Alkali-activated soapstone waste - Mechanical properties, durability, and economic prospects

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A B S T R A C T
Soapstone is a soft, magnesium-rich mineral widely used in the production of carved objects and architectural elements, for instance. The processing of soapstone causes the formation of significant amounts of waste powder, which is largely landfilled at the moment. The aim of the present study is to evaluate the suitability of soapstone waste as the main binder for the alkali-activation process using sodium silicate and hydroxide solutions as activators. The results demonstrate that soapstone alone reacts to some extent (compressive strength of 13 MPa at 28 day age), but mechanical properties are improved significantly after replacing 20% of soapstone by metakaolin (compressive strength of 31 MPa at 28 d age). The obtained mechanical properties are closely similar to those of virgin soapstone. Durability properties of the developed alkali-activated binders were similar or better than typical Portland cement-based binders in terms of high temperature, acid, and freeze-thaw resistance, and sorptivity. The material costs alkali-activated soapstone mortar were estimated as approximately 70 €/t. Thus, the results enable utilizing currently underexploited soapstone waste in a sustainable and economically interesting way.

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1. Introduction

Soapstone (also known as steatite or saponite) is relatively soft, magnesium-rich metamorphic rock largely composed of talc [1]. It is frequently used for carvings, sculptures, countertops, and architectural elements, to name just a few examples. However, the cutting and processing of soapstone produces a large amount of waste powder, which poses a disposal problem. For instance, in the production of dimension stones and other items in Brazil, 60 wt% of soapstone ends up as waste as the main binder for the alkali-activation process using sodium silicate and hydroxide solutions as activators. The results demonstrate that soapstone alone reacts to some extent (compressive strength of 13 MPa at 28 day age), but mechanical properties are improved significantly after replacing 20% of soapstone by metakaolin (compressive strength of 31 MPa at 28 d age). The obtained mechanical properties are closely similar to those of virgin soapstone. Durability properties of the developed alkali-activated binders were similar or better than typical Portland cement-based binders in terms of high temperature, acid, and freeze-thaw resistance, and sorptivity. The material costs alkali-activated soapstone mortar were estimated as approximately 70 €/t. Thus, the results enable utilizing currently underexploited soapstone waste in a sustainable and economically interesting way.

1. Soapstone

Soapstone (also known as steatite or saponite) is relatively soft, magnesium-rich metamorphic rock largely composed of talc [1]. It is frequently used for carvings, sculptures, countertops, and architectural elements, to name just a few examples. However, the cutting and processing of soapstone produces a large amount of waste powder, which poses a disposal problem. For instance, in the production of dimension stones and other items in Brazil, 60 wt% of soapstone ends up as waste and is disposed to landfills [2]. In Finland, some 110,000 tons of soapstone is produced annually (numbers from 2012) [3]. Of this amount, the generated waste is 60–75 wt%.

Consequently, there have been attempts to find uses for soapstone waste. One possibility is as a raw material in ceramics manufacturing [4,5]. Soapstone is also a potential oil spill sorbent due to the hydrophobicity of the talc it contains [6]. Ultrafine soapstone powder (d50 μm) is a suitable supplementary cementitious material that can replace up to 25% of Portland cement (PC) [7,8]. Another studied application is as the dispersed phase in composites containing PC as the binder [9]. Soapstone-containing PC mortars have been further supplemented with carbon fibers [10] or thermoset polymers [11] and used in the restoration of historical buildings. However, all of the above examples rely on either the use of high temperature (approximately 1000–1200 °C in ceramics production) or CO2-intensive PC as a co-binder, which decreases the environmental feasibility of the proposed utilization.

Alkali activation (or geopolymerization) is a promising route to utilize several mineral waste products in the manufacturing of low-carbon footprint concrete or ceramic-like products [12,13]. The most common method of alkali activation is to mix the solid raw materials (precursors) with a highly concentrated solution of alkali silicate and/or hydroxide at (near) room temperature. However, the precursor has to contain silicate and/or aluminate minerals, which are soluble at high pH. In the case of soapstone, the concentration of aluminum is low and silicon is (mainly) related to the presence of talc. The alkali-activation of talc has been attempted after grinding and dehydroxylation (at up to 1000 °C) but the reactivity was extremely low (possibly due to the 2:1 layer lattice structure of talc) and setting time long (3 d at 120 °C) [14]. Interestingly though, the alkali-activation of ultrafine soapstone (d50 = 2 μm) reportedly resulted up to 55 MPa compressive strength when using 16 M sodium hydroxide and sodium silicate solutions as activators and curing at 60 °C for 48 h [15].

In the present paper, soapstone waste powder as such and with metakaolin as a co-binder are studied as precursors for alkali activation. The mix design is optimized in terms of the strength development and binders are characterized for their chemical and mineralogical compositions, fresh and mechanical properties, durability, and drying shrinkage. Also, a preliminary economical evaluation is provided. The aim is to develop a method to turn currently underexploited soapstone waste into a useful material that could be utilized, for example, in similar
applications as primary soapstone (fireplace elements, tabletops, or tiles, for instance).

2. Materials and methods

2.1. Materials

Soapstone waste (Tulikivi Oyj, Finland) and metakaolin (Metamax; BASF, USA) were used as received. Their chemical compositions, loss on ignition (LOI), and particle size distributions are shown in Table 1. Standard sand [16], with particle size distribution between 0.08 and 2 mm, was used as aggregate throughout the experiments. The alkali activator consisted of sodium hydroxide pellets (~98%; VWR Chemicals) dissolved in water and sodium silicate solution (SiO₂ = 25.6–27.6 wt %, Na₂O = 7.5–8.5 wt%, molar SiO₂/Na₂O ≈ 3.5; VWR Chemicals). More details about the alkali activator composition are listed in Table 2.

2.2. Preparation of mortars

The studied mix designs are summarized in Table 2. Mortars were prepared by first mixing soapstone (with or without metakaolin) and sand for 3 min. Next, sodium silicate and hydroxide solutions were added, and mixing was continued for 6 min. Fresh mortar was cast in oiled molds (dimensions 40 × 40 × 160 mm³), and a jolting table was used for compacting. The mold was wrapped in plastic and kept at 60 °C for approximately 24 h. After that, specimens cured at 22 °C and 100% relative humidity until testing.

As the first step in the mix design development, the effect of the alkali activator solution’s silica modulus (R, molar ratio of SiO₂/Na₂O) was tested (samples IDs S100R1.0–S100R0.6 in Table 2). In these specimens, only soapstone was used as the binder. NaOH solutions with 8, 10, 12, 14, or 16 M concentrations (corresponding to silica modulus of approximately 1.0, 0.9, 0.8, 0.7, and 0.6, respectively, when mixed with sodium silicate) were prepared and employed as described above. The second step was to test the effect of the addition of 20% metakaolin (sample ID S80M20R0.9) using alkali activator SiO₂/Na₂O ≈ 0.9. Finally, in the third stage, samples with the sand/binder ratio 1 were prepared using S80M20R0.9 and S100R0.9 mixtures.

The addition of steel and basalt fibers was studied with the S80M20R0.9 (sand = 1) mix design. Steel fibers (Weidac, Germany) were 9 mm long and 0.18 mm diameter, had density of 7886 kg/m³, elastic modulus of 200 GPa, tensile strength ≥2200 MPa, and 3% elongation at break. Basalt fibers (Basaltex, Belgium) were 6 mm long and 0.018 mm diameter, had density of 2650 kg/m³, elastic modulus of 210 GPa, tensile strength of 2650 MPa, and 3% elongation at break. The amount of fibers added to the mixture was 0.5 or 1 volume-%.

2.3. Chemical characterization

The chemical compositions of soapstone and metakaolin were determined using a 4 kV wavelength dispersive X-ray fluorescence (XRF) spectrometer (AxiosmA; PANalytical). XRF analyses of fused samples were performed; 1.5 g of sample was melted at 1150 °C with 7.5 g of X-ray Flux Type 66:34 (%66% Li₂B₄O₇ and 34% LiBO₂) to obtain melt-fused tablets. LOI (at 950 °C) was determined using a thermogravimeter (prepASH; Precisa). Particle size distribution was determined with a Beckman Coulter LS 13320 laser diffraction particle size analyzer from samples dispersed in isopropyl alcohol.

Identification and quantification of crystalline phases were performed with powder X-ray diffraction (XRD) using a Rigaku Smartlab diffractometer (9 kW Cu X-ray source) in the range of 5–120° 2θ with 6°2θ/min scan speed. XRD analyses were performed of paste samples with 28 day aging. Before executing the analyses, the samples were pulverized using a Retch RS200 mill, and 10 wt% of rutile (≥99.9%; Aldrich) was added as an internal standard. Quantification of phases was performed using the Rietveld refinement method.

A field emission scanning electron microscope with an energy dispersive spectroscopy (SEM-EDS, Zeiss Ultra Plus; Zeiss) was used to take micrographs of hardened mortar intersections and to provide semi-quantitative information about the chemical composition. Analyses were conducted using a backscatter electron detector with 15 kV acceleration voltage and 8.5 mm working distance. The samples were prepared by casting specimens in epoxy resin (Buehler) and were polished with P120, P240, and P1200 abrasive grinding paper and ethanol flushing to reveal cross-sections. The samples were coated with carbon prior to measurement.

The solubility of silicon and magnesium was evaluated by placing 0.1 g of soapstone and 50 mL of 10 M NaOH in plastic centrifuge tubes and shaking the tubes at 60 °C up to 24 h. Solid material was separated by centrifuging (6000 rpm for 5 min), and supernatant was decanted for analysis with an optical emission spectrometer (IRIS Intrepid II XDL; Thermo Scientific).

Thermogravimetric analysis (TGA/DTG) of crushed S100R0.9 and S80M20R0.9 pastes were conducted by heating from 22 to 1000 °C at 5 °C/min in a nitrogen atmosphere to detect the changes in mass.

2.4. Fresh and hardened state properties

Fresh state properties were investigated in terms of initial and final setting times. These properties were estimated by keeping specimens...
at 22 °C or 60 °C and conducting a measurement once per hour with a Vicat apparatus (Vicatronic Matest).

Hardened state properties were addressed by the compressive and flexural strengths. The strength developments were determined by using a Zwick/Roell Z100 testing machine (with a load cell of 100 kN). Initially, the prismatic beams were assessed under flexural loading, and the broken half-specimens were used to evaluate the compressive strength. Loading rates were 50 N/s and 2.4 kN/s during the flexural and compressive strength tests, respectively, according to a standard [16].

Porosity was determined with the Archimedes method by applying a standard [17]. Dried and weighed samples were placed in a vacuum chamber, pressure was decreased to approximately 5 kPa for 2 h, and deionized water was added slowly. Samples were kept immersed under water for 24 h. Samples were then weighed as suspended in water and in saturated condition in air. Total and open porosities can be calculated according to Eqs. (1) and (2) (\(ms = \text{weight in saturated condition in air} \) [g], \(m_s = \text{dry sample weight} \) [g], \(m_h = \text{sample weight suspended in water} \) [g], \(\rho_h = \text{true density} \) [g/cm³], \(\rho_m = \text{density of water} \) [g/cm³]). True density was determined from a pulverized sample with a helium gas pycnometer (AccuPyc II 1340, Micromeritics).

Total porosity [%] = \( \left( \frac{m_s - m_h}{m_h} \times \rho_h \right) \times 100 \) (1)

Open porosity [%] = \( \left( \frac{m_s - m_h}{m_h} \right) \times 100 \) (2)

2.5. Durability characterization

Later, it will be presented and discussed that using metakaolin as a co-binder significantly improves the hardened state properties of alkali-activated soapstone binders, therefore, the mix S80M20R0.9 was used to assess the durability performance.

High temperature resistance was tested by keeping triplicate 50 × 50 × 50 mm² cubes (28 d age) at 350 °C, 500 °C, or 800 °C for 3 h. After exposure, the specimens were cooled at room temperature, and their compressive strength and mass change were measured.

The rate of water absorption (sorptivity) was tested by applying a standard method [2,18]. Four sides of a cube with an edge of 100 mm were covered with epoxy paint, leaving the top and bottom uncovered. The cube was placed in water so that the uncovered bottom surface was a maximum of 2 mm below the water surface. Before the test, the cube was conditioned at 50 °C for 3 d, and the weight was measured. During the test, the cube was weighted at 60 s, 5 min, 10 min, 20 min, 30 min, 60 min, 2 h, 3 h, 4 h, 5 h, 6 h, 1 d, 2 d, 3 d, 5 d, 7 d, and 9 d (the surfaces of the cube were wiped dry before weighing). The amount of absorbed water normalized by the cross-section area (I [mm]) was calculated based on Eq. (3) (\(I = \text{weight of specimen} \) [g], \(a = \text{exposed surface area} \) [mm²], \(d = \text{density of water} \) [g/mm³]) and plotted against the square root of time (s\(^{1/2}\)).

\[ I = \frac{m_t}{a \times d} \] (3)

An acid exposure experiment was conducted by immersing 50 × 50 × 50 mm³ cubes (28 d age) in 200 mL of 5% sulfuric acid or 5% acetic acid in a closed container. Before starting the test, specimens were flushed with deionized water, kept at 50 °C for 3 days, and weighed. After 1 d, 7 d, 14 d, and 28 d of exposure, samples were again flushed, dried, and weighed, and then fresh acid was placed in the containers. After 28 d of exposure, the compressive strength of the specimens was measured.

Freeze–thaw resistance was tested by applying a standard method [19]. Three 40 × 40 × 160 mm³ prisms (28 d age) were placed in a climate chamber, half exposed to water and half to air. In total, 120 freeze–thaw cycles were conducted. The temperature and duration of one cycle were from +20 to −15 °C and 6 h, respectively. After the test, the compressive and flexural strengths of the specimens were assessed.

2.6. Drying shrinkage

Shrinkage (i.e., unrestrained linear movement due to drying conditions) was determined by applying a standard method [20]. Three prismatic beams (40 × 40 × 160 mm³) with embedded studs were prepared as described in section 2.2. After approximately 24 h at 60 °C, they were moved to ambient conditions (average temperature and relatively humidity of 22 °C and 34%, respectively), and their dimensional stability was monitored for 51 days (until reading stabilized).

3. Results and discussion

3.1. Optimization of mix design

In terms of compressive and flexural strengths, the maximum was observed at the alkali-activator silica modulus of approximately 0.9 from the range of 0.6–1.0 when soapstone was used as a sole precursor (Fig. 1).

When 20% of soapstone was replaced by metakaolin (sample ID S80M20R0.9) and the sand/binder ratio was decreased from 2 to 1, the compressive and flexural strengths at the final age (56 d) improved from 11.0 to 31.9 MPa and from 4.4 to 9.5 MPa, respectively (Fig. 2). However, it appears that after 28 d there is no increase in the compressive or flexural strength. Compressive strength is lower than with typical metakaolin geopolymers cured at 60 °C (approximately 50 MPa at 28 d [21]) but it is still sufficient to enable use as construction materials [22]. Another comparison of the obtained results can be made to the results of Torres et al. [23], who used soapstone and kaolinite to prepare ceramic composites (hydraulic pressing at 35 MPa, drying at 60 °C for 72 h, and firing at 500–1200 °C for 2 h). They obtained only up to 10 MPa strength under the compressive loading. The flexural strength of the S80M20R0.9 mix (sand/binder = 1) is higher than with normal strength Portland cement concrete (approximately 3–6 MPa) [24] and is approximately similar to metakaolin geopolymer cured at 60 °C (approximately 8.5–11 MPa) [21]. Furthermore, as a comparison, virgin soapstone has compressive and flexural strengths of approximately 21 and 14 MPa, respectively, although they vary to some extent depending on the location [25].

The addition of steel or basalt fibers at 0.5 or 1 vol-% did not affect compressive or flexural strengths of the S80M20R0.9 mix (results not shown), which indicates a weak bond between the fibers and the binder matrix. Possibly some other fibre types could have improved the mechanical strength but steel and basalt were selected due to their temperature resistance (and thus a potential suitability for the fireplace element application). However, the addition of steel and basalt fibers decreased the shrinkage of samples clearly (see section 3.6).

3.2. Effect of thermal curing on setting time and strength development

The setting time of the S100R0.9 mix (only soapstone as the binder) was >7 d at 22 °C (100% RH). However, when the same mix was kept at 60 °C (100% RH), initial and final setting times were reached already at approximately 5 h and 6 h, respectively. In contrast, the mix with 20% metakaolin (S80M20R0.9) reached initial and final setting time at 75 min and 105 min, respectively, at 60 °C (100% RH). As a practical note, the S80M20R0.9 mix was possible to demold after 4 h at 60 °C, as it was completely hardened. At 22 °C (100% RH), the S80M20R0.9 mix required 6.2 h and 9.7 h for initial and final setting, respectively.

\[ \text{fl} \text{exural loadings, } \text{fl} \]
Curing at different temperatures had no great impact on the strength development of S80M20R0.9 after 7 days. The compressive and flexural strengths (7 d) were in practice similar regardless of temperature: 17 and 5 MPa, respectively, when cured at 60 °C and 15 and 4 MPa, respectively, when cured at 22 °C.

3.3. Solubility of silica and magnesium from soapstone

Only up to 9% and 4% of silicon and magnesium, respectively, were dissolved from soapstone in 10 M NaOH at 60 °C when mixed up to 24 h (see supplementary material, Fig. S1). The solid/liquid ratio was selected to be very low (2 g/L, that is, 0.0015 as w/w) to prevent an equilibrium formation. The low solubility of magnesium could be explained by its precipitation as Mg(OH)\textsubscript{2} at pH approximately over 9 [26]. However, these results indicate that soapstone dissolves slowly and to a relatively small extent in conditions used in alkali activation.

3.4. Microstructural analysis

Micrographs of S100R0.9 and S80M20R0.9 (Fig. 3) reveal a fundamental difference the morphology of samples. The matrix phase in S100R0.9 consists of polyphase material with large voids in between, whereas in S80M20R0.9 it represents a typical gel phase encountered in alkali-activated materials. Another aspect that can be seen from Fig. 3 is alkali-activated soapstone contains several mineral phases that are not dissolved during alkali activation and therefore act as micro fillers. The undissolved minerals in S100R0.9 and S80M20R0.9, based on the microprobe analyses and XRD results, are (the numbers refer to Fig. 3) 1) dolomite (CaMg(CO\textsubscript{3})\textsubscript{2}); 2) siderite (FeCO\textsubscript{3}) with contained chromium and pentlandite (FeNi)\textsubscript{8}S\textsubscript{8}, 3) magnesioferrite (MgFe\textsubscript{2}O\textsubscript{4}), 4) talc (Mg\textsubscript{3}Si\textsubscript{2}O\textsubscript{10}(OH)\textsubscript{2}) and chlorite group members, possibly clinohlore (Mg\textsubscript{6}Al\textsubscript{2}(AlSi\textsubscript{6}O\textsubscript{10})(OH)\textsubscript{8}) and chamosite (Fe\textsubscript{5}Al\textsubscript{2}(AlSi\textsubscript{3}O\textsubscript{10})(OH)\textsubscript{8}), and 5) aggregate (SiO\textsubscript{2}).

Fig. 1. Effect of alkali-activator silica modulus at 7 d on the A) compressive strength and B) flexural strength of alkali-activated soapstone.

Semi-quantitative analyses of the matrix phase (i.e., material in between the distinguishable particulates) are summarized in Table 3. S80M20R0.9 has molar ratios of SiO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3}, Na\textsubscript{2}O/SiO\textsubscript{2}, and Na\textsubscript{2}O/Al\textsubscript{2}O\textsubscript{3} that resemble typical low-calcium AAM (N-A-S-H gel) (the amount of calcium is low in the matrix phase of S100R0.9 (≈1.6 wt%) and especially S80M20R0.9 (0.0 wt%)). However, the amount of available aluminum is <1 wt% in S100R0.9, and therefore the SiO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3} and Na\textsubscript{2}O/Al\textsubscript{2}O\textsubscript{3} molar ratios are considerably large. There is an excessive amount of sodium (Na\textsubscript{2}O/Al\textsubscript{2}O\textsubscript{3} ≫ 1) in the structure, which causes S80 M20 to be prone to efflorescence formation. With S80M20R0.9, however, no efflorescence formation took place, which is also supported by Na\textsubscript{2}O/Al\textsubscript{2}O\textsubscript{3} < 1. It appears that both Mg and Fe are incorporated in the matrix, possibly as precipitated amorphous hydroxides.

Quantitative phase analysis (Table 4) of diffractograms (see supplementary materials, Fig. S2) indicates that raw soapstone contains mainly magnesite, talc, clinohlore, magnetite, dolomite, and amorphous material. The processing of soapstone might have destroyed some of the crystalline phases into amorphous material (soapstone waste was obtained as powder). When soapstone is alkali activated (sample S100R0.9), the amorphous content increases to 51%, which is quite close to the sum of the original amorphous content (18.7%) and the added alkali-activator solution (37.5%); 56.2%. This might indicate that the alkali activator forms amorphous material with soluble silica and magnesium (and other species). When metakaolin is introduced (sample S80M20R0.9), the amorphous content increases in comparison...
to soapstone waste and new aluminosilicate phases appear (nacrite and analcime). Behavior at elevated temperatures was studied in terms of thermogravimetric analysis (TGA) and differential thermogravimetry (DTG) as shown in Fig. 4. The mix design with only soapstone as the binder (S100R0.9) undergoes total 33% decrease in weight in comparison to only 23% with the mix design with metakaolin (S80M20R0.9) when temperature is increased up to 1000 °C. A significant difference between S100R0.9 and S80M20R0.9 is the weight loss at 20–200 °C, which is mainly water removal. The next weight loss occurs at 500–630 °C and is associated to the decomposition of magnesite (MgCO3) into periclase (MgO) and carbon dioxide [27]. Finally, the weight loss occurring at 670–820 °C can be associated to the decomposition of dolomite [27].

3.5. Durability properties

3.5.1. High temperature resistance

The exposure of S80M20R0.9 mix design to temperatures of 350 °C, 500 °C, and 800 °C for 3 h caused some linear decrease in compressive strength and weight (Fig. 5A). At 350 °C, the evaporation of water occurs (as also shown in TGA/DTG results, Fig. 4), which can damage the material because of increased pore pressure and dehydration of alkali-activation reaction products. However, the compressive strength after exposure to 350 °C is still acceptable (≈ 23 MPa) as it is similar to virgin soapstone (≈ 21 MPa) [25]. It should be also noted that if the soapstone mortar is used in the production of fire replace elements, which are not directly in contact with fire, the expected maximum temperature exposure is approximately 350 °C. When temperature is increased to 500 and 800 °C, the residual compressive strengths are approximately 20 and 14 MPa, respectively. However, it is known that soapstones exposed to high temperatures (up to 1200 °C) in fire replace constructions harden and gain strength over time due to a series of mineral decomposition and alteration processes [28]. Some of those processes could also occur in the alkali-activated soapstone mortars as many of the minerals present in the original soapstone remain largely unreacted during alkali activation (as shown in Table 4).

3.5.2. Acid resistance

Acid resistance is a relevant parameter to consider for instance if the alkali-activated soapstone materials are to be used as tabletops. Acid resistance results (Fig. 5B) indicate that 5% acetic acid and 5% sulfuric acid

Table 3

<table>
<thead>
<tr>
<th>SEM-EDS analysis of S100R0.9 (only soapstone) and S80M20R0.9 (soapstone and metakaolin) specimens as atomic percentage.</th>
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<td>SiO2/Al2O3</td>
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N = number of point analyses.

Table 4

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<tr>
<th>Quantitative XRD analysis of soapstone and paste samples (S100R0.9 and S80M20R0.9). The amount of internal standard, rutile (10 wt%), has been removed and the remaining quantities are normalized to 100%.</th>
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<td>Magnesioferrite (MgFe2O4)</td>
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<td>Talc (Mg3Si2O5(OH)4)</td>
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<td>Chlorite (Mg3Fe2Si2O7(OH)4)</td>
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<td>Dolomite (CaMg(CO3)2)</td>
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<td>Magnesite (MgCO3)</td>
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<td>Analcime (NaAlSi3O8·H2O)</td>
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<td>Siderite (FeCO3)</td>
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<td>Amorphous content</td>
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induce maximum 8% and 13% weight losses, respectively, when exposure is continued up to 28 d. Furthermore, acetic acid does not affect the compressive strength, as it remained 29.0 MPa after 28 d exposure (control 28.6 MPa). Sulfuric acid, however, caused compressive strength to decrease to 10.8 MPa. Exposure to strong acid (such as sulfuric acid) causes de-alumination of aluminosilicate structure and breakage of Si-O-Al bonds, whereas weak acid (such as acetic acid) merely causes exchangeable cations to be replaced by H+ [29]. The observed weight losses are in agreement with earlier published results about the acid resistance of low-Ca alkali-activated materials [30].

3.5.3. Rate of water absorption
The rate of water absorption (sorptivity) results (Fig. 5C) indicate that for the first 1 h ($t^{1/2} < 60 \text{ s}^{1/2}$), very little absorption takes place. Then, between 2 h and 72 h ($85 \text{ s}^{1/2} \leq t^{1/2} \leq 509 \text{ s}^{1/2}$), absorption increases linearly as a function of square root of time ($R^2 > 0.98$), and the rate of water absorption can be calculated from the slope as 0.0489 mm/s$^{1/2}$ (average of three samples). After 72 h ($t^{1/2} > 509 \text{ s}^{1/2}$), specimens are saturated. The obtained value is higher than with typical Portland cement concrete or low-calcium geopolymer concrete, which have water absorption rates of approximately 0.01–0.03 and 0.005 mm/s$^{1/2}$, respectively [31,32]. Furthermore, if increased temperature (in the range of 60–90 °C) during geopolymer concrete curing is used, it decreases sorptivity [32], which might also be used with alkali-activated soapstone if lower sorptivity values are required. The water absorption (weight increase) of S80M20R0.9 was 9.5% (average of three samples). The relatively high sorptivity can be explained by the high level of open porosity, which is 19.2% (average of three samples). Total porosity was 25.4%. The pores are clearly visible in the micrographs of S80M20R0.9 (Fig. 3D).

3.5.4. Freeze-thaw resistance
Freeze-thaw resistance was studied to indicate behavior if alkali-activated soapstone mortar would be used as outdoor material (e.g., pavement tiles) in cold regions. Exposure to 120 rapid freeze-thaw cycles caused compressive and flexural strength to decrease from 27.8 to 19.5 MPa and from 8.6 to 6.3 MPa, respectively. The observed approximately 30% decrease of strength is in good agreement with earlier published results about low-calcium fly ash-based geopolymer mortars, which were exposed for 150 freeze-thaw cycles [33].
3.6. Drying shrinkage

Shrinkage of the S80M20R0.9 mix stabilized to 0.05 mm/mm after 36 days when samples were kept at ambient conditions (temperature 22 °C and relative humidity 34%) (Fig. 6). The addition of basalt or steel fibers decreased the shrinkage significantly. The best results were obtained with 1 vol-% addition of basalt fibers, which decreased shrinkage 80% (to 0.01 mm/mm). The drying shrinkage was also evaluated in practice from a larger scale sample (505 × 300 × 45 mm³) and no crack development was observed (see supplementary materials).

3.7. Economic evaluation

The main economic drivers for the presented study are 1) avoiding landfilling costs and 2) obtaining material with a high added value. Landfilling cost was assumed to be 100 €/t, which represent a typical value in many European countries [34]. Thus, the price of soapstone waste in the calculation was assumed as −100 €/t (due to the avoided landfilling). The S80M20R0.9 mix design (with sand/binder = 2) was used as a basis for the preliminary economic evaluation (Fig. 7A). The raw material prices (Fig. 7B) represent approximate bulk chemical price levels. The material cost estimate for alkali-activated soapstone (Fig. 7C) reveals that sodium silicate accounts for the largest individual cost, which is the typical case with alkali-activated materials [35]. The material cost estimation does not include possibly required milling of soapstone waste, the cost associated to 60 °C curing, or labor. However, the estimated material cost (≈ 70 €/t) is very promising especially if the aim is to prepare high-end products such as fireplace elements (for which the retail price can be 3000–5000 €/t). To further evaluate the possibility of producing fireplace elements with the developed mix design, a demonstration fireplace element (size 505 × 300 × 45 mm³) was successfully prepared (see supplementary material). The workability of the mortar was satisfactory and no crack or efflorescence development was observed.

If using the soapstone waste generated in Finland as a case example (≈ 82,500 t/year), the amount of alkali-activated soapstone mortar that could be prepared using the S80M20R0.9 mix design is approximately 370,000 t/year.

4. Conclusions

The suitability of soapstone waste for the preparation of alkali-activated binder with or without metakaolin was demonstrated. When the mix design was optimized in terms of alkali-activator modulus, aggregate amount, and the amount of metakaolin as co-binder, 31.2 MPa compressive strength and 8.8 MPa flexural strength were reached at 28 d age. These numbers are approximately similar as with virgin soapstone mineral. It was found that 60 °C curing was beneficial for the reactivity of soapstone and making demolting possible already after 4 h.

Fig. 6. Shrinkage of the S80M20R0.9 mix and the same mix reinforced 0.5 or 1 vol-% of basalt or steel fibers at ambient conditions.

Fig. 7. Economic evaluation of alkali-activated soapstone: A) the employed mix design (S80M20R0.9) in weight percentage (wt%); B) prices of raw materials per ton; C) estimated cost of materials when preparing 1000 kg of alkali-activated soapstone mortar.
The durability results of soapstone-metakaolin mortar indicated acceptable resistance for high temperatures but a lower performance against strong acids or freeze-thaw cycles. The material has relatively high porosity, which causes, subsequently, high water absorption. These properties pointed out that the potential application for the developed alkali-activated material could be in the production of fireplace elements. Also the relatively low material costs (≈ 70 €/t) support this. A demonstration fireplace element (size 505 × 300 × 45 mm³) was successfully prepared: workability of the fresh mortar was found good and no crack development was observed. If there is a need to further decrease shrinkage, it can be achieved by the addition of basalt fibers as reinforcements.

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Appendix A. Supplementary data

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References