Plant Archives Vol. 24, No. 2, 2024 pp. 2653-2658 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2024.v24.no.2.379

PROMOTING SUSTAINABLE INFRASTRUCTURE DEVELOPMENT THROUGH SOIL STABILIZATION WITH RECYCLED MATERIALS: A REVIEW

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(Date of Receiving- 23-01-2024; Date of Acceptance- 04-04-2024)

ABSTRACT

As society advances, the development of infrastructure becomes indispensable. However, traditional construction methods have long posed significant threats to the environment, primarily through the release of carbon emissions. In light of the pressing need for sustainable construction practices, this research investigates soil stabilization with recycled materials as a green approach to infrastructure development. The study focuses on the application of recycled resources, including fly ash, recycled plastics, and reclaimed asphalt pavement (RAP), to enhance soil properties both mechanically and environmentally. The results demonstrate that soil stabilization with recycled materials is a cost-effective, eco-friendly strategy to create infrastructure while mitigating adverse environmental impacts. This paradigm shift towards environmentally responsible building techniques is imperative to safeguard our planet.

Key words**:** Soil Stability; Sustainable; Waste material; Construction; Recycle

Introduction

The world faces a dire environmental challenge as human activities, particularly in the construction, industrial, agricultural, and waste management sectors, contribute significantly to the emission of carbon dioxide (CO_2) and carbon monoxide (CO) (D'Alessandro *et al.*, 2017; Mostonejad *et al.*, 2017). These noxious gases are major contributors to global warming and climate change. Additionally, practices such as indiscriminate disposal of solid waste materials, including agricultural, household, municipal, and biomass waste, further worsen the environmental hazards we face (Fig. 1). To counter this imminent threat, there is a growing call for engineers and professionals in various fields to adopt eco-friendly, eco-efficient, and sustainable approaches to protect our planet from the perils of global warming (Onuh *et al.*, 2018; Mahmud *et al.*, 2018).

Ordinary Portland cement, a staple in the construction industry, is notorious for its substantial CO_2 emissions. It is employed in almost every civil engineering project, yet it exhibits limitations in terms of resistance to cracking, durability, fire and heat resistance, sulfate resistance, and brittleness. In stark contrast, solid waste materials, specifically ash (amorphous) and crushed waste (dust), have emerged as promising alternatives to cement. These materials, due to their high pozzolanic properties and aluminosilicates content, can not only replace cement but also enhance the resistance of infrastructures to various environmental stresses (Fig. 2) (Onyelowe *et al.*, 2018; Osinubi *et al.*, 2019). Furthermore, certain solid waste derivatives, such as bio-peels, have been employed in wastewater detoxification and purification. These environmentally friendly binders, called geopolymer cements, are derived from solid waste and alkali activators and find application in soft soil reengineering, asphalt and concrete modification (Fig. 3).

This research emphasizes that human activity, including solid waste generation, will continue on our planet, making it essential to sustain eco-friendly technologies. The list of solid waste derivatives utilized in various construction works is extensive, encompassing materials such as fly ash, quarry dust, rice husk ash, recycled plastics, and reclaimed asphalt pavement. This paper aims to review the recycling and reuse of solid waste materials as a central hub for achieving eco-friendly, eco-efficient, and sustainable civil and mechanical engineering infrastructures with minimal carbon emissions.

Conventional Soil, Concrete, Wastewater, and Pavement Engineering

For centuries, conventional engineering practices relied on traditional methodologies and chemical-based alterations to address environmental, structural, geotechnical, hydraulic, and mechanical challenges (Kathirvel *et al*., 2018; Saas *et al*., 2018). These practices aimed to achieve economical, efficient, and durable designs that offered optimal performance and longevity. However, these approaches were associated with the release of harmful byproducts into the environment.

In soil mechanics, the suitability of soil for construction is determined by its behavior under various forces and loads. The properties of soil are essential to ensure its safe use in construction and to enhance properties that do not meet the required standard (Hamidi *et al*., 2016). Ordinary Portland cement (OPC), widely used in civil engineering, releases an equivalent amount of CO_2 into the environment, making it a major contributor to carbon emissions. Additionally, the traditional materials used in construction, including cement and bitumen, emit CO2 and CO during their application. This research emphasizes the urgent need to transition toward eco-friendly and eco-efficient practices in civil engineering to protect our environment (Hoy *et al*., 2016) .

Recycling and Reuse of Wastes

• **Crushed Solid Wastes and Powders:** Recycling and reusing solid waste materials involves crushing them into various forms like crushed waste plastics, ceramics, glasses, and oyster shell powder. These materials have been found to be effective binders, fillers, and modifiers in soil stabilization, concrete production, and asphalt production. The high pozzolanic properties of these materials enhance cementation processes, and they contribute to the formation of compounds that improve the strength of treated mixtures. The key innovation is that these materials are derived from solid waste, making them environmentally friendly alternatives to traditional construction materials (Oluremi *et al*., 2018; Eberemu *et al*., 2018).

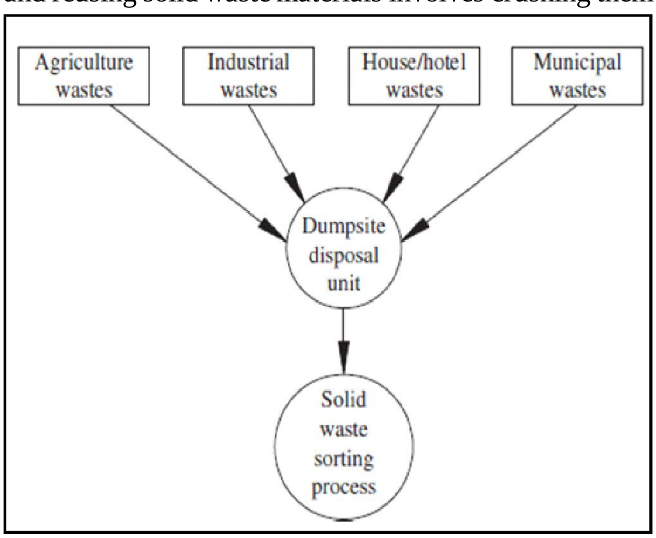

Fig. 1: Process used for solid waste sorting.

• **Burnt Solid Wastes and Ashes:** Most ash materials used in soil stabilization, concrete production, and asphalt modification are obtained through uncontrolled combustion, which poses a significant environmental threat (Osinubi *et al*., 2013; Atahu *et al*., 2019). To address this issue, controlled incineration models have been designed to capture the CO and CO_2 emissions during the burning process. This environmentally friendly approach allows for the use of ash materials without releasing harmful carbon oxides into the atmosphere. Additionally, certain solid waste derivatives, such as geopolymer cements, are synthesized using alkali activators, offering an eco-friendly alternative to traditional cements.

• **Activated Coupled Solid Waste Derivatives and Geopolymer Cements**: Geopolymer cements are coupled binders created by blending solid waste ash or crushed waste ash with alkali activators. These eco-friendly cements can partially or fully replace conventional cements in civil engineering projects, reducing carbon

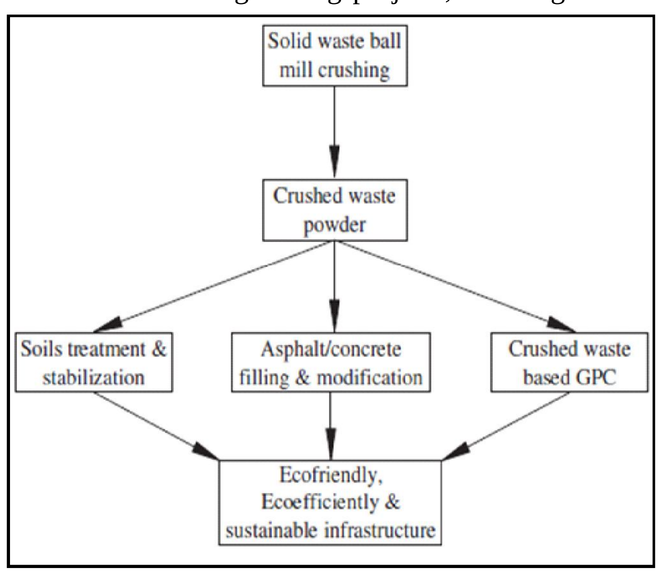

Fig. 2: The process of producing crushed solid waste and using it to develop sustainable, economical, and green infrastructure.

emissions. The alkali activators are produced using sodium hydroxide and sodium silicate, and research has shown that various forms of geopolymer cements can be synthesized using this approach. These cements have properties that enhance resistance to various environmental factors and improve the durability of civil infrastructures (Onyelowe *et al*., 2017; Onyelowe *et al*., 2018).

Eco-friendly, Eco-efficient, and Sustainable Re-engineering and Achievements

The research findings indicate that utilizing recycled materials, specifically RAP, fly ash, and recycled plastics, for soil stabilization leads to significant improvements in soil properties. This includes enhancements in compressive strength, shear strength, and load-bearing capacity. Additionally, the environmental impact assessment demonstrates reduced carbon emissions and resource conservation when compared to conventional stabilization methods. The cost-benefit analysis confirms the economic feasibility of using recycled materials for soil stabilization.

The ozone layer is being destroyed and global warming is being exacerbated by CO and CO_2 emissions from human activity and engineering for far too long. Climate change experts have emphasized the detrimental effects of CO/CO_2 emissions on our planet at a number of forums and summits. In order to repair our globe, those in charge of this environmental damage have been asked to look into eco-friendly methods. Since research indicates that ordinary Portland cement (OPC) releases an equivalent amount of CO_2 into the environment, one tonne of OPC used in construction releases an equivalent amount of CO2 into the atmosphere, the use of Portland cement in civil engineering projects has been identified as a significant contributor to carbon oxide emissions. This is alarming and dangerous, and our planet's future seems bleak and unknown if such actions continue. OPC is frequently used in civil engineering for the reengineering of soil and concrete, however because of its carbon dioxide emissions, it does not meet environmentally friendly standards. Moreover, its susceptibility to heat, sulphate, damp, cracking, and shrinkage makes it less durable.

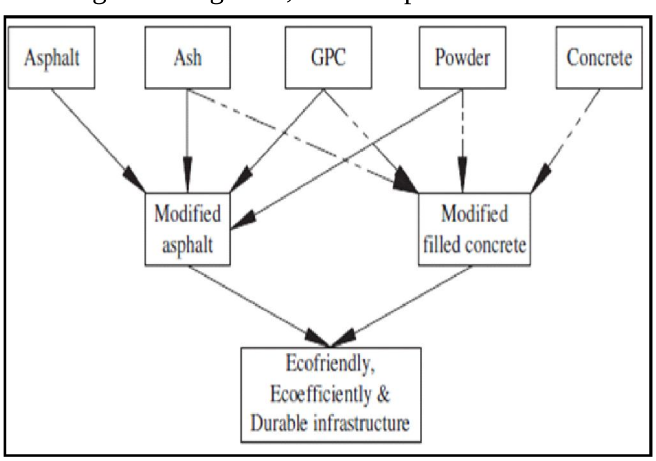

Fig. 3: Use of solid waste ash and powder in the alteration of concrete and asphalt.

However, environmentally acceptable compounds that can take the place of OPC as additional cementing materials are usually produced by procedures that also release CO_2 during combustion. Using ash from direct solid waste combustion, this research has successfully used SWI-NaOHOCEM to collect CO/CO_2 emissions during combustion. Based on this concept, ash materials can be modified for a range of geotechnical and construction applications, absorbing CO_2/CO_2 and producing eco-friendly products ($NaHCO_3$, Na_2CO_3, and H_2) suitable for domestic and commercial applications. In addition to being environmentally friendly, the application of ash and its products (geopolymer cements) to soil, concrete, asphalt, and other materials produces structural infrastructures that are highly resistant to heat, temperature changes, salt attacks, cracking, punching deformations, lateral shifts, and fluctuations in water levels. These deformations can cause volume changes, such as swelling and shrinkage, moisture and capillary actions, and brittleness. Previous research findings also show that these constructions are more durable. Given that human, agricultural, and industrial activities will always be part of our environment, the release of solid waste is an inevitable reality (Ariozet *al*., 2006; Jhatial *et al*., 2019).

- **Consistency Limits:** Experimental studies on soft clay soils treated with ash from solid waste and its related derivatives, including geopolymer cements and composites, have demonstrated very favorable consistency characteristics. These non-crystalline materials' properties, when used in the treatment process, make it easier for clay minerals and the dissociated ions from the additives within the activation complex interface to engage in pozzolanic and hydration reactions, which improves the treated soils' liquid limits, plastic limits, and plasticity indices. Two strategies have recently been proposed for identifying expendable clay structures in soft soils, a critical step in enhancing soils to meet engineering standards. Surprisingly, these successes were obtained without the use of regular Portland cement and instead through environmentally friendly methods. In order to meet the consistency requirements for using them as foundation materials, these test soils have changed from having a very high consistency to a medium consistency, and even to a low consistency.

• **Compaction:** The behavior of soft soils after being treated with additions made from solid waste, such as ash and powder, requires an analysis of the correlations between density and moisture. This is related to the stabilization process, which involves densifying the soils. This is often accomplished mechanically by using compactive efforts to minimize voids in the mixtures of treated additives and soils. This densification, which can be differentiated from properties arising from long-term consolidation of soft clay soils, allows constructed soils to tolerate additional loads without immediate compression. To assess improvements, it is necessary to investigate and determine the moisture-density behavior of both treated and untreated soils. Because ash materials are non-crystalline, they contain ions that, in cation exchange interactions with clay minerals and water, dissolve, creating ion combinations that strengthen the soil. As fillers, crushed materials (dust or powder) increase the treated samples' porosity and, as a result, their density. The optimum moisture content (OMC) of treated soils has continuously decreased, according to the results, especially when ash- or powder-based geopolymer cements are used. The polymers' enhanced hydration reactions and moisture resistance are credited with this decrease. Furthermore, the addition of ash, powder, and geopolymer cement in different ratios continuously enhances the maximum dry density (MDD) attained at OMC. Densification during compaction processes is facilitated by the enhancement of inter-granular pores through the inclusion of ash, powder, or ash/powder-based geopolymer cement. Soft clay soil behavior after stabilization is influenced by soil-specific characteristics such as the types of clay minerals present in treated soils and the morphology of soil grains. On the other hand, the way these additives interact with these elements at the interface has improved since their incorporation.

• **Volume Changes (Swelling and Shrinkage):** The behavior of engineering soils is significantly influenced by their swelling and shrinkage characteristics, particularly when these soils are utilized as foundation materials in hydraulically confined situations. Particularly in pavement structures, soil materials employed as foundations are susceptible to moisture-related problems brought on by capillary action, suction, changes in the water table, and lateral percolation. These variations in volume have the potential to produce undesired effects that compromise the functionality and long-term viability of pavement infrastructures and foundations.

These negative qualities in soft clay soils are substantially mitigated by adding ash, powder, or ash/powder-based geopolymer cements during the stabilization process, according to experimental results. First off, the composition and hydration structure of ash or powder materials, which are made from solid waste, are responsible for their moisture-resistant qualities, which enable the soils they treat to stay within reasonable swelling bounds. When these chemicals are used, the likelihood of soil swelling has been shown to decrease as a result of this method. Additionally, these materials demonstrate the ability to withstand drying when going through the depressurization phase of swelling. In soft clay soils, shrinkage usually results in lateral deformations and cracking; however, the addition of solid waste derivatives has changed this unwanted behaviour, mainly because of the ionic makeup of aluminosilicate admixtures.

• **California Bearing Ratio (CBR):** One important property of soil strength that is utilized to evaluate its resistance to shear deformations brought on by penetration and punching is the California bearing ratio (CBR). Determining the appropriate thickness of pavements and other horizontal infrastructure depends on this attribute. The maximum dry density (MDD), which is directly related to the density of compacted soils, has a direct impact on CBR values.

Axial loads are applied to both naturally occurring and treated compacted soils during CBR testing, with close observation of the resulting axial stresses. Typically, there are two conditions in this experiment: wet and unsoaked bearing ratios, which are measured at 2.5 mm and 5.00 mm penetrations, respectively.

• **Unconfined Compressive Strength and Durability Potential:** Unconfined compressive strength is an important measure of soft soil strength that also sheds light on the behavior and long-term performance of treated soils, especially when those treated soils are exposed to hydraulic forces via techniques like strength loss on immersion. This strength assessment determines the point at which the surface area of a treated and compacted sample fails under compression. The addition of ash, powder, and ash/powder-based geopolymer cements to soft soils promotes the development of calcium aluminates and silicate hydrates, strengthening the treated soils as a result. These hydrates are essential for increasing the treated samples' compressive strength. This innovation is unique in that it produces zero carbon oxide emissions into the environment by forming these strength-enhancing hydrates with ecologically friendly ingredients sourced from solid waste. The comparison of the compression index between fully air-cured and partially air-cured samples, as well as between entirely immersion and air-cured samples, yields the durability potential.

• **Resistance Value (R-Value) and Resilient Modulus:** In unbound building settings, robust modulus and resistance value are engineering parameters that are used to characterize materials, especially in pavement construction. These measures allow for the assessment and analysis of material stiffness under a variety of loading and environmental conditions, such as moisture, density, stress, temperature, vertical and lateral loading, and others. They also evaluate the stiffness of engineered materials, such as subgrade stiffness. The resistance value (R-value) of foundation materials is the measure of how well they can tolerate lateral displacement that occurs when they are subjected to vertical loading. It is imperative to stress that these characteristics are strength-related and contingent upon reaching a particular density at the ideal moisture content. In treated blends of soft clay soils, elements originating from solid waste, such as ash, crushed waste (powder), linked geopolymer cements, or other composite materials, interact with the minerals to form floccules and sequestrates. According to experimental results, these materials improve treated soft soils' resistance value, deviatoric stress, and resilient modulus, which helps them function as sustainable and environmentally friendly infrastructures.

• **Marshall Stability:** The measurement of the ideal binder content needed in bituminous pavements is known as Marshall Stability. The design and manufacturing of Marshall Asphalt concrete mixtures are intended to satisfy specified requirements with regard to stability, flow, porosity, and density characteristics. The amount and quality of binding materials employed in asphalt mixtures determine the degree of impermeability. Marshall stability-compliant asphalt concrete is always preferred, and this is contingent upon the binder's quality. It is crucial to take into account the circumstances surrounding the achievement of an ideal binder content that balances different design mixtures. In this regard, addressing emissions discharged into the atmosphere is also of utmost importance. In addition to lowering carbon oxide emissions, the addition of geopolymer cement formed from solid waste ash materials as modifiers in the asphalt production process produces a homogenous blend with excellent resistance to sulphate assaults and cracking. Furthermore, fillers such as ash or powder have been used to improve the concrete's porosity and flow.

Conclusion

The utilization of recycled materials for soil stabilization represents an eco-friendly and sustainable approach to infrastructure development, aligning with the global shift towards environmentally responsible construction practices. This research underscores the efficacy of using RAP, fly ash, and recycled plastics in enhancing soil properties while simultaneously reducing the environmental footprint. By advocating for resource conservation and waste reduction, this approach contributes to more sustainable infrastructure development, all the while preserving natural resources and mitigating environmental harm. In future, we can analyze the economic viability of using recycled materials for soil stabilization compared to traditional methods.

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