CETRA^{2024} 15-17 May 2024, Cavtat, Croatia
8th International Conferenceon Road and Rail Infrastructure

LOW-CARBON PAVEMENT SOLUTIONS: INTEGRATING INCINERATION ASHES IN PRECAST CONCRETE INNOVATIONS

Jelena Šantek Bajto[1], Ivana Carević[1], Nina Štirmer[1], Suzana Hozmec[2], Danica Jelenić[2]
[1] University of Zagreb, Faculty of Civil Engineering, Croatia
[2] Beton - Lučko d.o.o., Croatia

Abstract

In the European Union (EU), the incineration of wood biomass and sewage sludge yields approximately 25 million tons of waste residue annually. These residues currently present a significant challenge within the construction industry, as they are either directed towards low-value applications or left unused. Challenges such as limited public awareness of safety and environmental implications, inconsistencies in legislation, and market hesitation impede their widespread adoption. In light of climate change, circular economy principles, and stringent environmental regulations, the construction sector requires innovation to shift its status from surplus to critical need. The revised Construction Products Regulation (CPR) acknowledges this necessity and mandates the prioritized use of recycled materials. Within this context, the central focus of this paper is on an illustrative case study outlining the development and implementation of sewage sludge ash (SSA) in the pilot-scale production of precast semi-dry concrete pavement elements. Beginning with the a priori characterisation of incineration waste residues, the study evaluates the feasibility of utilizing these materials as a substitute for sand in large-scale concrete batching plants. Mechanical properties and durability are assessed in alignment with the technical requirements of precast concrete manufacturers. Beyond engineering considerations, the ecological significance is underscored by addressing the leaching of heavy metals from concrete composites containing waste ash, with a particular emphasis on environmental safety.

Keywords: low-carbon pavement solutions, incineration ashes, environmental impact, sustainability, circular concepts

1 Introduction

Presently, ashes resulting from municipal solid waste, biomass, and sewage sludge incineration often go underutilized, with a significant portion ending up in landfills. This practice leads to the loss of valuable metals, nutrients, rare earth elements, and minerals contained within the ashes. Moreover, landfilling incurs substantial costs, ranging from 100 to 500 euros per tonne, with projections indicating a rise in expenses in the future. To tackle these challenges, the project ‘Integration of underutilized ashes into material cycles by industry-urban symbiosis (AshCycle)’ is dedicated to developing innovative solutions for waste utilisation, aiming to reduce waste generation. As we progress towards establishing a climate-neutral economy, it becomes imperative to underscore the social dimension of industrial transformation, particularly within pivotal sectors such as energy and construction, which play a foundational role in shaping the economic and industrial framework of the EU. Engaging the community as well as a relatively conservative construction industry in these initiatives is

DOI: https://doi.org/10.5592/CO/CETRA.2024.1614

vital for enhancing acceptance of new technologies and fostering a broader understanding of alternative waste materials. Embracing a collaborative approach, the ‘AshCycle’ project aims to create a sustainable ecosystem where waste is transformed into valuable resources, contributing to the circular economy while addressing environmental concerns.

In numerous EU countries, the challenge of adequately managing sludge from wastewater treatment plants persists as an ongoing issue and financial burden for water companies, as it remains incompletely resolved and lacks comprehensive regulatory guidelines. Throughout the EU, approximately 27% of sludge undergoes thermal treatment, a proportion that continues to rise steadily. SSA emerges as the primary residue from thermal processing, with an annual generation rate of 0.7 million tonnes in the EU. Despite its relatively smaller production volume compared to ash from municipal waste or biomass, the notable phosphorus content (ranging from 5% to 10% by weight), a critical raw material listed by the EU, renders SSA a valuable resource of interest. Moreover, SSA can be employed as a fuel or raw material in hydrogen production facilities. The rising demand for hydrogen as an alternative fuel is driven by the imperative to transition towards cleaner energy sources, replacing fossil fuels and supporting decarbonization initiatives across sectors such as public transportation, manufacturing, and energy-intensive industries. Additionally, the resulting ash from this process presents a novel resource for construction sector. Another avenue for SSA recovery involves its direct integration into the concrete industry [1–5], which is the focal point of this paper.

2 Experimental framework

The research described herein was conducted within the framework of the ‘AshCycle’ project, with the aim of exploring opportunities for repurposing waste incineration ashes in the manufacturing of concrete products. Concrete specimens underwent production and testing with a precast concrete manufacturer Beton - Lučko. The outcomes of these tests will serve as the basis for prototype production within an existing facility and will guide the implementation of a comprehensive commercial process for manufacturing low-carbon pavement solutions incorporating underutilized incineration ashes.

2.1 Materials and methods

The experimental section of this paper aimed to assess the suitability of sewage sludge ash (SSA) as a partial substitute for conventional aggregates in concrete production. Dried and incinerated SSA, generated at a rate of 300 tonnes per month, was collected from a wastewater treatment plant located in Croatia. The SSA, characterised by its dark grey coloration, was utilized in its collected state without undergoing any other preliminary pre-treatment.

This assessment encompassed an analysis of the physical properties, including particle density and size distribution, as well as water absorption, alongside an examination of the chemical composition of SSA. The objective was to ascertain its impact on the mechanical properties and durability of cementitious composites. The engineering behaviour of the semi-dry concrete, including critical aspects such as compressive and bending strength, was evaluated alongside an analysis of durability, specifically focusing on water absorption of the finished pavement elements. Alongside mechanical considerations, the environmental implications were also addressed, particularly regarding the leaching of heavy metals from SSA. Emphasis was placed on ensuring environmental safety and compliance with the prescribed limit values for eluate parameters for recycled aggregates and backfill materials, as stipulated by the ‘Ordinance on the abolition of the waste status’ [6]. An assortment of double-phase methods pertaining to SSA and concrete levels were employed as outlined in Table 1 and Table 2.

Table 1 Test methods for assessment of SSA

Level	Property	Test period	Unit	Standard
SSA as aggregate substitute	Particle density	Prior to concrete production	Mg/m^3	EN 1097-6:2022
	Water absorption		%	
	Particle size distribution by sieving		µm	EN 933-1:2012
	Chemical composition		wt.%	ISO/TS 16996:2015
	Loss on ignition (LOI)			ASTM D 7348-13
	Leaching (heavy metal concentrations)		mg/kg	EN 12457-2:2005

Table 2 Test methods for assessment of semi-dry concrete flags

Level	Property	Test period	Unit	Standard
Precast concrete	Compressive strength	After 28 days of age	MPa	EN 1339:2004/AC:2007
	Bending strength		MPa	
	Water absorption		µm	

A semi-dry concrete mixture, denoted as SDC-SSA1, was formulated through the replacement of 14 wt.% of the total fine sand (0-4 mm fraction) with SSA. Concurrently, a reference mixture devoid of SSA, identified as SDC-R, was prepared for comparative analysis. Both concrete formulations were manufactured at the facilities of a precast concrete manufacturer in the form of semi-dry concrete slabs measuring 40x40x5 cm (Figure 1.). The resulting precast concrete paving flags were composed of Portland cement CEM II/A-LL 42.5 R, SSA, crushed and natural stone aggregates, and potable water, adhering to the specifications outlined in EN 1339 standard [7]. The water-to-cement ratio achieved in the SDC-SSA1 mixture was w/c = 0.208, adhering to the manufacturer's prescribed w/c ratio for the control SDC-R mixture. In addition, a concrete additive was integrated to optimise the compaction efficiency and increase the water resistance of semi-dry precast concrete paving flags.

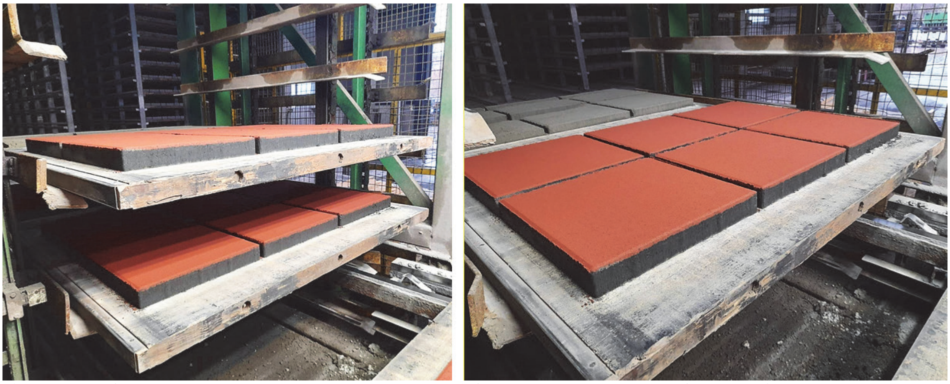

Figure 1 Fabrication of precast prototype concrete slabs incorporating SSA within an industrial setting

3 Results

3.1 SSA assessment

The data regarding physical properties offer valuable insights into the distinctions between SSA1 and the 0-4 mm fractions of crushed and natural aggregate. The notable water absorption of SSA1 suggests that it could elevate water demand in concrete mixes, potentially influencing properties such as workability, strength, and durability.

Table 3 Physical properties of SSA1 vs. 0-4 fractions of crushed and natural aggregate

Property	SSA1	0-4 mm crushed aggregate fraction	0-4 mm natural aggregate fraction
Particle density [Mg/m^3]	2.36	2.11	2.66
Water absorption [%]	21.51	0.3	0.7

Figure 2 illustrates the particle size distribution of SSA1 juxtaposed with the 0-4 mm and 4-8 mm fractions of crushed aggregate. In this context, SSA1 demonstrated a wider range of particle sizes compared to the more narrowly sized 0-4 mm and 4-8 mm fractions, positioning it between these two ranges.

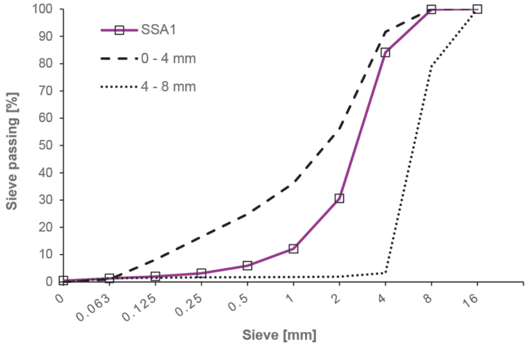

Figure 2 Comparative analysis of particle size distribution between SSA1 and crushed aggregate fractions (0-4 mm and 4-8 mm)

The potential for recycling SSA is heavily dependent on its physical properties and chemical composition. Various factors, including the characteristics of the wastewater, the technological processes used for water purification, and the method and temperature of thermal sludge treatment, significantly influence the composition of ash generated at wastewater treatment plants [8]. Analysis of the results presented in Table 4 reveals that the primary constituents of SSA1 are SiO_2 and CaO. Additionally, notable levels of P_2O_5, Al_2O_3, Fe_2O_3, and SO_3 were observed, consistent with findings in the literature [9]. Additionally, CaO and Fe_2O_3 enhance melting properties, facilitating lower melting temperatures during the sintering process and consequently reducing energy expenditures [5, 9].

Table 4 Chemical composition of SSA1

Compound [wt.%]	
SiO_2	28.01
CaO	19.62
free CaO	2.11
Al_2O_3	10.87
Fe_2O_3	5.97
Na_2O	0.66
K_2O	1.22
SO_3	3.85
Cl	0.07
P_2O_5	11.5
MgO	1.73
ZnO	0.13
CuO	0.026
TiO_2	0.581
MnO	0.098
Cr_2O_3	0.066
BaO	0.069
SrO	0.033
LOI (550 °C)	15.52
LOI (950 °C)	19.44

Table 5 Leaching of heavy metals form SSA eluate vs. limit values for leachate parameters in recycled aggregate and backfill material

Trace/Heavy elements	**SSA1** [mg/kg]		**Limit values for leachate parameters in recycled** aggregate and backfill material [mg/kg] **[6]**
Arsenic (As)	< 0.110		≤ 0.5
Barium (Ba)	8.36		≤ 20
Cadmium (Cd)	< 0.070	**H**	≤ 0.04
Cromium (Cr total)	< 0.090		≤ 0.5
Copper (Cu)	< 0.100		≤ 2
Mercury (Hg)	n/a		≤ 0.01
Molybdenum (Mo)	< 0.100		≤ 0.5
Nickel (Ni)	< 0.060		≤ 0.4
Lead (Pb)	< 0.180		≤ 0.5
Antimony (Sb)	< 0.180		≤ 0.06
Selenium (Se)	n/a		≤ 0.1
Zinc (Zn)	< 0.210		≤ 4
Fluorides	2.6		800
Chlorides	530	**H**	10
Sulphates	106		1000

The results of leaching of heavy metals from SSA eluate are presented in Table 5 alongside the limit values for leachate parameters in recycled aggregate set in [6].

Leaching testing according to EN 12457-2:2005 protocol involved the isolation of 20 grams of SSA, which was then placed into a sealed 250 mL bottle. Subsequently, 200 mL of solvent (deionised water) was added to achieve a liquid-to-solid ratio (L/S) of 10. The bottle containing the sample-water mixture was then subjected to rotation (mixing) for 24 hours. Following completion of the mixing process, the mixture was allowed to settle for 15 ± 5 minutes. The resulting eluate was subsequently filtered through a membrane with a pore diameter of 0.45 micrometres. Analysis of heavy metal concentrations was performed using a spectrometer equipped with inductively coupled plasma-optical emission spectroscopy (ICPE 9000, Shimadzu).

Provided that the values of the eluate, i.e. heavy metals concentrations are within or under the specified limit values detailed in Table 1, the recovered waste such as SSA could be exempted from its waste classification and utilized as a recycled aggregate suitable for its intended purpose. It was observed that only the concentrations of cadmium and chlorides exceed the limit values (marked with 'H'), while the concentrations of the remaining heavy metals as well as fluorides and sulphates are under the specified limit values. Although the SSA does not fully comply with all the requirements outlined in the Croatian national regulation on abolition of waste status, prior studies indicate that the incorporation of waste incineration ashes into the cement matrix, such as concrete, results in notable reductions in heavy metal concentrations. This phenomenon can be attributed to the diminished mobility of heavy metals, as they are effectively encapsulated within the cement matrix [4, 10, 11]. Hence, incorporating SSA into concrete manufacturing offers an alternative strategy for stabilizing hazardous waste, renowned for its effectiveness in reducing the leaching of hazardous substances, notably heavy metals, into the environment.

3.2 Mechanical properties and durability of precast semi-dry concrete pavement flags

The compressive strength of a total of 15 cubic specimens cut-out cured pavement flags after 28 days, each with dimensions of 5x5 cm (Figure 3), and incorporating SSA, ranged from 15.50 MPa to 18.64 MPa, with an average strength of 17.13 MPa. In comparison, the reference cubic specimens without SSA exhibited compressive strengths ranging from 15.79 MPa to 27.91 MPa, with an average strength of 21.49 MPa. These results indicate that, on average, cubic specimens with SSA have demonstrated a 20% downturn in compressive strength compared to those without SSA incorporation, consistent with previous research [1]. However, it's noteworthy that the compressive strength of specimens with SSA incorporation generally falls within a narrower range compared to specimens without SSA incorporation, implying a potential for sustained and uniform performance.

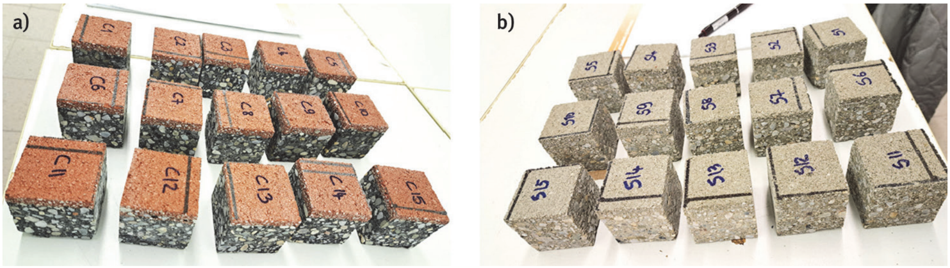

Figure 3 Cut-out cubic specimens: (a) SDC-SSA1 concrete, (b) SDC -R concrete

Table 6 Comparison of compressive strength values of semi-dry concrete cubes incorporating SSA1 and control values after 28 days

Cubic specimen ID with SSA incorporation	**Compressive strength** [MPa]	**Cubic specimen ID without SSA incorporation**	**Compressive strength** [MPa]
SDC-SSA1/C1	18.63	SDC-R/S1	18.42
SDC-SSA1/C2	16.65	SDC-R/S2	23.66
SDC-SSA1/C3	16.78	SDC-R/S3	15.79
SDC-SSA1/C4	17.76	SDC-R/S4	20.71
SDC-SSA1/C5	18.2	SDC-R/S5	23.73
SDC-SSA1/C6	15.5	SDC-R/S6	19.47
SDC-SSA1/C7	16.63	SDC-R/S7	16.97
SDC-SSA1/C8	16.37	SDC-R/S8	17.75
SDC-SSA1/C9	18.64	SDC-R/S9	27.91
SDC-SSA1/C10	17.21	SDC-R/S10	21.85
SDC-SSA1/C11	17.48	SDC-R/S11	21.57
SDC-SSA1/C12	17.94	SDC-R/S12	19.33
SDC-SSA1/C13	17.66	SDC-R/S13	21.73
SDC-SSA1/C14	15.81	SDC-R/S14	27.11
SDC-SSA1/C15	15.63	SDC-R/S15	26.36
SDC-SSA1/C average	**17.13**	**SDC-R/S average**	**21.49**

Bending strength was tested on 8 concrete flags according to EN 1339:2004. Table 6. shows the mean values of bending strength of concrete with SSA in relation to the reference mixture and the criteria prescribed by the standard. These results present a comparative analysis of the bending strength values exhibited by semi-dry concrete pavement flags with and without SSA incorporation. Across the specimens tested, the bending strength of the SSA-incorporated concrete (SDC-SSA1) ranged from 2.74 MPa to 3.22 MPa, with an average value of 3.01 MPa. Conversely, the bending strength of the reference concrete (SDC-R) varied between 2.64 MPa and 3.69 MPa, with an average of 3.31 MPa. These findings suggest that while there is a marginal reduction in bending strength with SSA incorporation, the difference in performance between the two types of concrete is not substantial. Furthermore, it’s essential to note that each individual bending strength result for the 8 pavement flags exceeds the minimum prescribed value of 2.8 MPa, meeting the required standard EN1339.

The results of testing the water absorption of concrete specimens with SSA are summarized in Table 8. Water absorption is expressed as a percentage of the specimen’s own weight, calculated as the difference between the mass of the water-saturated specimen and that of the dry specimen. It is observed that the mean water absorption across all samples from the SDC-SSA1 mixture exceeded the threshold specified by standard EN 1339, which dictates that no finished precast concrete element may have a water absorption exceeding 6% by mass. In contrast, the control mixture SDC-R exhibited an average water absorption of 5.3%, which falls below the standard threshold. These findings suggest a correlation between the elevated water absorption in concrete specimens containing SSA and the inherently high water absorption of the SSA material itself.

Table 7 Comparison of bending strength values of semi-dry concrete pavement flags incorporating SSA1 and control values after 28 days

Semi-dry concrete pavement flags ID with SSA incorporation	**Bending strength** [MPa]	**Semi-dry concrete pavement flags without SSA incorporation**	**Bending strength** [MPa]
SDC-SSA1/C1	3.07	SDC-R/S1	3.5
SDC-SSA1/C2	2.89	SDC-R/S2	2.64
SDC-SSA1/C3	2.92	SDC-R/S3	2.76
SDC-SSA1/C4	3.22	SDC-R/S4	3.64
SDC-SSA1/C5	2.93	SDC-R/S5	3.18
SDC-SSA1/C6	2.74	SDC-R/S6	3.65
SDC-SSA1/C7	3.12	SDC-R/S7	3.39
SDC-SSA1/C8	3.17	SDC-R/S8	3.69
SDC-SSA1/C average	**3.01**	**SDC-R/S average**	**3.31**

Table 8 Total water absorption of samples with SSA and control mix

Mix ID		**SDC-SSA1**	**SDC-R**
Total water absorption W_a [%]	Specimen 1	9.3	5.3
	Specimen 2	9.8	5.4
	Specimen 3	9.8	5.2
	$\mathbf{W_{a,\ mean\ value}}$	**9.6**	**5.3**

4 Conclusions

In this study, the behaviour of SSA was characterised to introduce an alternative raw material in precast concrete elements as a partial aggregate substitute, simultaneously addressing the issue of waste disposal. The potential of utilising SSA in concrete pavements was evaluated in accordance with the EN 1339 standard and the constraints imposed by concrete manufacturer. Based on the data related to compressive and bending strength, water absorption of concrete with SSA, several conclusions can be drawn, which can be used as references for future experimental work based on the investigations carried out. Utilization of SSA as a partial substitute for sand unfavourably altered the compressive strength of concrete as well as water absorption, while the reduction in bending strength was marginal. However, the decrease in compressive strength values and the increase in water absorption are not solely attributed to the incorporation of SSA; they are also influenced by the industrial setting, which may require further adjustment when introducing new components. When integrating SSA into concrete, it's crucial to consider the intended final application and the specific requirements of the end product. Attention should be focused on fine-tuning the concrete mix design, which includes determining the suitable amount and type of additives, to guarantee optimal performance and achieve the desired properties. Furthermore, the environmental impact of introducing SSA as an alternative raw material in precast concrete production was positively linked to the immobilization of heavy metals within the mineral matrix.

Acknowledgment

The findings presented within this paper were obtained as part of the scientific project ‘Ash-Cycle – Integration of Underutilized Ashes into Material Cycles by Industry - Urban Symbiosis’.

References

[1] Jamshidi, A., Jamshidi, M., Mehrdadi, N., et al.: Mechanical performance of concrete with partial replacement of sand by sewage sludge ash from incineration, Materials Science Forum, 730–732 (2013), pp. 462–467, DOI: /10.4028/www.scientific.net/MSF.730-732.462

[2] Feitosa, M.C.A., Ferreira, S.R.M., Delgado, J.M.P.Q., et al.: Use of Sewage Sludge for the Substitution of Fine Aggregates for Concrete, Journal of Composites Science, 7 (2023) 1, DOI: 10.3390/jcs7010021

[3] Lynn, C.J., Dhir, R.K., Ghataora, G.S. et al.: Sewage sludge ash characteristics and potential for use in concrete, Construction and Building Materials, 98 (2015), pp. 767–779, DOI: 10.1016/j.conbuildmat.2015.08.122

[4] Zabielska-Adamska, K.: Sewage sludge bottom ash characteristics and potential application in road embankment, Sustainability, 12 (2020) 1, DOI: 10.3390/SU12010039

[5] Chang, Z., Long, G., Zhou, J.L. et al.: Valorization of sewage sludge in the fabrication of construction and building materials: A review, Resources, Conservation and Recycling, 154 (2020) 104606, DOI: 10.1016/j.resconrec.2019.104606

[6] Ordinance on the abolition of the waste status, Narodne Novine, 55 (2023) 53–64

[7] EN 1339:2004 Concrete paving flags - Requirements and test methods, 2004.

[8] Vouk, D., Majetić, V., Bubalo, A. et al.: The importance of the synergy of economy and science in increasing the sustainability of waste disposal within the framework of the circular economy, Hrvatski graditeljski forum, pp. 157-178, Zagreb, 2.12.2022.

[9] Bubalo, A., Vouk, D., Stirmer, N. et al.: Use of sewage sludge ash in the production of innovative bricks - An example of a circular economy, Sustainability, 13 (2021) 6, DOI: 10.3390/su13169330

[10] Carević, I., Štirmer, N., Trkmić, M. et al.: Leaching characteristics of wood biomass fly ash cement composites, Applied Science, 10 (2020) 23, DOI: 10.3390/app10238704

[11] Jurić Kostanić, K.: Razvoj metodologije za primjenu pepela drvne biomase u betonu, University of Zagreb, 2021.