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Low-cement eco-concrete and the role of recycled concrete aggregates (RCA), supplementary cementitious materials (SCMs), and other additives in improving sustainability and durability

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ABSTRACT: This study focuses on the development of low-cement eco-concretes incorporating recycled concrete aggregates (RCA) and waste materials such as wood ashes, aiming to achieve a balance between sustainability and mechanical performance. Different concrete mixes were designed with varying cement content (240–290 kg/m³) and RCA replacement levels (25%–50% by weight). The materials used included II/A-LL 42.5 R cement, natural calcareous-silica aggregates, RCA from C30/37 concrete, wood waste ashes, and limestone filler. Experimental tests were conducted on fresh and hardened concrete, including workability, compressive strength, elastic modulus, carbonation resistance, freeze-thaw durability, and chloride penetration resistance. Results show that the mixtures with RCA demonstrated similar or better performance compared to conventional concrete, with C6 (using wood ashes from the burner) showing promising compressive strength and durability characteristics. The study demonstrates that these low-cement mixtures, using recycled aggregates and supplementary materials, can meet the durability requirements for sustainable infrastructure applications.

KEY WORDS: Eco-concrete; Cement supplementary materials; Recycled concrete aggregates; Wood waste ashes; Low cement concrete; Durability; Chemical additives.

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RESUMEN: *Hormigón ecológico de bajo contenido en cemento y el papel de los áridos de hormigón reciclado (RCA), materiales suplementarios del cemento (SCMs) y otros aditivos en la mejora de la sostenibilidad y durabilidad.* Este estudio se centra en el desarrollo de hormigones ecológicos de bajo contenido en cemento que incorporan áridos reciclados de concreto (RCA) y materiales residuales como las cenizas de madera, con el objetivo de lograr un equilibrio entre la sostenibilidad y el rendimiento mecánico. Se diseñaron diferentes mezclas de hormigón con contenido de cemento variable (240-290 kg/m³) y niveles de reemplazo de RCA (25%-50% en peso). Los materiales utilizados incluyeron cemento CEM II/A-LL 42.5 R, áridos naturales calcareo-sílice, RCA de concreto C30/37, cenizas de madera y filler de piedra caliza. Se realizaron pruebas experimentales tanto en el estado fresco como endurecido del concreto, incluyendo trabajabilidad, resistencia a la compresión, módulo elástico, resistencia a la carbonatación, durabilidad frente a ciclos de congelación-descongelación y resistencia a la penetración de cloruros. Los resultados muestran que las mezclas con RCA presentaron un rendimiento similar o superior al del concreto convencional, siendo la mezcla C6 (que utilizó cenizas de madera del quemador) la que mostró los mejores resultados en cuanto a resistencia a la compresión y durabilidad. El estudio demuestra que estas mezclas de bajo contenido en cemento, utilizando áridos reciclados y materiales suplementarios, pueden cumplir con los requisitos de durabilidad para aplicaciones sostenibles en infraestructuras.

PALABRAS CLAVE: Bajo contenido de cemento; Materiales complementarios del cemento; Áridos de hormigón reciclado; Durabilidad; Aditivos químicos.

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1. INTRODUCTION

The growing demand for sustainable construction materials has led to significant interest in reducing the environmental impact of concrete production. One promising avenue is the development of low-cement concrete mixtures, which aim to decrease the carbon footprint of concrete by reducing the amount of Portland cement, a major contributor to CO_2 emissions. Numerous studies have demonstrated the potential for replacing traditional cement with supplementary cementitious materials (SCMs) such as fly ash, slag, and natural pozzolans to improve sustainability without compromising concrete performance. However, the combination of low cement content with other sustainable materials, such as recycled concrete aggregates (RCA) and industrial by-products like wood waste ashes, has not been as extensively explored.

The use of recycled concrete aggregates (RCA) in concrete has gained increasing attention in recent decades, driven by the need to reduce waste and promote circular economy practices in construction. RCA, derived from the recycling of demolished concrete, has been found to be a suitable replacement for natural aggregates in concrete, although its use often results in lower compressive strength and increased porosity due to the presence of adhered mortar (1-4). Several studies have explored methods to mitigate these drawbacks, such as using higher-quality RCA, optimizing mix designs, and incorporating chemical admixtures or SCMs (5). Despite these efforts, the full potential of RCA in high-performance concrete has yet to be realized, especially when combined with other sustainable components.

Supplementary cementitious materials (SCMs) like fly ash, slag, and natural pozzolans have been widely studied as partial replacements for Portland cement, offering benefits such as reduced environmental impact, improved durability, and better workability. Wood waste ashes, a by-product from various industrial processes such as the burning of wood waste, have also shown promise as an alternative SCM (6, 7). Several studies have explored the use of wood ashes in concrete, reporting improvements in specific properties like workability and durability. However, challenges remain in optimizing the dosage and ensuring consistent performance due to variations in the chemical composition of the ashes.

In recent years, there has been growing interest in combining these sustainable materials—low cement content, RCA, and SCMs—into new concrete formulations aimed at reducing environmental impact without sacrificing structural performance or durability (8). While research on these materials is abundant, few studies have comprehensively investigated their combined use in a single concrete formulation, particularly in the context of infrastructure applications, where higher durability requirements are essential.

The novelty of this study lies in the development of eco-concretes with reduced cement content that incorporate both RCA and wood waste ashes, while also utilizing limestone filler to optimize workability and mechanical performance. Unlike previous studies, this research not only evaluates the individual effects of these materials but also explores their combined impact on the durability and sustainability of concrete, specifically for applications requiring high durability standards. This comprehensive approach allows for a better understanding of how different sustainable components interact and contribute to the overall performance of the concrete.

In the following sections, we present the design of various concrete mixes incorporating recycled aggregates and wood waste ashes, and the results of a series of experimental tests that assess the mechanical and durability properties of these innovative mixtures.

2. MATERIALS AND METHODS

2.1. Materials

- Cement: II/A-LL 42.5 R. The cement used is Portland-limestone cement. It is commonly used in construction for general-purpose applications.
- Natural aggregates: Hüntwangen (0-32 mm). The natural aggregates used is a calcareous-silica aggregate with a particle size range of 0-32 mm. These aggregates were separated into four fractions for mix design purposes: 0-4 mm, 4-8 mm, 8-16 mm, and 16-32 mm. The aggregates were selected based on their suitability for concrete production and their compatibility with other materials.
- The RCA used in this study were sourced from demolished concrete and were classified as C30/37 grade (type G), resistant to freezing. The RCA was screened to a size range of 0-32 mm and was included in the mix at replacement levels of 25% and 50% by mass of the natural aggregates. The RCA was characterized by higher porosity compared to natural aggregates, which is typical for recycled materials. This characteristic was taken into account when determining the mix proportions.
- Wood Waste Ashes: (< 0.5 mm). Coarser ashes obtained from the combustion of wood waste in industrial burners.
- Limestone filler was added to some of the mixes to improve the workability and stability of the

concrete. It is primarily composed of $CaCO_2$ (calcium carbonate) and has a fineness similar to that of fine aggregates. Limestone fillers are commonly used in concrete production as a way to partially replace cement and reduce the environmental impact of concrete without compromising its mechanical properties.

- Superplasticizer polycarboxylate ether: P6. It was used in all mixes to improve the workability of the fresh concrete and reduce the water-to-cement ratio. The dosage of the superplasticizer ranged from 0.8% to 1.8% by mass of cement, depending on the workability requirements of each mix. Superplasticizers enhance the flowability of concrete without increasing its water content, which is essential for maintaining the desired strength and durability in low-cement mixtures.

2.2. Mix design

The concrete mixes were produced in batches of 100 liters each to cast specimens for the required tests (EN 12390-2). Figure 1. Two reference mixtures were developed, followed by modifications to optimize the mix properties Table 1.

Reference Mixes:

- Mix C1 and C1.1: Cement content of 240 kg/m³.
- Mix C2: Cement content of 290 kg/m³.
- Mix C1.1 was an improvement over Mix C1. In Mix C1, the lack of fine material resulted in poor workability, with issues such as water segregation and excessive spreading. To address this, 50 kg/m³ of limestone filler was added to Mix C1.1, which significantly improved workability.

Optimization and Modifications:

For mixes with cement ≤ 240 kg/m³, 50 kg/m³ of limestone filler was found necessary to maintain workability.

- Mix C3: Cement was reduced by 15% (relative to the mass of cement) and replaced with wood waste ashes from the electro filter, starting from 240 kg/m³ cement content.
- Mix C4: Same procedure as Mix C3, but starting from 290 kg/m³ cement content.
- Mix C6: Similar to Mix C4, but using wood waste ashes from the burner instead of the electro filter.

Incorporation of Recycled Concrete Aggregates (RCA):

Mixes C7 to C10 were designed to assess the effect of RCA as a replacement for natural aggregates (9):

- C7 and C8: 25% replacement of natural aggregates with RCA (by mass).
- C9 and C10: 50% replacement of natural aggregates with RCA (by mass).

Additives:

A polycarboxylate-based superplasticizer, P6, was used in all mixes to improve workability. The amount varied between 0.8% and 1.8% by mass of cement, depending on the workability requirements of each mix.

Granulometric Distribution of Natural Aggregates:

The natural aggregates were divided into four sizes: 0-4 mm, 4-8 mm, 8-16 mm, and 16-32 mm. Each portion was added to the mixture according to the desired granulometric curve.

Table 1. Mix design of the concrete specimens.

	kg/m³								
Mix design	**C1**	**C1.1**	**C2**	**C4**	**C6**	**C7**	**C8**	**C9**	**C10**
CEM II/A-LL 42.5R (Colacem)	240	240	290	246.5	246.5	240	290	240	290
Wood Waste Ashes electro filter (15% in mass vs. cem) subs.	0	0	0	43.5	0	0	0	0	0
Wood Waste Ashes burner (15% in mass vs. cem) subs.	0	0	0	0	43.5	0	0	0	0
Limestone filler	0	50	0	0	0	50	0	50	0
RCA (0-32 mm) (25% / 50% sub. In mass vs aggregate) G	0	0	0	0	0	531	520	1040	1019
Natural Aggregate (0-32 mm)	2136	2087	2069	2166	2164	1593	1561	1040	1019
Chemical additives GK - P6 (0.5 - 2% in mass vs cem)	1.3	1	0.8	1	1.5	0.8	1.5	1.8	1.5
W_{total}/C	0.56	0.56	0.42	0.62	0.43	0.49	0.48	0.57	0.52

Figure 1. Concrete specimens.

2.3. Experimental test

To assess the durability of the concrete specimens, a series of tests were conducted on both the fresh and hardened states of the mixtures.

Fresh State of the Mixtures:

- Spreading Diameter [mm] / Workability: This test measures the spread of the concrete mixture to evaluate its workability.
- Air Content %: This test determines the percentage of air within the concrete mixture.

Hardened State of the Mixtures:

- Compressive Strength of Hardened Concrete: This test measures the ability of the hardened concrete to withstand compressive loads.
- Elastic Modulus: This test evaluates the stiffness of the hardened concrete.
- Resistance to Accelerated Carbonation: This test assesses how well the concrete resists carbonation under accelerated conditions.
- Resistance to Frost/Defrost Cycles in the Presence of Deicing Salts: This test determines the durability of the concrete when subjected to cycles of freezing and thawing in the presence of deicing salts.
- Resistance to Chloride Penetration: This test evaluates the concrete's ability to resist the penetration of chloride ions.
- Porosity and Water Permeability: These tests measure the porosity of the concrete and its ability to allow water to pass through, respectively.

3. RESULTS AND DISCUSSION

3.1. Spreading diameter

Given that a workability class had not been established for this project, we nevertheless tried to remain within a range delimited by the F3-F4 classes outlined by the standard EN 206-2013 - EN 12350-5 Figure 2, Table 2.

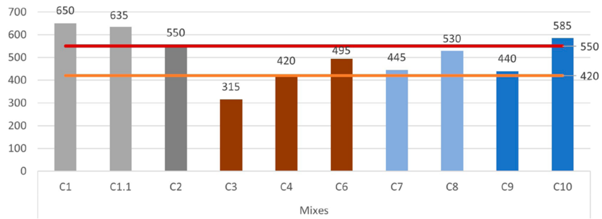

Figure 2. Spreading diameter [mm].

Mix C4 has been produced in two batches.

The C3 mixture was too stiff, due to the high water absorption of the Wood Waste Ashes from electro filter and the lack of fine material such as cement or limestone filler. This in spite of the increased water to cement ratio and the quantity of superplasticizer.

3.2. Compressive strength

The C4 mixture exhibited significantly lower resistance compared to the other mixtures, indicating that substituting cement with wood waste ashes from the electro filter does not provide any benefits. On the other hand, the C6 mixture, which utilized wood waste ashes from the burner as a cement replacement, showed promising resistance results in comparison with the reference mixtures.

Table 2. Air content and water to cement ratio (w/c).

Mix	C1	C1.1	C2	C3	C4	C6	C7	C8	C9	C10
a/c	0.56	0.56	0.42	0.6	0.62	0.43	0.49	0.48	0.57	0.52
% air	0.4	0.7	1.7	2.5	1.6	2	2.7	1.4	3.2	2.4
% air					4					

For the mixtures where natural aggregate was replaced with recycled concrete aggregate (RCA) (C7-C10), the resistance values were very similar to those of the reference mixtures C1, C1.1, and C2, which used 100% natural aggregates.

Due to the relatively low compressive strength exhibited by Mix C4 compared to the other mixtures, we decided to reassess its compressive strength after an extended curing period of 90 days (98 days) to determine if there was any further strength development. Notably, at 98 days, the C4 mixture showed a low increase in strength of 8 N/mm² compared to the values measured at 28 days Figure 3, 4 & 5.

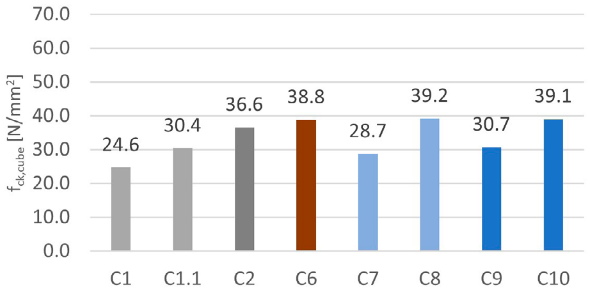

Figure 3. Compressive strength 2 days.

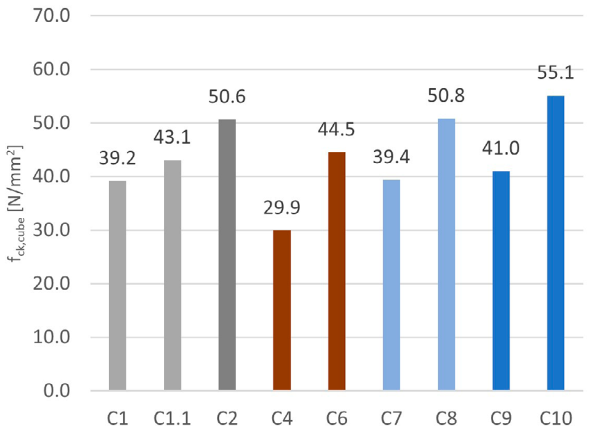

Figure 4. Compressive strength 7days.

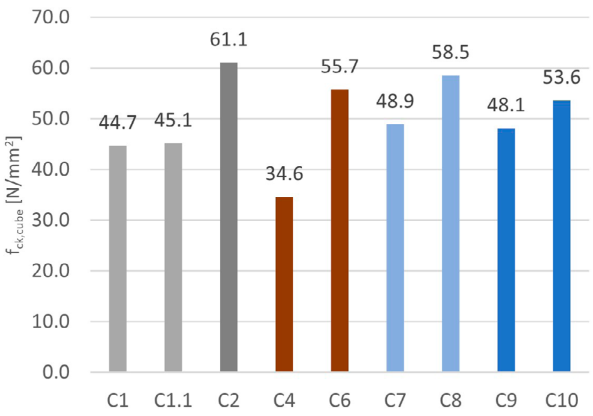

Figure 5. Compressive strength 28 days.

3.3. Elastic modulus

The high reference values of the natural aggregate concrete concerning the elastic modules are due to the type of aggregates used, in this case alluvial calcareous natural aggregates.

The graph below, reporting the results of the elastic modules, shows a decrease in the elastic modules of the mixtures C7, C8, C9 e C10 due to the replacement of natural aggregates with RCA recycled aggregates.

The graph indicates a value (orange line) commonly used in the construction world with an elastic modulus of 30000 MPa (Figure 6).

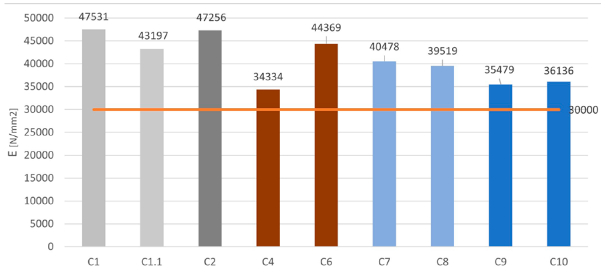

Figure 6. Elastic modules.

3.4. Freeze-Thaw Resistance in the Presence of De-icing Salts

In this test, the resistance to freeze-thaw cycles in the presence of salts of the mixtures is tested following the indications of the SIA standard (SIA 262/1, Annex C).

The samples are subjected to different cycles, at each cycle the material expelled from the surface is collected and weighed, the limits described by the standard and the results obtained from the tests are reported below.

The results show that all mixtures except C1 and C1.1 fall into the high resistance class XF4 ($m \leq 200$ g/m² or $m \leq 600$ g/m² and $\Delta m_{28} \leq (\Delta m_6 + \Delta m_{14})$.

3.5. Resistance to accelerated carbonation

The resistance to accelerated carbonation of the mixtures produced appears to be very good, slightly exceeding the value set by the standard (SIA 262/1 Annex 1) equal to XC4: KN ≤ 4.5 mm year for 100 years, for the results collected after 28 days.

The mixture with the worst result is C1, due to various factors, including the segregation of water during packaging and the high air content, consequently it turns out to be a very porous mixture which facilitates the entry of gases.

3.6. Resistance to chloride penetration

Chloride resistance indicates how quickly chloride ions can penetrate concrete. During analysis in accordance with SIA 262/1, Appendix B, the rate of penetration of chloride ions into concrete is determined within a few days. The method is based on an acceleration of the diffusion of chlorides by an electric field Figure 7.

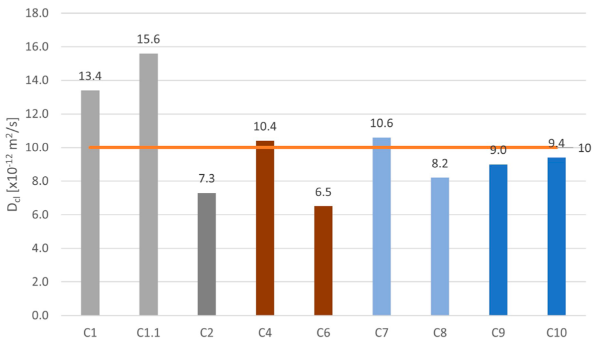

FIGURE 7. Resistance to chloride penetration.

The correlation between water-cement ratio and resistance to chloride penetration is noted; the lower the ratio, the more resistant the specimen.

Good resistance is denoted by mixtures with RCA and Wood Waste Ashes from burner.

4. CONCLUSIONS

The key findings of the study, focused on the development of low-cement eco-concretes incorporating recycled concrete aggregates (RCA) and wood waste ashes, with the goal of improving sustainability and maintaining required mechanical and durability performance, are:

- Reduction in Cement Content: All the concrete mixtures, even those with reduced cement content (as low as 240 kg/m³), exceeded a compressive strength of 25 MPa after just two days of curing. This demonstrates the potential for reducing cement content without compromising strength.
- Durability Performance: Durability tests showed that the eco-concretes performed comparably to or better than the reference mixtures in terms of resistance to carbonation, chloride penetration, and freeze-thaw cycles with de-icing salts. In particular, mixes incorporating wood waste ashes from the burner and recycled concrete aggregates (RCA) exhibited enhanced resistance to chloride penetration and carbonation.
- Workability and Adjustments: The addition of limestone filler and the use of superplasticizer effectively improved workability in low-cement mixes. For mixes with cement content below 240 kg/m³, the inclusion of 50 kg/m³ of limestone filler was essential to maintain proper workability.
- Effectiveness of Wood Waste Ashes: Replacing cement with wood waste ashes, particularly from the burner, resulted in improved concrete performance in terms of both mechanical strength and durability. However, ashes from the electro filter led to a reduction in compressive strength, likely due to the high water absorption and insufficient fine material.
- Recycled Concrete Aggregates (RCA): The replacement of natural aggregates with RCA, up to 50% by mass, did not adversely affect the mechanical properties. The mix design with RCA demonstrated comparable compressive strength and durability to conventional concrete, supporting the feasibility of using RCA in low-cement eco-concretes.

In conclusion, the study confirms that it is possible to produce sustainable, low-cement eco-concretes with high mechanical and durability performance by incorporating recycled materials and supplementary cementitious materials. The findings contribute to the development of more sustainable concrete formulations that meet both environmental and structural requirements for modern infrastructure.

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Declaration of competing interest

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

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Authorship contribution statement

Samuel Antonietti: Supervision, Methodology, Validation

Narayana Brioschi: Data curation, Formal analysis, Investigation, Methodology, Writing - original draft

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Ester Giner Cordero: Supervision, Writing - original draft

Christina Paglia: Conceptualization, Supervision, Methodology, Validation

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