

REUSE OF IRON EXPLOITATION WASTE AS A NEW BINDER FOR TAILINGS STABILISATION IN DRY STACKS: CIRCULAR ECONOMY APPROACH

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ABSTRACT

The dried allocation of the tailings, rather than the disposal in a slurry form, appears as an alternative to attend new legislation and improve the safety of mines operation. Also, the use of cementing agents in dry stacking facilities can enhance aspects of operations such as guaranteeing dilatant behaviour at the base and increasing tailings' strength. The present research assesses the technical and environmental viability of a new alkali-activated cement (AAC) in iron ore tailings stabilization. The mechanical response of compacted tailings-AAC specimens was evaluated through strength and shear modulus tests while Life Cycle Assessment (LCA) was performed to verify the sustainability of this new binder when compared to conventional AAC. This new binder is derived from the residues of iron exploitation and is intended for use in new disposal schemes, such as dry stacks. The AAC is mainly composed of metakaolin (MK), produced from the residual soil removed during the mining activity, and sodium silicate (SS), produced with sandy tailings. Using tailings and waste in AAC production aligns with sustainable practices, minimizing resource consumption and promoting waste recovery. Also, LCA demonstrates a lower impact for tailings AAC when compared to conventional AAC. In addition to environmental and mechanical aspects, using this AAC supports the application of circular economy in mining since it enables the reuse of waste produced in mine operation as a substitute for conventional cement (that involves another industry and raw materials).

1 INTRODUCTION

Due to recurring disasters, agencies in Brazil have introduced new regulatory frameworks prohibiting the construction of upstream tailings dams and requiring the closure of existing ones built with such a technique (Schaper et al., 2020). Kossoff et al. (2014) present several environmental impacts of tailings dam failures from immediate (e.g., deaths of animals and humans) to medium and longer-term impacts (e.g., soil and water contamination). According to the authors, dam failures have economic consequences related to environmental damage, cleanup of the affected area, and interruption in the mining and processing operations.

One alternative solution to attend to the novel regulations is the dried allocation of the tailings rather than slurry disposal. Stacked filtered tailings disposal is a methodology that has emerged alongside advances in dewatering technologies in recent decades (Gomes et al., 2016). Consoli et al. (2022) have presented the trend of disposing filtered tailings in stacks by considering Portland Cement-Iron Ore tailings mixtures. However, Ordinary Portland Cement (OPC) has been over-consumed in the last decades (Ahmed et al., 2021), and it is costly economically and environmentally, although being an efficient and trustworthy binder. Thus, it is necessary to find new cementitious materials to substitute the OPC.

Lately, alkali-activated cements (AAC) have gained notoriety as an OPC replacement (e.g. Corrêa-Silva et al., 2019; Lotero et al., 2021; Rivera, Castro, et al., 2021; Rivera, Coelho, et al., 2021). In essence, AAC results from the association of a precursor, usually a material with silico-aluminates in amorphous phases, and an alkaline solution as an activator. Then, the reaction of the activator and precursor forms a new material in a metastable state. This reaction product develops cementitious properties due to the combination of alkali-aluminosilicate and/or alkali earth-aluminosilicate phases through complex chemical interactions (Duxson et al., 2007).

The usage of AAC in the mining industry offers the opportunity to incorporate waste from the mining process as precursors and activators. This fact favours the transition of the mining industry to a more circular chain of production. The definition of the circular economy (CE) concept is not static, and can be broad, involving several principles and proposals (Merli et al., 2018). Still, in summary, it can be understood as the need to overcome the usual produce-use-waste linear thinking and look at ways of bringing value to materials considered waste (Lèbre et al., 2017; Upadhyay et al., 2021). Although there is no consensus over CE definition, some characteristics are recurrent on the definitions, such as fewer pollutant emissions, more recycling, environment-friendly disposal, reasonable utilization of resources, reducing waste, and maintaining the value of resources as long as possible (European Commission, 2017; Merli et al., 2018; Zhao et al., 2012).

Accordingly, this paper proposes using a novel Alkaline Activated Cement (AAC) produced from mining waste with Iron Ore Tailings (IOT) for cement-bonded dry stacking purposes. Therefore, unconfined compressive strength and ultrasonic pulse velocity tests (UPV) were carried out for compacted tailings-AAC specimens to evaluate their strength and stiffness response, respectively. A full factorial design setting was used considering four curing periods, five amounts of cement and three dry unit weights. Strength and stiffness results were correlated to the porosity/binder content index – η/B_{iv} (Consoli, Winter, et al., 2018). The new binder environmental impacts are evaluated through life cycle assessment (LCA) and compared to those of conventional AAC. Thus, the aim of this paper is to verify the technical and environmental feasibility of using an alternative ACC in dry stacking of IOT.

2 CIRCULAR ECONOMY IN MINING: CHALLENGES AND OPPORTUNITIES

The mining industry is one of the larger waste producers in the world. The waste management in this sector is usually linear (produce-use-waste), and there is little effort to establish sustainable production that accounts for waste reuse (Lèbre et al., 2017; Zhao et al., 2012). Thence, practices more aligned with CE can be valuable and applicable to this industry segment. The valorisation of tailings could contribute towards the adoption of a circular economy in mining, although this now confronts several challenges and bottlenecks in economic, technological, and environmental terms (Kinnunen & Kaksonen, 2019; Upadhyay et al., 2021).

Recycling is a relevant process within the circular economy. Besides limiting waste production, the reuse and recycling of mining wastes reduce the use of natural resources and favour the local economy. Reusing solid mining wastes and mining process waters also contributes to reducing the exposure of humans and the environment to contaminated products (Lottermoser, 2011). Nevertheless, the existing recycling methods in mining need further development. The recycling flowsheets are individual, and it is necessary to redesign them considering economic issues, tailings properties, and possible environmental impacts (Edraki et al., 2014).

2.1 PROCESSING AND DISPOSAL METHODS

Mining operations produce a wide range of waste which can be separated mainly into waste and tailings (Spitz & Trudinger, 2019). According to Blight (2010), the mine wastes are usually stored separately. The soil portion is stacked for future uses and the rocks are placed in dumps (with or without compaction) or are used as landfills. Already the tailings produced from ore exploration are found in a slurry form due the water use in process (Fig. 1) which favours their deposition in large impoundments as tailings' dams (Kossoff et al., 2014; Xiaolong et al., 2021). The tailings in the structures are routinely found in a loose and saturated state, which brings additional risks to this method of deposition (Islam & Murakami, 2021; Yao et al., 2021). Furthermore, slurry deposition form has unpleasant disadvantages, such as high embankment costs, extensive water handling, and difficulty rehabilitating the slimes (Spitz & Trudinger, 2019).

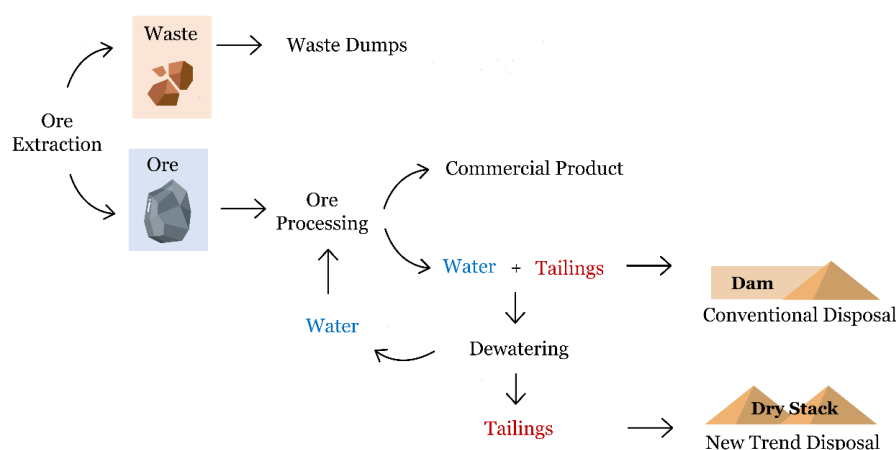


Figure 1: Comparison of disposal methods of tailings

One alternative method that follows the advances in dewatering technologies is the disposal of tailings by stacking (Consoli et al., 2022; Davies, 2011). In this method, the tailings are filtered to low moisture contents and disposed of in a compacted form in stacks that can achieve heights of around 200 to 300m (Lupo & Hall, 2011). Once such methodology

involves stacking dewatered tailings, the need to dispose of this material in dams is eliminated, which implies a more harmonious use of the landform. Moreover, the risks associated with the material's static and/or dynamic liquefaction are substantially diminished compared to the conditions encountered in traditional tailings dams (Chang et al., 2011; Hu et al., 2017; W. Li et al., 2018).

Water is part of the ore beneficiation process (Fig. 1). According to (Davies, 2011), the future of mining requires increasing attention to water use worldwide, mainly due to the large amount of water lost in conventional dam tailings by seep and evaporation. Furnell et al. (2022) suggest that dewatering techniques allow recovering water to reuse in ore beneficiation plants. The maximum water recovery may be achieved with filtered tailings. Also, water recovery usually offers a cost-benefit that offsets the capital and operating cost of the filtration plants (Davies, 2011).

The compacted tailings must attend prerequisites for stacking use, which depend on the projected use and geometric configuration. In this method the tailings are compacted at different compaction degrees within the stacking zones. At the borders (structural zones), the material is usually deposited in dense states, while it is deposited at lower compaction degree (or even loose) at the centre (non-structural zones) (Lupo & Hall, 2011). One fundamental aspect is the guarantee of dilatant behaviour under drained shearing at stacking base. The mixing of tailings with a cementitious compound, such as ordinary Portland cement (OPC), prior to the tailings stacking can contribute to achieving this condition (Consoli et al., 2022), reducing or even mitigating liquefaction potential.

2.2 ALTERNATIVE CEMENT ADDITIONS TO ENHANCE DRY STACKING

The use of OPC has proven to be a promising solution for the dry stacking of tailings (Consoli et al., 2022). Nonetheless, substantial amounts of energy and natural resources are demanded in its production, causing the emission of high quantities of carbon dioxide (CO₂) and other greenhouse effect gases (Çankaya & Pekey, 2019; Gálvez-Martos et al., 2021; M. Li et al., 2020). These side effects and the mining industry's requirements for environment-friendly solutions reinforce the idea of the new alternative search.

The AAC is recently being considered as a replacement for OPC, including solutions for tailings (Servi et al., 2022). These binders are characterized by a mixture of an alkaline activator and a precursor (a source of silica and aluminium in amorphous phases). After mixing these materials, a chain of reactions that produces a new stable phase with bonding properties develops (P. Krivenko, 2017).

One advantage of AACs is that various materials can be employed in their production. Thus, industrial by-products and construction wastes have already been tested for AACs production. The most regularly investigated precursors have been blast furnace slag, fly ash from coal combustion, and metakaolin, whereas sodium-based and potassium-based hydroxides and silicates have been the routinely employed activators (Fernández-Jiménez et al., 2017; Palomo et al., 2014; Zhang et al., 2021).

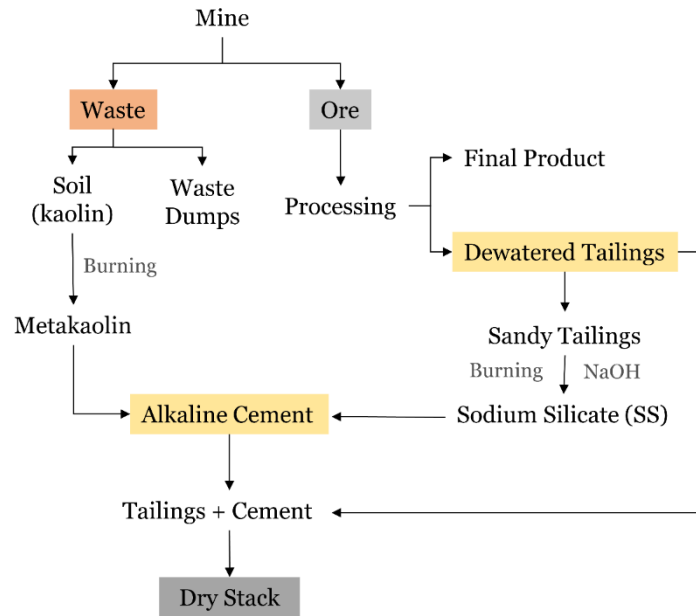
Regarding the activator choice, those that provide soluble silica, e.g. sodium silicate (SS), promote faster reaction rates than alkaline hydroxides (Lima et al., 2021; Torres-Carrasco & Puertas, 2017). However, the SS synthesis performed commercially demands high energy consumption and generates CO₂ in large quantities, being a bottleneck for reducing environmental impact of AACs (Dal Pozzo et al., 2019; Labianca et al., 2022).

Different materials have been used as substitute sources of silica for producing sodium silicate, such as rice husk ash (Andreola et al., 2020; Lima et al., 2021), waste glass (Tchakouté et al., 2016; Torres-Carrasco et al., 2014) bamboo leaves (Kow et al., 2014), silica fume (Bernal et al., 2012), among others. They have shown great feasibility in producing economically competitive and environment friendly AACs compared to conventional cements. In this regard, Vogt & Lameiras (2019) defined an innovative procedure to produce SS powder from sandy tailings obtained by the flotation process in the iron ore beneficiation plant. The procedure consists of removing ultrafine fraction from the tailings (particles smaller than 40 µm) and reducing moisture content through filtering, centrifugation, and drying processes (105 °C). Finally, the resulting material reacts with sodium hydroxide in a furnace at temperatures between 400 and 500 °C.

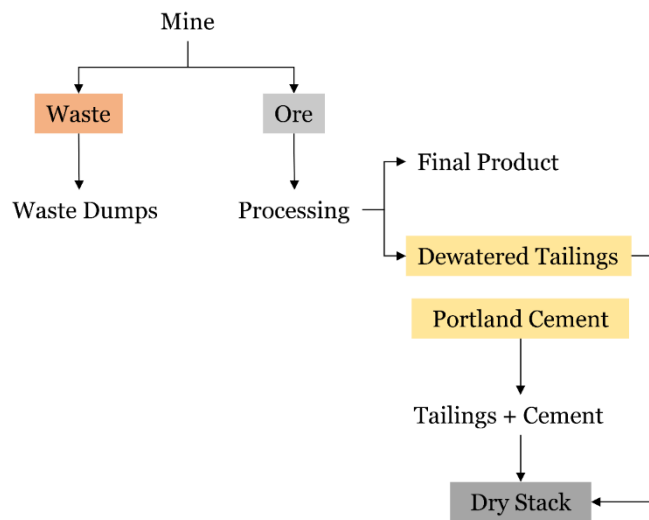
One commercially adopted solution for the precursor is metakaolin (MK), which is not usually considered a residue or by-product. However, iron ore exploitation involves excavating and removing soil, which can be rich in different minerals, including kaolinite. These soils are usually treated as waste and disposed of in waste dumps. Nonetheless, this material can give rise to MK after being calcinated at high temperatures (approximately 800°C). The use of the MK originated from waste in conjunction with an also waste-based SS, giving rise to a new AAC fully integrated into the production chain of iron ore exploitation.

Figure 2 compares the production chain considering the OPC versus the AAC addition to the tailings before disposal in the dry stack. It is noted that the AAC adoption reduces the disposal of tailings and soil waste by reusing these materials within the same production chain, transforming both in commercial products. It also avoids using other natural resources

or raw materials (as in the OPC industry). Furthermore, this AAC could provide means for implementing the circular economy practices in mining operations.



(a)



(b)

Figure 2: Production chain considering dry stacking deposition of (a) alkali-activated cement-iron ore tailings mixtures and (b) Portland cement-iron ore tailings mixtures

2.3 ENVIRONMENTAL SUSTAINABILITY

According to Nagaraj (2010), mineral processing research efforts are likely to prioritize economic outcomes. For Edraki et al. (2014), it is necessary to think primarily about reducing environmental problems in the long term and not only about the current cost benefits. In this regard, Zhao et al. (2012) divided the reuse of waste and tailings into two main perspectives: the reprocessing for further extraction of valuable ore that is still present in the materials, and the production of new substances, mainly as building materials, using waste as a raw material.

Concerns about environmental sustainability are directly correlated with the reuse of iron mining tailings. Basically, the tailings sent for storage in ponds have the potential to be used as raw material in the production of concrete (Che et al., 2019; Huang et al., 2013; Zhu et al., 2015), ceramic production (Das et al., 2000; Yellishetty et al., 2008) and in the pigment industry (Pereira & Bernardin, 2012), interlocking blocks (Filho et al., 2017; Ravi Kumar et al., 2012) among other processes that require granular aggregates, trace elements of iron and sources of silicates. The substitution of natural resources by tailings/waste meets the precepts established in the Brundtland Commission (Brundtland, 1987), formed under the supervision of the United Nations, which proposes a rational use of natural resources enabling that the needs of future generations are not compromised. However, a large portion of the tailings from the iron mining process still do not have a significant alternative destination that can avoid the disposal of this material in dams. In this case, the dry storage process with an alternative binder is a necessary path in the search for an environmentally friendly storage process that enables its future use as a resource source.

In this context, the production of sodium silicate and metakaolin with mining tailings to produce an alkali-activated cement, in the stabilization of the mining tailings themselves, is a technical alternative that avoids the use of natural resources, reduces the generation of tailings promoting environmental, economic and operational benefits. In the specific context of products that incorporate waste, Life Cycle Assessment has a fundamental role in identifying and quantifying environmental impacts in different categories, such as consumption of natural resources, greenhouse gas emissions, air, soil and water pollution, among others. This detailed analysis provides valuable information to guide decision-making in the selection of more sustainable materials and processes (Ouellet-Plamondon & Habert, 2015).

3 EXPERIMENTAL PROGRAM

3.1 MATERIALS CHARACTERIZATION

3.1.1 Iron Ore Tailings

The IOT were collected from a beneficiation plant in the Quadrilátero Ferrífero (Iron Quadrangle) located in Minas Gerais (MG), Brazil. The characterization for the IOT was carried out following the determinations and standards for geotechnical materials, as they would constitute the base material to be improved for the deposition in stacks.

The physical characteristics of the IOT were evaluated through the particle size distribution (ASTM, 2021a), the Atterberg limits (ASTM, 2017), and the specific gravity (ASTM, 2014). The compaction characteristics of the IOT were assessed using standard and modified efforts in agreement with ASTM standards (ASTM, 2021b, 2021c). Table 1 summarizes the main physical properties of the IOT.

Table 1: Physical characteristics of the iron ore tailings

Physical properties	Iron ore tailings	Test method
Liquid limit (%)	-	
Plastic limit (%)	-	ASTM D4318
Plastic index (%)	non-plastic	
Specific gravity	2.92	ASTM D854
Coarse Sand (2.00 mm < diameter < 4.75 mm) (%)	0	
Medium Sand (0.425 mm < diameter < 2.00 mm) (%)	4.0	
Fine Sand (0.075 mm < diameter < 0.425 mm) (%)	49.0	ASTM D7928
Silt (0.002 < diameter < 0.075 mm) (%)	42.0	
Clay (diameter < 0.002 mm) (%)	5.0	
Effective diameter (D_{10}) (mm)	0.0085	
Maximum dry unit weight at standard effort (kN/m ³)	19.2 ($w = 11.2\%$)	ASTM D698
Maximum dry unit weight at modified effort (kN/m ³)	20.6 ($w = 9.2\%$)	ASTM D1557

The chemical and mineralogical characteristics of the IOT were also evaluated. From X-ray fluorescence (XRF) analyses was determined that the major components present in IOTs (Table 2) were silicon (69.6%), iron (24.1%), and aluminium

(4.8%) which agrees with the crystalline peaks of quartz (SiO_2), hematite (Fe_2O_3) and kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), identified in the diffractogram of Fig. 3.

Table 2: Chemical composition (wt.%) of the iron ore tailings (IOT), metakaolin (MK) and sodium silicate (SS) obtained through X-ray fluorescence (XRF) analysis

% wt	SiO_2	Al_2O_3	Fe_2O_3	MnO	K_2O	CaO	Na_2O	SO_3	P_2O_5	Others	LOI ^a
IOT	69.6	4.8	24.1	0.4	0.15	< 0.1	< 0.1	0.1	< 0.1	0.15	0.2
MK	48.9	40.8	0.28	0.31	0.36	2.7	< 0.1	Nd ^b	0.13	0.6	< 0.1
SS	43.9	< 0.1	4.6	< 0.1	< 0.1	1.1	49.7	Nd ^b	< 0.1	0.2	0.12

^a LOI: loss on ignition.

^b Nd: Not detected.

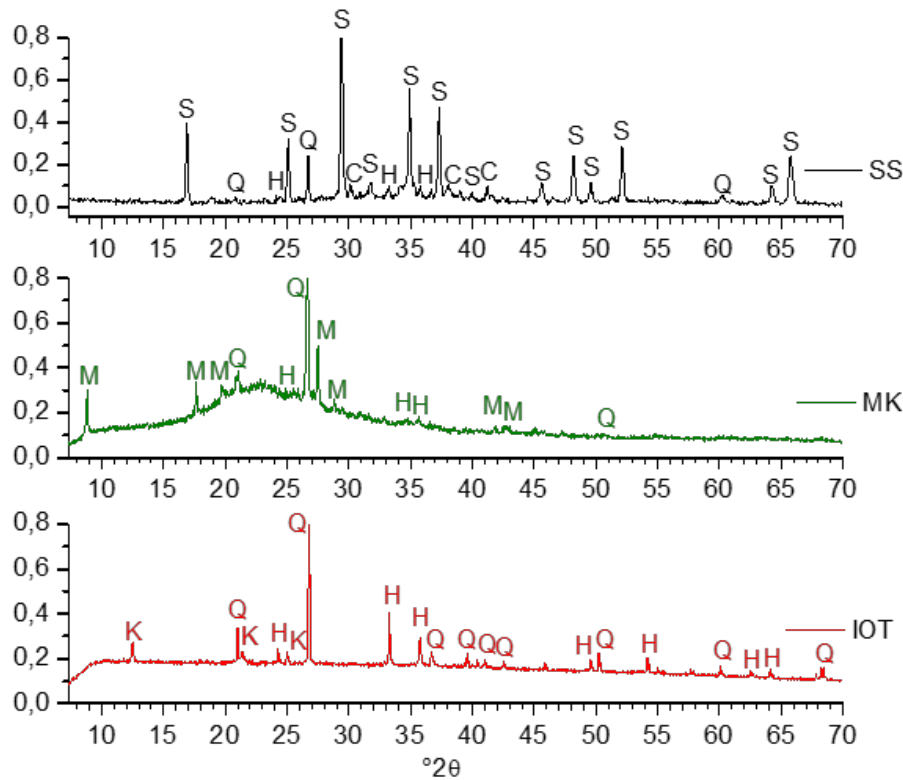


Figure 3: X-ray diffraction (XRD) analysis of the starting materials. S: Sodium silicate (Na_2SiO_3); Q: Quartz (SiO_2); C: Sodium carbonate (Na_2CO_3); H: hematite (Fe_2O_3); M: muscovite ($\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$); K: kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$)

3.1.2 Cement Components

The AAC is essentially made up of metakaolin (MK) and sodium silicate (SS). These two materials are originated from iron extraction plants and produced according to the methodology described in (Vogt & Lameiras, 2019). For them, it was performed chemical and mineralogical characterization.

The MK is originated from the waste soil above the ore deposit before exploration. The waste soil was initially investigated to confirm the presence of kaolinite and was calcinated at elevated temperatures (approximately 800° C) to produce the MK. The XRF tests results attested to the presence of the following major elements: silicon (48.9%), aluminium (40.8%) and calcium (2.7%) for MK (Table 2). Mineralogically, XRD analyses reveal a typical pattern of a semi-crystalline material, composed of a pronounced halo between 15° - 35° of 2θ angle (Fig. 3), usually associated with the reactive aluminosilicates present in the vitreous phase (Consoli et al., 2021; Lotero et al., 2021; Palomo et al., 1999),

with slightly pronounced peaks about the presence of quartz (SiO_2), muscovite ($\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$) and hematite (Fe_2O_3) minerals.

Regarding the SS, the XRF tests (Table 2) indicate the existence of sodium (49.7%), silicon (43.9%), iron (4.6%), and other trace elements in small amounts ($< 0.1\%$). In addition, XRD test results confirm, by the high intensity of the characteristic peaks in Fig. 3, that the SS is mainly composed of sodium silicate (Na_2SiO_3) and quartz (SiO_2) crystals with small amounts of sodium carbonate (Na_2CO_3) and hematite (Fe_2O_3). The specific gravity of the solid components of the AAC was 3.1 g/cm^3 , determined by the Le-Chatelier flask method (ASTM, 2016a).

3.2 GEOTECHNICAL TESTS

A fully crossed-design setting (Montgomery, 2013) was used for the strength and stiffness tests. Then, concerning the dosages, four curing periods (4, 7, 28, and 90 days), three different dry unit weight values (17, 18, and 19 kN/m^3), and five amounts of AAC (1, 2, 3, 4, and 5%) were tested. Therefore, 15 dosages were evaluated in triplicates, totalling 45 specimens for each of the four curing periods.

The increase in strength and stiffness over time in the mixtures was evaluated by adopting different curing periods. The chosen dry unit weight values were based on the compaction results (Tab. 1), and a single moulding moisture content (w) of 11% was established regardless of the adopted γ_d (e.g. Consoli et al., 2007, 2020; Corrêa et al., 2021; Festugato et al., 2021). The choice of AAC contents (up to 5%) was associated with economic issues and optimization. Higher strength could be achieved by the balance of compaction and binder content. Furthermore, small amounts of cement are considered to avoid difficulties for possible reprocessing tailings which may be of interest as new technologies develop.

3.2.1 Specimens Moulding and Curing

Cylindrical specimens (50 mm in diameter and 100 mm in height) were moulded using the undercompaction method (Ladd, 1978). The moulding process was initiated by the weighing and mixing the dry materials (IOT and AAC) until visual uniformity was obtained. The AAC was composed, in mass, of 62% of metakaolin and 38% of sodium silicate (Vogt, 2022). The amount of cement (C) was calculated over the mass of dry tailings, and the defined quantities follow the practice of tailings stabilization with OPC (e.g. Consoli et al., 2017; Consoli, Winter, et al., 2018; Festugato et al., 2013). Right after, distilled water was added, and the mixing progressed until a mass having a uniform consistency was formed. Then, the specimen was statically compacted in three layers inside a cylindrical split mould until reaching the target dry density. Following, the specimen was retrieved from the mould and cured in a humid room. The procedure adopted for constructing the dry stacks in the field would be very similar to that performed for the specimens. In this case, the AAC would be mixed with the filtered tailings (at the target moisture content) and then compacted in layers as in landfills and pavements where soil improvement is used.

3.2.2 Unconfined Compressive Strength Tests

The unconfined compressive strength tests were performed on an automatic loading press coupled to a 10 kN load cell (0.005 kN of resolution). A displacement rate of 1.14 mm per minute was used. Each specimen was submerged in a water tank for 24 hours before the test to minimize possible suction effects on the strength (e.g. Consoli et al., 2007). It established an acceptance criterion that the individual strength value (q_u) should not deviate by more than 10% of the triplicate's mean strength, considering the same mix design.

3.2.3 Ultrasonic Pulse Velocity Tests

The initial shear modulus (G_0) can be calculated as the product between the square of the shear wave velocity (V_s) and the apparent density (ρ) of the media for elastic isotropic media (ASTM, 2016b). In this sense, the G_0 of the compacted iron ore tailings-AAC specimens was assessed using an ultrasonic pulse velocity (UPV) device responsible for emitting shear waves at a constant frequency of 150 kHz. The shear wave velocity (V_s) was determined by measuring the travel time of these waves across the test specimens using transducers coupled to the ends of the samples. A special coupler gel was used to attach the transducers to the specimen. Since the UPV is a non-destructive test, it was performed on the identical specimens that would be submitted to the unconfined compression tests.

3.3 LIFE CYCLE ASSESSMENT

The purpose of conducting a Life Cycle Assessment was to assess the environmental impacts of two distinct methods for stabilizing tailings and to determine the suitability of these solutions within the context of a circular economy (Angelis-Dimakis et al., 2016; Biganzoli et al., 2018; Laso et al., 2018; Sassanelli et al., 2019). Using tailings as raw materials for AAC has an impact in reuse and recycling of materials, key principles in CE concept. Thus, the LCA was used to verify the performance of a system with reuse and recycle and identify the possible benefits in relation to commercially available solutions. The assessment focused on a functional unit of 100 m^3 of stabilized tailings with 4% of AAC. The first method involved using alkali-activation stabilization with alternative production of SS and alternative MK (using tailings as raw

materials), while the second method used alkali-activation stabilization with commercial metakaolin and sodium silicate (known as conventional alkali-activated cement, AAC). The life cycle assessment (LCA) involved conducting a cradle-to-gate analysis of the production process for the binder, which consisted of sodium silicate and metakaolin. The system studied in Fig. 4 accounted for all emissions related to the energy used in production and the raw materials involved. The commercial production technique for sodium silicate is through the hydrothermal process which involves dissolving a silica source with sodium hydroxide inside a reactor at elevated pressure and temperatures (8.15×10^3 MJ/tonne of SS). For the production of sodium silicate from mining tailings, the technique developed by (Vogt & Lameiras, 2019) is proposed. The process consists of heating the tailings with sodium hydroxide (1:1) in a furnace at a temperature between 400°C and 500°C (2×10^3 MJ/tonne of SS).

Metakaolin used in commercial production is obtained by prospecting kaolinitic clays and subjected to calcination. This calcination process alters the structure of the clay inducing chemical and physical changes in the generation of metakaolin. However, when producing metakaolin using mining waste, the conventional clay extraction operation is eliminated. Instead, clay from the overburden is utilized as a substitute for the conventional raw material. In the present work the impact assessment did not take into account the mixing process of sodium silicate, metakaolin, tailings, and water for the reaction and compaction processes in tailings stabilization. This is because the mixing process was identical for both binders and therefore did not contribute to any discernible differences in the impact assessment.

Secondary inventory data was collected from the Ecoinvent 3.8 database (Wernet et al., 2016) using SimaPro software. The quantity of each inventory is presented in Figure X flowcharts of the evaluated systems. The impact assessment was conducted using CML2001 method (Guinee, 2001). The assessment included the following impact categories: abiotic depletion (AD), global warming (GW), ozone layer depletion (OLD), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TAETP), photochemical oxidation (PHO), acidification (AC), and eutrophication (EU). Additionally, the Cumulative Energy Demand - CED was incorporated into the evaluation of the impact assessment.

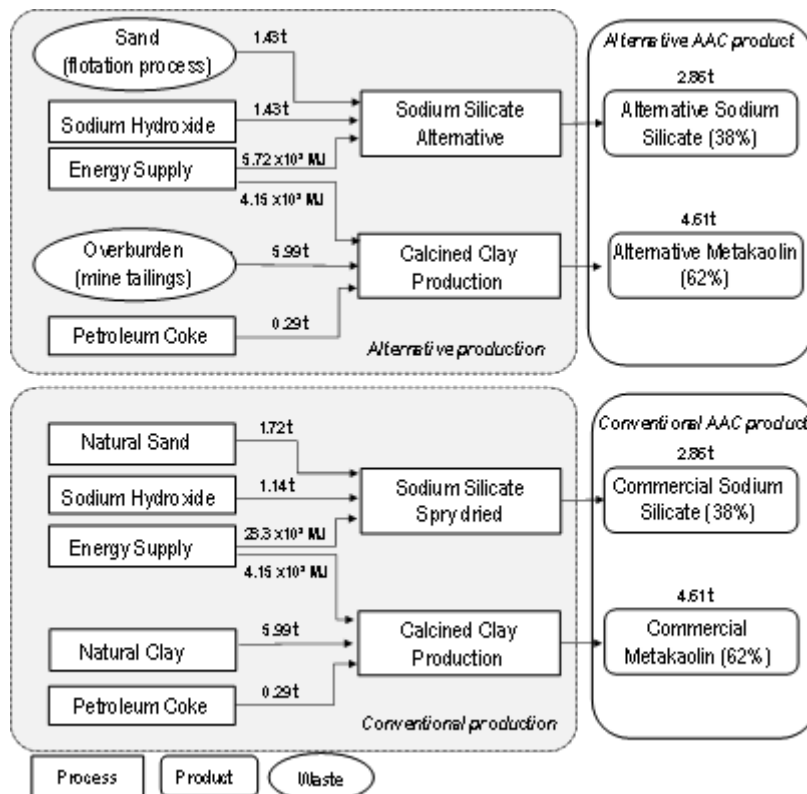


Figure 4: System boundaries and processes for the production of alkali-activated cement for stabilization of 100 m³ of tailings

4 RESULTS AND DISCUSSION

The specimens moulded using 1% of the AAC disintegrated when submerged (after each curing period), indicating that such an amount of cement could not generate an adequate cementing matrix considering the studied curing periods (Consoli et al., 2007). The same has occurred for the specimens of 2% of the AAC cured along 4, 7, and 28 days. For 90 days of curing, it was possible to prepare specimens. However, this period is too long to be considered for adoption in the field. Then, the analyses in this item were carried out only considering specimens with 3% of AAC or more.

The stability of a dry stack of cemented material depends on two main characteristics. One is the compaction degree, and another is cement content. Following (Consoli, Da Silva, et al., 2018; Consoli et al., 2020), these parameters are referred to as porosity (η) and amount of binder (B_{iv}) and can be gathered into a unique parameter, the porosity/binder content index (η/B_{iv}), and expressed as follows (Eq. 1):

$$\frac{\eta}{B_{iv}} = \frac{100 \cdot \left[1 - \frac{\gamma_d}{\gamma_s \cdot (1 + C/100)} + \frac{\gamma_d \cdot (C/100)}{(1 + C/100) \cdot \gamma_c} \right]}{100 \cdot \frac{(C/100) \cdot \gamma_d}{(1 + C/100)}} \quad (1)$$

where γ_d is the dry unit weight of the specimen, γ_s is the unit weight of the solids of the iron ore tailings, γ_c is the unit weight of the solids of the alkali-activated cement, and C is the amount of alkali-activated cement expressed in percentage.

The porosity/binder content index has been used as an important geotechnical parameter in studies of soil improvement. So, verify its validity for tailings-AAC mixtures is essential, as is the case in this study.

4.1 UNCONFINED COMPRESSIVE STRENGTH

Unconfined compression tests have extensively been used for the definition of improvement level for several reasons, such as the accumulated experience with this kind of test, the low cost, simplicity, and speed. Moreover, the results for different binders and materials are available in the literature, providing a direct comparison of the materials tested (Cerveira et al., 2017; Consoli et al., 2007; Correia et al., 2019; Festugato et al., 2021). Figure 5 displays the unconfined compression (q_u) as a function of the η/B_{iv} index. For each curing period, it was possible to correlate q_u to the η/B_{iv} parameter through a power-type relationship, Eq. 2. The exponent was adopted as -1.30 because this was found as a usual value for sandy materials (Consoli et al., 2010, 2012, 2017; Diambra et al., 2017).

$$q_u(kPa) = A \times 10^4 \left(\eta/B_{iv} \right)^{-1.30} \quad (2)$$

Likewise, Eq. 2 was adequate to model the strength results, as shown by the great R^2 values in Table 3. The decrement in the porosity implies the augment in the degree of interlocking between the particles, which favours the strength development (e.g. Consoli, Da Silva, et al., 2018; Consoli et al., 2007; Consoli, Winter, et al., 2018). Besides, it is evident that greater quantities of AAC ($\uparrow B_{iv}$) have led to strength gains owing to a more developed cement matrix (e.g. Cerveira et al., 2017; Consoli et al., 2021; Karatas et al., 2019). The cement phase evolves during the curing period, and the strength growth rate diminishes after 28 days.

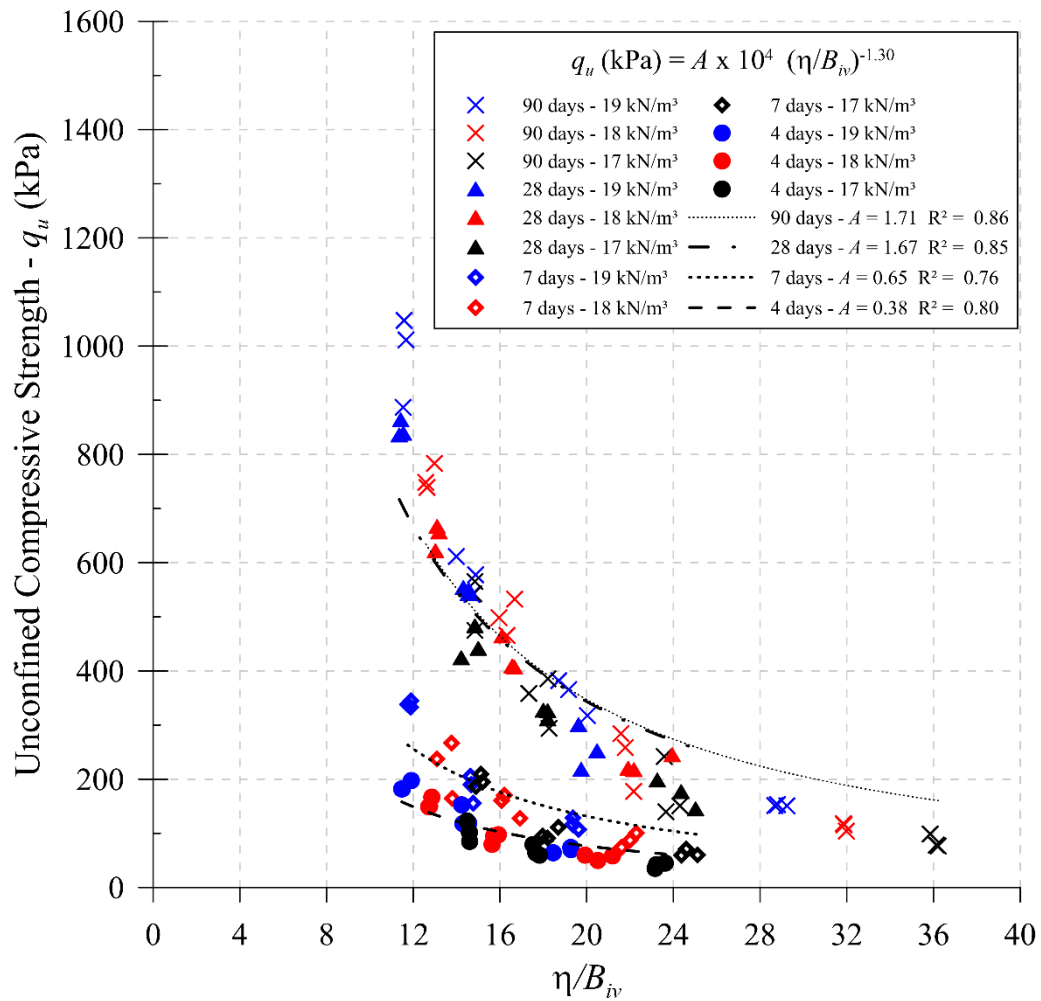


Figure 5: Unconfined compressive strength as a function of the porosity/binder content index

Table 3: Parameters for Eqs. (2) and (3)

Curing period	Stiffness data – G_0 (MPa)		Strength data – q_u (kPa)	
	A	Coefficient of determination – R^2	A	Coefficient of determination – R^2
90 days	1.66	0.96	1.71	0.86
28 days	1.44	0.98	1.67	0.85
7 days	0.69	0.84	0.65	0.76
4 days	0.36	0.79	0.38	0.80

The addition of the AAC to the tailings increased strength, especially for the case of 28 days of curing. This increased strength helps the fast development of the stacking, as higher strengths allow for the achievement of higher heights and steeper slopes. Furthermore, the bonding between particles proportioned by the cement suppresses the liquefaction potential in critical zones of the stack.

4.2 INITIAL SHEAR MODULUS

The measurement of shear wave velocities to determine G_0 is considered one of the most reliable methods (Iwasaki & Tatsuoka, 1977; Kramer, 1996). This modulus describes the behaviour of the soil under working loads and seismic

movements and defines the dynamic properties of soils (Lee & Albaisa, 1974). Figure 6 exhibits the initial shear modulus results (G_0) outcomes as a function of the porosity/binder content index (η/B_{iv}). The approach for stiffness results was the same for strength results and yielded equivalent tendencies. Hence, a linear relationship between G_0 and the η/B_{iv} was obtained as follows (Eq. 3):

$$G_0(MPa) = A \times 10^4 \left(\eta/B_{iv}\right)^{-1.30} \tag{3}$$

Table 3 summarizes the A scalar values and the respective coefficient of determination (R^2), considering each curing period for the compacted iron ore tailings-cement samples. A good agreement was obtained between the stiffness and the porosity/binder content index. Furthermore, the direct proportionality between G_0 and the η/B_{iv} ratio indicates that either (i) the increment in the compactness ($\downarrow \eta$) and the (ii) increase in the amount of utilized binder favour the stiffness development in an equivalent manner (Consoli et al., 2012, 2020; Corrêa et al., 2021). Both tendencies promote the increase in the contact area between tailings’ particles and lead to G_0 gains (Yun & Santamarina, 2005).

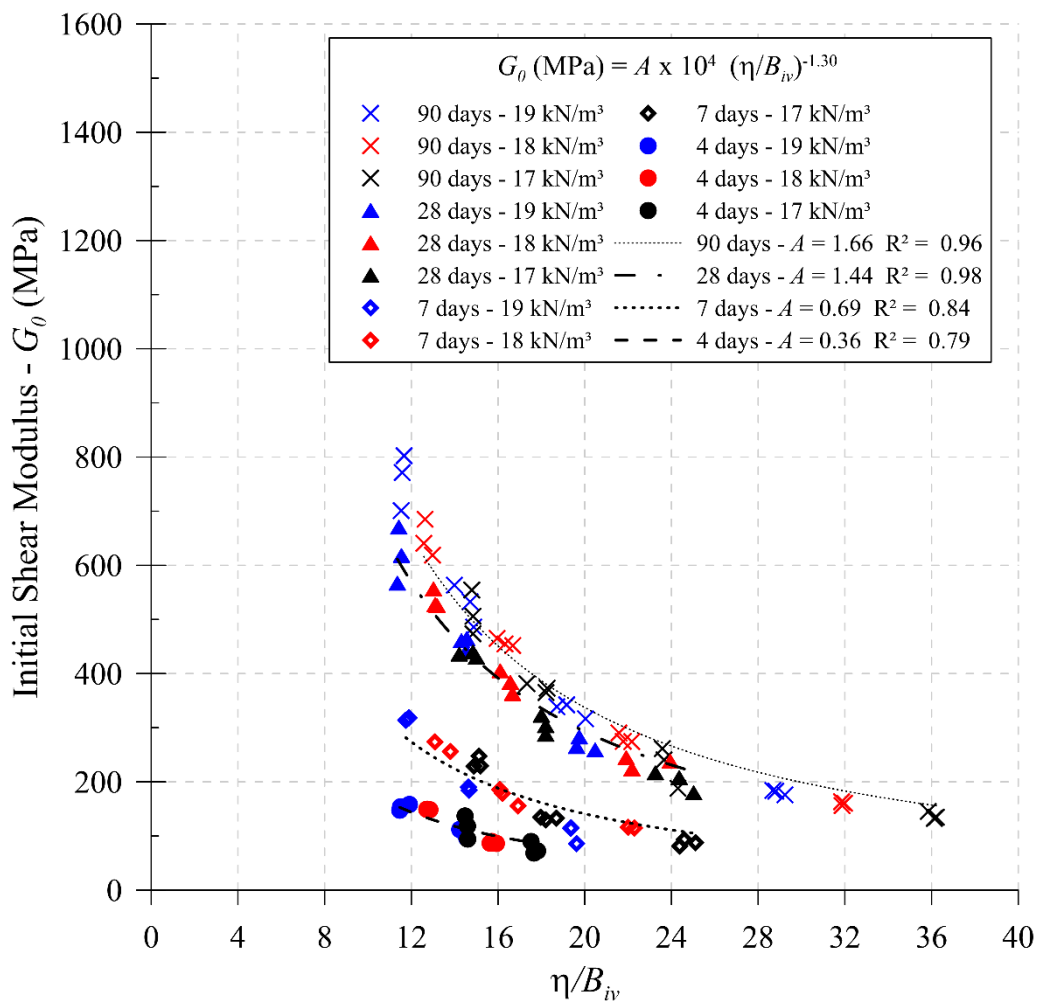


Figure 6: Initial shear modulus as a function of the porosity/binder content index

Following Diambra et al. (2017), the impact of the curing period is attested by the value of A , which has increased proportionally, whereas the other adjustment parameters remained constant. Moreover, the stiffness gain rate is much higher up to 28 days of curing, as indicated by the values of A depicted in Table 3. These results indicate that the development of the binding compounds is more intense during the early stages of curing than over the last. Thus, the material’s stiffness tends to stabilize with time, associated with the timing-dependent development of cementitious reaction products (Chen, 2021; Kim & Kang, 2020; Pinheiro et al., 2020).

Compared with Consoli et al. (2022) the use of Portland Cement has induced higher stiffnesses and strengths than the ones achieved in this experimental program. However, a significant gain was achieved for a waste-based cement aligned with circular economy approach.

4.3 STATISTICAL ANALYSIS

An analysis of variance (ANOVA) was carried out to evaluate the statistical significance of the controllable factors (and their interactions) on the unconfined compressive strength (q_u) and initial shear modulus (G_0) of the samples. A level of significance (α) equal to 5% was adopted, and the data relative to the specimens moulded using 2% of the alkali-activated cement were neglected from the analysis. In this regard, Table 4 summarizes the ANOVA results for the strength tests, Table 5 exhibits the same for the stiffness tests, whereas Fig. 7 portrays the main effects plot for both.

Table 4: ANOVA table for the strength results

Source	Degrees of freedom	Sum of squares	Mean squares	<i>p</i> value
Model	35	6,228,712	177,963	0.000
Linear	7	5,309,124	758,446	0.000
CP	3	3,153,161	1,051,054	0.000
γ_a	2	534,443	267,221	0.000
C	2	1,621,521	810,760	0.000
Interactions	16	859,204	53,700	0.000
CP* γ_a	6	180,925	30,154	0.000
CP*C	6	559,574	93,262	0.000
γ_a *C	4	118,705	29,676	0.000
Interaction	12	60,383	5,032	0.000
CP* γ_a *C	12	60,383	5,032	0.000
Error	72	52,690	732	-
Total	107	6,281,402		

Table 5: ANOVA table for the stiffness outcomes

Source	Degrees of freedom	Sum of squares	Mean squares	<i>p</i> value
Model	17	3,103,451	182,556	0.000
Linear	7	2,979,658	425,665	0.000
CP	3	2,262,673	754,224	0.000
γ_a	2	124,225	62,112	0.000
C	2	996,386	498,193	0.000
Interactions	10	75,386	7,539	0.000
CP* γ_a	6	61,063	10,177	0.000
γ_a *C	4	24,918	6,230	0.015
Error	81	153,200	1,891	-
Total	98	3,256,651		

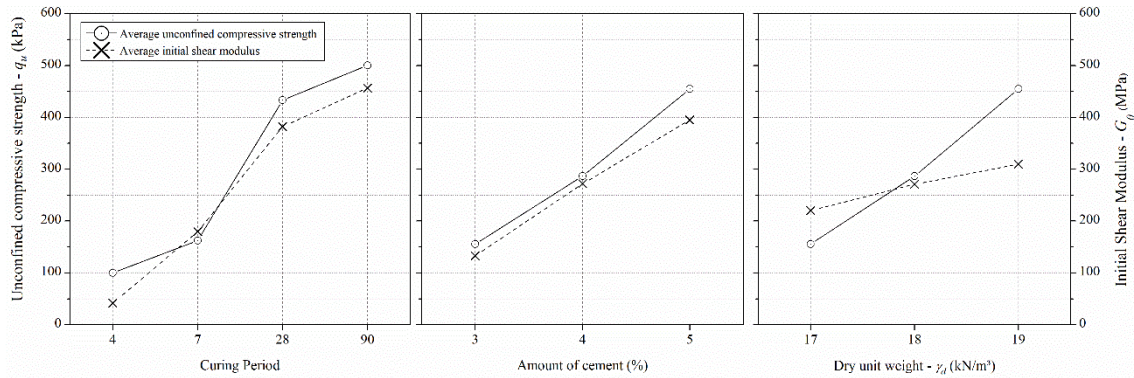


Figure 7: Main effects plot for the strength and stiffness results

All the main factors and interactions are statistically significant in altering the response variables (q_u and G_0) at the adopted level of significance (i.e., p values < 5%). This output means that the strength and stiffness of the cemented IOT were sensitive to alterations in the controllable variables (i.e., curing period, dry unit weight, and amount of cement). For example, the changing caused in q_u and G_0 by the rise on the dry unit weight, from 17 kN/m³ to 18 kN/m³, were statistically significant. The influence of the single factors (strength and stiffness) is more significant than the effect of their interactions, as demonstrated by the magnitude of the sum of squares values.

The main effects plot (Fig. 7) demonstrates that the q_u and G_0 results were similarly affected by the controllable variables, corroborating the trends previously described using the η/B_{iv} based relationships. It is visible the more significant influence of the curing period (CP) over the dry unit weight (γ_d) and amount of cement (C). The role of the dry unit weight is related to the degree of interlocking between the particles, whereas higher amounts of cement favour the binding between the tailings' constituents (e.g. Consoli, Da Silva, et al., 2018; Consoli, Winter, et al., 2018; Corrêa et al., 2021). In addition, a more compacted structure benefits the development of the cement matrix, which explains the statistical significance of the γ_d - C interaction. The formation of the binding compounds occurs over time which attests to the great effect exerted by the curing period and, as well, the significance of the interaction amidst the curing period and amount of cement (e.g. Correia et al., 2019; Pinheiro et al., 2020).

4.4 LIFE CYCLE ASSESSMENT

Figure 8 and Table 6 shows the results of the life cycle assessment established in this work. For the eleven impact categories evaluated, the binder that uses a production technique with mining tailings allowed a reduction in the environmental impact in 10 categories in the stabilization of 100 m³ of tailings for stockpiling. On average the binder provided a reduction of 29% compared to the conventional binder.

For the two binders compared, the production of sodium silicate generates a greater contribution in the impact categories and, consequently, metakaolin generates a lower impact even though it represents the largest portion of material in the binder. The production of sodium silicate uses sodium hydroxide in its production. According to Hong et al. (2014), the production process of sodium hydroxide involves the use of significant quantities of electricity, raw salt, sulfuric acid, sodium carbonate, sodium sulphite, and other materials. As a result, sodium hydroxide has a greater impact on the environment in terms of its contribution to environmental factors.

The reduction in energy for the production of sodium silicate, with the technique proposed by Vogt & Lameiras (2019), directly saved the consumption of 17.58 x10³ MJ. The use of mining tailings for the production of AAC, also in a direct way. The main categories of impacts affected were cumulative energy demand, global warming, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication. Therefore, the resulting change in AAC production has made it possible to create an environmentally friendly production chain and a more sustainable tailings stabilization. Along with the reuse of tailings and reduction of waste, the new binder production chain performance demonstrates that it contributes towards CE.

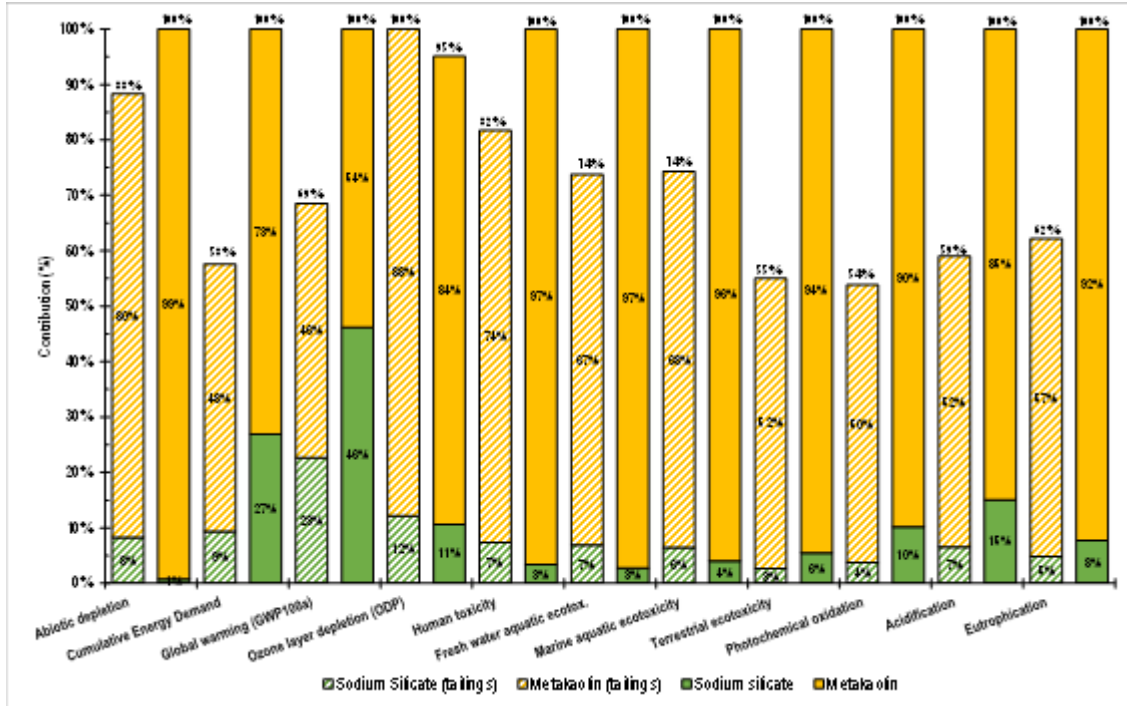


Figure 8: Eco-profile of AAC with tailings compared to conventional AAC

Table 6: Environmental impacts for the stabilization of 100m³ of iron ore tailings

Impact Category	Unity	Alternative AAC	Conventional AAC
Abiotic depletion	kg Sb _{eq}	2.60x10 ⁻²	2.94x10 ⁻²
Cumulative Energy Demand	MJ	4.53x10 ⁴	7.87x10 ⁴
Global warming	kg CO _{2eq}	2.30x10 ³	3.35x10 ³
Ozone layer depletion	kg CFC-11 _{eq}	1.27x10 ⁻³	1.20x10 ⁻³
Human toxicity	kg 1,4-DB _{eq}	1.39x10 ³	1.70x10 ³
Fresh water aquatic ecotox.	kg 1,4-DB _{eq}	8.76x10 ²	1.19x10 ³
Marine aquatic ecotoxicity	kg 1,4-DB _{eq}	1.51x10 ⁶	2.03x10 ⁶
Terrestrial ecotoxicity	kg 1,4-DB _{eq}	4.97	9.04
Photochemical oxidation	kg C ₂ H _{4eq}	0.57	1.06
Acidification	kg SO _{2eq}	8.65	14.7
Eutrophication	kg PO _{4eq}	2.16	3.47

5 CONCLUSIONS

The present research evaluated the technical and environmental viability of a novel alkaline-activated cement produced from mining waste. Using this new binder could enhance several aspects of the mining operation and cope with adopting circular economy in mining. Adapting the ore extraction industry to environmental aspects is a long process and involves the whole operation. However, the valorisation and reduction of waste generated in extraction and correct destination are some points to be improved. The methodology herein presented uses a waste-based source of silica and an alkaline-activator for use in dry stacks, relating all these issues in one application. Furthermore, the small amounts of binder

introduced could increase the structure's performance while still allowing the reprocessing of the tailings in the future. Thus, considering the boundaries of the study, specific conclusions can be drawn:

The porosity/binder content index could express the stiffness at small strains and the strength of the compacted cemented tailings for all the tested curing periods. The obtained curves can be used as dosage curves to predict of a required mechanical response for stacking filtered dry tailings.

Statistically, the curing period was the most important factor in modifying the strength and stiffness response of the mixtures studied. Increases in strength and stiffness greater than 2.5 times were reported between 7 and 28 days of curing.

The increased strength due to AAC addition allows achieving steeper slopes and higher heights in the dry stacking deposition method, which leads to a decrease in the new area impacted by the mining activity.

The AAC considered, which is derived from the waste and tailings, reduces in waste generation in mining operation and adds value to it composing a new binder that can be used for several activities.

The use of AAC with tailings presents an environmentally sustainable option for stabilizing iron tailings when compared to traditional alkaline binders. The energy and natural resources saved in their production provided superior performance in 10 of 11 environmental impact categories assessed.

NOTATIONS

B_{iv}	volumetric binder content
η	porosity
γ_d	dry unit weight
γ_s	unit weight of solids of the iron ore tailings
γ_c	unit weight of solids of the alkali-activated cement
w	moisture content
q_u	unconfined compressive strength
G_0	initial shear modulus
ρ	bulk density
ANOVA	analysis of variance
AAC	alkali-activated cement
OPC	ordinary Portland cement
IOT	iron ore tailings
MK	metakaolin
SS	sodium silicate
C	amount of alkali-activated cement expressed in percentage
UPV	ultrasonic pulse velocity
R^2	coefficient of determination
V_s	shear wave velocity

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