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Optimization Techniques for High-Rate Utilization of Bottom Ash and Marble Dust in Green Technologies

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Abstract

This study investigates the influence of bottom ash (BA) and marble dust powder (MD) as partial replacements for Ordinary Portland Cement (OPC) on the physical, mechanical, and mass loss performance of cement pastes under cyclic seawater exposure and their economic feasibility. Mixtures containing 0–20% BA and 0–20% MP were tested to evaluate their workability, strength, porosity, durability, and cost efficiency. The results indicate that BA reduces workability, which is reflected in the lower slump values of mixtures with a higher BA content, whereas MD enhances fluidity by filling the voids between particles and improving the packing density of the mixture, which results in better workability. The optimal composition, which was 15% bottom ash and 10% marble dust powder, achieved a superior mechanical performance, with compressive strength (CS) and flexural strength (FS) increases of 2.2% and 38.7%, respectively, at 28 days compared to the control. Increasing the BA and MD content up to a total of 35% of the binder generally led to a moderate reduction in early-age strength, while mixtures with 20% replacement exhibited comparable or improved long-term strength at 90 days. This led to decreased porosity and improved long-term mass loss performance under cyclic seawater exposure. The incorporation of BA and MD also reduced water absorption, indicating enhanced durability, with these beneficial effects becoming more pronounced at later ages. Economically, cement substitution with BA and MD reduced production costs by up to 39.6%. In summary, moderate incorporation of BA and MD enhances performance, reduces cost, and supports the sustainable utilization of industrial waste in cementitious materials. The mixture proportions investigated in this study offer a promising alternative binder for use in the sustainable building sector.

Keywords: bottom ash; marble dust; cement paste; mechanical properties; sustainability; building; durability; cost efficiency

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Academic Editors: Keun-Hyeok Yang and Yun Gao

Received: 23 January 2026
Revised: 9 March 2026
Accepted: 9 April 2026
Published: 10 April 2026

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1. Introduction

Ordinary Portland Cement (OPC), a binder commonly used in the building industry, contributes significantly to worldwide CO_2 emissions, accounting for 5–8% of total anthropogenic emissions [1]. Cement manufacturing produced about 2.9 billion tons of CO_2 globally in 2021, and the industry aims to achieve net zero emissions by 2050 [2]. Given the growing emphasis on carbon reduction and the worldwide promotion of ecologically sustainable development policies, several academics are actively exploring environmentally friendly low-carbon binders as alternatives to OPC. However, although these efforts are commendable, existing studies often overlook the practical limitations and economic feasibility of OPC substitution at higher proportions. In many of these studies, the replacement

levels proposed for low-carbon binders are optimized primarily on the basis of mechanical strength under standard curing conditions, with only limited consideration of long-term durability and cost at high substitution ratios. At the same time, existing literature provides only a fragmented picture of technically acceptable replacement ranges for alternative binders, and there is still no clear consensus on which ranges are simultaneously technically viable and economically attractive for large-scale applications in aggressive environments such as marine exposure [3–11]. In response, this study focuses on bottom ash (BA) and marble powder dust (MD) as two promising industrial by-products and investigates their use as partial replacements for OPC at moderate total replacement levels.

The sustainable development paradigm under discussion emphasizes the need to accept natural resources as finite and to manage waste effectively. In view of the increase in the amount of waste being generated, there is an urgent need to investigate innovative methods of disposal, with a particular focus on recycling. Nevertheless, the research community has yet to establish standardized methods of evaluating the long-term performance of recycled materials, which may limit their widespread adoption in construction. The engineering field has witnessed significant advancements in the realm of building materials, paving the way for substantial modifications in the composites employed in construction. Current research is increasingly focusing on waste management and emphasizing the potential to reuse waste materials as substitutes for traditional raw materials derived from non-renewable resources. Despite these advancements, a critical comparison between different waste-derived binders is lacking, resulting in fragmented knowledge regarding their optimal proportions and compatibility with cement matrices. Furthermore, most existing reviews compile performance data from individual case studies without systematically contrasting different by-product combinations under comparable mix designs and testing protocols. As a result, it remains difficult to draw robust conclusions about which specific industrial wastes and mixture proportions provide the best balance between mechanical behavior, durability and economic performance. In particular, previous investigations involving BA or MD have typically examined these materials in isolation or have focused on a narrow set of performance indicators, without providing a unified assessment that simultaneously considers workability, strength, porosity, mass loss under cyclic seawater exposure, and cost [3–13]. Consequently, there is a critical need for systematic studies that map the coupled effects of BA and MD over a range of practically relevant replacement levels. This is particularly pertinent to research on cement concrete technology, in which the utilization of diverse waste materials such as aggregates, additives, or cement components is a subject of considerable interest [13].

The fact that waste materials can be repurposed in cement binders is an important step towards sustainability, as recycling waste materials is very important for the environment and economy. Specifically, these waste materials should be utilized in the creation of energy. Reuse of waste materials is a good means of supporting the steady growth of the construction industry [14]. Within the next ten years, energy production and energy-related CO_2 emissions are expected to rise significantly, according to statistical studies. Consequently, it is predicted that energy production waste will rise by 70% by 2036 [15]. Although this projection underscores the urgent need to reuse waste, research efforts have primarily focused on laboratory-scale tests, leaving a gap in understanding the scalability and durability of reused waste materials under actual field conditions. Quantitatively, the most important waste residue obtained from the incineration process is BA, which comprises 15–25% of the mass of burned material [3]. BA waste, which is produced in very high amounts, has proven suitable for use in the construction industry as an alternative binder material, yet comprehensive life-cycle assessments comparing BA-based binders with conventional cements remain scarce, limiting the ability to fully justify their environmental benefits.

Previous findings indicate that incorporating BA at up to 20% of the binder mass can enhance the pozzolanic reaction and workability without compromising strength; this finding provides the technical rationale for the proportion tested in this study. The investigation of BA as a cement binder has attracted significant attention in recent years due to the need for sustainable construction materials and the effective management of waste by-products from industrial processes. A review of the extant literature on this subject reveals several findings on the properties, applications, and limitations of BA in cement and concrete formulations. However, the reported mechanical and durability performances are often inconsistent, owing to differences in ash source, combustion conditions, fineness and mixture proportions, which complicates direct comparison between studies [3–9,11]. However, conflicting results in terms of mechanical behavior and pozzolanic activity suggest that further systematic studies are needed to define optimal processing parameters. Additionally, high concentrations of SiO_2, Al_2O_3, and Fe_2O_3 found in BA enhance qualities like strength, alloy locking, and the pozzolanic effect. ASTM C618-25a standards state that a material is pozzolanic if its silica, alumina, and ferric iron contents total 70% [16]. These components have an impact on how C-S-H are formed during hydration [4]. A comprehensive examination of coal BA as a potential binder in the production of artificial fine aggregates was presented in [4]. The authors explored the multifaceted role of BA, which is often perceived as an inert filler, and demonstrated its active contribution to the formation of C-S-H in the early stages of the manufacturing process. OPC's performance was improved with this effect. There is considerable potential to incorporate BA into mortars, particularly with regard to enhancing workability and compressive strength (CS) [11]. Nonetheless, the influence of varying ash compositions and particle sizes on hydration kinetics remains underexplored, making it difficult to generalize these findings across different BA sources. Nonetheless, many of these investigations focus on strength development under standard curing, while giving limited attention to long-term durability indicators such as mass loss, porosity evolution and resistance to aggressive environments [17,18]. In addition, many BA-related investigations focus either on strength development or on isolated durability indicators, but rarely integrate mass loss under cyclic exposure, porosity evolution and water absorption into a single, coherent performance framework, particularly for marine-influenced conditions. Consequently, the long-term serviceability of BA-based binders in harsh environments, especially those affected by seawater exposure, remains only partially understood. The findings of the study demonstrate that mortar mixtures incorporating BA powder exhibit superior performance compared to those formulated with conventional cement and fly ash. Furthermore, the investigation established BA as a viable binder in cement-based applications. Finely ground and fractionally utilized pozzolanic elements help improve strength and reduce bonding time [5]. The high degree of pozzolanic activity associated with the use of BA is influenced by the grinding process; the pozzolanic reaction is minimal when large BA particles are used [6], while the silica component of finer particles is said to enhance the reaction [7]. C-S-H formation is increased by silica's efficient participation in the reaction. Microstructure studies have found that finer particles increase specific surface area, and the pozzolanic reaction is effectively enhanced by this larger area [8]. Despite these promising outcomes, challenges such as energy consumption during fine grinding and the potential leaching of heavy metals must be critically assessed before the large-scale application of BA. Discussion on this subject was further advanced by an examination of the water retention capabilities of BA, which suggested its potential as an internal curing agent in expansive mortars and concretes. The researchers' findings suggest that BA can function as a substitute for conventional aggregates. Furthermore, the utilization of this waste product has the potential to enhance the sustainability of concrete production processes [9]. This is consistent with the increasing interest in sustainable con-

struction practices. However, most of these claims remain based on short-term laboratory evaluations, warranting further investigation of long-term durability and performance under varying environmental conditions. However, most of these claims are still based on short-term laboratory evaluations, and only a limited number of studies have systematically related BA content to coupled changes in workability, mechanical performance, porosity, water absorption and mass loss under realistic cyclic exposure [3–9]. Taken together, the available findings therefore highlight both the promise and the remaining uncertainties associated with BA in cementitious systems. While moderate dosages may improve performance and support sustainability targets, the absence of standardized, multi-parameter assessment frameworks make it difficult to establish robust and practically applicable upper replacement limits for BA, particularly for structures exposed to marine-influenced environments [17,19,20].

The collective insights from these studies underscore the multifaceted role of BA in cement production. Whilst the incorporation of BA presents opportunities for enhancing material performance and promoting sustainability, challenges related to its chemical composition and mechanical properties must be addressed. Therefore, a more critical review of the mechanisms, environmental trade-offs, and durability implications of incorporating BA is essential to fully validate its applicability in sustainable construction practices. It is imperative that further research is conducted in order to optimize the use of BA in a range of concrete formulations and to fully realize its potential as a binder in cement production.

The increasing demand for sustainable construction practices has given rise to a growing interest in the utilization of waste materials, particularly MD. MD, predominantly calcium carbonate, functions primarily as a micro filler and may enhance particle packing and early-age strength through densification mechanisms. As a fine powder, it fills the capillary pores and micro-voids within the hardened cement paste. This pore refinement results in a denser, less permeable microstructure, which in turn reduces water absorption and limits the ingress of aggressive agents like chlorides and sulfates. The utilization of waste MD in concrete and cement mortar has been the subject of extensive research, which has revealed its potential as an environmentally sustainable alternative [21]. Nonetheless, the variability in particle properties and mineral composition across marble sources poses a challenge to achieving consistent mechanical performance. This potential application of waste MD is consistent with the overarching objectives of sustainable development, underscoring the need for innovative solutions within the construction industry. The study demonstrates that incorporating MD into concrete not only reduces its ecological impact but also enhances its physical properties, particularly with regard to carbonation and water resistance. Additionally, it minimizes shrinkage strain and decreases the amount of cement required in the mixture. Moreover, MD functions as an effective mineral additive in self-compacting concrete, thereby enhancing its mechanical performance. These findings indicate that the utilization of waste MD in concrete production not only addresses issues of waste disposal but also yields significant benefits for the mechanical properties and toughness of high-performance concrete. However, the potential sustainability of incorporating MD should be weighed against the environmental footprint of marble quarrying itself, which has rarely been addressed in existing research. Moreover, although several studies report improvements in selected properties such as carbonation resistance or shrinkage, the reported optimum MD contents vary widely and are often derived from small experimental matrices that do not systematically explore combined effects with other by-products. This fragmented evidence makes it difficult to define practically applicable substitution ranges for MD in real structures, particularly when it is used together with another industrial residue such as BA. This, in turn, supports the advancement of sustainable building materials. The sustainable utilization of MD has emerged as a significant consideration in the

construction industry, particularly in relation to enhancing the mechanical properties of concrete. Existing research has revealed that MD can serve as a partial replacement for cement [11]. Among the ratios examined, optimal behavior was observed for a 20% MD substitution, which resulted in a denser microstructure and improved mechanical strength due to its filler and pozzolanic effects. Consequently, the same ratio was adopted in this study to evaluate its combined influence with BA on strength and durability. However, previous investigations have generally treated BA and MD in isolation or have examined them in binary blends with single performance outputs, without providing a comprehensive assessment that simultaneously addresses workability, strength, porosity, mass loss under cyclic seawater exposure and cost. There is therefore a lack of systematic experimental programs that quantify how combined BA–MD replacements at different total and relative dosages affect both engineering performance and economic feasibility within a unified mix-design framework. The present study is specifically designed to address this gap by mapping the coupled effects of BA and MD on fresh, mechanical, durability and cost indicators over a wide range of practically relevant replacement levels. In addition, previous investigations on BA and MD have generally identified technically acceptable replacement ranges in the order of 10–20%, with higher dosages frequently associated with marked reductions in CS and, in some cases, increased permeability or durability concerns [19,22]. This body of evidence further supports focusing the present work on mixtures in which the replacement level of each material does not exceed 20%. This is beneficial for two reasons. First, it reduces the environmental impact associated with cement production. Second, it contributes positively to the overall strength and durability of concrete mixes [12,23]. The incorporation of MD into concrete formulations has been demonstrated to be associated with enhanced CS and improved durability, indicating that it is a viable alternative binding material. Nevertheless, the heterogeneity of results across studies highlights a need for comparative analyses under standardized testing conditions to draw reliable conclusions. The utilization of industrial by-products like MD aligns with the growing emphasis on environmentally friendly construction practices, as it not only addresses waste management issues but also promotes sustainability. The beneficial properties of MD, including its pozzolanic activity, underscore its potential to enhance the performance of concrete. Still, the long-term chemical stability and potential durability problems associated with MD incorporation require further empirical validation. Importantly, it has been asserted that although the incorporation of granite powder enhances CS, it may concomitantly reduce flexural strength (FS), a factor that is of paramount importance for structural applications. Thus, a balanced assessment of the mechanical trade-offs between CS and FS is necessary to determine the practical feasibility of such substitutions. Recent research has shifted focus to the economic aspects of industrial waste utilization, including MD, in cementitious composites [24]. The research emphasizes the importance of reducing cement clinker content while maintaining high performance standards in construction materials. Overall, combining 20% BA and 20% MD as cement replacements is anticipated to yield synergistic improvements in strength and durability by refining the pore structure, reducing permeability, and promoting the formation of additional C–S–H phases. This approach also represents a balanced solution in which performance benefits and sustainability objectives intersect. However, despite increasing attention, cost–benefit analyses and regional availability assessments of these waste resources remain limited, which constrains their global applicability [4,10]. The investigation of MD as a supplementary cementitious material is consistent with ongoing efforts to develop environmentally friendly composites and manage waste effectively, thus addressing both resource depletion and environmental concerns. A more integrative approach comparing technical viability, life-cycle impact, and

economic performance would strengthen the current understanding and inform sustainable implementation strategies [25].

OPC, regarded as the most energy-intensive constituent of concrete, represents a significant opportunity for optimization. It is recommended to reduce the clinker content in cement to decrease both economic and energy costs, which can be achieved by incorporating active mineral additives and fine-grained fillers. In line with this recommendation, research has increasingly focused on the use of industrial by-products as partial replacements for OPC to meet both performance and sustainability targets. Overall, the existing literature demonstrates the technical potential of BA and MD but does not yet provide a consolidated basis for selecting optimized combinations that are simultaneously durable and cost-effective in marine-influenced environments. In particular, there is a shortage of studies that (i) determine practically acceptable upper replacement limits for BA and MD based on systematic strength data, (ii) couple these findings with detailed porosity, water absorption and mass loss evaluations under cyclic seawater exposure, (iii) integrate a transparent cost analysis built on realistic regional price and transportation assumptions. This study explores alternative material solutions, MD and BA, which have the potential to improve the ecological footprint of construction practices. Building on the gaps and potentials identified in previous research on BA and MD, this work was intended to experimentally verify whether these materials can be used at practical replacement levels without compromising, and potentially improving, key performance indicators. In OPC, BA contributes to a chemical process known as the pozzolanic reaction. Over time, it reacts with calcium hydroxide (CH), a soluble and less desirable by-product of cement hydration, to form additional C-S-H gel. This secondary C-S-H gel is the same compound that provides strength and cohesion in standard concrete, meaning that the pozzolanic reaction effectively increases the volume of the strength-giving binder and further densifies the concrete's microstructure. Therefore, the combination of MP's immediate physical pore-filling effect and BA's contribution to the long-term pozzolanic reaction creates a complementary system: the initial density provided by the MD creates an ideal environment for the subsequent pozzolanic reaction involving BA, resulting in a progressively stronger and more durable matrix [11,26].

Previous investigations into BA and MD generally identify technically acceptable replacement ranges on the order of 10–20%, with higher dosages frequently associated with marked reductions in CS and, in some cases, increased permeability or other durability concerns [19,22]. This body of evidence provides a literature-based motivation for focusing the present work on mixtures in which the replacement level of each individual material does not exceed 20%. In addition, a preliminary pilot study on BA–MD binary blends, conducted prior to the main experimental program, showed that mixtures with up to 20% replacement maintained at least 85–90% of the control mix's 28-day CS, whereas contents above 20%, and particularly beyond 25%, led to pronounced and unacceptable strength reductions exceeding 25–30%, which would not meet typical engineering requirements [19,22,27]. Therefore, the maximum replacement level of 20% for each material adopted in this study is supported by both existing literature and new experimental evidence. In this study, the 20% replacement levels of BA and MD are expected to have a positive effect on both strength and durability when they are used together in the binder. Although some strength loss is likely to occur at early ages due to the reduced cement content, it is anticipated that the 20% BA + 20% MP mixture will still achieve adequate CS at later ages through improved particle packing and a more uniform distribution of voids. From a durability perspective, this replacement level is expected to help reduce overall porosity and water absorption compared with mixtures containing higher waste contents, which can limit the penetration of aggressive agents. In particular, the selected BA and MP contents are assumed to improve

resistance to mass loss and surface damage under cyclic seawater exposure by producing a denser and more stable paste matrix. Thus, the 20% BA and 20% MD combination is considered a reasonable compromise that can ensure acceptable mechanical performance while also enhancing key durability-related properties. In this study, the main objective is to provide a comprehensive assessment of the technical feasibility of BA and MD as alternative binders by evaluating the effects of their combined use on the performance of cement paste. The performance and suitability of BA and MD waste were evaluated in relation to key parameters, including the physical characteristics of flow, slump, and water absorption. A highly promising solution lies in the circular economic approach of utilizing these by-products as partial replacements for binder in OPC. The aim of this approach is to establish sustainable "alternative binder" systems that reduce the carbon footprint of OPC, conserve natural resources, and provide a value-added application for industrial waste. Thus, this study was conducted to provide a more complete assessment of the technical feasibility of BA and MD as alternative binders.

2. Materials and Methods

2.1. Materials

The materials used in this study were BA, OPC, and MD. Cement with a strength class of 42.5 (Boğaz Endüstri ve Madencilik Ltd., Kalecik, İskele, Northern Cyprus) was used, according to the ASTM C150/C150M-24 standard [28]. It was a fine gray powder with a fineness and specific gravity of 3930 cm^2/g and 2.96 g/cm^3, respectively. The chemical composition is provided in Table 1. The OPC primarily consisted of CaO (53.1%), with Al_2O_3, SiO_2, and Fe_2O_3 percentages of 4.10%, 29.40%, and 3.70%, respectively. BA was obtained from a coal brick factory (Levent Plant) in Nicosia, where it is produced during the firing process (at approx. 1100 °C) in the kiln. Coal was collected from the bottom of the kiln after each burning process. It is a light material similar in color to OPC, with a specific gravity of 2.18 g/cm^3. The BA was mostly composed of CaO, SiO_2, Al_2O_3, and Fe_2O_3, which, combined, formed around 46.70% of its total mass. Its chemical composition is provided in Table 1. MD was acquired from the manufacturing unit of a marble manufacturer (Levent Plant) in Nicosia. The waste MD and BA used in this study were processed from their raw, as-received state to achieve the required fineness. The raw waste MD initially consisted of larger particles, with some pieces measuring up to 3 cm. Prior to use, both the waste MD and BA were finely ground, and the resulting powders were sieved to ensure all particles could pass through a 50 µm sieve. The raw BA was mechanically sieved, and only the fraction that passed through the 50 µm sieve was collected and used for the mixtures in this study. This procedure was adopted to remove excessively coarse particles, which can compromise strength, and to achieve a finer, more uniform gradation that enhanced particle packing within the cementitious matrix. The chemical composition of the MD used is shown in Table 1.

Table 1. Chemical compositions of the used Ordinary Portland Cement, bottom ash and marble powder dust.

Oxides	OPC	BA	MD
SiO_2 (%)	29.4	55.1	8.1
Al_2O_3 (%)	4.1	28.1	0.7
Fe_2O_3 (%)	3.7	8.2	0.7
CaO (%)	53.1	1.1	44.3
MgO (%)	1.6	0.3	5.6
SO_3 (%)	3.01	0.3	0.04

The particle size distributions of OPC, BA and MD were assessed by dry sieving on 200 µm, 90 µm, 63 µm and 45 µm sieves after all powders had been passed through a 50 µm sieve. OPC exhibited a very fine gradation, with about 97–98% retained on the 90 µm sieve and roughly 89% retained on the 45 µm sieve. The ground BA showed a coarser and broader distribution, with approximately 85% and 68% retained on the 90 µm and 45 µm sieves, respectively, reflecting its more porous and angular morphology. In contrast, MD was predominantly micro-fine, with around 92% retained on 90 µm and 78% on 45 µm, consistent with its role as a filler material improving particle packing. The corresponding particle size distribution curves for OPC, BA and MD are presented in Figure 1.

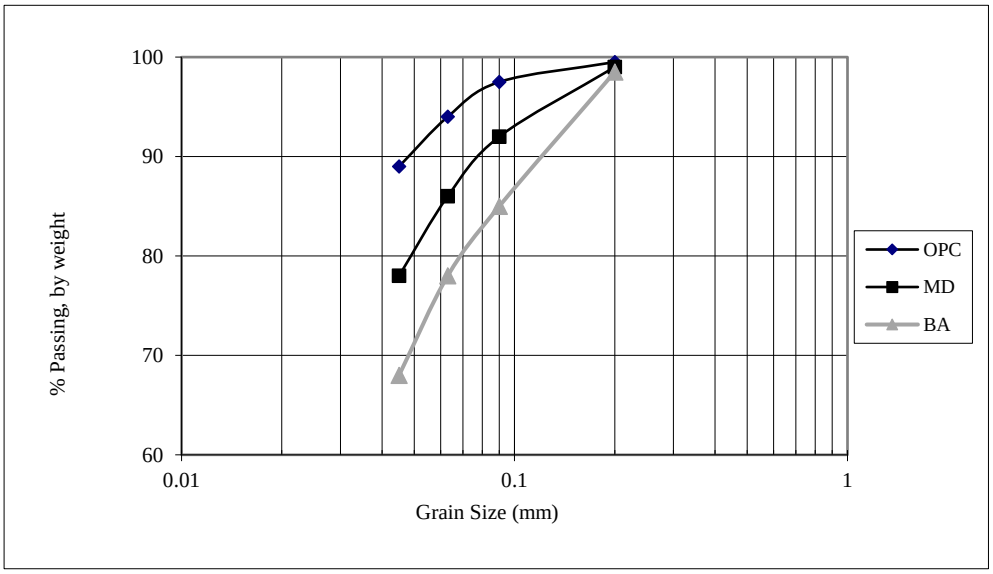

Figure 1. Particle size distribution curves for Ordinary Portland cement, bottom ash and marble powder dust.

2.2. Specimen Preparation

A mixer with a 2.5 L capacity was used to combine the mixture with Hobart cement (Turkey). After mixing the dry BA, MD, and cement for 30 s, tap water was added. After that, the mixes were cast and solidified for one minute on a vibrating table (Turkey). After demolding, the samples were kept for 1–2 days before being placed in an environment with 70% relative humidity at 20 ± 1 °C until testing (on days 7, 28, and 90).

A 50 mm^3 cubic mold and a 40 mm × 40 mm × 160 mm prismatic mold (Turkey) were used for the CS and FS tests, respectively. Strength tests were conducted in accordance with the ASTM C109/C109M-24 [29] and ASTM C348-21 [30] standards. In compliance with the ASTM C230/C230M-23 [31] and WK27311 [32] guidelines, the workability of each prepared mixture was evaluated using a flow table and mini slump cone test (Turkey). Standards ASTM C1585-20 [33] and ASTM C666/C666M-15 [34] were used for evaluating water absorption and durability. The porosity was calculated using the equations provided in the RILEM and ASTM standards [35–37].

A total of 108 cubes were cast, and tests were conducted on 36 cubes for each aging period. The mean values were calculated and are presented in this study. The experiments were carried out with cement paste to obtain suitable reference values for evaluating the durability of the composites under harsh environmental circumstances, even though this technique is usually applied for aggregates. The specimens' mass loss was determined after ten cycles of soaking in a seawater solution and oven drying at 110 ± 5 °C.

Prior to the main experiment, a comprehensive investigation was conducted to determine the technically viable upper limits for the partial replacement of cement with the

sourced BA and MD. This was followed by evaluation of the 7-, 28-, and 90-day CS of the binary blended cement pastes, as this is a primary indicator of performance. This comprehensive pilot study extends co-author's previous work [27] exploring binary blends with high replacement levels of both BA and MD.

Prior to the main experiment, a comprehensive pilot investigation was carried out on BA–MD binary blends to determine technically viable upper limits for partial cement replacement. In this preliminary phase, mixtures incorporating up to 20% BA or 20% MD consistently maintained at least 85–90% of the control mix's 28-day CS whereas contents above 20%, and particularly beyond 25%, resulted in substantial and unacceptable strength reductions exceeding 25–30%. The pilot data thus provide clear quantitative support for capping the replacement level of each individual material at 20% in the main experimental program, in line with previous findings that also report performance losses at higher dosages [19,22]. The mixture proportions of BA, MD, and cement and the control sample are given Table 2. The paste samples are represented by notations of the form BxMyCz, where x, y, and z stand for the relative weight percentages of BA, MD, and cement, respectively. BA and MD volumes of 5%, 10%, 15%, and 20% each and cement volumes of 65%, 70%, 75%, and 80% were used. A critical parameter of the experimental design was that the water-to-binder (w/b) ratio was held constant at 0.37 across all mixtures.

Table 2. Mix proportions of mixtures.

Samples Name	OPC	BA	MD	W/B Ratio
B0M0C100	100	0	0	0.37
B5M15C80	80	5	15	0.37
B15M5C80	80	15	5	0.37
B10M10C80	80	10	10	0.37
B15M10C75	75	15	10	0.37
B10M15C75	75	10	15	0.37
B12.5M12.5C75	75	12.5	12.5	0.37
B15M15C70	70	15	15	0.37
B20M10C70	70	20	10	0.37
B15M20C65	65	15	20	0.37
B20M15C65	65	20	15	0.37
B17.5M17.5C65	65	17.5	17.5	0.37

In order to quantify the individual roles of BA and MD, the mix design included BA-rich compositions (B15M5C80 and B20M10C70), MD-rich compositions (B5M15C80 and B10M15C75), and balanced compositions (B10M10C80 and B15M10C75) at comparable total replacement levels. This arrangement enables a direct numerical comparison of how BA and MD individually affect workability, strength, porosity, water absorption, and durability. Therefore, even though BA and MD are not tested in completely isolated single-variable series, the systematic variation in their relative ratios across the matrix provides sufficient contrast to disentangle and interpret their individual effects within the same experimental framework.

3. Results and Discussion

3.1. Workability

The workability of the cement paste was determined using a flow table test and a slump test for freshly mixed cement paste containing 0–20% MA and 0–20% BA. The flow of B0M0C100 was 235 mm at 100% OPC, and the flow of cement paste was 290 mm per 5 min. This flow can be categorized as fair because of the lower limit of the 30–40% class [38]. The flow table test results ranged from 170 mm to 240 mm, and a clear decrease in

fluidity was observed at higher total replacement levels. Mixes rich in MD (e.g., B5M15C80) showed slightly enhanced fluidity, with flow table values increased by approximately 2% compared to the control. This difference is attributed to the fine, smooth nature of the MD particles, which impart a ball-bearing effect, as mentioned in previous studies. Conversely, mixes dominated by BA (e.g., those with 20% BA) demonstrated significant reductions in flowability of 23–28% as a direct result of the porous and irregular morphology of BA particles, which increases inter-particle friction and water demand. The mixture B5M15C80 attained the highest flow table value, which was 2.12% higher than the control sample. The increase in MD content systematically improved flow, confirming that MD imparts additional plasticity and enhances fluidity. These findings confirm the improved fluidity achieved with MD, demonstrating the effectiveness of its inclusion in the mixtures as a partial replacement for OPC [39]. Initially, mixtures containing a small percentage of BA showed a good flow table value. However, an increase in this percentage resulted in a decrease in the flow table value, indicating insufficient flowability in the mixture. Figure 2 presents the flow table test results of cement pastes containing BA and MD as partial replacements for cement, and Figure 3 shows the flow table results.



Figure 2. Flow table test application of marble–bottom ash cement paste composites.

Research on the workability of cement paste, initially conducted without retarders and using a fixed water–cement ratio of 0.5, demonstrated that the use of 10% to 20% BA reduced the flowability of the cement paste, with a more pronounced decrease observed at the 20% usage rate [9]. The flow table test results for B20M10C70 and B20M15C65 indicated reductions in flowability of 27.66% and 23.40%, respectively, compared to the control sample. This decrease in flowability can be attributed to the fineness of BA. BA can replace some of the cement particles and thus increase the flowability of the cement paste [40]; however, including a greater amount of BA reduces the flowability of the paste, which is largely consistent with the findings of this study. In contrast to BA, the partial replacement of cement with MP generally improves workability, particularly at lower replacement levels (e.g., up to 10–15%). This is due to the filler effect. The fine particles of MP fill the voids between cement grains, increasing the paste volume and creating a denser suspension [10,41]. Additionally, the relatively smooth and fine nature of MP particles [42,43] enable them to act as a lubricant, reducing inter-particle friction and enhancing the flowability of the concrete mixture.

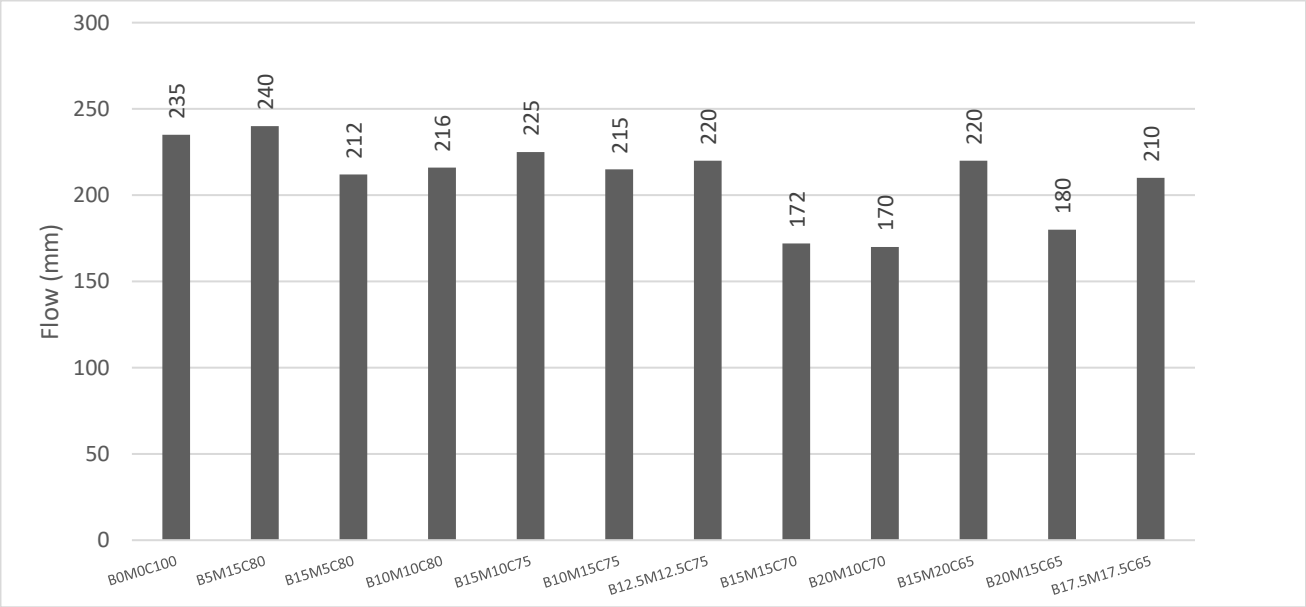

Figure 3. Flow table results of cement pastes containing bottom ash and marble powder dust.

3.2. Water Absorption

Figure 4 illustrates water absorption at 7, 28 and 90 days of hardening. The addition of waste materials at high proportions increased the water content and facilitated greater water absorption compared to the reference mix, causing an increase in the overall absorption rate [44].

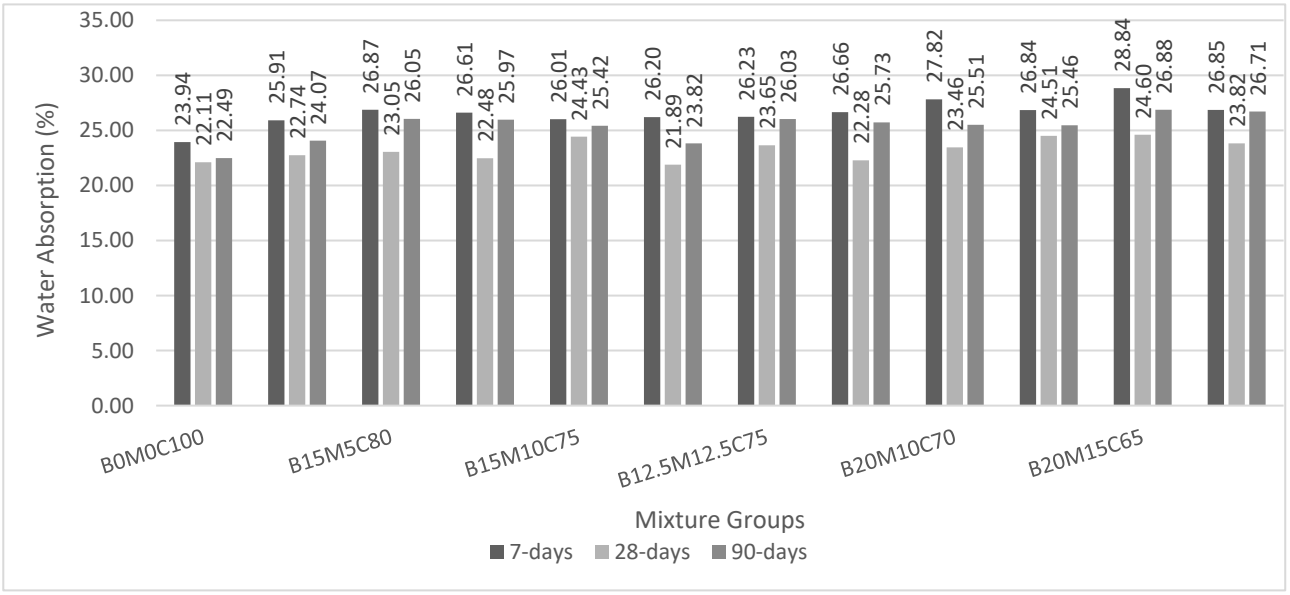

Figure 4. Water absorption result of cement pastes containing bottom ash and marble powder dust.

For total replacement levels of 20%, 25%, 30%, and 35% BA + MD, the 7-day water absorption of the cement pastes increased by approximately 8–12%, 9–10%, 11–16%, and 12–20%, respectively, compared to the control mix. At 28 days, the maximum increase in water absorption for all mixes remained around 11%, indicating that the relative difference between the modified pastes and the control decreases with time. Comparing the 7- and 90-day results, the control mixture B0M0C100 showed a reduction of about 6.1% in water absorption, while the mixture with the minimum BA content (5%) showed a reduction of about 7.1%, confirming that BA contributes to long-term internal curing and a gradual

decrease in absorption, whereas higher MD contents mainly increase early-age absorption through additional pore channels.

The inclusion of BA as a partial cement replacement typically leads to a reduction in workability, which is attributed to BA's high capacity for water absorption. BA particles are generally porous and have a large internal surface area [3,4]. They absorb a portion of the mixing water, reducing the amount available to lubricate the mixture, thereby increasing its viscosity and decreasing flow. Additionally, particle angularity, i.e., the irregular and angular shape of BA particles, increases inter-particle friction within the paste [11,39], further hindering flowability compared to the relatively spherical particles of cement. Consequently, mixtures rich in BA required a higher superplasticizer dosage or exhibited lower slump/flow values when the water-to-binder ratio was held constant. The negative impact of BA's high-water absorption capacity on workability can be effectively compensated by the lubricating and filler effects of MP. This allows for the formulation of ternary blends with acceptable workability, even at higher total replacement levels, without requiring a superplasticizer.

The addition of BA and MD causes the hardened cement paste to absorb more water than the original base because the waste materials have higher water absorbency than cement. Cement pastes with a total replacement rate of 20% demonstrated increases in water absorption of 8.25%, 12.25%, and 11.19% in 7 days compared to a control cement paste; cement pastes with a total replacement rate of 25% demonstrated increases in water absorption of 8.68%, 9.46%, and 9.58% in 7 days; cement pastes with a total replacement rate of 30% demonstrated increases in water absorption of 11.38%, 16.23%, and 16.23% in 7 days; and cement pastes with a total replacement rate of 35% demonstrated increases in water absorption of 12.14%, 20.48% and 12.19% in 7 days. In particular, the highest proportion of BA included, 20%, increased the water absorption at 7 days by 16.23% and 20.48%. This is reasonable since the porosity of the paste samples containing BA is greater than that of the control paste samples, resulting in a higher water absorption value.

As MD acts mainly as a fine filler, higher MD contents reduce the cement binder fraction and can create additional capillary pores, with sizes above about 250 nm, which increases water absorption in the hardened paste [10,21]. At 28 days, in the test results, water absorption increased by a maximum of 11.26%. BA has the ability to retain water due to its high porosity. Comparing the 7- and 90-day test results, the control mixture, B0M0C100, has 6.05% less water absorption at 90 days. The mixture with the minimum proportion of BA, 5%, has 7.11% less water absorption. This trend, together with the known high water-retention capacity of BA, suggests that BA may provide an internal curing effect, although in this study this role is inferred only from macroscopic indicators such as water absorption and porosity, without direct pore size distribution or microstructural measurements. It has been reported that the integration of waste materials into mixtures positively affected the decrease in water absorption without needing an additional water reducing agent [45].

3.3. Compressive Strength

The results of the CS test of various mixtures after 7, 28 and 90 days of curing are illustrated in Figure 5. The MD-rich mixture B5M15C80 demonstrated a decline in CS at all ages, with reductions of 12.78% at 7 days, 19.98% at 28 days, and 17.21% at 90 days. This decline is consistent with the dilution of the cement content at high MD dosages, where the largely inert MD particles replace reactive clinker and reduce the amount of hydration products available to carry load. The reduction in cement content in mixtures with high replacement levels (e.g., B15M15C70, B20M15C65) led to pronounced 28-day CS losses to the order of 30–35%. In contrast, the mixture B15M10C75 showed markedly improved

performance, attaining a roughly 15% higher 28-day CS and about 40% higher FS than the control. These findings indicate an optimal replacement range in which the fine MD fraction improves particle packing and reduces defects in the hardened paste, while a moderate BA content still contributes beneficially to strength development. The optimum mixture B15M10C75 exhibited a slight increase in CS of about 2.2% in 7 days. Compared with B0M0C100, this blend achieved an increase of about 15.5% in 28 days while maintaining an almost similar value after 90 days: the 90-day CS was only about 0.3% lower than the 28-day strength. BA-rich mixtures such as B15M15C70 and B20M15C65 showed significant CS decreases of 9.4% and 29.4% at 7 days and 16.1% and 34.5% at 28 days, respectively, demonstrating the negative effect of a high BA content. These results indicate that BA alone tends to reduce CS at higher doses, while MD can significantly increase CS when combined with moderate levels of BA. This behavior is attributed to the dilution of the reactive cement fraction and the relatively slow pozzolanic reaction of BA at early ages [39,46]. At later ages (28 days and beyond), the pozzolanic activity of BA becomes significant. It reacts with CH, a by-product of cement hydration, to form additional C-S-H, which is the primary strengthening compound in concrete. This process leads to strength recovery and often results in long-term strengths comparable to or even exceeding that of the control mixture, as pore structure becomes more refined. The sample B15M10C75 demonstrated an increase to 18.71 MPa, indicating a 2.24% improvement over the control, likely because the optimal balance of materials promoted better early strength development.

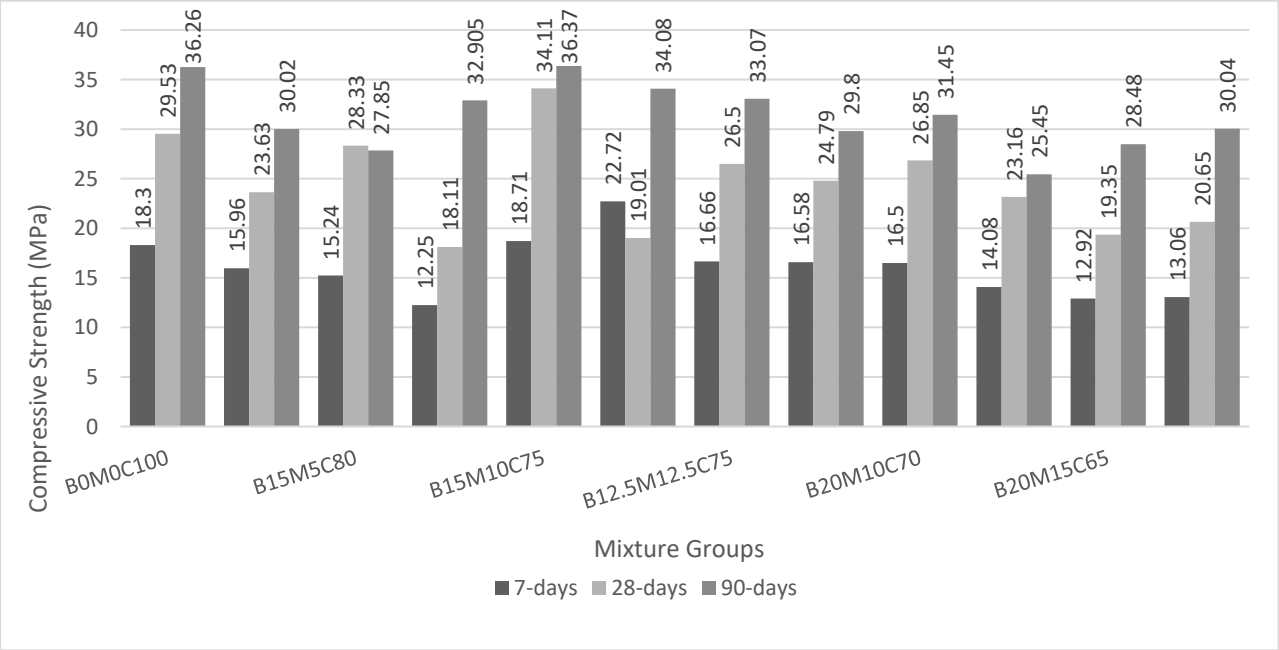

Figure 5. Compressive strengths of cement pastes containing bottom ash and marble powder dust.

BA was characterized as coarser and porous in nature, primarily comprising silica, alumina, and iron oxides, with findings indicating that higher BA replacement rates could lead to reduced CS [46]. Blends comprising BA, such as B15M15C70 and B20M15C65, exhibited substantial reductions in strength, with reduction percentages of 9.40% and 29.40% at 7 days and 16.05% and 34.47% at 28 days, respectively. It is hypothesized that the early hydration process may be adversely affected by the incorporation of BA. In the case of B15M5C80, the CS was determined to be 15.24 MPa, 28.33 MPa, and 27.85 MPa at 7, 28, and 90 days, respectively. The results of this study indicate approximate reductions of 16.7%, 22.0%, and 23.2% in comparison to the control mix. The high BA content at this

substitution level likely reduces particle packing density and interfacial adhesion, resulting in lower strength [47].

MP mainly exerts a physical influence that is most pronounced at early ages. MP accelerates cement hydration by providing additional nucleation sites for C–S–H, which increases early-age strength and, together with the filler effect, creates a denser microstructure [14,21]. Since MP is largely inert and does not possess pozzolanic properties, its contribution to long-term strength is limited, and at higher replacement percentages the dilution of cement dominates, leading to reduced long-term strength compared to the control [41]. At higher replacement percentages, the diluting effect predominates, leading to a reduction in long-term strength compared to the control mix, as there is simply less cement to hydrate.

The mix B15M10C75 achieved a CS of 18.71 MPa, representing a 2.2% increase compared to B0M0C100 and a 15.51% increase at 28 days. This enhancement suggests that the inclusion of 15% BA and 10% MD creates a more favorable microstructure that enhances the binding properties and overall strength of the composite at an early age. However, B10M10C80 demonstrated a significant decline to 12.25 MPa and 18.11 MPa, indicating 33.06% and 38.69% reductions at 7 and 28 days, respectively, compared to the control. This behavior is consistent with an unfavorable balance between BA and MD, where the combined dilution of cement by two largely non-cementitious constituents' limits hydration product formation. However, a decline of approximately 0.3% was observed in B15M10C75 at the 90-day mark, which indicates that the ratio between BA and MD may enhance early hydration reactions, in line with the previously reported pozzolanic behavior of such blends [48]. However, in this study, no direct reactivity measurements were performed; this effect was inferred indirectly from the observed strength retention and porosity trends rather than demonstrated by microscopic or chemical evidence.

The mix B10M15C75 demonstrated a substantial increase in strength of 24.1% at 7 days, followed by a decline of 47.7% at 28 days. Thereafter, a 0.5% increase was observed on the 90th day. This fluctuation indicates that while the mix offers initial hydration benefits, the concrete's long-term performance suffers due to inadequate cementitious material content [45]. The 24.1% strength increase at 7 days can be attributed to a temporary favorable balance between BA and MD that improves packing and early bonding, but this effect is not sustained at later ages. However, the decline observed on the 28th day highlights potential concerns regarding long-term strength development, likely due to insufficient cementitious materials.

Other mixes, such as B20M10C70 and B15M20C65, consistently yielded lower CSs than the control, with strengths of 16.50 MPa, 26.85 MPa, and 31.45 MPa, reflecting reductions of 9.8%, 26.1%, and 13.1% at each interval, respectively, recorded for B20M10C70. These outcomes further emphasize the challenges posed by higher proportions of MD and BA.

3.4. Flexural Strength

The FS test results for the pastes are presented in Figure 6. Comparing all mixes to the control, B0M0C100 and B15M10C75, with moderate substitutions of both materials, yielded the highest increases in FS, with approximately 9.6% at 7 days, 38.7% at 28 days, and 19.4% at 90 days. This trend indicates enhanced microstructural development, consistent with the micro-filling effect of MD and the contribution of a moderate BA content to overall matrix densification at these usage rates [45]. Given that no direct reactivity tests were conducted, any potential pozzolanic contributions of BA and MD are only inferred and were not quantified in this work; thus, the discussion mainly relies on the experimentally observed relationships between FS, porosity, and water absorption.

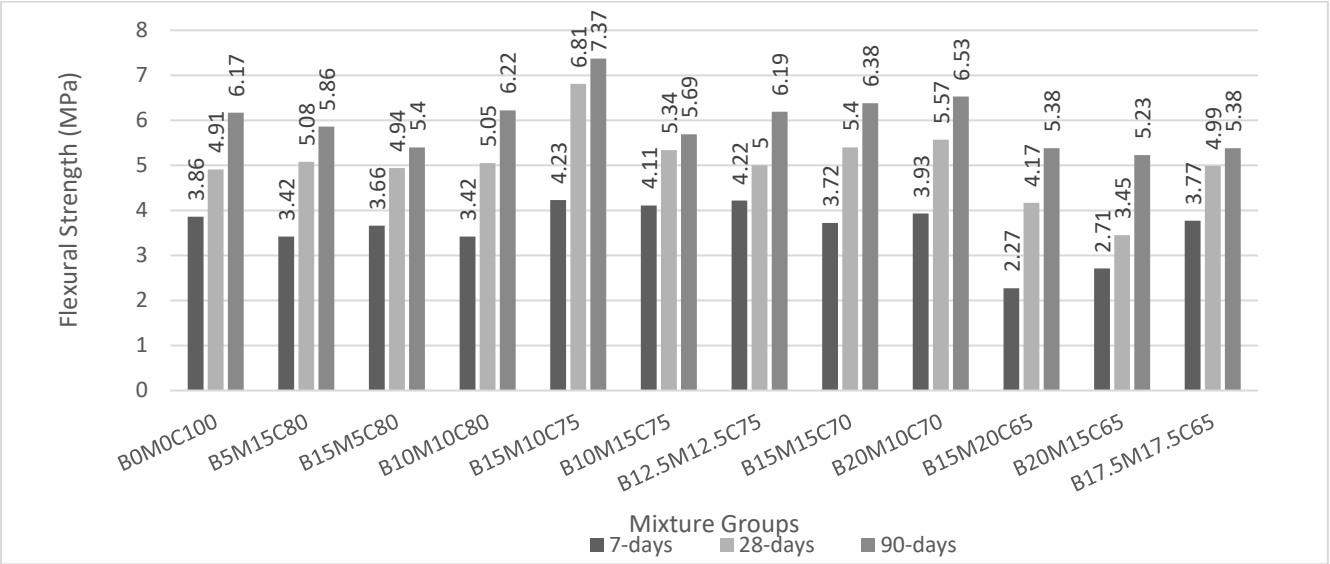

Figure 6. Flexural strengths of cement pastes containing bottom ash and marble powder dust.

In contrast, BA-dominant mixes with high total replacement proportions, such as B15M20C65 and B20M15C65, exhibited FS decreases of up to about 41.2% at 7 days and 29.7% at 28 days. A more moderate MD-rich mix, B5M15C80, showed a decrease in FS of about 11.4% at 7 days but a slight increase of about 3.5% at 28 days relative to BA0MD0C100. Taken together, these results indicate that MD is mainly beneficial for FS when used with limited BA content, whereas BA-rich systems suffer significant reductions in FS. Figure 7 shows the test specimen during loading and after cracking.

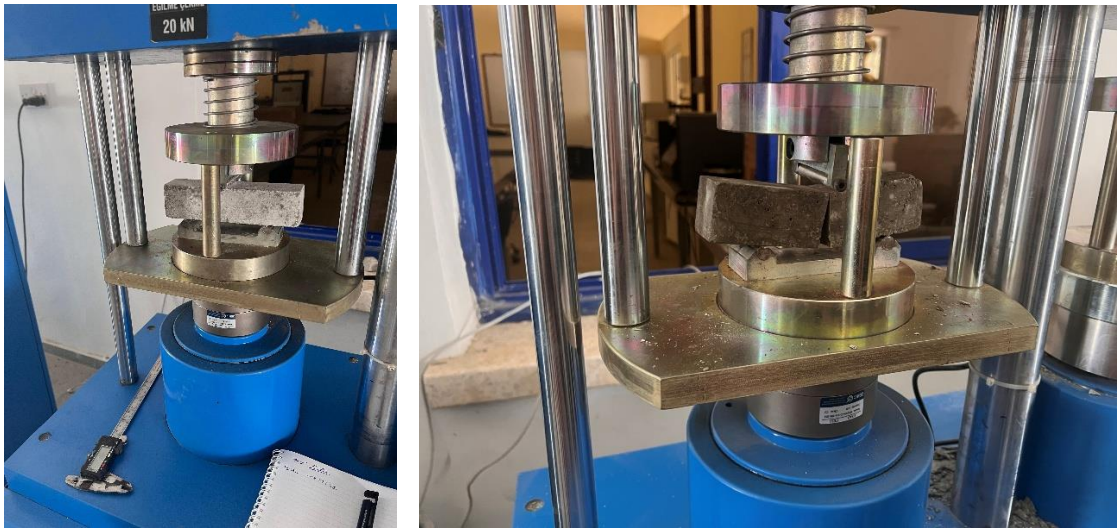

Figure 7. Flexural strength test machine with cement pastes containing bottom ash and marble powder dust before and after the test.

Higher replacement levels of BA combined with MD (above about 15–20%) correspond to marked reductions in FS at all curing ages; for example, B15M20C65 and B20M15C65 show FS decreases of up to 41.2% at 7 days and 29.7% at 28 days compared to the control. This decline is attributed to increased porosity and weaker cementitious bonding caused by excess BA, which reduces matrix integrity and load-transfer capacity under flexural stress.

The FS development over curing time shows that the gains at 28 and 90 days are generally greater than those at 7 days, which is consistent with progressive matrix densification

and the time-dependent contribution of Supplementary Materials to the microstructure. Intermediate mixes with balanced proportions benefit from the synergistic role of MD in microstructure refinement and improved packing, which supports higher FS. In contrast, excessive BA proportions diminish these benefits through increased voids and less effective bonding [42,43].

Higher utilization rates of BA combined with MD of more than about 15–20% tend to reduce FS, especially at early and later ages. The FS of B15M20C65 decreased by 41.2%, 15%, and 12.8% at 7, 28, and 90 days, respectively. This can be explained by the increased porosity and weaker bond formation resulting from the rough texture and inert nature of BA [49]. Conversely, the combination of a lower BA and higher MD proportion showed minor improvements or slight reductions at 7 days but improvement at 28 days. One such example is B5M15C80, for which FS decreased by 11.4% at 7 days and increased by 3.5% at 28 days, reflecting the stabilization of the micro-filling effect and the gradual densification of the matrix.

In summary, the BA and MD usage ratios demonstrate that improved flexural performance can be achieved when their proportions are carefully controlled. The good performance of mixtures such as B15M10C75 highlights that an optimum BA–MD ratio is critical for maximizing FS, whereas high replacement levels reduce the cementitious matrix and increase porosity, resulting in lower FS.

3.5. Porosity

The porosity development of different mixtures containing BA and MD was evaluated by comparing them with a control mixture (B0M0C100) over periods of 7, 28, and 90 days. At 7 days, the control mixture showed an initial porosity of 45.20, which decreased to 37.13 at 28 days and remained relatively stable at 37.60 by 90 days, setting a standard for comparison. At early ages (7 days), various mixtures exhibited greater porosity than the control. In the porosity results presented in Figure 8, B17.5M17.5C65, B15M20C65, B5M15C80, and B10M15C75 showed 29.77%, 19.26%, 17.39%, and 11.18% higher porosity, respectively. This suggests that replacing cement with BA and MD at high proportions may initially degrade the matrix and result in a more open pore structure before contributing to densification during the hydration process. Porosity measurements showed a direct correlation with the efficiency of the binder system. The high-volume replacement mixes (B15M20C65 and B17.5M17.5C65), which had the lowest reactive binder content, displayed porous matrices, with a 30–50% increase in porosity. In contrast, the more optimized compositions (such as B20M10C70 and B15M10C75) achieved tangible densification, reducing porosity by 5–7% below the control level. This points to a successful combination of the particle packing effect provided by MD and the pozzolanic contribution of BA.

Between 7 and 28 days, the control mixture's porosity decreased by about 17.9%, whereas B20M10C70 and B15M15C70 reached 28-day porosity values that were approximately 7.2% and 5.4% lower than the control, indicating stronger densification in these more balanced mixes. At 90 days, the porosity of B15M10C75 and B20M10C70 remained similar to or slightly below the control, while B10M15C75 and B15M20C65 exhibited porosity increases of 26.7% and 47.7%, respectively. Taken together, these comparisons help to distinguish the separate roles of BA and MD: BA tends to increase porosity at high replacement levels, whereas at moderate doses, MD promotes densification, as stated in other studies [4,10], but can destabilize the matrix when used in very high amounts. Additionally, increasing the BA ratio tends to increase porosity, which is consistent with the inherently porous nature of BA and its tendency to create a more open pore structure. The internal curing effect provided by BA can be beneficial, but in mixes with higher ash contents it is accompanied by an overall increase in porosity. In this study, the possible

internal curing effect is inferred from the evolution of bulk properties, particularly the slower decrease in water absorption and long-term trends in strength and mass loss. These combined observations are understood to reflect changes in the pore system over time rather than interpreted solely from early-age measurements.

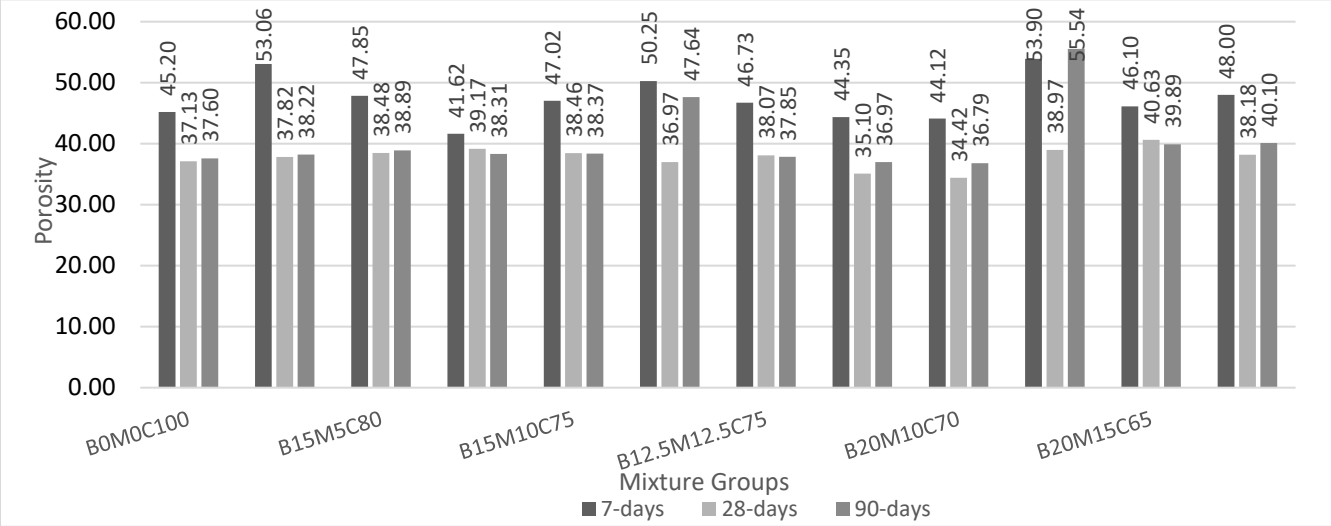

Figure 8. Porosity of cement pastes containing bottom ash and marble powder dust.

In most mixtures, a significant decrease in porosity was observed at 28 days, indicating a gradual improvement in microstructure during curing. Specifically, the B20M10C70 and B15M15C70 mixtures achieved the lowest 28-day porosity, which was significantly lower than that of the control mixture by 7.19% and 5.40%, respectively. This significant decrease can be attributed to the combined action of BA and MD, whereby MD provides a clear physical filler effect and BA contributes to a modified pore structure [25]. Since no microstructural or chemical characterization was performed, the mechanistic explanation is limited to these physical observations based on the measured porosity and strength, and any potential pozzolanic reaction is treated only as a possible, but not experimentally confirmed, contribution [5,15,46].

The results of the 90-day long-term porosity test showed that the porosity of B15M10C75 and B20M10C70 increased by 0.65% and decreased by 1.66%, respectively, exhibiting stabilized porosity levels similar to or slightly below the control mixture's porosity. However, two specific mixtures, B10M15C75 and B15M20C65, showed a significant increase in porosity to 26.69% and 47.72%, respectively. This increase indicates that achieving an optimal balance between the percentages of BA and MD incorporated is crucial. At high MD contents, long-term stability can be adversely affected, which is most likely related to an insufficient supply of binding material to form a compact and dense matrix rather than to any confirmed expansive reaction.

In summary, the strategic combination of BA and MD can effectively reduce porosity, with the most successful mixtures performing better than the control after 28 days. However, the effectiveness of these mixtures largely depends on achieving optimum binder substitute proportions. This study establishes a relationship between binder composition and key engineering properties. Consequently, the conclusions are drawn from macroscopic data for strength, porosity, and durability. The exploration of specific chemical mechanisms through direct microstructural analysis is the logical next step to build upon the performance benchmarks established herein.

3.6. Preliminary Mass Loss Assessment Under Cyclic Seawater Exposure

The weight loss results for the pastes are presented in Figure 9. It is evident that the control sample, B0M0C100, exhibited a weight loss of 5.98% at 28 days and 8.37% at 90 days. This serves as a baseline for assessing the durability of the various mixtures. The other formulations showed varying degrees of weight loss, indicating their respective durability. The mixture B5M15C80 resulted in a significant reduction in weight at 28 days (4.02%) compared to the control sample, suggesting an improvement in durability. However, at 90 days, this mixture experienced a weight loss of 7.04%, which is still lower than the control but indicates a decrease in performance over time. This trend indicates that the initial incorporation of MD can improve short-term durability, whereas its benefits at later ages are more limited. This trend aligns with findings from [40], which highlight the importance of monitoring durability over extended periods. It should be noted that this mass loss test, which was based on repeated cycles of immersion in a seawater solution followed by oven-drying of the paste specimens, provides only a preliminary indication of resistance to combined chemical and thermal stress; it is not equivalent to standardized durability indicators such as ion penetration, diffusion coefficients, or long-term chemical stability tests. Pastes containing BA exhibited less mass loss after 30 immersion–drying cycles, indicating superior physical integrity and resistance to surface degradation under these specific environmental conditions.

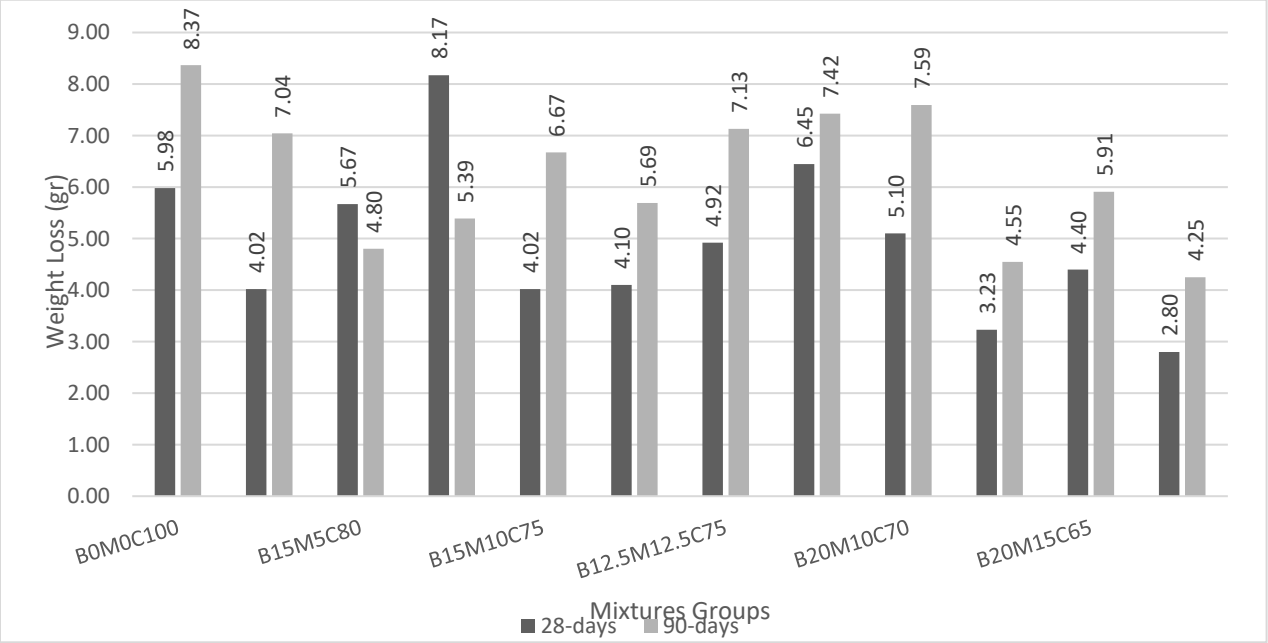

Figure 9. Weight loss of cement pastes containing bottom ash and marble powder dust.

In contrast, the formulation B15M5C80 showed a weight loss of 5.67% at 28 days, which is higher than B5M15C80, but improved to 4.80% at 90 days, indicating a complex interaction between the materials that may initially lead to higher porosity but subsequently allows for better water retention and reduced weight loss over time This suggests that the mixture's durability improved over time, potentially due to MD's micro-filling effect and the gradual densification of the matrix as hydration progressed [41]. Importantly, this effect is inferred from the coupled changes in weight loss and porosity rather than from direct microstructural or chemical evidence. The decrease in weight loss at later ages aligns with the observed porosity reduction and the lower long-term water absorption of mixes in which BA and MD promote microstructural refinement.

The mixture B10M10C80 showed an initial weight loss of 8.17% at 28 days, which is higher than the control sample, but it improved to 5.39% at 90 days. This initial deterioration could be due to the interaction between BA and MD, where the early hydration products may not be sufficient to counteract the negative effects of the BA. However, the later reduction in weight loss suggests that continued hydration and matrix densification can compensate for the initial drawbacks and contribute to improved long-term durability. This indicates that while the initial performance may be compromised, the mixture has potential for enhanced durability as the curing period extends. The mixture B15M15C70, with weight losses of 6.45% at 28 days and 7.42% at 90 days, also shows a concerning trend as it surpassed the control mixture's weight loss at 28 days. This suggests that while BA can enhance certain properties, an optimal balance is required to avoid detrimental effects on durability. In particular, the durability of these mixtures under the applied cyclic seawater exposure correlates with the porosity data, where higher replacement levels are associated with increased pore volume and, consequently, higher water absorption capacity. Therefore, the observed durability trends are interpreted mainly through these physical indices rather than through detailed chemical mechanisms, which were beyond the scope of this experimental program.

Notably, the mixtures B15M20C65 and B20M15C65 had weight losses of 3.23% and 4.40% at 28 days, respectively, with slight increases at 90 days, indicating a trend toward reduced durability, highlighting that excessive incorporation of BA and MD can lead to a significant degradation in durability in the long term. The mixture B17.5M17.5C65 also showed concerning results, with the lowest weight loss of 2.80% at 28 days and 4.25% at 90 days, suggesting that while initial durability may appear favorable, the long-term effects are detrimental. The excessive inclusion of both BA and MD appears to compromise the structural integrity of the cement paste, which is consistent with the higher porosity and water absorption measured for these mixtures. This is supported by the porosity and water absorption results, which demonstrate that mixtures with higher total replacement rates exhibit increased porosity and higher absorption, both of which are detrimental to long-term durability despite seemingly low short-term weight loss values.

For example, mixes with moderate replacement rates (20% BA + MD) showed favorable weight loss results, which is consistent with their low porosity and water absorption. Conversely, the higher weight loss observed in mixes with 30–35% replacement corresponds directly to their increased porosity and water uptake. A clear trend emerged in which moderate-replacement mixes (20% BA + MD, such as B15M5C80 and B10M10C80) paired low 90-day weight loss with low porosity and water absorption, reflecting a dense and durable matrix comparable to the control. By contrast, mixtures with higher total replacement levels (30–35% BA + MD, such as B15M20C65, B20M15C65 and B17.5M17.5C65) combined higher porosity and markedly increased water absorption with less favorable long-term weight loss behavior, indicating reduced durability. Overall, these results suggest that the most durable compositions are achieved at moderate replacement levels of around 20% BA + MD, where the simultaneous control of weight loss, porosity, and water absorption results in a more compact and durable microstructure. Nevertheless, it should be emphasized that these durability assessments are based on global indicators (mass loss, total porosity, and water absorption) rather than on detailed pore size distribution or microstructural observations; therefore, the proposed explanation of the durability behavior should be regarded as indicative rather than fully mechanistically resolved.

3.7. Cost Analysis

The primary benefit of utilizing BA and MD in cement production is the reduction in cost, as the materials are by-products, and only transportation expenses are relevant. This

analysis considers the costs of all constituent materials, including cement, water, and the industrial by-products. In this cost analysis, only the direct material costs of cement, water, BA and MD were considered on a per-cubic-meter basis; labor, equipment, and overhead costs were assumed to be similar for all mixes and were therefore excluded from the comparison. The primary cost of the BA and MD waste materials was transportation from the source to the laboratory, as they were supplied at zero material cost. The transportation cost per ton was calculated based on the following realistic parameters: round-trip distance to the material source, vehicle capacity (light truck), and average fuel consumption of the vehicle. Fuel prices in Turkey reported at the time of the study were used [50,51]. No additional processing or grinding treatment was applied to the BA or MD; they were only sieved and used in this condition. Therefore, no extra processing cost was considered in the analysis. The prevailing cement price in Turkey is 0.118 USD/kg, while the cost of water is 0.006 USD/kg. The manufacturing cost of 1 m^3 of cement paste mixtures utilized in this study is outlined in Table 3, including the following: B + M0C100, B + M20C80, B + M25C75, B + M30C70, and B + M35C65. The general approach adopted for the mixture design and cost evaluation is consistent with methodologies previously applied in the literature for sustainable cement pastes containing industrial by-product [50,51].

Table 3. Costs for bottom ash and marble powder dust cement pastes.

Material		Mass Required (kg/m^3)					Unit Cost (USD/kg)
		B + M0C100	**B + M20C80**	**B + M25C75**	**B + M30C70**	**B + M35C65**	
Cement		1506	1205	1130	1054	989	0.118
Bottom Ash + Marble Powder Dust (A: Up to 20 km)		0	340	425	510	595	0.00083
Bottom Ash + Marble Powder Dust (B: 20–100 km)		0	340	363.75	436.5	509.25	0.0015
Bottom Ash (C: 100+ km)		0	340	363.75	436.5	509.25	0.0026
Water		557	446	418	390	366	0.0006
Total Cost (USD/m^3)	Category A	178.04	143.31	134.55	125.75	118.26	
	Category B	178.04	144.00	135.32	126.67	139.34	
	Category C	178.04	145.11	136.56	128.20	121.11	

Considering contemporary prices in Turkey, the cost of the BA and MD was calculated for each of the designated cement paste combination groups, which were divided into three different distance-based categories. The distance was categorized as follows: 'Category A' is defined as a distance of up to 20 km, 'Category B' is defined as a distance between 20 km and 100 km, and 'Category C' is defined as a distance of more than 100 km.

Table 3 shows that there is a clear and practically relevant difference in the cost of cement paste combinations with different amounts of MD and BA. The cost difference between mixes was therefore evaluated by comparing the total material cost per cubic meter of paste for each replacement level, using the same unit prices and transport assumptions across all groups. The calculations were based on the total quantity of waste materials. Price comparisons were conducted, with reductions in cement of 20%, 25%, 30%, and 35% used as the basis of the analysis. In the specific case of BA and MD, it should also be noted that these materials are industrial wastes and were supplied to the research team free of charge; therefore, the only cost component associated with their use was transportation. The materials were collected using a university-owned light truck from a source located approximately 59 km from the production site, resulting in a round-trip distance of 118 km.

Considering an average fuel consumption of 10 L/100 km for this vehicle, the total fuel usage for the trip was about 11.8 L. Using the current gasoline price in Turkey of 1.27 USD/L, the additional transportation cost associated with obtaining the BA and MD amounted to approximately 15.0 USD in total. In light of the superior engineering properties exhibited by the B + M25C75 mix, a cost and economic gain comparison was conducted. The results indicate that the B + M25C75 mix is about 25% more cost-effective than the B + M0C100 control sample, even within category A, with a cost difference of more than 44 USD per cubic meter. This means that the technically optimal mixture identified in this study also provides a substantial reduction in material cost on a per-volume basis. The utilization of B + M20C80, B + M25C75, B + M30C70 and B + M35C65 in lieu of B + M0C100 results in economic gain percentages of 19.5%, 24.4%, 29.4%, and 33.6%, respectively (calculated for Category A transportation conditions). This observation underscores the substantial economic benefit derived from the incorporation of BA and MD. In light of the substantial increase in cement and concrete prices on a global scale in recent years, the utilization of waste materials such as BA assumes even greater significance. The cost analysis presented in this study is grounded in an established methodology reported in the literature and is supported by realistic transportation and material pricing assumptions, ensuring that the reported economic gains are robust and comparable to those reported in previous sustainability-oriented cost studies. It should be emphasized that this cost analysis is based on regional price conditions, specific transportation distances, and the assumption of free BA and MD supply in this project. As such, the analysis is intended to illustrate the order of magnitude of potential savings for similar regional contexts, rather than to prescribe a fixed unit cost for BA–MD pastes. Therefore, it should be regarded as a case-specific economic assessment rather than a universally applicable cost model.

4. Conclusions and Recommendations

Based on the experimental results, the main conclusions of this study can be summarized as follows:

- At a constant water-to-binder ratio, MD increased flowability (B5M15C80 showed a flow table value about 2% higher than B0M0C100), whereas mixtures with 20% BA (B20M10C70, B20M15C65) exhibited flow reductions of approximately 24–28% compared with the control.
- The optimum binder composition was 15% BA + 10% MD (B15M10C75), which achieved CS values slightly higher than the control at 7 days and more than 15% higher at 28 days, together with FS gains of about 9–10% at 7 days, nearly 40% at 28 days, and around 20% at 90 days relative to B0M0C100.
- Mixtures with balanced BA–MD ratios, such as B20M10C70 and B15M15C70, reached 28-day porosity values 5–7% lower than the control, while moderate-replacement mixes around 20% BA + MD (e.g., B15M5C80, B10M10C80) combined 90-day mass losses comparable to or lower than B0M0C100 with controlled water absorption, indicating a denser and more durable microstructure.
- In contrast, higher total replacement levels (30–35% BA + MD) led to increased porosity, higher water absorption and reduced strength, whereas total replacement levels of up to about 25% maintained an acceptable mechanical and durability performance.

The experimental findings confirm that the combined use of BA and MD can effectively improve the sustainability and economic viability of cement paste production without significantly compromising performance when used at optimal levels. Workability tests showed that MD increased the fluidity of the mixtures, with B5M15C80 exhibiting a flow table value that is about 2% higher than the control mix B0M0C100, whereas higher BA contents (e.g., 20% BA in B20M10C70 and B20M15C65) reduced flowability by approximately

24–28% compared to the control, indicating that high BA dosages adversely affect fresh behavior. While higher proportions of BA and MD tend to reduce workability, increase porosity, and weaken mechanical strength, moderate substitution—particularly at 15% BA and 10% MD—enhances CS and FS and provides a denser microstructure. Specifically, the B15M10C75 mix achieved CS values that are slightly higher than the control at 7 days and more than 15% higher at 28 days, and it also provided FS gains of about 9–10% at 7 days, nearly 40% at 28 days, and around 20% at 90 days relative to B0M0C100. The filler effect of MD and the pore structure modifications induced by moderate BA contents contribute to improved hydration conditions and long-term performance at the macroscopic scale. Any potential pozzolanic activity of BA and MD was not directly measured in this study and is therefore considered only as a possible, but not experimentally confirmed, complementary mechanism rather than a proven primary cause. Porosity results indicated that some mixtures with balanced BA–MD ratios, such as B20M10C70 and B15M15C70, achieved 28-day porosity values that are 5–7% lower than the control, while mass loss indicators under cyclic seawater exposure showed that mixes with moderate levels of total replacement (around 20% BA + MD, e.g., B15M5C80 and B10M10C80) had 90-day weight losses comparable to or lower than B0M0C100, together with controlled water absorption, confirming a more compact and durable microstructure. Although water absorption and early-age porosity increase with a higher waste content, some mixtures with moderate BA–MD levels show reduced porosity and more stable water absorption at later ages, suggesting a tendency toward a denser matrix at the macroscopic scale. From a cost perspective, the use of industrial by-products leads to a significant reduction in material expenses, making this approach both economically and environmentally beneficial. The cost analysis showed that increasing the total BA + MD replacement proportion from 20% to 35% reduced the production cost of 1 m^3 of cement paste by roughly 20–35% compared with the reference mix, even when realistic transportation costs for the waste materials were included. Therefore, it can be concluded that incorporating BA and MD at levels of up to 25% total replacement offers an optimal balance between strength, durability, and sustainability, presenting a promising solution for greener cementitious materials. Overall, the results suggest that moderate replacement levels (around 15% BA and 10% MD) provide the most favorable combination of workability, mechanical performance, durability, and cost efficiency, whereas higher dosages lead to increased porosity, higher water absorption, and reduced strength.

The material examined in this study is considered a promising concrete binder due to its potential to reduce environmental impacts and its sufficient mechanical performance. In particular, the mix designs that demonstrated improved CS and FS together with acceptable mass loss and absorption performance under the cyclic seawater exposure applied highlight the suitability of BA–MD binders for structural and semi-structural applications where both performance and sustainability are desired. The findings suggest that the material could be used as a binder, particularly in road infrastructure, for concrete barriers and similar safety elements designed to prevent traffic accidents. Furthermore, its potential cost advantage compared to traditional binders makes this material an economically viable alternative. The significant cost reductions observed for BA–MD mixtures, combined with their satisfactory engineering properties, indicate that such binders could be a competitive option for large-volume infrastructure projects where material costs are critical.

In this regard, it is recommended that future studies focus on on-site applications of the material and evaluate its long-term durability and environmental performance under real service conditions. Pilot-scale field trials should be carried out for the most promising mixtures, such as B15M10C75, to verify their behavior under traffic loads, cyclic environmental actions and aggressive exposures. Furthermore, the material's suitability for production in existing concrete plants should be examined in detail in terms of workability and scalability

to support its integration into industrial use. Further research on optimization of BA and MD particle size distribution, curing regimes and admixture compatibility would also help to refine the mix designs and maximize the performance and robustness of BA–MD-based cementitious materials. It is important to emphasize that the wetting–drying test used in this study provides a measure of physical integrity under a specific set of conditions and should not be interpreted as a comprehensive assessment of overall durability. A full evaluation of long-term performance would require standardized tests to measure key transport properties and chemical resistance, such as rapid chloride permeability in accordance with ASTM C1202 [52], sulfate attack resistance in accordance with ASTM C1012 [53], and carbonation depth.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings16081489/s1.

Author Contributions: Conceptualization, E.A.; Methodology, E.A.; Validation, E.A.; Formal analysis, A.B.B.; Investigation, A.B.B.; Data curation, A.B.B.; Writing—original draft, A.B.B.; Writing—review & editing, E.A.; Supervision, E.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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