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Geo-polymerization of mining tailing for use as a pavement construction material – a review

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Abstract

Pavement construction usually involves using large quantities of natural aggregate materials majorly extracted from quarries and, in many cases, with the use of conventional stabilizers such as Portland cement, lime, and bitumen. In many developing countries, the exploitation of quarries has been so massive that there exists a shortage of these aggregates. Hence, the use of conventional stabilizers is a common practice. However, the use of conventional stabilizers is a major source of environmental contamination for the environment. Therefore, alternative aggregate materials and stabilization techniques in pavement construction are highly sought after. Recently, some researchers have proposed a new approach as an alternative to using conventional binders via alkali activation called geo-polymerization to produce geopolymers. Some studies have shown that mine tailings (MT) can be used as a road base material through geopolymerization. Even though there are different types of tailings, specific interest is on copper, iron, and gold tailings, this is due to their dominance in mining areas of South Africa. This paper presents a review of the mechanical properties of geopolymerized tailings to enhance understanding of their potential application in sustainable infrastructures, such as pavements.

Keywords: Geopolymerization, pavement, mine tailings, mechanical strength, stabilization.

1. INTRODUCTION

Pavements are structures designed to withstand traffic loads and are composed of several layers made up of natural aggregate materials such as sand, cobblestones, and laterites. The functionality of the pavement is determined by the geotechnical properties of these aggregates and binding materials. Pavement construction requires a large quantity of natural aggregate materials, with an average of 20,000 tons of aggregate needed for every kilometre of the roadway [1]. Around 90% of the aggregates used in pavement construction are either virgin or sourced directly from quarries [1]. Developing nations are already experiencing a shortage of high-quality natural aggregate materials. This scarcity poses a significant challenge to the construction and maintenance of pavements, which are vital to transportation infrastructure. In areas facing a shortage of natural construction materials, two options exist: finding new quarries or using conventional stabilizers like Portland cement (OPC) and lime to enhance the mechanical properties of low-grade materials like soils and mine tailings (MT). However, the use of these stabilizers has significant environmental consequences, including high energy consumption and emission of greenhouse gases [2].

Mine tailings are waste materials generated during the extraction, chemical, and physical treatment of mineral ores, and the mining industry produces vast amounts of them annually [3]. In South Africa, over 315 million tons of tailings are generated every year, with gold tailings accounting for 105 million tons [4], it was also stated that copper tailings in South Africa occupied a large surface area of land [5-6]. The properties of tailings vary depending on the type of mineral ore and the compounds they contain, such as silicon, aluminium, quartz, pyrite, lead, and uranium. Although tailings are considered useful for geopolymerization due to their fine particle sizes, high Silica (Si) and Aluminium (Al) content. However, they contain toxic elements/metals, in the form of chlorides or sulphate solutions [1, 5]. Due to the existence of hazardous materials in tailings, they cannot be utilized in civil construction projects. Therefore, tailings are required to be reprocessed into less hazardous waste before disposal or reuse for construction purposes [8]. Disposing of mine tailings is costly and can result in various environmental problems such as land use, air pollution, water bodies contamination, and tailings dam failures [9].

Geopolymerization of MT offers sustainable and eco-friendly solutions to environmental problems caused by mine tailing disposal. This process involves the chemical reaction of alumino-silicates materials in an alkaline solution, creating a geopolymer material. Geopolymers offer several advantages over conventional stabilizers, including rapid strength development, acid resistance, immobilization of toxic metals, reduced energy consumption, and greenhouse gas emissions [10-12]. As a result, geopolymer has been identified as a potential alternative construction material, with some researchers studying its potential use in road construction.

2. TYPES OF MT AND THEIR PROPERTIES

Tailings from various minerals have been used as substitutes for aggregate materials in road construction, with iron, copper, coal, tungsten, granite, and gold being the most used types [9]. These tailings are predominantly sand-sized ranging from 28% to 70%, and fall under the ML, SM, and SP categories of the Universal Soil Classification System (USCS), [13-16]. The geotechnical properties of tailings are determined by their mineral composition and collection location [9]. Tables 1 and 2 summarize the geotechnical and chemical properties of various types of tailings.

Table 1. Geotechnical properties of various types of MT

Types of MT	Specific gravity	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Maximum Dry Density (KN/m^3)	Optimum Moisture Content (%)	Sand size (%)	Finer than micron (%)	USCS	Ref
Iron	3.08 - 3.74	28	19	9	_	_	_	_	_	[17] [18]
Copper	2.72 - 2.82	25.2 – 28	11.5 - 13	13.7 -15.	16.7 -16.9	13.3 -16.0	43-55	45 -57	SC	[15],
Gold	2.78 - 2.86	44.0	_	Non-plastic	15.7 -17.0	17 -22.5	17-28	72 -83	ML	[15],
Coal	2.03	_	_	Non-plastic	15.5	12.0	70	15	SM	[20]
Bauxite	3.00	37	33	4	_	_	3	30	ML	[21]

ML: Low plasticity silts
SM: Silty-sand mixtures
SP: Poorly- graded sands

Table 2. Chemical Composition of various types of MT

Types of MT	AlO_3	SiO_2	Na_2O	SO_3	K_2O	Fe_2O_3	MgO	CaO	MnO	Ref.
Iron	3.36 - 3.40	41.95 - 45.64	0.41	_	0.61	31.32- 47.70	_	_	_	[22], [23]
Copper	13.96 - 14.10	55.90 - 71.52	3.02 - 4.12	2.22	1.82 - 3.89	3.07 - 3.64	0.49 - 1.78	0.16- 2.27	0.06 - 0.07	[16], [24]
Gold	15.05	60.40	_	0.30	0.40	6.60	1.70	6.90	_	[24]
Bauxite	14.00	1.20	_	_	_	30.90	_	2.50	1.70	[25]
Tungsten	14 - 16.66	53 - 55.60	0.62	3 - 5.80	3.5 - 7.6	12.33 - 14.60	1.27	_	_	[26]

3. STABILIZATION OF MT THROUGH GEOPOLYMERIZATION

Previous studies have documented the use of conventional stabilizers to stabilize MT [15, 17-20]. However, these stabilizers have significant drawbacks such as high energy consumption and the emission of large amounts of carbon dioxide (CO_2) during manufacturing. In 2016, the production of OPC accounted for nearly 8% of global CO_2 emissions [21]. As a result, there is a pressing need for more environmentally sustainable MT stabilization methods.

Researchers have studied the stabilization of different MTs alone or in integration with other materials based on geopolymerization [9,22-25,28-36]. These indicate the possibility of geopolymerized tailings being used in construction based on their mechanical strength: Unconfined Compressive Strength (UCS) in accordance with the aggregate material specifications for road construction in different countries. Table 3. summarizes the UCS required by the standards of several countries for cement-treated materials in road base and subbase layers. So far, only a few researchers have investigated the geopolymerization of MT as a road base construction material. Tables 4 and 5 show the stabilization of MT with conventional stabilizers and through geopolymerization MT.

Table 3. Requirements for cement-treated materials as road base/subbase in different countries.

Country	Stabilizer OPC content (%)	7-day UCS (MPa) – (base/subbase)
South Africa	1.5 – 3.0	1.5 – 3.0 (base)
United Kingdom (UK)	2 – 5.0	2.5 – 4.5 (base)
China	> 4 (road-mix method) > 5 (central-plant mixing)	> 2 (subbase), > 4 (base)
Spain	3.5 – 6.0	4.5 – 6.0 (base)
U.S.A	3 - 10	1.03 – 2 .75 (base) [26] 2.06 – 5.51 (base) [27]

Table 4. Stabilization of MT with conventional stabilizers.

No.	Waste material (wt.%)	Grain size	Stabilizer	Curing Condition	Test conducted	UCS (MPa)	Ref.
1	Copper MT (100%)	1.0 - 0.001 mm, 41% passing No. 200 sieve (0.0075 mm)	OPC (2-12%)	At ambient temperature: OPC: for 7, 28, and 90 days.	UCS, tensile, and shear strength	3.45 (8% OPC) – 7 days	[28]
2	Kimberlite MT	0.075- 0.020 mm	OPC (5%)	Cured in moisture sand for 7 and 28 days	CBR and UCS	1.33 (7 days), 2.05 (28 days)	[29]
3	Granite MT	97% < 4.75 mm	OPC (3-6%)	Ambient temperature for 7, 28, and 90 days	UCS, drying shrinkage	4.37, 6.39, and 7.17 (5% OPC), 7, 28, and 90 days	[30]
4	Iron MT (90- 99%)	85% < 0.075 mm	OPC (1-10%)	for 7 days;	UCS, CBR,	1.32 (5% OPC)	[31]
5	Gold MT (93- 97%	28% < 0.425, mm 71% < 0.075 mm	OPC (3-7%	Mixtures were placed in a humid room at 23 ±2˚C for 7 days	UCS, pulse velocity test	1.8 (7% OPC)	[32]
6	Iron MT (0- 10%)	< No. 200 sieve	OPC (1-4%)	7- and 28-day curing	UCS	-	[33]

Table 5. MT improved through geopolymerization.

No	Waste material (wt.%)	Grain size	Alkali activator	Curing condition	Test conducted	UCS (MPa)	Ref.
1	Copper MT (100%)	100%< 0.420 mm	NaOH (0, 3, 5, 7, and 11 M)	Oven at 35^{0}C for 7 days	UCS, SEM	5.32 (11 M (NaOH)	[9]
2	Copper MT (100%)	36%< 0.075 mm	NaOH (0- 6%)	Ambient temperature for 7 days	UCS, SEM	2.5 (2% NaOH)	[34]
3	Tungsten MT (100%)	100%< 2 mm	-	-	Los Angeles abrasion test and freeze-thaw resistance	-	[35]
4	Gold MT (100%)	74% < 0.075 mm	Na_2SiO_3	8, 14, 21, and 28 days at room temperature	UCS	30(8% of Na_2SiO_3)	[9]
5	Copper MT	100%< 0.420 mm	NaOH (5, 10, 15 M)	ambient temperature for 4 days	UCS	4.4(10 M)	[36]

4 DISCUSSION

The lack of quality natural construction materials and the disposal problem associated with MT prompted the interest of researchers in the field of transportation engineering to find an alternative solution. These reviews showed that geopolymerized MT as an alternative material for road construction has good mechanical properties compared to construction materials being stabilized with conventional stabilizers. The research on the unconfined compressive strength (UCS) of geopolymerized MT is the common variable stipulated by different standards. In terms of (UCS), the standards presented in Table 3 and the 7-day UCS values by the studies listed in Tables 4 and 5 are compared, it was observed that geopolymerized MT conforms to the specifications of various countries, indicating the feasibility of MT as a suitable aggregate material for road construction. As with any waste, the use of MT for pavement construction should incorporate environmental considerations such as leachate of toxic metals/elements and durability for long-term use. The standards related to the use of wastes as alternative aggregate materials in construction are limited.

5. CONCLUSIONS

As a result of systematic reviews on the use of geopolymerized MT as a material for road construction, the following conclusions have been derived:

• The most significant benefit of geopolymerization is the use of a variety of industrial by-products as the basic raw materials in their composition.

• Geopolymerized MT has good compressive strength suitable for road construction.

• Geopolymerized MT represents an important step towards sustainability since conventional stabilizers are characterized by high energy consumption levels and leave a large carbon footprint (the geopolymerized binder effuses 80% less CO_2 than Ordinary Portland cement) [37].

• In addition, the utilization of industrial by-products in the geopolymerization allows waste to be recycled and lowers the surface area of landfill space required while simultaneously supporting environmental conservation.

Despite the general acceptance of Ordinary Portland cement, geopolymerization has the potential to revolutionize cement production due to its advantages. However, insufficient information is evident in some areas of geopolymerization, which necessitates further research. Thus, more studies are needed to understand the compressive strength of geopolymerized tailings with multiple precursors and their behaviour under both laboratory and field conditions.

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