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# DEVELOPMENT OF SUSTAINABLE CONCRETE USING WASTE ASHES AS RECYCLED AGGREGATES: SOLUTION FOR GREEN URBAN INFRASTRUCTURE

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## Abstract

The construction sector, particularly concrete production and aggregate use, significantly contributes to resource depletion, $CO_2$ emissions, and the accumulation of industrial by-products. This study evaluates the feasibility of using wood biomass ash (WBA) as a 6 wt.% partial replacement for natural aggregates in recycled aggregate concrete (RAC), promoting circular economy principles and sustainable material sourcing. Industrially produced RAC mixtures incorporating WBA were assessed for fresh properties, 28-day compressive strength, and durability, including water absorption and freeze-thaw resistance. Both concrete planter (CP) and street concrete bench (CB) mixtures demonstrated mechanical and durability comparable to conventional concrete, confirming their suitability for urban precast elements. Prototype elements, including a bench and garden planters, demonstrated practical applicability, while leaching tests confirmed environmental safety. Within the EU regulatory context, including the AshCycle project and recent CPR revisions, WBA-based RAC is a technically viable, sustainable, and regulatory-compliant alternative for urban infrastructure, supporting waste valorization and climate-conscious construction practices.

*Keywords: waste-derived aggregates, industrial by-products, green urban infrastructure, environmental performance, construction products regulation (CPR)*

## 1 Introduction

The construction sector is a major consumer of natural resources and a significant source of $CO_2$ emissions, largely due to the extensive use of natural aggregates in concrete production [1]. Increasing pressure on raw material availability and environmental protection has intensified interest in alternative materials that support circular economy principles. In this context, wood biomass ash (WBA), generated in increasing quantities from biomass-based energy production, represents a promising secondary material for concrete applications [2-4]. The use of WBA as a partial replacement for natural aggregates offers several advantages, including reduced consumption of virgin resources, waste valorization, and potential improvements in material efficiency [1, 2]. However, challenges related to the variability of ash properties, possible effects on concrete performance, and environmental safety, particularly the leaching of potentially hazardous substances, must be addressed carefully before widespread implementation [5, 6]. To date, most studies on WBA incorporation in concrete have been limited to laboratory-scale investigations, with little evidence of performance under industrial production conditions [5].

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This lack of semi-industrial or full-scale data is a significant barrier to the practical adoption of WBA-based concrete products in the construction sector [7]. In parallel, the European regulatory framework for construction products is evolving. The Construction Products Regulation (CPR) 305/2011 established essential requirements for construction works, while the revised CPR (2024/3110) places greater emphasis on emissions into the outdoor environment of construction works and the sustainable use of natural resources [8]. These changes highlight the increasing importance of environmental performance and lifecycle considerations, alongside traditional mechanical and durability requirements [6]. Against this background, this study investigates the feasibility of using wood biomass ash as a partial aggregate replacement in recycled aggregate concrete (RAC) produced under industrial conditions. The research evaluates fresh, mechanical, and durability properties, validates practical applicability through prototype urban elements, and situates the results within the current EU regulatory context, providing a foundation for future assessment of environmental emissions, including leaching behavior.

## 2 Materials

WBA from bottom used in this study originated from energy production facilities in Babina Greda, Croatia. The physicochemical characteristics of WBA are shown in figure 1. The ash was collected directly at the production site and transported to a storage silo at the concrete production plant, where it was stored before use as a recycled aggregate component in concrete mixtures.

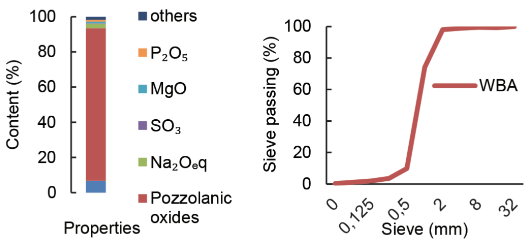


**Figure 1** The physicochemical characteristics of WBA

As part of trial-batch production and in collaboration with the concrete producer, RAC mixes incorporating WBA were designed, manufactured, and tested in accordance with EN 206 [9] and additional technical specifications defined by the producer. The experimental program focused on poured concrete mixtures intended for precast elements of green urban infrastructure. Two poured RAC mixtures were developed using WBA from Babina Greda as a partial replacement for natural aggregates, with a constant replacement level of 6 wt.% of the total aggregate content. The mixture designated as CP was used for producing concrete planters. The mixture designated as CB was used for manufacturing a precast street concrete bench. Both concrete mixtures used natural aggregates with a maximum nominal size of 16 mm. The aggregate consisted exclusively of natural river-graded sand (PPF), combined with potable mixing water in accordance with EN 206 requirements. The water-to-cement (w/c) ratio was adjusted to achieve the target workability for poured concrete applications. Chemical admixtures, including a superplasticizer and an air-entraining agent, were added in dosages consistent with the standard mix design procedures routinely applied by the concrete producer. The detailed mix compositions for both CP and CB mixtures are presented in table 1, while the corresponding precast concrete elements are shown in figure 1 and figure 2.

**Table 1** Poured concrete mix design with WBA as aggregate replacement

| Component | | Mix ID | |
|---|---|---|---|
| | | CP | CB |
| | | Mass fraction [wt.%] | |
| Holcim Lumen CEM II/A-LL 42.5 R | | 100 | 100 |
| Admixtures | Superplasticizer | 0.65 | 0.64 |
| | Air-entraining agent | 0.11 | 0.16 |
| Aggregates | 0–4 mm PPF | 38 | 40 |
| | WBA | 6 | 6 |
| | 4–8 mm PPF | 18 | 14 |
| | 8–16 mm PPF | 37 | 40 |
| Water-to-cement ratio | | 0.38 | 0.36 |

**Figure 2** Concrete planters (CP) with WBA as partial aggregate replacement

**Figure 3** Poured concrete bench (CB) with WBA as partial aggregate replacement

## 3 Methods

Poured RAC samples were tested as shown in table 2. The effect of WBA as recycled aggregate was evaluated in both fresh (density, air content, slump) and hardened states (28-day compressive strength, water absorption, and freeze-thaw resistance with de-icing salts). All specimens were cured under controlled humid conditions and tested at 28 days.

**Table 2** Methods for assessment of poured concrete produced with WBA and aggregate replacement

| Level of investigation | Property | Test timeframe | Standard/method [10-15] |
|---|---|---|---|
| Fresh state | Density | Immediately upon mixing of concrete | EN 12350-6:2019 |
| | Air content | | EN 12350-7:2019 |
| | Consistency (Slump-flow test) | | EN 12350-2:2019 |
| Hardened state | Compressive strength | After 28 days | EN 12390- 3:2019 |
| | Water absorption | | EN 13198:2004 |
| | Freeze-thaw resistance with de-icing salts (scaling after 28 cycles) | | EN 13198:2004<br>CEN/TS 12390-9 |

Leaching tests on WBA-containing RAC were conducted according to EN 12457-2:2005 [16]. Samples (< 4 mm) were mixed with deionised water at a 10:1 liquid-to-solid ratio, stirred for 24 hours, and filtered. pH and electrical conductivity were measured, and concentrations of As, Ba, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, and Zn were determined using ICP-MS. Measurements were performed in duplicate, and mean values were compared with Croatian regulatory limits for inert and non-hazardous waste to assess environmental safety.

# 4 Results

## 4.1 Fresh state properties

The fresh properties of the poured RAC mixtures incorporating WBA are summarised in table 3. Both mixtures, CP and CB, exhibited comparable densities, with values of 1776.3 kg/m³ and 1778 kg/m³, respectively, indicating minimal influence from the slight variation in aggregate grading on the overall mix weight. The air content was also similar, at 8.2% for CP and 8.0% for CB, reflecting consistent incorporation of the air-entraining admixture and suggesting good workability and potential for improved frost resistance. Consistency, assessed via the slump test, showed a slightly higher flow for the CB mixture (210 mm) compared to CP (160 mm), although both mixtures fall within slump class S4, suitable for highly flowable poured concrete applications.

**Table 3** Fresh state properties of poured RAC incorporating 6% WBA

| Mix ID | | CP | CB |
|---|---|---|---|
| Density [kg/m³] | | 1776.3 | 1778.0 |
| Air content [%] | | 8.2 | 8.0 |
| Consistency (Slump test) | mm | 160 | 210 |
| | slump class | S4 | S4 |

Overall, the fresh state measurements confirm that both CP and CB mixtures possess adequate workability, air content, and density for precast concrete applications, demonstrating that partial replacement of natural aggregates with WBA does not adversely affect the fresh properties at the semi-industrial scale.

## 4.2 Mechanical properties

The mechanical performance of poured RAC incorporating WBA is presented in table 4. The early-age compressive strength (at 2 days) was higher for CP (28.4 MPa) than for CB (22.9 MPa), likely due to slight differences in mix design, particularly aggregate grading and water-to-cement ratio. Compressive strength was measured on three specimens for each mix.

**Table 4** Compressive strength of poured RAC containing 6% WBA at 2- and 28-day ages

| Mix ID | | CP | CB |
|---|---|---|---|
| Compressive strength [MPa] | 2 days | 28.4 ± 1.88 | 22.9 ± 1.65 |
| | 28 days | 39.8 ± 4.72 | 39.9 ± 1.15 |

The results indicate that partially replacing natural aggregates with 6 wt.% WBA maintains the target compressive strength and meets standard requirements for precast elements. Furthermore, the 28-day compressive strength values of both mixtures exceed the minimum strength requirements for concrete strength class C25/30 according to EN 13198:2004 [14], confirming the suitability of WBA as a recycled aggregate component in concrete.

## 4.3 Durability-related properties

The durability of poured recycled aggregate concrete (RAC) incorporating 6 wt.% WBA was evaluated in terms of water absorption and freeze-thaw resistance with de-icing salts (table 5). Water absorption was tested on three specimens, and freeze-thaw resistance after 28 cycles was evaluated on four specimens. Water absorption was low for both mixtures, at 5.0% for CP and 4.8% for CB, and remained below the 6% limit specified by EN 13198:2004 [14], indicating good impermeability of the RAC mixtures. Freeze–thaw resistance, assessed after 28 cycles in the presence of de-icing salts, showed excellent performance, with average mass losses ($\Delta m_{average, total}$) of 0.300 kg/m² for CP and 0.067 kg/m² for CB, and maximum individual losses ($\Delta m_{max, ind}$) of 0.37 kg/m² and 0.19 kg/m², respectively, all well within the limits set by HRN 1128:2023 [17]. These results confirm high resistance to scaling under freeze–thaw cycles for both mixtures, with CB exhibiting slightly better performance, likely due to its lower water absorption and optimised aggregate grading.

**Table 5** Durability-related properties od poured RAC containing 6% WBA

| **Mix ID** | | **CP** | **CB** | **Performance according to EN 13198:2004** | **Performance according to HRN 1128:2023** |
|---|---|---|---|---|---|
| Water absorption [% by mass] | | 5.0 | 4.8 | < 6 | - |
| Freeze-thaw resistance with de-icing salts (scaling after 28 cycles) | $\Delta m_{average, total}$ [kg/m²] | 0.300 | 0.067 | - | ≤ 0.5 |
| | $\Delta m_{max, ind}$ [kg/m²] | 0.37 | 0.19 | ≤ 1.5 | ≤ 1.0 |

Overall, the results indicate that partial replacement of natural aggregates with WBA does not compromise durability, making both CP and CB mixtures suitable for precast applications exposed to harsh environmental conditions.

## 4.4 Environmental impact

Leaching results for both WBA and RAC at the end of life (table 6) show that the concentrations of all analysed elements are well below the limit values prescribed by the Regulation on End-of-Waste Status in Croatia [18]. For both materials, Ba and Mo showed the highest concentrations; however, their values remained significantly lower than the regulatory thresholds for inert waste. All other potentially hazardous elements were detected at concentrations several orders of magnitude below the prescribed limits.

Table 6 The concentration of 12 different elements, measured in leachates using ICP-MS

| Element [mg/kg] | WBA [mg/kg] | End life of CB [mg/kg] | Limit values for leachate parameters in recycled aggregate and backfill material [mg/kg] |
|---|---|---|---|
| Arsenic (As) | 0.002 | 0.002 | ≤ 0.5 |
| Barium (Ba) | 5.712 | 5.504 | ≤ 20 |
| Cadmium (Cd) | < 0.002 | 0.001 | ≤ 0.04 |
| Chromium (Cr total) | 0.311 | 0.035 | ≤ 0.5 |
| Copper (Cu) | < 0.001 | 0.009 | ≤ 2 |
| Mercury (Hg) | < 0.001 | 0.002 | ≤ 0.01 |
| Molybdenum (Mo) | 0.077 | 0.015 | ≤ 0.5 |
| Nickel (Ni) | 0.008 | 0.012 | ≤ 0.4 |
| Lead (Pb) | < 0.005 | 0.001 | ≤ 0.5 |
| Antimony (Sb) | < 0.001 | 0.002 | ≤ 0.06 |
| Selenium (Se) | < 0.003 | 0.005 | ≤ 0.1 |
| Zinc (Zn) | 0.01 | 0.009 | ≤ 4 |

Notably, the incorporation of 6 wt.% WBA into RAC did not increase leaching compared to WBA alone, indicating effective immobilization of elements within the cementitious matrix. This is especially evident for Cr values. These results confirm the environmental acceptability of WBA-based RAC both before and after its service life.

## 5 Conclusion

This study shows that WBA can replace 6 wt.% of natural aggregates in RAC without affecting fresh, mechanical, or durability properties. Both CP and CB mixtures showed adequate workability, consistent density and air content, and 28-day compressive strengths corresponding to concrete strength class C25/30, as well as excellent water absorption and freeze-thaw resistance, meeting EN standards for precast elements. Prototype urban elements - a concrete bench and planters - demonstrated practical applicability, while WBA use supports waste valorisation, reduced reliance on natural aggregates, and circular economy principles. Overall, WBA-based RAC provides a durable, environmentally responsible alternative for precast urban infrastructure, in line with EU sustainability and construction regulations.

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