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Life Cycle Analysis Comparison of Stabilizing Materials for Expansive Soils

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Abstract

Expansive soils present significant challenges to infrastructure stability, necessitating the use of stabilizing materials. This study conducts a comprehensive life cycle analysis (LCA) research design to evaluate the environmental sustainability of various stabilizing materials for expansive soil. The study uses a quantitative analysis assessing materials, including cement, limestone, natural pozzolana, iron ore tailings, and geopolymers (especially alkali-activated slag cement). The method involves a comprehensive LCA, considering phases from raw material extraction through production, use, and disposal. The analysis reveals distinct differences in environmental impact. Cement and lime, common stabilizers, show a high carbon footprint. Natural pozzolana and iron ore tailings exhibit potential as supplementary cementitious materials with reduced environmental impact. Geopolymers, particularly alkali-activated slag cement, offer promising alternatives with lower carbon emissions. This research contributes insights into sustainable geotechnical practices, guiding material selection aligned with environmental goals for effective expansive soil stabilization.

Keywords

Environmental Sustainability; Expansive Soil; Stabilizing Materials; Life Cycle Analysis

1. Introduction

Expansive soils (ES) pose serious challenges to the stability of infrastructures worldwide due to the presence of clay minerals susceptible to volume changes under moisture content variation. These soils undergo significant swell-shrink behavior when they are exposed to alternate periods of wetness and dryness, leading to severe structural damage to civil engineering works. This dynamic behavior makes the ES significantly impact the durability and safety of infrastructures.

In response to these challenges, geotechnical engineers have adopted various soil stabilization techniques to prevent the damaging effect of ES. Stabilizing materials, such as binders and pozzolanic materials, are commonly used to enhance the ES properties and minimize volume changes over time. The utilization of materials that minimize the environmental impact of ES stabilization contributes to sustainable construction practices.

Numerous studies have investigated the environmental effects of traditional stabilizing agents, such as cement and lime. Cement, a widely employed stabilizer, has been subjected to examination due to its high carbon footprint during production (Ellis et al., 2020). Previous research by Chang et al. (2019) and Garcez et al. (2024) have explored the carbon footprint associated with cement-based stabilization and emphasized the need for alternative materials with lower environmental impact.

On the other hand, the literature suggests that natural pozzolana (NP) and iron ore tailings (IOT) can be used as supplementary cementitious materials with reduced environmental impact. Studies by Ghadir & Ranjbar (2018), Bahadori et al. (2018), and Soğancı et al. (2023) demonstrated the viability of these materials in enhancing the mechanical properties of ES while minimizing their environmental footprint.

Geopolymers, particularly alkali-activated slag cement, have garnered attention as a promising alternative with lower carbon emissions (Zeghichi & Benghazi, 2011; Benghazi et al., 2022). The work of Disu & Kolay (2021) shows the potential of geopolymers in sustainable soil stabilization. Understanding the environmental advantages offered by these newer materials is important to guide geotechnical practices toward more sustainable solutions.

In that context, researchers have also conducted several studies on the possibility of recycling mine ore tailings to use them as stabilizing materials, such as lead-zinc ore tailing (Odumade et al., 2022) and IOT (Osinubi et al., 2015). However, their environmental sustainability has not been comprehensively explored. As infrastructure development continues to escalate globally, understanding the ecological impact of soil stabilization becomes a necessity.

This study aims to investigate the sustainability of different stabilizing materials, contributing valuable insights into sustainable geotechnical practices. A life cycle analysis (LCA) is conducted to evaluate and compare the environmental impacts of IOT with natural pozzolana and alkali-activated slag cement, as well as with high carbon footprint conventional materials: cement and lime. The LCA provides a holistic approach by considering the environmental implications of these materials, from extraction to their final disposal after use. This work's findings provide recommendations for environmentally sustainable geotechnical techniques.

2. Materials and Methods

The LCA is led on one tonne of ordinary Portland cement (OPC), Lime (LL), IOT, NP, and alkali-activated slag cement (AASC), with a specific surface area ranging from 3000 to 3500 cm^2/g. Tables 1 and 2 illustrate the physical properties and chemical composition of the studied materials. As their production process varies, their environmental impact also varies (Fig. 1).

The LCA encompasses the different life cycle phases of each stabilizing material. This includes raw material extraction, energy consumption, transportation, water consumption, and carbon footprint.

Table 1: Provenance and physical properties of studied materials.

Material	Provenance	Color	Bulk density (kg/m^3)	Specific gravity	Surface area (cm^2/g)
OPC (CEM II/A)	Cement plant of Tebessa, Algeria	Grey	1371	3.18	3500
LL	Eastern cement & derivatives company, Constantine, Algeria	White	791	3,345	3080
NP	Beni Saf, Algeria	Brown	1030	2.72	3430
AASC	Granular blast furnace slag of El Hadjar steel factory, Annaba, Algeria	Greyish	927	1.85	3350
IOT	Boukhadra Iron Mine, Tebessa, Algeria	Brown	1853	3.95	3410

Table 2: Chemical composition of studied materials (% wt.).

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	Na_2O	Cl^-	LOI
OPC	27,430	05,400	03,480	53,710	01,410	00,920	02,590	00,160	00,004	01.790
LL	01.400	03.540	00.790	81.860	02.130	00.190	00.160	00.062	-	00.270

NP	46,250	17,340	10,260	10,180	02,900	01,640	00,800	03,640	00,010	04.480
AASC	39,700	09,260	01,470	40,250	04,130	00,890	00,590	00,140	00,004	01.590
IOT	20.010	06.000	43.160	02.540	00.390	00.280	01.330	-	-	02.420

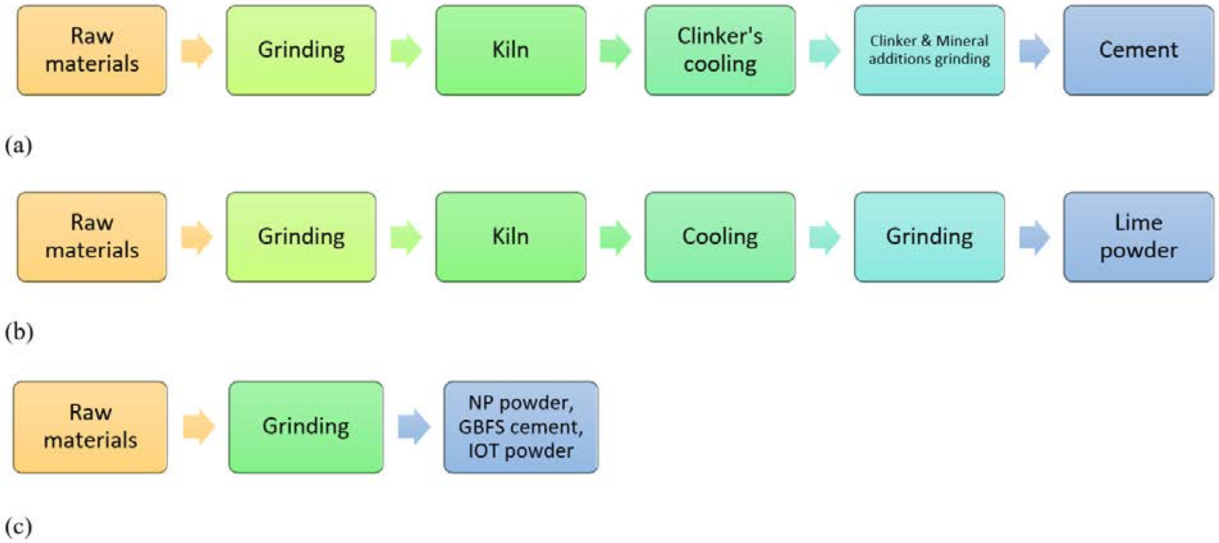

Figure 1: The studied materials' manufacturing flow chart: (a) OPC production; (b) LL production; (c) NP powder, AASC, and IOT powder production

3. Life cycle analysis and discussion

3.1. Raw materials extraction

OPC primarily comprises 80% limestone and 20% clay (Aïtcin, 2016; Benghazi et al., 2022). The extraction of limestone, a pivotal component, poses a significant environmental impact during quarrying due to processes like blasting and haulage, leading to the emission of dust and CO_2. Similar environmental implications arise in the extraction of LL and NP.

Conversely, IOT are byproducts of iron mining activities and are not extracted independently. The IOT from the Boukhadra mine consists of rocks and particles of varying sizes, with a substantial content of low-grade ore exceeding 30 million tonnes (Rouaiguia et al., 2017).

Granulated blast furnace slag (GBFS) is also a byproduct that results from the steel manufacturing process and does not directly contribute to pollution. Consequently, the transportation phase becomes the focal point for potential pollution of IOT and GBFS in this life cycle phase.

In optimizing this transportation stage, the utilization of rail transport emerges as a more advantageous choice than trucks. This choice not only proves economically advantageous but also aligns with low carbon emissions practices. By prioritizing rail transport, we can mitigate the environmental impact associated with the movement of raw materials, thereby fostering a more sustainable and eco-friendly approach.

3.2. Raw materials grinding and calcination

Both grinding and calcinating of the different raw materials for OPC are electricity-consuming processes. The calcination of the clinker in kilns (about 1450°C) is the most polluting phase in OPC manufacturing, with about 0.83 tonnes of CO_2 per tonne of clinker (Antunes et al., 2022) due to both the fuel combustion and the decomposition of calcium carbonates ($CaCO_3$) lime during this phase. The same for the Limestone calcination at a temperature of 900 to 1200 °C, with 1.8 tonnes of CO_2 per tonne of LL (Greco-Coppi et al., 2023). in the case of this work's chosen materials, the complete decomposition of LL calcium carbonates ($CaCO_3$) would produce about 50% more CO_2 per tonne (≈ 1.251 tonnes CO_2/tonne) compared to clinker. The ($CaCO_3$) occurs at a minimum temperature of 900°C (Fig. 2).

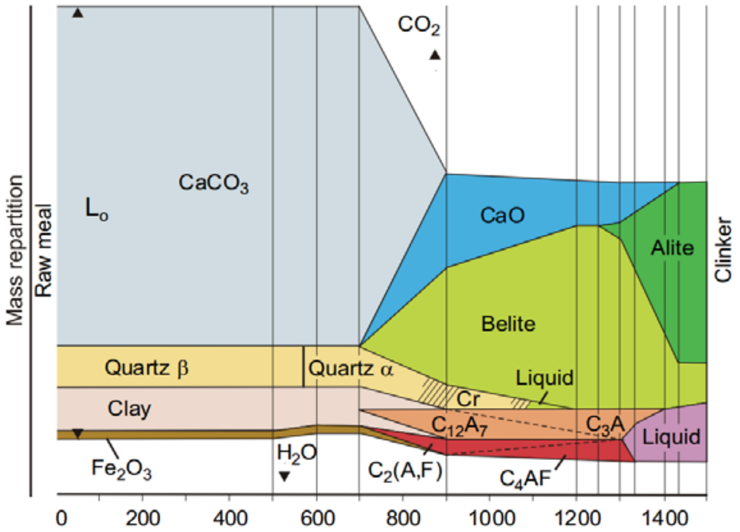

Figure 2: Transformation of raw meal into clinker (Aïtcin, 2016)

3.3. Final Grinding

During this stage in OPC manufacturing, the amalgamation of final ingredients (mineral additions and clinker) takes place, which is accomplished through the grinding and mixing process utilizing ball mills. Clinker demands approximately 40 kWh/tonne to achieve a specific surface area (SSA) of 3500 cm²/g, which is approximately equal to 60% of the total energy consumption in OPC plants (Benghazi et al., 2022).

In contrast, the entire manufacturing process of GBFS cement consumes 43.52 kWh/tonne (Ciments Lafarge, 1999). This divergence in energy consumption underscores the distinctive energy profiles associated with these materials, emphasizing the importance of considering energy efficiency in the manufacturing process.

In this study, both IOT and NP underwent laboratory grinding. Notably, IOT exhibited a grinding time comparable to that of GBFS, indicating similar processing requirements. Conversely, NP necessitated a more extended grinding duration, approximately 1.5 times longer than GBFS, to achieve the targeted SSA. This difference in grinding times depends on the material's chemical composition, porosity, and mineralogical properties.

Tables 3 and 4 present the energy consumption and the carbon footprint of the studied stabilizing materials, respectively.

Table 3: Energy consumption estimation of studied stabilizing materials based on Wächter et al. (2021) and Simoni et al. (2022) work

Material	Energy Consumption (kWh/tonne)
OPC	110,28
LL	20 to 50
NP	62.64
AASC	46.32
IOT	46.34

Table 4: Carbon footprint estimation of studied stabilizing materials based on Wächter et al. (2021) and Simoni et al. (2022) work

Material	Carbon footprint (tonnes CO_2/tonne)
OPC	0.834
LL	1.0 to 1.8
NP	0.150
AASC	0.140
IOT	0.150

3.4. Water consumption

Water consumption in OPC manufacturing plants varies widely, spanning from 0.14 to 1.28 L/kg of cement (Nydrioti et al., 2023). As depicted in Figure 3, the water demand of the investigated stabilizing materials is showcased. OPC demands 28% of water to achieve normal consistency, a factor that significantly influences its water consumption.

Pozzolanic materials exhibit a positive impact on reducing water demand, particularly evident in the cases of NP and Industrial IOT. Additionally, AASC, formulated using NaOH as an activator with a concentration of 5 mol/L, demonstrates a lower water demand compared to OPC. This is attributed to the small Ca/Si ratio (Zeghichi & Benghazi, 2011), signifying a crucial aspect of environmental stabilization. The diminished water demand implies that less water is required for the stabilization process when employing AASC, NP, and IOT, compared to OPC and LL.

While geopolymers and pozzolanic materials (AASC, NP, and IOT) exhibit a slower development of early mechanical strength in comparison to soil stabilized with cement, it is notable that these materials continue to enhance their long-term mechanical strength beyond the conventional 28-day period (Zeghichi & Benghazi, 2011; Ahmed et al., 2019). This characteristic highlights the enduring and sustainable nature of these alternative materials in the stabilization context, emphasizing their potential for long-term infrastructure resilience.

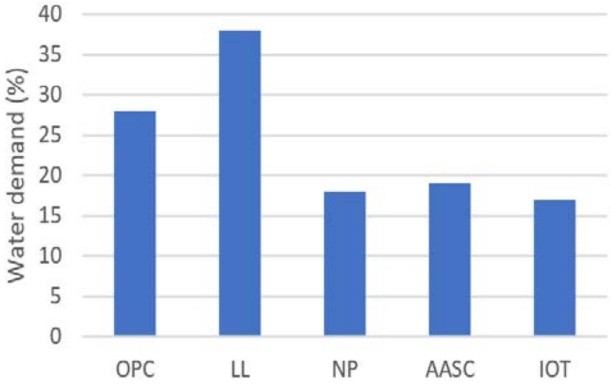

Figure 3: Water demand of the different studied stabilizing materials

Table 5 provides a comparative overview of the environmental impact of OPC, LL, NP, and AASC based on data from existing literature. It can be noticed that the current study values from Tables 3 and 4 are generally consistent with those found in the literature. However, it is important to note that some values are not reported in the literature, particularly those for IOT. This gap is attributed to the relatively nascent stage of research in utilizing IOT as a stabilizing material. Therefore, the current findings of the present paper contribute valuable preliminary data, offering a foundation for further exploration and validation.

Table 5: Summary of literature review on OPC, LL, NP, and AASC as stabilizing materials

Material	Reference	Energy consumption (kWh/tonne)	Carbon footprint (tonnes CO_2/tonne)	Water demand (%)
OPC	Wächter et al. (2021)	110.28	0.834	-
	Simegn et al. (2021)	-	-	0.26 to 0.33
LL	Simoni et al. (2022)	20 to 50	1.0 to 1.8	0.40
NP	Heath et al. (2014)	-	0.004 to 0.435	-
AASC	Black (2016)	-	0.052 to 0.143	-
	Zeghichi et al. (2011)	-	-	0.19

4. Conclusions

This life cycle analysis (LCA) compares the environmental impact of expansive soil stabilizing materials, emphasizing the need for sustainable geotechnical practices. Traditional stabilizers like cement and lime exhibit high carbon footprints, prompting the exploration of alternative materials.

NP and IOT emerge as eco-friendly options, offering reduced environmental impact as supplementary cementitious materials. Geopolymers, especially alkali-activated slag cement, present lower carbon emissions The LCA encompass and diminished water demand, making them promising alternatives for environmental stabilization.

Consideration of energy efficiency during raw material extraction, grinding, and final manufacturing stages underscores the importance of sustainable material selection. While geopolymers and pozzolanic materials exhibit slower early mechanical strength development, they compensate with continued long-term mechanical strength enhancement, showcasing their potential for enduring infrastructure resilience.

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Ethics approval

Not applicable.

Conflict of interest

The authors declare that there is no competing interest.

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