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SUSTAINABLE SOIL STABILIZATION OF ROAD PAVEMENT LAYERS USING WASTE MATERIALS: A MINI-REVIEW

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ABSTRACT

The escalating generation of waste necessitates sustainable management strategies. This review explores the potential of waste materials as sustainable stabilizers for soil used in road construction. Conventional stabilizers like cement, while effective, comes with environmental drawbacks that should be addressed. Alternatively, diverse waste-based materials are being investigated as potential substitutes. Their usage in this regard contributes to lessen adverse ecological impact and improve soil properties at potentially low costs. Prior to the application of a specific soil stabilised with a specific waste material for a specific purpose, the potential risk of local environmental and health impacts from release and spreading of harmful substances due to leaching or escape of fugitive dust must be assessed and appropriate action (precautions, mitigating measures, changes of the soil/stabilizer mixture) must be taken when necessary to prevent unacceptable impacts. If properly managed, the utilization of waste materials for soil stabilization aligns with several United Nations Sustainable Development Goals (SDGs). By diverting waste from landfills and promoting their use in construction, this approach presents a win-win scenario for both economic and environmental sustainability. Further research and development efforts are crucial to optimize waste-based soil stabilization techniques, ensuring durable and eco-friendly pavements. These wastes ultimately improve strength of the target soil, however, careful consideration should be given to determine the performance of these wastes as stabilizers and to know what aspects would require mitigation to maximize the potential of these waste materials to be used for good, instead of causing more harm to the ecosystem.

1. INTRODUCTION

The pace of waste generation is skyrocketing globally. As per a World Bank assessment executed in 2022, the world produced solid wastes (SW) which amounted to 2.24 billion tons in 2020, estimating 0.79 kg of SW generated each day per individual (The World Bank, 2022). Dense population expanse and industrialization are forecasted to cause the yearly waste accumulation to climb by 73%, from 2020 to over 3.88 billion tons by 2050. Conforming to the United States Environmental Protection Agency (USEPA) in 2022, nearly every single person, business and overall human activities produces wastes of some kind, which include sewage sludge, hazardous and non-hazardous industrial waste, medical waste, nuclear waste, demolition and construction debris, distillation and mining waste, wastes from producing oil and gas, residues and ashes from thermal treatment of industrial, agricultural and domestic waste and from energy production. Inefficient handling of waste has a detrimental effect on inhabitants of world economies. Hence, waste management should be properly investigated. Sustainable waste management is a component of the new 'green' economy, which strives to encourage economic expansion while safeguarding the environment.

The generation, collection, storage, processing (recovery), transportation, and disposal phases are the six segments that make up the typical division of the solid waste management procedures. Inadequate administration/regulation and oversight of these activities may have undesirable effects on health and our ecosystem. The cycle of negative impacts that plagues improper management of wastes would continue to go on if they are not checked.

Waste management strategies like recycling and reuse are the most typical in the building sector, where waste materials have been recycled for use as or in conjunction with other materials to yield potentially sustainable and cost-effective building materials (Ofuyatan et al., 2020). Barbuta et al. (2015) stated that employing disposal resources while also lowering environmental pollution are both possi-

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ble with the new generation construction materials that are blended with various wastes. The assessment of waste usage in construction has been known to be broad especially in road pavement construction where recycled materials have been used for asphalt concrete and bitumen (Rahman et al., 2020); and also, for subsoil and embankment stabilization (Vukićević et al., 2019) so as to strengthen the geotechnical attributes of the soils used in pavement layer design. In this review paper, a detailed examination of the use of wastes for sustainable soil treatment is presented. These materials are investigated to determine their potential to improve soil properties in pavement applications. This eco-friendly and cost-effective approach could mitigate the harmful effects of these wastes on human health and the environment.

2. SOIL TYPES AND STABILIZATION TECHNIQUES IN ROAD CONSTRUCTION: GEOTECHNICAL PROPERTIES, ENVIRONMENTAL CONSIDERATIONS, AND APPLICABILITY

One of the most crucial and fundamental media for any building project is soil. Any structure's durability and strength are contingent on the soil's strength capabilities. The complex blend of mineral substances, matter that is organic, gaseous substances, fluids, and innumerable biological organisms that makes up soil is what preserves existence on the Earth. Defective soils are viewed as those that do not satisfy all or part of the requirements necessary for them to function competently in geotechnical building work. Poor load-bearing capacity, severe shrink-swell potential, rapid water drainage, and pollution are frequent characteristics of these deficient soils. These are likely to be seen in base courses for roadways, embankments for roads or dams, subsurface bases for foundations, clay liners for leachate control, and fills for retaining structures (Alhassan & Mustapha, 2015). Stabilization would eventually be necessary to achieve an improvement in the geotechnical characteristics of these weak and defective soils. The process of modifying a natural soil to enhance one or more of its characteristics by adding specialized soil, cement, or other chemicals is known as "soil stabilization" (Habiba, 2017). For overall soil improvement, a variety of techniques have been established and used, as shown in Figure 1. These techniques start with the more fundamental ones, like soil replacement, excavation, and drainage, while moving on to more sophisticated ones, like chemical-based treatment, the reinforcement approach, variable modification (hydraulic, electrical, thermal mechanical), and so on (Gomes Correia et al., 2016; Md Zahri & Zainorabidin, 2019; Scope et al., 2021). The methods are suited for deep, medium, and shallow soil modification, and are commonly classified into two groups based on the site details and geotechnical requirements: a) mechanical techniques including soil replacement or displacement, phased construction, the preloading phase, the use of stone columns, embankment supports, and applications of synthetic reinforcing (Bordoloi et al., 2017); and b) chemical methods, such as stabilization of surfaces and deep integration/mixing in place with the use of admixtures including slag from blast furnaces, cement, gypsum, fly ash, bentonite, silica fume etc. (Celik & Nalbantoglu, 2017; Sharma & Sivapullaiah, 2016; Yadu & Tripathi, 2013).

Conventional stabilizers, such as cement, have been widely used to stabilize soil over time. Cementitious reactions act to link particles, enhancing stiffness and strength while decreasing strain and enhancing permeability. Its calcium-rich nature is essential to its setting, development of strength, and general effectiveness. However, the production of cement is associated with substantial energy

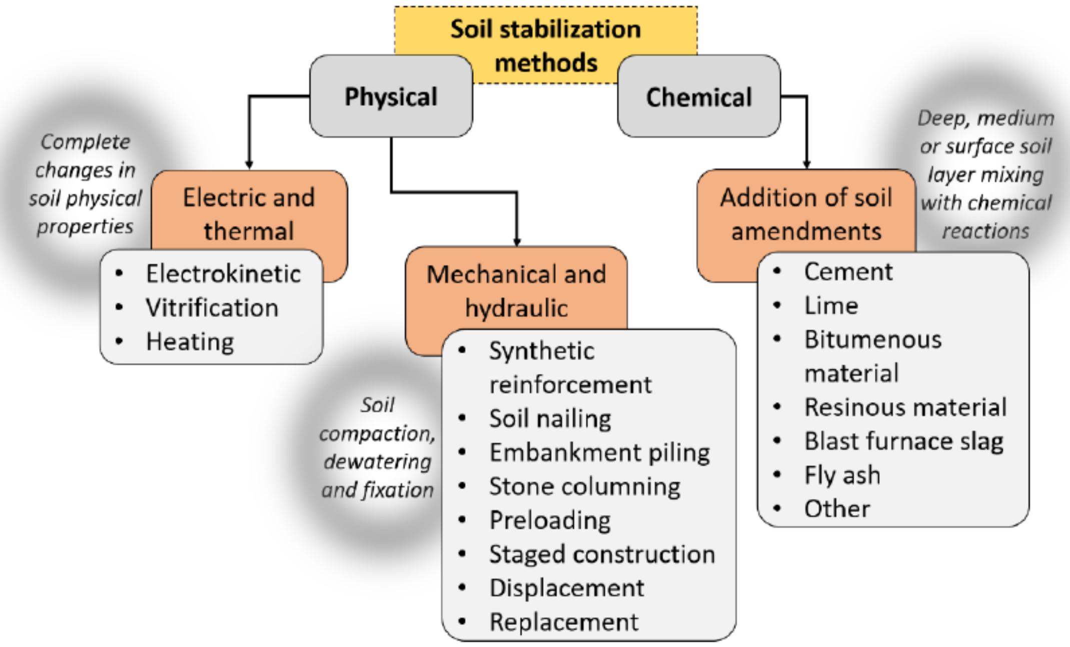

FIGURE 1: Methods of Soil Stabilization (Gomes Correia et al., 2016).

and non-renewable resource consumptions as well as a significant global carbon dioxide (CO_2) generating process (Akinwumi et al., 2023), soil cracking and high cost. The production of cement is thought to produce significant discharges of greenhouse gases, which contribute significantly to global warming and climate change (Tesanasin et al., 2022). This is considered very alarming. Hence, alternative materials to cement are a current necessity (Pelissaro et al., 2023). As a substitute to cement/lime, the development of innovative sustainable binding agents is crucial to promoting greener manufacturing and lowering carbon emission (Dahal et al., 2019).

To improve soil for the construction of road pavements, researchers have been investigating this and are continuously coming up with ways to use waste materials like fly ash, rice husk, calcium carbide residue, bagasse ash, etc., to create environmentally friendly substitute binders. The development of these cutting-edge low-carbon stabilization products and procedures is continually progressing and forging a new path for the field of civil engineering (Yu et al., 2024). These substitute admixtures are taken into consideration because of how well they enhance soil characteristics. Reclaimed asphalt pavements (RAP), for instance, have a better capacity to release stresses conveyed to subgrade, reduce permeability, and have excellent durability against imposed loads, all of which can improve the mechanical performance of the pavement layers (Hashemian et al., 2023). Furthermore , when employed as stabilization agents, waste ash from materials like plantain peels, rice husk, bagasse, etc., exhibits pozzolanic properties. The primary cause of stabilization efficacy is the pozzolanic interaction that occurs between calcium-based compounds and soil. Calcium hydroxide is transported by water and combines with alumina and silica in aggregates to generate calcium aluminate hydrate (C-A-H) and calcium silicate hydrate (C-S-H), which are the products of the pozzolanic reaction, which is often slow and lengthy (Komaei et al., 2023). The C-S-H gel contributes to the adhesion of the particles, strengthening the mixtures (Juveria et al., 2023). By virtue of pozzolanic processes, clay soil that has chemical additions becomes stronger with time. Upon reaction with the aluminates and silicates in the soil to form cement gels, the calcium hydroxide (CaOH) creates a pozzolanic reaction that reinforces the stabilized soil. Stronger cementation results from higher particle binding as the amount of cement gels created rises (Sosahab et al., 2023). These waste products have the effect of obstructing pores. As a result of their low coefficient of permeability, capillary pores that are blocked cause permeability reduction, acting as a hydraulic barrier (Karami et al., 2021), which subsequently supports improved strength and expansion (Mansour et al., 2022).

In general, alternative binders with strong mechanical qualities and energy conservation have become very popular recently. This is because using them to treat soil potentially keeps them out of landfills, which may help in reducing several environmental difficulties and land waste issues (Li et al., 2024). Due to their low specific gravity, waste ashes can pollute land, air, and water, while leakage into groundwater can result from their disposal in open pits. However, these issues can be potentially remedied by mixing them with soil, which when wet, reacts to produce cementitious materials. Considering these cementitious products are eco-friendly, using their waste materials for road pavement stabilization turns out to be an environmentally suitable way to manage waste (Khandelwal et al., 2023). Before utilizing these materials in this regard, environmental and health that may arise from their usage should be assessed and take steps should be taken prevent them.

Ultimately, the future of soil stabilization lies in embracing beneficial alternatives. By utilizing waste materials as stabilizers, we can achieve strong, durable construction while minimizing environmental impact. Research into novel low-carbon binders and processes is crucial for promoting cleaner production and a lower carbon footprint in the civil engineering industry. This shift towards sustainable soil stabilization presents a win-win scenario for both construction and the environment.

3. WASTE MATERIALS USED FOR SOIL STABILIZATION: OPTIMIZING GEOTECHNICAL PROPERTIES AND MINIMIZING ENVIRONMENTAL IMPACTS

Through mix proportions and introducing the appropriate additives or stabilizers, soil stabilization seeks to augment the integrity or bearing capability of the soil involved (Díaz-López et al., 2023). The use of conventional stabilizers like cement and lime has been employed over the years for soil improvement and has been effective irrespective of the expensive nature (Anburuvel et al., 2023). Nevertheless, most highway agencies are not inclined to commit money on these typical stabilizers for soil restoration because of budgetary constraints (Zimar et al., 2022) and also due to their unfavorable impact on the ecosystem as at a global level, the processing of cement generates around 7% of greenhouse gas emissions (Chen et al., 2020). As a result, road authorities and researchers seek industrial byproducts with pozzolanic characteristics that are potentially sustainable and more affordable. Some of these waste materials that have been investigated for use as soil stabilizers are reviewed in this paper. They include reclaimed asphalt pavement (RAP), recycled concrete aggregates (RCA), , ground granulated blast-furnace slag (GGBS), steel slag (SS), rice husk ash (RHA), coal fly ash (CFA), granite dust (GD), plantain peel ash (PPA), calcium carbide residue (CCR) and bagasse ash (BA).

3.1 Reclaimed asphalt pavement (RAP)

Maintenance of asphalt roads typically involves milling the pavement, sometimes down to its full depth, followed by applying a fresh layer of pavement. The material removed during milling, known as reclaimed asphalt pavement (RAP), consists of granular fragments that, when reused, enhance an asphalt mixture's resistance to moisture and deformation (Spreadbury et al., 2021; Aravind & Das, 2007; Zaumanis & Mallick, 2014).

Reusing RAP offers significant financial savings and ecological benefits such as reduced greenhouse gas emissions, landfill diversion, and lower transportation costs (Foye, 2011; Nassar & Nassar, 2006; Huang et al., 2009; Celauro et al., 2015; Yang et al., 2015). RAP has become increasingly popular for soil stabilization due to its environmental advantages, conserving natural resources and reducing environmental pollution (Avirneni et al., 2016). It contains bitumen and aggregates that improve soil strength and reduce water permeability, making it beneficial for road construction (Alhaji & Alhassan, 2018). For instance, it has been successfully used as a granular subbase (GSB) material, enhancing structural integrity and stability (Pradhan & Biswal, 2022; Lima et al., 2023).

Despite these benefits, challenges exist. "Old" asphalt based on tar has a much higher content of potentially hazardous polycyclic aromatic hydrocarbons (PAH) than "newer" asphalt based on bitumen (IARC, 2010), which should be considered. Preferably, utilization of tar-based asphalt should be avoided. Also, variability in RAP composition, including potential contaminants like heavy metals or PAHs, requires careful testing and mix design optimization to ensure consistent performance (Edeh et al., 2011; Legret et al., 2005). Strategies such as determining optimal RAP proportions and evaluating specific RAP properties are crucial for effective soil stabilization (Ahmed et al., 2019). Prior to using RAP-stabilized soil, assessing and mitigating risks of harmful substance release through leaching or dust to prevent adverse environmental and health effects is vital. Overall, RAP offers a beneficial solution for soil stabilization, reducing the global demand for virgin aggregates and energy consumption while diverting waste from landfills (Milad et al., 2020; Ochepo, 2014). Careful consideration and management are essential to maximize its benefits and mitigate potential drawbacks in construction projects.

3.2 Recycled concrete aggregates (RCA)

The disposal of construction and demolition (C&D) debris, particularly concrete waste, is escalating worldwide due to the proliferation of structures in developed and developing nations. In Europe alone, over 800 million tons of C&D waste are generated annually, with concrete constituting up to 75% of this waste by weight (Wang et al., 2023). Recycling and reusing these concrete wastes for pavement layers have gained global attention as an environmentally sustainable approach to construction (Lu et al., 2021; Poltue et al., 2020; Saberian et al., 2018; Yaghoubi et al., 2018). Recycled concrete aggregates (RCA) predominantly constitute C&D waste, ranging from 65% to 80% natural aggregates (NA) and 20% to 35% cement mortar, typically sized between 20 and 30 mm (Saberian et al., 2020; Al-Obaydi et al., 2021; Tavakol et al., 2020; Sohrabpour & Long, 2021; Arulrajah et al., 2022). RCA finds applications in various construction contexts such as backfills around culverts, railroad capping layers, stabilized road pavements, and geobag walls (Sohrabpour & Long, 2021; Mohammadinia et al., 2020; Vegas et al., 2011; Arulrajah et al., 2014; Wu et al., 2020).

Recent research highlights the superior cementitious properties of sand-sized RCA (less than 5 mm), which contain higher cement paste compared to gravel-sized RCA, making them suitable as supplementary cementitious materials (Evangelista et al., 2015; Moreno-Juez et al., 2021; Mikos et al., 2021). In soil stabilization, RCA has proven effective in enhancing engineering properties such as reduced plasticity, improved compaction efficiency, and increased bearing capacity. For instance, it has been successfully used to stabilize clay soils and improve the bearing potential of soils like black cotton soil (Kianimehr et al., 2019; Pazare et al., 2023). The addition of RCA to soils enhances their strength and stability, making them suitable for various construction applications including subgrade or subbase of road pavements. RCA usage in pavement construction may also be characterized by reduced costs. This is because as CBR rises, it is possible to decrease pavement thickness, thereby lowering construction costs (Datta & Mofiz, 2021).

However, the application of RCA is not without challenges. Variability in RCA properties due to differences in source concrete composition and processing methods necessitates rigorous testing and optimized mix designs (Datta & Mofiz, 2021). The angular and rough texture of RCA can affect workability, requiring adjustments in mixing techniques or additives (Shourijeh et al., 2022). Moreover, residual contaminants like heavy metals from the original concrete, such as chromium, lead, and arsenic, pose potential risks of leaching into the soil under certain conditions (Galvín et al., 2013). Careful engineering design, thorough testing of RCA and soil mixes, and selecting low-contamination risk sources should be taken into consideration (Tavakol et al., 2019; Kianimehr et al., 2019). Conducting a thorough evaluation of potential environmental and health risks from leaching or dust in RCA-stabilized soil and taking steps to mitigate these impacts before application is important. In conclusion, while RCA offers potentially significant benefits in terms of cost savings, resource conservation, and environmental sustainability in construction, careful consideration of its properties and likely drawbacks is crucial for its effective application in soil stabilization and other construction activities.

3.3 Ground granulated blast-furnace slag (GGBS)

Increasing the use of supplemental cementing components like ground granulated blast-furnace slag (GGBS), which are often discarded in lagoons and landfills, is essential for reducing construction costs and greenhouse gas emissions from traditional stabilizers like cement and lime, such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) (Sharma & Sivapullaiah, 2016). GGBS is a byproduct of pig iron production, ground into a fine, non-crystalline form after rapid cooling. Its reuse in engineering applications is considered environmentally beneficial, frequently serving as a binding agent in concrete and mortar (Pal et al., 2003; Jin et al., 2015; Zhao et al., 2023). With increasing availability, GGBS has also been applied in soil treatment and stabilization.

Rasool and Kapoor (2017) explored GGBS as a substitute for cement or lime to support increased traffic stresses on foundation structures. They added GGBS to clayey sand in proportions of 0%, 6%, 12%, 18%, and 24%, finding that 18% GGBS maximized the CBR value. These results suggest that the effectiveness of GGBS can be enhanced with an activator to break its glassy phase, as GGBS is a latent hydraulic material (Mumtaz & Bhatia, 2022). Yadu and Tripathi (2013) also assessed GGBS for soft soil stabilization, combining soil with 3%, 6%, 9%, and 12% GGBS. They observed improved soil strength and physical properties, reduced OMC, and increased MDD, attributed to GGBS's higher specific gravity (2.89) compared to soil (2.56). Additionally, they reported a significant reduction in soil swelling and an increase in UCS and CBR values, with 9% GGBS being optimal. Further studies indicate that GGBS can improve various soil types. Patel et al. (2020) found a 15% inclusion optimal for black cotton soil, while for soft clay with poor shear strength, 40% was most effective. Research consistently supports GGBS as a beneficial and efficient replacement for traditional stabilizers, enhancing soil strength and stability while addressing environmental concerns. Optimizing GGBS activation methods could yield even greater benefits (Pathak et al., 2014).

However, caution is necessary due to potential drawbacks. GGBS effectiveness can vary with its chemical composition, influencing its reaction with soil components (Al-khafaji et al., 2017; Sharma & Sivapullaiah, 2016; Rizki Abdila et al., 2020). In certain soils or environmental conditions, elements in GGBS may leach into the environment (Müllauer et al., 2015). Before using soil stabilized with GGBS, assessing the risk of environmental and health impacts from harmful substances leaching or dust escaping, and taking necessary precautions to prevent negative effects is vital.

3.4 Steel slag (SS)

Urban expansion has led to a significant rise in steel slag (SS), an alkaline waste product from iron and steel smelting processes. Annually, China alone generates over 100 million tons of SS (Yu et al., 2024). While SS is used in various applications such as iron-ore processing, road fillers, and railroad ballast, its utilization rate remains low, below 25% (Pang et al., 2015). This underutilization exacerbates environmental concerns due to SS disposal.

Efforts to harness SS more effectively have focused on enhancing soil properties, particularly for soil stabilization purposes. Studies have shown promising results in improving geotechnical characteristics when incorporating fine steel slag aggregate (FSSA). For instance, Aldeeky and Hattamleh (2017) demonstrated that adding 20% FSSA to high-plasticity subgrade soil reduces plasticity index and free swell by 26.3% and 58.3%, respectively. Moreover, it increases unconfined compressive strength (UCS), maximum dry unit weight, and California Bearing Ratio (CBR) by 100%, 6.9%, and 154%, respectively. Similar benefits were observed in lateritic soils and expansive soils, where SS additions improved workability and reduced swelling potential (Jaja & Tamunoemi, 2022; Kabeta & Lemma, 2023).

Optimal SS content varies by soil type but generally ranges between 8% to 25%. Above this range, diminishing returns and increased leaching risks of heavy metals become concerns (Navarro et al., 2010; Piatak et al., 2019). Several types of steel slag exist such as basic oxygen furnace (BOF) slag, Electric Arc Furnace (EAF) slag, Ladle Furnace Slag (LFS), and others. BOF slag, the most common type, is produced during oxygen injection to remove impurities (Chen et al., 2023). Also, EAF slag is formed during electric arc melting of scrap steel (Skaf et al., 2017), while LFS is produced during refining stages in a ladle after BOF or EAF (Najm et al., 2021) and has similar composition to BOF slag but finer particles. These various steel slag types differ in both functional and leaching properties, and the most problematic substances with respect to leaching and environmental impact are generally Barium (Ba), Vanadium (V), Molybdenum (Mo), Chromium (Cr), and Fluorine (F) (Riley & Mayes, 2015; Spanka et al., 2017). The leaching properties may change with time after application due to changes in pH (carbonation of the generally alkaline slags) and changes in redox potential (Van Zomeren et al., 2011). The potential of SS to undergo Alkali-Silica Reaction (ASR) with silica-rich soils, leading to expansion and cracking is also a concern (Choi & Yang, 2020). Before applying soil stabilized with SS, identifying and addressing risks of harmful substances leaching or dust escaping to safeguard the environment and health is a necessary step to take. In conclusion, while SS offers a cost-effective solution for improving soil properties and mitigating environmental impact from steel production (Akinwumi, 2014), careful consideration of its application and potential risks is crucial to ensure beneficial use and effective soil stabilization practices.

3.5 Rice husk ash (RHA)

Rice husks, a byproduct of paddy dehusking, vary in weight from 20% (Mehta, 1986) to 23% (Della et al., 2002) of the total paddy weight. Traditionally regarded as waste, they are often incinerated in boilers used for processing paddy, with about 20% of their weight converting to ash (Mehta, 1986). Rice husk ash (RHA) predominantly consists of silica, its amorphous nature influenced by burning methods (Nair et al., 2006), making it a pozzolanic material (Mehta, 1986). Annually, India alone generates over 4 million tons of RHA from its 100-million-ton paddy production (Kumar & Gupta, 2016), while China produces approximately 40 million tons (Yan et al., 2022), and Nigeria contributes an estimated 2 million tons (Oyetola & Abdullahi, 2006). As rice milling is ongoing, the accumulation of rice husks in the environment continues to rise, prompting efforts to find beneficial solutions like soil stabilization.

Using RHA for soil enhancement can lead to cost-effective construction methods and environmentally friendly waste disposal, reducing cement use, energy consumption, and greenhouse gas emissions (Kumar & Gupta, 2016). Due to its pozzolanic properties, RHA can effectively stabilize soil as an alternative to conventional binders like lime and cement (Basha et al., 2005). Studies have shown that incorporating RHA can enhance soil strength, as observed in various soil types such as A-7-6 lateritic soil (Alhassan, 2008; Paul & Sarkar, 2023) and black cotton soil (Ghutke et al., 2018). Optimal results typically occur at specific RHA concentrations, such as 6-8% for lateritic soil (Alhassan, 2008; Okafor, 2009) and 12% for black cotton soil (Ghutke et al., 2018), underscoring the importance of precise mix proportions.

While RHA offers advantages in terms of cost-effectiveness and environmental benefits (Behak, 2017; Pushpakumara & Mendis, 2022; Reis et al., 2022), its efficacy as a stabilizer can vary due to factors like inconsistent burning temperatures during production (Tuhin et al., 2020). High alkalinity in RHA can also pose risks of element leaching upon contact with water (Reis et al., 2022). Assessing and mitigating potential environmental and health risks from harmful substances in soil stabilized with RHA before use should be considered to prevent adverse effects from leaching or dust. In conclusion, RHA presents a promising option for soil stabilization, offering both technical and environmental advantages, provided proper production and application protocols are observed.

3.6 Coal fly ash (CFA)

Geotechnical and transportation engineers are keen on improving materials for highway pavement layers, as deficient pavement layers significantly raise construction costs. Stabilizing the base, sub-base, and subgrade layers is crucial when naturally occurring materials are inadequate. Coal fly ash (CFA), a byproduct of coal combustion in thermal power plants, is increasingly used in soil stabilization due to its low cost, regional availability, and environmental benefits.

CFA, known for its pozzolanic properties, enhances the qualities of pavement layers by reducing the swell potential of highly plastic clays and improving the strength and compressibility of weak soils. Studies have shown that adding CFA to soils can significantly improve their engineering properties. For example, CFA addition to black cotton soil reduced Atterberg limits and increased CBR and UCS values. Optimal CFA content for various soils varies, with 10-20% often recommended (Gireesh Kumar & Harika, 2021; Andavan & Hassaan, 2018). The use of CFA in soil stabilization not only improves pavement performance but also addresses environmental concerns by reducing landfill waste from coal-fired power plants. It provides a cost-effective and sustainable solution for enhancing weak pavement layer materials (Renjith et al., 2021).

However, CFA properties can vary depending on the source coal, affecting its stabilization effectiveness. Additionally, some CFA contains trace heavy metals, posing environmental and health risks if not properly managed (Wang et al., 2022). For alkaline CFA, the major potentially critical substances with respect to leaching and environmental impact are the oxyanions formed by chromium (Cr), arsenic (As), selenium (Se), vanadium (V), and molybdenum (Mo) (Cornelis et al., 2008), while for acidic CFA metals like cadmium (Cd), zinc (Zn), and copper (Cu) are of greater relevance (Liu et al., 2005). Evaluating environmental and health risks from leaching or dust in CFA-stabilized soil and implementing necessary precautions before application to avoid harmful impacts is key. In conclusion, CFA is a valuable tool for highway and geotechnical engineers, offering benefits such as improved soil strength and stability, beneficial waste management, and reduced construction costs. With ongoing research and optimization, CFA's role in sustainable pavement construction is likely to grow.

3.7 Granite dust (GD)

Granite dust (GD) results from cutting and grinding granite, forming colloidal waste when mixed with water and becoming a non-biodegradable dry pile in landfills (Singh et al., 2016; Taji et al., 2019). Industrial processes on granite yield about 65% waste, leading to environmental concerns like water pollution, air contamination, and land infertility (Singh et al., 2016; Danish et al., 2021). To mitigate these issues, GD has been increasingly used as a supplementary cementitious material (SCM), replacing cement to reduce environmental impact, CO_2 emissions, energy consumption, and resource depletion (Arel, 2016; Danish et al., 2019). Researchers have shown interest in using GD to create cementitious materials, benefiting the construction industry by reducing disposal costs, promoting beneficial use, and enhancing composite properties (Li et al., 2019; Aydin & Arel, 2019; Sadek et al., 2016).

GD is also useful in soil stabilization. Eltwati et al. (2020) investigated GD's impact on clayey soil, finding that adding 8% GD significantly improved soil density, CBR, and shear strength, enhancing engineering properties to be about 2.8 times better than untreated soil. Babu and Nagaraju (2022) observed similar results with black cotton soil, noting GD's cost-effectiveness and environmental benefits. Amulya et al. (2021) found GD to be a low-carbon-intensity component for geotechnical and concrete activities; reducing CO_2 emissions and improving soil properties through enhanced inter-particle bonding and new mineral formation (Abdelkader et al., 2022).

Despite its benefits, GD's effectiveness depends on the optimal content and soil type (Eltwati et al., 2020). Thorough laboratory tests are essential to determine the best GD content for specific soils, ensuring effective stabilization. Proper gradation of GD particles can improve the packing density and strength of stabilized soil. Additionally, conducting a risk assessment for harmful substance release from soil stabilized with GD is necessary. It is also important to ensure preventive measures are in place to mitigate environmental and health impacts before use. In summary, GD, once a waste product, now offers sustainable solutions in construction and soil stabilization, supporting a more economically and ecologically beneficial future.

3.8 Plantain peel ash (PPA)

The global agro-industry generates significant agricultural waste annually, causing environmental issues (Villamizar et al., 2012). Experts have explored alternatives like soil stabilization to limit waste, with plantain peels gaining attention, especially in developing nations where they are abundant. Nigeria, a top plantain producer, consumes most of its yield domestically, leading to considerable waste (Amaya, 2018; Usman et al., 2018). The disposal of plantain peels produces harmful gases like ammonia (NH_3) and hydrogen sulfide (H_2S) (Ifetayo & Pretorius, 2018).

Researchers have investigated using plantain peel ash (PPA) for soil stabilization. Ishola et al. (2019) studied its impact on tropical red soil strength. Plantain peels were dried, burned at 500°C, and sieved to produce ash. Tests showed varying specific gravity, reduced plasticity index, liquid and plastic limits, and moisture content, with increased maximum dry unit weight. Unconfined compressive strength (UCS) peaked at 10% PPA, and California Bearing Ratio (CBR) improved at 4% PPA. PPA, combined with lime or cement, was suggested for road pavement layers to reduce construction costs. Akinwumi et al. (2023) found PPA-treated soil suitable for rural road embankments and fills due to pozzolanic reactions forming calcium silicate hydrate (C-S-H), which densifies the soil matrix. This process causes soil particles to agglomerate, enhancing strength over time. PPA is seen as a beneficial, cost-effective soil stabilizer, particularly in developing nations with high plantain production.

However, PPA might not always meet high-strength requirements for all applications, and its effectiveness depends on soil type and ash amount (Ishola et al., 2019). There is also a risk of heavy metals leaching (Olabanji et al., 2012). Prior to using PPA-stabilized soil, assessing and mitigating risks of harmful substance release through leaching or dust to prevent adverse environmental and health effects are necessary steps to take.

3.9 Calcium carbide residue (CCR)

Certain waste materials rich in $Ca(OH)_2$, such as calcium carbide residue (CCR), a byproduct of acetylene manufacturing, can be repurposed to create cementitious materials, benefiting the environment and economy (Horpibulsuk et al., 2013). CCR, primarily a slurry with high alkalinity and water content, often pollutes water sources and contributes to environmental degradation when stockpiled (Krammart & Tangtermsirikul, 2004; Sharma & Reddy, 2004; Du et al., 2011). China alone produces around 28 million tons of CCR annually, most of which ends up in landfills (Li et al., 2024).

A low-carbon, energy-efficient way to mitigate CCR stockpiles is to use it for soil stabilization, which also alleviates environmental concerns (Horpibulsuk et al., 2012). CCR has been effective in pavement and geotechnical applications. Field tests by Du et al. (2016) demonstrated that CCR is a cost-effective, environmentally friendly binder for stabilizing soft subgrade soils, with significant engineering, economic, and environmental benefits. Chindaprasirt et al. (2020) confirmed that CCR-stabilized laterite's engineering properties improve due to pozzolanic reactions. Higher CCR concentrations enhance soil strength and durability, making it a viable alternative to traditional stabilizers like lime and cement (Ayodele et al., 2020). Research shows a direct proportionality between UCS, CBR, and CCR contents, enhancing soil workability and strength (Akinwumi et al., 2018). An optimal 4% CCR application is recommended for stabilizing sand in road construction, offering a low-cost, eco-friendly method, especially for developing countries. Using CCR reduces pollution from stockpiled waste, lowers construction costs, and produces strong, durable soil for various construction uses.

However, CCR usage has potential drawbacks. Strength may decrease after repeated wetting and drying cycles, necessitating further durability studies (Julphunthong et al., 2024). CCR may also contain trace heavy metals, risking soil and groundwater contamination if not properly managed (Hassan et al., 2019). Combining CCR with other pozzolanic stabilizers can further improve long-term strength. Furthermore, ensuring a risk assessment for environmental and health impacts from harmful substance release in soil stabilized with CCR is important, as well as applying necessary precautions to avoid unacceptable outcomes. In summary, CCR offers a sustainable solution for waste management while enhancing soil properties, providing a viable and cost-effective alternative to traditional soil stabilizers.

3.10 Bagasse ash (BA)

Bagasse, the fibrous residue from crushed sugarcane, and its ash (BA), produced when bagasse is burned, pose environmental risks if improperly disposed of. Inhaling bagasse dust can lead to "bagassosis," a rare but serious respiratory condition (Choudhari et al., 2020). Proper disposal and utilization of BA are crucial, particularly in engineering applications.

With high silica content, BA is a valuable pozzolanic material suitable for stabilizing road subgrades (Hasan et al., 2016). It offers an eco-friendly and cost-effective alternative for soil improvement, essential given the significant sugarcane production in countries like Brazil, India, China, and Thailand (Shahbandeh, 2024). The use of BA in construction can support sustainable development by recycling industrial waste into building materials (Dang et al., 2021). Research indicates BA's effectiveness in stabilizing wet, unstable soils, reducing soil swell, and mitigating settlement issues (Khandelwal et al., 2023; Gandhi, 2012; Srinivasa et al., 2017). It also improves low to high plastic clays and can stabilize expansive soils and peat, supporting road embankments in agricultural or rural areas (Khan, 2019; Surjandari et al., 2017; Abu Talib & Noriyuki, 2017).

While BA is cost-effective and improves soil strength, it may not match cement's strength for high-traffic applications (Osinubi et al., 2009). Variations in BA composition due to different sugarcane varieties and burning conditions necessitate project-specific testing to determine optimal dosages (Xu et al., 2018). Combining BA with other pozzolanic stabilizers and sourcing from reliable suppliers can enhance its performance (Awadalseed et al., 2023). Before using soil stabilized with BA, the risk of environmental and health impacts from harmful substances leaching or dust escaping should be assessed, and necessary precautions to prevent negative effects should be taken.

4. SUSTAINABILITY IN UTILIZING ALTERNATIVE STABILIZERS

It is no surprise that numerous researchers have been looking into various waste materials aimed at boosting earth mineral content by originating avenues to incorporate them as environmentally suitable equivalent resources for developing and upholding roads (Oyebisi et al., 2020; Bamigboye et al., 2021). Studies like these verify that utilizing such wastes, notably for improving soil, assists in transforming wastes in a beneficial manner (Ewa et al., 2022). Careful attention must also be given when utilizing these wastes for soil stabilization as their usage may be characterized by some potential drawbacks as summarized in Table 1. Ultimately, it is necessary to ascertain the geotechnical properties (strength, leaching, workability, etc.)

of the soil and stabilizer combination and perform relevant risk assessments. This would help to determine the performance of these wastes as stabilizers and also to know what aspects would require mitigation and/or precautions to maximize the potential of these waste materials to be used for good, instead of causing more harm to the ecosystem. This points to the fact that prior to the application of a specific soil stabilised with a specific waste material for a specific purpose, the potential risk of local environmental and health impacts from release and spreading of harmful substances due to leaching or escape of fugitive dust must be assessed and appropriate action (precautions, mitigating measures, changes of the soil/stabilizer mixture) must be taken when necessary to prevent unacceptable impacts.

As a criterion for choosing stabilizers for soil stabilization, sustainability must be the principal focus. One of the major aims of seeking for alternative soil stabilizers in contrast to the traditional method used (cement-soil and lime-soil stabilization) is to protect the environment from the environmental hazard associated with these conventional methods; as CO_2 emission is characterized with their production (Tesanasin et al., 2022). CO_2, a greenhouse gas, is characterized by its increasing concentration in the atmosphere which contributes to increasing temperatures on Earth. This is a source of concern in our ecosystem. Thus, selecting alternative soil stabilizers should be of beneficial use in terms of cost-effectiveness and environmental safety. Stabilization using waste ash and waste slag is an economical way of reducing these pollutants and inducing considerable soil strength. However, on the long run, they may induce weak shear planes in the soil when applied beyond optimal points, thus impeding further strength gain (Kassa et al., 2020). This can be a major problem during freeze-thaw cycles and increased traffic loads which can adversely affect the road pavement. On the other hand, waste materials like GD, CCR and RCA have been known to produce better results compared to the aforementioned, which may be attributed to having some cementituous properties comparable to traditional stabilizers (Danish et al., 2019; Gencel et al., 2020). They yield appreciable strength for sub-grade while providing sustainable disposal strategies for waste mitigation. Therefore, waste materials to be used for soil stabilization should be chosen based on the criteria that its usage would not pose any danger to the environment; and that its financial feasibility and has potentially beneficial use. Also, when utilizing waste ash for soil stabilization, careful attention should be given to the combustion process. To optimize beneficial use, the combustion process producing the ash should take place under properly controlled conditions, including cleaning of the stack gases and proper management of quench water so as to mitigate emissions of chemicals that are harmful to human health and the environment and also to regulate the entire combustion system for process efficiency and control.

Mekonnen et al. (2020) concluded that conventional stabilizers, like cement/lime, are costly; In some places, the cost can even triple that of alternative additives, and this cost increases even further when the bulky materials need to be transported over lengthy distances to low-volume road construction destinations. Ultimately, utilizing waste materials for improving the qualities of road pavement layer materials reduces construction cost since the waste materials are often readily available and far cheaper, or even free, compared to conventional stabilizers like cement or lime. This translates to direct savings on material procurement. Using waste materials for soil improvement means that they are essentially being diverted from landfills. This eliminates tipping fees associated with waste disposal, leading to additional cost savings. Also, using these waste materials as alternative soil stabilizers contributes to several Sustainable Development Goals (SDGs) by the United Nations (2015), as seen in Figure 2. It supports SDG 6 – Clean Water and Sanitation. Improper waste disposal can contaminate water sources. By diverting waste from landfills and putting it to good use, we can help protect water quality. In essence, using waste as a soil stabilizer offers a potentially beneficial and environmentally friendly approach to construction compared to traditional methods. Furthermore, utilizing these alternative materials encourages SDG 11 – Sustainable Cities and Communities. This goal aims for sustainable development in cities and communities. Reusing waste materials for construction purposes reduces reliance on virgin materials and minimizes landfill waste, contributing to a more sustainable built environment. It also fosters SDG 12 – Responsible Consumption and Production. This goal promotes responsible production and consumption patterns. By finding beneficial uses for waste products, we lessen the environmental impact of production processes and reduce the overall amount of waste generated. SDG 15 – Life on Land is also promoted. This objective is to safeguard, replenish, and encourage beneficial use of our terrestrial ecosystems. Stabilizing weak soils with waste materials can help prevent erosion and improve land quality, promoting healthy ecosystems.

Utilizing waste materials for soil stabilization presents a compelling solution. It not only offers a cost-effective alternative to traditional methods stemming from local production and minimal transport, but also promotes environmental sustainability by reducing CO_2 emissions, diverting waste from landfills, and contributing to several UN Sustainable Development Goals. It is also important to note that the degree at which the release of potentially harmful substances to the environment will be reduced as regards the utilisation of a waste material as a soil stabiliser depends on the quality and operation of the landfill and the leaching properties of the stabilised soil as well as on the conditions of use, i.e. the utilization scenario (and the climatic conditions). Before using waste-stabilized soil, assessing and mitigating risks of harmful substance release through leaching or dust to prevent adverse environmental and health effects are key steps to take to ensure optimal usage. As we move forward, continued research and development in this area can further optimize waste-based soil stabilization techniques, ensuring strong, potentially beneficial, and eco-friendly construction practices.

TABLE 1: The advantages and potential drawbacks of utilizing waste materials for soil stabilization.

Waste Materials	Advantages in stabilizing soil	Drawbacks
Reclaimed asphalt pavement (RAP)	Reduces demand for virgin aggregates, lowers energy consumption during production of new materials and diverts waste from landfills (Ochepo, 2014; Milad et al., 2020).	"Old" asphalt based on tar has a much higher content of potentially hazardous polycyclic aromatic hydrocarbons (PAH) than "newer" asphalt based on bitumen (IARC, 2010). RAP composition can vary depending on the source and age of the asphalt pavement, requiring careful testing and mix design optimization for consistent performance (Edeh et al., 2011). RAP may contain trace amounts of heavy metals that could leach into the surrounding environment if not properly managed (Legret et al., 2005).
Recycled concrete aggregated (RCA)	Strength enhancing qualities, cost savings in construction projects, and resource conservation (Tavakol et al., 2019; Datta & Mofiz, 2021).	RCA properties can vary depending on the source concrete's composition and processing methods. This inconsistency requires careful testing and mix design optimization (Datta & Mofiz, 2021). The angular shape and rough texture of RCA can make mixtures less workable compared to smooth, rounded natural aggregates (Shourijeh et al., 2022). Heavy metals from the original concrete e.g. chromium, lead, arsenic etc., can leach into the soil under certain conditions (Galvín et al., 2013).
Ground granulated blast-furnace slag (GGFS)	Improve various engineering properties of soil in a cost effective and environmentally friendly way (Pathak et al., 2014).	The effectiveness of GGBS can vary depending on its chemical composition, which can influence its reaction with soil components (Al-khafaji et al., 2017; Sharma & Sivapullaiah, 2016; Rizki Abdila et al., 2020). There's a risk of some elements in GGBS leaching into the surrounding environment (Müllauer et al., 2015).
Steel slag (SS)	Proffers a cost effective and sustainable way of improving soil properties (Akinwumi, 2014).	Steel slag can potentially leach heavy metals like barium, vanadium, molybdenum, chromium, and fluorine into the surrounding environment if not properly characterized and managed (Riley & Mayes, 2015; Spanka et al., 2017). Steel slag with high alkalinity can react with silica-rich soils leading to expansion and cracking within the stabilized soil (Choi & Yang, 2020).
Rice husk ash (RHA)	Cost-effective, environmentally friendly and ability to boost soil strength (Behak, 2017; Pushpakumara & Mendis, 2022; Reis et al., 2022).	Inconsistent burning temperatures can affect its effectiveness as a stabilizer (Tuhin et al., 2020). RHA with high alkalinity can lead to leaching of certain elements upon exposure to water (Reis et al., 2022).
Coal fly ash (CFA)	Offers several advantages such as improving strength and stability of soil, sustainable waste management and reduction of construction costs (Ahmad et al., 2024)	CFA properties can vary depending on the source coal, which can affect its effectiveness in stabilization (Bhatt et al., 2019). Some CFA contains trace amounts of heavy metals. For alkaline CFA, the major potentially critical substances with respect to leaching and environmental impact are the oxyanions formed by chromium, arsenic , selenium, vanadium and molybdenum (Cornelis et al., 2008), while for acidic CFA metals like cadmium, zinc, and copper are of greater relevance (Liu et al., 2005). Improper use can lead to leaching into groundwater, posing environmental and health risks (Wang et al., 2022).
Granite dust (GD)	Strength inducing capabilities in soil, cost effective and eco-friendly (Zorluer & Gücek, 2017; Babu & Nagaraju, 2022).	The optimum content of GD is crucial as this significantly impacts the results. The effectiveness of GD can vary depending on the soil type (Eltwati et al., 2020).
Plantain peel ash (PPA)	Moderately improves soil strength.	It might not always meet the high-strength requirements for all construction applications. The effectiveness of PPA is dependent on the specific soil type and the amount of ash used (Ishola et al., 2019). There is also a likelihood of trace amounts of heavy metals leaching into the soil from PPA (Olabanji et al., 2012).
Calcium carbide residue (CCR)	Offers a sustainable solution for managing waste while improving the qualities of soil.	While CCR initially improves strength, there is a likelihood of a potential decrease in strength after repeated wetting and drying cycles (Julphunthong et al., 2024). CCR can also contain trace amounts of heavy metals (Hassan et al., 2019), raising concerns about potential soil and groundwater contamination if not properly managed.
Bagasse ash BA)	Offers a cheaper alternative to conventional stabilizers in improving workability of soil.	While BA improves soil strength, it might not achieve the same level of strength as cement, particularly for high-traffic applications (Osinubi et al., 2009). The composition of BA can vary depending on sugarcane variety, burning conditions, and other factors (Xu et al., 2018).

5. CONCLUSIONS AND RECOMMENDATIONS

An overview of sustainable soil stabilization techniques for road pavement layers using waste materials is presented in this study. It highlights the growing concern of the global emergence of wastes and its detrimental impact on health and the ecosystem. Through examination of various waste materials (reclaimed asphalt pavement, recycled concrete aggregates, ground granulated blast-furnace slag, steel slag, rice husk ash, coal fly ash, granite dust, plantain peel ash, calcium carbide residue and bagasse ash), this review highlights the potential of these materials in enhancing soil properties for road construction while

FIGURE 2: SDGs promoted through the utilization of wastes as soil stabilizers.

mitigating environmental impacts. Since traditional stabilizers like cement and lime are linked to significant carbon emissions and environmental risks, the study highlights the significance of finding beneficial substitutes. Not only can constructing expenses be minimized but landfill contamination can be prevented by using waste materials as stabilizers. Utilizing waste materials also supports the Sustainable Development Goals, which include protecting life on land, fostering sustainable cities and communities, clean water and sanitation, and responsible consumption and production. Additionally, the need for careful consideration in selecting stabilizers to ensure beneficial use in terms of cost-effectiveness and environmental safety remains key for sustainable waste management. While waste materials offer promising solutions, their optimal usage should be determined to prevent potential drawbacks such as weak shear planes and impeded strength gain. Furthermore, continued research and development in waste-based soil stabilization techniques are essential to optimize their effectiveness and promote eco-friendly construction practices. Also, conducting field trials and case studies to validate the effectiveness of waste-based soil stabilization techniques in real-world construction projects is recommended. These trials can provide valuable insights into the practical challenges and benefits associated with using waste materials for road pavement layers. In general, the stabilization potential of more waste materials should also be investigated. An in-depth investigation of these wastes having cementitious properties should be looked into on how they can be used conjointly to stabilize soils of different kinds so as to rid the environment of these waste pollution in a cost-effective and potentially beneficial manner. These wastes ultimately improve strength of the target soil; however, careful consideration should be given to determine the performance of these wastes as stabilizers. The geotechnical properties (strength, leaching, workability, etc.) of the soil and stabilizer combination as well as relevant risk assessments should be conducted to know what aspects would require mitigation to maximize the potential of these waste materials to be used for good, instead of causing more harm to the ecosystem. This simply suggests that prior to the application of a specific soil stabilised with a specific waste material for a specific purpose, the potential risk of local environmental and health impacts from release and spreading of harmful substances due to leaching or escape of fugitive dust must be assessed and appropriate action (precautions, mitigating measures, changes of the soil/stabilizer mixture) must be taken when necessary to prevent unacceptable impacts.

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