suggesting that the strength–absorption connection is less predictable and more variable. Increased porosity resulting from higher water absorption at this ratio negatively impacts compressive strength.

In all cases, the 56-day lines lie above the 28-day lines (higher intercepts), reflecting strength gain and reduced absorption with curing. These statistics confirm that the strength–absorption linkage is strong for WC = 0.40–0.45 (R^2 ≈ 0.92–0.95) and moderate for WC = 0.50 (R^2 ≈ 0.82–0.83). According to Hasim et al.[6], values greater than 0.85 indicate a strong relationship; thus, only the WC = 0.50 condition falls below this threshold. The trend agrees with previous findings shown in **Figure 4**, where at WC = 0.50, varying CBA content (10–20%) had little influence on strength, consistent with prior observations that high WC produces larger, more connected pores that elevate absorption and depress strength[49]. The findings show similar moderate correlations between absorption (surface/internal) and strength have been reported by Zhang and Zong[50]. However, these results showed that the WC ratio R^2 values of 0.40 and 0.45 were approaching 1. This indicates a significant correlation between water absorption and compressive strength. The WC ratio is held within 0.40–0.45, mixes with 10–20% CBA and exhibits a robust inverse strength–absorption relationship governed by porosity and interfacial microstructure. Once the WC ratio rises to 0.50, the enlarged pore system diminishes this coupling.

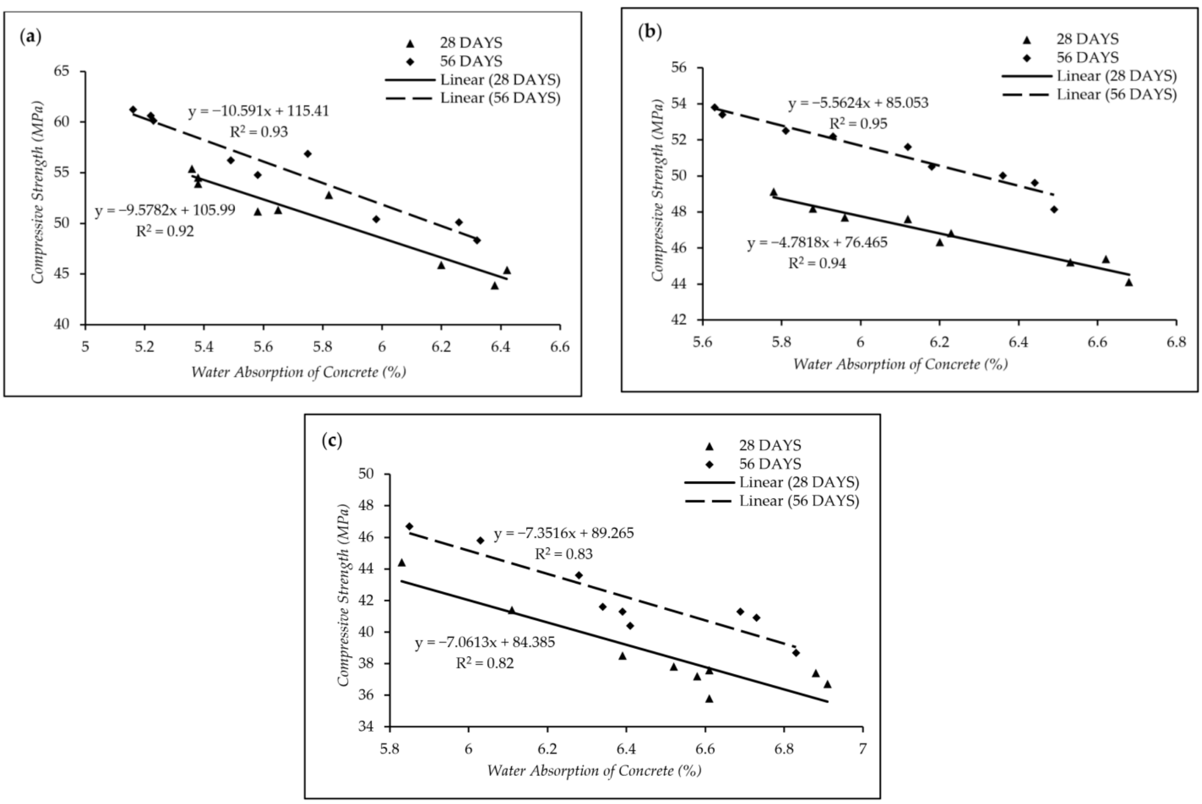


Figure 6. Compressive strength–water absorption correlation plots for CBA concrete at: (**a**) WC = 0.40; (**b**) WC = 0.45; and (**c**) WC = 0.50.

The statistical error indicators further validate the correlation between water absorption and compressive strength. Accordingly, the root mean squared error (RMSE), relative absolute error (RAE), and relative root mean squared error (RRMSE) were evaluated to quantify the predictive accuracy and robustness of the developed correlation. RMSE quantifies the overall magnitude of prediction errors, with lower values indicating closer agreement between predicted and experimental results and reduced sensitivity to large deviations. The relative indicators, RAE and RRMSE, normalise errors relative to observed data, enabling consistent comparisons across different WC ratios and curing ages. Overall, these metrics confirm the reliability and stability of the proposed relationship under varying mix proportions and curing conditions. **Tables 4 and 5** summarise the statistical indicators of error for the correlation between water absorption and compressive strength at 28 and 56 days. At both curing ages, the lowest error values are consistently observed for WC = 0.45, with RMSE of 0.36 MPa at 28 days and 0.40 MPa at 56 days, accompanied by very low RAE (≈0.72–0.74%) and RRMSE (≈0.76–0.78%). These results, supported by the highest R^2 values (≈0.94–0.95), indicate excellent agreement between predicted and measured strengths, confirming that water absorption is a highly reliable predictor at this WC ratio and showing minimal scatter across specimens.

Table 4. Statistical error indicators for the correlation between water absorption and compressive strength at 28 days.

WC Ratio	RMSE (MPa)	RAE (%)	RRMSE (%)
0.40	1.15	2.09	2.28
0.45	0.36	0.74	0.76
0.50	1.07	2.63	2.77

Table 5. Statistical error indicators for the correlation between water absorption and compressive strength at 56 days.

WC Ratio	RMSE (MPa)	RAE (%)	RRMSE (%)
0.40	1.22	1.98	2.19
0.45	0.40	0.72	0.78
0.50	1.01	2.45	2.39

For WC = 0.40, slightly higher error values are recorded, with RMSE ranging from 1.15 to 1.22 MPa and RRMSE between 2.28% and 2.19% at 28 and 56 days. Nevertheless, the relative error indicators remain low, demonstrating that the correlation between water absorption and compressive strength is still strong and stable at this WC ratio, as further supported by high coefficients of determination (R^2 ≈ 0.92–0.93). The modest increase in error compared to WC = 0.45 reflects minor microstructural variability associated with a denser but less optimally packed cement matrix. In contrast, WC = 0.50 exhibits the highest error indicators at both curing ages, with RMSE values of 1.07 MPa (28 days) and 1.01 MPa (56 days) and RRMSE approaching 2.80%. This is further reflected by the reduction in R^2 to approximately 0.82–0.83. These higher error levels indicate greater scatter in the strength–absorption relationship, attributed to the formation of a more open and interconnected pore structure at higher WC ratios. As a result, compressive strength becomes increasingly influenced by pore connectivity and interfacial microstructural characteristics beyond what is captured by water absorption alone.

The results confirm that both the WC ratio and the CBA content significantly influence compressive strength and water absorption. While increasing CBA content generally reduces strength due to its porous and weaker particle structure, a replacement level of 10% CBA at a WC ratio of 0.45 offers an effective balance between strength retention and durability-related performance, suggesting a practical substitution limit for conventional concrete applications. Low values of RMSE, RAE, and RRMSE, particularly for WC = 0.45 at both 28 and 56 days, indicate minimal deviation between predicted and measured compressive strengths, confirming that water absorption is a robust predictor of mechanical performance under optimised WC conditions. Conversely, higher RMSE and relative error indicators observed at WC = 0.50 signify greater data scatter and reduced model accuracy, reinforcing the conclusion that excessive water content diminishes the strength–absorption coupling. Overall, the consistently low relative error metrics across all mixes confirm that the correlation between water absorption and compressive strength is statistically reliable at both 28 and 56 days. The results further demonstrate that predictive accuracy is highest at WC = 0.45, remains strong at WC = 0.40, and is moderately reduced at WC = 0.50 due to increased microstructural heterogeneity.

4. Conclusions

This paper evaluated the potential of employing CBA as a partial sand replacement to address environmental pressures and dwindling natural river sand resources, testing 10% and 20% CBA at WC ratios of 0.40, 0.45, and 0.50 to quantify effects on compressive strength and water absorption. The results show that CBA can be incorporated effectively, provided water demand is kept under control. Mixes with up to 20% CBA achieved strengths comparable to the control, e.g., at 28 days for WC of 0.40 and 0.45, compressive strengths of 43.3 MPa and 45.4 MPa, respectively, versus the respective control strengths. It was confirmed that adequate performance is retained when the mix is optimised. All mixtures exhibited low water absorption at 10% CBA after 28 days with 5.82%, 6.23%, and 6.58% for WC 0.40, 0.45, and 0.50, respectively. It's indicating no meaningful loss of impermeability. At lower WC ratios, correlation analysis showed a substantial inverse association between compressive cube strength and absorption (R^2 = 0.92–0.94 for WC ratios of 0.40–0.45). On the other hand, the link weakened at WC = 0.50 ($R^2 \approx 0.83$), indicating that as additional water expands the pore network, there is greater unpredictability and less predictability. The reliability of these correlations was further substantiated through statistical error analysis. Overall, the factorial experimental design, replicated testing at 28 and 56 days, and combined use of correlation coefficients and multiple statistical error indicators provide strong confidence in the robustness of the findings. Future research should investigate durability performance with respect to chloride ingress, carbonation, and sulphate resistance. Additionally, emerging computer vision techniques and deep learning may support automated assessment of material morphology, material interactions, and crack behaviour through image-based analysis in CBA concrete.

Author Contributions

Conceptualisation, K.M.F.K.M., Z.O. and S.K.M.; methodology, S.K.M.; formal analysis, K.M.F.K.M.; investigation, Z.O.; resources, K.M.F.K.M.; writing—original draft preparation, K.M.F.K.M.; writing—review, rephrasing and editing, Z.O. and S.K.M.; visualisation, K.M.F.K.M.; supervision, Z.O.; funding acquisition, K.M.F.K.M. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to the nature of the research and institutional data management policies, the dataset is not currently publicly archived. However, no proprietary or confidential information is included, and the authors are committed to transparency and data sharing for academic purposes.

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Conflicts of Interest

Other than AI use stated in the section below, the authors declare no conflict of interest related to the content of this article.

AI Use Statement

The authors utilised ChatGPT (OpenAI, GPT-5.2) solely for language-related tasks, including grammar checking, sentence structure refinement, and improving the overall readability of the manuscript. It is also disclosed that this manuscript was previously submitted to a non-Scopus-indexed journal, resulting in a pre-print publication on *Research Square*. Upon recognising the indexing limitation, the authors formally withdrew the submission. Due to the subsequent high similarity index detected from the Research Square pre-print, the authors employed AI assistance to paraphrase and refine relevant sections of the manuscript. All AI-generated outputs were critically reviewed and edited under the authors' supervision to ensure academic integrity. Meanwhile, all scientific ideas, data interpretations, analyses, and conclusions were developed independently by the authors, who take full responsibility for the academic content presented herein.

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