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Sustainable and Environment-Friendly Infrastructure Development: A Study for Waste Management and Circular Economy

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ABSTRACT

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Infrastructure development needs sustainable and innovative methods that minimize the environmental impact while sustaining structural integrity. For instance, traditional subgrade stabilization methods relied on materials (i.e. cement or sand) or mechanical compaction, which consumed extensive natural resources or significantly contributed to carbon emissions. On the other hand, the waste management of sewage sludge, which is frequently disposed of without consideration of its potential value, represents a critical challenge. The study examines the performance of clayey soil treated with varying proportions (2%, 4%, and 6%) of sludge powder for geotechnical improvement. The expansive soil sample was collected from problematic zone. The results indicated that sludge powder improved the performance of soil and demonstrated economic and environmental benefits of soil modifiers which resulted in reduction of approximately 17.42 million PKR and 71,282 Kg carbon dioxide emissions for two lane highway pavement with dimensions (500m x12m x 0.2m) and 1649.9 Kg/m^3 dry density of soil. This research will help to develop sustainable, eco-friendly infrastructure and promote circular economy while improving soil performance in parallel.

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1.0 Introduction

As people continue to expand and modernize the world and their surroundings, the need for durable and sustainable infrastructure is greater than ever. Subgrade stabilization is an initial and prime step in road construction, as it ensures durability and strength of the soil. It directly affects the durability of roads as the stronger foundation leads to better pavement design. Stabilization methods depend on soil type and load it must bear followed by the selection of stabilization process that may follow mechanical, chemical, or both biological techniques. Traditional stabilization is either mechanical or includes stabilizers like cement, lime, sand, and bitumen yet these methods come with a heavy cost i.e. the depletion of natural resources and significant carbon emissions. At the same time, millions of tons of sewage sludge are simply discarded each year, often without recognizing its potential as a valuable resource. By rethinking waste as an opportunity, rather than a burden, new possibilities emerge for greener and more cost-effective construction practices researchers are now exploring sustainable alternatives by considering several waste materials as potential replacers. Studies have been done on several other waste material for example basalt rock powder was used and it effectively improved the strength and durability of clay soils and highlighted the dual benefits of geotechnical enhancement and environmental value through sustainable waste reuse (Pathak & Hayano, 2025). Similarly use of sewage sludge ash (SSA) combined with limestone was used and it was observed that it improved the microstructure and compressive strength of cement-based composites (Chang et al., 2025). A research also investigated use of various industrial waste materials (e.g. cement dust, fly ash) to improve compaction and load bearing properties of local clayey soils for road subgrade (Al-Tamimy et al., 2025). Eco-friendly road infrastructure innovations, stressing the adoption of sustainable construction materials and techniques to minimize environmental impacts. Their findings align with geotechnical practices such as soil stabilization and low-carbon alternatives to cement, which are essential for sustainable infrastructure development (Tafida et al., 2024). Recent studies also highlight the use of recycled and bio-based materials as sustainable alternatives to conventional binders.

It underscores how such innovations, including the reuse of construction waste and development of eco-friendly composites, can enhance soil stabilization and concrete performance, thereby contributing to sustainable infrastructure development (Wulan, 2024). Researchers have also investigated the use of sustainable waste materials for stabilizing expansive soils in rural road subgrades. Their results demonstrate improved geotechnical performance while reducing dependence on virgin resources, thereby contributing to low-carbon construction and advancing circular economy principles in sustainable infrastructure development (Farooq & Hasan, 2024). Considering the principles of the circular economy, sludge powder, a by-product of waste treatment, is explored in this study to improve clayey soils in road construction. Sludge is often disposed and mismanaged in developing countries like Pakistan. This would not only enhance geotechnical properties of soil but also to reduce costs and carbon footprints, moving infrastructure development toward a more sustainable future.

This study is about the utilization of waste material in fact waste management following the circular economy concept for improvement of soil performance for infrastructure improvement. Low-cost completion of an infrastructure project for human benefit is prime target of the technical knowledge. Practical solution for sustainable infrastructure improvement is ultimate target. The completion of this task can be tested through lab performance testing as a prototype methodology for field implementation and sustainable practices.

2.0 Literature Review

During the construction of road projects, soil stabilization is a process that consumes a lot of resources to be able to be utilized as a subgrade (Alazigha et al., 2016; Phummiphan et al., 2018; Rajeswari et al., 2018; Soltani et al., 2017; Tizpa et al., 2015). Sometimes soil has a week bearing capacity and CBR values are an indicator for measurement of soil strength. Initial testing of soil provides details about the planning and designing of road projects (Aamir et al., 2019). These testing and calculation finally have an impact on cost planning and management of the projects. The link between the technical profile of existing soil and designing of future roads some time influence on project cost. The worldwide cost of different projects increased only because of that stabilization process and requirements (Aamir et al., 2019). So, the nature of the soil is important to be studied before designing a road. Different countries have a major land with weak soil properties and require improvement during any construction project (Jahandari et al., 2018; Saberian & Rahgozar, 2016). In developing countries due to varying soil conditions, high plastic clayey soil exists in abundance. Construction of highway or road design on such soil is a tough job. For any treatment done to stabilize soil ASTM D4609-08 (Testing et al., 2008),(Standard that helps to determine the effectiveness of admixture added for soil stabilization) is used. According to the standard and increase in unconfined compressive strength 345kpa (50 Psi) or more is to be achieved to say that an additive is an effective stabilizer. In addition to it, if the CBR of soil is increased to 10% or more, the additive is again beneficial for enhancing soil physical properties.

In geotechnical engineering stabilization of soil is the first step for the construction of any structure. Stabilization is being done over the years by different methods, either by adding any materials to soil or by mechanical means which are selected based on depth. Some of the methods include preloading, removal and replacement of the weak soil layer, piles, stone columns, by compaction in rolling and introduction of several additives to the soil. The additives generally used are, cement, lime, gypsum, fly ash, nano chemicals, pond ash, blast furnace slag, waste tyre chips and powders (Al-Malack et al., 2016; Basha et al., 2005; Kollaros & Athanasopoulou, 2016; Lacuoture & Gonzalez, 1995; Lin et al., 2007; Muntohar, 2004; Rajeswari et al., 2018; Soltani et al., 2018; Yadav et al., 2017). Physical properties of soil like cohesion, stability, durability, dry density unconfined compressive strength, California bearing ratio etc., are enhanced by these additions. There is a wide discussion on all these additives and the respective physical properties they improve on addition(Chemeda et al., 2015; Cheshomi et al., 2017; Cong et al., 2014; Esaifan et al., 2016; Esmaeili & Khajehei, 2016; Jahandari et al., 2017; Jahandari et al., 2019; Jahandari et al., 2018; Khabiri, 2010; Rahgozar & Saberian, 2015, 2016; Saberian et al., 2017; Saberian & Khabiri, 2018; Saberian et al., 2018; Wong et al., 2013). The methods described above can be costly while some of them might not be eco-friendly either in term of its addition to soil or its production (Saberian & Khabiri, 2018; Saberian & Rahgozar, 2016). As the population is increasing the need for urbanization has also increased due to which the production of chemicals especially cement is surging considerably and due to artificial manufacturing of additive including cement, certain harmful gasses, and other wastes are increasing. This is a serious environmental threat especially due to an increase in CO2 emission that is also one of the major causes of global warming(Cao et al., 2016; Jahandari et al., 2019). Some developed countries including Poland have taken step towards the eco-friendly stabilization of soil using waste material that is being dumped in certain ways, one such additive is RHA(Van Ruijven et al., 2016). According to research in(Kwofie et al., 2017; Shiravan, 2014), it is briefed that CO2 emissions of about 1 t/t are produced while cement is manufactured, on the other hand, RHA production emits 0.8 g/kg of CO2. Still, other additives are there which do not emit any carbon dioxide during their manufacture, for example, alum sludge, the additive used in this paper.

The soft grounds or clayey soils have always been a challenge for construction because of foundation problems (Mohamad et al., 2016). Generally soft grounds are avoided by engineers when selecting sites for construction. But because of rapid urbanization and increasing population the soft grounds can no more be neglected for construction purpose. It was reported by Department of Quaternary Geological Map of Malaysia in 2010, that along coastal plain maximum of area comprises of soft soil considered as organic or peat soil (Kaniraj & Joseph, 2006). Similarly in Pakistan, Nandipur Punjab, an area situated in Province Punjab has a lot of clayey soil (Aamir et al., 2019).

Currently, the improvisation of ground is being carried out by several different methods. These method include replacement of problematic soil after excavating it, compacting soil for its densification also known as mechanical modification, reduction of water table also termed as dewatering or hydraulic modification, stabilization of soil with addition of some admixtures, electro-osmosis i.e. electrical modification method, modification of soil by thermal affects etc. (Mathew & Sasikumar, 2017; Raju & Daramalinggam, 2012; Zahri & Zainorabidin, 2019).

In order to improve the strength of week soil several stabilizers have been in use amongst which cement is one of the most widely used stabilizers for improving the strength of soil. In 20th century cement was first used as a stabilizing agent (Azzam, 2014). But still, the oldest stabilizer is lime which was being used for the purpose even before cement (Qingquan et al., 2004). Followed by lime and cement some other binders have also been used for stabilization and those include fly ash, slag, gypsum, kiln dust, bituminous materials, and stone dust (Borthakur & Singh, 2014; Marto et al., 2014; Mirzababaei et al., 2017; Naeini & Ghorbanali, 2010). The most commonly used stabilizers include fly ash, lime and cement (Al-Jabban et al., 2017; Talib & Noriyuki, 2017; Yong & Ouhadi, 2007). Unfortunately, a few of these stabilizers generate a negative impact on the environment and directly or indirectly are reported by occupational health safety (Indraratna et al., 2013). The negative effects generated are because of excessive omission of CO2. As per research done by Alyeldeen and Kitazumi 2017 (Ayeldeen & Kitazume, 2017), production of cement is followed by ton of production of carbon dioxide. Another research concluded that 8% of the total production of carbon dioxide is because of cement industry (Andrew, 2018). Generally these traditional stabilizers required more time for curing and a large quantity of stabilizer too (Naeini & Ghorbanali, 2010; Yong & Ouhadi, 2007). The reason behind the prolonged curing time is because of the pozzolanic reactions which generally take 28 days for completion (Teja et al., 2015). Quantity of material and time are the two factors that affect construction cost. Some studies even concluded that the traditional stabilizer results in brittle behavior of the soil because of which it shall be effected easily by seismic activities (Chen et al., 2010). This may increase the probability of unsound foundation and may result in structure failure. Other then the mentioned issues the addition of traditional stabilizer often increase soils' pH value, effecting ground water and reducing the fertility of soil (Indraratna et al., 2013; Nalbantoglu & Tuncer, 2001; Vinod et al., 2010).

The stabilizers are being classified on several bases including dominant chemical basic (Qingquan et al., 2004).In addition to traditional additives some other additives have also been tested and used i.e. enzymes, resin, acids, liquid polymer, ions silicate, and lignin derivatives (Hafez et al., 2008; Horpibulsuk et al., 2010; Kassim et al., 2005). Stabilizers not being used traditionally generally overcome disadvantages of traditional stabilizers. Still the research work and developmental plans for enhancing and improving the soft ground is being continued. The geotechnical engineers have to work hard to come across the most appropriate techniques to deal with problems of the soft ground.

This study focuses on the economical soil stabilization using eco-friendly stabilizers for the pre-construction improvement of soil properties. Furthermore, considering an example of the motorway project section, the cost saving of fuel consumption has also been evaluated which will be an additional benefit to soil strength improvement and economical road construction.

3.0 Methodology

Initially, the research work started after a thorough study of the soil and waste materials. After the selection of waste materials, the source for soil and sludge was decided. The materials were eventually collected and transported to the laboratory which was oven dried, crushed, and followed by the physical and mechanical properties testing of soil as per ASTM or AASHTO standards. Detailed methodology framework has been given in Fig.1.

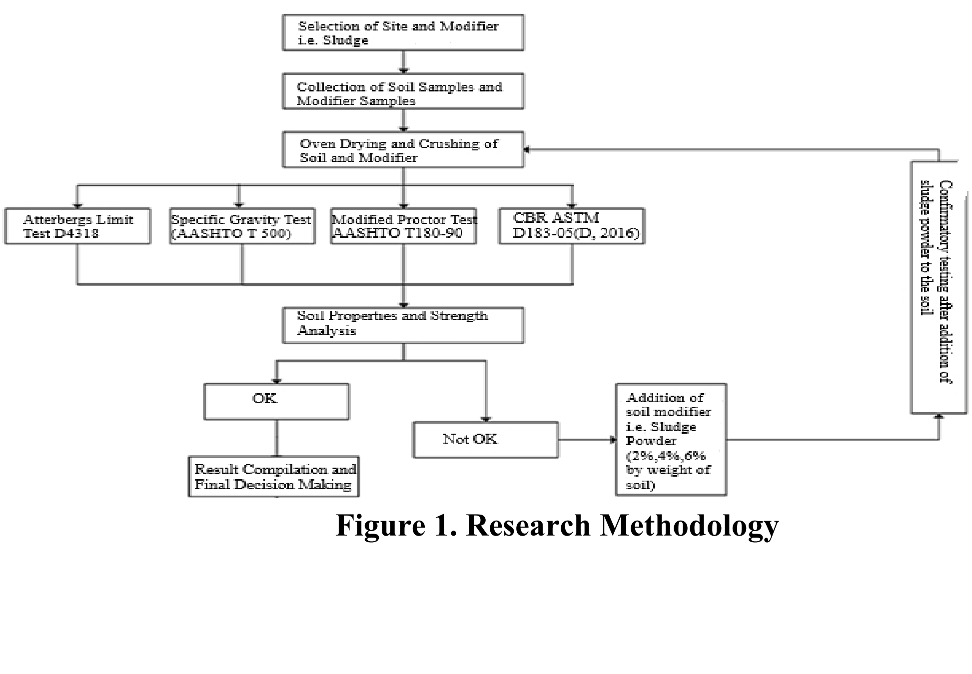

Figure 1. Research Methodology

3.1 Site Selection

The soil sample was collected from a problematic zone located in upper Punjab, Pakistan. The soil was selected based on previous literature and studies done on the soil according to which the soil had weak properties. The soil sample was collected from a depth of one meter approximately. The soil was oven-dried before any testing.

Sludge was obtained from a wastewater treatment plant located in the I-9 sector, Islamabad, Pakistan. The treatment plant is operated by the capital development authority (CDA). The sludge was sun-dried and then oven dried. The oven-dried sludge was then crushed into a fine powder that could pass sieve#100 completely and partially pass sieve#200 as well.

3.2 Sample Preparation

The soil, sludge powder was oven dried for 24 hours at 110 ± 5°C each. After the drying process, the materials were crushed and sieved separately through sieve numbers 100 and 200. Sludge powder was added to the soil separately by 2%, 4%, 6%, and 8% by weight. Each test was done first on soil without any percentage of modifiers, i.e., sludge and after the addition of modifier, the samples were tested again.

3.3 Atterberg's limits

According to ASTM standards, D 4318(Standard, 2010) liquid and plastic limit test was performed. When a soil loses its moisture content and the state of soil changes from plastic to liquid, the particular moisture content is termed as liquid limit. Liquid limit is basically moisture content of any soil at which it changes from plastic to liquid state. Whereas, plastic limit is obtained when the soil thread at specific moisture content fails to roll down till 3.22mm. the difference between liquid limit and plastic limit helps to determine the plasticity index of the soil.

3.4 Proctor Test

The proctor test initially was introduced by Raplh R Proctor in early 1930s termed as the standard proctor test, which was further modified and is known as modified proctor test. The test is described in AASHTO T99 (ASTM D-698)(Soil & Rock, 2007) and compacted to 600kNm/m3. In 1958, standard Proctor test was modified and later known as modified Proctor test which is defined in AASHTO T180-90 and ASTM D1557-91, at compaction energy equivalent to 2700 kN.m/m3.

3.5 California Bearing Ratio

In order to determine the strength of soil, California Department of transportation introduced CBR test. The test is detailed in AASHTO T193. According to ASTM standards, the method of calculation of CBR varies from lab to field. For the lab, it is defined in ASTM standards D183-05(D, 2016) where for the field is ASTM D4429.

4.0 Findings and Results

The soil was classified under AASHTO standards and was initially categorized as A-7-6 soil, which is highly plastic clay and usually determines poor engineering properties. Sludge powder were prepared by drying, crushing, and sieving followed by mixing them with the soil in proportions of 2%, 4%, and 6% by weight. When sludge was added, the soil remained in the A-7-6 category at 2%, but improved to A-4, a fair-quality silty soil, at 4%. At 6%, the classification changed again to A-5, representing less silty soil. The following table 1 summarizes the soil index properties as well as the optimum moisture content and maximum dry density of the soil.

Table 1. Properties of Soil with Modifier (Sludge)

Sludge	0%	2%	4%	6%
AASHTO	A-7-6	A-7-6	A4	A-5
Liquid Limit	56.15	50.67	42.66	36.63
Plastic Limit	20.31	20.78	22.12	26.44
Specific Gravity	2.68	2.58	2.49	2.45
MDD lb/ft3	102.89	113.62	116.33	100.26
OMC %	11.24	13.48	14.49	16.89

4.1 Modified Proctor Test

Modified Proctor test was performed on sludge powder each individually. The soil sample was prepared by adding different percentages of sludge powder to it i.e., 2%, 4%, and 6%. The graph between dry density and moisture content is plotted below for both modifiers i.e., sludge powder. The dry density of the soil increased from 102.8 lb./ft^3 to approximately 116.3 lb./ft^3 with the addition of 4% sludge to the soil. While the optimum moisture content of soil increased from 11.24% to 14.49% at the same percentage of sludge. Comparative performance has been shown in Fig.2.

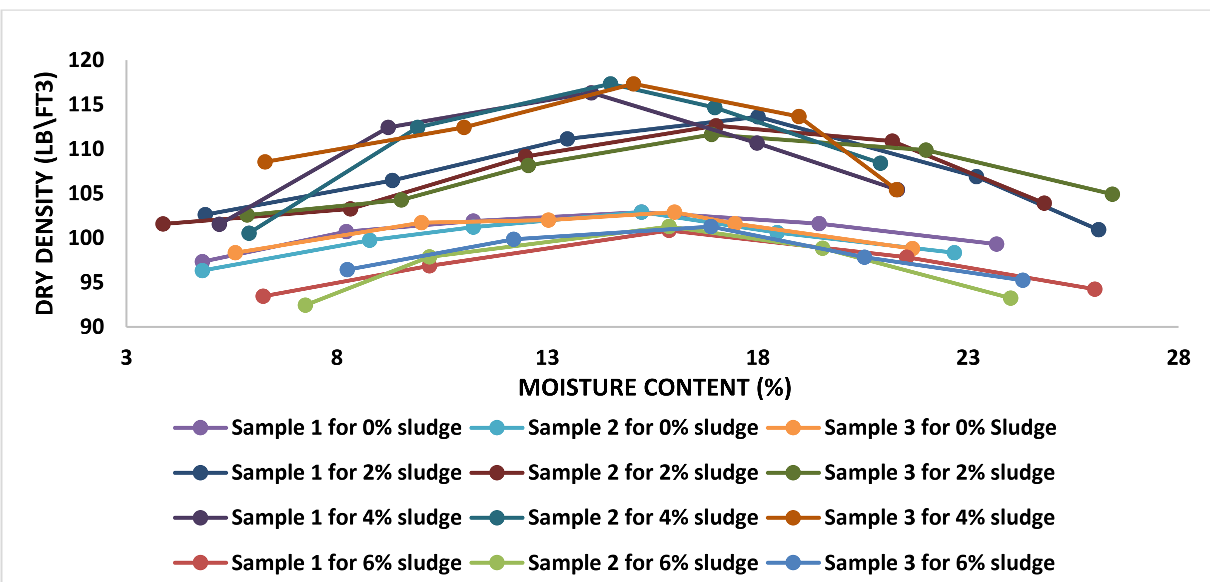

Figure 2. Moisture Content vs Dry Density by Modified Proctor (Sludge)

4.2 California Bearing Ratio test

The California bearing ratio (CBR) test was performed on soil for three different number of blows i.e., 10, 30, and 56. CBR percentage increased with an increase in the modifier percentage until the modifier percentage reached 4%. After 4% at 6% the CBR again started to decline. For 10 number of blows the CBR percentage increased from 5.23% to 7.98% whereas, at 6% again CBR decline to 5.61%. For 30 number of blows the CBR calculated when no modifier was added was 6.75% and it increased to 11.04% on addition of 4% of sludge. When the sludge percentage was increased to 6% the CBR dropped to 9.12%. The maximum CBR was observed for 56 number of blows when CBR increased from 8.69% to 14.79% for 4% addition of sludge to the soil. Comparative CBR performance has been shown in Fig.3.

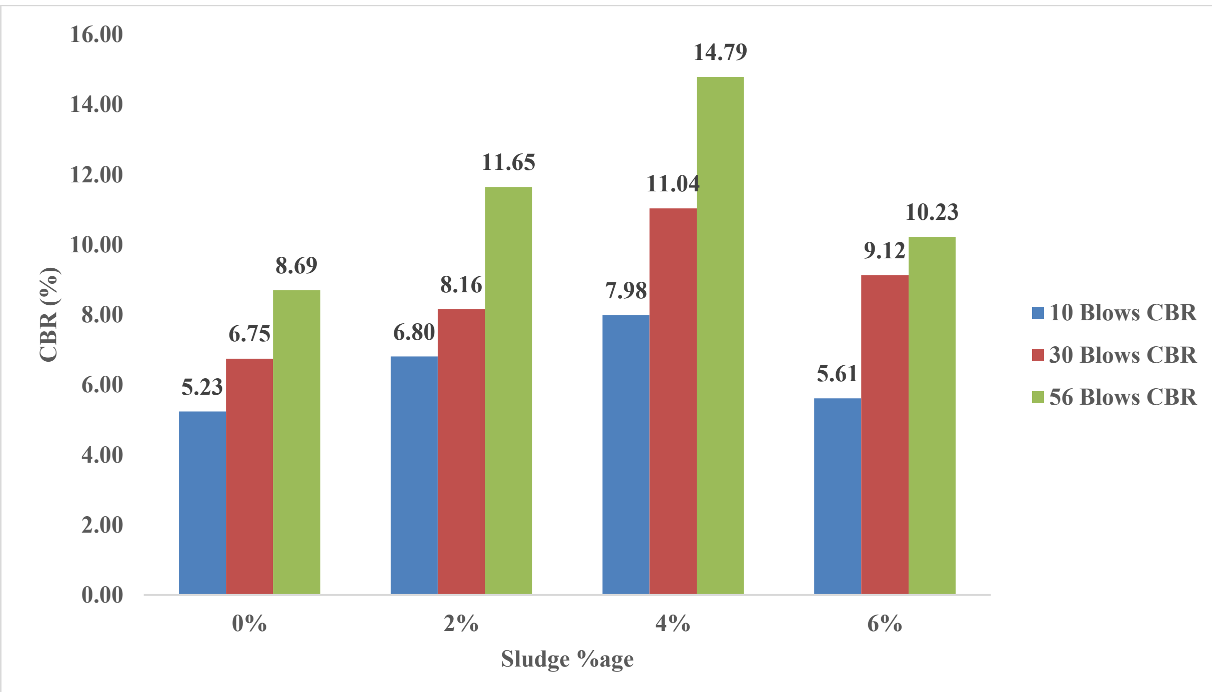

Figure 3. CBR % vs Sludge %age

4.3 Financial and Environmental Analysis

4.3.1 Financial Analysis

Cement stabilization is one of the traditional methods of soil stabilization. In this method of stabilization generally certain amount of cement is added to soil to increase the strength of subgrade. In this research we tested our soil samples with complete replacement off cement. For financial analysis when cement is substituted, let's suppose that we need to stabilize the soil of subgrade of two-lane highway pavement with a width of 12 meter and for just 500m (length) section. The thickness on this upgrade is taken as 0.2 meter. So, for these dimensions the calculated volume of soil is 1200m^3. The density of soil was calculated to be 1649.9 kgm^{-3}.

$$Mass\ of\ Soil = Density \times Volume = 1979880\ kg$$

If 4% cement replacement is required, then.

Mass of cement= 4% of 1979880 = 79195.2 kg

Since one bag of cement contains 50kg thus, 1584 bags of cement will be required. Since one bag of cement at least costs 1100 rupees in Pakistan. So, for 1584 bags of cement the total cost of cement required in the subgrade will be Rs 1742400. As we have completely replaced cement for stabilization in our research project so we can save an amount of about 1.7 million rupees for only a small section of road. Even partial replacement also helps to save budget. Therefore, it can be concluded that replacing cement with any Material like sludge powder can affect the total cost of the project significantly.

4.3.2 Environmental Analysis

Cement industry is one of the major contributors of CO_2 and many other pollutants in the environment. It is estimated that 0.9 pounds of carbon dioxide are produced for every single pound of cement. As per the calculations done in the previous section of this thesis 79195.2 kilograms of cement will be required for a section of 500m of two-lane highway. Since 1kg equals 2.204lbs the CO_2 produced will be, 157135.97lbs or 32330.094kg.

This means replacement of sludge powder will be reducing utilization of cement for subgrade stabilization and will be directly reducing the emissions of carbon dioxide in the air. Therefore, utilization of sludge powder will be a step towards environmentally friendly and sustainable stabilization.

5.0 Discussion and Conclusion

In this study weak soil from problematic zone was stabilized using sludge powder that enhanced CBR for subgrade while supporting circular economy practices. The addition of 4% of the sludge powder changed the soil type from A-7-6 which is a high plastic clayey soil as per AASHTO classification to A-4 which is silty soil and possesses relatively better properties. But as soon as the percentage addition of sludge powder increased to 6%, the soil properties began to decline again. The addition of Sludge Powder significantly improved the CBR of soil from 8.69% to 14.79% and 16.11% respectively. The increase in percentage of modifiers up to 4% improved the unconfined compressive strength of soil by almost three times. The cost and environmental analysis of replacement of cement with these modifiers in soil for a very small section of road could reduce the cost and CO_2 production significantly. The use of these materials can help in promoting circular economy, sustainability, and environmentally friendly stabilization of soil.

The following recommendations may be considered for further studies.

As this study has been conducted on high plastic clayey soil of problematic zone, the soil type could be changed in further studies to figure out if the modifier will bond with other soil types too or is it only limited to this soil.

Authors Contribution

Aqsa Nisar: Problem Identification, Theoretical Framework and Data Analysis,

Sunera Imtiaz: Supervision and Drafting

SARS Shah: Methodology and Revision

Conflict of Interests/Disclosures

The authors declared no potential conflicts of interest in this article's research, authorship,and publication.

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