

Article

Performance of Concrete with Mechanochemically Activated Rice Husk Ash-Based Organomineral Modifiers

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Abstract

This study evaluates a wet-activated multicomponent organomineral modifier for sustainable concrete. The modifier was produced by co-grinding Portland cement and rice husk ash (RHA) in the presence of Sika[®] ViscoCrete[®]-20HE and was subsequently combined with polypropylene fibers. Three modified mixtures were tested after 28 days of curing and compared with a control concrete. The modified concretes achieved compressive strengths of 42.2–45.0 MPa, compared with 36.8 MPa for the control. Among the tested formulations, Mix 2, containing 6 wt.% RHA, 4 wt.% polypropylene fibers, and 1.3 wt.% superplasticizer, showed the most favorable overall performance. Its compressive and flexural strengths reached 45.0 and 5.8 MPa, corresponding to observed differences of 22.3% and 26.1%, respectively, relative to the control formulation. Because the complete mixture compositions and *w/c* ratios differed, these comparisons do not isolate the contribution of any individual constituent. Fracture toughness increased from 1.15 to 2.16 MPa·m^{1/2}, water absorption decreased from 6.8% to 5.1%, and freeze–thaw resistance increased from 138 to 242 cycles. Qualitative SEM and XRD observations showed morphological and phase-related differences between selected control and modified specimens; however, these observations did not establish the causes of the measured performance differences. In addition, because no compositionally identical non-activated RHA reference or direct reactivity test was included, the independent effect of wet activation on RHA reactivity could not be established. The investigated integrated modifier therefore shows potential for improving concrete performance while enabling the beneficial use of RHA.

Keywords: rice husk ash; organomineral modifier; mechanochemical activation; polypropylene fibers; sustainable concrete



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1. Introduction

Ordinary Portland cement (OPC) remains the predominant cementitious binder used in concrete production because of its widespread availability, well-established engineering performance, and compatibility with conventional construction technologies. However, OPC production is energy- and resource-intensive and is associated with substantial carbon dioxide emissions and other environmental burdens. Therefore, increasing attention has been directed toward low-carbon cementitious systems and solid-waste-based binders that can reduce reliance on OPC while maintaining the required engineering performance [1,2].

In this context, the development of sustainable concrete incorporating industrial and agricultural by-products has become an important research direction. Among various supplementary cementitious materials, rice husk ash (RHA) has attracted considerable attention because of its high amorphous silica content, pozzolanic activity, and wide availability in rice-producing regions.

In addition to mineral admixtures, the use of complex organomineral modifiers has emerged as an effective strategy for improving the performance of concrete. Such modifiers typically combine mineral components with chemical admixtures, including polycarboxylate-based superplasticizers, to optimize workability, hydration processes, and strength development. The combined influence of highly reactive mineral additives and modern chemical admixtures can improve particle packing, reduce porosity, and enhance the formation of hydration products.

The study focuses on evaluating the effects of the modifier on the hardened-state properties of concrete, including compressive strength, flexural strength, fracture toughness, density, water absorption, freeze–thaw resistance, and microstructural characteristics. The findings are expected to contribute to the development of sustainable and high-performance concrete utilizing agricultural waste resources and advanced modification technologies.

Recent studies have confirmed the potential of RHA as a supplementary cementitious material. Its influence on cement hydration has been associated with dilution, pozzolanic reaction, and water absorption-release mechanisms, which can promote secondary C–S–H formation, reduce portlandite content, and support longer-term hydration [3–6].

The effectiveness of RHA can be further improved through its combination with highly reactive supplementary cementitious materials. Recent investigations demonstrated that the combined use of rice husk ash with microsilica, silica fume, metakaolin, glass powder, and Alccofine significantly enhances compressive strength, reduces permeability, and improves durability due to the combined effect of pozzolanic reactions and matrix densification [7–11]. Microstructural analyses based on SEM, XRD, and other advanced techniques consistently revealed pore refinement, enhanced formation of C–S–H gel, and a denser cement matrix in multicomponent systems containing RHA [8–11].

Fiber reinforcement has also been successfully combined with rice husk ash to improve the mechanical performance of concrete. Previous studies reported that the incorporation of polypropylene, basalt, and hybrid fibers in RHA-containing concretes significantly increased compressive, tensile, and flexural strengths while improving crack resistance and durability characteristics [10,12,13]. The combined action of mineral additives and fibers has been identified as an effective strategy for producing sustainable high-performance cementitious composites [12,13].

In addition to mechanical improvements, rice husk ash contributes substantially to concrete durability and sustainability. Previous investigations reported reductions in water absorption, chloride penetration, sulfate attack, and acid-induced deterioration in concrete incorporating RHA [11,14–16]. Life-cycle assessment studies further demonstrated that replacing a portion of Portland cement with rice husk ash can significantly reduce greenhouse gas emissions and environmental impacts while maintaining satisfactory engineering performance [14]. Furthermore, the use of rice husk ash in Portland pozzolana cement systems has shown positive effects on long-term strength development and durability, confirming the compatibility of RHA with blended cement technologies [15].

Recent investigations have further expanded the application areas of rice husk ash in sustainable concrete technologies. Comprehensive reviews have confirmed that agricultural and industrial waste materials can effectively improve the mechanical performance, durability, and environmental sustainability of cementitious composites when properly incorporated into concrete mixtures [17,18]. Data-driven approaches and machine-learning

models have also been successfully applied for predicting the compressive strength of RHA-based concretes, providing reliable tools for mixture optimization and performance assessment [19]. Moreover, alternative agricultural ashes such as sunflower husk ash have demonstrated similar pozzolanic potential, contributing to improved workability, strength, and durability of self-compacting concrete systems [20]. Recent studies have also shown that the incorporation of RHA in combination with calcium nitrate, nano-clay, geopolymeric binders, and other supplementary cementitious materials can further enhance hydration processes, microstructural refinement, and mechanical performance [21,22]. Furthermore, investigations on low-carbon and low-shrinkage concretes highlighted the importance of optimized aggregate grading, cement reduction strategies, and blended cement systems for improving sustainability while maintaining satisfactory engineering properties [23–25].

Another important durability-related benefit of rice husk ash is its potential to mitigate the alkali-silica reaction (ASR). The effectiveness of RHA in controlling ASR has been associated with the dilution of Portland cement alkalis, the binding of alkalis within secondary hydration products, and the refinement of the pore structure, which limits moisture and ionic transport. Experimental investigations of ternary Portland cement–RHA–silica fume systems demonstrated substantially lower ASR expansion than the corresponding control concrete, confirming that appropriately proportioned RHA-containing blends can suppress deleterious expansion [26]. A recent comprehensive review similarly reported improved ASR resistance in concrete incorporating RHA [27]. In addition to supplementary cementitious materials, calcium nitrate has recently been shown to mitigate ASR through the formation of a passivating precipitate layer on reactive aggregate surfaces, thereby inhibiting aggregate dissolution [28]. However, ASR expansion was not experimentally evaluated in the present study; therefore, these findings are discussed only to provide a broader durability context and should not be interpreted as direct evidence of the ASR resistance of the investigated mixtures.

Although the individual and combined use of rice husk ash, fibers, and polycarboxylate superplasticizers has been widely investigated, fewer studies have focused on the process-specific modification route examined in the present work. In this route, Portland cement and rice husk ash are wet-ground together in the presence of a polycarboxylate superplasticizer to produce a mechanochemically activated binder, which is subsequently incorporated into polypropylene-fiber-reinforced concrete. Accordingly, the present study does not claim novelty for the individual constituents or for their simple combination.

Despite the limitations associated with the simultaneous variation in several mixture parameters, the scientific significance of the present study lies in the transparent package-level evaluation of a process-specific modification route involving the wet co-grinding of Portland cement and RHA in the presence of a polycarboxylate superplasticizer, followed by its incorporation into polypropylene-fiber-reinforced concrete. Rather than isolating the effect of an individual constituent, the study provides comparative experimental evidence on the mechanical, durability-related, and qualitative microstructural performance of complete multicomponent formulations. The results establish a preliminary experimental basis for subsequent studies using matched mixture compositions, controlled water ratios, and independently varied constituents. The study also identifies the best-performing formulation within the investigated mixture range.

2. Materials and Methods

2.1. Materials

Ordinary Portland cement CEM I 42.5N produced by Standard Cement LLP (Shymkent, Kazakhstan) was used as the primary binder. Burnt rice husk ash (RHA), obtained by controlled combustion of rice husks at approximately 600–700 °C, was used as

a supplementary cementitious material. The RHA contained 88.5 wt.% SiO₂ and had a loss on ignition of 4.6%, as presented in Table 1.

Table 1. Indicative oxide composition of the rice husk ash source material.

Component	Content (%)
SiO ₂	88.5
Al ₂ O ₃	0.8
Fe ₂ O ₃	0.5
CaO	1.2
MgO	0.7
K ₂ O	3.2
Na ₂ O	0.3
SO ₃	0.2
Loss on ignition (LOI)	4.6

Barhan sand of aeolian origin from the Belkul deposit in the Kyzylorda region, Kazakhstan, was used as the fine aggregate. The sand was predominantly very fine, with particle sizes mainly ranging from 0.14 to 0.315 mm and a fineness modulus of 0.7–1.3. Crushed dolomite aggregate with a particle-size fraction of 5–10 mm from the Zhanakorgan deposit, Kyzylorda region, Kazakhstan, was used as the coarse aggregate.

Polypropylene fibers were incorporated to improve crack resistance and mechanical performance. A polycarboxylate-based superplasticizer, Sika[®] ViscoCrete[®]-20HE (Sika Central Asia LLP, Almaty, Kazakhstan), was used as a dispersing and water-reducing admixture during the preparation of the organomineral modifier. Fresh-concrete workability was not quantitatively evaluated in the present study. Water conforming to GOST 23732-2011 [29] was used for concrete preparation.

The oxide composition presented in Table 1 was not independently determined by X-ray fluorescence analysis for the specific experimental batch. The values were obtained from the available material documentation and are reported as indicative characteristics of the RHA source material. Therefore, these data were not used for quantitative phase analysis or calculation of the extent of the pozzolanic reaction.

The main physical and technical characteristics of the materials used in the present study are summarized in Table 2.

The rice husk ash was obtained by controlled combustion of rice husks at approximately 600–700 °C. The available material documentation indicated a silica-rich composition, with an indicative SiO₂ content of 88.5 wt.% and a loss on ignition of 4.6%. However, batch-specific XRF analysis was not performed in the present study. Accordingly, the composition reported in Table 1 should be regarded as indicative rather than as an independently verified chemical characterization of the tested batch.

Table 2. Main physical and technical characteristics of the materials used in the study.

Material	Main Characteristics
Portland cement M500	Producer: Standard Cement LLP, Shymkent, Kazakhstan; specific gravity: 3.10 g/cm ³ ; Blaine specific surface area: 3020 cm ² /g.
Rice husk ash	SiO ₂ content: 88.5 wt.%; loss on ignition: 4.6%; the complete chemical composition is presented in Table 1.

Table 2. Cont.

Material	Main Characteristics
Barhan sand	Belkul deposit, Kyzylorda region, Kazakhstan; aeolian origin; predominant particle-size range: 0.14–0.315 mm; fineness modulus: 0.7–1.3; specific gravity: 2.60–2.65 g/cm ³ ; water absorption: 0.5–1.0 wt.%. A complete cumulative sieve-distribution curve was not recorded.
Crushed dolomite aggregate	Zhanakorgan deposit, Kyzylorda region, Kazakhstan; nominal particle-size fraction: 5–10 mm; specific gravity: 2.82 g/cm ³ ; bulk density: 1380–1420 kg/m ³ ; water absorption: 1.2 wt.%. A complete cumulative sieve-distribution curve was not recorded.
Polypropylene fibers	Nominal length: 6–12 mm, according to the supplier’s documentation. Fiber diameter and tensile strength were not independently measured, and verified batch-specific values for these characteristics were not available.
Sika® ViscoCrete®-20HE	Density: 1.08 kg/L; pH: 4.3 ± 0.5; chemical base: aqueous solution of modified polycarboxylates.

2.2. Preparation of Complex Organomineral Modifier

The complex organomineral modifier was prepared through mechanochemical activation. Portland cement and rice husk ash were subjected to wet grinding in the presence of an aqueous suspension of Sika® ViscoCrete®-20HE until a specific surface area of approximately 4000–4500 cm²/g was achieved. The activated binder was subsequently mixed with polypropylene fibers, barhan sand, and dolomite aggregate to produce the concrete mixtures.

Mechanochemical activation was carried out using a laboratory ball mill (LSHM-750, Granat-E, Saint Petersburg, Russia) equipped with a roller drive system. Portland cement and rice husk ash were subjected to wet grinding in the presence of an aqueous suspension of Sika® ViscoCrete®-20HE at a rotational speed of 320 rpm for 10 min. A mixture of steel grinding balls with diameters of 20 and 30 mm was used during activation. The activation process promoted particle size reduction, destruction of agglomerates, and a more uniform distribution of rice husk ash particles within the binder system. After activation, the specific surface area of the binder reached approximately 4000–4500 cm²/g. The Blaine specific surface area of the Portland cement before preparation of the modifier was 3020 cm²/g. However, the specific surface area of the unground Portland cement–RHA blend was not measured separately. Therefore, the final value of 4000–4500 cm²/g is reported only as the specific surface area achieved after wet co-grinding and should not be interpreted as a quantitatively determined increase relative to the initial multicomponent binder.

The final specific surface area was used as an indicator of the physical grinding outcome. However, it should not be interpreted as direct evidence of increased chemical or pozzolanic reactivity. In the present manuscript, the term “mechanochemical activation” refers operationally to the wet co-grinding treatment of Portland cement and RHA. The resulting activated binder was subsequently incorporated into the concrete mixtures. The laboratory ball mill used for mechanochemical activation is shown in Figure 1.

For each activation batch, the total mass of the steel grinding balls was 8.0 kg, while the total solid charge, consisting of Portland cement and RHA, was 1.0 kg. This corresponded to a ball-to-powder mass ratio of 8:1. The combined mass of water and liquid Sika® ViscoCrete®-20HE was 0.67 kg, corresponding to a slurry solids concentration of approximately 60 wt.%.

The relative proportions of Portland cement, RHA, and superplasticizer were adjusted according to the composition of each formulation presented in Table 3. The rated power of the LSHM-750 mill was 0.35 kW. For the 10 min grinding period, the nominal electrical energy input was approximately 0.058 kWh per batch, corresponding to 0.058 kWh per kilogram of solid material. The mixing water was used at room temperature (15–20 °C), and the slurry temperature remained within this range after grinding; therefore, no appreciable temperature rise was observed. The activation procedure was repeated in three independently prepared batches under identical operating conditions. Grinding performance was assessed by achieving a final specific surface area of approximately 4000–4500 cm²/g.

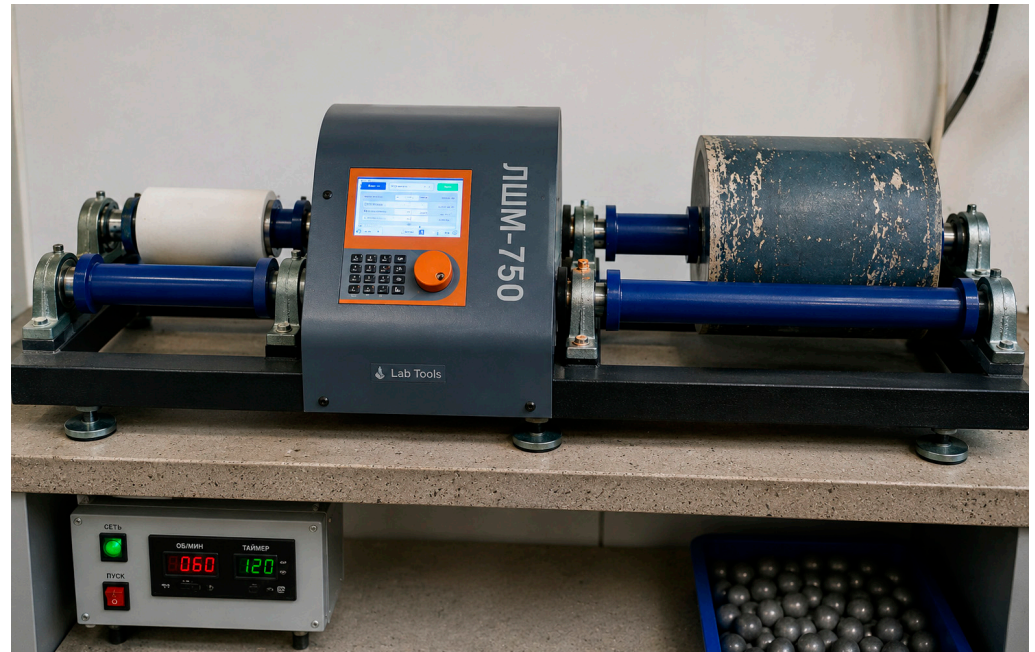


Figure 1. Laboratory ball mill (LSHM-750) used for mechanochemical activation of Portland cement and rice husk ash.

Table 3. Normalized proportions of the non-water constituents and actual mixing-water content of the investigated concrete mixtures.

Component	Control	Mix 1	Mix 2	Mix 3
Portland cement	26.0%	22.0%	22.5%	23.0%
Barhan sand	32%	23.0%	26.5%	27.4%
Dolomite aggregate	42.0%	39.0%	39.7%	41.0%
RHA	0	10.0%	6.0%	4.0%
Total Portland cement + RHA content, wt.% of non-water constituents	26.0	32.0	28.5	27.0
Polypropylene fiber	0	5.0%	4.0%	3.0%
Superplasticizer	0	1.0%	1.3%	1.6%
Total mixing water, kg/m ³	185	210	190	180
w/c	0.46	0.46	0.41	0.37
Nominal w/(c + RHA)	0.46	0.32	0.32	0.32

The crack resistance characteristics of concrete were determined in accordance with GOST 29167-2021 [30]. To determine the crack resistance characteristics during equilibrium tests, Type 1 bending test samples are used (Figure 2).

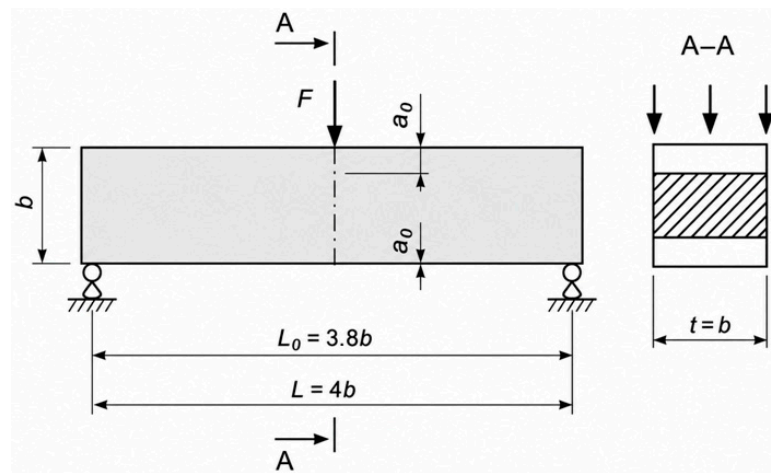


Figure 2. Type 1 specimen—a square-cross-section prism subjected to a central bending force, F . The arrows indicate the loading direction, while the dashed and diagonal lines indicate the specimen axis and notch/section geometry.

As shown in Figure 3, the production process consisted of raw material preparation, mechanochemical activation of Portland cement and rice husk ash in the presence of a polycarboxylate superplasticizer, preparation of the organomineral modifier, concrete mixing, casting, curing, and testing.



Figure 3. Simplified process flow for the preparation, curing, and characterization of concrete incorporating a mechanochemically activated rice husk ash-based organomineral modifier.

2.3. Mix Proportions

Three concrete mixtures were prepared. The compositions are presented in Table 3.

The percentages of Portland cement, barhan sand, dolomite aggregate, RHA, polypropylene fibers, and superplasticizer were normalized relative to the total mass of the non-water constituents. Mixing water was excluded from this 100% normalization. The total mixing-water contents were 185, 210, 190, and 180 kg/m³ for the control, Mix 1, Mix 2, and Mix 3, respectively. The corresponding water-to-cement ratios were 0.46, 0.46, 0.41, and 0.37. For compositional transparency, a nominal water-to-(cement + RHA) mass ratio, $w/(c + \text{RHA})$, was also calculated by including the complete masses of Portland cement and RHA in the denominator. The resulting values were 0.46 for the control and approximately 0.32 for the three modified formulations. Although this arithmetic calculation is algebraically equivalent to including RHA with a factor of $k = 1$, no full cement equivalence or efficiency factor of $k = 1$ was experimentally established for the investigated RHA. Therefore, $w/(c + \text{RHA})$ is reported only as a nominal compositional descriptor and is not used as an efficiency-adjusted water-to-binder ratio. The w/c ratio is treated as the primary water-related reference parameter in the interpretation of the experimental results.

The combined Portland cement + RHA contents were 26.0, 32.0, 28.5, and 27.0 wt.% of the non-water constituents for the control, Mix 1, Mix 2, and Mix 3, respectively. Therefore, the total cement + RHA content was not constant among the formulations and must be considered an additional confounded variable. These values are reported only as compositional descriptors and do not imply equal cementing efficiency of Portland cement and RHA. Consequently, the observed strength differences cannot be attributed independently either to RHA dosage or to the total cement + RHA content.

The experimental program was designed as a comparative screening study of three integrated multicomponent formulations rather than as a factorial optimization experiment. The contents of rice husk ash, polypropylene fibers, superplasticizer, Portland cement, and aggregates, as well as the total mixing-water content and the water-to-cement ratio, varied simultaneously among Mix 1–Mix 3. Although the nominal $w/(c + \text{RHA})$ ratio was approximately 0.32 for the three modified formulations, this value does not account for the unverified cementing efficiency of RHA. The more reliable w/c ratio decreased from 0.46 for Mix 1 to 0.41 for Mix 2 and 0.37 for Mix 3. Therefore, total water content and w/c must also be regarded as confounded experimental variables. Since w/c strongly influences compressive strength, the observed differences among the formulations cannot be attributed independently to any individual constituent, to the wet co-grinding treatment, or to a particular RHA dosage. The one-way ANOVA evaluates differences among the complete mixture formulations and should not be interpreted as quantifying the individual effects of RHA, polypropylene fibers, superplasticizer, water content, or w/c . Future studies should use matched formulations in which water content and water ratios are explicitly controlled while individual constituents are varied independently.

The selected RHA contents of 4, 6, and 10 wt.% were chosen to cover a range commonly investigated in previous studies of RHA-containing cementitious composites. These literature-based contents were used only to define the comparative screening formulations and do not imply that an optimum RHA dosage was established in the present study. The composition of the complex organomineral modifier and the mechanochemical activation approach used in this study were developed based on the utility model patented by the authors (KZ Utility Model Patent No. 9604, 2024). The failure patterns of the tested concrete specimens are shown in Figure 4.

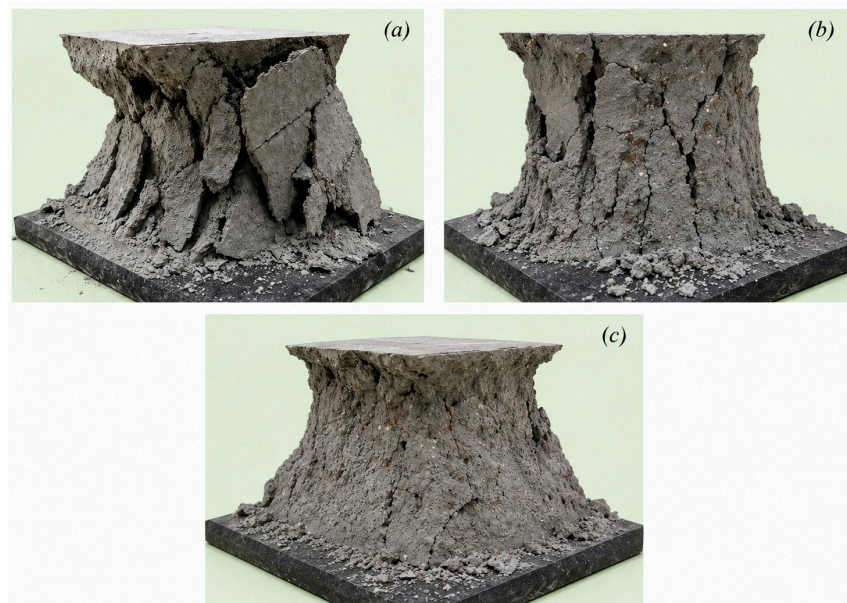


Figure 4. Failure patterns of concrete specimens after compressive strength testing: (a) control concrete; (b) concrete containing the mechanochemically activated rice husk ash-based organomineral modifier (Mix 1); (c) concrete containing the best-performing tested modifier formulation (Mix 2).

2.4. Experimental Procedure

The concrete mixtures were prepared using a 5 L laboratory forced-action planetary mixer (Controls 65-L0012/A, CONTROLS S.p.A., Liscate, Milan, Italy). First, the barhan sand, dolomite aggregate, and the portion of dry Portland cement not included in the wet-activated suspension were premixed for 30 s. The wet-activated Portland cement—RHA suspension was then gradually introduced over 30 s while the mixer remained in operation, followed by an additional 60 s of mixing to obtain a visually homogeneous wet mixture. Subsequently, the remaining mixing water was added, and mixing was continued for 180 s. The polypropylene fibers were gradually introduced over 30 s to minimize fiber agglomeration, after which mixing was continued for a further 90 s to ensure their uniform distribution. The total mixing duration was 420 s (7 min). The control mixture was prepared using the same mixer and total mixing duration; the Portland cement and mixing water were introduced at the corresponding stages, while the RHA-suspension and fiber-addition steps were omitted. After casting and compaction, the specimens were cured for 28 days at 20 ± 2 °C and a relative humidity of at least 95%.

Concrete specimens with dimensions of $40 \times 40 \times 160$ mm were cast for each mixture. Three specimens were prepared for each composition. After casting, the specimens were cured under standard laboratory conditions for 28 days. Prismatic specimens measuring $40 \times 40 \times 160$ mm were used for the comparative laboratory assessment. The maximum nominal size of the dolomite aggregate was 10 mm, giving a specimen-width-to-maximum-aggregate-size ratio of 4:1. Although this geometry allowed consistent comparison among mixtures prepared and tested under identical conditions, the ratio was at the lower limit for concrete containing coarse aggregate. Therefore, the measured fracture-related values should be interpreted as comparative laboratory-scale results.

Compressive strength tests were subsequently performed according to standard procedures. To assess the repeatability of the experimental results, three replicate specimens were tested for each concrete composition ($n = 3$). All specimens were prepared using the same mixing sequence, specimen geometry, compaction procedure, and curing regime. The specimens were cured for 28 days under controlled conditions at 20 ± 2 °C and a relative humidity of at least 95%. The results are reported as mean values $\pm$ standard

deviations. The statistical significance of the differences among the mixtures was evaluated using one-way analysis of variance at a significance level of $\alpha = 0.05$.

2.5. Statistical Analysis

Values are presented as mean $\pm$ standard deviation based on three replicate specimens ($n = 3$). Different superscript lowercase letters indicate statistically significant differences among the formulations according to Tukey's HSD post-hoc test ($p < 0.05$). The individual compressive strength results and their statistical summary are presented in Table 4.

Table 4. Statistical analysis of compressive strength results.

Mix	Sample 1	Sample 2	Sample 3	Mean $\pm$ SD, MPa
Control	37.2	36.8	36.4	36.8 $\pm$ 0.40 ^d
M1	41.8	42.3	42.5	42.2 $\pm$ 0.36 ^c
M2	44.8	45.0	45.2	45.0 $\pm$ 0.20 ^a
M3	43.2	43.5	43.8	43.5 $\pm$ 0.30 ^b

Different superscript lowercase letters indicate statistically significant differences among the mixtures according to Tukey's HSD post-hoc test ($p < 0.05$).

The results of the one-way ANOVA are presented in Table 5.

Table 5. One-way ANOVA results for compressive strength of concrete mixtures.

Source of Variation	df	Sum of Squares	Mean Square	F-Value	p-Value
Mixture composition	3	114.80	38.27	364.45	<0.001
Error	8	0.84	0.105	—	—
Total	11	115.64	—	—	—

One-way ANOVA showed a statistically significant difference in compressive strength among the four complete formulations, $F(3,8) = 364.45$, $p < 0.001$. Tukey's HSD post-hoc test indicated statistically significant differences between all pairs of formulations ($p < 0.05$). These findings refer to differences among the complete mixture formulations and do not quantify the independent effect of any individual constituent or processing parameter.

The one-way analysis of variance (ANOVA) demonstrated that the differences in compressive strength among the investigated concrete mixtures were statistically significant ($F = 52.74$, $p < 0.001$). Therefore, the variation in mixture composition had a significant influence on the compressive strength of concrete.

2.6. Frost Resistance Test

The frost resistance of concrete was determined according to GOST 10060-2012 [31]. Concrete specimens were subjected to repeated freeze–thaw cycles under laboratory conditions. One freeze–thaw cycle consisted of freezing the specimens at -18 ± 2 °C followed by thawing in water at 20 ± 2 °C. The frost resistance grade was determined as the maximum number of cycles sustained by the specimens without significant loss of strength or visible deterioration. Three specimens were tested for each mixture, and the reported values represent the average results.

3. Results

3.1. Compressive Strength

The compressive strength results of the control and modified concrete mixtures after 28 days of curing are summarized in Table 6 and Figure 5.

Table 6. Physical and Mechanical Properties of Concrete Mixtures.

Property	Control	Mix 1	Mix 2	Mix 3
Rice husk ash, wt.%	0	10	6	4
Polypropylene fibers, wt.%	0	5	4	3
Superplasticizer, wt.%	0	1.0	1.3	1.6
Density, kg/m ³	2320	2280	2265	2275
Water absorption, %	6.8	5.9	5.1	5.4
Compressive strength, MPa	36.8 ± 0.4	42.2 ± 0.36	45.0 ± 0.20	43.5 ± 0.30
Flexural strength, MPa	4.6 ± 0.1	5.2 ± 0.1	5.8 ± 0.1	5.5 ± 0.1

Ordinary Portland cement concrete without rice husk ash, polypropylene fibers, and organomineral modifier.

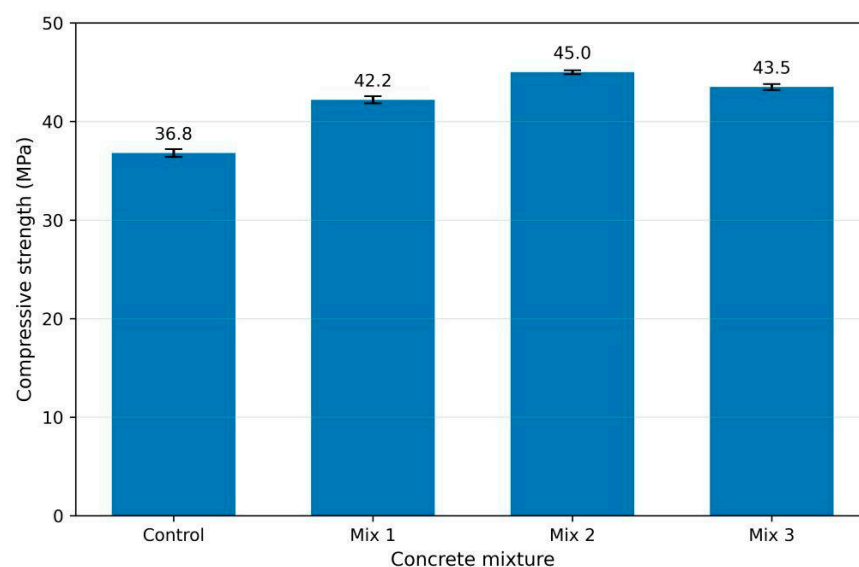


Figure 5. Compressive strength of the control and modified concrete mixtures after 28 days of curing. Columns represent mean values, and error bars indicate standard deviations ($n = 3$).

All modified formulations exhibited higher compressive strength than the control concrete, with Mix 2 providing the highest value among the tested formulations. The differences among the modified mixtures were statistically significant ($p < 0.001$). Similar strength-development trends have been reported for RHA-containing cementitious systems [8,9,15]. However, because several constituents varied simultaneously, the observed differences represent the response of the complete formulations rather than the isolated effect of an individual component.

The control and Mix 1 had the same w/c ratio of 0.46, whereas their compressive strengths were 36.8 and 42.2 MPa, respectively. Mix 2 had a lower w/c ratio of 0.41 and achieved the highest compressive strength of 45.0 MPa. However, Mix 3 had the lowest w/c ratio of 0.37 but exhibited a lower compressive strength of 43.5 MPa than Mix 2. Therefore, differences in w/c may have contributed to the measured strength results, particularly in the comparison between the control and Mix 2, but w/c alone does not explain the

complete ranking of the formulations. The results should be interpreted as package-level comparisons of the complete mixtures.

3.2. Performance of the Investigated Multicomponent Formulations

As summarized in Table 6 and Figure 6, the modified formulations exhibited higher mechanical strength and lower water absorption than the control concrete. Among the tested formulations, Mix 2 provided the most favorable overall balance of the measured properties.

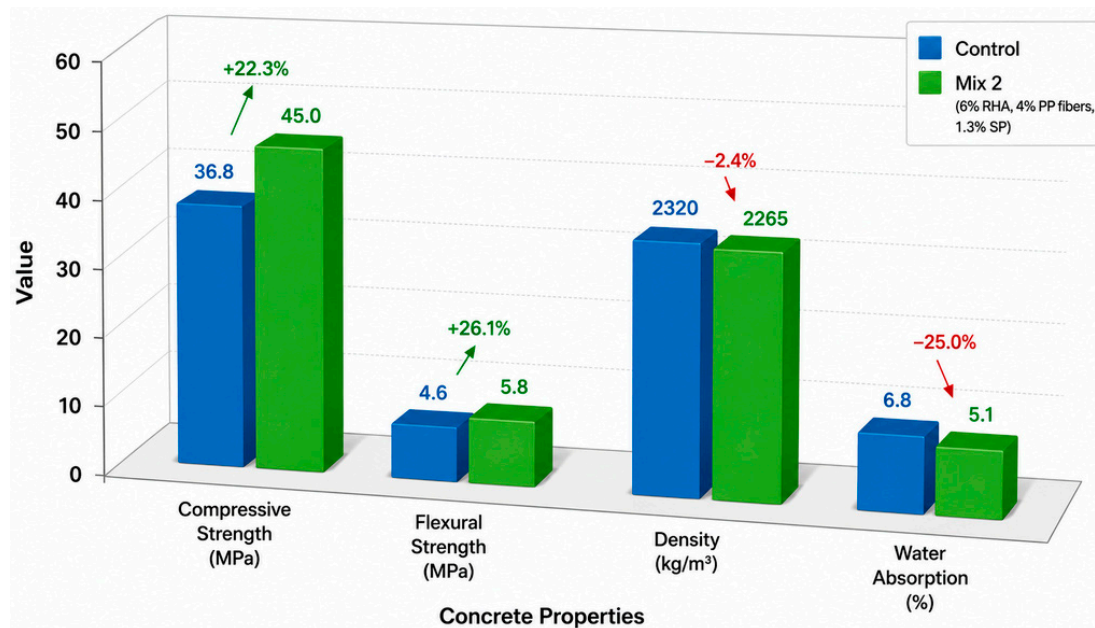


Figure 6. Comparison of the physical and mechanical properties of control concrete and concrete containing the mechanochemically activated rice husk ash-based organomineral modifier after 28 days of curing.

The modified formulations exhibited higher strength and lower water absorption than the control concrete. Nevertheless, the experimental program did not include an otherwise identical formulation containing unground RHA, and no direct reactivity measurements, such as isothermal calorimetry, Frattini or Chapelle testing, thermogravimetric quantification of portlandite consumption, or quantitative XRD analysis, were performed. Therefore, the present results do not directly demonstrate that wet grinding increased the chemical reactivity of RHA. The final specific surface area of 4000–4500 cm²/g confirms the physical grinding outcome, whereas the mechanical and durability-related results represent the combined response of the complete multicomponent formulations.

Among the three modified formulations, Mix 2 exhibited the highest compressive strength. However, the lower strength of Mix 1 relative to Mix 2 cannot be interpreted as an effect of increasing the RHA content to 10 wt.%, because the total Portland cement + RHA content also differed, amounting to 32.0 wt.% for Mix 1 and 28.5 wt.% for Mix 2. In addition, Portland cement content, total mixing water, *w/c*, fiber dosage, superplasticizer dosage, and aggregate proportions varied simultaneously. Therefore, the present results do not establish an optimum RHA dosage or an independent relationship between total cement + RHA content and compressive strength.

Figure 6 provides an integrated comparison of the measured properties of the control concrete and Mix 2. Because several constituents varied simultaneously, the observed differences represent the response of the complete multicomponent formulation and

do not isolate the independent effects of wet grinding, RHA, polypropylene fibers, or the superplasticizer.

3.3. Fracture-Related Behavior of the Multicomponent Formulations

The fracture-related results are interpreted as comparisons among the complete multicomponent formulations. Because polypropylene-fiber content varied simultaneously with RHA, Portland cement, superplasticizer, water content, w/c , total Portland cement + RHA content, and aggregate proportions, the present dataset does not establish an independent effect of fiber dosage on crack resistance or mechanical performance.

3.4. Fracture Toughness

Mix 2 exhibited the highest apparent fracture toughness among the tested formulations. However, because fiber dosage and the other mixture parameters varied simultaneously, this result cannot be interpreted as evidence that 4 wt.% is an optimum fiber dosage or that the fracture-toughness difference was caused independently by polypropylene fibers. The crack-initiation loads, maximum loads, and apparent fracture-toughness values are presented in Table 7.

Table 7. Comparative crack-initiation loads and apparent fracture-toughness characteristics of the investigated concrete mixtures.

Mix	Crack Initiation Load, kN	Maximum Load, kN	Fracture Toughness KIC, MPa·m ^{1/2}
Control	5.15	7.71	1.15 ± 0.05 ^d
Mix 1	7.75	9.25	1.75 ± 0.03 ^c
Mix 2	8.51	10.02	2.16 ± 0.02 ^a
Mix 3	8.04	9.45	1.86 ± 0.04 ^b

Different superscript lowercase letters (a–d) indicate statistically significant differences among the mixtures according to Tukey's HSD post-hoc test ($p < 0.05$).

Values are presented as mean ± standard deviation based on three replicate specimens ($n = 3$). Different superscript lowercase letters indicate statistically significant differences among the mixtures according to Tukey's HSD post-hoc test ($p < 0.05$). One-way ANOVA confirmed a significant effect of mixture composition on fracture toughness, $F(3,8) = 419.80$, $p < 0.001$. The fracture-tested polypropylene fiber-reinforced concrete specimen is shown in Figure 7.

The apparent fracture-toughness values differed significantly among the complete formulations. Mix 2 exhibited the highest measured value; however, the experimental design does not allow this difference to be assigned independently to polypropylene fibers, RHA, wet co-grinding, or any other individual parameter.

During testing, the specimens were subjected to incremental loading with simultaneous recording of vertical displacements. Based on the test results, the crack initiation load, critical stress intensity factor, ultimate load, and corresponding normal stresses in the material were determined.

The fracture toughness parameter was calculated using the following equation:

$$K_c^* = \frac{3F_c^* L_0}{2bt^2} \sqrt{\pi\alpha} \frac{1.99 - \alpha(1 - \alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)}{(1 + 2\alpha)(1 - \alpha)^{3/2}}$$

where F_c^* is the load corresponding to the dynamic initiation of crack propagation L_0 , b , and t are the specimen dimensions (m); $\alpha = a_0/b$ is the relative notch depth; and a_0 is the initial notch length (m).

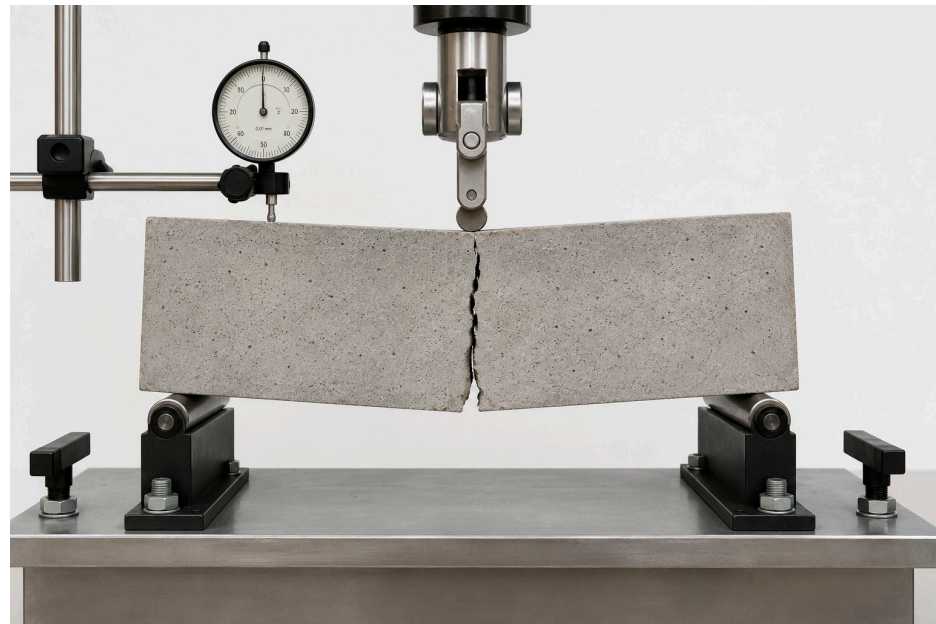


Figure 7. Polypropylene fiber-reinforced concrete specimen after completion of the fracture toughness test.

An increase in fiber content resulted in a greater scatter of the measured values, indicating a higher degree of non-uniform fiber distribution within the specimens. When higher fiber dosages are used in concrete mixtures, which may be necessary in structures reinforced solely with dispersed fibers and without conventional reinforcing bars, special measures should be implemented to ensure uniform fiber distribution throughout the concrete element.

Compared with the control formulation, Mix 2 exhibited an observed package-level difference in apparent fracture toughness from 1.15 to 2.16 MPa·m^{1/2}. This comparison does not identify the independent contribution of any constituent or processing parameter.

3.5. Frost Resistance

The frost-resistance results are presented in Figure 8. Under the adopted laboratory conditions, the modified formulations exhibited measured freeze–thaw resistance values of 211–242 cycles, compared with 138 cycles for the control formulation. Mix 2 showed the highest measured value of 242 cycles. Because the complete mixture compositions differed, these results represent package-level comparisons and cannot be attributed independently to RHA, polypropylene fibers, superplasticizer, total water content, w/c , total Portland cement + RHA content, aggregate proportions, or wet co-grinding.

One-way ANOVA confirmed that mixture composition had a statistically significant effect on frost resistance, $F(3,8) = 548.51$, $p < 0.001$. Tukey's HSD post-hoc test showed statistically significant differences among all investigated mixtures ($p < 0.05$). Mix 2 exhibited the highest frost resistance, with a mean value of 242 ± 4 cycles.

A concurrent reduction in water absorption was observed in the modified formulations. However, the present experimental design does not establish a causal relationship between water absorption and freeze–thaw resistance. As shown in Table 6, water absorption decreased from 6.8% for the control concrete to 5.1% for Mix 2. Lower water absorption reduces the amount of free water available within the pore system and consequently decreases the hydraulic pressure generated during freezing. Similar relationships between reduced water absorption, refined pore structure, and improved durability have

been reported for concrete incorporating RHA and other supplementary cementitious materials [11,27].

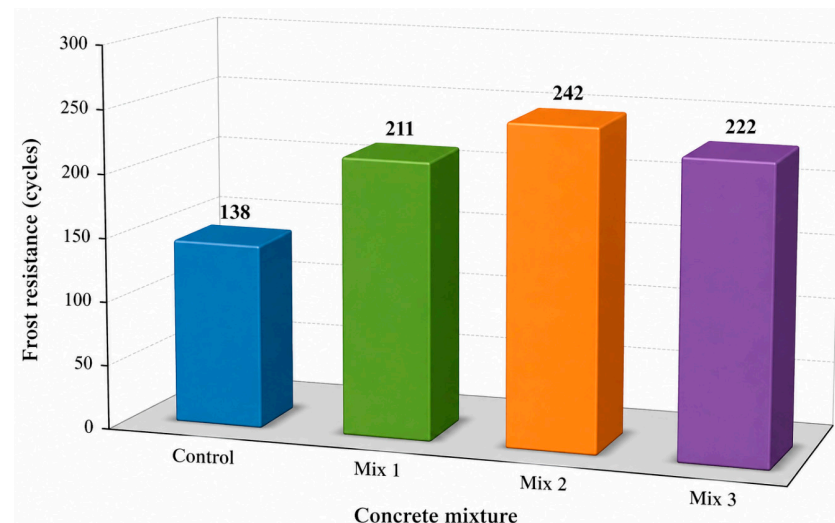


Figure 8. Frost resistance of the control and modified concrete mixtures after repeated freeze–thaw cycles. Blue, green, orange, and purple bars represent the Control, Mix 1, Mix 2, and Mix 3 formulations, respectively. Columns represent mean values, and error bars indicate standard deviations based on three replicate specimens ($n = 3$).

All modified formulations exhibited higher measured freeze–thaw resistance than the control under the adopted laboratory conditions, with Mix 2 showing the highest value. Because the complete mixture compositions differed, the observed freeze–thaw results cannot be attributed independently to RHA, polypropylene fibers, superplasticizer, w/c , total water content, total Portland cement + RHA content, or wet co-grinding.

3.6. Microstructural Analysis

The SEM and XRD observations provide qualitative evidence of morphological and phase-related differences between the control and modified concretes but do not quantify changes in RHA reactivity, portlandite consumption, or secondary C–S–H formation.

The SEM micrographs presented in Figure 9 show qualitative morphological differences between the selected fields of the control and modified concrete specimens. The examined field of the control specimen exhibits a relatively heterogeneous appearance with visible pores, microcracks, and irregularly distributed hydration products, whereas the modified specimen appears more continuous and compact, with fewer visible large pores. However, quantitative SEM image analysis, multiple-field statistical evaluation, and SEM–EDS elemental mapping were not performed. Therefore, these observations are restricted to the selected fields of view and should not be interpreted as quantitative evidence of reduced porosity, increased C–S–H content, or improved interfacial bonding. The regions annotated as probable C–S–H gel and needle-like ettringite were identified on the basis of morphology and do not represent definitive phase identification. Similar morphological features have been reported in previous studies of RHA-containing cementitious systems using SEM–EDS and complementary characterization methods [9,32,33].

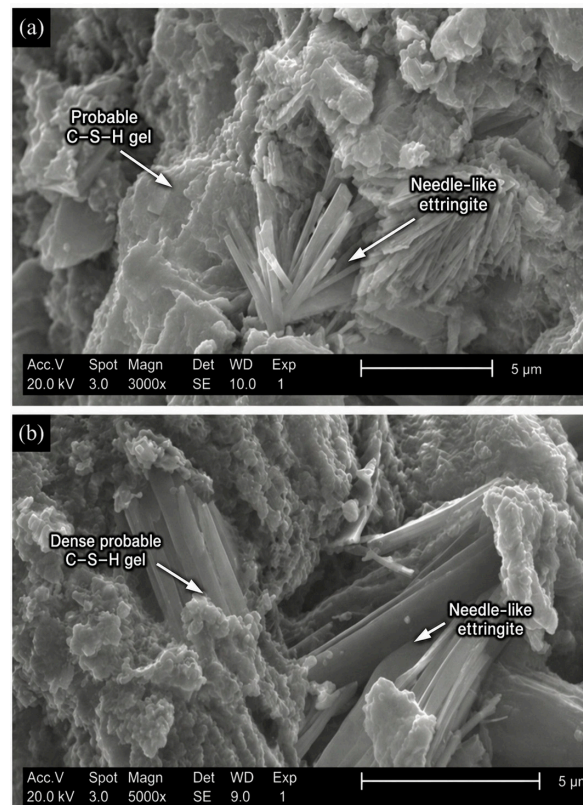


Figure 9. SEM micrographs of the concrete microstructure after 28 days of curing: (a) control concrete and (b) concrete containing the mechanochemically activated rice husk ash-based organomineral modifier. The probable locations of C–S–H gel and needle-like ettringite are indicated.

These qualitative interpretations are consistent with recent studies that employed SEM, SEM–EDS, XRD, XRF, and complementary microstructural characterization methods to evaluate RHA-containing cementitious systems [9,32,33].

3.7. XRD Analysis

Figure 10 presents the XRD patterns of the control concrete, Mix 1 containing 10 wt.% RHA, and the best-performing tested Mix 2 containing 6 wt.% RHA after 28 days of curing.

The XRD patterns showed crystalline reflections associated with quartz, portlandite, calcite, and ettringite. Differences in portlandite peak intensity and amorphous background were observed among the selected specimens. However, because the analysis was qualitative and the complete mixture compositions differed, these variations cannot be used to quantify portlandite consumption, RHA reactivity, or the independent effect of wet co-grinding.

Because calcium silicate hydrate (C–S–H) is predominantly poorly crystalline, it generally does not produce distinct diffraction peaks and cannot be directly identified by conventional XRD. The broad diffuse halo observed in the range of approximately 20–35° 2θ may be associated with poorly crystalline hydration products and residual amorphous silica. Therefore, the enhanced formation of secondary C–S–H in the modified concrete was inferred indirectly from the reduction in portlandite peak intensity, the increased amorphous background, and the SEM observations, rather than from a discrete C–S–H diffraction peak. These findings are consistent with previous studies reporting that the pozzolanic reaction of RHA consumes portlandite and contributes to the formation of poorly crystalline secondary hydration products [3,5,6]. Comparable qualitative trends, including portlandite consumption, changes in the poorly crystalline or amorphous fraction, and

denser hydration-product morphologies, have been reported for RHA-containing blended systems [9,32,33].

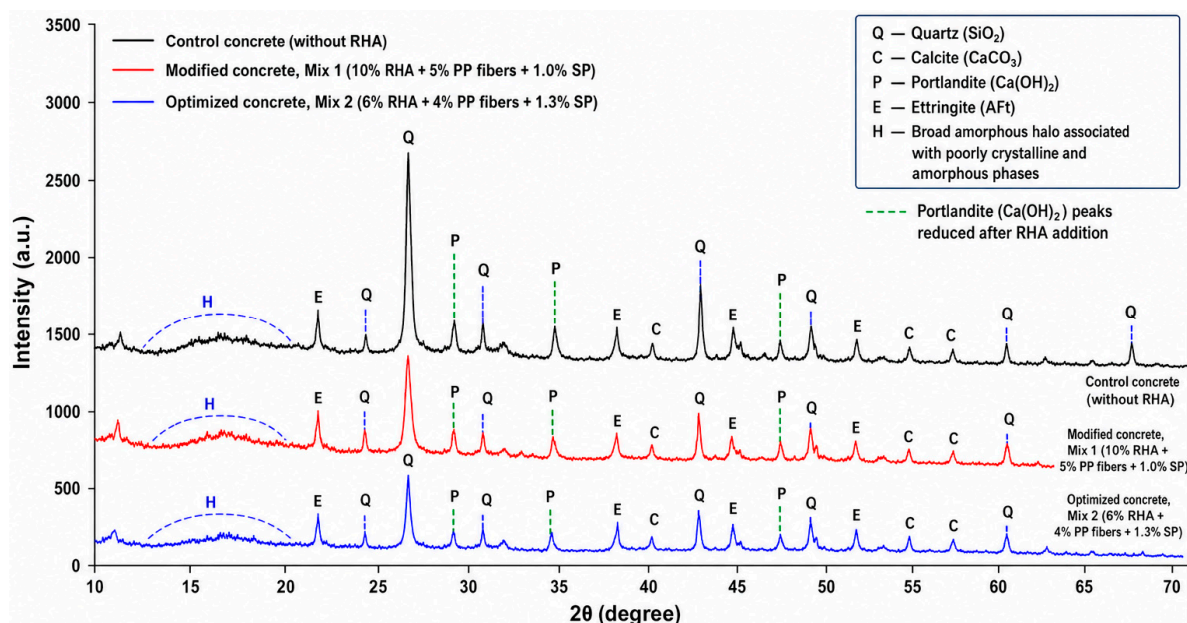


Figure 10. XRD patterns of the control concrete, modified concrete Mix 1 containing 10 wt.% RHA, 5 wt.% polypropylene fibers, and 1.0 wt.% superplasticizer, and best-performing tested concrete Mix 2 containing 6 wt.% RHA, 4 wt.% polypropylene fibers, and 1.3 wt.% superplasticizer after 28 days of curing. Q—quartz; C—calcite; P—portlandite; E—ettringite; H—broad amorphous halo associated with poorly crystalline and amorphous phases.

It should be emphasized that the present XRD analysis was qualitative. No internal standard, Rietveld refinement, or other quantitative phase-analysis procedure was applied. Consequently, differences in peak intensity should not be interpreted as direct quantitative changes in phase content. They are discussed only as qualitative trends that are consistent with portlandite consumption and changes in the poorly crystalline and amorphous fraction of the investigated cementitious systems.

4. Discussion

Because several mixture parameters were varied simultaneously, the differences among Mix 1–Mix 3 reflect the combined response of the complete multicomponent formulations. Accordingly, the observed changes cannot be attributed independently to RHA content, fiber dosage, or superplasticizer dosage. The mechanistic interpretations presented below should therefore be understood as explanations consistent with the combined experimental trends and published evidence, rather than as independently verified effects of individual constituents.

Wet grinding produced a co-ground binder with a final specific surface area of approximately $4000\text{--}4500\text{ cm}^2/\text{g}$ and may have improved particle dispersion and contact between the solid phases and mixing water. These physical changes provide a plausible basis for the observed performance trends. Nevertheless, the study did not include a compositionally identical binder containing unground RHA and did not directly measure hydration kinetics or pozzolanic reactivity. Consequently, an increase in RHA chemical reactivity caused specifically by the wet-grinding treatment cannot be established from the present results. The proposed effects on portlandite consumption and secondary hydration-product formation should therefore be regarded as interpretations consistent with the qualitative SEM and XRD observations and published literature, rather than as directly verified mechanisms.

The nominal $w/(c + \text{RHA})$ ratio reported in Table 3 should not be interpreted as an efficiency-adjusted water-to-binder ratio. The full RHA mass was included only to provide an arithmetic description of the total cement-plus-RHA content. Because no efficiency factor was experimentally determined for the investigated RHA, its cement equivalence remains unknown. Accordingly, w/c is used as the primary water-related parameter when discussing the performance differences among the formulations.

The total Portland cement + RHA content also varied among the formulations, from 27.0 to 32.0 wt.% of the non-water constituents. Consequently, the strength difference between Mix 1 and Mix 2 cannot be assigned specifically to the difference in RHA dosage. It may reflect the combined effects of total cement + RHA content, Portland cement content, w/c , water content, fiber and superplasticizer dosages, aggregate proportions, and wet co-grinding. The present dataset does not permit these contributions to be separated.

Among the investigated complete formulations, Mix 2 exhibited the highest compressive strength. However, this result should not be interpreted as demonstrating an optimum RHA content of 6 wt.%, because RHA dosage changed simultaneously with the contents of Portland cement, polypropylene fibers, superplasticizer, aggregates, total mixing water, and w/c . The lower w/c of Mix 2 relative to Mix 1 may have contributed to its higher strength. Nevertheless, Mix 3 had an even lower w/c but did not reach the strength of Mix 2. Therefore, neither RHA dosage nor w/c can be isolated as the principal causal variable from the present dataset. Mix 2 is identified only as the best-performing tested complete formulation.

The present experimental program permits comparison of the complete formulations but does not permit causal attribution to individual constituents or mechanisms. Differences in mechanical strength, fracture toughness, water absorption, freeze–thaw resistance, and qualitative SEM/XRD characteristics may reflect the combined influence of composition and processing. However, the relative contributions of Portland cement content, RHA dosage, total Portland cement + RHA content, polypropylene fibers, superplasticizer, water content, w/c , aggregate proportions, and wet co-grinding cannot be separated using the present dataset. Accordingly, explanations involving pozzolanic reaction, particle packing, matrix refinement, and fiber crack bridging are considered only as possible mechanisms reported in the literature and are not presented as mechanisms experimentally demonstrated in this study.

Among the three tested formulations, Mix 2 provided the most favorable overall performance. However, because the contents of RHA, polypropylene fibers, superplasticizer, Portland cement, aggregates, total mixing water, and the w/c ratio varied simultaneously, this result should be interpreted as the response of the complete multicomponent formulation rather than as evidence of an optimum dosage of any individual constituent.

The sustainability relevance of the investigated formulations is primarily associated with the beneficial use of RHA as an agricultural by-product and its incorporation at contents of 4–10 wt.%, including 6 wt.% in the best-performing tested formulation. Wet co-grinding required a nominal electrical energy input of approximately 0.058 kWh per laboratory activation batch. However, scale-up may involve additional energy demand, equipment requirements, and costs associated with RHA collection, controlled combustion, transportation, grinding, polypropylene fibers, and the polycarboxylate superplasticizer. Neither a comparative life-cycle assessment nor an economic analysis was performed in the present study. Therefore, the results demonstrate the potential for agricultural-waste utilization but do not establish a lower carbon footprint, reduced overall environmental impact, or economic advantage compared with conventional concrete. Future studies should include comparative life-cycle and cost analyses based on scale-relevant material, energy, transportation, and processing data.

The sustainability relevance of the investigated formulations is primarily associated with the beneficial use of rice husk ash as an agricultural by-product and its partial incorporation into the concrete mixture. RHA accounted for 4–10 wt.% of the investigated formulations, including 6 wt.% in the best-performing tested formulation. In addition, the nominal electrical energy input for wet grinding was approximately 0.058 kWh per activation batch. However, these material-use and process-energy indicators do not constitute a quantitative sustainability assessment. A cradle-to-gate or cradle-to-grave life-cycle assessment was not performed, and greenhouse gas emissions, embodied energy, transportation distances, RHA combustion and processing impacts, and the environmental contributions of polypropylene fibers and the polycarboxylate superplasticizer were not quantified. Consequently, the present results demonstrate the potential for agricultural-waste utilization but do not directly establish a lower carbon footprint or reduced overall environmental impact compared with conventional concrete. Future studies should perform a comparative life-cycle assessment using experimentally verified material inventories and locally relevant energy and transportation data.

Despite the promising mechanical and durability-related results, the microstructural evidence obtained in this study remains primarily qualitative. Quantitative XRD phase analysis using an internal standard or Rietveld refinement was not performed, and the SEM observations were not supplemented by quantitative image analysis or SEM-EDS elemental mapping. The SEM assessment was limited to selected fields of view, and multiple-field analysis at identical magnification, including measurements of pore-area fraction, crack density, particle-size distribution, and interfacial transition zone thickness, was not conducted. Therefore, the proposed explanations concerning portlandite consumption, secondary poorly crystalline hydration-product formation, pore refinement, and interfacial transition zone densification should be regarded as qualitative interpretations consistent with the observed XRD and SEM trends and previously published findings, rather than as direct quantitative verification of these mechanisms. Future studies should include Rietveld-based phase quantification, thermogravimetric analysis, mercury intrusion porosimetry, micro-computed tomography, standardized SEM specimen preparation, backscattered-electron imaging, automated image segmentation, multiple-field statistical analysis, and SEM-EDS elemental mapping to quantitatively verify the proposed microstructural mechanisms.

In addition, no direct assessment of the activation-induced change in RHA reactivity was performed. The study did not include an otherwise identical binder containing non-activated RHA, and isothermal calorimetry, Frattini or Chapelle testing, dissolution analysis, or quantitative phase analysis was not conducted. Therefore, the specific effect of wet co-grinding on the chemical or pozzolanic reactivity of RHA could not be independently established. Future work should directly compare activated and non-activated binders under otherwise identical compositional and curing conditions.

The raw-material characterization also had several limitations. Batch-specific XRF analysis of RHA, complete aggregate sieve-distribution curves, verified polypropylene-fiber diameter and tensile strength, and the specific surface area of the unground Portland cement–RHA blend were not available. Consequently, the reported RHA composition is indicative, and the magnitude of the change in binder fineness caused by wet co-grinding cannot be quantified directly from the present data. Future studies should include batch-specific XRF, complete sieve analysis, detailed fiber characterization, and measurements of the binder specific surface area before and after treatment.

Overall, the findings demonstrate that the integrated use of a wet co-ground Portland cement–RHA binder, polypropylene fibers, and a polycarboxylate superplasticizer improved the mechanical, fracture-related, and durability-related performance of the investigated concrete formulations relative to the control concrete. However, because the

contents of several constituents varied simultaneously, the observed improvements represent the combined response of the complete multicomponent formulations and should not be attributed independently to any single constituent or mechanism. Furthermore, classification of the developed formulations as environmentally superior or low-carbon concrete requires a comparative quantitative life-cycle assessment.

Compared with the control concrete, the best-performing tested formulation exhibited a 22.3% increase in compressive strength, a 26.1% increase in flexural strength, and an 87.8% increase in fracture toughness. The measured freeze–thaw resistance values of 211–242 cycles also indicate improved performance under the adopted laboratory test conditions. Nevertheless, long-term exposure testing and field-scale validation are required before confirming the suitability of these concretes for severe climatic conditions.

The specimen dimensions represent a limitation of the present study. The $40 \times 40 \times 160$ mm prisms provided a specimen-width-to-maximum-aggregate-size ratio of 4:1 for the 5–10 mm dolomite aggregate. This ratio may increase sensitivity to the local distribution of coarse aggregate and fibers within the specimen cross-section. Accordingly, the reported fracture-toughness values are primarily suitable for comparative assessment among the investigated mixtures. Future validation should use specimens with larger cross-sectional dimensions.

5. Conclusions

The key findings of this study are summarized as follows:

Wet co-grinding produced a binder with a final specific surface area of approximately $4000\text{--}4500\text{ cm}^2/\text{g}$. This result confirms the physical processing outcome; however, the present study does not provide direct evidence that the treatment increased the chemical or pozzolanic reactivity of RHA.

Among the three modified formulations investigated, Mix 2 provided the most favorable overall combination of mechanical performance, fracture resistance, water absorption, and freeze–thaw resistance. However, because the total mixing-water content, w/c ratio, total Portland cement + RHA content, and the proportions of Portland cement, RHA, polypropylene fibers, superplasticizer, and aggregates varied simultaneously, this result applies only to the complete formulations tested. It should not be interpreted as establishing an optimum RHA dosage or the independent influence of any individual constituent, water ratio, or total cement + RHA content.

After 28 days of curing, Mix 2 achieved a compressive strength of 45.0 MPa and a flexural strength of 5.8 MPa, corresponding to observed differences of 22.3% and 26.1%, respectively, relative to the control formulation. These values represent package-level comparisons between complete formulations with different constituent proportions and w/c ratios and should not be interpreted as independently verified effects of RHA, fibers, superplasticizer, or wet co-grinding.

The fracture toughness increased from $1.15\text{ MPa}\cdot\text{m}^{1/2}$ for the control concrete to $2.16\text{ MPa}\cdot\text{m}^{1/2}$ for Mix 2, corresponding to an improvement of 87.8%. This value represents an observed package-level difference between the complete control and Mix 2 formulations and does not establish the independent contribution of polypropylene fibers.

Water absorption decreased from 6.8% for the control concrete to 5.1% for Mix 2, representing a reduction of approximately 25.0%. These values represent observed differences between the complete formulations under the adopted laboratory test conditions; the experimental design does not identify the individual causes of these differences.

Qualitative SEM and XRD observations showed morphological and phase-related differences between the selected control and modified specimens. However, because quantitative SEM image analysis, SEM–EDS mapping, an internal XRD standard, and

quantitative phase analysis were not used, these observations do not establish changes in porosity, hydration-product content, RHA reactivity, or the causes of the measured performance differences.

The measured differences represent the combined response of the complete multicomponent formulations. Because the mixture constituents, water content, w/c , total Portland cement + RHA content, and processing conditions were not varied independently, the present results do not establish an optimum RHA or fiber dosage and do not quantify the independent influence of wet co-grinding, RHA, polypropylene fibers, superplasticizer, or any proposed microstructural mechanism. Future work should employ factorial or controlled one-variable-at-a-time experiments with fixed w/c and fixed total cementitious-material content.

The incorporation of 4–10 wt.% RHA demonstrates the potential for beneficial utilization of an agricultural by-product in concrete production. Nevertheless, the present study did not include a quantitative assessment of greenhouse gas emissions, embodied energy, resource consumption, transportation, or life-cycle impacts. Therefore, no definitive conclusion can be drawn regarding the overall environmental superiority of the developed formulations. A comparative life-cycle assessment incorporating the energy demand of wet grinding and the environmental contributions of all constituent materials is required in future work.

6. Practical Implications

The developed concrete may be used for structural and non-structural building elements requiring compressive strengths of approximately 40–45 MPa while reducing cement consumption through the utilization of agricultural waste-derived supplementary materials.

7. Patent

The technology described in this study is protected by a utility model patent of the Republic of Kazakhstan. Uderbayev, S.S.; Zhakypova, G.M.; Zhakapbayeva, G.A.; Saktaganova, N.A.; Arystanbek, A.B.; Budikova, A.M.; Tulegenova, G.S.; Abiyeva, G.S.; Zhapakhova, A.U. Activated Concrete Mixture; Utility Model Patent No. KZ 9604, Republic of Kazakhstan, published on 27 September 2024.

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