

Article

Sustainable Mortar for Non-Structural Applications Using Alkali Bypass Dust

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Abstract

This study investigates the potential of alkali bypass dust (ABD) as a supplementary material to partially replace cement in paste and mortar formulations. The selection of ABD is motivated by the dual objectives of utilizing an industrial waste product to promote sustainable construction and reducing the carbon footprint associated with cement production. The chemical and mineralogical composition of ABD was characterized using X-ray fluorescence (XRF) and X-ray diffraction (XRD), revealing a composition similar to Portland cement but with a notably lower CaO content (44.32%) and the presence of calcite, portlandite, quartz, and free lime. The incorporation of ABD as a cement replacement significantly influenced the fresh and hardened properties of the mixtures. In paste mixtures, results demonstrated a proportional increase in water demand and setting times with higher ABD content, attributed to its lower reactivity and higher water absorption. Mechanical properties were adversely affected; compressive and flexure strengths in paste mixtures decreased substantially, with a 40% reduction observed at just 10% replacement. This was corroborated by a decrease in density, an increase in water absorption, and a significant drop in ultrasonic pulse velocity (UPV), indicating a more porous and less dense microstructure. In mortar mixtures, a 30% cement replacement with ABD yielded compressive and flexure strengths that remained within acceptable ranges for plastering and masonry applications, despite a reduction in workability. The findings suggest that while high-volume ABD replacement negatively impacts performance, a 30% replacement level presents a viable, sustainable alternative for specific non-structural applications, contingent upon further durability assessments.



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1. Introduction

Manufacturing cement is a significantly important industry in Saudi Arabia and world-wide. Saudi Arabia has been the leading cement producer within the Gulf Cooperation Council states with 55 thousand metric tons of cement produced during 2021 [1]. Portland cement production raises serious environmental concerns. The primary issues are its CO₂ emissions, which contribute approximately 5–8% to the global total, and the disposal of its waste materials [2].

High-quality cement is produced from several key substances. Calcareous materials, such as limestone, provide essential calcium carbonate, which decomposes to form the cement clinker. Argillaceous materials, like clay and shale, supply silica, alumina, and iron. These compounds facilitate the chemical reactions that give cement its strength and binding properties [3].

The raw materials contain many chemical compounds that are not necessarily needed to produce cement. For example, the limestone contains chemicals other than the calcium oxides; the shale material contains not only the aluminum oxides but also silica, alumina, iron, calcium, magnesium, sulfate, etc. [4]. In the raw materials used in cement production, there are compounds that are beneficial in the production of cement and others that are unwanted and can reduce the quality of the final product.

The primary raw materials contain impurities, including compounds of potassium (K) and sodium (Na). During clinkerization, these compounds volatilize in the high-temperature burning zone [5]. The volatilized alkalis then condense on the cooler raw mix particles in the preheater tower, forming alkali chlorides and sulfates. This creates an internal cycle where alkalis are continuously evaporated and re-condensed, leading to their accumulation within the preheater system [6].

Excessive buildup of these circulating volatiles can cause operational issues such as preheater coating and blockage due to the formation of sticky deposits that reduce gas flow and heat transfer efficiency. Also, the quality of clinker is lower due to the high alkali content in the clinker, which leads to deleterious expansion and cracking in concrete due to alkali–silica reaction (ASR). Finally, coating build-up can disrupt the steady flow of material, which leads to unstable kiln operation.

To maintain product quality and process stability, these volatiles are selectively removed from the system via an alkali bypass installed in the preheater. The alkaline dust collected from this process is captured in bag filters or electrostatic precipitators [7]. This collected material, known as alkali bypass dust (ABD), is traditionally considered a waste product, presenting storage and disposal challenges for the industry.

ABD is highly variable in composition, depending on the raw materials and fuels used in the specific cement plant. In general, it is characterized by very high concentrations of water-soluble alkalis (K^+ and Na^+), sulfates (SO_4^{2-}), and chlorides (Cl^-). Typical compositions can range from 15–40% K_2O , 5–15% Na_2O , 5–20% SO_3 , and 5–15% Cl^- . The remaining portion consists of calcium carbonate ($CaCO_3$), unburned raw mix powder, and minor oxides. ABD is a very fine, dry, and powdery material with a high specific surface area. Its particle size is typically below 100 μm [3]. The fine and dry powder is easily wind-blown, causing air pollution and potentially impacting local ecosystems and communities.

Historically, ABD has been landfilled as non-hazardous waste, though this practice is increasingly scrutinized. The environmental challenges associated with its disposal include land use where large volumes of dust require significant landfill space. In addition, the high solubility of ABD constituents can raise a critical environmental concern due to the high leachability of ABD ionic components (K^+ , Na^+ , Cl^- , SO_4^{2-}). If stored in uncontrolled landfills, rainwater can leach these salts into soil and groundwater, posing a contamination risk. This necessitates careful landfill management with liners and leachate collection systems to prevent groundwater pollution. These challenges, coupled with rising landfill costs and stricter environmental regulations, have driven the cement industry to seek sustainable alternatives for ABD management, focusing on recycling and valorization within the cement production circuit or in other applications [8,9].

Research has studied the reuse of ABD as partial reintroduction into the cement production process. This is achieved by feeding a controlled amount of ABD back into the kiln system. This must be performed carefully to avoid re-establishing the volatile cycle it was designed to break. Studies have shown that small, metered quantities can be reintroduced at specific points (into the kiln burner or the pre-calciner), so that high temperatures can incorporate the alkalis into the clinker silicate phases without causing excessive volatilization [10]. This approach reduces waste volume but requires sophisticated process

control. Chatterjee (2011) found that ABD that is rich in alkali sulfates (K_2SO_4 , Na_2SO_4) can partially replace natural gypsum, typically up to 30–50% [3]. Alkali bypass is also used as a stabilization agent for soil, although its high soluble salt content must be carefully evaluated for each specific case [11].

Most specifications prohibit reusing ABD in the production of cement and limit its content to less than 0.6% [12]. In addition, ABD is not used in construction industry. In this research, an attempt is made to reuse ABD with cement to produce a product that can be used as a construction material. This will reduce the air pollution from this powdery material, increase the sustainability of cement by using a waste material, eliminate contamination of water by preventing this material from being dissolved, which can lead to harmful diseases to human and animals, and improve the economy of cement.

Saudi Arabia is one of the largest producers and consumers of plastering and masonry assemblage in the Middle East, with annual production estimated in the tens of millions of tons to support its ongoing urban and economic transformation. This immense scale underscores the critical need to reduce the environmental impact of its primary building materials.

This paper investigates the development of a sustainable mortar for non-structural applications by incorporating ABD as a partial cement replacement (0%, 10%, 30%, and 50%). Targeting uses like plastering and masonry, where high mechanical strength is non-critical, the research accepts a potential strength reduction in exchange for enhanced sustainability and lower costs. The methodology involves a comprehensive characterization of ABD and an evaluation of the fresh and hardened properties of the modified paste and mortar. The findings will determine the viability of this approach for reducing the carbon footprint and expense of construction, concluding in a recommended optimal blend and usage protocol.

2. Materials and Methods

2.1. Materials

The materials used for this project are Portland cement from Riyadh cement as per ASTM C 150, and the chemical composition of the cement is shown in Table 1. ABD was collected from the bypass system installed in the kiln at the Riyadh Cement Factory (Riyadh, Saudi Arabia).

Table 1. Chemical compositions of cement.

Chemical Analysis	Cement	Standard Method	Specifications SASO-GSO 1914/2009
Loss on Ignition%	2.4		3.0% Max
Insoluble Residue%	0.8		1.5% Max
SiO ₂	20.25		-
Al ₂ O ₃ %	5.06		-
FeO ₃ %	4.28		-
CaO%	63.66	ASTMC114	-
MgO%	0.74		5.0% Max
SO%	2.74		3.0%Max (C3A ≤ 8%)
Chlorides%	0.02		3.5%Max (C3A ≥ 8%)
LSF	94.33		
C3A	6.17		
Total Alkalis Equivalent	0.45	ASTMC150	<0.60 for Low Alkali

Representative samples were collected from alkali bypass system by following the ISO 13909 (hard coal and coke—mechanical sampling) [13]. Then, the X-ray fluorescence

(XRF) spectroscopy technique (Bruker-S8 TIGER series, Bruker, Billerica, MA, USA) was selected to analyze the chemicals composing ABD [14]. In addition, X-ray diffraction (XRD) (Bruker-D8 Advance) analysis was used to study the crystalline phases present in ABD grains and provide information about the mineral composition, crystallinity, and phase transformations during hydration or aging [15]. The specific gravity was determined to be 2.168 as per ASTM C188 [16]. The sieve analysis is shown in Table 2 as per ASTM C430 [17].

Table 2. Sieve analysis of ABD.

Sieve Size	45 μm	65 μm	90 μm
Average value	8.8	3.2	16.6

The standard sand from Normalise as per ASTM C C778 [18] was used to produce mortar mixtures.

2.2. Mix Design

This work aims to investigate the possibility of reusing the waste ABD from cement factories. First, the effect of replacing the cement with ABD on paste mixtures was investigated. Then, mortar mixtures containing ABD were explored.

2.2.1. Paste Mixtures

This section discusses the properties of paste mixtures containing ABD as a cement replacement. The replacement ratios were 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% by weight, as shown in Table 3. These increments were selected to closely investigate the impact of ABD on the fresh and hardened paste properties.

Table 3. Mixture proportions for paste.

ABD (%)	0	10	20	30	40	50	60	70	80	90
Cement (g)	650	585	520	455	390	325	260	195	130	65
ABD (g)	0	65	130	195	260	325	390	455	520	585

The mixing procedure of the paste mixtures was in line with ASTM C305—20 [19]. The plastic consistency of each mixture was determined using ASTM C187-23 [20]. Then, the mixtures were placed in molds measuring 4 cm $\times$ 4 cm $\times$ 16 cm. After demolding, the specimens were stored in a curing tank at 25 °C. Note that for every test at a different curing period, three samples were prepared, and an average was reported.

ASTM C191 [21] was used to determine the impact of replacing cement with ABD on the initial setting time (the time elapsed between the moment the water is added to the cement and the time when the paste starts to lose its plasticity) and final setting time (the time elapsed between the moment the water is added to the cement and the time when the paste has completely lost its plasticity and has attained sufficient firmness to resist a defined penetration pressure). The setting time was calculated as the final setting time subtracted from the initial setting time.

Compressive and flexure strength were measured for the cured specimens at 3 days, 7 days, and 28 days in accordance with ASTM C349 [22] and ASTM C348 [23]. The preliminary compressive strength results established a clear performance ceiling at approximately 50% ABD replacement, beyond which the material is no longer suitable. Therefore, to ensure this research remained focused on industrially applicable solutions, three key replacement levels—10%, 30%, and 50%—were strategically selected for the remaining tests in this research. This approach allowed us to thoroughly characterize the practical per-

formance window, optimize experimental resources, and generate actionable data for the development of sustainable mixtures.

For the nondestructive tests that can give some indications about durability, the water absorption test (ASTM C1585 [24]), the density (ASTM C138 [25]), and the ultrasonic pulse velocity (UPV) ASTM C597 [26] were used. The ABD replacement percentages were 10%, 30%, and 50%.

The water absorption test was conducted on the paste samples measuring 100 mm in diameter and 30 mm in length, as per the procedure mentioned in ASTM C1585.

To measure the water absorption of a paste mixture, the fresh cement paste was cast into a clean, rigid, non-absorbent mold with internal dimensions of 100 mm in diameter and 30 mm in length. After demolding, specimens were transferred into a curing tank at a controlled temperature of 25 °C. After 28 days of curing, the samples were put in a ventilated oven at a temperature of 105 ± 5 °C until they achieve constant mass. After drying, the specimens were allowed to cool at room temperature for 24 ± 4 . Then, they were weighed to record their masses as the oven-dry mass. The specimens were then immersed in water and removed at specific time intervals (1, 5, 10, 20, 30 min, then 1, 2, 3, 4, 5, 6 h, then every 24 h for 3 days). The weights were recorded after each time interval, and the calculations were performed according to ASTM C1585.

To measure the density of a paste mixture, the fresh cement paste was cast into a clean, rigid, non-absorbent mold with internal dimensions of 4 cm $\times$ 4 cm $\times$ 16 cm. After demolding, specimens were transferred into a curing tank with a controlled temperature of 25 °C. After 28 days of curing period, the samples were taken out of the curing tank and brought into saturated surface-dry (SSD) condition. The weights of these specimens were measured, and the volumes of the specimens were calculated. The density of each specimen was calculated as the weight divided by volume.

To measure the UPV of a paste mixture, specimens measuring 4 cm $\times$ 4 cm $\times$ 16 cm were prepared and cured as discussed previously. For a 4 cm $\times$ 4 cm $\times$ 16 cm prism, the Direct (Transverse) Transmission Method was the most accurate. Using a caliper, the distance between the two opposite 4 $\times$ 4 cm faces was measured (the pulse travel path length, $L = 16$ cm). Then, the transducers were positioned against the center of the two opposite 4 $\times$ 4 cm faces, ensuring they were aligned axially. The instrument measured and displayed the time (T) it took for the pulse to travel through the sample. The reading is typically in microseconds (μ s). Three readings were obtained, and the average was calculated. Finally, the pulse velocity (V) was calculated using the equation $V = L/T$.

2.2.2. Mortar Mixtures

To study the impact of ABD on the compressive and flexure strength and flow of mortar [27], mortar mixtures were prepared. A control mixture with only Portland cement and standard sand was prepared with the proportion fixed at 1–3 cement-to-sand ratio and a w/c ratio of 0.5 was selected, which is a typical mix ratio for mortar mixtures. Then, ABD replaced the cement by weight at 0%, 10%, 30%, and 50%, as shown in Table 4.

Table 4. Mixture proportions for mortar.

Materials	ABD 0%	ABD 10%	ABD 30%	ABD 50%
Cement (g)	450	405	315	225
ABD (g)	0.0	45	135	225
Water (g)	225	225	225	225
Standard Sand (g)	1350	1350	1350	1350

The mixtures were prepared and mixed according to ASTM C 305-20 [19] and placed in molds measuring 4 cm × 4 cm × 16 cm to produce specimens for compressive and flexure strength measurements as per ASTM C 349 and ASTM C348, respectively, at 3 days, 7 days, and 28 days. After demolding, the specimens were stored in a curing tank at 25°.

3. Results

3.1. Chemical Composition of ABD

The chemical composition of ABD gathered from Riyadh Cement Company was determined by the XRF method. It is commonly known that the chemical composition of ABD can vary between cement plants and overtime but generally mirrors that of Portland cement. Table 2 presents the major components of the studied ABD, namely calcium oxide (CaO) content (44.32%), silicon dioxide (SiO₂) content (14.28%), and aluminum oxide (Al₂O₃) content (5.13%). Although these major quantities are typically representative of the chemical composition of clinker kiln dust (CKD), the low CaO content should be noted, especially since values above 50% are often reported in the literature [28,29]. On the other hand, other secondary compounds may be present in varying quantities, depending on the raw materials of Portland cement, such as alkalis (Na₂O and K₂O), sulfates (SO₃), and chlorides (Cl[−]). Table 5 shows the presence of the three compounds in ABD studied although their quantities remain relatively low <1%. The results also show that the studied ABD is characterized by a very low loss of ignition (Table 5).

Table 5. Chemical compositions of ABD.

	SiO ₂	Al ₂ O ₃	FeO ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃
Chemical	14.28	5.13	0.237	44.32	0	0.11	0.12	0.07
Analysis	CI	LOI	Moist	QV *	LSF *	SM *	AM *	Eq AIC *
	0.053	1.06	-	0.38	95.95	2.66	21.65	0.19

* QV: quotient of volatiles, LSF: lime saturation factor, SM: silica modulus, AM: alumina modulus, Eq AIC: equivalent alkali as chloride.

3.2. Mineralogical Composition of Materials

The XRD analysis of ABD confirms the chemical composition discussed above. Indeed, the XRD pattern of the ABD sample indicates a diverse mixture of crystalline phases, primarily consisting of calcite (CaCO₃), portlandite (Ca(OH)₂), quartz (SiO₂), and free lime (CaO). The prominent calcite peak at 29.4° signifies considerable carbonation, which may result from exposure during storage or the intrinsic composition of ABD, as shown in Figure 1. The detection of portlandite peaks at 18° and 34° implies partial hydration, likely due to water exposure during the processes of handling or aging. The distinct peaks of CaO (lime) observed at approximately 37° and 40° validate the existence of free, unreacted lime, a characteristic feature of kiln dust obtained from high-temperature areas. Lastly, the quartz peaks represent the inert siliceous residue derived from raw materials or the dusting of clinker minerals (Figure 1).

XRD analysis indicates a distinct mineralogical transformation in Portland cement mortars as ABD substitution increases, shown in Figure 2. The control sample (M0) is primarily characterized by portlandite, an essential hydration product, along with minor amounts of calcite and quartz. With a rise in ABD content, the peaks of portlandite significantly diminish, suggesting the consumption of CH through pozzolanic reactions or a dilution effect on the cement content. Concurrently, the sharp peaks of calcite (~29.4° 2θ) and quartz (~26.6° 2θ) become more pronounced, highlighting the crystalline carbonate and siliceous characteristics of ABD. At a 50% replacement level (M50), the diffraction pattern is predominantly influenced by inert fillers (quartz) and carbonation products (calcite), while portlandite is nearly nonexistent. The detection of unhydrated lime in samples M30–M50

indicates an excess of free CaO in ABD that remains unreacted, which could potentially affect long-term durability.

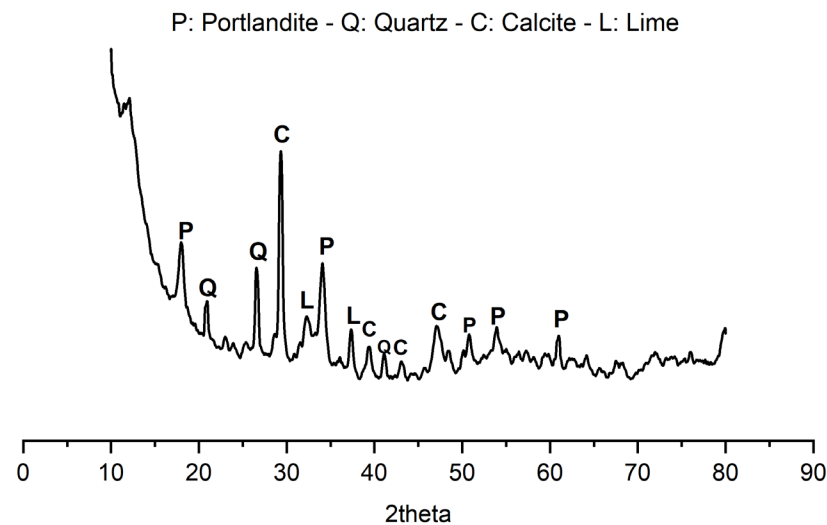


Figure 1. The XRD analysis of an alkali bypass dust specimen.

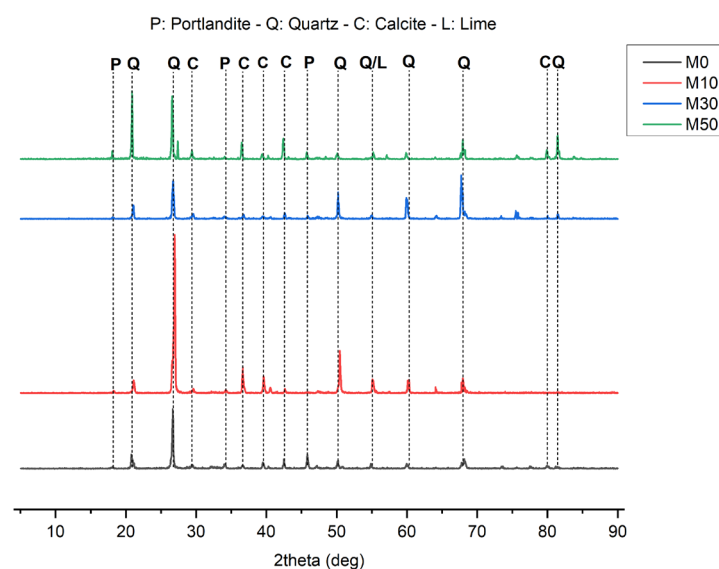


Figure 2. The XRD analysis of mortar mixtures containing ABD at 0%, 10%, 30%, and 50%.

3.3. Paste Mixtures Results

3.3.1. Water Requirement

The water requirement for each paste mixture was determined by measuring the consistency of the cement paste. Figure 3 illustrates the effect of ABD content on the water demand of the mixtures.

As shown in Figure 3, the water demand increased proportionally with the ABD replacement percentage. The control mixture (0% ABD) required 26.8% water, while the mixture with 90% ABD required 36.2%. This corresponds to an approximate 1.18% increase in water demand for every 10% increment in ABD replacement. The observed trend suggests that ABD is a highly powdery material with greater water absorption capacity than cement.

Notably, beyond 60% ABD replacement, the water demand exceeded the recommended range (26–33%) for achieving standard cement consistency, potentially impacting workability and performance.

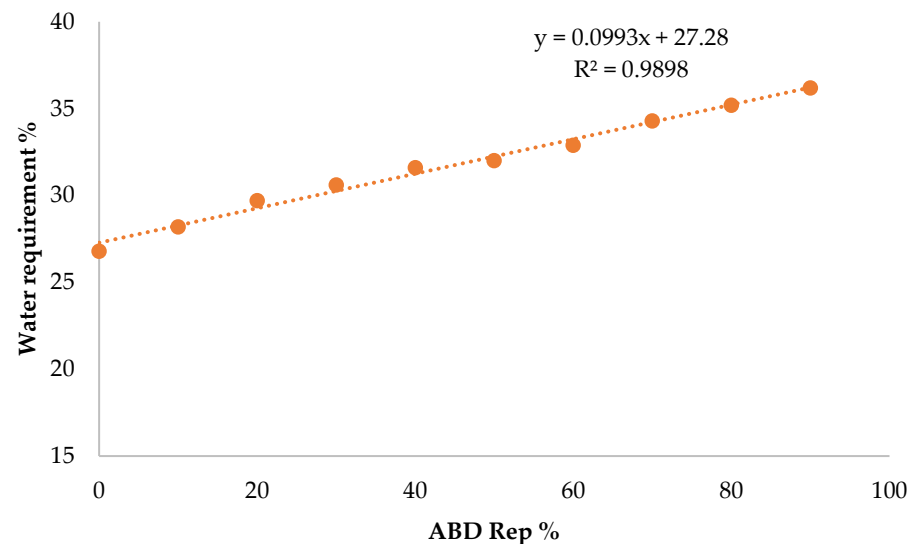


Figure 3. The effect of replacing cement with ABD on the water demand in paste mixtures.

3.3.2. Setting Time

The effect of ABD as a cement replacement on the initial and final setting times of paste mixtures is shown in Figure 4.

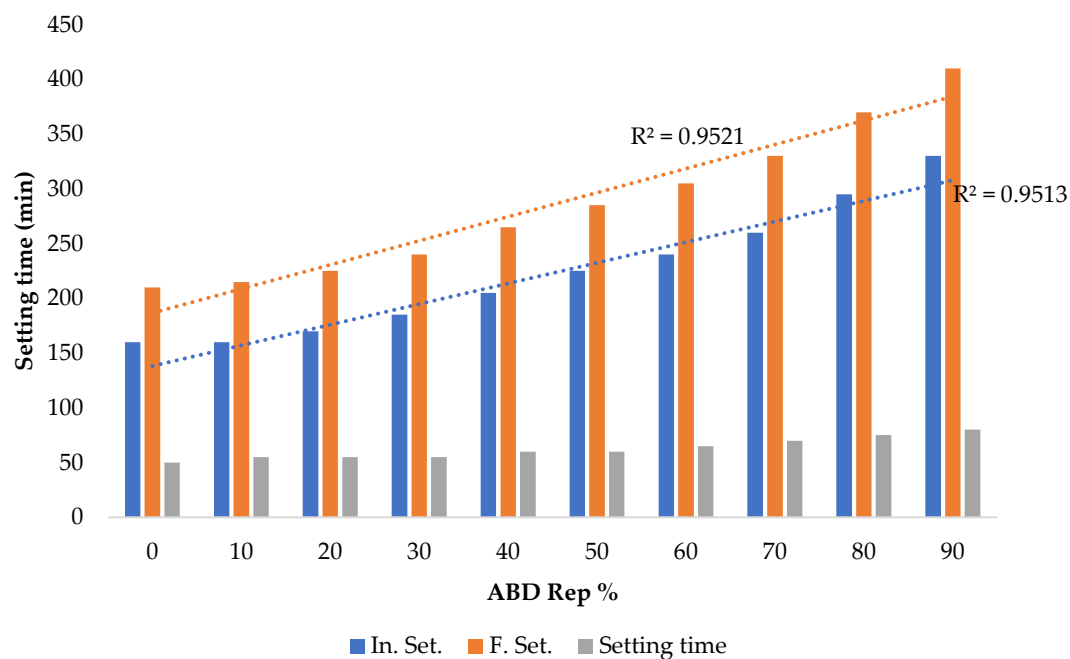


Figure 4. The impact of ABD on the setting times of paste mixtures.

It can be observed that both the initial and final setting times increased with higher ABD replacement percentages. This delay suggests that ABD was less reactive than cement, and at higher replacement levels, there were insufficient reactive materials to initiate the hardening process. The setting period remained relatively constant at 55 ± 5 min for replacement levels up to 50% ABD. However, beyond 50% replacement, the setting time increased at a rate of 5 min per 10% increment of ABD. This prolonged setting time could significantly influence the workability of concrete or mortar during construction, affecting placement and finishing operations.

3.3.3. Compressive and Flexure Strength Measurements for Paste Mixtures

The effect of replacing cement with ABD on the strength of paste mixtures was evaluated through compressive and flexure strength tests as shown in Figures 5 and 6, respectively.

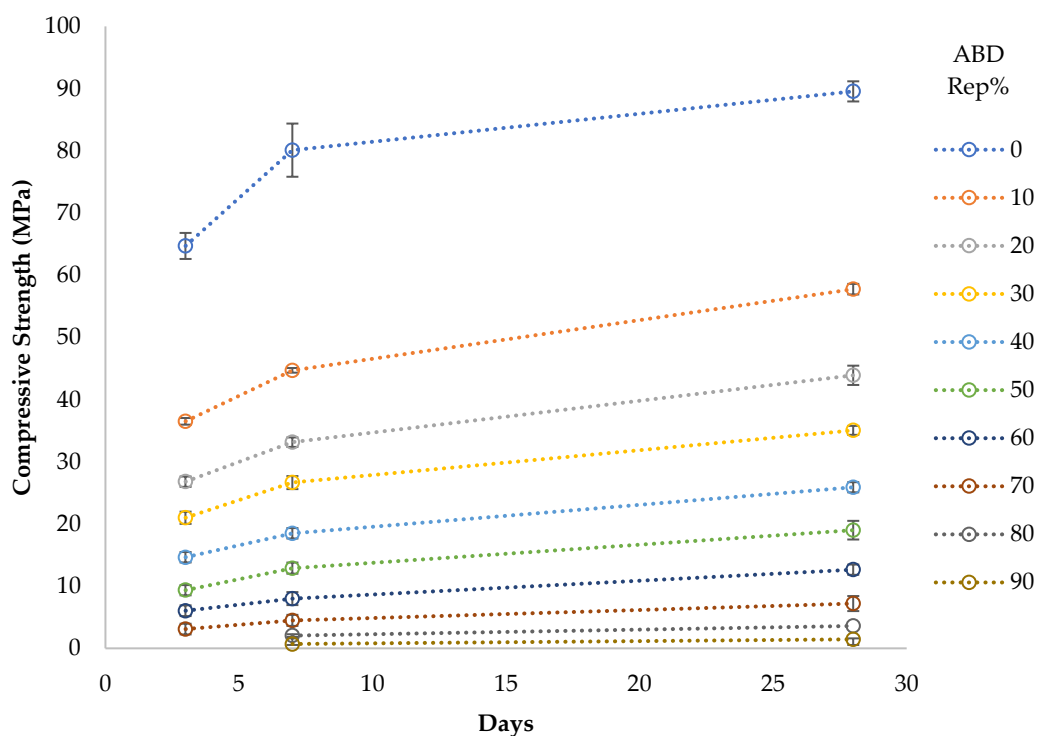


Figure 5. The effect of replacing cement with ABD on the compressive strength of paste mixtures.

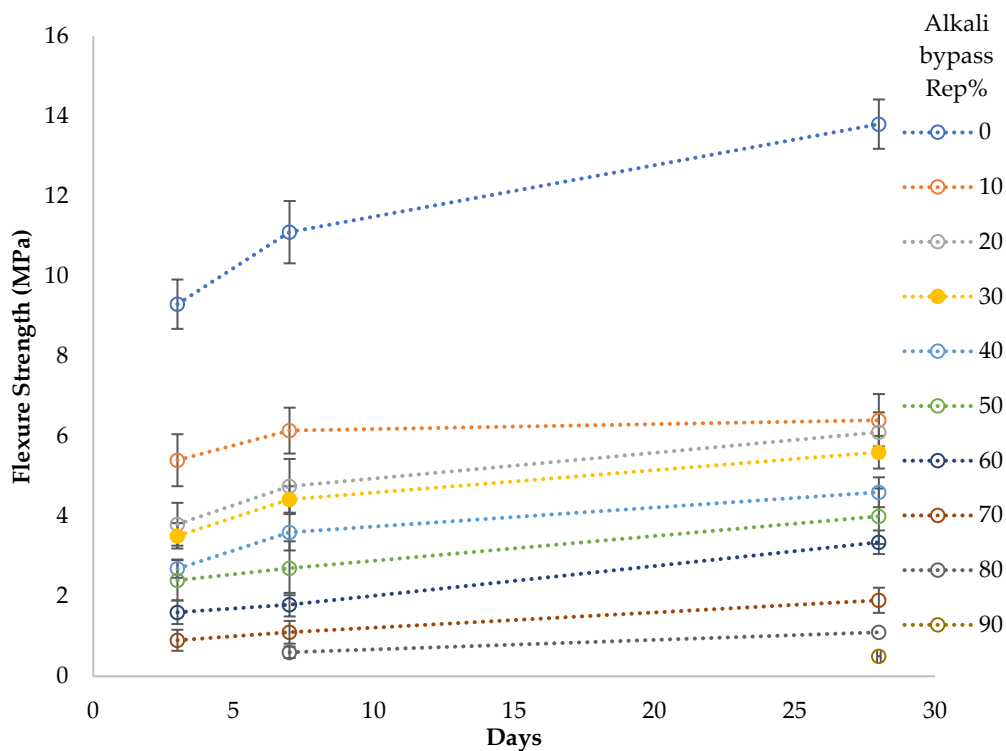


Figure 6. The effect of replacing cement with ABD on the flexure strength of paste mixtures.

From Figure 5, A 10% replacement of cement with ABD resulted in an approximate 40% reduction in compressive strength. Strength continued to decline with higher replacement

percentages. At 90% replacement, no measurable compressive strength was observed at 3-day curing periods.

As for Figure 6, the flexure strength decreased across all tested curing ages upon ABD addition. A 46% average reduction occurred at 10% replacement, with further declines as ABD content increased.

Based on the above results, it can be concluded that the lower reactivity of ABD compared to cement reduced hydration product formation, directly weakening the paste structure as replacement levels rose.

3.3.4. Water Absorption

The impact of ABD on water absorption in a paste mixture was measured for the 28-day specimens, as shown in Figure 7.

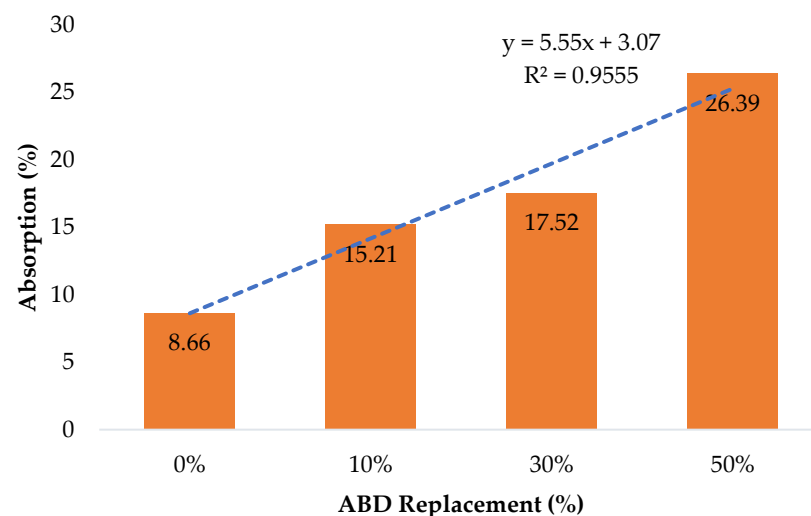


Figure 7. The relationship between the water absorption of paste mixtures and the ABD replacement percentage.

As ABD replaced cement, the cement content decreased. Less cement means fewer hydration products (e.g., C-S-H gel, CH), which normally fill pores and densify the paste matrix. Hydration products, from cement, are crucial for pore refinement and reducing permeability. With fewer hydration products, more capillary pores remain unfilled, increasing porosity and water absorption.

3.3.5. Density

To examine the effect of ABD on paste mixture density, Figure 8 presents mixtures with varying ABD levels as cement replacements.

It can be observed that there was a decrease in the density of the paste mixtures with increasing ABD content at an approximate rate of 47 kg/m³ for every 10% replacement. This can be explained by the difference in the specific gravities of cement and alkali bypass, as well as the replacement level. Since ABD has a lower specific gravity than cement, replacing cement with ABD reduces the overall mass of solids in the paste for the same volume, leading to lower density.

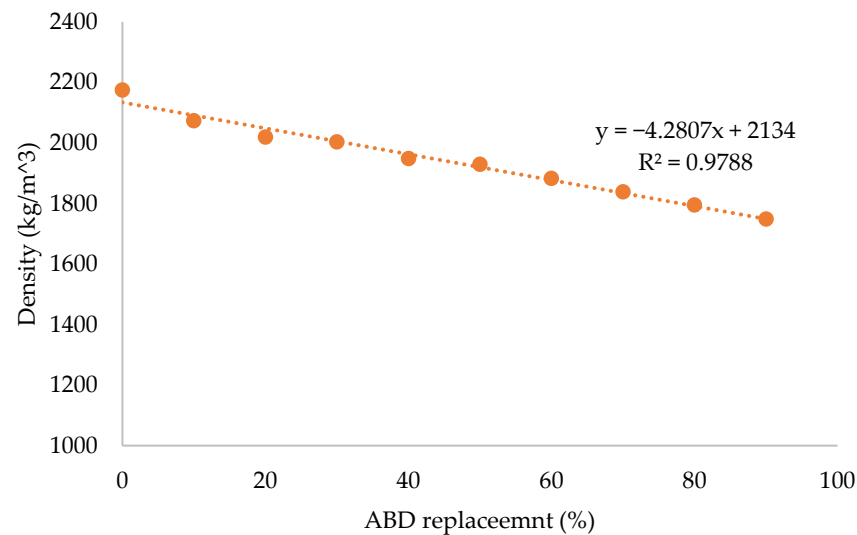


Figure 8. The effect of replacing cement with ABD on the density of paste mixtures.

3.3.6. Ultra-Pulse Velocity (UPV)

The UPV test was used to indirectly assess the microstructure of paste mixtures containing ABD. Figure 9 shows the effect of replacing cement with ABD on pulse velocity.

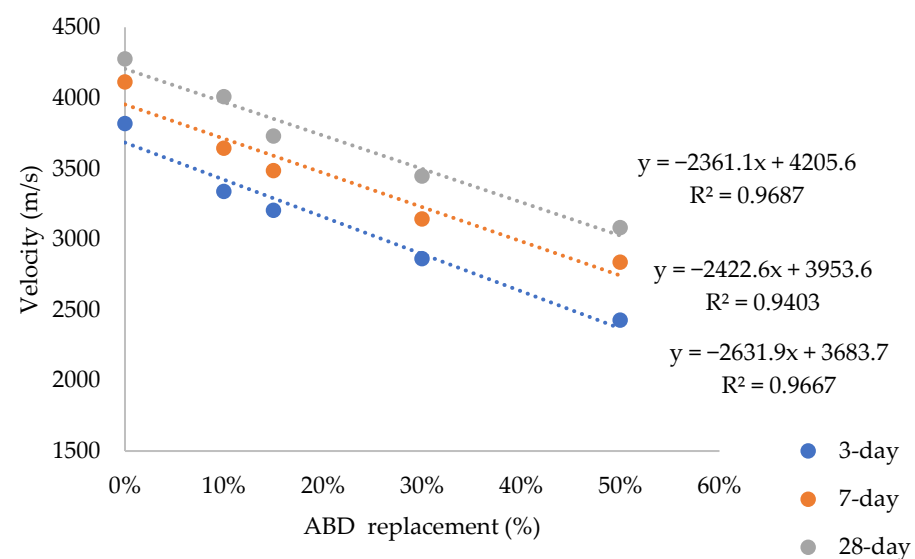


Figure 9. The effect of replacing cement with ABD (0%, 10%, and 50%) on the UPV of paste mixtures.

From Figure 9, it can be seen that as ABD content increased (0% to 50% cement replacement), UPV values decreased significantly (from 4278 m/s to 3083 m/s). At 30% ABD replacement, the UPV value was below the recommended range (3500–4500 m/s) for well-cured and dense paste (ASTM C597). This may indicate higher porosity since ABD was less reactive compared to cement, leading to fewer hydration products. This reduced matrix density and increased porosity, which slowed ultrasonic pulse propagation.

3.3.7. Correlation Between Compressive Strength, Density, and UPV Properties

To understand the relationship between compressive strength, UPV, and density, Figure 10 shows correlation between the above parameters.

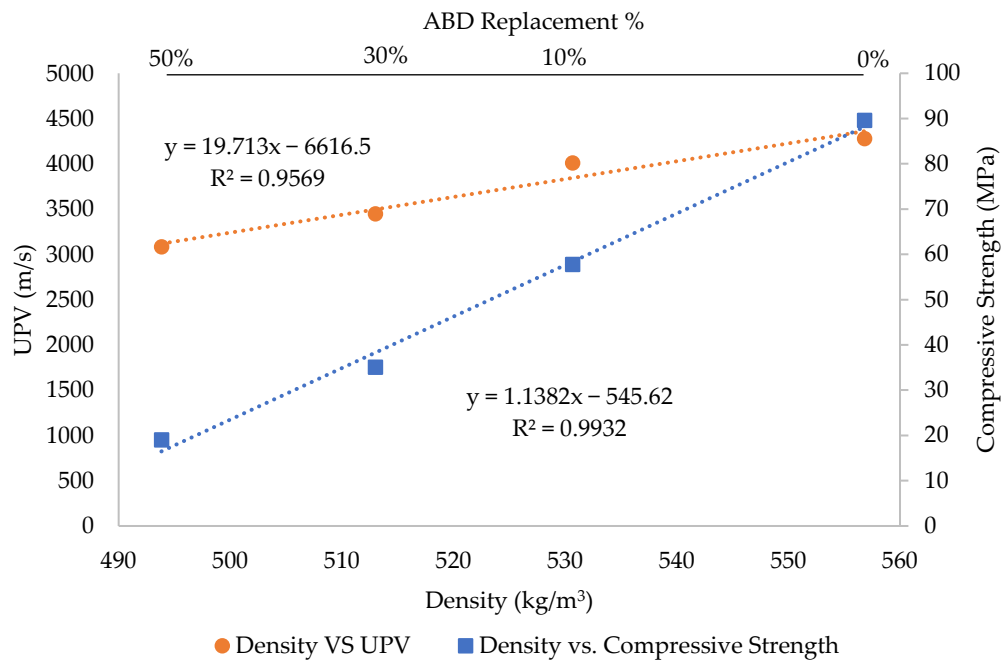


Figure 10. Correlation (with 8 points) between compressive strength, UPV, and density of paste mixtures containing ABD.

It can be noted that as density decreased, both compressive strength and UPV values also decreased. This reduction in density and associated properties was linked to higher ABD replacement levels, suggesting that increased replacement negatively impacted the material performance. The consistent decline in all three parameters implied that ABD replacement adversely affected the material's microstructure leading to weaker, less dense, and acoustically slower (lower UPV) specimens. For all correlations (compressive strength vs. density, UPV vs. density), the relationships were statistically strong, with $R^2 > 0.9$.

Density is a direct proxy for porosity and solidity. A higher density means a greater volume fraction of solid, load-bearing material and a lower volume fraction of weak, empty pores. Under a compressive load, stress lines flow through the solid network. When these stress lines encounter a pore, which cannot carry load, they are forced to divert around it. This concentration of stress at the edges of pores can exceed the local strength of the material, initiating microcracks that eventually combine and lead to failure. More pores and lower density mean more of these failure initiation points. Fundamentally, strength is force per unit area. If the cross-section of a specimen has a certain percentage of pores, the actual solid area carrying the load is reduced. Lower density directly translates to a smaller effective load-bearing area.

As for UPV vs. density, UPV measures how fast a pulse wave travels through a material. The velocity is governed by the material's density. Pulse waves travel fastest through the solid, elastic phases of the material. They are slowed down by pores and cracks because the wave must diffract around them or because the air in the pores has a much lower wave velocity than the solid. A high UPV value indicates a continuous, well-connected, and elastic solid network. Thus, as density decreases, compressive strength and UPV also decrease.

3.4. Mortar Mixtures Results

3.4.1. Flow of Mortar

The flow table test was used to determine the impact of ABD on the workability of mortar mixtures. Figure 11 shows the flow percentage on the Y-axis and the ABD replacement percentage on the X-axis.

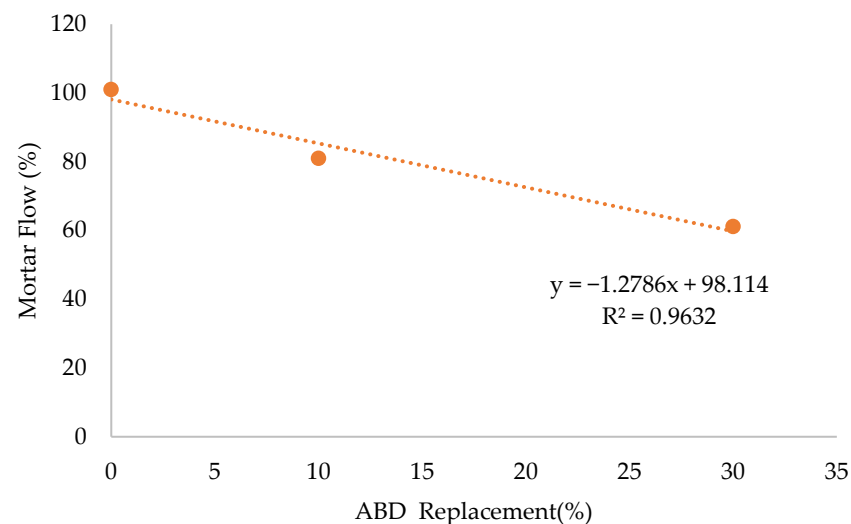


Figure 11. The effect of replacing cement with ABD (0%, 10%, and 50%) on the flow of mortar mixtures.

The observations from the flow table test highlighted several key points regarding the impact of ABD on mortar workability. The inverse relationship between ABD replacement percentage and flow percentage indicates that ABD negatively impacted workability. This could be due to the higher water demand ABD required in paste mixtures, as discussed previously.

It can be noted that there was a loss of cohesion at high replacement (50%), and the flow table test could not be performed, which was likely because the water content was insufficient to coat and lubricate ABD particles, as shown in Figure 12. To match the flow (workability) of the reference mixture (0% ABD), additional water would be needed. The drawback of increasing water would be increasing the water-to-cement ratio (w/c), which could reduce compressive strength and durability. While ABD can be a sustainable supplementary material, its incorporation requires careful balancing of workability, strength, and durability. Further testing with chemical admixtures or particle optimization is recommended to maximize its usability.



Figure 12. The cohesionless mortar mixture due to 50% of ABD replacement.

3.4.2. Compressive and Flexure Strength Measurements for Mortar Mixtures

The effect of ABD on the compressive and flexure strength of mortar mixtures is shown in Figures 13 and 14, respectively. Note that there are no data points for the compressive and flexural strengths of the mixture with 50% ABD due to its noncohesiveness.

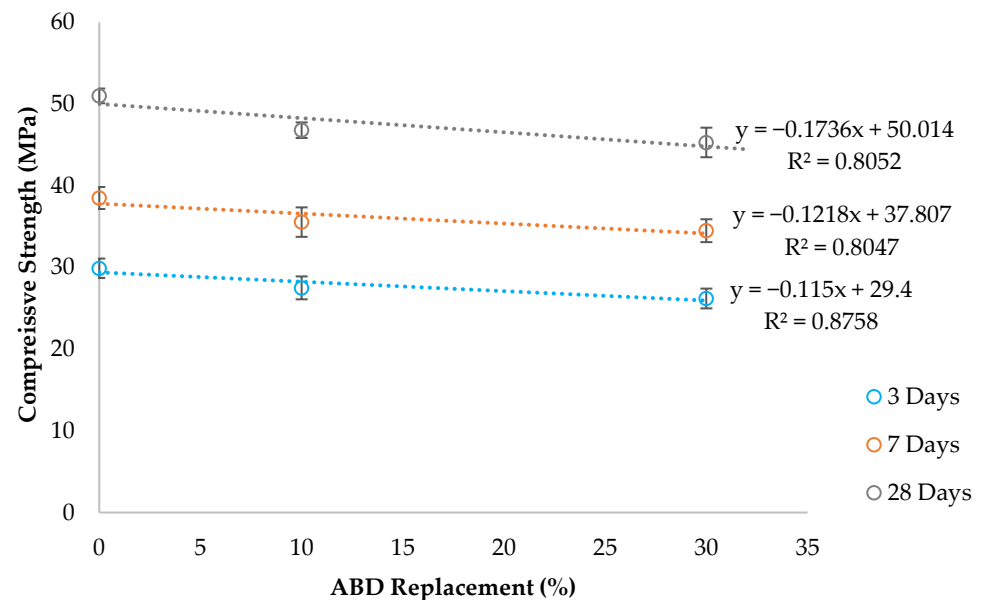


Figure 13. The effect of replacing cement with ABD on the compressive strength of mortar mixtures.

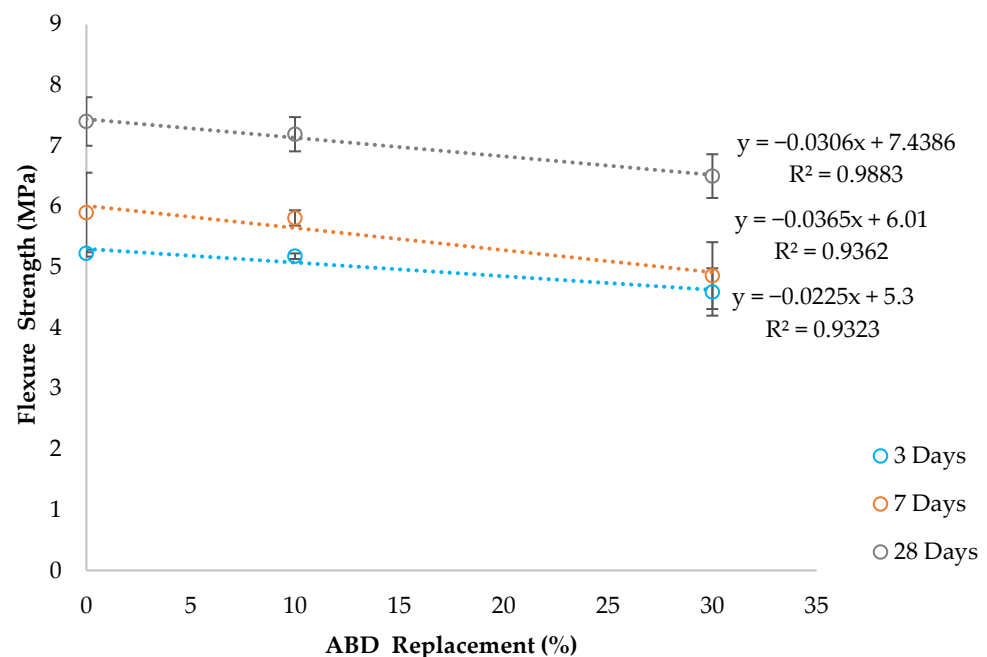


Figure 14. The effect of replacing cement with ABD on the flexure strength of mortar mixtures.

Figure 13 illustrates the effect of ABD content on the compressive strength of mortar. A slight reduction in strength was observed at the 10% ABD replacement level. When the replacement level was increased to 30%, the compressive strength decreased from 51 MPa for the control mixture to 45.9 MPa, representing an approximate 10% reduction. A similar trend was observed for flexural strength, as shown in Figure 14, where a 30% ABD content led to a reduction of approximately 14%. This decline in mechanical properties could be attributed to ABD acting as a partial cement replacement, which reduces the clinker-based

binder content. Since cement is the primary source of hydration products, its reduction directly results in fewer binding phases and, consequently, lower strength.

Despite this reduction, the resulting mortar remained suitable for non-structural building elements, such as plastering and masonry assemblies. These components, while not part of the primary load-bearing system, require sufficient compressive strength to support their self-weight, withstand handling stresses, and resist incidental impacts. The compressive strength requirements for these applications are considerably lower than for structural elements. For instance, ASTM standards specify compressive strength ranges of 0.5–17 MPa for masonry mortar (ASTM C270 [30]), 1–15 MPa for plaster (ASTM C926 [31]), and 13–40 MPa for masonry units (ASTM C90 [32]). The measured compressive strength of 45.9 MPa for the 30% ABD mixture far exceeds these requirements.

Therefore, replacing 30% of cement with ABD presents a practical and sustainable alternative for non-structural mortars. This approach not only meets the requisite performance standards but also enhances sustainability by valorizing an environmentally harmful waste product. Additional benefits include a reduction in material costs for masonry and plastering work and a significant lowering of the carbon footprint associated with cement production. While this study demonstrates short-term viability, further durability investigations are recommended to confirm the long-term performance of ABD-modified mortars.

4. Practical Significance

A 30% replacement of cement with ABD in non-structural mortars is a viable, sustainable, and cost-effective strategy for the construction industry. It provides a practical solution for repurposing an environmentally harmful waste product (ABD) into a valuable construction material. This reduces landfill waste and the environmental burden associated with its disposal. By directly replacing 30% of cement, a major source of global CO₂ emissions, this approach significantly lowers the carbon footprint of producing masonry and plastering mortars, contributing to greener construction practices. Using ABD as a partial cement substitute leads to a reduction in material costs for common building applications like plastering and masonry work, making construction more economical.

Despite a 10% reduction in compressive strength, the resulting mortar (45.9 MPa) exceeds the minimum compressive strength requirements set by ASTM standards for its intended non-structural applications. This gives builders and engineers confidence that the material will perform reliably in real-world conditions for elements like walls, partitions, and general masonry work.

In essence, the research demonstrates that the industry can immediately adopt this 30% ABD mixture for non-structural elements to achieve sustainability goals and cost savings without compromising the required mechanical performance. The recommendation for further durability studies ensures that this is presented as a promising, practical solution with a clear path for validating its long-term use.

5. Conclusions

The comprehensive evaluation of alkali bypass dust (ABD) as a partial cement replacement leads to the following conclusions.

The studied ABD possesses a chemical composition analogous to Portland cement but is distinguished by a lower CaO content and the presence of significant crystalline phases of calcite and quartz, alongside portlandite and free lime. This mineralogy indicates partial carbonation and hydration, influencing its reactivity.

The incorporation of ABD detrimentally affects the fresh state of paste and mortar. Water demand increases linearly due to ABD's powdery nature and high water absorption

capacity. Furthermore, setting times are prolonged, especially beyond 50% replacement, indicating a dilution of the reactive cement components and slower reaction.

The mechanical performance of paste mixtures declines sharply with increasing ABD content, a direct consequence of reduced cement content and the lower reactivity of ABD, leading to fewer hydration products. This results in a weaker, more porous matrix, as evidenced by decreased density, increased water absorption, and lower UPV values. The strong correlation ($R^2 > 0.9$) between decreasing compressive strength, density, and UPV confirms that ABD replacement compromises the structural integrity and density of the paste.

In mortar mixtures, a 30% replacement of cement with ABD was identified as a potential threshold. At this level, the compressive and flexure strengths, though reduced, remain within the specified ranges for plastering and masonry applications per ASTM standards. However, this comes at the cost of reduced workability, which would necessitate careful mix proportioning or the use of chemical admixtures to maintain ease of placement.

In summary, while ABD is not a direct substitute for cement due to its lower reactivity and negative impact on key properties, it demonstrates promise as a sustainable supplementary material for non-structural applications. The successful utilization of ABD in cement-based materials, particularly at replacement levels up to 30%, requires a balance between mechanical performance, workability, and durability. Future work should focus on long-term durability studies and strategies to mitigate its high water demand to optimize its use in sustainable construction.

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Abbreviations

The following abbreviations are used in this manuscript:

ABD	Alkali bypass dust
XRF	X-ray fluorescence
XRD	X-ray diffraction
UPV	Ultrasonic pulse velocity

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