Characterization of mineral waste as potential precursors for alkali-activated materials

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In the European Union (EU), major mineral wastes such as soils, hard rocks and concrete account for about 1.4 billion tons (European Environment Agency, 2023). In Austria, mineral waste represents the largest waste stream, comprising about 75% of the total waste. Currently, over 50% of this waste is deposited in landfills (BMK, 2023).

The building and construction sector contributes nearly 40% of global operational energy and process-related CO_2 emissions, with approximately 6% merely attributed to the production of concrete, steel and aluminum used in the building construction (United Nations Environment Programme, 2022). Concrete is the most used building material and contains Ordinary Portland cement (OPC), whose production process, particularly due to the production of Portland cement clinker, alone accounts for 5-7% of global CO_2 emissions (Benhelal et al., 2013; IEA, 2018; Huang et al., 2020). Additionally, the building and construction industry is responsible for the consumption of considerable amounts of primary resources.

Geopolymers, a subset of alkali-activated materials (AAM), are inorganic binders which are produced by mixing of a solid aluminosilicate precursor with an alkaline activator. Regarding geopolymers, the alkali activation reaction (AAR), leads to the formation of a 3D network consisting of aluminate and silicate tetrahedra (Provis and van Deventer, 2009). The most utilized precursors include calcined clays, fly ash, blast furnace slag or natural pozzolans (Provis, 2014), to serve as sources for soluble Al and Si components for the alkali activation process.

However, other inorganic solid Si- and/or Al-rich substances, such as mineral waste or secondary raw materials, could serve as substitutes. Therefore, to decrease the amount of landfilled waste and the negative environmental impact of the building and construction sector, geopolymer construction materials are aimed to be produced, using currently unexploited Austrian waste materials. These waste-based geopolymers could represent an environmentally friendly and highly resistant alternative to OPC products in the context of circular economy. An example for a potential application field are biochemically aggressive environments, such as biowaste treatment facilities, sewer manholes or tanks.

As first task the identification and selection of relevant mineral waste streams and secondary raw materials was carried out. Material streams, *e.g.*, glass waste, metallurgical slags, construction and demolition waste (C&D), brick waste or mineral wools were selected. The chosen materials were characterized chemically and mineralogically, using XRF (X-ray fluorescence) and XRD (X-ray diffraction) techniques, respectively. The XRD results were used to identify and quantify crystalline phases and the amorphous content of the materials by applying Rietveld refinement, using an external standard (Jansen et al., 2011). The sum of reactive phases (Sum RP) was calculated from the amorphous content and the content of reactive crystalline phases, which mainly control the reactivity of the materials by readily providing Si and Al by dissolution during the alkali activation process.

Obtained results of selected samples for the current study are displayed in Table 1, and indicate the presence of materials with higher SiO_2 content then Al_2O_3, except for slag. Since most materials are Si-rich but Al-deficient, Al-rich materials are further required to replace primary Al-rich materials (*e.g.*, metakaolin) as an Al-source in the geopolymer production.

Glass and mineral wool waste reveal preferable quantities in the SiO_2 content and the Sum RP, implying a high amount of reactive SiO_2 content. C&D and brick waste, however, exhibit a lower quantity of Sum RP, indicating less reactive SiO_2 available for the AAR. In comparison to the other samples presented in Table 1, the slag exhibits lower SiO_2- and Al_2O_3-contents but shows an acceptable Sum RP (>20 wt.-%). This observation is due to the reactive phases represented by belite (*e.g.*, γ-dicalcium silicate) and tricalcium aluminate (C_3A), which are common mineral phases in steel slags (Engström et al., 2013). All presented materials are characterized by a Sum RP >20 wt.-% and in most cases a SiO_2 content >55 wt.-%, indicating adequate suitability as precursors for the development of geopolymer construction materials.

Table 1: Bulk geochemical characterization of representative waste materials and secondary raw materials, presenting relevant elements in oxide form. Sum RP indicates the sum of reactive phases, as derived from XRD and Rietveld refinement.

	Material				
in wt.-%	C&D waste	Brick waste	Glass waste	Mineral wool waste	Slag
SiO_2	67.16	56.98	71.45	60.21	16.15
Al_2O_3	9.54	11.82	1.76	11.94	16.77
Fe_2O_3+FeO	3.07	4.83	0.51	1.12	27.04
CaO	1.80	13.02	9.96	18.29	29.39
Sum RP	22.05	26.50	99.64	99.70	33.07

Multivariate statistical methods, such as principal component analysis (PCA), were further applied on the bulk geochemical and mineralogical datasets of more than 30 investigated waste samples. Preliminarily results demonstrate the capability of the PCA in revealing waste-stream-related patterns by classifying the waste materials in the following groups: (i) clay-based waste, including brick waste, (ii) C&D waste, (iii) glass-waste, (iv) mineral wools and (v) slags. Such an approach enables the creation of a material database of relevant Austrian waste and secondary raw materials, which will be continuously extended with newly added materials.

Eventually, this material database will be used to define geochemical (*e.g.*, SiO_2 or Al_2O_3 content) and mineralogical (*e.g.*, amorphous content) parameters to facilitate the classification of waste materials, with or without pretreatment steps, regarding their suitability as precursors for geopolymer production.

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