Cleaner Engineering and Technology 20 (2024) 100752

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

Exploring the synergistic effect of recycled glass fibres and agricultural waste ash on concrete strength and environmental sustainability

Timoth Mkilima [a,*], Yerlan Sabitov [b], Zhanbolat Shakhmov [b,**], Talgat Abilmazhenov [b], Askar Tlegenov [b], Atogali Jumabayev [b], Agzhaik Turashev [b], Zhanar Kaliyeva [b]

[a] *Department of Environmental Engineering and Management, The University of Dodoma, P. O. Box 259, Dodoma, Tanzania*
[b] *Faculty of Architecture and Construction, Department of Technology of Industrial and Civil Engineering, L.N. Gumilyov Eurasian National University, 010008, Astana, Kazakhstan*

ARTICLE INFO

Keywords:
Recycled glass fibres
Agricultural waste ash
Concrete strength
Sustainability
Environmental protection

ABSTRACT

In today's age, finding harmony between construction endeavors and safeguarding the environment is of utmost importance. Consequently, there is a substantial requirement to explore the feasibility of utilizing waste materials as a replacement for traditional construction substances. Unfortunately, there is a lack of information regarding the possibilities of incorporating recycled glass, rice husk, and sugarcane bagasse ash into concrete production. This study investigated the viability of integrating recycled glass fibres and agricultural waste ash into concrete to bolster its strength and sustainability. When evaluating mechanical and durability properties across five mixtures, the concrete formulations ranged in fibre content percentages from 1% to 3% and in ash content percentages from 10% to 20%. Specifically, Mixtures 1, 2, 3, 4, and 5 contained 1% fibre and 10% ash, 2% fibre and 15% ash, 2.5% fibre and 20% ash, 3% fibre and 12% ash, and 1.5% fibre and 18% ash respectively. Mixture 2 and Mixture 5, boasting heightened fibre and ash content, showcased outstanding compressive strength at 38.5 MPa and 37.2 MPa, respectively, indicating a positive correlation between these materials and concrete strength. Conversely, Mixture 3, burdened with excessive fibre and ash content, witnessed diminished strength, underscoring the necessity for meticulous optimization. In terms of tensile and flexural strength, Mixture 2 and Mixture 5 displayed commendable performance, while Mixture 3 suffered setbacks from excessive content. Durability assessments unveiled Mixture 1 and Mixture 4's superior freeze-thaw resistance, with minimal mass loss (1.5% and 1.8%, respectively) and no visible damage, rendering them favorable choices for sustainable construction. Contrastingly, Mixture 3 exhibited poorer freeze-thaw resistance and higher environmental impact, highlighting the need for careful consideration in material selection. Overall, this study underscores the importance of optimizing concrete formulations through the integration of recycled materials, paving the way for stronger, more durable, and environmentally friendly construction practices.

1. Introduction

Concrete, as a versatile and widely used construction material, has played a pivotal role in the development of modern infrastructure. However, the conventional production of concrete is associated with significant environmental concerns, including high carbon emissions, energy consumption, and depletion of natural resources (Cazacliu and Ventura, 2010). In recent years, the construction industry has been actively seeking sustainable alternatives to improve the environmental performance of concrete while maintaining its strength and durability (Yücel et al., 2023). One promising approach to address these challenges is the integration of waste materials into concrete production (Qaidi et al., 2022). Researchers and engineers have explored various waste materials, such as recycled glass fibres and agricultural waste ash, as potential replacements or additives in concrete mixtures. These materials offer multiple advantages, including waste reduction, enhanced

---

* Corresponding author.

** Corresponding author.

E-mail addresses: timoth.mkilima@udom.ac.tz (T. Mkilima), sabitov_yeye@enu.kz (Y. Sabitov), shakhmov_zha@enu.kz (Z. Shakhmov), abilmazhenov_tsh@enu.kz (T. Abilmazhenov), tlegenov_az@enu.kz (A. Tlegenov), dzhumabaev_aa@enu.kz (A. Jumabayev), turashev_as@enu.kz (A. Turashev), kaliyeva_zh@enu.kz (Z. Kaliyeva).

https://doi.org/10.1016/j.clet.2024.100752
Received 10 March 2024; Received in revised form 27 April 2024; Accepted 1 May 2024

mechanical properties, and reduced environmental impact (Ahmad et al., 2022; Bheel et al., 2023). It is important to note that the incorporation of fibres into concrete mixtures has emerged as a promising strategy for enhancing mechanical strength and durability in construction materials. Fibre reinforcement, whether natural or synthetic, has been shown to improve concrete's resistance to cracking, impact, and fatigue, thereby extending its service life and enhancing structural performance. Fibres act as reinforcement elements within the concrete matrix, redistributing stresses and preventing crack propagation. Additionally, fibres can improve the ductility and toughness of concrete, enabling it to withstand higher loads and harsh environmental conditions (Çevik and Niş, 2023).

Recycled glass fibres, derived from waste glass bottles and containers, provide an eco-friendly alternative to conventional steel reinforcement in concrete. By incorporating glass fibres, the demand for steel can be reduced, leading to resource conservation and a decrease in carbon emissions associated with steel production (Khan et al., 2020;Al et al., 2023; Moreno-Maroto et al., 2019). Glass fibres also offer excellent resistance to corrosion and high tensile strength, which can enhance the overall performance and durability of concrete structures (Hamada et al., 2022; Fu et al., 2021). Similarly, agricultural waste ash, obtained from sources such as rice husks and sugarcane bagasse, has emerged as a valuable supplementary cementitious material. When properly processed and incorporated into concrete, agricultural waste ash exhibits pozzolanic properties, enabling it to partially replace cement (Diniz et al., 2022; Iftikhar et al., 2022). This substitution not only reduces the carbon footprint of concrete production but also enhances its mechanical properties, such as compressive strength and durability (Ismaeel et al., 2023; Hameed and Kalaiyarasan, 2022).

While the integration of recycled glass fibres and agricultural waste ash in concrete shows tremendous potential, several challenges need to be addressed. The optimization of fibre dosage, ash content, and their compatibility with other concrete constituents require careful consideration. Additionally, the implications on fresh and hardened concrete properties, as well as long-term durability, must be thoroughly investigated to ensure the feasibility and effectiveness of these sustainable materials. Prior research efforts in this field have demonstrated encouraging results. Studies have reported improvements in the tensile, flexural, and impact strength of fibre-reinforced concrete, along with enhanced resistance to cracking and improved durability against chemical attacks. For instance, Ahmadi (2022), conducted a study on the impact of using glass waste as a substitute for cement on the mechanical properties of concrete. The results obtained from the compressive strength test revealed a positive correlation between the inclusion of glass powder in the concrete mixture and the strength of the concrete. Notably, the sample that contained 15 wt% of glass powder displayed the highest compressive strength value among all the tested samples. This finding highlights the beneficial effect of incorporating glass powder on enhancing the structural strength of the concrete material.

Similarly, the incorporation of agricultural waste ash has shown positive effects on the mechanical properties and durability characteristics of concrete, including increased strength development, reduced permeability, and enhanced resistance to chloride ion penetration (Kilani et al., 2022; Kareem et al., 2023; S. B. et al., 2023). In a study conducted by Hamada et al. (2023), the aim was to optimize the properties of sustainable concrete by incorporating two key components: palm oil clinker (POC) and nano-palm oil fuel ash (NPOFA). The authors employed response surface methodology to analyze the effects of these additions. The results demonstrated that the inclusion of NPOFA binder had a positive impact on both the workability and compressive strength of the concrete material. Moreover, the utilization of NPOFA contributed significantly to enhancing the overall sustainability of the concrete industry. In addition to the technical improvements, the study also evaluated the economic and environmental aspects of the modified concrete. It was found that the addition of NPOFA and POC led to significant cost reductions and a decrease in carbon emissions associated with concrete production. Notably, NPOFA demonstrated a particularly pronounced effect in reducing both costs and environmental impact. However, as previously highlighted, despite these advancements, there is still a need for further research and development to optimize the integration of recycled glass fibres and agricultural waste ash in concrete.

This study aims to investigate the innovative integration of recycled glass fibres and agricultural waste ash in concrete to enhance both its strength and sustainability. The research focuses on determining the optimal levels of fibre reinforcement and ash content through a comprehensive experimental program. The mechanical properties, including compressive strength, tensile strength, and flexural strength, will be evaluated to assess the performance of the developed concrete mixtures. Additionally, the durability properties, such as freeze-thaw resistance, chloride ion permeability, and abrasion resistance, will be examined to ensure the long-term durability and serviceability of the concrete.

2. Materials and methods

2.1. *Material collection and preparation*

2.1.1. *Recycled glass fibres*

The process began by gathering waste glass bottles and containers from local recycling centers, emphasizing the importance of sourcing materials sustainably (Fig. 1). Subsequently, the collected glass underwent a meticulous cleaning procedure, ensuring the removal of labels, dirt, and contaminants. Following the cleaning phase, a mechanical crusher was employed to crush the glass into smaller pieces (with typical lengths ranging from 1 to 50 mm and aspect ratios ranging from 10:1 to 80:1), facilitating further processing. The crushed glass underwent additional refinement in a ball mill, ultimately transforming it into a fine glass powder. To attain the desired particle size range for fibre production, the glass powder underwent sieving. The sieved glass powder was then introduced into a fibreizing machine, where a combination of heat and mechanical forces transformed it into fibres with specific lengths and diameters. The resulting glass fibres underwent thorough inspection to ensure quality and were subsequently stored in a dry and secure area to prevent moisture absorption. This comprehensive process highlights the systematic and sustainable approach taken to convert waste glass into high-quality fibres suitable for various applications.

2.1.2. *Agricultural waste ash*

The initial phase involved acquiring rice husk ash from local rice mills and sugarcane bagasse ash from sugar refineries, emphasizing the sourcing of these materials from community-based establishments (Fig. 2). Subsequently, the collected ash underwent a preliminary air-drying process to eliminate excess moisture, a crucial step in preparing the material for further treatment. Following the drying stage, the dry ash was subjected to controlled calcination in a furnace maintained at 600 °C for a duration of 2 h. The calcining process at 600 °C for 2 h was selected based on prior experimental data, which indicated that this combination achieved the desired level of transformation in the material while ensuring optimal energy consumption and practical feasibility. This calcination process aimed to enhance the pozzolanic properties of the ash, crucial for its intended applications. After calcination, the ash was finely ground using a ball mill to achieve a consistent powder texture. To ensure uniformity in particle size and remove any coarse particles, the ground ash underwent sieving. The sieved ash powder was then meticulously stored in airtight containers, implemented as a preventive measure against moisture absorption, safeguarding the quality and integrity of the final product. This detailed procedure underscores the systematic approach in obtaining, processing, and preserving rice husk ash and sugarcane bagasse ash for optimal utilization in various applications.

Fig. 1. Recycled glass.

Fig. 2. Agricultural waste ash (a) rice husk ash (b) sugarcane bagasse ash.

2.2. *Experimental groups*

2.2.1. *Control group*

The control group consisted of concrete prepared using Ordinary Portland Cement (OPC), sand, and coarse aggregates without any additional waste materials (Table 1).

2.2.2. *Mixture groups*

The mixture contents for the materials used in the study were achieved through variations in both fibre content and ash content in the concrete mixtures. The researchers labeled these mixtures as Mixture 1, Mixture 2, Mixture 3, Mixture 4, and Mixture 5 (Table 2). The fibre content in each mixture was adjusted to different percentages, while the ash content was also varied accordingly. In terms of fibre content, the specific percentages used in each mixture were as follows: Mixture 1 had a fibre content of 1%, Mixture 2 had 2%, Mixture 3 had 2.5%, Mixture 4 had 3%, and Mixture 5 had 1.5%. On the other hand, the ash content in the mixtures also differed. Mixture 1 had an ash content of 10%, Mixture 2 had 15%, Mixture 3 had 20%, Mixture 4 had 12%, and Mixture 5 had 18%. By manipulating the fibre content and ash content in each mixture, the researchers were able to examine and analyze the effects of varying levels of fibre reinforcement and ash content on the properties of the concrete. This allowed them to gain insights into how these changes influenced the overall characteristics and performance of the concrete material.

Table 1
Properties of the cement used in the study.

Property	Typical Value	Unit
Chemical Composition	–	–
- Silica with a chemical formula: SiO_2	24.4	wt%
- Alumina with a chemical formula Al_2O_3	8.1	wt%
- Iron Oxide with a chemical formula Fe_2O_3	5.5	wt%
- Calcium Oxide with a chemical formula CaO	62	wt%
Physical Properties	–	–
- Specific Gravity	2.3–2.6	unitless
- Fineness (Blaine)	300–500	mˆ2/kg
- Setting Time	Initial: 30–90, Final: 180-360	minutes
Investigated Mechanical Properties	–	–
- Recycled glass concrete Compressive Strength	3 days: 20–40, 28 days: 40-60	MPa
- Recycled glass concrete Tensile Strength	3.2	MPa
- Recycled glass concrete Flexural Strength	4.6	MPa
Thermal Properties	–	–
- Heat of Hydration	70–90	cal/g
Other Characteristics	–	–
- Color	Varies	–
- Setting Retarders	Presence/Absence	

Table 2
Summary of the mixture contents.

Concrete Mixture	Fibre Content (%)	Ash Content (%)
Mixture 1	1	10
Mixture 2	2	15
Mixture 3	2.5	20
Mixture 4	3	12
Mixture 5	1.5	18

2.3. Mix design

Following the guidelines outlined by the American Concrete Institute (ACI), the mix design process adhered to specific criteria for optimal concrete performance. A consistent water-to-cement ratio (w/c) of 0.45 was maintained across all concrete mixes to ensure uniformity. Proportions of sand, coarse aggregates, and cement were meticulously adjusted to meet the specified workability and strength requirements. To enhance flowability and workability, a polycarboxylate ether (PCE) superplasticizer admixture was introduced into the concrete formulations, especially considering the incorporation of fibres and ash. The determination of mix proportions for each experimental group was a result of systematic trial mixes and subsequent adjustments, undertaken to achieve the targeted fresh and hardened properties, thereby emphasizing a precision-driven and guideline-compliant approach in the concrete mix design process.

2.4. Testing plan

2.4.1. Mechanical properties

To assess the compressive strength, concrete cubes measuring 150 mm × 150 mm x 150 mm were carefully cast and subjected to a water curing process for a period of 28 days before testing (Fig. 3). The determination of compressive strength followed the guidelines outlined in ASTM C39 standards (American Society for Testing and Materials et al., 2001), employing a compression testing machine. For the split tensile strength analysis, cylindrical concrete specimens with a diameter of 150 mm and a height of 300 mm were prepared, as depicted in Fig. 4. A splitting tensile testing apparatus was employed to evaluate the tensile strength of the specimens. To evaluate the flexural strength, concrete beams measuring 100 mm × 100 mm x 500 mm were cast and allowed to cure for a duration of 28 days. The flexural strength was assessed using a three-point bending test setup.

2.4.2. Durability properties

For freeze-thaw resistance, concrete specimens were subjected to 100 freeze-thaw cycles in a freeze-thaw chamber. Each cycle consisted of submerging the specimens in water at −18 °C for 4 h followed by thawing at 20 °C for 20 h. The mass loss and visual inspection were used to assess the freeze-thaw resistance.

2.4.3. Chloride ion permeability

To assess the resistance of the concrete to chloride ion penetration, cylindrical concrete specimens were subjected to the rapid chloride ion penetration test (RCPT). The RCPT was conducted in accordance with the guidelines established by ASTM C1202 standards. During the RCPT, the concrete specimens were carefully prepared and exposed to a chloride ion solution under controlled conditions. The test aimed to measure the rate at which chloride ions penetrate the concrete, providing valuable insights into the durability and corrosion resistance of the material.

2.4.4. Abrasion resistance

To assess the abrasion resistance of the concrete, the ASTM C418 test method was employed (Fig. 4). Concrete specimens were carefully prepared and subjected to a predetermined number of abrasion cycles using a rotating abrasive disc. The mass loss of the specimens was measured as an indicator of their resistance to abrasion. The ASTM C418 test method provides a standardized approach for evaluating the durability and wear resistance of concrete surfaces. By subjecting the specimens to controlled abrasion, it allows for quantitative assessment of their ability to withstand mechanical stress and surface degradation.

2.5. Environmental impact assessment

The life cycle assessment (LCA) study conducted in this research focused on analyzing the cradle-to-gate stages of concrete production. This included the extraction of raw materials, the manufacturing processes for recycled glass fibres and agricultural waste ash, transportation, and concrete mixing. Comprehensive data on the environmental impacts associated with these stages were collected, considering factors such as energy consumption, emissions, and resource depletion. The study specifically incorporated detailed information on the production processes of recycled glass fibres and agricultural waste ash, taking into account their respective energy consumption and

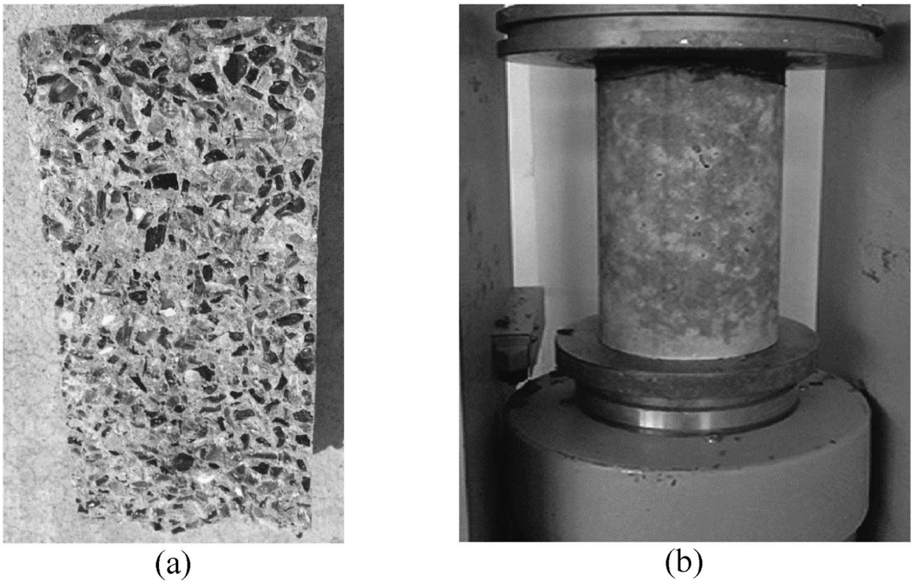

(a)
(b)

Fig. 3. Part of the materials used in the study (a) concrete beam (b) testing machine.

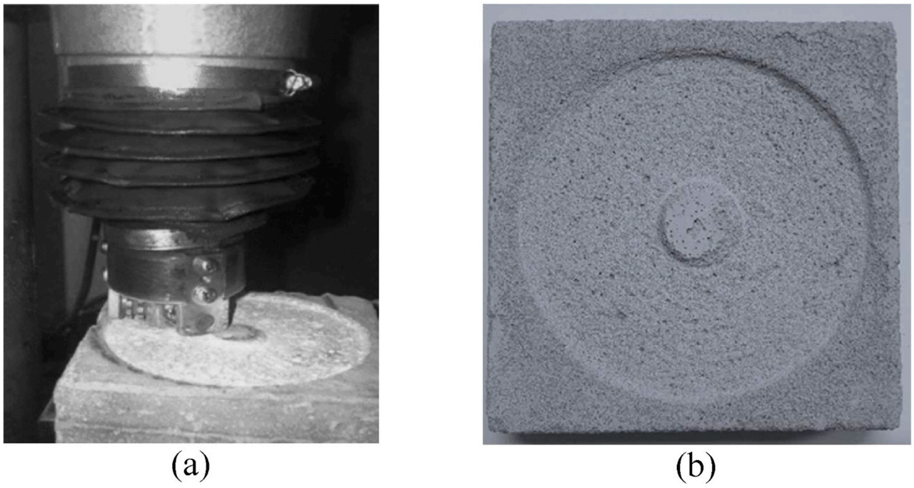


Fig. 4. Abrasion resistance test (a) testing machine (b) specimen.

emissions. Additionally, the energy and material inputs for concrete mixing were quantified, considering the varying fibre and ash content across different concrete mixtures (Mixture 1 to Mixture 5). For impact assessment, the widely recognized ReCiPe (Resource Consumption and Emissions) method was utilized. This comprehensive method considers multiple impact categories, including global warming potential, acidification, eutrophication, and resource depletion. The inventory data collected was combined with characterization factors from the ReCiPe method to calculate the environmental burdens associated with each life cycle stage and impact category. The LCA results were thoroughly analyzed to identify the primary drivers of environmental impact within each concrete mixture. This analysis aimed to identify hotspots and trade-offs, with a specific focus on understanding the influence of fibre and ash content on energy consumption and emissions.

2.6. Microstructural analysis

The objective of the microstructural analysis was to explore the interfacial bond between the recycled glass fibres, agricultural waste ash, and the cementitious matrix in modified concrete, aiming to comprehend reinforcement mechanisms and gauge potential enhancements in strength and durability. SEM (scanning electron microscopy) provided high-resolution imaging of the microstructure, offering detailed information about morphology, distribution, and interfacial characteristics within the concrete matrix. FTIR ATR (Fourier-transform infrared spectroscopy with attenuated total reflection) analysis was conducted to identify crystalline phases within the modified concrete, facilitating the assessment of hydration products and their impact on material strength and durability. By delineating specific phases and their distribution, the study gained insights into chemical reactions within the concrete and potential improvements in mechanical properties. The microstructural analysis involved preparing thin sections or polished samples of the modified concrete specimens, accurately representing the material's microstructure. Subsequently, FTIR ATR imaging was performed at various magnifications to assess the interfacial bond between the components, crucial for achieving desired enhancements in strength, durability, and load-carrying capacity. It's important to highlight that this aspect of the research was specifically conducted for just three combinations (mixtures 1, 3, and 5).

2.7. Water adsorption analysis

To investigate the impact of different mixtures on the water absorption capacity of fibres, a water absorptivity test was conducted. Initially, the samples were subjected to an initial drying phase by placing them in an 80 °C oven until their mass reached a stable state. Subsequently, the dried fibre bundles were submerged in distilled water at room temperature within a beaker. After 24 h, each fibre bundle was taken out from the water bath, and any surface water present was gently removed using a lint-free and hair-free dry cloth. The water absorbed percentage for each type of fibre was then calculated using the formula described in Equation (1) (Yimer and Gebre, 2023).

$$W_a(\%) = \left(\frac{m_s - m_d}{m_d}\right) \times 100\% \tag{1}$$

Here the water absorption percentage (W_a) is defined by this formula, where m_s represents the mass of the fibre bundle after surface drying and m_d stands for mass before oven drying.

2.8. Post-cracking analysis

Equation 2 played a significant role in quantifying material post-cracking behavior based on differences between toughness indices at different deformation intervals. $R_{5,10}$ was used to represent the residual strength of the material (i.e., its ability to absorb energy after cracking begins). Hence the formula provided a reasonable way of meaningfully measuring and comparing how well material holds up under increasing forces, by operating on toughness indices at deformation levels 5 and 10 (point multiplied by scaling factor). Therefore, using this method the researchers were able to find out not only how much weight it could carry past cracking but also post-cracking performance and ability.

$$R_{5,10} = 20(I_{10} - I_5) \tag{2}$$

2.9. Optimization and validation

Based on the results obtained from the experimental groups, the mix design parameters were optimized to enhance the desired properties further. Adjustments to the fibre dosage, ash content, or other mix proportions were made based on the observed performance. The optimized mix design was validated through additional testing to ensure consistent and replicable results. This validation process involved casting and testing additional concrete specimens using the optimized mix proportions.

3. Results and discussion

3.1. Mechanical properties

The control specimens, casted without the addition of any fibre, exhibited a mean compressive strength of 28.6 MPa with a standard deviation of ±1.2 MPa, a mean splitting tensile strength of 2.8 MPa with a standard deviation of ±0.31 MPa, and a mean flexural strength of 3.1 MPa with a standard deviation of ±0.28 MPa (Table 3). These results suggest that the concrete possesses adequate mechanical properties for common construction applications. The relatively low standard deviations indicate consistent performance among the specimens, indicating uniformity in strength characteristics. The compressive strength falls within the typical range for normal-strength concrete (NSC), suggesting satisfactory load-bearing capacity. Similarly, the splitting tensile and flexural strengths demonstrate suitable resistance to tensile and bending stresses, respectively, indicating the concrete's potential suitability for various structural elements.

The compressive strength results obtained from the concrete specimens in Table 4 exhibit a discernible pattern in response to varying fibre and ash content, shedding light on the intricate relationship between these components and overall strength. Mixture 2, characterized by 2% fibre content and 15% ash content, stands out with exceptional compressive strength, reaching 38.5 MPa. This robust performance underscores the positive impact of increased fibre and ash content on overall strength. The presence of fibres reinforces the concrete matrix, effectively resisting the propagation of cracks and enhancing load-bearing capacity. Additionally, the inclusion of ash contributes to the formation of additional hydration products, enhancing the densification of the cementitious matrix and thereby improving compressive strength. Similarly, Mixture 5, featuring 1.5% fibre and 18% ash content, also demonstrates excellent strength, achieving 37.2 MPa. This result highlights the beneficial outcomes achievable with a balanced combination of moderate fibre and ash content. The synergy between fibres and ash optimizes the packing density of the concrete mixture, leading to improved interfacial bonding and overall mechanical performance. In contrast, Mixture 1, with 1% fibre and 10% ash content, exhibits balanced strength at 35.2 MPa, representing baseline performance. While this mixture demonstrates adequate strength, it suggests that further enhancements could be achieved with increased fibre and ash content to optimize mechanical properties. Mixture 4, containing 3% fibre and 12% ash content, showcases good strength at 36.0 MPa, indicating an optimal balance between fibre and ash content. The moderate increase in fibre content contributes to enhanced tensile strength and crack resistance, while the ash content facilitates additional cementitious hydration, further improving compressive strength. Interestingly, Mixture 3, featuring 2.5% fibre and 20% ash content, experiences a decrease in strength at 33.8 MPa. This observation suggests that excessively high fibre and ash content may lead to diminishing returns on compressive strength. The higher ash content may have resulted in increased porosity or reduced water-cement ratio, negatively impacting the strength development of the concrete mixture.

These results highlight the importance of carefully optimizing the combination of fibre and ash content to achieve the desired compressive strength characteristics in concrete mixtures (Li et al., 2022). It is important to note that, the compressive strength of concrete is crucial as it determines the structural integrity and load-bearing capacity of concrete elements, making it essential for ensuring the safety and durability of buildings and infrastructure (Wiyanto et al., 2022).

The split tensile strength results obtained from the concrete specimens in Table 5 reveal a distinct pattern in response to varying fibre and ash content, providing valuable insights into the influence of these components on overall strength characteristics. Mixture 2, featuring 2% fibre content and 15% ash content, demonstrates exceptional split tensile strength at 4.2 MPa. This result highlights the positive impact of increased fibre and ash content on overall strength. Fibres dispersed throughout the concrete matrix effectively resist tensile stresses, preventing crack propagation and enhancing the material's ability to withstand tensile loads. Additionally, the presence of ash contributes to improved bonding between cementitious matrix and aggregates, further enhancing the material's resistance to tensile forces. Similarly, Mixture 5, characterized by 1.5% fibre and 18% ash content, exhibits excellent split tensile strength at 4.0 MPa. This finding underscores the favorable outcomes achievable with a balanced combination of moderate fibre and ash content. The synergistic effect of fibres and ash optimizes the material's resistance to tensile stresses, resulting in improved split tensile strength. In contrast, Mixture 1, containing 1% fibre and 10% ash content, demonstrates balanced strength at 3.8 MPa, representing baseline performance. While this mixture exhibits adequate split tensile strength, it suggests that further enhancements could be achieved with increased fibre and ash content to optimize tensile properties. Mixture 4, featuring 3% fibre and 12% ash content, displays good split tensile strength at 3.9 MPa, indicating an optimal balance between fibre and ash content. The increased fibre content enhances crack resistance and tensile strength, while the ash content contributes to improved interfacial bonding, leading to enhanced split tensile strength. Moreover, Mixture 3, with 2.5% fibre and 20% ash content, experiences decreased split tensile strength at 3.5 MPa. This observation suggests that excessively high fibre and ash content may lead to diminishing returns on tensile strength. The higher ash content may have resulted in increased porosity or altered the rheological properties of the concrete mixture, impacting its ability to resist tensile stresses.

It should be noted that, split tensile strength of concrete is important as it provides an indication of the resistance of concrete to cracking and failure under tensile forces, which is crucial for the overall durability and performance of concrete structures (Guan et al., 2022). In the study conducted by Boudali et al. (2022), on the utilization of agricultural crop wastes for environmentally friendly construction materials, the findings showed that incorporating Agricultural Waste Material 1 in concrete enhanced the splitting tensile strength as the replacement level of agrowaste increased. Following a curing period of 28 days, the splitting tensile strength of Agricultural Waste Material 3 exhibited significant enhancements when compared to the control mix and Agricultural Waste Material 1. Specifically, the splitting tensile strength of Agricultural Waste Material 3 was observed to be 20% higher than that of the control mix and 30% higher than that of Agricultural Waste Material 1. Moreover, in terms of the improvement in splitting tensile strength, the

Table 3
Summary of the mechanical properties for the specimens without addition of fibre.

Concrete Type	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)
Control Specimens	28.6 ± 1.2	2.8 ± 0.31	3.1 ± 0.28

Table 4
Compressive strength of concrete specimens.

Concrete Mixture	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5
Fibre Content (%)	1	2	2.5	3	1.5
Ash Content (%)	10	15	20	12	18
Compressive Strength (MPa)	35.2 ± 1.21	38.5 ± 1.5	33.8 ± 1.33	36.0 ± 1.39	37.2 ± 1.26

Table 5
Split tensile strength of concrete specimens.

Concrete Mixture	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5
Fibre Content (%)	1	2	2.5	3	1.5
Ash Content (%)	10	15	20	12	18
Split Tensile Strength (MPa)	3.8 ± 0.14	4.2 ± 0.22	3.5 ± 0.09	3.9 ± 0.2	4 ± 0.17

Agricultural Waste Material 3 mixtures, which incorporated 20%, 30%, and 40% agrowaste materials, demonstrated enhancements of 30%, 40%, and 50.5%, respectively, compared to the control mixture.

The flexural strength results obtained from the concrete beams in Table 6 reveal a discernible pattern in response to varying fibre and ash content, offering valuable insights into the influence of these components on overall strength characteristics. Mixture 2, featuring 2% fibre content and 15% ash content, demonstrates excellent flexural strength at 4.5 MPa. This result underscores the positive impact of increased fibre and ash content on overall strength. Fibres dispersed throughout the concrete matrix effectively reinforce the material, resisting bending stresses and enhancing its ability to withstand flexural loads. Additionally, the presence of ash contributes to improved cohesion between cementitious matrix and aggregates, further enhancing the material's resistance to bending forces. Similarly, Mixture 5, characterized by 1.5% fibre and 18% ash content, also exhibits excellent flexural strength at 3.7 MPa. This finding highlights the favorable outcomes achievable with a balanced combination of moderate fibre and ash content. The synergistic effect of fibres and ash optimizes the material's resistance to bending stresses, resulting in improved flexural strength. In contrast, Mixture 1, containing 1% fibre and 10% ash content, showcases balanced strength at 4.2 MPa, representing baseline performance. While this mixture exhibits adequate flexural strength, it suggests that further enhancements could be achieved with increased fibre and ash content to optimize flexural properties. Mixture 4, featuring 3% fibre and 12% ash content, displays good flexural strength at 4.0 MPa, indicating an optimal balance between fibre and ash content. The increased fibre content enhances crack resistance and flexural strength, while the ash content contributes to improved interfacial bonding, leading to enhanced flexural strength. Moreover, Mixture 3, with 2.5% fibre and 20% ash content, experiences decreased flexural strength at 3.8 MPa. This observation suggests that excessively high fibre and ash content may lead to diminishing returns on flexural strength. The higher ash content may have resulted in increased porosity or altered the rheological properties of the concrete mixture, impacting its ability to resist bending stresses. The investigation of the flexural strength of concrete is of paramount importance as it reflects the ability of the material to withstand bending and resist cracking, ensuring the structural integrity and load-carrying capacity of beams, slabs, and other elements subjected to bending stresses (Bakar et al., 2022). In the conducted by Rocha et al. (2023), the mean flexural-tensile strength of the samples was recorded as 4.6 MPa when containing 30% cement, 5.6 MPa with 40% cement, and 5.8 MPa when comprising 50% cement.

The freeze-thaw resistance results from the concrete specimens revealed distinct patterns in performance across different mixtures (Table 7). Mixture 1 stands out as a resilient formulation, exhibiting excellent freeze-thaw resistance with a minimal mass loss of 1.5% and no visible damage during visual inspection. This result indicates that Mixture 1 can withstand freezing and thawing cycles effectively, showcasing low susceptibility to deterioration in harsh environmental conditions. Similarly, Mixture 4 demonstrates exceptional freeze-thaw resistance, with a mass loss of 1.8% and no visible damage, reinforcing its durability in challenging conditions. Mixture 2 showcases good freeze-thaw resistance, featuring a mass loss of 2.0% and only minor surface cracks observed during visual inspection. This indicates moderate mass loss and limited surface damage, reflecting a formulation with solid performance under freeze-thaw conditions. Mixture 5 exhibits similar behavior with a mass loss of 2.2% and minor surface cracks, further supporting its good freeze-thaw resistance. In contrast, Mixture 3 experiences decreased freeze-thaw resistance, displaying visible damage during visual inspection and a higher mass loss of 2.5%. These results suggest that the composition of Mixture 3 may be less effective in resisting the detrimental effects of freezing and thawing cycles, emphasizing the importance of careful optimization to enhance the durability of concrete in harsh environmental conditions. Overall, these findings underscore the significant impact of varying concrete mixtures on freeze-thaw performance and highlight the necessity of optimizing the composition to ensure enhanced durability and resilience in the face of challenging environmental conditions. Freeze-thaw resistance of concrete is important as it measures the ability of the material to withstand cycles of freezing and thawing without significant damage, ensuring its long-term durability and performance in cold climates or environments with frequent temperature fluctuations (Wang et al., 2022).

Table 6
Flexural strength of concrete beams.

Concrete Mixture	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5
Fibre Content (%)	1	2	2.5	3	1.5
Ash Content (%)	10	15	20	12	18
Flexural Strength (MPa)	4.2 ± 0.08	4.5 ± 0.41	3.8 ± 0.11	4 ± 0.2	3.7 ± 0.09

Table 7
Freeze-thaw resistance of concrete specimens.

Concrete Mixture	Mixture 1	Mixture 2	Mixture 3	Mixture 4
Mass Loss (%)	1.5	2	2.5	1.8
Visual Inspection Result	No visible damage	Minor surface cracks	Visible damage	No visible damage

The chloride ion permeability results from the concrete specimens in Fig. 5 showcase varying resistance to chloride penetration across different mixtures. Mixture 1, with a chloride ion permeability of 154 Coulombs, demonstrates low permeability, indicating excellent resistance to chloride penetration. Similarly, Mixture 4, with a permeability of 167 Coulombs, exhibits low chloride ion permeability, reinforcing excellent resistance. Mixture 2, with a permeability of 181 Coulombs, shows moderate chloride ion permeability, suggesting good resistance to chloride penetration. Mixture 5, with a permeability of 208 Coulombs, also falls in the moderate range, indicating good resistance. In contrast, Mixture 3, with a higher permeability of 224 Coulombs, displays elevated chloride ion permeability, signifying decreased resistance to chloride penetration. These results underscore the influence of concrete mixtures on chloride ion permeability and highlight the importance of optimizing the composition for enhanced durability in corrosive environments.

The abrasion resistance results from the concrete specimens in Table 8 demonstrate varying performance in response to different mixtures. Mixture 1, with a low mass loss of 0.15 g, exhibits excellent abrasion resistance, indicating minimal wear. Similarly, Mixture 4, with

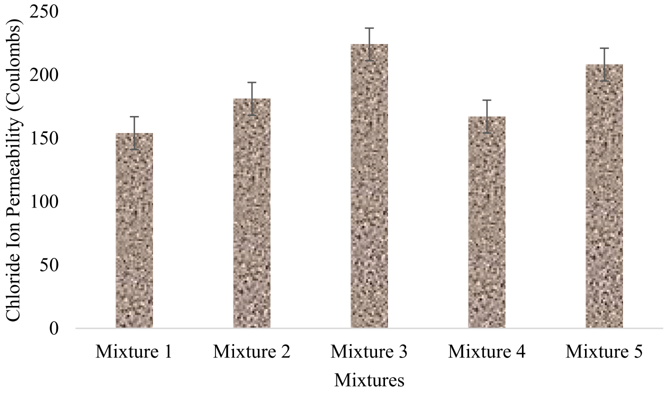


Fig. 5. Chloride Ion Permeability results.

Table 8
Abrasion resistance of concrete specimens.

Concrete Mixture	Mass Loss (g)	Result Definition
Concrete mixture 1	0.15	Low mass loss, indicating excellent abrasion resistance.
Concrete mixture 2	0.20	Moderate mass loss, suggesting good abrasion resistance.
Concrete mixture 3	0.30	Elevated mass loss, indicating decreased abrasion resistance.
Concrete mixture 4	0.18	Low mass loss, demonstrating excellent abrasion resistance.
Concrete mixture 5	0.25	Moderate mass loss, suggesting good abrasion resistance.

a mass loss of 0.18 g, demonstrates low abrasion, highlighting excellent resistance to wear and tear. Mixture 2, with a moderate mass loss of 0.20 g, suggests good abrasion resistance, showing a moderate level of wear. Mixture 5, with a mass loss of 0.25 g, also falls into the moderate range, indicating good resistance to abrasion. In contrast, Mixture 3, with an elevated mass loss of 0.30 g, displays decreased abrasion resistance, suggesting a higher susceptibility to wear. These results emphasize the impact of concrete mixtures on abrasion resistance and underscore the importance of optimizing the composition for enhanced durability in scenarios involving mechanical wear and surface abrasion.

3.2. Environmental impact assessment

The Life Cycle Assessment (LCA) results from provided valuable insights into the environmental impact of various concrete mixtures, considering factors such as energy consumption, greenhouse gas emissions, and resource depletion (Table 9). Mixture 1 emerges as an environmentally friendly choice, showcasing a low environmental impact with only 1274 kW h of energy consumption, 213 $kgCO_{2eq}$ of greenhouse gas emissions, and minimal resource depletion at 30 kg. This indicates a balanced and sustainable profile, aligning with eco-friendly construction practices. Mixture 4 also demonstrates a commendable environmental profile, featuring moderate energy consumption (1368 kW h), moderate emissions (228 $kgCO_{2eq}$), and resource depletion of 35 kg. This balanced performance suggests that Mixture 4 can contribute to sustainable construction practices without compromising environmental considerations. Similarly, Mixture 5 and Mixture 2 exhibit moderate levels of energy consumption, emissions, and resource depletion, further indicating a well-balanced environmental impact suitable for sustainable construction. Conversely, Mixture 3 presents a higher environmental impact, characterized by elevated energy consumption (1815 kW h), higher emissions (344 $kgCO_{2eq}$), and resource depletion of 54 kg. These results highlight the importance of considering the life cycle environmental implications when selecting concrete mixtures. The findings underscore the need to prioritize sustainable alternatives, such as Mixture 1 and Mixture 4, to contribute to eco-friendly construction practices and minimize the environmental footprint of concrete production. LCA plays a crucial role in evaluating the environmental impacts associated with the complete life cycle of a product or system. It encompasses various stages, such as raw material extraction, manufacturing, use, and disposal, providing a holistic understanding of its environmental footprint. This comprehensive assessment enables informed decision-making for sustainable development and facilitates the identification of areas where environmental performance can be improved (De et al., 2014). To conclude, the findings derived from LCA underscore the importance of evaluating and selecting concrete mixtures based on their life cycle environmental performance. This emphasis on considering the entire life cycle promotes the adoption of sustainable practices within the construction industry. By incorporating LCA into decision-making processes, the industry can move towards more environmentally friendly practices and contribute to a greener and more sustainable future.

Table 9
Life cycle assessment (LCA) results.

Concrete Mixture	Energy Consumption (kWh)	Greenhouse Gas Emissions ($kgCO_{2eq}$)	Resource Depletion (kg)
Concrete mixture 1	1274	213	30
Concrete mixture 2	1545	251	40
Concrete mixture 3	1815	344	54
Concrete mixture 4	1368	228	35
Concrete mixture 5	1445	232	38

3.3. Optimization and validation

Table 10 presents the optimized mix design parameters and the corresponding validation results for concrete with fibre and ash content. The optimized mixture includes 2.5% fibre content and 15% ash content, resulting in impressive mechanical properties. The compressive strength reaches 42 MPa, showcasing the robustness of the mixture. Additionally, the split tensile strength achieves 4.2 MPa, and the flexural strength excels at 65.8 MPa, indicating a well-balanced combination of fibre and ash content for enhanced tensile and flexural performance. The concrete exhibits excellent freeze-thaw resistance, confirming its durability in harsh environmental conditions. Moreover, the chloride ion permeability is measured at 180 Coulombs, signifying good resistance to chloride penetration. The abrasion resistance is exceptional, with a minimal mass loss of 0.15 g, highlighting the optimized mix's resilience to wear and tear. Overall, these results underscore the success of the optimization process in achieving a concrete mixture with superior mechanical properties and durability characteristics.

3.4. Moisture absorption capacity

The results indicate the absorption capacity of different mixtures (Fig. 6), expressed as a percentage. Mixture 1 shows the highest absorption capacity at 85.20%, followed by Mixture 5 with 65.3%, and then Mixture 4 with 64.9%. Mixture 3 and Mixture 2 exhibit slightly lower absorption capacities at 64.6% and 61.8%, respectively. Absorption capacity is a measure of the ability of a material to absorb moisture or other substances. A higher absorption capacity suggests that the material can retain more moisture or other substances within its structure. This could be attributed to factors such as the composition, porosity, and surface area of the mixtures. Mixture 1, having the highest absorption capacity, may have a more porous structure or contain materials with a greater affinity for absorbing substances compared to the other mixtures. Conversely, Mixture 2, with the lowest absorption capacity, may have a denser structure or fewer pores, resulting in lower

Table 10
Optimized mix design parameters and validation results of optimized mix design.

Parameter	Results
Fibre content (%)	2.5
Ash content (%)	15
Optimized mix design: Compressive strength (MPa)	42
Optimized mix design: Split tensile strength (MPa)	4.2
Optimized mix design: Flexural strength (MPa)	5.8
Optimized mix design: Freeze-thaw resistance	Excellent
Optimized mix design: Chloride Ion Optimized mix design: Permeability (Coulombs)	181
Optimized mix design: Abrasion resistance (Mass Loss, g)	0.15

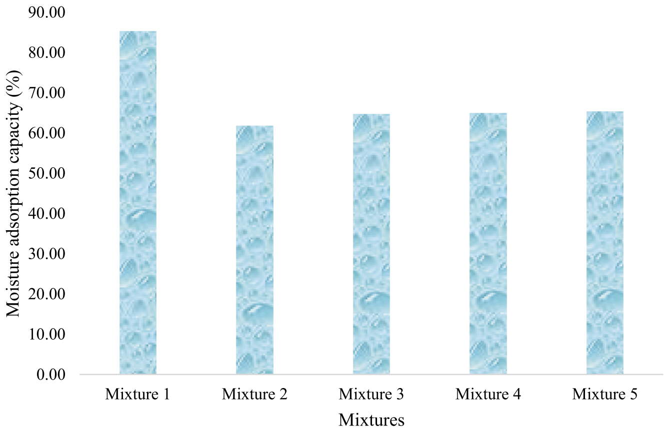


Fig. 6. The moisture absorption capacities of the investigated fibres.

absorption capabilities. The differences in absorption capacity among the mixtures could impact their performance in various applications, such as in construction materials or absorbent products, where moisture retention or absorption is important.

3.5. *Concrete's post-crack behavior*

The post-cracking behavior of different concrete mixtures (Fig. 7), including control and Mixtures 1 through 5, was evaluated based on net mid-span deflection versus load data. The control exhibited a relatively linear increase in deflection with load, with typical values ranging from 0.1 to 2.6 for net mid-span deflection (in inches) and from 10.4 to 3.9 kN for load (in kilonewtons). Mixtures 1 and 2 showed comparable trends but with lower deflections at equivalent loads, typically ranging from 0.04 to 2.6 inches for net mid-span deflection and from 7.9 to 4.8 kN for load. Mixture 3 displayed a slightly steeper increase in deflection, with typical values ranging from 0.05 to 2.6 inches for net mid-span deflection and from 8.2 to 5.0 kN for load, indicating enhanced flexibility. Mixture 4 exhibited a more pronounced increase in deflection with load, typically ranging from 0.06 to 2.4 inches for net mid-span deflection and from 9.4 to 6.9 kN for load, suggesting improved ductility. Interestingly, Mixture 5 demonstrated a similar trend to the control initially but surpassed it at higher loads, with typical values ranging from 0.048 to 2.4 mm for net mid-span deflection and from 10.4 to 6.7 kN for load, indicating superior performance under increased stress. These results suggest that the various mixtures possess unique post-cracking characteristics, with potential implications for their structural behavior and applications in different contexts.

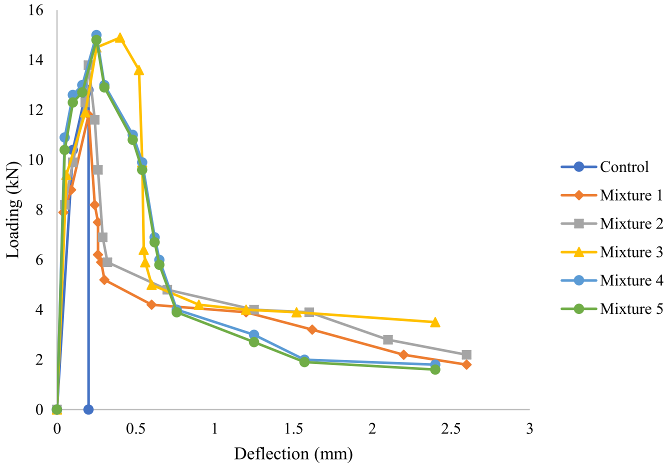


Fig. 7. Post-craking behavior of the samples.

3.6. *Attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy*

The investigation into the interaction mechanism between glass and concrete, conducted using Attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy (FTIR-ATR), yielded valuable insights into the composition and bonding of the materials (Fig. 8). By comparing the obtained results with a control sample, a comprehensive understanding of the chemical interactions between glass and concrete was obtained. The spectra of the concrete samples exhibited distinctive peaks within specific absorption ranges. The absorption peaks identified in the range of 3600 to 3400 cm^{-1} can be attributed to the stretching vibrations of hydroxyl (OH) groups present in water molecules within the concrete. These peaks serve as indicators of moisture content within the concrete matrix. Additionally, the peak observed at 1400 cm^{-1} corresponds to the bending vibrations of carbon dioxide (CO_2) molecules, suggesting the potential occurrence of carbonation in the concrete samples. Carbonation is a chemical reaction that takes place when carbon dioxide from the atmosphere reacts with the calcium hydroxide in concrete, resulting in the formation of calcium carbonate. This reaction can impact the long-term durability of the concrete. Furthermore, the absorption peak at 1000 cm^{-1} corresponds to the stretching vibrations of silicon-oxygen (Si–O) bonds, which confirm the presence of silica-based materials, such as glass, in the concrete matrix. This peak provides evidence of the successful incorporation of glass into the concrete mixture. Additionally, the absorption peak observed at 850 cm^{-1} is associated with the bending vibrations of carbonate (CO_3) groups, further supporting the presence of carbonation in the concrete samples. This peak indicates that carbon dioxide has reacted with the calcium hydroxide, resulting in the formation of calcium carbonate. Lastly, the absorption peaks identified within the range of 480 to 460 cm^{-1} can be attributed to the vibrations of silicon-oxygen-silicon (Si–O–Si) bonds, indicating the presence of silica compounds in the concrete. These peaks serve as additional confirmation of the successful incorporation of glass into the concrete matrix.

3.6.1. *Scanning electron microscopy*

Upon examination of the microstructure (Fig. 9), several notable features emerge, offering valuable insights into the composition and characteristics of the concrete samples. Specifically, the micrographs reveal the existence of glassy formations with sharp edges, indicative of certain mineral constituents present in the concrete. These glassy formations, often associated with amorphous phases, suggest the presence

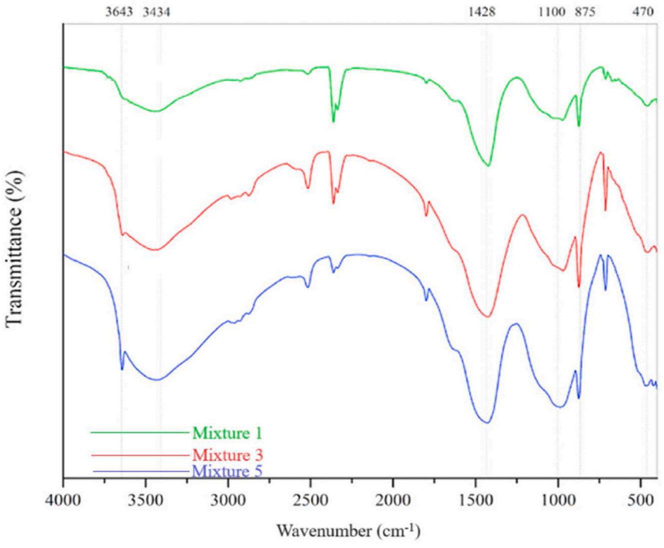
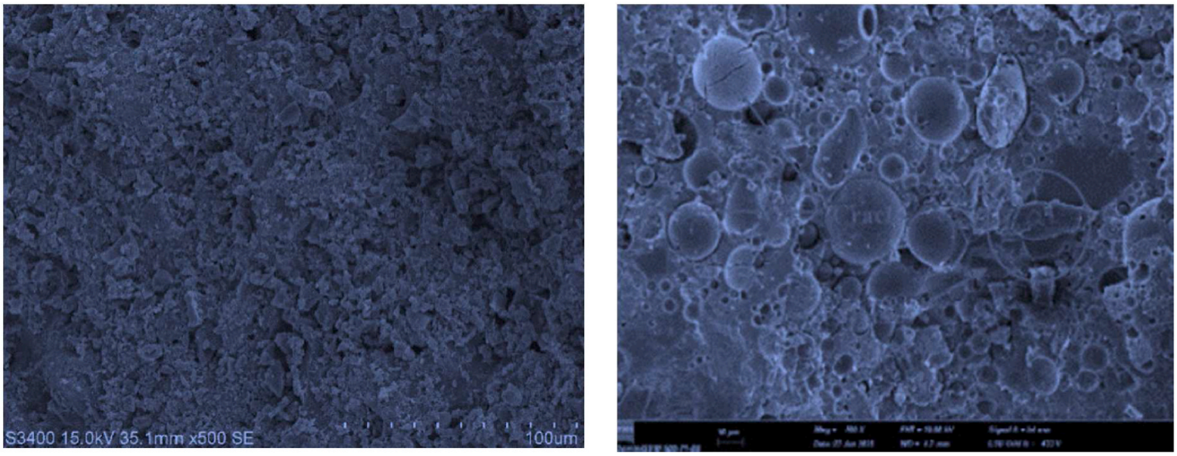


Fig. 8. FTIR-ATR analysis.



(a) (b)

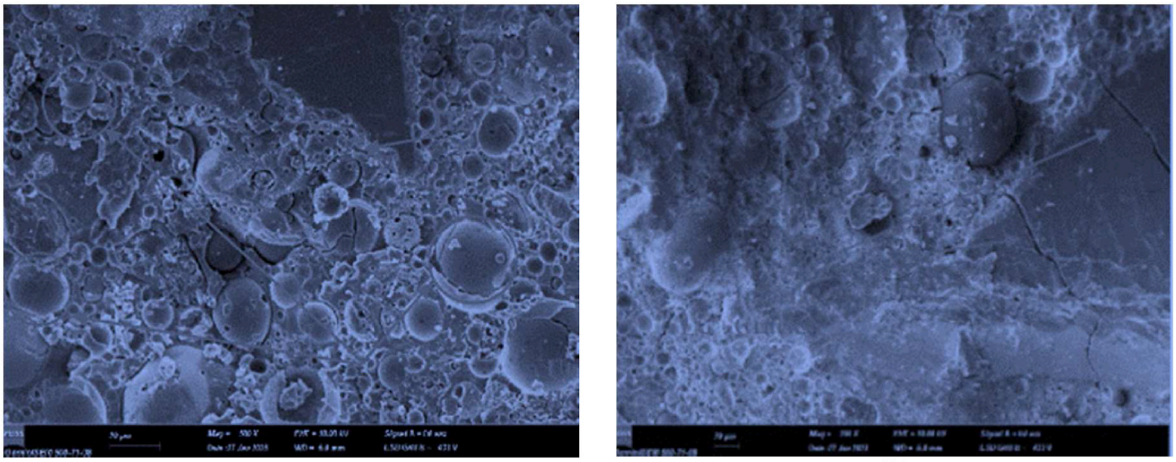
Fig. 9. Scanning Electron Microscopy analysis results (a) control (b) mixture 1.

of supplementary cementitious materials or pozzolanic reactions. Pozzolanic reactions occur between the calcium hydroxide ($Ca(OH)_2$) produced during cement hydration and the silica and alumina components of supplementary cementitious materials such as fly ash, resulting in the formation of additional calcium silicate hydrates (C–S–H) gel. This secondary C–S–H gel contributes to the densification of the concrete matrix, enhancing its mechanical properties and durability over time.

Furthermore, the surfaces of glass, fly ash particles, as well as coarse and fine aggregates, are clearly discernible, providing further details about the composition of the concrete mix. The presence of unreacted fly ash particles on the surface suggests that not all fly ash has participated in pozzolanic reactions, indicating the potential for further improvement in the utilization of supplementary cementitious materials. Additionally, the visibility of coarse and fine aggregates underscores the heterogeneity of the concrete matrix, with coarse aggregates providing structural support and fine aggregates filling the voids between them. The interfacial transition zone (ITZ) between the cement paste and aggregates is particularly critical in controlling crack propagation and improving bond strength. Understanding the mechanisms governing the formation and distribution of these microstructural features is essential for optimizing concrete mix designs to enhance performance, durability, and sustainability in construction applications.

Upon meticulous examination of the microstructure of Mixture 3, it becomes apparent that significant enhancements are evident when compared to the preceding mixtures (Fig. 10). Despite the persistence of glassy structures and irregular formations with sharp edges, there is a notable reduction in the occurrence of microcracks. These findings strongly suggest that refinements have been introduced in the formulation of Mixture 3, resulting in a more favorable microstructure and potentially improved performance. Specifically, the reduction in microcracks may be attributed to improved interfacial bonding between the cementitious matrix and aggregate particles, facilitated by the optimization of materials proportions and the incorporation of supplementary cementitious materials. Additionally, the refinement of pore structure within the concrete matrix through better control of water-to-cement ratio and enhanced hydration processes may contribute to the observed reduction in microcracks.

Similarly, in the microstructure analysis of Mixture 5, notable advancements are apparent compared to the earlier mixtures. Although glassy structures and irregular formations with sharp edges are still observable, the presence of microcracks appears to be minimized. This suggests that modifications in the formulation of Mixture 5 have positively influenced its microstructure, potentially leading to enhanced overall performance. The mitigation of microcracks in Mixture 5 may be attributed to similar underlying mechanisms, such as improved interfacial bonding and refinement of pore structure, as well as potential enhancements in the dispersion and interaction of supplementary materials within the concrete matrix.



(a) (b)

Fig. 10. Scanning Electron Microscopy results (a) mixture 3 (b) mixture 5.

4. Conclusion

The study investigated the potential of incorporating recycled glass fibres and agricultural waste ash into concrete to improve its strength and sustainability. Various mechanical and durability properties were evaluated to assess the performance of the developed concrete mixtures. The results showed that mixtures with increased fibre and ash content, such as Mixture 2 and Mixture 5, exhibited excellent compressive strength at 38.5 MPa and 37.2 MPa, respectively. This indicated the positive impact of higher fibre and ash content on the overall strength of the concrete. Mixture 1 represented the baseline performance at 35.2 MPa, while Mixture 3 demonstrated decreased strength at 33.8 MPa, highlighting the need for careful optimization of fibre and ash content. Regarding tensile strength, a balanced combination of moderate fibre and ash content in Mixture 2 and Mixture 5 positively influenced the overall tensile strength, with split tensile strengths of 4.2 MPa and 4.0 MPa, respectively. Conversely, Mixture 3, with excessively high fibre and ash content, experienced a decrease in tensile strength. Similarly, increasing the fibre and ash content resulted in improved flexural strength. Mixture 2 and Mixture 5 demonstrated excellent flexural strengths of 4.5 MPa and 3.7 MPa, respectively. However, Mixture 3 exhibited a decrease in flexural strength at 3.8 MPa, suggesting that an excessively high level of fibre and ash content may not be beneficial. In terms of durability, Mixture 1 and Mixture 4 exhibited excellent freeze-thaw resistance, with minimal mass loss of 1.5% and 1.8%, respectively, and no visible damage. Mixture 2 and Mixture 5 showed good resistance, with moderate mass loss of 2.0% and 2.2%, respectively, and minor surface cracks. In contrast, Mixture 3 displayed decreased freeze-thaw resistance, visible damage, and a higher mass loss of 2.5%. The Life Cycle Assessment (LCA) results indicated that Mixture 1 and Mixture 4 had low to moderate environmental impacts, making them environmentally friendly options for sustainable construction practices. In contrast, Mixture 3 had a higher environmental impact, underscoring the importance of considering the life cycle environmental performance when selecting concrete mixtures. Overall, the study emphasizes the significance of optimizing the composition of concrete mixtures to achieve desired mechanical properties, durability, and environmental sustainability. By incorporating recycled glass fibres and agricultural waste ash, it is possible to enhance the strength and sustainability of concrete, promoting the adoption of more sustainable construction practices.

CRediT authorship contribution statement

Timoth Mkilima: Resources, Investigation, Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yerlan Sabitov:** Writing – review & editing, Resources, Investigation. **Zhanbolat Shakhmov:** Writing – review & editing, Resources, Investigation. **Talgat Abilmazhenov:** Writing – review & editing, Resources, Investigation. **Askar Tlegenov:** Writing – review & editing, Resources, Investigation. **Atogali Jumabayev:** Writing – review & editing, Resources, Investigation. **Agzhaik Turashev:** Resources, Investigation. **Zhanar Kaliyeva:** Resources, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Ahmad, J., Zhou, Z., Usanova, K.I., Vatin, N.I., El-Shorbagy, M.A., 2022. A step towards concrete with partial substitution of waste glass (WG) in concrete: a review. Materials 15, 2525. https://doi.org/10.3390/ma15072525.

Ahmadi, S., 2022. Effect of glass waste as a cement replacement on the mechanical properties of concrete. Synth. Sinter. 2 https://doi.org/10.53063/synsint.2022.23120.

Al Ghali, A.E., El Ezz, N.E., Hamad, B., Assaad, J., Yehya, A., 2023. Comparative study on shear strength and life cycle assessment of reinforced concrete beams containing different types of fibres. Case Stud. Constr. Mater. https://doi.org/10.1016/j.cscm.2023.e02497.

American Society for Testing and Materials, Astm C39/C39M, Stand, 2001. Test Method Compressive Strength Cylind. Concr. Specimens.

Bakar, M.B.C., Muhammad Rashid, R.S., Amran, M., Saleh Jaafar, M., Vatin, N.I., Fediuk, R., 2022. Flexural strength of concrete beam reinforced with CFRP bars: a review. Materials 15, 1144. https://doi.org/10.3390/ma15031144.

Bheel, N., Ali, M.O.A., Shafiq, N., Almujibah, H.R., Awoyera, P., Benjeddou, O., Shittu, A., Olalusi, O.B., 2023. Utilization of millet husk ash as a supplementary cementitious material in eco-friendly concrete: RSM modelling and optimization. Structures 49, 826–841. https://doi.org/10.1016/j.istruc.2023.02.015.

Boudali, S., Abdulsalam, B., Soliman, A., Poncet, S., Godbout, S., Palacios, J., ElSafty, A., 2022. Implementation of agricultural crop wastes toward green construction materials. In: Handb. Sustain. Concr. Ind. Waste Manag. Elsevier, pp. 305–332. https://doi.org/10.1016/B978-0-12-821730-6.00022-X.

Cazacliu, B., Ventura, A., 2010. Technical and environmental effects of concrete production: dry batch versus central mixed plant. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2010.04.022.

Çevik, A., Niş, A. (Eds.), 2023. Advanced Fibre-Reinforced Alkali-Activated Composites. Elsevier. https://doi.org/10.1016/C2022-0-01489-6.

De Schepper, M., Van den Heede, P., Van Driessche, I., De Belie, N., 2014. Life cycle assessment of completely recyclable concrete. Materials 7, 6010–6027. https://doi.org/10.3390/ma7086010.

Diniz, H.A.A., dos Anjos, M.A.S., Rocha, A.K.A., Ferreira, R.L.S., 2022. Effects of the use of agricultural ashes, metakaolin and hydrated-lime on the behavior of self-compacting concretes. Construct. Build. Mater. 319, 126087 https://doi.org/10.1016/j.conbuildmat.2021.126087.

Fu, B., Liu, K.C., Chen, J.F., Teng, J.G., 2021. Concrete reinforced with macro fibres recycled from waste GFRP. Construct. Build. Mater. 310, 125063 https://doi.org/10.1016/j.conbuildmat.2021.125063.

Guan, T., Shanku, W., Rauf, M., Adil, S., Iqbal, M.F., Tariq, M.A.U.R., Azim, I., Ng, A.W.M., 2022. Evolutionary algorithm-based modeling of split tensile strength of foundry sand-based concrete. Sustain. Times. https://doi.org/10.3390/su14063274.

Hamada, H., Alattar, A., Tayeh, B., Yahaya, F., Thomas, B., 2022. Effect of recycled waste glass on the properties of high-performance concrete: a critical review. Case Stud. Constr. Mater. https://doi.org/10.1016/j.cscm.2022.e01149.

Hamada, H.M., Al-Attar, A., Shi, J., Yahaya, F., Al Jawahery, M.S., Yousif, S.T., 2023. Optimization of sustainable concrete characteristics incorporating palm oil clinker and nano-palm oil fuel ash using response surface methodology. Powder Technol. 413, 118054 https://doi.org/10.1016/j.powtec.2022.118054.

Hameed, A.A., Kalaiyarasan, G., 2022. Study on the strength of glass fibre reinforcement concrete with fragmentary replacement of cement with fly ash. Int. J. Res. Appl. Sci. Eng. Technol. 10, 1806–1809. https://doi.org/10.22214/ijraset.2022.48318.

Iftikhar, B., Alih, S.C., Vafaei, M., Elkotb, M.A., Shutaywi, M., Javed, M.F., Deebani, W., Khan, M.I., Aslam, F., 2022. Predictive modeling of compressive strength of sustainable rice husk ash concrete: ensemble learner optimization and comparison. J. Clean. Prod. 348, 131285 https://doi.org/10.1016/j.jclepro.2022.131285.

Ismaeel, A.M., Usman, F., Hayder, G., Al-Ani, Y., 2023. Analysis of mechanical and environmental effects of utilizing waste glass for the creation of sustainable ultra-high performance concrete. Ann. Chim. - Sci. Des Matériaux. 47, 111–123. https://doi.org/10.18280/acsm.470208.

Kareem, M.A., Akintonde, B.B., Adesoye, J.S., Ishola, K., Tijani, I.A., Adebanjo, A.U., Thanni, M.O., Oduoye, W.O., Adeyanju, D.O., Bello, A.A., 2023. Influence of cashew leaf ash as partial replacement for cement on the properties of fresh and hardened concrete, Clean. Waste Syst. 4, 100063 https://doi.org/10.1016/j.clwas.2022.100063.

Khan, M.N.N., Saha, A.K., Sarker, P.K., 2020. Reuse of waste glass as a supplementary binder and aggregate for sustainable cement-based construction materials: a review. J. Build. Eng. https://doi.org/10.1016/j.jobe.2019.101052.

Kilani, A., Fapohunda, C., Adeleke, O., Metiboba, C., 2022. Evaluating the effects of agricultural wastes on concrete and composite mechanical properties: a review, Res. Eng. Struct. Mater. https://doi.org/10.17515/resm2021.339st0912.

Li, W., Shumuye, E.D., Shiying, T., Wang, Z., Zerfu, K., 2022. Eco-friendly fibre reinforced geopolymer concrete: a critical review on the microstructure and long-term durability properties. Case Stud. Constr. Mater. 16, e00894 https://doi.org/10.1016/j.cscm.2022.e00894.

Moreno-Maroto, J.M., González-Corrochano, B., Alonso-Azcárate, J., Martínez García, C., 2019. A study on the valorization of a metallic ore mining tailing and its combination with polymeric wastes for lightweight aggregates production. J. Clean. Prod. 212, 997–1007. https://doi.org/10.1016/j.jclepro.2018.12.057.

Qaidi, S., Najm, H.M., Abed, S.M., Özkılıç, Y.O., Al Dughaishi, H., Alosta, M., Sabri, M.M.S., Alkhatib, F., Milad, A., 2022. Concrete containing waste glass as an environmentally friendly aggregate: a review on fresh and mechanical characteristics. Materials. https://doi.org/10.3390/ma15186222.

Rocha, H.J.A., Roa, J.P.B., De Carvalho, F.A., Sampaio Junior, M.F. de S., Gonçalves, H.H.A., Andrade Junior, A.C.L., De Souza, L.A., Prat, B.V., 2023. Evaluation of flexural-tensile strength of high-performance soil-cement (HPSC) specimen bodies. Cuad. Educ. y Desarro. 15, 1904–1924. https://doi.org/10.55905/cuadv15n2-043.

S. B., Patil, N., Jaiswal, K.K., Gowrishankar, T.P., Selvakumar, K.K., Jyothi, M.S., Jyothilakshmi, R., Kumar, S., 2023. Development of sustainable alternative materials for the construction of green buildings using agricultural residues: a review. Construct. Build. Mater. 368, 130457 https://doi.org/10.1016/j.conbuildmat.2023.130457.

Wang, R., Hu, Z., Li, Y., Wang, K., Zhang, H., 2022. Review on the deterioration and approaches to enhance the durability of concrete in the freeze–thaw environment. Construct. Build. Mater. 321, 126371 https://doi.org/10.1016/j.conbuildmat.2022.126371.

Wiyanto, H., Makarim, C.A., Gondokusumo, O., Siregar, J.P., Irawan, A.P., Cionita, T., Najid, N., 2022. Determining concrete structure condition rating based on concrete compressive strength. Buildings 12, 776. https://doi.org/10.3390/buildings12060776.

Yimer, T., Gebre, A., 2023. Effect of fibre treatments on the mechanical properties of sisal fibre-reinforced concrete composites. Adv. Civ. Eng. 2023, 1–15. https://doi.org/10.1155/2023/2293857.

Yücel, H.E., Dutkiewicz, M., Yıldızhan, F., 2023. The effect of waste ballast aggregates on mechanical and durability properties of standard concrete. Materials. https://doi.org/10.3390/ma16072665.