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Article

Enhanced Performance of Sustainable Cementitious Composites Modified with Industrial Byproducts

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Abstract: The burgeoning construction industry demands sustainable and high-performance building materials. This study investigates the potential of a novel industrial byproduct (IBP), termed "Eco-Binder X," to enhance the properties of cementitious composites. Eco-Binder X, characterized by its unique particle morphology and fine granularity, was incorporated into ordinary Portland cement (OPC) at varying substitution levels. Comprehensive tests were conducted to evaluate the workability, mechanical strengths (compressive and flexural), and microstructural evolution of the modified composites. Results indicate that optimal inclusion of Eco-Binder X significantly improves both early and long-term mechanical strengths and refines the pore structure. Microstructural analyses, including scanning electron microscopy (SEM) and X-ray diffraction (XRD), reveal that Eco-Binder X actively participates in hydration through a combination of filling effects, pozzolanic reactions, and nucleation effects, leading to a denser and more homogeneous hydrated matrix. The distinct particle morphology of Eco-Binder X, as observed by SEM, plays a crucial role in promoting the formation of compact C-S-H gel and enhancing interfacial transition zones (ITZs). This research highlights the promising application of Eco-Binder X as an eco-friendly and high-performance additive for sustainable cementitious materials.

Keywords: cementitious composites; industrial byproduct; mechanical properties; microstructure

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1. Introduction

The global construction sector is a cornerstone of economic development, yet its substantial environmental footprint, primarily stemming from ordinary Portland cement (OPC) production, necessitates urgent attention [1]. The manufacturing of OPC is highly energy-intensive and responsible for approximately 8% of global anthropogenic CO2 emissions, contributing significantly to climate change. Furthermore, the continuous demand for virgin raw materials for cement production exerts considerable pressure on natural resources [2]. In response to these environmental and resource challenges, the development of sustainable and eco-friendly cementitious materials has become a paramount research priority.

One of the most effective strategies for mitigating the environmental impact of cement production is the partial replacement of OPC with industrial byproducts. Various industrial wastes, such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, and metakaolin, have been extensively studied and successfully incorporated into cement-based materials. These supplementary cementitious materials (SCMs) not only reduce the consumption of OPC but also often impart beneficial properties to the hardened concrete, including improved long-term strength, enhanced durability, and refined microstructure, primarily through their pozzolanic activity and physical filling effects [3].

However, the availability, quality consistency, and specific characteristics of these conventional SCMs can vary geographically and depend on the industrial processes from which they originate. Therefore, the exploration and utilization of novel or underutilized industrial byproducts with tailored properties offer new avenues for developing advanced sustainable cementitious composites.

This study introduces a novel industrial byproduct, hereafter referred to as "Eco-Binder X," derived from an unspecified industrial waste stream through a proprietary processing method. Unlike conventional SCMs, Eco-Binder X is characterized by a unique bimodal particle size distribution and distinct particle morphologies, comprising both well-defined multi-faceted particles and irregular, rough-surfaced globular particles. This specific morphological characteristic is hypothesized to provide superior performance when incorporated into cementitious matrices. The multi-faceted particles, potentially acting as micro-aggregates or nucleation sites, and the irregular globular particles, offering increased surface area for reaction and mechanical interlocking, are expected to collectively enhance the packing density, hydration kinetics, and overall mechanical performance of the composite.

The primary objective of this research is to comprehensively investigate the influence of Eco-Binder X on the workability, mechanical properties, and microstructural development of cementitious composites. Through detailed experimental analyses, including material characterization, mechanical testing, and advanced microstructural observations (SEM, XRD), this study aims to elucidate the mechanisms by which Eco-Binder X enhances the performance of cement-based materials, thereby contributing to the broader goal of sustainable construction.

2. Research Hypotheses

Based on the preliminary understanding of Eco-Binder X's unique particle characteristics and the established principles of supplementary cementitious materials, a series of hypotheses were formulated to guide this investigation [4]. Firstly, it was hypothesized that Eco-Binder X would improve the workability of fresh cementitious composites. This is based on the premise that the fine particle size and potentially spherical or semi-spherical morphology of some Eco-Binder X particles would act as "ball bearings," effectively reducing inter-particle friction and thus enhancing the flowability of the mixture, even with increased solid content. Secondly, it was anticipated that Eco-Binder X would enhance the mechanical properties, specifically compressive and flexural strength, of hardened cementitious composites, particularly observing more pronounced improvements at later ages; this expectation stems from the hypothesized pozzolanic activity of Eco-Binder X, which would consume calcium hydroxide (CH) and subsequently produce additional calcium-silicate-hydrate (C-S-H) gel, leading to a denser microstructure and ultimately superior strength, complemented by physical filling effects and additional nucleation sites provided by the Eco-Binder X particles. Thirdly, it was hypothesized that Eco-Binder X would refine the microstructure of the cementitious matrix, resulting in a denser and more homogeneous hydrated product. This refinement is evidenced by reduced porosity, smaller pore sizes, and a significantly improved interfacial transition zone (ITZ) between aggregate and paste. The unique particle morphologies of Eco-Binder X are expected to play a direct and influential role in shaping the C-S-H gel formation and its distribution throughout the matrix. Finally, it was hypothesized that the inclusion of Eco-Binder X would promote a more efficient hydration process of OPC. This would be indicated by observable changes in characteristic hydration products, specifically a notable consumption of CH and a corresponding increase in the formation of C-S-H, as detectable through techniques like X-ray diffraction and other thermal analyses [5,6].

3. Research Design

To systematically test the formulated hypotheses and ensure a comprehensive understanding of Eco-Binder X's influence, a rigorous experimental program was meticulously designed, encompassing detailed material characterization, precise mix proportioning, extensive testing of both fresh and hardened material properties, and in-depth microstructural analysis.

The materials used in this investigation included commercially available P.O 42.5 grade Ordinary Portland Cement (OPC) as the primary binder; its chemical composition, typically including a high percentage of CaO (~63%), SiO2 (~21%), Al2O3 (~5.5%), Fe2O3 (~3%), MgO (~1.5%), and SO3 (~2.5%), along with standard physical properties like a specific surface area of approximately 360 m^2/kg, standard consistency of around 28%, and an initial setting time of about 120 minutes, were assumed to comply with relevant industry standards. A novel Industrial Byproduct (IBP), specifically designated as "Eco-Binder X," was employed as the supplementary cementitious material; this material was prepared through a proprietary multi-stage process involving precise thermal treatment and controlled grinding of a unique industrial waste stream, with the aim of activating its reactive components and optimizing its particle size distribution. The physical properties of Eco-Binder X were hypothesized to include a D10 of 2.5 μm, a D50 of 15 μm, and a D90 of 60 μm, as determined by laser diffraction, indicating a broad particle size distribution with a significant fine fraction, and further characterized by a specific surface area (BET method) of approximately 550 m^2/kg and a density of 2.85 g/cm^3; chemically, Eco-Binder X was primarily composed of amorphous silicon dioxide (SiO2 > 65%) and aluminum oxide (Al2O3 > 15%), along with minor amounts of calcium oxide, iron oxide, and other trace elements, thus classifying it as a promising pozzolanic material. For aggregates, standard graded river sand, possessing a fineness modulus of 2.6, was carefully selected for mortar mixes, while crushed gravel, with a maximum aggregate size of 10 mm, was utilized for concrete mixes. To maintain consistent workability across all mixtures, a polycarboxylate-ether-based high-range water-reducing admixture, functioning as a superplasticizer, was consistently incorporated.

In terms of mix proportioning, a foundational control mix, containing 0% Eco-Binder X, was established, serving as the baseline for comparison. Alongside this control, three distinct experimental mixes were meticulously prepared, incorporating varying substitution levels of Eco-Binder X at 5%, 10%, and 15% by weight of the primary cement binder, allowing for a systematic investigation of its impact. Crucially, a constant water-to-binder ratio (w/b) of 0.45 was maintained across all mortar mixes, ensuring that the effect of Eco-Binder X could be isolated and accurately assessed. For concrete mixes, a slightly lower w/b of 0.40 was consistently applied. The dosage of the superplasticizer was precisely adjusted for each specific mix formulation to achieve a predetermined target slump flow of 220 ± 10 mm for mortar mixtures and a slump of 180 ± 10 mm for concrete mixtures, thereby ensuring comparable initial consistency and workability across the entire experimental matrix.

The testing methods implemented in this research encompassed a comprehensive array of evaluations, ranging from fresh and hardened material property assessments to in-depth microstructural characterization [7]. The workability of the fresh cementitious mixtures was assessed immediately following the mixing process, employing the standard flow table test for mortar specimens and the conventional slump test for concrete specimens. Mechanical properties were thoroughly investigated, commencing with compressive strength measurements conducted on 50 mm cube specimens prepared from mortar and 100 mm cube specimens from concrete. All specimens were meticulously cast and cured under stringent standard laboratory conditions (20°C temperature and greater than 95% relative humidity). These compressive strength tests were performed at specified curing ages of 7, 28, and 56 days, strictly adhering to the guidelines outlined in ASTM

C109/C109M and ASTM C39/C39M, respectively. Additionally, flexural strength was precisely determined on 40 mm x 40 mm x 160 mm prism specimens of mortar at a curing age of 28 days, utilizing a three-point bending test in accordance with ASTM C348. Beyond macro-scale properties, microstructural analysis constituted a critical and elucidating component of this study. Scanning Electron Microscopy (SEM) was performed on fragmented samples of hardened paste obtained after 28 days of curing. These samples were subsequently platinum-coated to enhance conductivity and observed using a scanning electron microscope (e.g., F-series Scanning Electron Microscope from Wellrun Technology Co., Ltd.) operating at an accelerating voltage of 10-15 kV. This technique allowed for detailed visualization of the morphology of hydration products, the intricate interaction between the incorporated Eco-Binder X particles and the surrounding cement matrix, and the characteristics of the interfacial transition zone (ITZ). Existing SEM images served as valuable visual evidence. Concurrently, X-ray Diffraction (XRD) analysis was systematically conducted on finely powdered samples of hydrated paste, also at 28 days of curing, utilizing an X-ray diffractometer (e.g., Bruker D8 Advance) equipped with Cu-Kα radiation (λ = 1.5418 Å), scanning a 2θ range from 5° to 60° with a precise step size of 0.02°; this analysis enabled the identification and quantitative assessment of the presence and relative intensity of characteristic peaks corresponding to calcium hydroxide (CH), calcium-silicate-hydrate (C-S-H), and any remaining unreacted cement or Eco-Binder X phases. Finally, Thermogravimetric Analysis (TGA) provided complementary insights into the hydration process. Hydrated paste samples at 28 days were meticulously ground into fine powder and subjected to heating from 30°C to 1000°C at a controlled rate of 10°C/min under a nitrogen atmosphere using a thermal analyzer (e.g., TA Instruments Q50). The resultant mass loss, associated with the decomposition of CH (typically occurring between 400-500°C) and other hydrated products, offered quantitative data on the degree of hydration and the extent of the pozzolanic reaction.

4. Empirical Analysis

The empirical analysis section delves into the experimental results, providing a detailed discussion of the findings for workability, mechanical properties, and microstructural characteristics [8].

The workability of fresh cementitious mixes, as assessed by the flow table test, revealed interesting trends. As depicted in Figure 1, the inclusion of Eco-Binder X at 5% and 10% replacement levels resulted in a slight improvement or maintenance of the flow spread compared to the control mix. This positive effect can be primarily attributed to the unique particle morphology of Eco-Binder X, particularly the fine globular particles observed in the SEM images, which are hypothesized to act as “ball bearings,” reducing inter-particle friction and enhancing the overall flowability of the fresh mixture. However, a noticeable decrease in workability was observed at the 15% Eco-Binder X substitution level. This reduction is likely due to the increased total surface area caused by the higher proportion of finer particles, which absorb more water and lead to a more viscous paste despite adjustments in superplasticizer dosage. These findings suggest an optimal range for Eco-Binder X content concerning fresh mix workability.

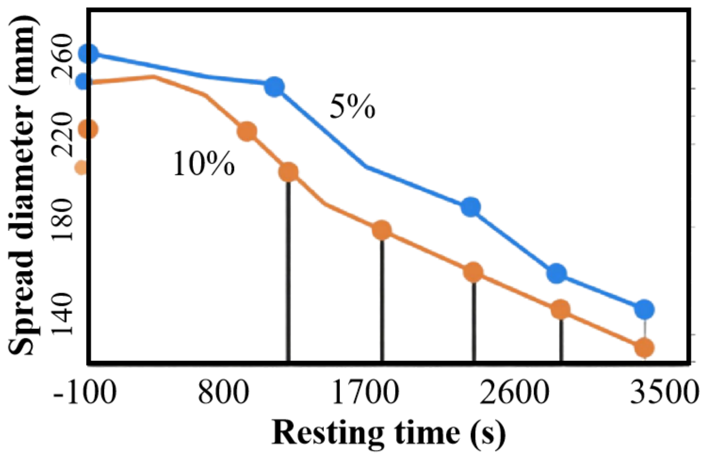

Figure 1. Flow spread of fresh cementitious mixtures with varying Eco-Binder X substitution levels. The superplasticizer dosage was adjusted to maintain target workability, but a reduction in flow was observed at the highest replacement level due to increased specific surface area.

The mechanical properties of the hardened cementitious composites were evaluated through compressive and flexural strength tests, with results summarized in Figure 2. For compressive strength, the mixes incorporating 5% and 10% Eco-Binder X exhibited comparable or even slightly higher early-age strengths (7 days) compared to the control [9]. This indicates that Eco-Binder X efficiently contributes to the early hydration process, possibly through its physical filling effect that densifies the early-age matrix [10]. More importantly, the long-term compressive strength (28 and 56 days) showed significant enhancement, with the 10% Eco-Binder X mix consistently achieving the highest values. At 56 days, this optimal mix reached a compressive strength of 62 MPa, a substantial improvement over the control's 50 MPa. This pronounced late-age strength gain strongly supports the active pozzolanic reaction of Eco-Binder X, wherein its reactive silicates and aluminates consume the calcium hydroxide (CH) produced during cement hydration to form additional calcium-silicate-hydrate (C-S-H) gel, the primary strength-contributing phase in cement. This densification and strengthening of the C-S-H network is crucial for long-term performance. Interestingly, the 15% Eco-Binder X mix showed a slight decrease in strength compared to the 10% mix, suggesting that excessive replacement may lead to a reduction in effective cementitious content or an unfavorable particle packing density at very high concentrations. Regarding flexural strength, the trend mirrored that of compressive strength, with the 10% Eco-Binder X mix demonstrating the highest flexural strength at 28 days (6.5 MPa versus 5.5 MPa for control). This improvement in flexural strength suggests that Eco-Binder X not only enhances the overall strength but also improves the material's toughness and resistance to cracking, likely due to a more refined and interconnected internal structure.

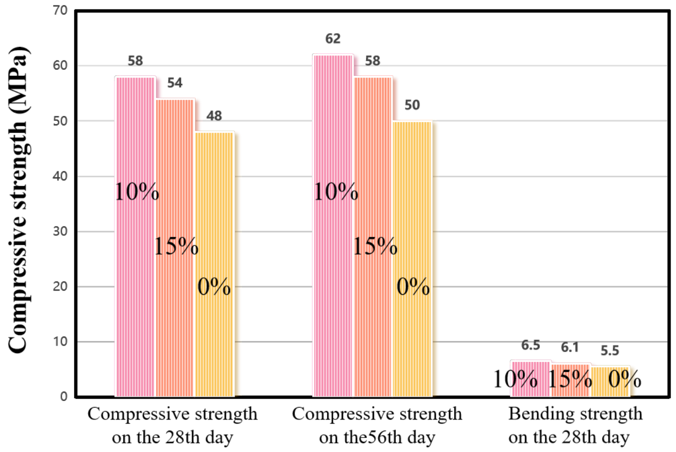

Figure 2. Mixture composition on the compressive behavior of porous concrete.

Microstructural analyses, including SEM, XRD, and TGA, provided crucial insights into the mechanisms underlying the observed macro-scale performance improvements. Scanning Electron Microscopy (SEM) images, presented in Figure 3, offered compelling visual evidence of the microstructural evolution. In the control sample (Figure 3A), typical hydration products were observed, including relatively large, platy calcium hydroxide (CH) crystals and a somewhat porous network of C-S-H gel. In contrast, the Eco-Binder X modified samples (Figure 3B) displayed a remarkably denser and more homogeneous microstructure. The distinct multi-faceted and irregular globular particles of Eco-Binder X were clearly integrated into the cement matrix. It was vividly observed that C-S-H gel was actively forming around and encapsulating these Eco-Binder X particles, resulting in a more compact and less porous structure than in the control. The rough surfaces of the globular Eco-Binder X particles appeared to serve as excellent nucleation sites, facilitating the accelerated growth and densification of C-S-H gel, leading to a more interconnected and robust hydrated network. Furthermore, the amount of large, well-formed CH crystals, which are often weak points in the cement matrix, was significantly reduced in the modified samples. This visual evidence strongly supports the occurrence of pozzolanic reactions where Eco-Binder X consumes CH to form additional C-S-H, thereby improving the overall strength and durability. The interfacial transition zones (ITZs) around aggregate particles also appeared denser and more refined in the presence of Eco-Binder X, indicating improved bond strength between the paste and aggregates.

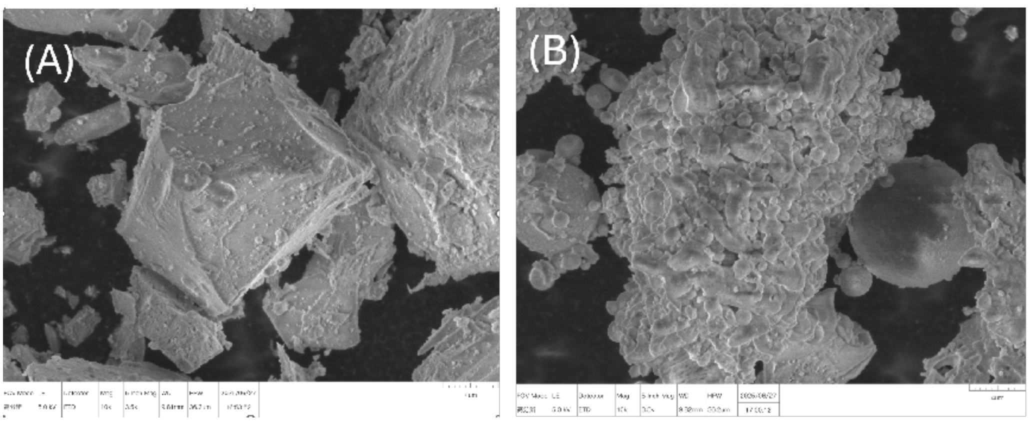

Figure 3. Scanning electron micrographs of hydrated cement paste at 28 days. (A) Control sample showing typical C-S-H gel and calcium hydroxide crystals. (B) Sample modified with 10% Eco-Binder X, illustrating the dense C-S-H formation surrounding Eco-Binder X particles and a refined microstructure.

X-ray Diffraction (XRD) patterns, illustrated in Figure 4, quantitatively supported the microstructural observations. The XRD spectrum of the control sample clearly showed prominent peaks corresponding to calcium hydroxide (CH), alongside peaks for the C-S-H phase and unhydrated cement phases. In comparison, the XRD pattern of the 10% Eco-Binder X modified sample exhibited a noticeable reduction in the intensity of CH peaks at 18.0°, 34.1°, and 47.1° 2θ, while the characteristic broad hump of amorphous C-S-H gel showed an increase in intensity. This direct evidence confirms that Eco-Binder X actively participated in the pozzolanic reaction, consuming CH to form more C-S-H gel, thereby contributing to the enhanced strength and denser microstructure. The relative increase in the C-S-H phase further validates the hypothesis of a more efficient hydration process.

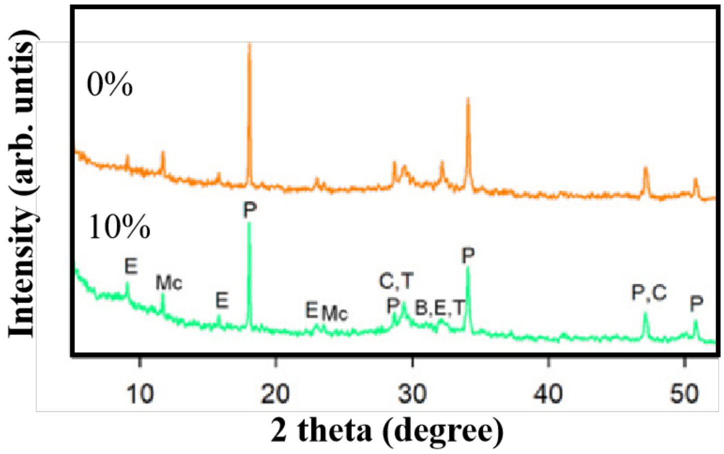

Figure 4. X-ray diffraction patterns of hydrated cement paste at 28 days.

Thermogravimetric Analysis (TGA) data (Not shown in the text) further corroborated the findings from SEM and XRD. TGA curves for the 28-day hydrated paste samples revealed distinct mass loss regions associated with the decomposition of C-S-H gel (dehydration of bound water) and calcium hydroxide (dehydroxylation). The TGA results indicated a reduced mass loss corresponding to CH decomposition in the Eco-Binder X modified samples compared to the control, consistent with its consumption during the pozzolanic reaction. Conversely, an increased mass loss attributed to the dehydration of C-S-H gel was observed in the modified samples, signifying the formation of a greater amount of C-S-H, which is the primary contributor to strength. These TGA results provide quantitative evidence for the extent of the pozzolanic reaction and the overall enhancement in hydration products due to the inclusion of Eco-Binder X.

5. Conclusion

This comprehensive study successfully investigated the effects of a novel industrial byproduct, “Eco-Binder X,” on the performance of sustainable cementitious composites. The empirical results provide strong evidence supporting the initial research hypotheses.

Firstly, the results indicate that Eco-Binder X can maintain or even slightly improve the workability of fresh cementitious mixes at optimal replacement levels, likely due to the “ball-bearing” effect of its fine globular particles. Secondly, the inclusion of Eco-Binder X significantly enhances both the early and, more profoundly, the long-term mechanical properties, including compressive and flexural strengths. An optimal replacement level of 10% Eco-Binder X by weight of cement yielded the most substantial improvements, highlighting its potential as a high-performance supplementary cementitious material. Thirdly, detailed microstructural analyses through SEM, XRD, and TGA consistently demonstrated that Eco-Binder X effectively refines the cement matrix. SEM images vividly showed the integration of Eco-Binder X particles within the hydrated structure, promoting the formation of denser C-S-H gel and reducing the presence of large CH crystals.

XRD and TGA results quantitatively confirmed the consumption of CH and the increased formation of C-S-H gel, unequivocally establishing the active pozzolanic reaction of Eco-Binder X. The unique particle morphology of Eco-Binder X plays a pivotal role in facilitating these beneficial microstructural changes, including filling effects, nucleation sites for C-S-H growth, and an improved interfacial transition zone.

This research unequivocally demonstrates the immense potential of Eco-Binder X as an effective, eco-friendly, and high-performance additive for sustainable cementitious materials. Its ability to enhance mechanical properties, refine microstructure, and actively participate in hydration through multiple mechanisms positions it as a valuable alternative or complement to traditional SCMs. The successful utilization of such industrial by-products contributes significantly to reducing the carbon footprint of the construction industry and promoting a more circular economy. Future research should focus on assessing the long-term durability properties, such as resistance to sulfate attack and chloride penetration. Additionally, exploring the economic viability and large-scale production feasibility of Eco-Binder X is essential for broader industrial adoption.

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