MASTER DIPLOMA PIECE

Ali Fahem Obaid Almamoori

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UNIVERSITY OF SOPRON

FACULTY OF FORESTRY

MSc in Environmental Engineering

PRODUCTION OF ECO-FRIENDLY MORTAR USING PARTIAL CEMENT REPLACEMENT WITH WOOD ASH AND FLY ASH

Ali Fahem Obaid Almamoori

Supervisor:Dr. Tamás Hofmann
Co-supervisor:Prof. Dr. Tibor László Alpár

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UNIVERSITY of SOPRON
FACULTY OF FORESTRY
Institute of Environmental Protection and Natural Conservation

4 Bajcsy Zsilinszky Str, 9400 Sopron, Hungary. web: emk.uni-sopron.hu

MASTER DIPLOMA WORK TASK STATEMENT

Name of the author of diploma work: Al-Mamoori Ali Fahem Obaid (MSc EE student, Neptun code: QIICK6)

Title of diploma work: Production of eco-friendly mortar using partial cement replacement with wood ash and fly ash

Tasks set for writing the diploma work:

1. Carry out literature research on cement substitute ash, especially wood-based ash.
2. Examine the chemical components of various wood-based ashes, like local wood chip, annual plant and Iraquian palm tree.
3. Carry out hardening tests on ash-cement concrete, with various mixing ratio of ash of the above-mentioned species.
4. Make standard tests on the experimental products.
5. Define/analyze the environmental effects of substitution of cement.
6. Summarize the results of your examination, as well as other findings related to them

Consultants:

Dr. Tamás Hofmann (US, Faculty of Forestry, Institute of Environmental Protection and Natural Conservation)

Prof. Dr. Tibor Alpár (US, Faculty of Wood Sciences and Creative Industries, Institute of Applied Sciences)

Sopron, November 1, 2024

(place of seal)

Dr. Tamás Rétfalvi
Head of the Institute

Dr. András Polgár
Responsible person for EE MSc

Prof. Dr. Bálint Heil
Dean of Faculty of Forestry

ANNEX 4: Student statement

STATEMENT

I, Ali Fahem Obaid Almamoori the undersigned, (Neptune Code:QIICK6). signing. this Statement, declare that the titled

"Production of Eco-Friendly Mortar Using Partial Cement Replacement with Wood Ash and Fly Ash"

Diploma Piece;

(hereinafter: thesis) is **my independent work**, during the preparation of the dissertation I abided *the rules of the copyright law LXXVI of 1999* and the regulations of the university concerning the preparation of the thesis, with regard to references and quotations.[9]

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ALI FAHEM OBAID ALMAMOORI

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ABSTRACT

This study investigates the potential of utilizing wood ash and fly ash as partial replacements for Portland cement in the production of environmentally friendly mortar. The research aimed to address two critical challenges in the construction industry: reducing the environmental footprint of cement production and maintaining acceptable mechanical performance in alternative mortar mixes.

A comprehensive experimental program was conducted, involving chemical characterization of various ash types, compressive strength testing, and a Life Cycle Assessment (LCA). The ashes analyzed included fly ash sourced from the University of Sopron's biomass heating plant and bamboo-derived wood ash, both demonstrating favorable pozzolanic properties.

Compressive strength tests revealed that while the control mortar achieved the highest strength (30.23 MPa at 28 days), the mortar incorporating university-sourced fly ash achieved a comparable strength of 26.85 MPa. The bamboo wood ash mortar also demonstrated acceptable strength levels of 23.61 MPa, confirming the viability of these alternative binders in structural applications.

The LCA results highlighted significant environmental benefits of the ash-based mortars. The bamboo wood ash mortar exhibited a near-zero carbon footprint, while the university fly ash mortar achieved an 88% reduction in global warming potential compared to the control mix. Additional environmental impact categories, including ozone depletion, acidification, eutrophication, and resource use, also showed marked improvements.

The findings underscore the effectiveness of using industrial byproducts such as fly ash and wood ash to produce sustainable construction materials. The university fly ash mortar offered the optimal balance between mechanical strength and environmental performance, while the bamboo wood ash mortar provided the greatest environmental advantages with adequate mechanical properties. These results contribute valuable insights into sustainable material design and promote the adoption of eco-friendly practices in the construction industry.

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Definition	Abbreviation
Fly Ash	FA
Wood Ash	WA
Supplementary Cementitious Material	SCM
Ordinary Portland Cement	OPC
Calcium Silicate Hydrate	C-S-H
Life Cycle Assessment	LCA
Life Cycle Inventory	LCI
Global Warming Potential	GWP
Carbon Dioxide	CO_2
American Society for Testing and Materials	ASTM
International Organization for Standardization	ISO
Electrostatic Filtration (FA-EF = Fly Ash collected via Electrostatic Filtration)	EF
Solid Recovered Fuel (FA-SRF = Fly Ash from SRF burner)	SRF
Fly Ash collected from University biomass plant	FA-Uni
Wood Ash derived from bamboo combustion	WA-Bamboo
Silicon Dioxide	SiO_2
Aluminum Oxide	Al_2O_3
Ferric Oxide	Fe_2O_3
Calcium Oxide	CaO
Potassium Oxide	K_2O
Magnesium Oxide	MgO
Loss on Ignition	LOI
Water to Cement ratio	W/C

Chapter One

Introduction and Theoretical Framework

1.1 General

In our contemporary world, defined by growing environmental concerns, coupled with natural resource exploitation and industrial pollution, we breach essential biodiversity boundaries and call for novel, effective approaches on a global scale [1].

Sustainability concerns are prominent in everything, especially in industries like cement manufacturing, which consume natural resources and emit a significant proportion of greenhouse gases. This puts them at the center of the ongoing discourse on environmental sustainability [2].

This work seeks to resolve this dilemma by analyzing different approaches that would help reduce the construction industries' adverse effects on the environment while optimizing the efficacy of materials [3].

The cement industry is one of the most carbon emission-intensive industries and economically underperforming industries. It accounts for about 8% of the estimated global carbon emissions [4].

As shown in Fig. 1, CO_2 emissions have a significant impact level compared to other environmental factors, such as energy consumption, land degradation, and waste generation.

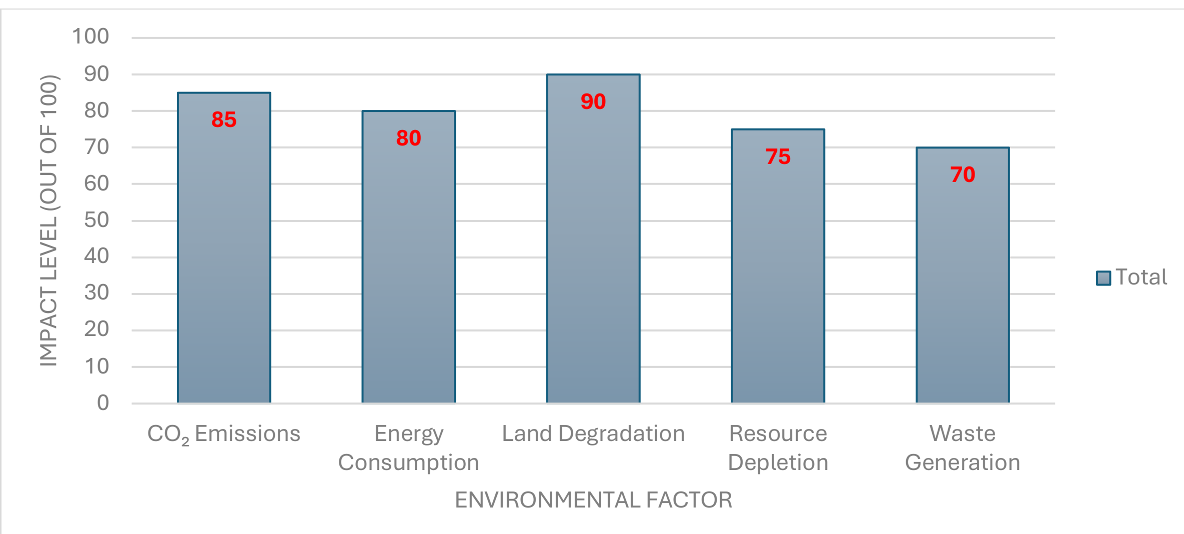

Figure 1:Contribution of CO_2 emissions and other factors to environmental impact in cement manufacturing[4].

All these emissions come from burning fossil fuel, which sustains the high temperatures needed in the different cement production processes. In addition, the production of cement also requires the extraction of materials which severely damages the environment through disrupting landscapes and depleting biodiversity [2].

Table 1:CO_2 Emissions Contribution by Industry[2].

Industry	CO_2 Emissions Contribution (%)
Cement Industry	8%
Energy Sector	40%
Transportation	25%
Other Industries	27%

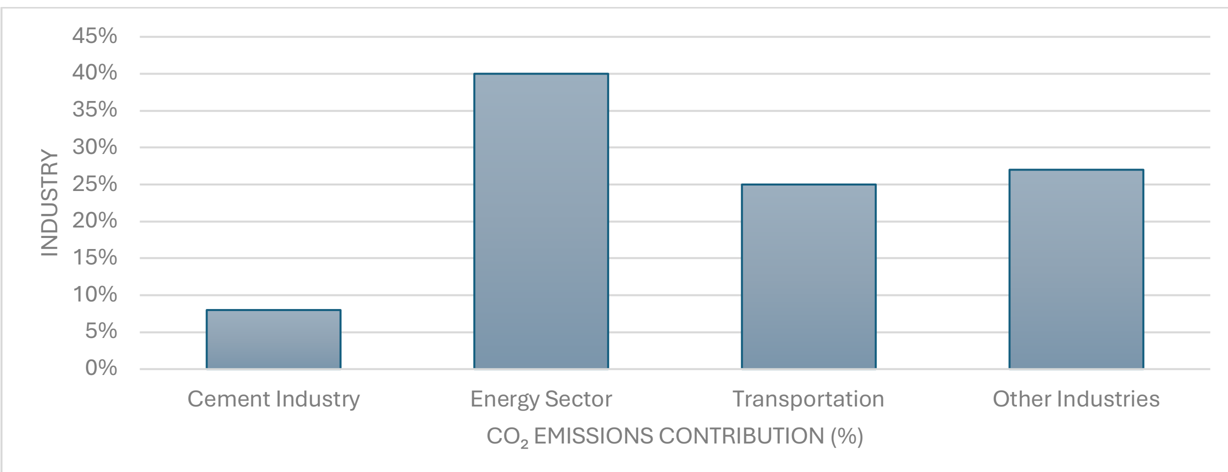

Figure 2:CO_2 Emissions Contribution by Industry[2].

Because of all these issues, alternative construction materials need to be developed which assist in minimizing harm to the environment, especially for the development of sustainable practices [5].

The research examines the possibility of using wood ash from certain Hungarian and native trees, as well as palm trees from Iraq(***Phoenix dactylifera***) , as a source of ash. Moreover, it investigates the viability of using fly ash from thermal plants and other combustion processes as a replacement for a part of the cement used in Mortar [1].

The focus on these materials is twofold: They offer an effective way to recycle waste products and have the potential to improve the properties of Mortar such as strength and durability while minimizing the carbon impact made with conventional cement [3].

Furthermore, this study is conducted against the backdrop of the emerging consensus worldwide regarding the importance of sustainable construction practices. This work is part of environmental engineering and seeks to address how the integration of modern technologies as well as innovative materials science could be used positively to help improve construction activities and materials so that, instead of harming the environment, they would help it, such as the use of wood ash and fly ash as building materials [1].

The expected outcomes of this study will be pioneering to the construction industry in a way that will propel more sustainable practices. These measures are important for mitigating the negative impacts of the construction industry on the environment and for meeting the overall sustainable development objectives of the world [6].

This thesis seeks to illustrate with an in-depth analysis of different options of materials how modern science can enable progress towards a more sustainable and eco-friendly construction industry in the future [1].

To provide a solid theoretical foundation for the study, a comprehensive review of the existing literature on fly ash and wood ash is essential. This review explores the types, properties, and effects of these materials in Mortar applications, supporting the rationale for their selection in sustainable construction research.

1.2 Literature Review

1.2.1 Classification of Ash Used in Mortar

The type of ash used in Mortar is fundamental in expressing its action on Mortar properties and interaction with other materials. Ash types in Mortar depend largely on the chemical composition and pozzolanic reactivity. There are two types: fly ash and wood ash, by provenance.

Class F and Class C of fly ash have been described in the articl [7] ,and its classification is determined by the calcium oxide (CaO) content. A Class F Fly Ash is such that it contains less than 18% calcium oxide and depends mainly on pozzolanic reactions with calcium hydroxide ($Ca(OH)_2$) produced during cement hydration. Likewise, Class C Fly Ash is one that exhibits a calcium oxide (CaO) content exceeding 18% and is self-cementing, allowing it to hydrate by itself, with little or no additional pozzolanic materials.

Wood ashes have been reviewed in [8], where their classification hinges on chemical origin and physical properties. Types include Biomass Wood Ash and Bamboo Ash; Biomass Wood Ash results from the combustion of biomass, while Bamboo Ash adds to increasing Mortar durability due to its high silica content.

Additionally, Biomass Fly Ash demonstrates immediate compatibility with Mortar applications; however, its chemical composition varies significantly based on combustion conditions and feedstock material, as noted in the study [9].

Additionally, five distinct types of industrial fly ash have been analyzed, with findings indicating that their chemical composition is influenced by coal type and combustion temperature. Study results show that industrial fly ash is a good substitute for cement, especially when the replacement of cement equals 10% to 30%, leading to enhanced compressive strength and reduced autogenous shrinkage in Mortar[7].

Overall, key factors in ash classification include calcium oxide (CaO) content, pozzolanic activity, and raw material sources. Certain types, such as Class F Fly Ash, Biomass Wood Ash, and Bamboo Ash, enhance the durability of Mortar and reduce permeability, making them suitable as partial cement replacements. On the other hand, Class C Fly Ash and industrial fly ash exhibit superior early-age strength development when precise dosage control is applied to optimize performance[10].

1.2.1.1 Fly Ash (FA)

Fly ash (FA) is a byproduct generated from the combustion of coal in power plants and is widely used as a supplementary cementitious material in the production of mortar and concrete. According to ASTM C618 [10], fly ash is classified into two main categories based on its chemical composition and cementitious behavior: Class F and Class C.

Class F fly ash is primarily produced from the combustion of anthracite and bituminous coal[10]. It is characterized by a low calcium oxide (CaO) content (less than 18%) and high contents of silica (SiO_2) and alumina (Al_2O_3). Due to this chemical composition, Class F fly ash exhibits strong pozzolanic activity, requiring an external source of calcium hydroxide ($Ca(OH)_2$) to initiate reactions that contribute to strength development through the formation of additional hydration products.

Conversely, Class C fly ash results from the combustion of lignite or sub-bituminous coal [10] and contains a higher concentration of calcium oxide (greater than 18%). This higher CaO content imparts self-cementing properties to Class C fly ash, enabling it to hydrate and gain strength independently, without the need for an external calcium hydroxide source. Consequently, Class C fly ash can contribute to both early-age and long-term strength development in cementitious systems.

Understanding the distinction between Class F and Class C fly ash is crucial for selecting the appropriate material for mortar and concrete applications, depending on the specific requirements for early strength, long-term performance, and durability.

1.2.1.2 Wood Ash (WA)

Wood ash is a byproduct resulting from the combustion of various wood sources, including agricultural residues, industrial waste, and biomass-based materials. Its chemical and physical properties vary significantly with the feedstock type, combustion temperature, and burning conditions, which directly influence its cementitious potential in Mortar [8].

Classified based on its chemical composition and physical characteristics, wood ash primarily consists of silicon oxide (SiO_2), calcium oxide (CaO), potassium oxide (K_2O), and magnesium oxide (MgO), and is widely recognized as a supplementary cementitious material. However, in some types, the high alkali content can lead to an Alkali-Silica Reaction in Mortar, necessitating pre-treatment before use [11].

Among its various types, Biomass Wood Ash is produced by the combustion of biomass materials, including agricultural residues and sawdust, characterized by high SiO_2 and CaO content, making it effective for partial cement replacement only when its fineness and combustion conditions are optimized [8]. Similarly, Bamboo Ash (BA) contains a high silica content, which enhances Mortar durability and reduces permeability, thereby making it suitable for applications requiring higher resistance to environmental degradation [12].

The incorporation of wood ash in Mortar affects both fresh and hardened properties, depending on the level of replacement and prior treatment. Due to its high porosity and irregular particle shape, it increases water demand, often requiring chemical admixtures to maintain workability [5]. Furthermore, replacing 10-20% of cement with wood ash has shown long-term improvements in compressive strength, provided the ash has a balanced chemical composition and sufficient fineness [8]. Additionally, wood ash plays a key role in reducing waste from industrial combustion processes and lowering carbon emissions associated with cement production, making it a viable material for sustainable Mortar [12].

Wood ash exhibits significant pozzolanic properties, making it a promising alternative to cement in Mortar applications, particularly in projects prioritizing durability and sustainability. However, successful utilization requires proper optimization of replacement ratios, comprehensive chemical characterization, and appropriate modifications to Mortar mix design to ensure optimal performance.

The chemical and physical properties of WA and FA play a crucial role in determining their performance as supplementary cementitious materials. Table 2 summarizes the key characteristics of these materials, highlighting their potential benefits and limitations in Mortar applications.[1]

Table 2: Key Characteristics of Fly Ash and Wood Ash as Supplementary Cementitious Materials[1].

Property	**FA**	**WA**
Main Components	SiO_2, Al_2O_3, Fe_2O_3, CaO	CaO, SiO_2, K_2O, MgO, P_2O_5
Density (g/cm³)	2.1 - 2.6	2.35 - 2.76
Loss on Ignition (% LOI)	10.Jan	20.May
pH	10.Aug	9 - 13.5
Pozzolanic Activity	High (Class F), Moderate (Class C)	Low to Moderate
Reactivity	Pozzolanic, self-cementing (Class C)	Alkali-rich, may cause ASR in Mortar
Fineness (µm)	10 - 100	86 - 176
Moisture Content (%)	Low (usually <1%)	Can be high (>5%)

1.2.2 Effect of Ash on Fresh Properties of Mortar

The inclusion of fly ash (FA) and wood ash (WA) significantly alters not only the fresh properties of Mortar but also its workability and setting time. These effects primarily depend on the type, chemical composition, and particle morphology of the ash used in a Mortar mix [7][1, 13].

Table 3:Effect of Fly Ash and Wood Ash on Fresh Properties of Mortar.

Property	**(FA)**	**(WA)**
Workability (Slump in mm)	Increases with FA replacement up to 20%	Decreases significantly with higher WA content due to high water absorption
Setting Time	Delayed setting, particularly with Class F FA	Accelerated setting at low replacement levels, delayed at high levels
Early-Age Strength (7 days, MPa)	Reduced compared to control, but gains long-term strength due to pozzolanic activity	Lower than FA-modified Mortar due to irregular particle shape and high porosity
Long-Term Strength (28 days, MPa)	Higher at 20-30% FA replacement due to continued pozzolanic reaction	Can reach acceptable strength at ≤10% replacement but weakens at higher percentages
Durability (Permeability & ASR Resistance)	Reduces permeability and increases resistance to sulfate attack	High alkali content in WA can increase risk of alkali-silica reaction (ASR)

The data in Table 3 demonstrates that FA improves workability and delays setting time, making it suitable for Mortar requiring extended placement time. On the other hand, WA increases water demand and can cause setting time variations, depending on its fineness and chemical composition. Regarding strength development, FA supports long-term compressive strength gain through pozzolanic reactions, while WA shows a more variable performance, requiring optimized replacement ratios to achieve structural efficiency.

Fly ash generally enhances the workability of Mortar due to its spherical particle morphology, which reduces internal friction and improves the flowability of the mix. Fly Ash indicate that Class F and Class C fly ashes exhibit distinct behaviors in this regard. Class F fly ash, being finer and lower in CaO content, increases setting times and reduces water demand, making it advantageous for large-scale Mortar placements where extended workability is required. Conversely, Class C fly ash, with a higher percentage of calcium oxide (CaO), exhibits self-cementing properties, which may lead to shorter setting times and improved early-age strength [7].

On the other hand, wood ash behaves differently due to its irregular particle shape and high porosity, which generally increase water demand and reduce workability[14]. WA particles, due to their angular shape and high surface area, lead to higher water absorption and lower slump values in WA-incorporated mixtures compared to FA-containing mixes. Moreover, the high alkali content and unburnt carbon in WA may influence the viscosity and consistency of fresh Mortar, often necessitating the use of chemical admixtures to maintain acceptable workability [14].

With regard to setting time, previous studies indicate that WA demonstrates variable effects on setting time, primarily dictated by its chemical composition and fineness. Some studies suggest that high-calcium wood ash accelerates setting, whereas wood ash with a high silica-to-calcium ratio tends to delay it. Therefore, careful selection and pre-treatment of WA are crucial before its incorporation into Mortar [3].

Furthermore, research has shown that biomass-derived fly ashes exhibit behavior similar to FA but contain higher alkali content, which may impact workability and early hydration characteristics. The study emphasizes the need to optimize FA and WA proportions in Mortar mixes to maintain an optimal balance between workability, strength, and durability [15].

In conclusion, the effectiveness of FA and WA on fresh Mortar properties is primarily governed by their fineness, particle shape, and chemical composition. FA generally enhances workability and extends setting time, whereas WA often increases water demand and has unpredictable effects on setting time. Thus, optimizing replacement ratios and incorporating proper admixtures can mitigate negative impacts and improve Mortar performance.

1.2.3 Effect of Ash on Compressive Strength of Mortar

The incorporation of (FA) and (WA) significantly affects compressive strength, a key parameter determining the structural integrity and load-bearing capacity of Mortar. FA and WA enhance compressive strength through pozzolanic reactions, microstructural densification, and filler effects,**Table 4** summarizes the impact of different **replacement percentages of FA and WA** on Mortar compressive strength at **7 and 28 days**

Table 4: Effect of Fly Ash and Wood Ash Replacement on Mortar Compressive Strength [1][3].

Replacement Material	Replacement Percentage	Compressive Strength (MPa) at 7 days	Compressive Strength (MPa) at 28 days
Fly Ash	5%	23.4	29.0
	10%	20.9	27.3
	15%	18.7	26.8
Wood Ash	5%	21.45	27.54
	10%	19.52	25.66
	20%	15.36	22.31
	30%	15.12	19.52

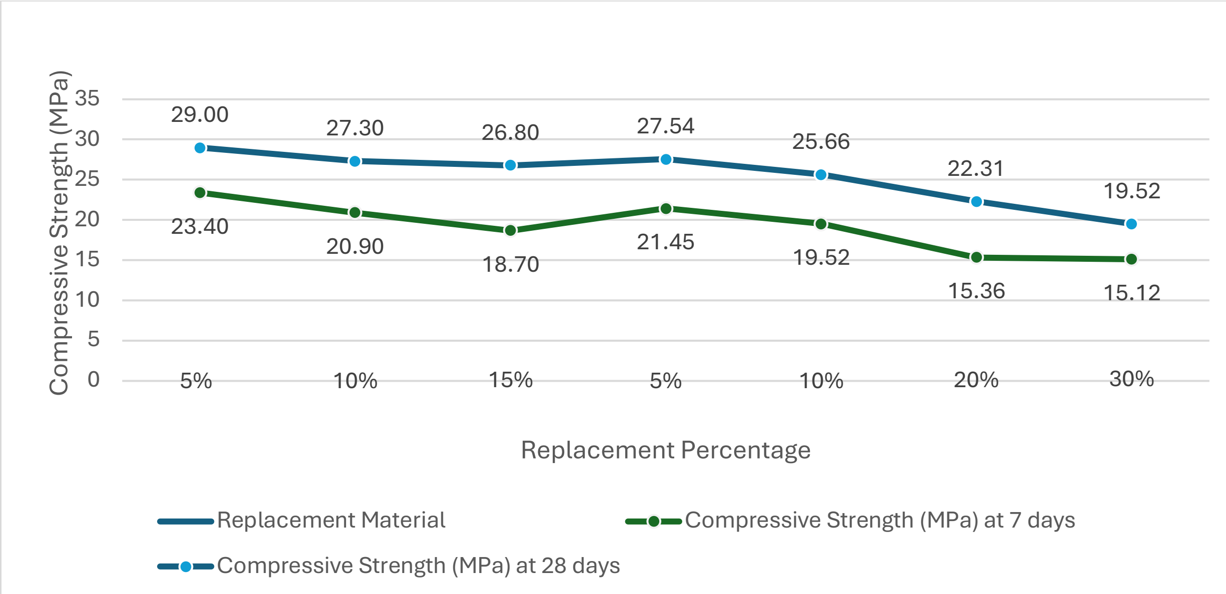

Figure 3:Effect of Fly Ash and Wood Ash Replacement on Mortar Compressive Strength [1][3].

- **Effect of Fly Ash Type and Content on Compressive Strength Development**

The inclusion of 10–30% FA has been found to enhance long-term compressive strength due to its reaction with calcium hydroxide ($Ca(OH)_2$) released during cement hydration, leading to additional calcium silicate hydrate (C-S-H) formation, which reinforces the Mortar matrix. Class F FA, with low calcium oxide (CaO) content (<18%), requires an external source of $Ca(OH)_2$ for activation. Consequently, strength gain occurs gradually over time, resulting in lower early strength but significantly higher long-term compressive strength due to sustained pozzolanic activity and pore refinement [3].

In contrast, FA Class C, which contains higher CaO levels (>18%), behaves differently as it exhibits self-cementing properties, meaning it can hydrate independently without additional calcium hydroxide. This characteristic enables FA class C to contribute to early-age strength gain, making it beneficial for applications requiring rapid strength development [16].

The optimal replacement level of FA varies depending on the desired performance. Studies indicate that replacing 10–20% of cement with FA provides a balance between early and long-term strength, whereas higher replacement levels (~30%) may delay early strength gain but result in greater durability and higher ultimate compressive strength due to prolonged hydration reactions. Furthermore, the fineness of FA plays a crucial role in compressive strength development. Finer FA particles improve packing density, reduce voids, and enhance matrix densification, contributing to higher strength over time [17].

- **Influence of Wood Ash Characteristics on Mortar Strength Performance**

Compared to FA, WA exhibits more variable effects on compressive strength due to differences in chemical composition, alkali content, and particle fineness. WA is often rich in silica (SiO_2), potassium oxide (K_2O), and calcium oxide (CaO), but its high porosity and irregular morphology increase water demand, which may hinder strength development [13].

Research suggests that high-calcium WA accelerates hydration reactions, leading to shorter setting times and higher early-age compressive strength. In contrast, high-silica WA requires extended curing times to reach full pozzolanic potential, behaving similarly to Class F FA [14]. However, proper processing, such as grinding WA into finer particles, can mitigate some of its drawbacks, allowing it to fill voids and improve compressive strength. Conversely, untreated WA with high alkali or unburnt carbon content may negatively impact compressive strength, making Mortar mixtures weaker [8].

Several studies indicate that finely ground WA improves compressive strength, particularly when used at replacement levels of 10–15%. However, excessive WA content (>20%) has been shown to negatively impact early compressive strength due to high water absorption and reduced workability. Therefore, incorporating WA as a partial cement replacement requires careful mix proportioning, particle refinement, and mineralogical assessment to ensure optimal performance [12].

1.2.4 Life Cycle Assessment (LCA) and Sustainability

The environmental footprint of cement production has become a critical concern due to its high carbon emissions, intensive energy consumption, and significant resource depletion. The integration of fly ash and wood ash as supplementary cementitious materials (SCMs) presents a sustainable alternative, mitigating emissions while supporting circular economy practices. LCA is a fundamental tool for evaluating the long-term sustainability of FA and WA, particularly in terms of carbon footprint reduction and economic viability.

Table 5: Life Cycle Assessment (LCA) and Sustainability of Fly Ash and Wood Ash.

Environmental Factor	Traditional Cement	Fly Ash	Wood Ash
CO_2 Emissions (kg/ton)	800 - 900	Reduces emissions by up to 25%	Can contribute to CO_2 neutrality due to biomass carbon cycle
Energy Consumption	High (Clinker production requires extreme temperatures)	Reduces energy demand by 15%	Lower than cement, but requires preprocessing for better reactivity
Landfill Waste	Large cement kiln dust waste	FA diverts waste from coal power plants and reduces landfill demand	WA minimizes wood combustion waste and aligns with circular economy practices
Natural Resource Consumption	High (Extraction of limestone and clay)	Reduces demand for virgin raw materials by 30%	Utilizes industrial byproducts, decreasing reliance on non-renewable resources
Durability and Service Life	Standard durability, requires frequent maintenance	Increases durability by 40%, reducing maintenance needs	Potential improvement in service life but highly dependent on preprocessing

Table 5 highlights the significant environmental benefits of using FA and WA as partial cement replacements. FA contributes to CO_2 emission reduction and energy savings by optimizing the pozzolanic reaction in cement hydration. Similarly, WA aligns with sustainability goals by minimizing wood combustion waste and reducing the reliance on virgin raw materials. However, WA's environmental impact is highly dependent on preprocessing techniques, such as grinding and chemical stabilization, which influence its effectiveness as a cement substitute.

1.2.4.1 Carbon Footprint Reduction

The cement industry accounts for approximately 7–8% of total global CO_2 emissions, making it one of the most significant contributors to climate chang, To contextualize the environmental impact ofcement production, Table 6 compares CO_2 emissions across different industries, emphasizing the need for sustainable alternatives in the construction sector[2][6].

Table 6: CO_2 Emissions Across Different Industries.

Industry	Average CO_2 Emissions (kg/ton of product)
Cement Production	800 - 900
Iron & Steel Production	1,800 - 2,200
Aluminum Production	11,000 - 12,000
Glass Production	1,000 - 1,200
Paper Production	400 - 600
Plastic Production	1,500 - 3,000
Coal-based Power Generation	900 - 1,200
Gas-based Power Generation	400 - 500

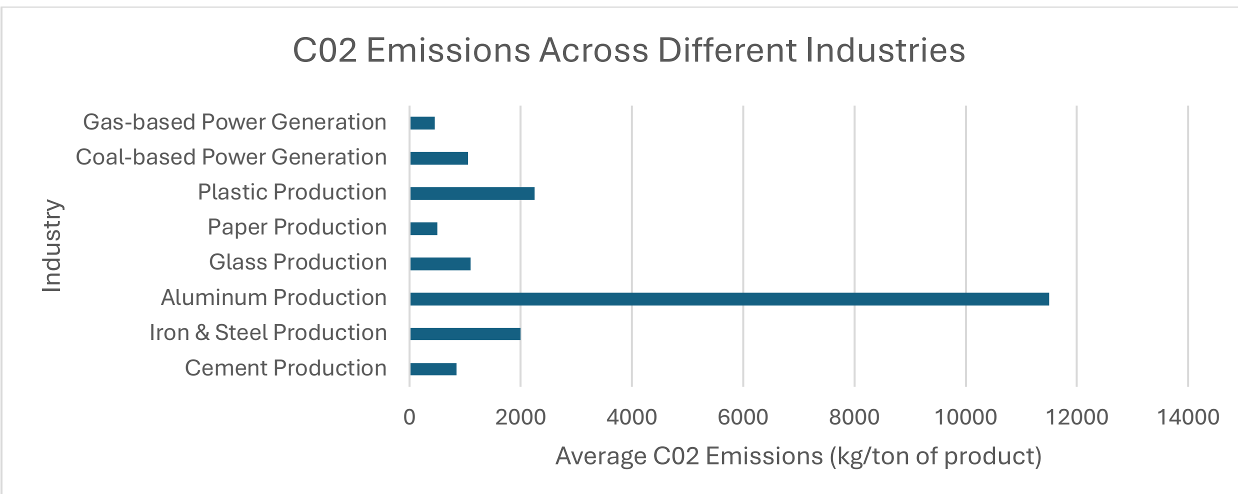

Figure 4:CO_2 Emissions Across Different Industries [2][6].

These emissions primarily originate from two key processes:

1. **Fossil fuel combustion** used to generate extreme temperatures in kilns.
2. **The calcination reaction**, where limestone decomposes into lime (CaO) and CO_2.

Beyond direct emissions, cement production also demands large-scale extraction of raw materials, leading to deforestation, biodiversity loss, and land degradation. Given these environmental concerns, reducing reliance on ordinary Portland cement is imperative for meeting global sustainability targets [6].

Incorporating FA and WA into Mortar reduces CO_2 emissions through two primary mechanisms. First, FA and WA serve as partial replacements for cement, thereby reducing clinker consumption, which is the most carbon-intensive component of cement. Depending on the replacement ratio, this can result in CO_2 reductions of up to 30%. Second, both FA and WA promote pozzolanic reactions, generating additional calcium silicate hydrate (C-S-H) gel, which enhances durability and reduces the need for frequent cement-intensive maintenance throughout a structure's lifespan. Additionally, the use of FA and WA allows for the repurposing of industrial byproducts, thereby minimizing landfill waste and its associated environmental burdens [3].

Despite these benefits, WA presents challenges due to its variable composition and significant alkali content, which may impact durability if not properly processed. Studies highlight the necessity of preprocessing techniques such as grinding and chemical stabilization to optimize WA's reactivity and maximize its long-term sustainability potential. Furthermore, transportation-related emissions should be considered, as long-distance hauling of FA and WA may offset some of the carbon savings achieved through clinker reduction [7].

1.2.4.2 Economic Viability

Beyond environmental advantages, the utilization of FA and WA offers economic incentives by reducing the demand for virgin raw materials in clinker production. The economic feasibility of these materials depends on several key factors, including availability, transportation costs, preprocessing requirements, and regulatory frameworks. FA has an established supply chain, making it logistically viable and cost-effective for widespread use. In contrast, WA remains under research and development, and its economic competitiveness varies due to source variability and the need for additional processing [2].

A major economic advantage of FA and WA is their potential to reduce long-term maintenance costs. FA-modified Mortar exhibits higher durability, leading to lower repair and rehabilitation expenses over the structure's service life. Similarly, WA, when properly processed, can enhance service life and decrease repair frequency, contributing to cost reductions in infrastructure projects. Furthermore, FA and WA utilization aligns with waste management strategies, allowing industries to reduce landfill disposal costs while transforming these byproducts into marketable materials for the construction sector [8].

However, despite these advantages, the initial investment in WA preprocessing remains a significant barrier to its widespread adoption. Some WA sources require thermal treatment or grinding to enhance their pozzolanic reactivity, which adds to production costs. Additionally, the economic feasibility of FA and WA is highly influenced by regional policies and government incentives promoting sustainable construction materials. In regions where carbon trading or emissions reduction incentives exist, the use of FA and WA becomes more financially attractive due to their ability to offset cement-related CO_2 emissions[18].

1.2.5 Research Gaps and Future Directions

Even with various studies conducted on fly ash and wood ash use in Mortar, there are unrevealed areas of knowledge that still have to be addressed for their intended use as a supplementary cementitious material. These gaps in knowledge appear to concern comparative assessments of the different fly ash and wood ash types, long-term durability assessments of these two materials under extreme conditions, and economic feasibility at large-scale utilization.

1.2.5.1 Comparative Evaluation of Different Types of Fly Ash and Wood Ash

However, the comparative analysis from different sources is lacking; while many studies on the different forms of FA or WA exist. The correlation of chemical compositions between FA and WA is quite variable, depending on the source of biomass and combustion process, thus differing in the pozzolanic activity, mechanical properties, and durability in the long term. Future research should:

- Comparative studies should be carried out on various types of fly ashes and waste ashes under identical conditions.
- Study the effect of particle size, fineness, and composition on reactivity and performance.
- Investigate the impact of alkalis, unburned carbon, and heavy metals as impurities on the Mortar properties[12].

1.2.5.1 Economic Feasibility of Large-Scale Implementation

Although the economic concerns are challenging, the advantages of FA and WA use are well appreciated on the environment. Several barriers cost-wise have to be overcome such as:

- Variability in the chemical composition that might require more processing steps for uniformity.
- Producing chemical, thermal treatment, or grinding further increases the cost of production.
- The expense of logistics and transportation can cancel the carbon savings achieved if FA and WA have to be moved over long distances[11].

To further support the area in question, future studies may focus on:

- Conducting cost-benefit analyses on the usage of FA and WA with other supply chain management systems (SCM).
- Determining sourcing and processing approaches that enhance cost efficiency.
- Investigating the effect of public subsidies, carbon credits, and policies regarding sustainable development on the adoption of FA and WA[19].

By addressing these knowledge gaps will enable the scientific community as well as the construction industry to capitalize on the benefits of FA and WA as economically feasible and environmentally friendly substitutes for cementitious materials.

1.3 Objectives

The primary objective of this thesis is to assess the effectiveness of using wood ash and fly ash as partial substitutes for cement in Mortar mixtures, focusing on improving the mechanical properties of Mortar and reducing its environmental footprint. The subsidiary objectives include:

- Studying the environmental impact of traditional cement production compared to the use of wood ash and fly ash.
- Analyzing the applicability of these alternative materials under various construction conditions.

1.4 Research Questions

1. How can the use of wood ash and fly ash impact the Mortar properties such as Comperssive strength compared to traditional cement?
2. What are the environmental effects of replacing part of the cement with wood ash and fly ash in Mortar mixtures?

1.5 Scope of Research

This study focuses on the use of wood ash extracted from specific types of Hungarian wood and palm trees in Iraq, as well as fly ash from Biomass heating plants and various combustion processes. Experiments will be conducted under controlled laboratory conditions to ensure the accuracy of the results.

1.6 Assumptions and Limitations

In conducting this study, several limitations and assumptions were noted that could affect the results and conclusions. Understanding these limitations is crucial to evaluate their overall impact on the research.

1.6.1 Assumptions:

1. **Homogeneity of Ash Properties**: The research assumes that the properties of wood ash and fly ash are consistent across various sources, which may not be entirely accurate due to variations in combustion conditions and raw materials.
2. **Consistency of Ash Composition**: The composition of ash which rests stable remains unchanged, this doesn't take into account factors such as the surrounding processes and storage

1.6.2 Limitations:

1. **Variation in quality and availability of materials**: Where there is wood or charcoal combustion, the quality of ash generated can differ remarkably which as a result is going to directly alter the output of the experiments that were conducted.
2. **Working Across Multiple Sites**: The study had two distinct locations - Hungary where work involved wood and plant ash from local resources and fly ash, while in Iraq, palm wood from date palms was processed into ash. Due to this locale distribution, the approaches used and the experimental conditions set were difficult to manage,which may limit the generalizability of the results.
3. **Challenges of transportation and coordination**: The transportation of assets between Hungary and Iraq entails some logistical complexity that, in turn, raises the need for

thorough coordination to preserve the research's integrity in continuity and accuracy. These challenges lead to difficulties in effectively synchronizing data collection and analysis.

1.6.3 Addressing Limitations:

To address these limitations, it is necessary to develop standardized protocols for standard sampling and analyses be designed for both of the research sites. Moreover, more comparative studies should be done, especially in well-defined laboratory experiments and geoenvironmental ash analysis, to understand the aspects of place and region as it relates to ash quality and reactivity in Mortar mixes. Such actions will be useful towards increasing the scope of the results and making correct and pertinent decisions in relation to the design of Mortar mixes in the industry.

1.7 Glossary

- **Wood Ash**: Wood ash is the residue that remains after wood or wood-based products have been combusted and is commonly produced in biomass or industrial processes. Ash has pozzolanic characteristics which makes it a viable alternative for replacing cement. Moreover, when in contact with water and Lime, it generates Calcium Silicate Hydrate (CSH) which is responsible for increasing the Mortar's compressive strength and longevity. in addition, the use of wood ash can effectively limit industrial waste while simoultaneously aiding resource preservation which works toward sustainable construction objectives[17, 20].

- **Fly Ash**: Fly ash is the residue collected from the off-gases of coal or wood thermal power plants combustion processes, which is mostly used for construction purposes. It is trapped out of the exhaust gases by filters or electrostatic precipitators. Fly ash is effectively used as a supplementary cementitious materia(SCM) in Mortar, where it partially replaces for Portland cement. It undergoes pozzolanic reaction together with water, and in the presence of calcium hydroxide, produces more calcium silicate hydrate (CSH) which significantly improves workability, strength, and long-term durability of Mortar. Fly ash also improves the sulfur and chloride attack resistance and decreases Mortar permeability and shrinkage. Moreover, fly ash usage leads to reduced carbon dioxide emissions, less consumed energy, and less landfill waste, which promotes sustainable construction efforts[17].

1.8 Research Layout

Chapter One: Introduction and Literature Review

- This chapter sets the stage for the research by providing an introduction and reviewing the literature related to alternative materials and their environmental impacts, establishing a scholarly context for the study.

Chapter Two: Methodology and Experimental Details

- This chapter outlines the methodology and provides detailed descriptions of the laboratory experiments conducted during the study.

Chapter Three: Presentation of Results and Analysis

- This chapter details the results obtained from the experiments and provides an analysis of these results within the context of the research questions and hypotheses.

Chapter Four: Conclusions and Recommendations for Future Research and Practical Applications

- The final chapter summarizes the findings and offers conclusions and recommendations for future research and practical applications in the field.

Chapter Two

Methodology and Experimental Details

2.1 Research Methodology

This chapter explains the methodology used to investigate the potential of fly ash and wood ash as partial replacements for cement in Mortar production. A quantitative, laboratory-based research approach was employed to study the mechanical properties and environmental effects of Mortar mixtures containing these materials. All experiments and material analyses were carried out under controlled conditions at the University of Sopron –Natural Resours Reaserch Center, in Hungary, to reduce variability and ensure consistent results. The selected methodology aimed to support the research objective: evaluating the strength, durability, and sustainability of Mortar modified with supplementary cementitious materials.

The chapter outlines the materials used, the procedures for mix design, sample preparation, and the testing methods applied. Additionally, it presents the physical and chemical characterization of FA and WA. Finally, the life cycle assessment methodology used to assess the environmental performance of the developed mixtures is also described.

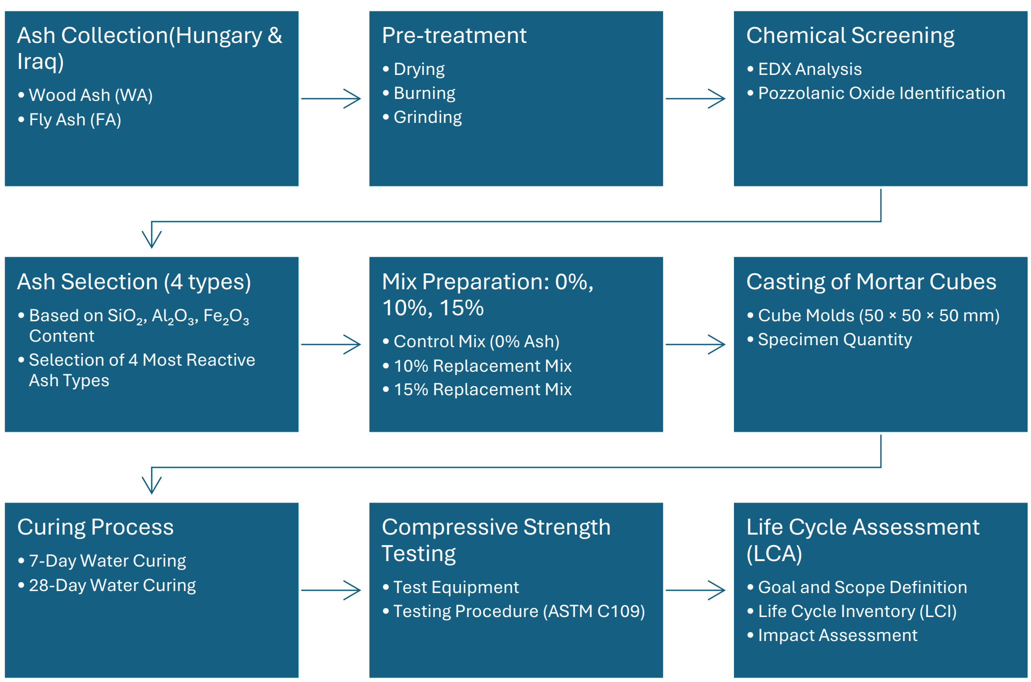

Figure 5:Overview of the Experimental Workflow for Ash-Based Cement Replacement in Mortar Production.

2.2 Materials

The experimental program included the use of several key materials to produce and evaluate Mortar mixtures with partial cement replacement. All materials were sourced and prepared in Hungary, and the experiments were conducted at the University of Sopron – Faculty of Wood Sciences. The main materials utilized in this study are outlined below:

2.2.1 Cement

The cement utilized in this study was a general-purpose Portland that cement conforming to the European standard EN 197-1, supplied by **Danucem Slovensko a.s.** (Rohožník, Slovakia).The specific type used was **CEM II/A-S 42.5 R**, which mainly consists of Portland cement clinker and ground granulated blast furnace slag.It is commonly used in construction applications such as Mortar, mortar, and plaster.The cement was handled and stored according to the safety recommendations provided in the product's Safety Data Sheet (SDS)[21]

2.2.2 Aggregates

In this research, only fine aggregate (sand) was used, with no coarse aggregate incorporated, as the study focused on the influence of supplementary cementitious materials within the cementitious matrix of mortar.

The sand used was a commercially packaged product branded as **Sahara Spielsand**, manufactured by **Weco GmbH & Co. KG**, based in Germany. The sand used in this study exhibited uniform fineness and was free from organic matter and clay content. Its smooth, sub-rounded particle shape enhanced the workability and stability of the mortar mixtures. The sand was used in its natural state, without any sieving or drying, and was incorporated into the mortar mixes prepared in the laboratory during this phase of the research. This setup enabled the evaluation of the effects of FA and WA as partial replacements for cement, supporting the study's objective of advancing sustainable alternatives in cement-based construction materials.

2.2.3 Ash Materials

Ash was explored in this study as a partial replacement for cement to assess its impact on mortar properties and its potential contribution to sustainable construction practices. Two types of ash were investigated: wood ash and fly ash , both obtained from different sources across Hungary.

The wood ash originated from a variety of biomass sources, including several Hungarian tree species, the trunk of an Iraqi date palm, and an unspecified mixed wood material typically used as biomass fuel. All ash samples were processed in the laboratory by drying and grinding to achieve a fineness comparable to that of Portland cement, ensuring consistency and improving their reactivity.

The **fly ash** was collected from two locations within the **University of Sopron**: the **biomass heating plant** serving the university's research and laboratory buildings, and the **heating system of the student dormitory**. Additionally, fave distinct fly ash samples were obtained from a company working in the field of biomass energy, where the ash was collected as a **residue from combustion processes** across several biomass-fired power stations.

In the following sections, each ash type will be briefly described in terms of its origin and **pozzolanic oxide content** (such as SiO_2, Al_2O_3, and Fe_2O_3), which contribute to its reactivity and performance in cementitious mixtures.

2.2.3.1 Wood Ash

Several types of wood ash were used in this study to investigate their individual effects on the performance of cement mortar when used as partial cement replacements. The aim was to compare the influence of different biomass sources and identify which ash type offers the most promising pozzolanic potential.

The wood types used to produce ash included:

- ***Secale cereale* L.** (rye straw)
- ***Hordeum vulgare* L.** (barley straw)
- Bamboo
- A mixed wood sample commonly used in biomass heating plants (Biomass Plant Mix – West Wood)
- ***Phoenix dactylifera*** (An Iraqi date palm trunk)

Each wood type was burned separately in a laboratory-controlled environment. The combustion process was carried out at the University of Sopron in a specialized muffle furnace, following the **ISO 18122** for determining ash content in solid biofuels. Prior to incineration, all samples were pre-dried at temperatures between **100–200°C** for one hour, then combusted at **550°C** for at least 10 hours to ensure complete decomposition and stable ash residue.[22]

After combustion, the resulting ash was processed through grinding to achieve a fineness similar to that of cement, which is necessary to promote better reactivity and dispersion within the mortar mixes.

Each type of wood ash was tested individually in mortar mixtures at different replacement levels. The detailed oxide composition and performance analysis of each ash type will be discussed in the relevant sections of this thesis.

Figure 6:Preparation of Diverse Wood-Based Materials for Investigating Ash Performance in Cementitious Applications.

2.2.3.2 Fly Ash

In this study, six types of fly ash were used. Two of them were collected from **biomass heating systems** within the **University of Sopron**; one from the **main university heating plant A10** and the other from the **heating system of the student dormitory**. The remaining four types were obtained from **Falco wood industry company**, a company located in **Szombathely, Hungary**.

At FALCO Co., fly ash is produced as a by-product of **biomass-based thermal energy generation**, where mixed biomass waste originating from the company's own industrial activities is used as fuel. The heat generated is utilized for **technical purposes**, such as **heating thermo oil in hot press systems** and **building heating**. These operational processes result in the accumulation of various types of ash suitable for evaluation in cementitious applications.

The four fly ash types supplied by the company included:

- **Fly Ash (SRF porégő pernye)** – from a dust (wood) burner
- **Fly Ash (Kombinált elektrofilter pernye)** – collected through an electrostatic filter
- **Biomass Ash (Biomassza kazán fahamu)** – ash residue from a biomass boiler
- **Biomass Fly Ash (Biomassza kazán pernye)** – fine ash from biomass combustion
- **Dust Burner Ash (SRF porégő hamu)** – ash from dust combustion technology

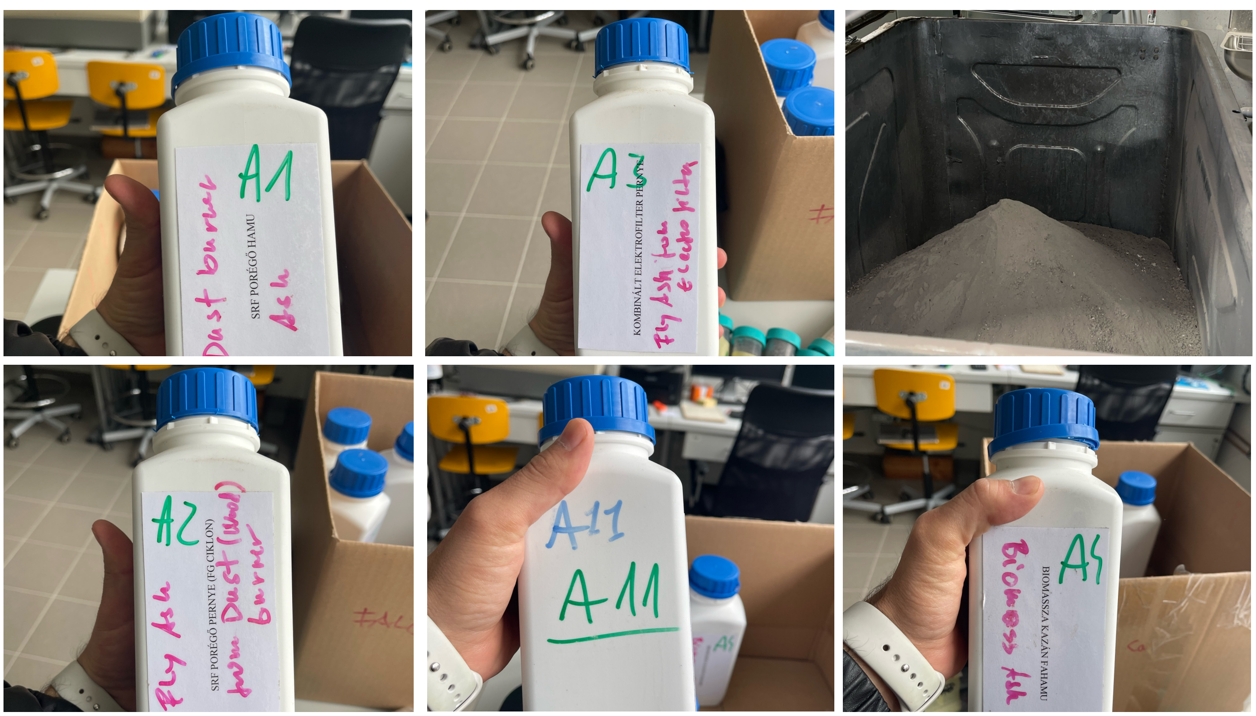

Figure 7:Collection and Preparation of Fly Ash samples from Biomass Combustion for Cementitious Applications.

These ashes exhibited noticeable differences in **color, particle gradation, impurity content, and fine material proportions**, depending on their source and combustion process. Before their incorporation into mortar, all samples were **oven-dried** and **sieved** using mesh sizes of **175 µm, 75 µm, and 45 µm**, in order to enhance fineness and reduce undesirable contaminants.

For the experimental mortar mixes, **the most promising fly ash types** were selected based on their **higher content of pozzolanic oxides**, particularly silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3), which are known to improve chemical reactivity and long-term performance in blended cement systems.

Further details about the oxide composition and performance comparisons of the selected fly ash types will be presented in the following chapters.

2.2.3.3 Chemical Screening and Sample Selection Based on EDX Analysis(method)

All collected ash samples, including both wood ash and fly ash, were subjected to Energy Dispersive X-ray Spectroscopy (EDX) to determine their elemental composition. **The primary objective** of this analysis was to identify the presence of key elements such as silicon (Si), aluminum (Al), and iron (Fe), which are crucial for assessing pozzolanic activity.

The data from EDX were quantitatively converted into their respective oxide equivalents: silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and ferric oxide (Fe_2O_3). **This conversion was critical** for further evaluation of the pozzolanic potential of each ash type. **The criteria for sample selection were based on the total pozzolanic oxide content**, aiming to identify ash types with the highest potential for enhancing the properties of cementitious systems.

Four ash samples were subsequently selected for experimental inclusion based on their pozzolanic oxide content. These samples were chosen for **their potential to improve reactivity and durability** in mortar mixes. The selected ashes included:

- **Fly Ash (SRF porégő pernye) FA-SRF**
- **Fly Ash (Kombinált elektrofilter pernye) FA-EF**
- **Fly Ash (collected from the University of Sopron’s biomass heating plant)FA-Uni**
- **Wood ash (derived from bamboo combustio)WA-Bamboo**

Other ash types, including those derived from barley, rye, palm, and biomass boilers, were also analyzed and exhibited acceptable pozzolanic properties but were not selected for further testing due to **comparatively lower Si, Al, and Fe contents**. The ash from the Iraqi palm trunk was also found to be chemically suitable for use as a supplementary cementitious material through EDX analysis but was excluded from mortar mix preparation due to **limited availability**, and it was retained solely for reference and documentation. The preparation process of the ash samples prior to EDX analysis is illustrated in Figer 8.

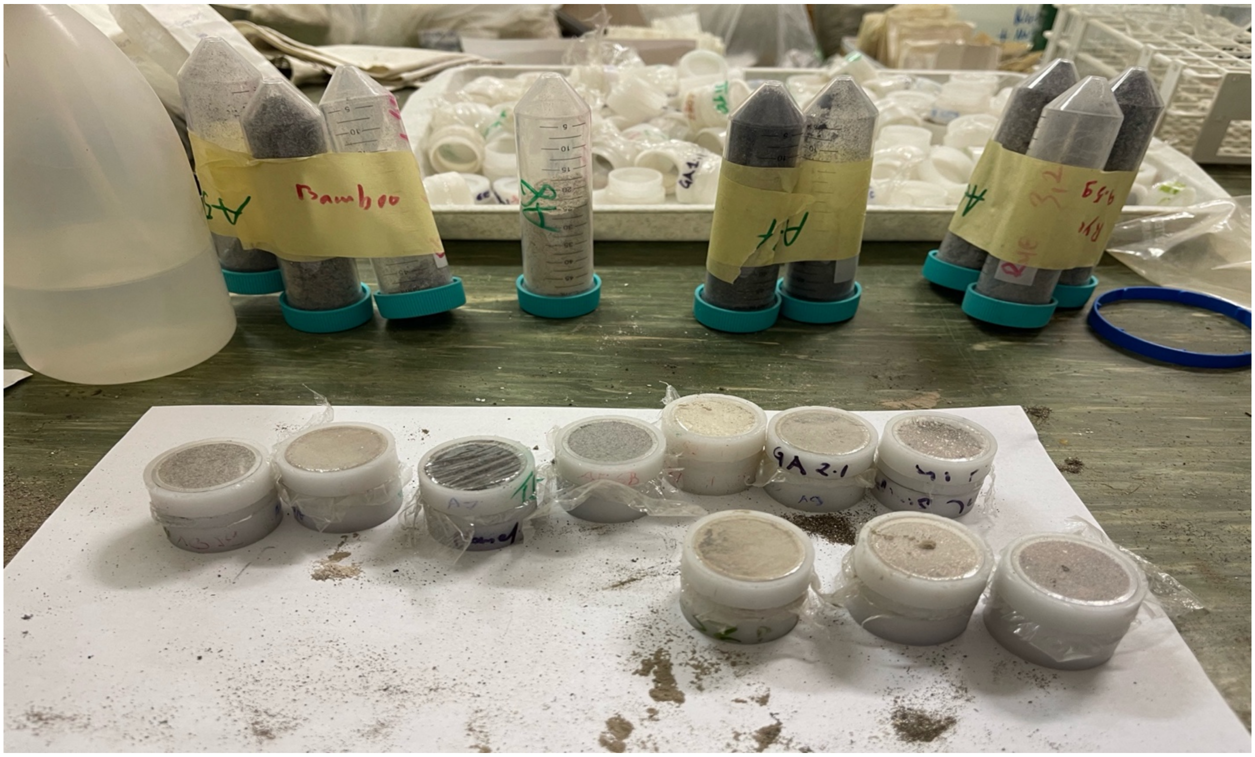

Figure 8: Preparation of ash samples for elemental analysis using Energy Dispersive X-ray Spectroscopy(EDX).

2.2.4 Mixing and Preparation of Mortar Samples

To evaluate the effect of ash on mortar performance, mixes were prepared by replacing **10% and 15% of cement by weight** with selected types of ash. These replacement levels were applied uniformly across all selected ash types. The replacement was performed by **reducing the cement content accordingly and adding an equal weight of ash** to maintain the total binder content.

The **reference mix** (control) was designed with a **cement-to-sand ratio of 1:2.75**, and a **water-to-cement (W/C) ratio of 0.55**. The quantities used for the control mix were:

- **Cement:** 450 grams

- **Sand:** 1240 grams
- **Water:** 250 grams

For the ash-replaced mixes, the cement quantity was reduced proportionally and replaced by ash as follows:

- **10% replacement:**
    - **Cement:** 405 grams
    - **Ash:** 45 grams
- **15% replacement:**
    - **Cement:** 382.5 grams
    - **Ash:** 67.5 grams

Mixing was carried out using a **mechanical tilting drum mixer**, following the procedures and timings prescribed in **ASTM C305 – Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency**[23].

According to ASTM C305, the mixing process involves:

- **Initial mixing for 30 seconds**
- **A 90-second pause**, during which the sides and bottom of the mixing bowl are scraped to ensure even distribution
- **Final mixing for 60 seconds**

Figure 9:Laboratory Procedure for Mixing, Casting, and Curing of Mortar Specimens with Partial Cement Replacement Using Ash.

The workability (flow) of the fresh mortar was checked and controlled in accordance with **ASTM C1437 – Standard Test Method for Flow of Hydraulic Cement Mortar**, to ensure that all mixtures had comparable plastic consistency and were suitable for mold casting[24].

The mortar was cast into **50 × 50 × 50 mm cube molds made of wood ,** in accordance with **ASTM C109**, the standard method for compressive strength testing of hydraulic cement mortars. **The ambient temperature during casting and early curing was maintained around 23 ± 2°C**, which complies with the ideal mixing and curing temperature specified in ASTM standards for mortar (typically **23°C**), ensuring consistency and proper hydration . For each mix (control, 10%, and 15% replacement), **six specimens** were prepared[25].

Molds were removed **48 hours after casting**, and the specimens were cured in **water** for two designated durations: **7 days** and **28 days**. After the completion of the curing periods, compressive strength tests were performed on each mortar mix. For every replacement percentage, three cube specimens were tested, along with three cubes from the control mix. This procedure helped ensure consistency among the mixtures and enabled a reliable assessment of the short-term (7-day) and long-term (28-day) mechanical performance of mortars incorporating ash.

2.2.5 Compressive Strength Testing Procedure

The compressive strength of mortar specimens was evaluated according to ASTM C109 – the standard test method for determining the compressive strength of hydraulic cement mortars, using 50 × 50 × 50 mm cube specimens. Testing was conducted after 7 and 28 days of continuous water curing. For each mixture and curing age, three specimens were tested to ensure repeatability and consistency of the results.

Prior to testing, each cube was visually inspected to confirm that the top and bottom surfaces were flat, properly aligned, and free from dust or surface defects. The tests were conducted using a Matest C089N – Servo Plus Evolution compression testing machine, equipped with a servo-controlled hydraulic system and a touchscreen digital interface. The equipment offers automated loading, precise calibration, and accurate data recording. Spacers were placed within the loading chamber to ensure proper alignment of the small-sized cube specimens.

The test was carried out in **automatic loading mode**, with a constant loading rate set according to **ASTM C109**, which specifies:

- **0.9 ± 0.2 MPa/s**, equivalent to approximately **2.25 kN/s** for a 50 mm cube (2500 mm² cross-sectional area)

The compressive strength results were **automatically displayed on the machine's digital screen**, calculated using the standard formula embedded within the system. However, as an added layer of verification and for hands-on learning, **manual calculations** of compressive strength were also performed using the following equation:

$$F^c = \frac{P}{A}$$

Where:

- F^c: Compressive strength (MPa)
- P: Maximum load applied (N)
- A: Loaded area (mm²), which equals **2500 mm²** for 50 mm cubes

The final compressive strength value for each mix and curing duration was determined by averaging the results from the three tested specimens.

Figure 10:Compressive Strength Testing of Mortar Cubes Using a Servo-Controlled Hydraulic Press in Accordance with ASTM C109.

2.3 Life Cycle Assessment (LCA) Methodology

This section summarizes the practical implementation of Life Cycle Assessment (LCA) as part of the experimental work. In addition to the mechanical evaluation of mortar performance, this study incorporates an LCA to assess the environmental impacts associated with replacing a portion of cement with fly ash (FA) and wood ash (WA) in mortar production.

The LCA is designed to provide a comparative analysis between: The LCA is designed to provide a comparative analysis between a **conventional cement-based mortar** using 100% cement as the binder (**reference mix**) and **mortar mixes** containing **FA** and **WA** as partial cement substitutes.

2.3.1 Goal and Scope Definition

The main goal of the LCA is to evaluate the potential reduction in environmental burdens, particularly CO_2 emissions, resulting from the use of alternative supplementary cementitious materials (SCMs), following the general framework established in ISO 14040 standard [26]

- **Functional Unit:** 1 kg of mortar
- **System Boundary:** Cradle-to-gate (from raw material extraction through to mortar production)
- **Impact Categories Considered:**
  - Global Warming Potential (GWP)
  - Energy consumption
  - Waste reduction and resource conservation

2.3.2 Life Cycle Inventory (LCI)

The life cycle inventory will include the following data:

- Cement production emissions **(e.g., 0.9 kg CO_2/kg cement, as reported in literature or SDS)**
- **Energy and emissions** related to FA and WA production **(including drying, grinding, and sourcing)**
- **Transportation distances** and modes for each material
- **Water and electricity consumption** during mortar production

2.3.3 Data Sources and Assumptions

- **Emission factors** for cement are sourced from **standard databases and published studies**.
- FA and WA emissions are estimated based on **known biomass combustion emission factors** or calculated from **local lab data**.

- **Transport distances** are approximated based on **actual sourcing routes and logistics records.**
- All mixes are assumed to be produced under **identical laboratory conditions** for comparability.

Note: Inventory data is compiled and presented in Chapter Three

2.3.4 Assessment Tools and Approach

The LCA calculations were conducted using **Microsoft Excel** with structured environmental impact formulas. Each environmental impact indicator was calculated using:

$$\boldsymbol{Impact} = \sum(\boldsymbol{Material} \times \boldsymbol{Emission\ factor})$$

A life cycle inventory was compiled for each of the **nine mixes**, including **one reference mix** and eight containing **10% and 15% replacements** of cement with FA and WA. The Excel model incorporated:

- **Mass** of each component (cement, ash, sand, water),
- **Real emissions** from bamboo combustion in the **Hargassner MAGNO SR 2000 furnace**,
- **Electricity and water usage** measured during mixing,
- **Transport impacts** based on actual sourcing (e.g., FALCO Co. for FA).

Impact categories were selected based on **EN 15804 +A2 (EF 3.1)** standards, including **GWP, water use, fossil energy demand, lan**d **use, toxicity, eutrophication, and acidification.**[27]

The results of the LCA are summarized in **Chapter Three**, with full comparisons of the **environmental performance** of each **mortar mix**.

Chapter Three

Results and Discussion

3.1 Overview

This chapter presents and analyzes the key findings obtained from the experimental program, focusing on compressive strength and the influence of different ash types and replacement levels. Results are interpreted in relation to the standard strength criteria and discussed in the context of their practical and environmental implications.

3.2 Elemental Characterization of Selected Ash Samples

Following the procedures described in Chapter 2, all collected ash samples were subjected to chemical screening using **Energy Dispersive X-ray Spectroscopy (EDX)** to determine their elemental composition and assess their suitability for use as partial cement replacements. The EDX analysis focused on identifying the presence and relative abundance of key pozzolanic oxides, particularly **silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and ferric oxide (Fe_2O_3)**, which are critical for effective pozzolanic reactivity in cementitious systems.

This screening process served as the basis for selecting the most promising ash types for further mechanical and environmental evaluation. Out of a total of **twelve different ash samples**, only four were selected based on their high pozzolanic oxide content, low levels of unwanted impurities, and consistent chemical profiles. The remaining **eight ash types were excluded** from the experimental phase due to either low reactivity potential or insufficient availability, as explained in Chapter 2.

The four selected ashes that proceeded to the mortar testing phase are:

- **Fly Ash (SRF porégő pernye)** – from a wood dust burner, FALCO Co.
- **Fly Ash (Kombinált elektrofilter pernye)** – collected via electrostatic filtration, FALCO Co.
- **Fly Ash** – collected from the biomass heating plant at the University of Sopron
- **Bamboo Wood Ash** – derived from controlled combustion of bamboo biomass

Each of these ashes was analyzed using one representative EDX spectrum to ensure internal consistency and chemical homogeneity. The fly ash collected from a wood dust burner at FALCO Co. showed a favorable elemental composition dominated by silicon (Si), aluminum (Al), and iron

(Fe), which correspond to the key pozzolanic oxides SiO_2, Al_2O_3, and Fe_2O_3. It also contained moderate levels of calcium (Ca), and trace elements such as potassium (K), magnesium (Mg), sodium (Na), and titanium (Ti), none of which are expected to adversely affect performance. **Figure 10** presents the EDX spectrum of this sample.

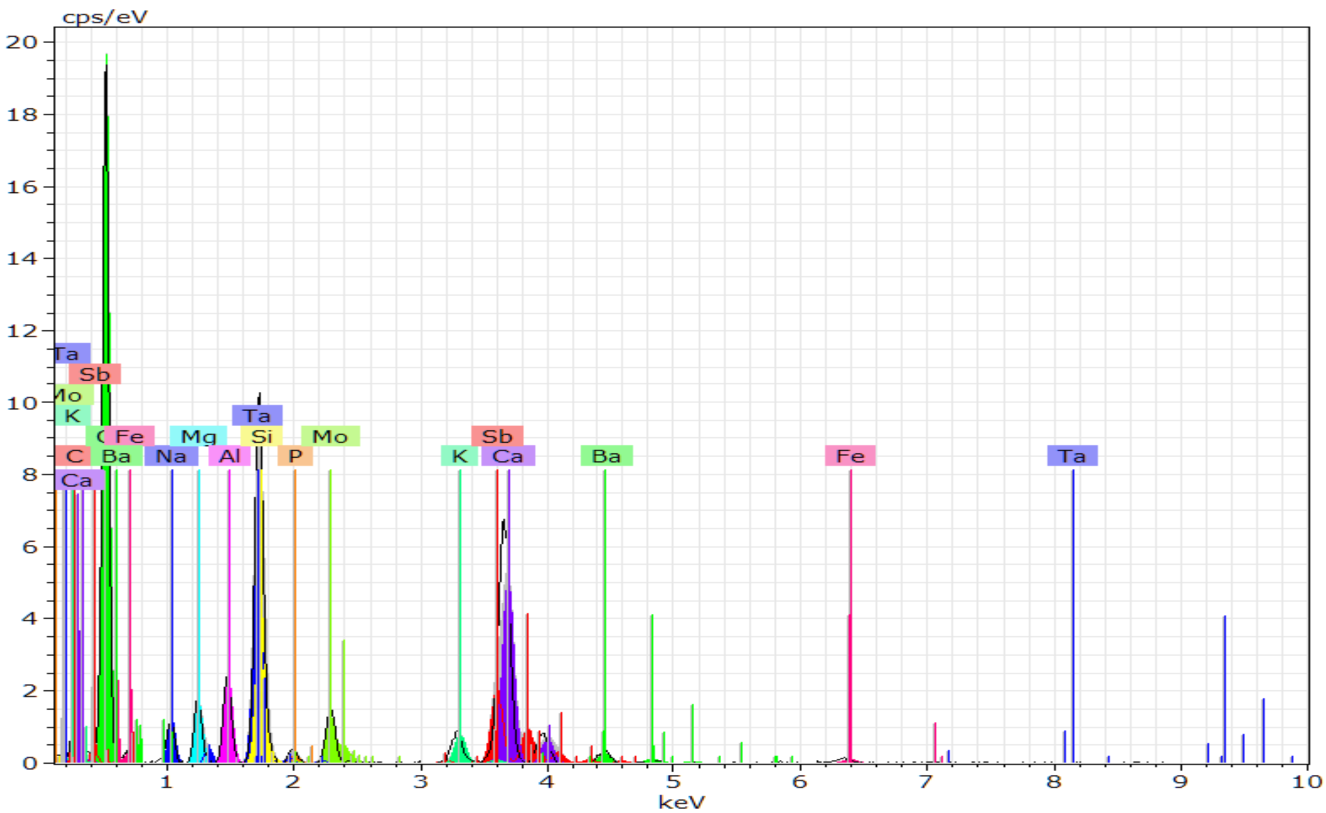

Figure 11:EDX Spectrum of Fly Ash (SRF porégő pernye).

The second sample, fly ash collected via electrostatic filtration at FALCO Co., displayed a similarly rich oxide profile, with a slightly higher calcium content suggesting some self-cementing behavior. The consistent presence of silicon, aluminum, and iron supports its reactivity and suitability for mortar use.The corresponding spectrum is shown in **Figure 11**.

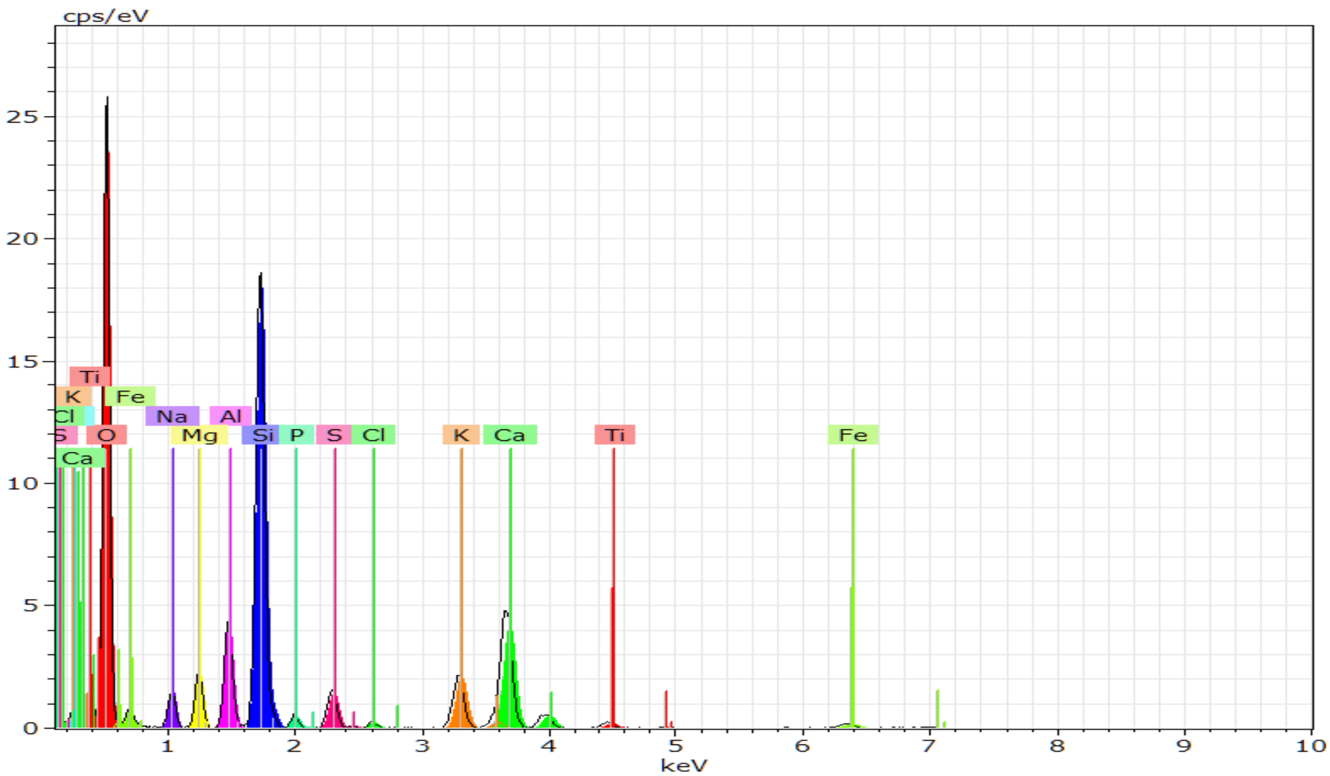

Figure 12:EDX Spectrum of Fly Ash electrostatic filtration.

The third sample, fly ash from the University of Sopron biomass heating plant , showed moderate silicon and aluminum peaks with a defined iron content. While slightly lower in oxide intensity compared to the industrial ashes, it retained the essential pozzolanic constituents required for secondary cementitious reactions.**Figure 12** illustrates the EDX results for this sample.

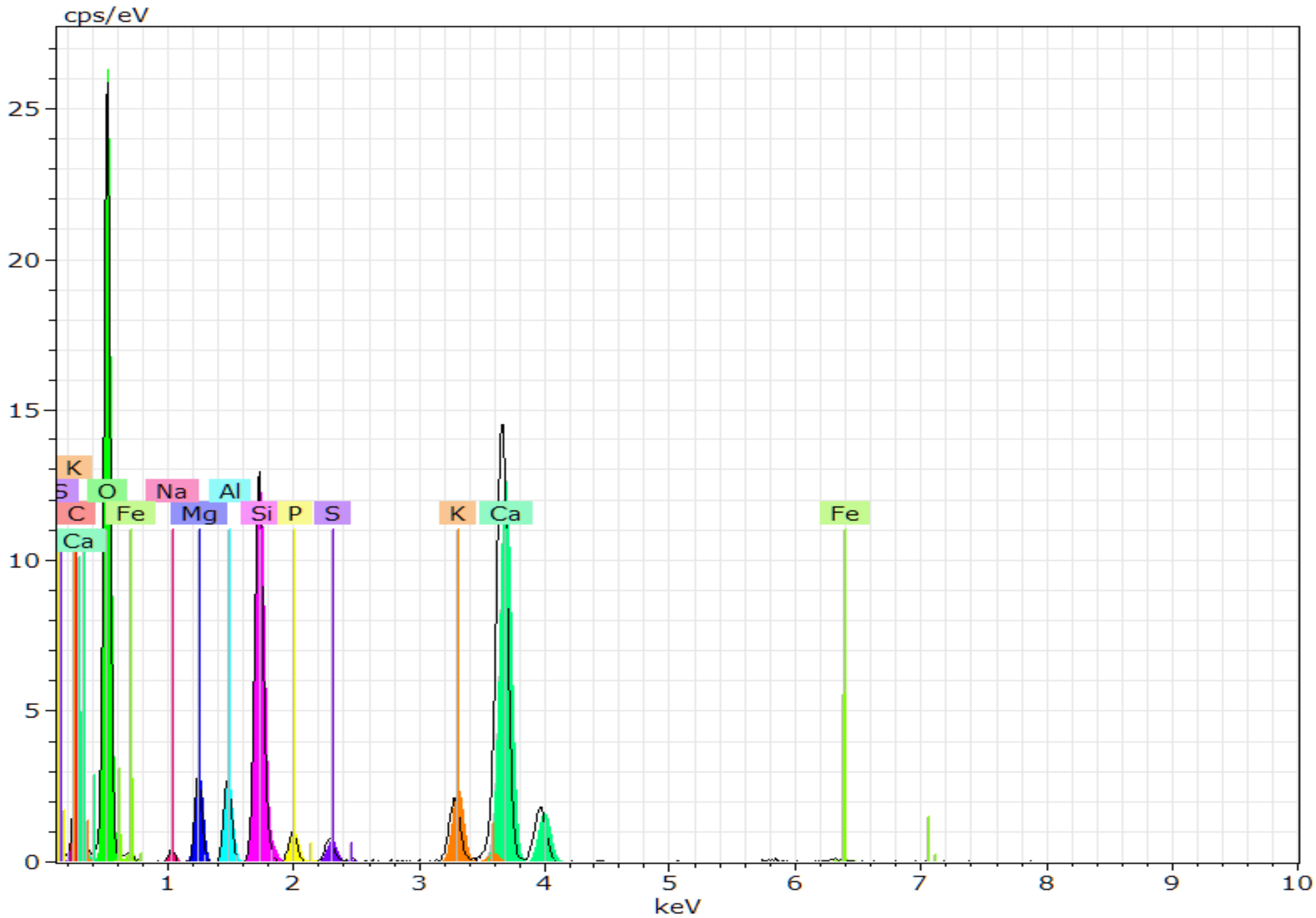

Figure 13:EDX Spectrum of Fly Ash from the University Biomass Plant.

Finally, the bamboo wood ash derived from controlled laboratory combustion demonstrated a high silicon peak along with relatively lower aluminum and iron levels. However, calcium and potassium appeared in higher concentrations, a typical characteristic of biomass-based wood ash. This composition indicates that the ash has pozzolanic potential, especially when properly ground and cured.The representative spectrum is presented in **Figure 13**.

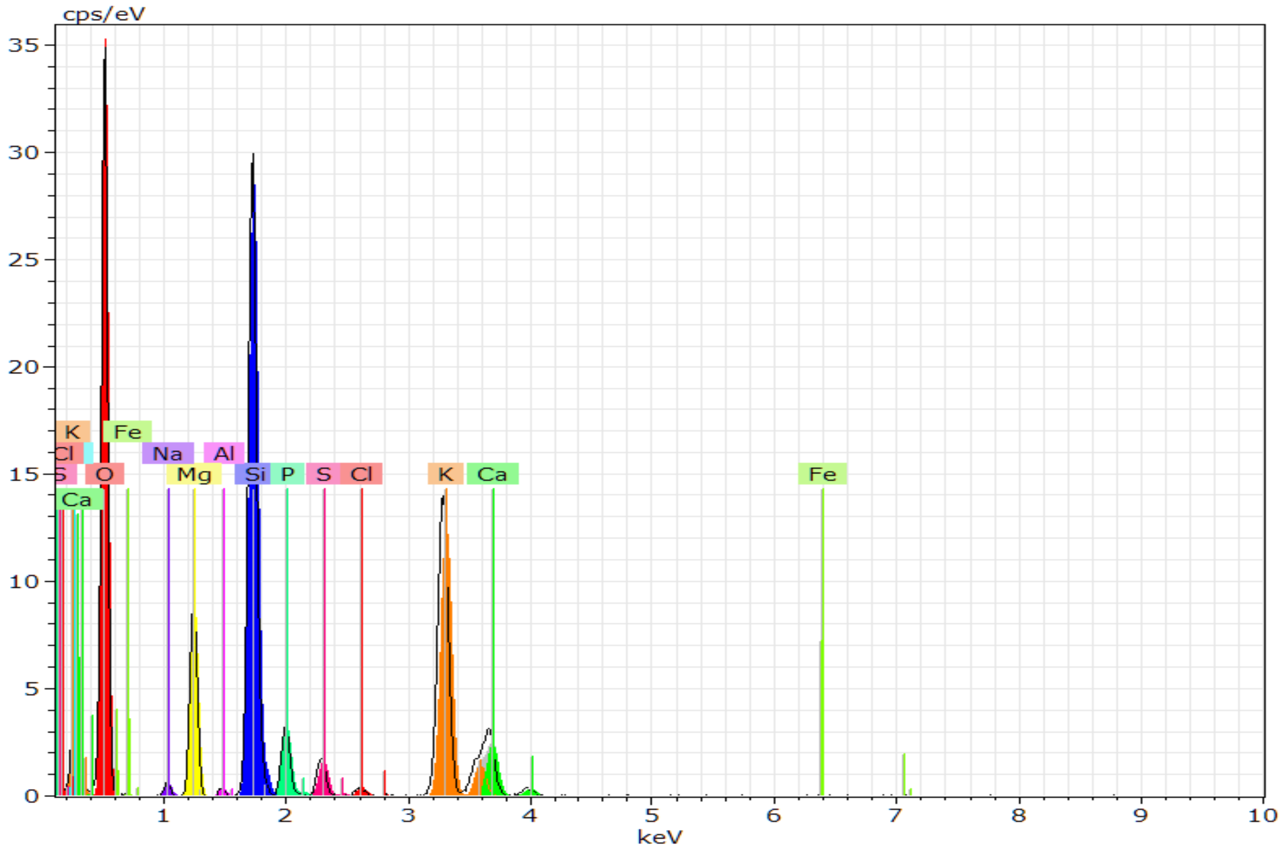

Figure 14:EDX Spectrum of Bamboo Wood Ash.

These chemical characteristics provided the foundation for selecting appropriate cement replacement levels (10% and 15%) in the subsequent mortar mix design and strength testing phases.

In addition to the individual EDX spectra presented in **Figures 10–13**, **Table 7** offers a comparative summary of the average elemental compositions of the selected ash types. The elemental composition of the ash samples was initially obtained in terms of pure elements (Si, Al, and Fe) through EDX analysis. However, for the purpose of evaluating pozzolanic activity in cementitious materials, it is more appropriate to express these elements in the form of their corresponding oxides

silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and ferric oxide (Fe_2O_3) as these are the chemically active compounds involved in secondary hydration reactions.

To perform this conversion, standard molecular weight-based factors were applied using the following equation:

$$wt\%\ oxide = wt\%\ element\ \times \left(\frac{Molecular\ weight\ of\ oxide}{Molecular\ weight\ of\ element}\right)$$

The conversion factors used are:

- **Si → SiO_2**: × 2.139
- **Al → Al_2O_3**: × 1.8895
- **Fe → Fe_2O_3**: × 1.4297

These converted values provide a more meaningful basis for comparison between different ash types, and are presented in **Table 7** below.

Although the spectral figures reflect the raw analytical outputs, the averaged values in the table were interpreted in conjunction with the observed behavior of each ash during mortar testing. This approach ensures that both the chemical potential and the practical performance of the ashes are considered together.

For this reason, ashes such as **FA-Uni** and **WA-Bamboo** were found to be among the most effective in improving mortar properties and were accordingly placed at the top of the comparative ranking. The table thus reflects not only the compositional characteristics but also the real contribution of each ash type to the intended cement replacement strategy.

Table 7:Elemental composition of pozzolanic oxides (Si, Al, Fe) in selected ash types used for partial cement replacement.

Ash type	**SiO_2 (%)**	**Al_2O_3 (%)**	**Fe_2O_3(%)**	**Total (%)**
FA-Uni	38.5	15.2	13.1	66.8
FA-EF	36.7	11.56	8.44	56.7
FA-SRF	19.62	14.59	12.99	47.2
WA-Bamboo	32.4	5.6	4.7	42.7

3.3 Compressive Strength Results and Interpretation

The compressive strength results for the control and ash-modified mortar mixes are presented in **Table 8 .** The control mix, containing 100% cement with no replacement, exhibited the highest strength at both curing intervals, reaching **18.23 MPa** at 7 days and **30.23 MPa** at 28 days. These values provide a baseline for assessing the performance of mortars incorporating wood ash and fly ash.

Among the ash-blended mixes, the mortar containing **FA-Uni** demonstrated the closest performance to the control. At 10% replacement, it reached **17.79 MPa** after 7 days and **26.85 MPa** at 28 days, showing excellent pozzolanic reactivity and good compatibility with Portland cement. Even at the higher replacement level of 15%, it maintained acceptable strength levels (**14.97 MPa** at 7 days and **22.02 MPa** at 28 days), which supports the favorable oxide content (SiO_2, Al_2O_3, Fe_2O_3) observed in the EDX analysis.

The **Bamboo WA** mix also showed promising results. At 10% replacement, it recorded **15.35 MPa**at 7 days and **23.61 MPa** at 28 days. Although slightly lower than FA-Uni, these values indicate stable strength development over time. The lower early-age strength is attributed to higher water demand and slower pozzolanic activity typical of wood ash, but the long-term performance confirms its suitability as a partial cement replacement when properly processed.

The mortar mix containing **FA-EF** showed moderate strength values of **13.76 MPa** and **20.85 MPa** at 7 and 28 days, respectively, for 10% replacement. This relatively lower performance may result from less reactive oxide composition or higher unburnt content, although it still remained within an acceptable range for mortar applications.

In contrast, the mix with **FA-SRF** showed the weakest performance among all ashes, particularly at 15% replacement where strength dropped to **7.58 MPa** (7 days) and **12.42 MPa** (28 days). This result likely reflects suboptimal combustion conditions, low fineness, or elevated impurity content, despite the presence of pozzolanic oxides detected via EDX.

Across all types, increasing the ash replacement level from 10% to 15% generally resulted in reduced compressive strength, both at early and later curing stages. This trend aligns with established research, which indicates that excessive cement replacement can dilute the binder matrix and hinder strength development, particularly during early hydration stages.

In conclusion, **FA-Uni and WA-Bamboo** were identified as the most effective ash types for partial cement replacement in this study. Their favorable chemical composition, adequate reactivity, and solid mechanical performance underscore their potential for promoting eco-friendly and sustainable mortar production.

Table 8: Compressive Strength of Ash-Based Mortar Mixes at 7 and 28 Days.

Mix	7 Day MPa (10%)	7 Day MPa (15%)	28 Day MPa (10%)	28 Day MPa (15%)
Control	18.23		30.23	
FA-SRF	9.21	7.58	14.62	12.42
FA-EF	13.76	11.93	20.85	18.35
FA-Uni	17.79	14.97	26.85	22.02
WA-Bamboo	15.35	12.94	23.61	20.54

3.5 Life Cycle Assessment (LCA) Highlights

In addition to the mechanical performance evaluation, a comprehensive Life Cycle Assessment (LCA) was conducted to assess the environmental impacts of the control mortar and the ash-based mortar mixes. The assessment followed the EN 15804+A2 (EF 3.1) standards [27, 28], considering a cradle-to-gate system boundary. Key environmental indicators analyzed included climate change (global warming potential), ozone depletion, acidification, eutrophication (freshwater, marine, and terrestrial), photochemical ozone formation, and resource use (minerals and fossil fuels).

3.5.1 Climate Change Impact

The control mortar mix, containing 100% Portland cement, exhibited the highest carbon footprint, with a global warming potential of 0.466826 kg CO_2 equivalent per kilogram of mortar. In contrast, the mortar incorporating bamboo wood ash achieved a nearly negligible carbon footprint, reflecting the significant environmental advantage of utilizing biomass-derived ash materials. The mortar containing fly ash sourced from the University of Sopron's biomass heating plant also demonstrated a remarkable reduction in carbon emissions, lowering its global warming potential by approximately 88% compared to the control.

Table 9: Global Warming Potential (GWP) of the investigated mortar mixes (kg CO_2 eq per kg mortar

Mix	GWP (kg CO_2 eq/kg mortar)
Control	0.466826
FA-SRF	0.010137
FA-EF	0.402118
FA-Uni	0.054549
WA-Bamboo	0.010137

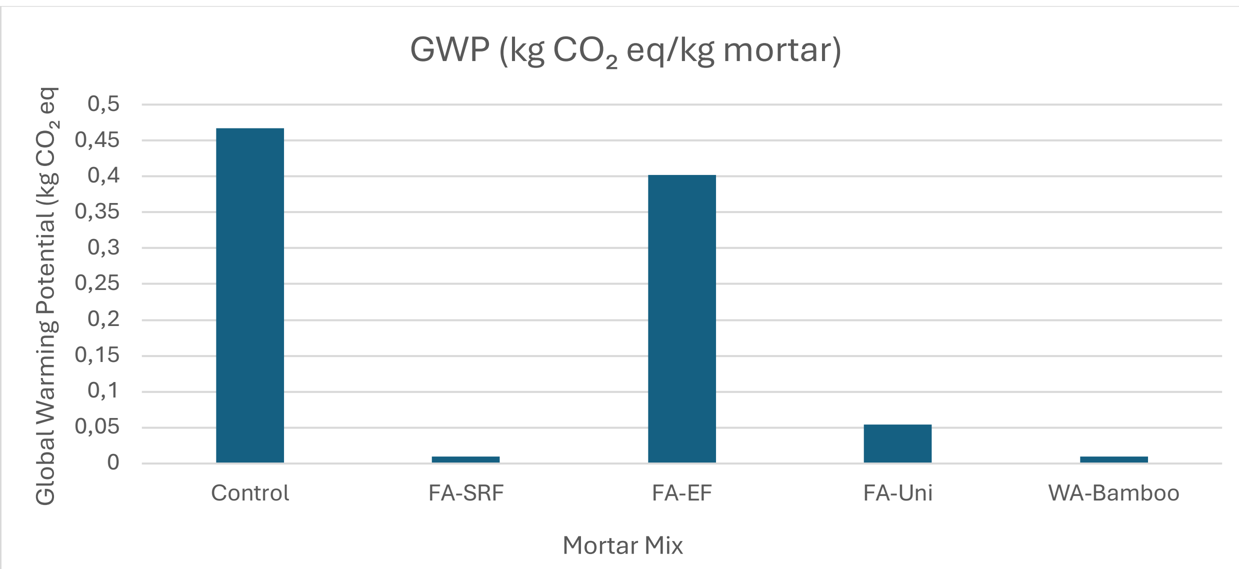

Figure 15: Comparison of Global Warming Potential (GWP) for the investigated mortar mixes.

3.5.2 Performance Across Other Environmental Categories

Beyond climate change, the ash-based mortars showed substantial environmental benefits across other categories. Ozone depletion potential was significantly lower in all ash-modified mixes. Acidification and eutrophication impacts were also considerably reduced, particularly in mixes utilizing bamboo wood ash and university-sourced fly ash. Furthermore, these mixes exhibited lower contributions to photochemical ozone formation and reduced dependency on virgin raw materials and fossil fuels, underscoring their alignment with sustainable construction practices. The summarized results of key environmental impact categories are presented in **Table10.**

Table 10: Summary of key environmental impacts for the investigated mortar mixes.

Impact Category	Control	FA-SRF	FA-EF	FA-Uni	WA-Bamboo
Ozone depletion (kg CFC-11 eq.)	1.98E-09	3.05E-13	1.54E-09	4.42E-10	3.05E-13
Acidification (Mole of H^+ eq.)	1.25E-03	1.23E-05	8.44E-04	3.98E-04	1.23E-05
Eutrophication, freshwater (kg P eq.)	5.23E-05	4.84E-08	4.12E-05	1.10E-05	4.84E-08
Eutrophication, marine (kg N eq.)	3.45E-04	4.66E-06	2.51E-04	8.87E-05	4.66E-06
Eutrophication, terrestrial (Mole of N eq.)	3.83E-03	4.46E-05	2.83E-03	9.59E-04	4.46E-05
Photochemical ozone formation (kg NMVOC eq.)	1.12E-03	1.11E-05	8.09E-04	3.01E-04	1.11E-05

3.5.3 Optimal Balance Between Mechanical and Environmental Performance

Among all tested mixes, the mortar containing fly ash from the university's biomass plant achieved the best overall balance. It maintained a high 28-day compressive strength of 26.85 Mpa closely approaching the 30.23 MPa of the control mix while substantially reducing environmental impacts. The bamboo wood ash mixture, although displaying a slightly lower compressive strength of 23.61 MPa, excelled in environmental performance, making it highly suitable for applications where sustainability is a primary concern.

3.6 Summary of Findings

The experimental investigation demonstrated the significant potential of incorporating fly ash and wood ash as partial replacements for cement in mortar production, addressing both environmental sustainability and mechanical performance.

The chemical characterization of various ash types confirmed that fly ash derived from the University of Sopron's biomass heating plant and bamboo wood ash possessed high pozzolanic reactivity, making them suitable candidates for cement substitution. These materials exhibited favorable oxide compositions, particularly in silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and ferric oxide (Fe_2O_3), which are critical for enhancing mortar properties.

Compressive strength testing revealed that the control mortar, containing 100% Portland cement, achieved the highest strength values, as expected. However, the mortar incorporating fly ash from the university's biomass plant achieved a compressive strength of **26.85 MPa at 28 days**, closely approaching the control's **30.23 MPa**, while significantly reducing the environmental impact. The bamboo wood ash mixture also maintained an acceptable compressive strength of **23.61 MPa**, confirming its mechanical viability.

The Life Cycle Assessment (LCA) highlighted substantial reductions in environmental impacts across all ash-modified mixes. The bamboo wood ash mixture achieved the lowest overall environmental footprint, with negligible greenhouse gas emissions. The university fly ash mixture reduced its global warming potential by approximately **88%** compared to the control, while also minimizing ozone depletion, acidification, eutrophication, photochemical ozone formation, and resource use.

In summary, the study identified the university-sourced fly ash mortar as the most balanced solution, offering high mechanical strength and outstanding environmental performance. The bamboo wood ash mortar emerged as the most sustainable option from an environmental perspective, with adequate strength for practical applications.

Chapter Four

Conclusions and Recommendations

4.1 Conclusions

This study successfully achieved its primary objective of evaluating the feasibility and effectiveness of using wood ash and fly ash as partial replacements for cement in mortar production, aiming to enhance both mechanical performance and environmental sustainability.

The chemical characterization of various ash types confirmed that fly ash sourced from the University of Sopron's biomass heating plant and bamboo-derived wood ash exhibited favorable pozzolanic properties, including high contents of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and ferric oxide (Fe_2O_3). These properties contributed significantly to the improved mechanical and durability characteristics observed in the mortar mixes.

Compressive strength testing demonstrated that while the control mortar (100% Portland cement) achieved the highest strength values, the mortar incorporating university-sourced fly ash achieved a compressive strength of 26.85 MPa at 28 days, which closely approached the control's 30.23 MPa. The bamboo wood ash mix also maintained an acceptable compressive strength of 23.61 MPa, confirming its structural viability.

The Life Cycle Assessment (LCA) revealed substantial reductions in environmental impacts for all ash-modified mortars compared to the control. The bamboo wood ash mortar achieved the lowest overall environmental footprint, including negligible greenhouse gas emissions. The university fly ash mortar demonstrated a remarkable reduction in global warming potential by approximately 88%, along with significant decreases in ozone depletion, acidification, eutrophication, photochemical ozone formation, and resource use.

Overall, this research highlights the potential of utilizing industrial byproducts, such as fly ash and wood ash, to produce sustainable construction materials. The university-sourced fly ash mortar emerged as the optimal solution, offering a superior balance between mechanical strength and environmental performance. The bamboo wood ash mortar presented an excellent environmentally friendly alternative, with sufficient mechanical performance for practical applications.

4.2 Recommendations

Based on the findings of this research, the following recommendations are proposed:

4.2.1 Practical Applications:

- The mortar containing fly ash sourced from the university's biomass plant is recommended for use in general construction projects where both strength and sustainability are priorities.
- Bamboo wood ash can be considered for projects emphasizing environmental sustainability, particularly where slightly lower compressive strength is acceptable.

4.2.2 Future Research:

- Further studies should explore the long-term durability of ash-based mortars under various environmental conditions, including freeze-thaw cycles, chemical exposure, and humidity variations.
- Investigation into optimizing the grinding and preprocessing of wood ash to enhance its reactivity and mechanical performance is encouraged.
- Life Cycle Assessments should be extended to include the use phase and end-of-life scenarios to provide a complete sustainability profile.

4.2.3 Policy and Industry Recommendations:

- Promote the adoption of supplementary cementitious materials (SCMs) like fly ash and wood ash in national and international construction standards.
- Encourage industrial collaborations to ensure a steady and standardized supply of quality-controlled ash materials.
- Develop incentives or regulations to support the recycling of industrial byproducts in the construction industry to reduce environmental impacts.

References

1. Teker Ercan, E.E., Andreas, L., Cwirzen, A., Habermehl-Cwirzen, K.: Wood Ash as Sustainable Alternative Raw Material for the Production of Concrete—A Review, (2023)

2. Cheng, D., Reiner, D.M., Yang, F., Cui, C., Meng, J., Shan, Y., Liu, Y., Tao, S., Guan, D.: Projecting future carbon emissions from cement production in developing countries. Nat Commun. 14, (2023). https://doi.org/10.1038/s41467-023-43660-x

3. Malaiškienė, J., Vaičienė, M.: The Influence of Silica Fly Ash and Wood Bottom Ash on Cement Hydration and Durability of Concrete. Materials. 17, (2024). https://doi.org/10.3390/ma17164031

4. Intergovernmental Panel on Climate Change (IPCC): Climate Change 2021 – The Physical Science Basis. Cambridge University Press (2023)

5. Gabrijel, I., Skazlić, M., Štirmer, N.: Long-Term Behavior of Concrete Containing Wood Biomass Fly Ash. Applied Sciences (Switzerland). 12, (2022). https://doi.org/10.3390/app122412859

6. Ige, O.E., Von Kallon, D.V., Desai, D.: Carbon emissions mitigation methods for cement industry using a systems dynamics model, (2024)

7. Akbulut, Z.F., Yavuz, D., Tawfik, T.A., Smarzewski, P., Guler, S.: Enhancing Concrete Performance through Sustainable Utilization of Class-C and Class-F Fly Ash: A Comprehensive Review, (2024)

8. Fořt, J., Šál, J., Žák, J., Černý, R.: Assessment of wood-based fly ash as alternative cement replacement. Sustainability (Switzerland). 12, 1–16 (2020). https://doi.org/10.3390/su12229580

9. Lehmusto, J., Tesfaye, F., Karlström, O., Hupa, L.: Ashes from challenging fuels in the circular economy. Waste Management. 177, 211–231 (2024). https://doi.org/10.1016/j.wasman.2024.01.051

10. Rahman, Md.T., Rabbi, M.S., Siddiqui, M.A.S.: From Waste to Strength: A Comprehensive Review on Using Fly Ash in Composites with Enhanced Mechanical Properties. Journal of Engineering Advancements. 94–106 (2024). https://doi.org/10.38032/jea.2024.04.001

11. Danish, A., Karadag, O., Bilir, T., Ozbakkaloglu, T.: Valorization of biomass ashes in the production of cementitious composites: A comprehensive review of properties and performance, (2023)

12. Silvestro, L., Scolaro, T.P., Ruviaro, A.S., Santos Lima, G.T. dos, Gleize, P.J.P., Pelisser, F.: Use of biomass wood ash to produce sustainable geopolymeric pastes. Constr Build Mater. 370, (2023). https://doi.org/10.1016/j.conbuildmat.2023.130641

13. Yang, Z., Huddleston, J., Brown, H.: Effects of Wood Ash on Properties of Concrete and Flowable Fill. Journal of Materials Science and Chemical Engineering. 04, 101–114 (2016). https://doi.org/10.4236/msce.2016.47013

14. Gabrijel, I., Rukavina, M.J., Štirmer, N.: Influence of wood fly ash on concrete properties through filling effect mechanism. Materials. 14, (2021). https://doi.org/10.3390/ma14237164

15. Teixeira, E.R., Camões, A., Branco, F.G., Matos, J.C.: Effect of biomass fly ash on fresh and hardened properties of high volume fly ash mortars. Crystals (Basel). 11, 1–21 (2021). https://doi.org/10.3390/cryst11030233

16. Alaj, A., Krelani, V., Numao, T.: Effect of Class F Fly Ash on Strength Properties of Concrete. Civil Engineering Journal (Iran). 9, 2249–2258 (2023). https://doi.org/10.28991/CEJ-2023-09-09-011

17. Fahim Huseien, G., Hussein Joudah, Z., Hafizah A. Khalid, N., Rahman Mohd Sam, A., Md. Tahir, M., Hasanah Abdul Shukor Lim, N., Alyousef, R., Mirza, J.: Durability performance of modified concrete incorporating fly ash and effective microorganism. Constr Build Mater. 267, (2021). https://doi.org/10.1016/j.conbuildmat.2020.120947

18. Govindan, B., Kumarasamy, V.: Sustainable valorization through the reuse of incinerated paper mill sludge ash in building brick production. Constr Build Mater. 439, (2024). https://doi.org/10.1016/j.conbuildmat.2024.137291

19. Ndahirwa, D., Zmamou, H., Lenormand, H., Chenot, E., Potel, S., Leblanc, N.: Wood ash-based binders for lightweight building materials: Evaluating the influence of hydraulic lime and cement on the setting and mechanical properties of wood ash pastes. Results in Engineering. 24, (2024). https://doi.org/10.1016/j.rineng.2024.102738

20. Lehne, J., Preston, F.: Chatham House Report Making Concrete Change Innovation in Low-carbon Cement and Concrete #ConcreteChange.

21. Duna-Dráva Cement Kft.: Biztonsági adatlap: DanuCement Általános használatú cementek (EN 197-1 szerint)

22. Solid biofuels-Determination of ash content Biocombustibles solides-Méthode de détermination de la teneur en cendres COPYRIGHT PROTECTED DOCUMENT. (2015)

23. ASTM International: ASTM C305-06: Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. (2006)

24. ASTM International: ASTM C1437-20: Standard Test Method for Flow of Hydraulic Cement Mortar. ASTM International, West Conshohocken, PA (2020)

25. ASTM International: ASTM C109/C109M-23: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). (2023)

26. International Organization for Standardization: ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. (2006)

27. British Standards Institution: EN 15804:2012+A2:2019 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products. (2019)

28. European Commission Joint Research Centre: Environmental footprint — EPLCA Platform