CETRA[2022] 11-13 May 2022, Pula, Croatia
7th International Conferenceon Road and Rail Infrastructure

SUSTAINABLE PRECAST CONCRETE PRODUCTS WITH WOOD BIOMASS ASH – KERBS AND DRAINAGE CHANNELS

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Abstract

Construction materials need to be observed through a lifetime carbon footprint. Due to the high greenhouse gas emissions from cement production, the lack of natural raw materials such as sand, a significant increase of WBA and the problem of its disposal, there has been a serious disturbance of the ecosystem. Therefore, it is necessary to encourage the use of production processes that consume less materials and energy, use waste-free resources, and include full recycling at the end of the product's life. One of the possible solutions is the use of locally available wood biomass ash as a substitute for cement or sand in concrete mixes for non-structural precast concrete products. To achieve this goal, the relevant mechanical and durability properties of concrete products - kerbs and drainage channels, were investigated by replacing cement or fine aggregate with 15 % of WBA and comparing it to a reference mixture without WBA. For this study, 5 different types of WBAs were collected from biomass power plants in the Republic of Croatia. This paper presents the effects of WBAs on the mechanical properties and durability of concrete products, which represents a possible more environmentally friendly alternative for industrial waste recycling compared to existing waste management options.

Keywords: wood biomass ash, precast concrete elements, innovative construction products, kerb, drainage channels

1 Introduction

In order to meet the requirements of 40 % of energy use from renewable sources set by the European Commission in the new legislative package "Fit for 55 %", power plants based on wood biomass play the largest role [1, 2]. In accordance with these goals, numerous biomass power plants are being commissioned in Croatia, which will soon have to look for alternative solutions for the disposal of the waste produced - wood biomass ash (WBA). According to [3], a biomass power plant consumes an average of 37, 900 tons of wood biomass per year, i.e. from the combustion of 1 ton of wood biomass an average of 3.1 % of WBA is generated. By meeting the requirements ahead, the amounts of WBA will be even higher, so it is necessary to find an appropriate utilization of WBA. Past practice has shown that the majority (70 %) of WBA is dumped in landfills [4-7], causing enormous environmental and economic losses. On the other hand, the construction industry is well known for its one-sided model of production and exploitation of resources, disrupting the natural balance, as construction products are made from raw materials, used, and then labelled as waste [8]. Therefore, the sustainability of the precast concrete industry can be improved by using alternative supplementary-cementitious materials (SCM), using WBA as a partial replacement for cement and fine aggregates [9]. In this way, the basic requirement of Directive 305/2011 "sustainable use

DOI: https://doi.org/10.5592/CO/CETRA.2022.1396

of natural resources" would be met [10], but also the issues related to WBA and construction waste disposal, greenhouse gas emissions, and natural resource depletion would be resolved creating innovative, more environmentally friendly materials.
This study provides an overview of the mechanical and durability properties tested on precast concrete products - kerbs and drainage channels - using WBA as a partial replacement for cement and fine aggregate. WBA is used in precast products in System 4 of Assessment and Verification of Constancy of Performance, in which testing of the essential product properties is carried out by the manufacturer.

2 Experimental procedure

This research was carried out as part of the project "Development of innovative construction composites using bio-ash" to determine the effects of different types of WBA on the relevant properties of precast concrete products - kerbs and drainage channels – by partial replacement of cement and fine aggregates with 15 % WBAs.

2.1 Materials and methods

2.1.1 Materials

The manufacturer's original concrete mix designs were used for the development of the precast concrete products, i.e., the mixes for semi-dry concrete for kerbs, and precast concrete for drainage channels. The materials listed in Table 1 were used for the production of concrete mixtures for precast products.

Table 1 Materials used for the production of concrete mixes for precast concrete products – kerbs and drainage channels

Kerbs	Drainage channels
Portland cement CEM I 42.5 R	Portland cement CEM I 42.5 R
potable water	potable water
crushed stone aggregate (0/4, 4/8, 8/16 mm)	natural stone aggregate (0/4, 4/8, 8/16 mm)
natural aggregate (0/4 mm)	superplasticizer
hydrophobic additive	air-entraining agent

Table 2 shows the chemical composition of the WBAs used as 15 % partial replacements for cement and fine aggregate (crushed stone fraction 0/4 mm - kerbs; natural stone fraction 0/4 mm - drainage channels). The WBAs collected for the purposes of this research originate from biomass power plants in Croatia, where mainly grate combustion technology is used. The wood biomass used as raw material is pure wood chips, whole wood chips, and residues from wood extraction, with the most common wood species being mixed wood, oak, hornbeam, and beech.

Table 2 Chemical composition of WBAs

		WBA1	WBA2	WBA3	WBA4	WBA5
WBA samples						
pH value		13.61	13.22	12.89	12.92	12.84
LOI (950 °C)	wt. %	11.5	3.9	6.6	6	8
P_2O_5		2.86	3.36	2.93	5.26	2.49
Na_2O		0.47	1.07	1.17	0.73	1.72
K_2O		12.03	11.55	7.68	7.68	7.04
CaO		49.07	36.59	27.85	45.08	18.25
MgO		3.89	4.43	4.17	4.06	3.08
Al_2O_3		3.73	6.15	9.79	4.49	12.12
TiO_2		0.42	0.9	0.68	0.23	0.86
Fe_2O_3		2.3	3.56	4.03	1.97	4.04
SiO_2		21.87	30.1	38.58	22.11	45.47
MnO		1.26	0.72	0.34	0.49	0.46
SO_3		1.38	1.26	2.18	7.68	4.17
$SiO_2 + Fe_2O_3 + Al_2O_3$		27.9	39.8	52.4	28.6	61.6
Na_2O_{eq}		8.39	8.67	6.22	5.78	6.35

2.1.2 Methods

For the production of precast concrete kerbs, 5 mixtures of semi-dry concrete were prepared, designated M0_K (reference mixture without WBA), M1_K (WBA1), M2_K (WBA2), M3_K (WBA3), in which 15 % of fine aggregates were replaced by WBA, and M4_K (WBA5), in which 15 % of cement was replaced by WBA. In addition, for the production of drainage channels, 6 mixtures of precast concrete were prepared, designated M0_DC (reference mixture without WBA), M1_DC (WBA1), M2_DC (WBA2), M3_DC (WBA3), in which 15 % of the fine aggregates were replaced by WBA, and two mixes in which 15 % of the cement was replaced by M4_DC (WBA4) and M5_DC (WBA5). The relevant mechanical and durability properties of the concrete products were investigated according to the experimental plan shown in Table 3.

Table 3 Experimental plan for precast concrete products – kerbs and drainage channels

State	Properties	Standards	
		Kerbs	Drainage channels
Fresh	Consistence	-	EN 12350-2:2019 [11]
	Density	-	EN 12350-6: 2019 [12]
	Air content	-	EN 12350-7: 2019 [13]
	Temperature	-	EN 12350-1: 2019 [14]
Hardened	Compressive strength	EN 12390-3:2019 [15]	EN 12390-3: 2019 [15]
	Bending strength	EN 1340:2003 [16]	-
	Total water absorption	EN 1340:2003 [16]	EN 1433:2002+AC:2004 [17]
	Freeze-thaw resistance with de-icing salts	-	CEN/TS 12390-9:2016 [18]

3 Results

3.1 Fresh state properties of concrete mixtures with WBAs

Table 4 shows the results of testing the properties of fresh precast concrete with 15 % of WBAs, whether it was used as a replacement for cement or fine aggregate, casted into the molds for drainage channels. According to the manufacturer's requirements for precast concrete, the specified slump class is S3 (100 - 150 mm), which was met by the reference mix. However, all mixes with WBAs had a higher slump class compared to the reference mix. The loss of workability is probably due to the increased water demand by the application of WBAs due to their irregular shape and highly porous particle surface structure with high specific surface area and high carbon content and free CaO [8, 19, 20], increased alkali content [21], despite the use of superplasticizers. The densities of the fresh precast concrete with WBA were slightly lower compared to the reference mix, but no significant change was observed. The air content was lower for all concrete mixtures with WBA compared to the reference mixture, but within the limits set by the manufacturer, ranging from 4.5 to 7.0 %, except for mix M2_ DC.

Table 4 Properties of fresh precast concrete for drainage channels

Properties	M0_DC	M1_DC	M2_DC	M3_DC	M4_DC	M5_DC
Consistence [mm]	150	200	220	190	165	210
Density [kg/m³]	2280	2270	2270	2250	2260	2230
Air content [%]	6, 5	5, 4	4	6, 2	5, 2	4, 9
Temperature [°C]	19, 5	17, 7	14, 6	15, 5	25, 2	14, 9

3.2 Hardened state properties of concrete mixtures with WBAs

3.2.1 Mechanical properties

The mechanical properties of precast concrete products are presented by testing the compressive and bending strength, depending on the prescribed requirements for each concrete element (Table 3). Figure 1 shows the results of the compressive strength test after 28 days of concrete kerbs with 15 % WBA as a substitute for cement and fine aggregate compared to the reference mix that did not contain WBA. The mixtures designated M2_K, M3_K and M4 showed an increase in compressive strength of 14.8 %, 5.9 %, and 2.2 %, respectively, compared to the reference mix. The exception is the M1_K mixture, whose compressive strength decreased by 14.8 % compared to the reference mixture. This may be attributed to the high LOI content (11.5 %) and a lower sum of pozzolanic oxides (27.9 %) in WBA1 compared to other semi-dry concrete mixtures containing WBAs (Table 2).

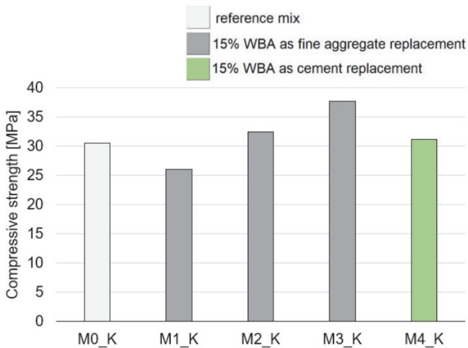

Figure 1 Compressive strength of concrete kerbs with 15 % WBA as a substitute for cement and fine aggregate

Figure 2 shows the results of compressive strength testing of precast concrete for drainage channels after 1 and 28 days with 15 % WBA as a substitute for cement and fine aggregate. All mixes with WBA showed a lower increase in compressive strength after 1 day compared to the reference mix (Figure 2a and 2b). The use of WBAs decreases the compressive strength in early ages ash due to the high content of free Cao, free MgO, LOI, and alkali. After 28 days, the compressive strengths of all concrete mixes with WBAs were lower compared to the reference mix in a range from 5.06 % (M1_DC) to 22.57 % (M4_DC). However, the mixes M1_DC and M2_DC met the manufacturer's criteria for concrete class C35/45.

Table 5 Compressive strength of drainage channels after 1 and 28 days, a) 15 % WBA as fine aggregate replacement, b) 15 % WBA as cement replacement

Kerbs					Drainage channels					
Mix ID										
M0__K	M1__K	M2__K	M3__K	M4__K	M0_DC	M1_DC	M2_DC	M3_DC	M4_DC	M5_DC
Total water absorption, B [%]										
4, 9	4, 4	4, 6	4, 6	4, 9	5, 2	5	5, 5	5, 8	5, 3	6, 4
Requirements										
B ≤ 6 % as a mean value					W ≤ 6, 5 % as a mean value; no individual results ≥ 7, 0 %					

Bending strength was tested on 8 kerbs according to EN 1340:2004. Figure 3 shows the mean values of bending strength of concrete kerbs with WBAs in relation to the reference mix and the criteria prescribed by the standard. The results show that all values of bending strength of concrete kerbs are higher than those of the reference mix. Concrete kerbs met the prescribed criterion for kerb manufacturer's bending strength Class 1, i.e., T ≥ 3.5 MPa. In addition, each individual result for the bending strength of the 8 kerbs must be greater than the minimum prescribed value of T_{min} ≥ 2.8 MPa, which is also satisfied.

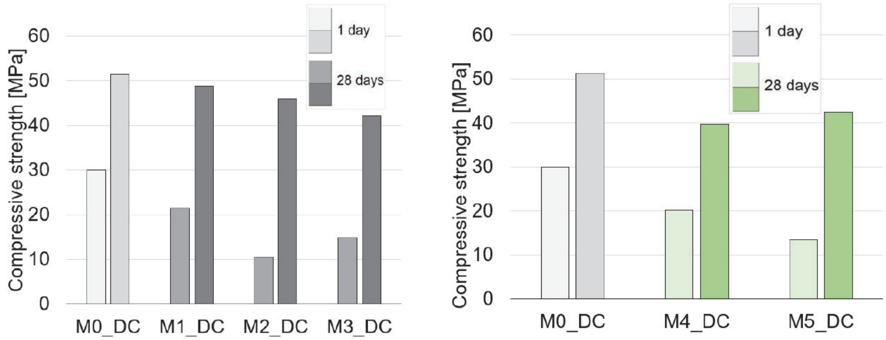

Figure 2 Bending strength of concrete kerbs with 15 % WBA as a substitute for cement and fine aggregate

3.2.2 Durability properties

The durability properties of precast concrete products are presented by testing the total water absorption and freeze-thaw resistance with de-icing salts, depending on the prescribed requirements for each concrete element (Table 3). The results of total water absorption of precast concrete products – kerbs and drainage are shown together in Table 5, according to the requirements given in the standards.

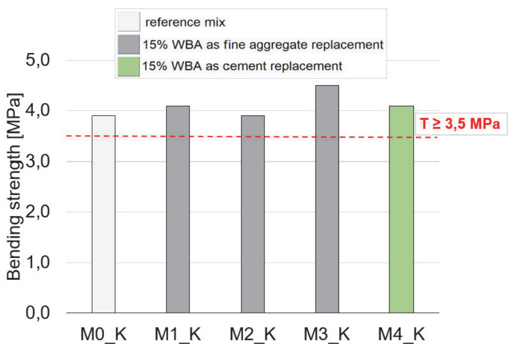

Figure 3 Total water absorption of precast concrete kerbs and drainage channels with WBAs

Observing the results of the mean water absorption values for precast concrete kerbs, all mixes - reference (M0_K) and with WBAs - met the prescribed criterion of B ≤ 6 % for Class 2, regardless of whether WBA was used as a substitute for cement or fine aggregates. In addition, the mixes (M1_K, M2_K, and M3_K) with WBA as a substitute for fine aggregate had lower water absorption compared to the reference mix M0_K, while the mix with WBA as a substitute for cement (M4_K) had the same water absorption as the reference mix M0_K. Concrete mixes for drainage channels showed similar behaviour, meeting the prescribed criterion of W ≤ 6.5 % for Class 2 drainage channels, with mix M1_DC having a lower water absorption of 3.85 % compared to reference mix M0_DC. These results indicate that the addition of WBA to the concrete mix for the production of precast concrete products has a positive effect on the durability property - total water absorption.
Figure 4 shows the mass loss of material from the test surface of concrete specimens for drainage channels during a freeze-thaw attack in the presence of de-icing salts. Since the prescribed criterion for precast concrete is exposure class XF4, the average scaling after 56 cycles should not exceed 0.5 kg/m^2 for drainage channels. It can be seen that all concrete

mixes except M5_DC met the prescribed criteria. In addition, the average mass of material loss after 28 cycles of freeze-thaw with de-icing salts was limited to 1.0 kg/m^2 according to EN 1340, which was met by all mixes except M5_DC.

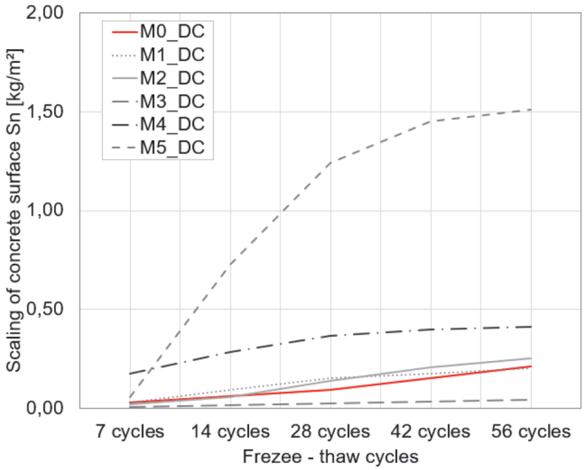

Figure 4 Scaling of test surface concrete samples for drainage channels due to freeze-thaw attack up to 56 cycles

4 Conclusion

Both precast concrete products - kerbs and drainage channels with WBA - showed great potential for the use in terms of improving the mechanical properties and durability of concrete, inventing more environmentally friendly concrete production, and sustainable construction. Most concrete kerbs with 15 % WBA replacing cement and aggregates showed an increase in compressive strength compared to the reference mix, with the exception of mix M1_K. In contrast, the precast concrete for drainage channels showed a slight decrease in compressive strength compared to the reference mix. The results of the bending strength test meet the prescribed criteria for Class 1. The results of the durability test - total water absorption and freeze-thaw resistance with de-icing salts, for both products - kerbs and drainage channels, meet the prescribed criteria, except for mix M5_DC. Converting the waste of one industry (WBA) into the raw material of another industry (concrete industry) solves the problems of excessive greenhouse gas emissions, depletion of natural resources, and energy consumption. On the other hand, it helps to solve the problem of improper disposal of WBA and reduce the associated financial costs.

Acknowledgment

This research was performed as a part of the research project KK.01.2.1.01.0049 „Development of innovative construction products using bio-ash“, which was funded by the European Regional Development Fund.

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