Mineral Waste Into Alkali-Activated Pavements

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The study highlights the pressing need to recycle mineral waste to mitigate resource depletion and environmental damage. It focuses on creating sustainable pavement slabs through alkali activation, using a variety of waste materials such as bio-ash, local slags and mineral wool. Through extensive testing of different mix designs, the optimal mixture was identified: bio-ash, ladle slag, and metakaolin, activated with sodium silicate. This combination demonstrated good mechanical properties and showed low concentrations of toxic elements in leaching tests, confirming environmental safety. The research also prioritized energy efficiency, with the curing process conducted at room temperature and demolding after just one day. A test field at Termit d.d. was established to assess the practical application and potential for commercial use of these innovative paving materials, aiming to support a circular economy by extending the lifecycle of resources.

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1 Introduction

Alkali-activated materials (AAMs) are sustainable binders produced by activating industrial by-products such as slag and various ashes with alkaline solutions. They offer an environmentally friendly alternative to conventional cement, reducing carbon emissions while ensuring high strength and durability. Alkali-activated pavements must have high compressive and bending strength to withstand heavy loads and traffic. Durability is essential, with resistance to abrasion, chemical attack and freeze-thaw cycles ensuring long-term performance. They should have low permeability to prevent water ingress and avoid moisture damage. Appropriate surface texture and slip resistance are critical for safety, while thermal stability and minimal shrinkage help maintain structural integrity. In addition, these coverings should align with sustainability goals by containing industrial by-products and reducing environmental impact.

The durability of concrete is largely influenced by the properties of its pore structure and the extent of cracking. The ability of water, chloride ions, carbon dioxide, acids (including chlorides) and sulfates to penetrate the pavement directly affects its long-term performance and resistance to degradation (Mohd Tahir et al., 2022). When it comes to alkali-activated pavements, research studies mainly use ground granulated blast furnace slag (GGBFS) and fly ash (FA) as base materials and activate them with sodium silicate/sodium hydroxide (Girish et al., 2018; Girish et al., 2017; Badkul et al., 2022; Marathe et al., 2021; Phummiphan et al., 2018). Pavement construction promotes the development of special concretes with reduced cement content, which are produced from inexpensive raw materials and exhibit high early strength and improved durability, fatigue strength and shrinkage resistance. However, there is a lack of knowledge about the long-term performance of AAM, especially in terms of durability and AAM produced with unconventional raw materials (Rambabu et al., 2022).

Some studies have already described the production of alkali-activated paving slabs, but not all studies focus on the durability aspects. The study by Frankovič et al. used copper slag mixed with GGBFS and activated with a K-based alkali silicate solution. The results of splitting tensile strength, abrasion resistance, slip and skid resistance, freeze-thaw resistance and freeze-thaw resistance in the presence of de-icing salts show comparable results to those of commercially available concrete pavers. In

addition, certain properties (e.g. abrasion resistance, freeze-thaw resistance and freeze-thaw resistance in the presence of de-icing salts) were significantly better (Frankovič et al., 2020). Another study shows that a significant increase in pavement quality can be achieved by increasing the activator concentration and the GGBFS/FA content. However, an increase in the activator concentration above 12 M and a GGBFS content of over 28% did not show any significant effects (Badkul et al., 2022). By using GGBFS and FA in a weight ratio of 75:25 and recycled concrete aggregates, the desired mechanical strength and durability of the pavements were achieved, but only when up to 50% recycled aggregates were used (Marathe et al., 2021). The comparison of metakaolin (MK)-based concrete and Portland cement concrete shows comparable performance with higher stiffness and resistance to surface abrasion in the fuel resistance test (Eisa et al., 2022). In the study by Hossiney et al. alkali-activated pavers were produced using FA, GGBFS, NaOH, sodium silicate, natural aggregates and recycled asphalt aggregate (RAP), with 0, 25, 50 and 75% replacement of natural aggregates by weight. The tests showed that RAP reduced the compressive strength and abrasion resistance, but still met the standards for pedestrians and non-motorised road users. In addition, the use of RAP aggregates reduced production costs by up to 25.8% (Hossiney et al., 2020). Rambabu et al. investigated alkali-activated concrete for road pavements using low calcium FA partially replaced by 30% GGBFS, using an 8 M NaOH solution and curing at room temperature. Key tests included mechanical properties, abrasion resistance, shrinkage strain and microstructural analysis, as well as fatigue life comparison with Pavement Quality Concrete (PQC). The mixture of 70% FA and 30% GGBFS achieved optimum results after 28 days with a compressive strength of 45.7 MPa, a splitting tensile strength of 3.8 MPa and a bending strength of 4.6 MPa, while the shrinkage strains after 90 days were 31% lower than with PQC (Rambabu et al., 2024).

In the present work, various local mineral wastes (bio-ash, slag, waste stone wool) were used to develop and optimize a mix design for alkali-activated pavers. Through trial and error approach, many different mixes (pastes and mortars) were produced and the most suitable mix was selected based on mechanical properties, visual appearance and durability (freeze-thaw test, leaching test). Testing field was made to evaluate the long-term stability of the prepared pavements.

2 Materials and methods

Sample preparation

Various precursors (three bio-ashes labelled as B5, B6 and B7, ladle slag labelled as LS, waste stone wool labelled as SW and metakaolin labelled as MK) were selected as testing precursors for alkali-activated paving stones. The SW used for alkali-activation was first ground in a vibrating disc mill (Siebtechnik) and then sieved to below 63 μm. LS and three bio-ashes were sieved below 250 μm to remove larger particles such as pebbles, wood, etc. MK was used as received.

The alkali-activated paste was prepared by manually mixing different precursors and adding sodium silicate stepwise for 10 minutes. Sodium silicate Silvez (mining company Termit, 11.9% Na_2O and 28.5% SiO_2, M_{SiO_2/Na_2O} = 2.5) was used for alkali activation. After mixing, the slurry was poured into silicone or urethane rubber moulds. All samples were cured at room temperature in closed PVC bags to prevent dehydration.

Analysis of the precursors and AAMs

All precursors were characterised based on their chemical and mineralogical composition using X-ray fluorescence (XRF) and X-ray powder diffraction (XRD). All samples used for XRF and XRD analysis were ground using the disc vibrating mill (Siebtechnik) and sieved below 125 μm.

The loss on ignition (LOI) was determined at 950 °C. XRF analysis (XRF; Thermo Scientific ARL Perform'X Sequential XRF) was performed on melt beads prepared with Fluxana(s) (FX-X50-2, lithium tetraborate 50% / lithium metaborate 50%) to a lower melting point and with the addition of LiBr(l) (prepared from 50 ml H_2O and 7.5 g LiBr(s) from Acros Organics) to prevent the melt from sticking to the platinum vessel. The measured data were characterised using UniQuant 5 software. The chemical analyses of the measured samples are listed in Table 1.

Table 1: Chemical composition determined by XRF analysis.

	LS (wt%)	SW (wt%)	MK (wt%)	B5	B6	B7
Na_2O	-	2,14		1,02	0,41	0,79
MgO	8,11	11,5	0,17	4,56	0,64	5,58
Al_2O_3	21,8	18,5	44,4	7,28	32,1	10,6
SiO_2	17,2	38,6	52,2	39,0	10,9	37,8
SO_3	1,57	0,02	-	0,76	4,09	0,14
K_2O	-	0,80	1,30	3,01	2,21	6,34
CaO	47,5	15,8	0,07	29,4	17,7	23,6
Other oxides	1,22	2,14	1,41	2,20	2,20	4,48
LOI	-	3,28	0,63	9,38	23,4	5,39

The mineralogical analysis (XRD analysis, Empyrean PANalytical X-ray diffractometer, Cu X-ray source) was performed using the X'Pert Highscore plus 4.1 software. Rietveld refinement was performed using the external standard corundum NIST SRM 676a to determine the amount of amorphous phase and minerals in the waste materials. The amount of amorphous phase is listed in Table 2.

Table 2: The amount of amorphous phase in the precursors used for alkali activation.

Sample	Amount of amorphous phase (wt%)
Ladle slag (LS)	31.9
Stone wool (SW)	99.7
Metakaolin (MK)	57.0
Bioash 5 (B5)	63.0
Bioash 6 (B6)	59.5
Bioash 7 (B7)	74.7

Measurements of the bending and compressive strength of AAMs were carried out using a compressive and bending strength testing machine (ToniTechnik ToniNORM) after 28 days of curing at room temperature.

The presence of toxic elements in the leachate was assessed after 28 days in accordance with the European standard SIST EN 12457-2 (SIST, 2002). The AAM was crushed to a particle size of less than 4 mm and placed in a glass bottle with deionized water, using a mass ratio of solid to liquid of 1:10. The suspensions were rotated around the vertical axis for 24 hours at room temperature and then filtered to a particle size below 0.45 μm. The filtered solution was acidified to a pH value below 2. All prepared solutions were used to determine the amount of released metals using an inductively coupled plasma mass spectrometer (ICP-MS, Agilent

7900). The results were compared with the total amount of toxic trace and trace elements measured in the preliminary stage and with the figures from the legislation (Decree on the landfill of waste (Official Gazette of Republic Slovenia, 2014) and Decree on waste (Official Gazette of Republic Slovenia, 2022)).

The durability of the prepared mortars under cold weather conditions was tested using the freeze–thaw test (the test was modified from the standard for roof tiles SIST EN 539-2/2013 and for concrete pavers ETAG 004). The samples were dried at 110 °C, weighed and examined for defects. They were then gradually immersed in water over a period of 5 days. After the coverings were fully immersed, they were soaked for a further 72 hours, then removed and weighed. They were then subjected to 150 freeze–thaw cycles, with the temperature operated in a range of (−16 ± 1) °C to (+ 17 ± 1) °C and the humidity in a range of 10% to 95% according to the standard procedure. In each cycle, the temperature of the samples is decreased from + 17 °C to 1 °C in 20 minutes, then from + 1 °C to -3 °C in 40 minutes, then from −3 °C to -16 °C in 1 hour and the temperature is maintained, then increased to 5 °C in 20 minutes, and then to + 17 °C in 30 minutes. The samples were tested at 30, 90 and 150 cycles. The samples were examined for cracks and other surface damage (spalling, flaking, peeling), delamination, fractures, structural damage etc. After 150 cycles, the samples were evaluated by visual observations for any change in surface properties and any deformation at the edges of the samples is also reported.

Pilot production

At Termit d.d., a separate area was set up for the machines and materials needed for the pilot production of paving stones. The main equipment included a machine for preparing the solid parts (a mixer for dry components), a dissolver mixer (R60, 1999, 2 kW) for batches of up to 50 kg, molds for shaping, a mobile frame for curing and a vibrating table (0.40 x 0.35 m, 0.18 kW) for compacting the mixture. The laboratory equipment included an electronic balance (EOB 35K10) for precise measurements and a slump test setup to assess the consistency of the slurry. Bending and compressive strength measurements were taken for each batch after 28 days of curing at room temperature.

Figure 1: Mixer for the production of mixes selected for the production of pavements slabs (wet mix).

3 Results and discussion

Mix design development

Many different mix designs were prepared (mixes with different mechanical properties, all cured at room temperature). Further selection was based on the workability of the mixture, the mechanical properties, the visual appearance of the cured samples (e.g. efflorescence, curvature, disintegration in water, etc.) and the concentrations of toxic elements (determined by the leaching tests). The prepared mixtures (pastes and mortars) are listed in Tables 3 and 4.

The mechanical properties of all the mixtures produced (pastes and mortars) were measured and the results are shown in Figures 2 and 3. The combination of different bio-ashes and a small amount of LS resulted in compressive strengths below 20 MPa and bending strengths around 10 MPa or below (Figure 2). The mechanical properties increase with the increase in LS and the addition of MK. Mixture Z (B7 with a combination of MK) shows the highest compressive strength (50.8 MPa), while the highest bending strength is exhibited by mixture AC (21.1 MPa).

Table 3: Various pastes prepared using three different bio-ashes (B5, B6 and B7), SW, LS, MK and sodium silicate as alkali activator.

Mass (g)	B5	B6	B7	SW	LS	MK	Alkali activator
Mixture A	100	25	25	/	/	/	80
Mixture A	100	25	/	/	25	/	80
Mixture C	100	/	25	/	25	/	80
Mixture D	/	50	50	/	50	/	80
Mixture E	25	100	25	/	/	/	80
Mixture F	/	100	25	/	25	/	80
Mixture G	25	100	/	/	25	/	80
Mixture H	25	25	100	/	/	/	80
Mixture I	/	25	100	/	25	/	80
Mixture I	25	/	100	/	25	/	80
Mixture K	25	25	/	/	100	/	80
Mixture L	/	25	25	/	100	/	80
Mixture M	25	/	25	/	100	/	80
Mixture N	50	/	/	/	50	50	80
Mixture O	/	50	/	/	50	50	80
Mixture P	/	/	50	/	50	50	80
Mixture R	25	25	25	/	25	50	80
Mixture S	25	25	/	/	50	50	80
Mixture Š	/	25	25	/	50	50	80
Mixture T	25	/	25	/	50	50	80
Mixture U	50	/	/	/		100	80
Mixture V	/	50	/	/		100	80
Mixture Z	/	/	50	/		100	80
Mixture Ž	25	25	25	/		75	80
Mixture X	50	/	50	/		50	80
Mixture Y	75	/	/	25		50	80
Mixture	50	/	25	25		50	80
Mixture	25	/	50	25		50	80

Table 4: Various mortars prepared using bioash B5, MK, LS, cement, aggregate (0-2 mm) and sodium silicate as alkali activator.

Masa (g)	B5	MK	Agreg	Cement	LS	Alkali
Mixture AD	30	30	80	10	/	80
Mixture AE	30	50	60	10	/	80
Mixture AF	30	30	70	20	/	80
Mixture AG	30	30	60	30	/	80
Mixture AH	30	30	50	40	/	80
Mixture AI	50	40	50	10	/	80
Mixture AI	50	40	40	20	/	80
Mixture AL	50	30	50	20	/	80
Mixture AM	50	20	50	30	/	80
Mixture AO	30	50	60	/	10	80
Mixture AP	30	50	50	10	10	80
Mixture AR	30	50	50	/	20	80
Mixture AS	30	50	40	/	30	80
Mixture AŠ	30	60	50	5	5	80
Mixture AT	30	60	40	10	10	80
Mixture AU	30	80	30	/	10	80
Mixture AV	30	40	30	10	40	80

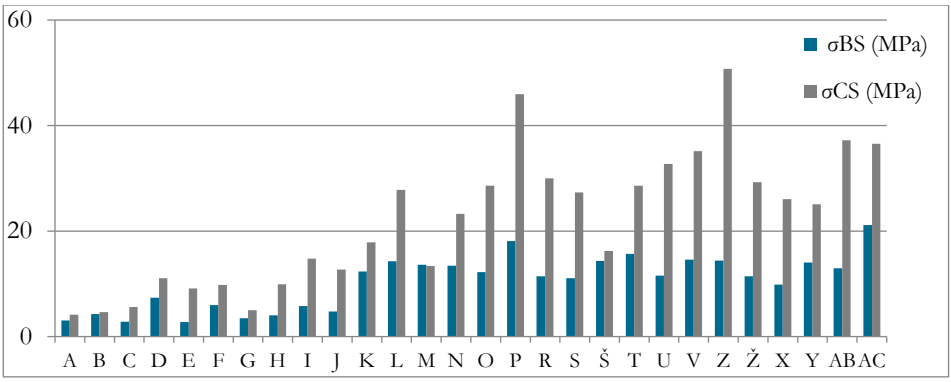

Figure 2: Mechanical properties of prepared pastes.

Compressive strengths of around 20 MPa and bending strengths in the range of 4.7-8.6 MPa were measured with the AD-AO mortar mixtures (Figure 3). Cement was added in all cases, except in mix AO, where LS was added instead of cement. In the AP-AV mixes, LS was added in addition to B5, MK and aggregate. In some cases, however, a small amount of cement was also added (AP, AŠ, AT and AV). The compressive strength increased to around 30 or even over 40 MPa (mixture AS), while bending strength was around 10 MPa (Figure 3).

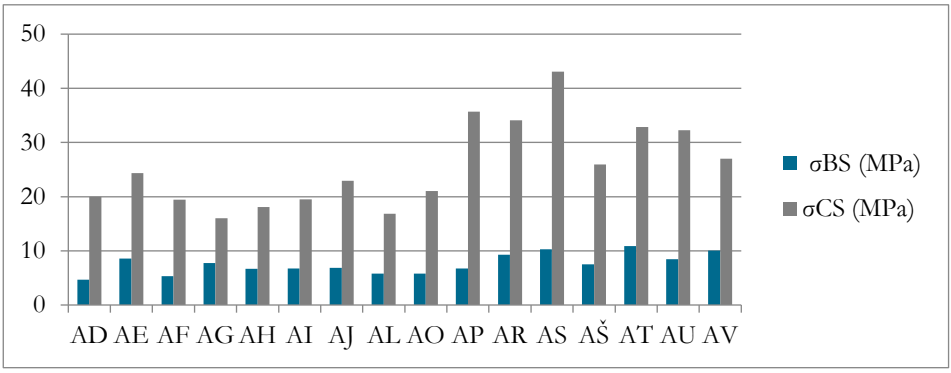

Figure 3: Mechanical properties of prepared mortars.

After measuring the compressive and bending strength, all samples were placed in water to see if they were stable or degraded under water conditions (Figure 4). If the samples showed signs of degradation, efflorescence or strong leaching of alkalis, indicated by the formation of a gel-like solution, these samples were excluded from

further testing. Some samples showed a coloured solution, probably due to the presence of organic compounds in the mixture.

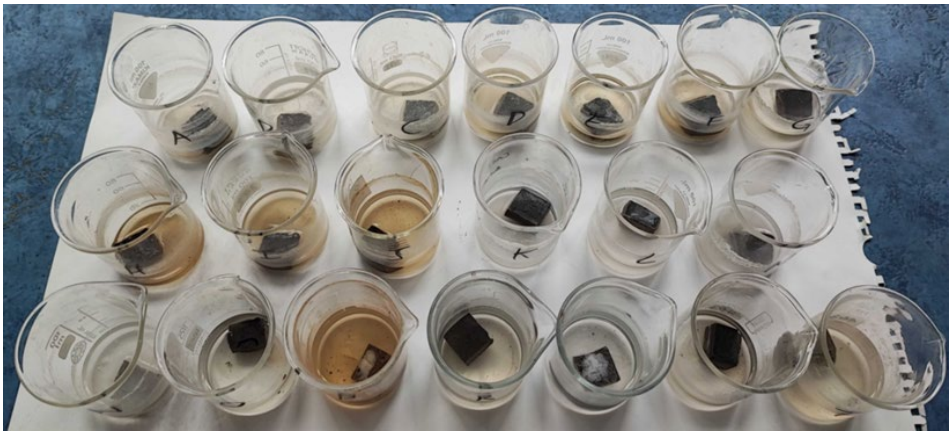

Figure 4: Various samples were placed in water to test the initial water resistance of the prepared samples.

Based on the consistency of the mixture and curing time, mechanical properties and water resistance test (visual appearance of the sample after exposure to water), samples with good mechanical properties, no degradation in water, no efflorescence and no curvature were selected for leaching experiments to evaluate environmental acceptability.

Leaching tests

Leaching tests were first carried out to assess the environmental acceptability of the raw materials used. Table 5 shows the concentrations of toxic elements in the leachates of the starting materials. The concentrations for Cr, Mo, Ba, As and Pb in some samples were above the permissible limits for inert waste (taking into account the Directive on the landfill of waste with the establishment of criteria for the acceptance of waste in landfills) and/or the Slovenian Decree on Waste. However, the leaching potential of AAMs may differ from the leaching of elements from precursors.

Table 5: Concentrations of toxic elements in the leachates of various precursors. Red numbers indicate that the concentrations of the elements have exceeded the limits specified in the legislation (values in grey).

mg/kg	Cr	Co	Ni	Cu	Zn	As	Se	Mo	Cd	Sb	Ba	Hg	Pb
B5	0.826	0.006	0.011	0.043	0.110	0.000	0.027	0.669	<0.002	<0.001	8.091	<0.001	0.768
B6	0.308	0.011	0.006	0.022	0.002	0.525	0.480	6.546	0.007	0.004	1.379	<0.001	0.006
B7	0.416	0.006	0.008	0.076	0.390	0.001	0.006	0.294	<0.002	<0.001	57.11	<0.001	0.213
MK	0.001	<0.002	<0.002	0.006	<0.002	0.008	<lod	0.063	<0.002	<0.001	<0.002	<0.001	0.002
C42.5	17.04	0.028	0.007	0.084	0.048	<0.001	0.059	0.911	<0.002	<0.001	7.166	<0.001	0.106
SW	0.013	<0.002	0.008	0.025	0.002	0.015	0.003	0.024	<0.002	0.002	0.015	<0.001	0.001
LS	<0.002	<0.002	<0.002	<0.001	0.007	0.001	0.203	<0.002	<0.002	<0.001	14.24	<0.001	<0.005
Decree on waste	0.5	0.03	0.4	0.5	2.0	0.1	0.6	0.5	0.025	0.3	5.0	0.005	0.5
Inert waste	0.5	/	0.4	2.0	4.0	0.5	0.1	0.5	0.04	0.06	20.0	0.01	0.5
Non-hazardous waste	10.0	/	10.0	50.0	50.0	2.0	0.5	10.0	3	0.7	100.0	0.20	10.0

Table 6: Concentrations of toxic elements in the leachates of various pastes. Red numbers indicate that the concentrations of the elements have exceeded the limits specified in the legislation (values in grey).

mg/kg	Cr	Co	Ni	Cu	Zn	As	Se	Mo	Cd	Sb	Ba	Hg	Pb
Mixture K	0.506	0.008	0.008	0.112	0.021	5.225	0.719	6.242	0.006	0.102	0.019	<0.002	0.002
Mixture N	0.304	0.002	0.005	0.021	<0.002	0.422	0.112	1.650	0.001	0.062	0.037	<0.002	0.003
Mixture S	0.316	0.005	0.027	0.028	0.010	12.63	0.262	3.380	0.003	0.177	0.045	<0.002	0.009
Mixture L	0.503	0.010	0.013	0.090	0.009	5.567	0.424	5.956	0.005	0.104	0.020	<0.002	0.001
Mixture R	0.343	0.004	0.026	0.041	0.005	15.05	0.959	2.679	0.002	0.249	0.110	<0.002	0.058
Mixture T	0.332	0.003	0.020	0.032	<0.005	0.490	0.084	2.045	0.001	0.066	0.048	<0.002	0.004
Decree on waste	0.5	0.03	0.4	0.5	2.0	0.1	0.6	0.5	0.025	0.3	5.0	0.005	0.5
Inert waste	0.5	/	0.4	2.0	4.0	0.5	0.1	0.5	0.04	0.06	20.0	0.01	0.5
Non-hazardous waste	10.0	/	10.0	50.0	50.0	2.0	0.5	10.0	3	0.7	100.0	0.20	10.0

When testing the leaching concentrations of toxic elements produced from selected AAMs (pastes), some elements exceeded the limit values (e.g. Cr, As, Se and Mo) (Table 6). As and Se in the case of mixture R are even above the limit values for non-hazardous waste. Based on these results, additional mixtures were produced to reduce these concentrations.

The addition of a small amount of cement significantly reduced the leaching of Se and Mo, as well as that of As, but on the other hand an increase in Cr was observed (Table 7). Toxic metals can be immobilised by sorption in C-S-H (including physical and chemical adsorption (Chen et al., 2009)) or by ion substitution in ettringite (Glasser, 1997). In cement, however, Mo could also be immobilised in the form of powellite ($CaMoO_4$) (Diaz Caselles et al., 2021; Minocha and Goyal, 2013). Although we were able to significantly reduce the high As concentrations in some samples, the addition of cement still resulted in a slight increase in As in all samples analysed (Table 7). The study by Wang et al. suggests that the addition of $Ca(OH)_2$ to calcined clay enables the hydration of clay minerals with efficient immobilisation of As and Pb by physical encapsulation (Wang et al., 2019). Bothe and Brown also suggested the addition of lime to reduce the mobility of As through the formation of poorly soluble Ca–As precipitates (Bothe and Brown, 1999). However, a high amount of lime is required, which affects the acceleration of hydration and thus shortens the setting time and increases the rate of early strength development. Based on our previous experiments (Pavlin et al., 2022), the presence of lime has a strong influence on workability and due to the fast setting time, it is sometimes almost impossible to mould the mixture.

A modification of the mixture was necessary to reduce the concentrations of Cr and As. Therefore, some additional mixtures were prepared in which we reduced the amount of cement or even removed it from the mixture. Six samples (AP, AR, AS, AŠ, AT and AU) were selected for leaching tests on the basis of their mechanical properties and appearance (no curvature, no efflorescence, no decomposition on contact with water). Due to the Mo concentrations in the leachates of the mixtures AP, AR, AS and AT, which were above the limits specified in the Slovenian Decree on waste, we selected the mixtures AŠ and AU for further testing (yellow colour in the Table 8). The mixture AŠ contains a small amount of cement, the mixture AU does not. As can be seen in Table 8, we have significantly reduced the amount of Cr, while the concentration of As is still slightly above the limit values of the Slovenian Decree on waste.

Table 7: Concentrations of toxic elements in the leachates of various mortars. Red numbers indicate that the concentrations of the elements have exceeded the limits specified in the legislation (values in grey).

mg/kg	Cr	Co	Ni	Cu	Zn	As	Se	Mo	Cd	Sb	Ba	Hg	Pb
Mixture AE	3.579	0.004	0.051	0.122	0.114	0.465	0.021	0.292	0.001	0.126	0.207	0.003	0.197
Mixture AD	3.325	0.003	0.039	0.111	0.078	0.463	0.022	0.301	0.001	0.155	0.136	0.003	0.108
Mixture AI	3.436	0.003	0.025	0.094	0.092	0.487	0.023	0.350	0.001	0.179	0.172	0.002	0.115
Mixture AL	6.903	0.002	0.008	0.054	0.024	0.574	0.031	0.502	0.001	0.255	0.081	0.002	0.025
Mixture AJ	6.791	0.002	0.008	0.046	0.053	0.568	0.029	0.491	0.001	0.230	0.092	0.002	0.024
Mixture AF	6.779	0.003	0.017	0.056	0.016	0.558	0.032	0.445	0.001	0.221	0.090	0.002	0.038
Decree on waste	0.5	0.03	0.4	0.5	2.0	0.1	0.6	0.5	0.025	0.3	5.0	0.005	0.5
Inert waste	0.5	/	0.4	2.0	4.0	0.5	0.1	0.5	0.04	0.06	20.0	0.01	0.5
Non-hazardous waste	10.0	/	10.0	50.0	50.0	2.0	0.5	10.0	3	0.7	100.0	0.20	10.0

Table 8: Concentrations of toxic elements in the leachates of selected mortars. Red numbers indicate that the concentrations of the elements have exceeded the limits specified in the legislation (values in grey).

mg/kg	Cr	Co	Ni	Cu	Zn	As	Se	Mo	Cd	Sb	Ba	Hg	Pb
Mixture AP	0.503	0.002	0.023	0.175	<0.002	0.582	0.068	0.686	<0.001	0.155	0.109	0.003	0.115
Mixture AR	0.201	0.002	0.029	0.059	<0.002	0.553	0.032	0.887	<0.001	0.099	0.134	0.003	0.106
Mixture AS	0.248	0.001	0.025	0.064	<0.002	0.583	0.038	1.242	<0.001	0.093	0.072	0.003	0.058
Mixture AŠ	0.268	0.002	0.051	0.110	<0.002	0.496	0.046	0.353	<0.001	0.114	0.247	0.003	0.328
Mixture AU	0.204	0.003	0.030	0.127	0.112	0.471	0.055	0.433	<0.001	0.101	0.567	0.002	0.642
Mixture AT	0.581	0.002	0.039	0.057	<0.002	0.598	0.063	0.697	<0.001	0.146	0.120	0.005	0.109
Decree on waste	0.5	0.03	0.4	0.5	2.0	0.1	0.6	0.5	0.025	0.3	5.0	0.005	0.5
Inert waste	0.5	/	0.4	2.0	4.0	0.5	0.1	0.5	0.04	0.06	20.0	0.01	0.5
Non-hazardous waste	10.0	/	10.0	50.0	50.0	2.0	0.5	10.0	3	0.7	100.0	0.20	10.0

Freeze-thaw test of selected samples AŠ and AU

Before we started pilot production, freezing and thawing tests was carried out to test the pavers' resistance to outdoor environmental conditions. The first step was to test water absorption. Less water was absorbed in the AU mix (Table 9). However, no damage occurred during freezing and thawing in either mixture or the loss of mass was lower in the AŠ mixture. It follows that both tested samples (Figure 5, mixtures AŠ-left and AU-right) pass the test of 150 freeze-thaw cycles. As we want to produce a low-carbon product, the AU mixture was chosen for the pilot production as it does not contain cement.

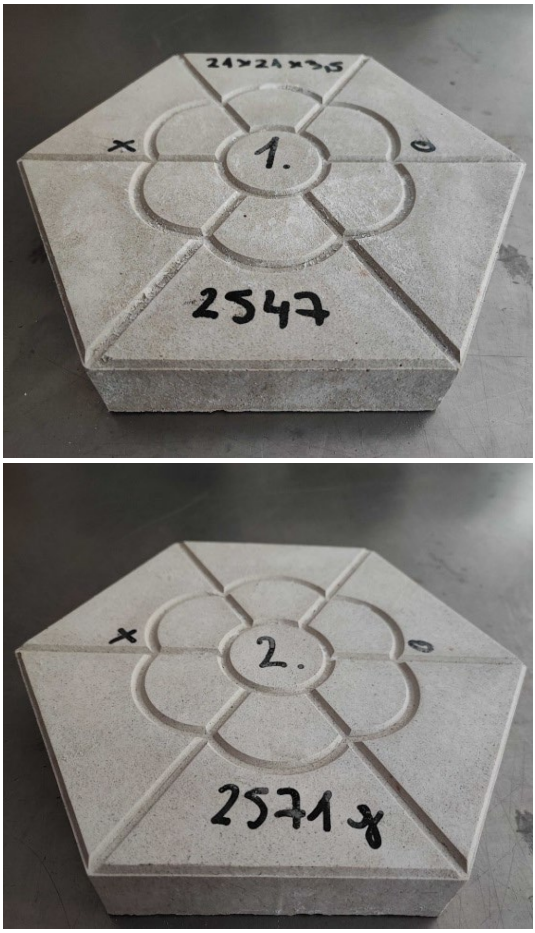

Figure 5: Pavements of mixtures AŠ (left) and AU (right) after freeze-thaw testing.

Table 9: Freeze-thaw test.

Sample	Water absorption			Mass loss during frezze-thaw test (g)	Desription of damage
	m_0 (g)	m_1 (g)	w_a (%)		
1_AŠ	2547	2618	2,8	139	No damage
2_AU	2571	2629	2,2	164	No damage

Pilot production

The process began with the mixing of the dry components (quartz aggregate, MK, bio-ash and local slag), which were gradually added to a mixer with a glass of water and mixed for 10 minutes. The mixture is then poured into moulds, placed on a vibrating table for 5 minutes and left to harden for a day at room temperature and covered with the plastic bag. The next day, the pavers are demolded, placed on a rack and cured further at room temperature. Once 250 pavers had been produced, the test surface was prepared by levelling the ground, applying a crushed stone base layer compacted with a vibrating plate, spreading sand and laying the pavers. This area is used to test the performance and durability of the paving stones under real conditions.

Testing of mechanical properties (quality control of pilot production): Mechanical properties were measured after 28 days for each batch of prepared pavements. Figure 6 shows the compressive and bending strength of the mixtures produced in the pilot production. Although the same formulation was used each time, slight variations in the mechanical properties were observed during the production of the pavements.

Another quality control parameter for the pilot production was slump test. By performing the slump test, we assessed the consistency (workability) of the fresh alkali-activated concrete. Table 10 shows the measured diameters of the spread, which vary slightly between the different batches.

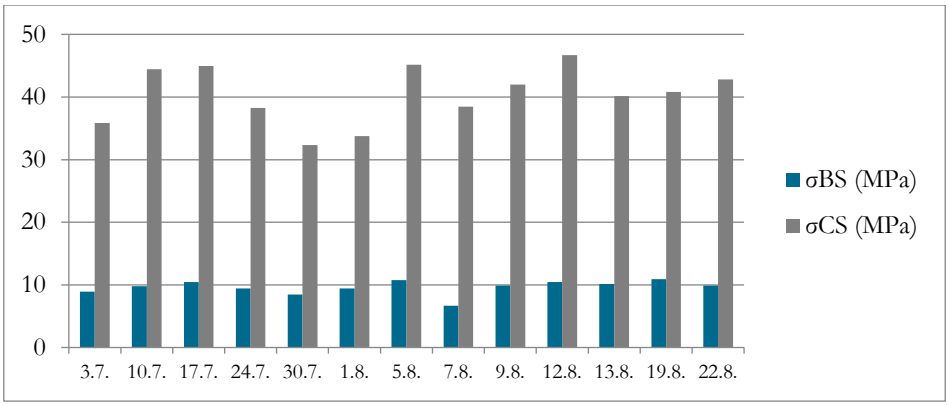

Figure 6: Quality control of the mechanical properties of prepared paving stones. Although the same material was used and the same sample preparation was carried out, there are some deviations due to the slight variations between the waste materials used in the alkali activation.

Table 10: Spread of the prepared mixture.

Sample (batch)	Slump test (mm/mm)
3. 7.	/
10. 7.	140/140
17. 7.	135/140
24. 7.	146/150
30. 7.	145/145
1. 8.	145/145
5. 8.	145/145
7. 8.	145/145
9. 8.	151/151
12. 8.	/
19. 8.	145/145
22. 8.	/

As can be seen in Figure 7 (left), the mixture was not so liquid that it could simply be poured into the molds, but we used our hands to pour the mixture into each mold. It should be emphasized that the mixture was not too dense and was easy to work with.

The final step was to create a test field in Termit d.d., as shown in Figure 7 (right). It provides a controlled environment to evaluate the performance of alkali-activated pavers under real-life conditions.

Figure 7: Filling the molds with the mixture AU (left) and testing field in the company Termit d.d. (right).

4 Conclusions

In this study a mix design for alkali-activated pavements slabs was successfully developed, taking into account critical parameters such as mechanical strength, durability and environmental acceptability. By using waste materials such as bio-ash, slag and mineral wool and testing different mix designs, the optimum formulation was determined. The selected mixture based on bio-ash, LS and MK activated with sodium silicate showed the desired mechanical properties, freeze-thaw resistance and low environmental impact. However, the mix design still needs to be optimised in the future to reduce two toxic elements (As and Pb) whose concentrations are slightly above the limit values. Curing was energy efficient at room temperature to reduce the CO_2 footprint. Further testing, including abrasion resistance and freezing in the presence of de-icing salt, will ensure product quality. The establishment of a test field at Termit d.d. is an important step towards the commercial application and long-term evaluation of these innovative paving solutions.

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The data presented in this study are openly available from the repository DiRROS at link: http://hdl.handle.net/20.500.12556/DiRROS-20951

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