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Improvement of the Mechanical Properties of Clayey Sand by Addition of Demolition Debris for Use in Road Bases

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Abstract

The mechanical quality of a road depends heavily on its sub-base layer, which must ensure adequate load-bearing capacity and effective load distribution. This study investigates the enhancement of mechanical properties of clayey sands abundant in southern Côte d'Ivoire through the addition of demolition debris. Five sites were examined: Samo, Cocody, Dabou, Songon, and Grand-Lahou. Characterization tests (particle size analysis, Atterberg limits, Proctor compaction, and CBR tests) revealed that, in their natural state, the clayey sands exhibit insufficient plasticity and bearing capacity for use as base layers. The progressive incorporation of demolition debris (up to 12%) significantly improves the CBR index, reaching up to 142% for the soil from Dabou. This valorization of recycled materials offers a sustainable, cost-effective solution that meets the technical requirements of road construction projects.

Keywords

Clayey Sand, Demolition Debris, Road Geotechnics, CBR, Recycling

1. Introduction

Côte d'Ivoire, located on the West African coast between Ghana, Liberia, and Guinea, features remarkable geographical diversity, ranging from coastal plains to inland plateaus and mountainous reliefs in the west. Geologically, the country lies predominantly on the ancient Precambrian West African Shield, which was once connected to Brazil before the opening of the Atlantic Ocean [1] [2]. Two major geological units structure the territory: A Precambrian basement covering approximately 97.5% of the national surface, and a secondary-tertiary sedimentary basin forming a narrow 2.5% strip along the coastline [3].

Abidjan, the economic capital and main urban hub of the country, is located within this sedimentary zone. It is experiencing ultra-rapid urban growth, driven by the concentration of economic activities and the quality of existing infrastructure. This dynamic is transforming the urban landscape, notably through the demolition of informal settlements as part of development, renovation, and public infrastructure projects (roads, bridges).

These road projects require earthworks and the implementation of complex pavement structures, whose quality heavily depends on the materials used—particularly for the sub-base layer. This layer is critical to the mechanical performance of the pavement and must consist of materials capable of supporting and transmitting traffic loads to the lower layers [4] [5]. Gravelly materials are generally recommended for this purpose, but their availability in the southern part of the country, especially in the sedimentary basin, is limited. In contrast, clayey sands are abundant in this region [6] [7], opening the door to local valorization in a sustainable development perspective [3].

However, in their natural state, clayey sands exhibit insufficient mechanical performance and durability for road construction [8]. The use of hydraulic binders to improve their properties is a proven technique, requiring specialized equipment and rigorous protocols [9] [10]. In a changing economic context and in response to environmental imperatives, integrating alternative materials such as shales, marls, or recycled materials (concrete debris, glass, etc.) is emerging as a promising avenue [11].

Among these alternatives, debris from urban demolitions represents a potential resource to be valorized. This study aligns with that logic and aims to investigate the geotechnical characteristics of a mixture of clayey sand and demolition debris, with a view to its use as a sub-base layer in road construction techniques. The main objective is to assess the influence of these additions on the mechanical properties of clayey sand, in order to propose a local, sustainable, and economically viable solution for road infrastructure in Côte d'Ivoire.

2. Materials and Method

2.1. Materials

Clayey sand (**Figure 1(a)**) was collected from five (05) zones (Z), namely: Samo (Z1), Cocody (Z2), Dabou (Z3), Songon (Z4), and Grand-Lahou (Z5). As for the demolition debris (**Figure 1(b)** and **Figure 1(c)**), it was sourced from a demolition site located in Koumassi, a district of the city of Abidjan.

As for the demolition debris, it originates from various urban areas of the city of Abidjan, without prior sorting, in order to reflect a realistic approach to valorization in the local context. This diversity of origin includes demolition concrete, fragments of bricks, mortar, and cement blocks.

(a) (b) (c)

Figure 1. (a) Clayey sand; (b) building under demolition; (c) demolition debris.

2.2. Method

The samples were subjected to grain size analysis, Atterberg limits tests, the Proctor compaction test, and the California Bearing Ratio (CBR) test. Subsequently, varying proportions of demolition debris 2%, 4%, 6%, 8%, 10%, and 12% will be added to the clayey sand from each zone and then tested using the CBR method (see Table 1).

Table 1. Composition of the different samples from the clayey sand-demolition debris mixture.

Demolition Debris Content	Mass of Clayey Sand(g)	Mass of Demolition Debris (g)
0%	7000	00
2%	6860	140
4%	6720	280
6%	6580	420
8%	6440	560
10%	6300	700
12%	6160	840

The variation range of 2% to 12% was selected for this study to represent a gradual and meaningful progression of the parameters studied in recycled materials. This choice is based on several considerations, such as technical representativeness, covering a realistic range of dosages or proportions commonly encountered in road construction materials, particularly for subgrade layers or stabilized granular mixtures. It also provides sufficient resolution to detect progressive effects on mechanical properties (bearing capacity, permeability, strength, etc.).

Beyond the 12% threshold, the materials may exhibit non-linear behavior or saturation risks, which justifies limiting the dosage to 12% in order to remain within a technically suitable range. The table below presents the composition of the different samples.

3. Characterization of Clayey Sand

3.1. Equipment (Apparatus)

3.1.1. Particle Size Analysis of the Clayey Sands (NF P 18-560)

The purpose of the test is to determine the dimensional distribution of particles within a granular material, with particle sizes ranging from 0.063 mm to 125 mm. It enables the classification of grains into different size fractions, which is essential for identifying the material and assessing its suitability for use in road construction.

The principle of the test involves the mechanical separation of the material using a stack of sieves with progressively smaller mesh sizes. The material retained on each sieve is called the retained fraction, while the portion that passes through is referred to as the sieve passing. The masses of the retained fractions are related to the initial dry mass of the material, allowing for the calculation of cumulative retained percentages and the construction of the particle size distribution curve.

3.1.2. Atterberg Limits of the Clayey Sands (NF P 94-051)

The test is used to characterize the consistency of fine-grained soils based on their water content. It aims to determine two fundamental parameters: the liquid limit (LL), which is the water content at which the soil transitions from a plastic to a liquid state, and the plastic limit (PL), which represents the water content at which the soil changes from a plastic to a semi-solid state. These two limits are essential for assessing the clay content of a soil and for calculating the plasticity index (PI).

3.1.3. Proctor Compaction Test of the Clayey Sands (NF P 94-093)

This test determines the optimal compaction conditions of a soil, specifically the optimum moisture content (w_opt) that yields the maximum dry density (γd_{max}) for a given soil.

3.1.4. California Bearing Ratio (CBR) Test on Clayey Sand and Clayey Sand-Demolition Debris Mixture (NF P 94-078)

Figure 2. CBR press.

This laboratory test is used to assess the bearing capacity of a material intended for road infrastructure, particularly for subgrade, foundation, or base layers. It involves measuring the resistance of a soil sample to the penetration of a standard cylindrical plunger, compared to that of a reference material (crushed stone). The test consists of driving a 50 mm diameter cylindrical plunger (see **Figure 2**) into a compacted soil specimen at a constant rate of 1.27 mm/min. The forces required to reach penetrations of 2.5 mm and 5.0 mm are recorded. The California Bearing Ratio (CBR) is expressed as a percentage, representing the ratio between the force measured on the tested soil and that obtained on the reference material for the same penetration depths.

4. Results

4.1. Characterization of Clayey Sands

4.1.1. Particle Size Distribution of Clayey Sands from Different Zones

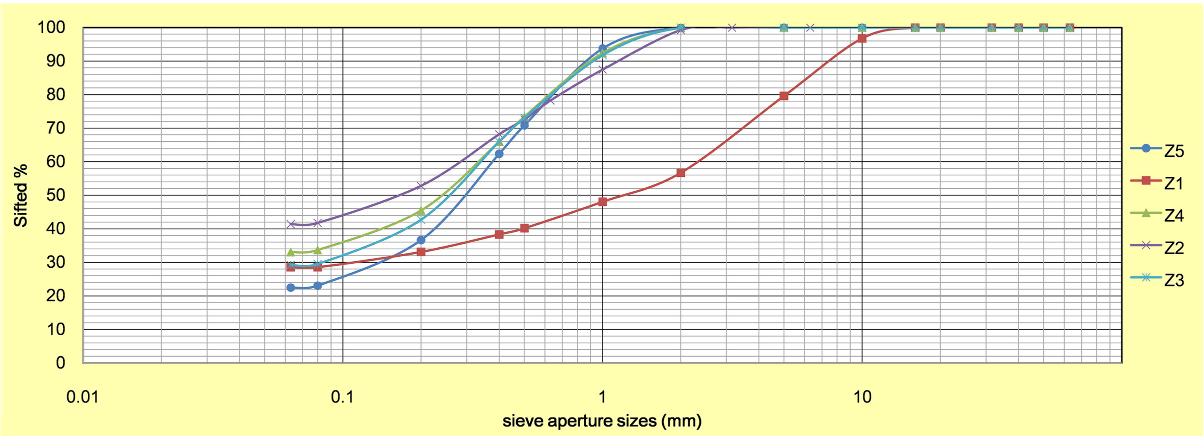

Figure 3. Grain size distribution curve of the clayey sands.

The curves (**Figure 3**) are progressive, indicating a continuous distribution of particles. They show no abrupt breaks or horizontal plateaus, which means the materials exhibit no marked discontinuities between grain size classes. The curve for the Samo Z1 material reveals a very fine texture with a high proportion of particles smaller than 0.1 mm, likely rich in clay or silt. The curve suggests a poorly graded material, making it less suitable for compaction without treatment. The soils from Cocody Z2 and Dabou Z3 display a balanced granulometry, more spread out with a mix of fines and medium-sized grains. The interlocking of grains of different sizes suggests good potential for compaction. Finally, the soils from Songon Z4 and Grand-Lahou Z5 show a significant presence of coarse particles (>2 mm), which could enhance bearing capacity but reduce cohesion. The fine content for Samo (28.55%), Dabou (29.24%), Songon (30.04%), and Grand-Lahou (22.54%) complies with LBTP standards, which recommend a maximum of 30% fines for base layer soils. Cocody, however, has a fine content of 41.38%.

Petrographically, the demolition debris is predominantly silico-calcareous, with a variable presence of natural and artificial aggregates. The fines content, measured by sieving, remains below 17%, which meets the recommended thresholds for subgrade or foundation layers in road construction. No hazardous components (asbestos, heavy metals, hydrocarbons) were detected during environmental compliance testing.

4.1.2. Water Content, Plastic and Liquid States of Clayey Sands

The various results for LL, PL, and PI are presented in Table 2 below.

The plastic limit values are relatively close (ranging from 22 to 27), indicating a consistent plastic behavior among the tested soils.

Table 2. Liquidity and plasticity status of the clayey sand.

Clayey Sand from the Localities	Wl	Wp	PI = Wl − Wp
Samo	49	22	27
Cocody	47	27	20
Dabou	41	24	17
Songon	46	26	20
Grand-Lahou	44	26	18

Analysis of the table shows that the plasticity index (PI) values range between 17 < PI < 27. The highest PI value is 27 at the Samo site, while the lowest is 17 at the Dabou site. The soil from Samo, with the highest PI (27), is highly plastic, which suggests it may be difficult to compact without treatment.

In contrast, the soil from Dabou, with the lowest PI (17), appears easier to handle and stabilize. The other locations Cocody, Songon, and Grand-Lahou have intermediate PI values (18 - 20), indicating moderately plastic soils.

According to the specifications in [6], for a material to be suitable for use as a base layer, the Plasticity Index (PI) must be less than or equal to 20%. Values above 20% suggest that these soils may require treatment ideally a combined lime-cement stabilization approach [12].

4.2. Mechanical Properties of Clayey Sands

4.2.1. Proctor Compaction Test

Table 3 results show that dry density varies with the soil's water content and reaches a peak corresponding to the Modified Proctor Optimum.

The soils from Cocody and Dabou exhibit the highest dry densities (2.12 and 2.11 g/cm^3), indicating good compaction potential and a favorable granular structure.

In contrast, the soils from Samo, Songon, and Grand-Lahou have lower dry densities (2.01 g/cm^3), which may reflect a finer texture or lower natural compactness.

The soil from Samo has a high Modified Proctor Optimum Moisture Content (WOPM) of 12.05%, consistent with a more clayey texture requiring more water to achieve maximum density. The other locations show lower WOPM values (≈8% - 9%), typical of sandier or well-graded soils.

The soil from Cocody, despite having excellent dry density, exhibits excessively high natural moisture content, which may hinder compaction and bearing capacity. Drying or treatment is recommended.

Table 3. Proctor references for the various soils

Soils from the Localities	Natural Moisture Content (Wn) (%)	Dry Density (γdOMC)	Optimum Moisture Content (WOMC) (%)
Samo	1258	2.13	9.40
Cocody	22.27	2.02	8.40
Dabou	11.78	2.01	12.05
Songon	11.78	2.01	10.50
Grand-Lahou	11.78	2.04	8.20

The soil from Samo, on the other hand, is naturally well-balanced, but its dry density is lower. This can be improved by adding coarser materials or through stabilization.

The soils from Dabou, Songon, and Grand-Lahou are naturally close to their optimum moisture content, with acceptable dry densities, which will facilitate implementation and are expected to perform well under compaction.

According to the technical specifications of the CCTP, the dry density for a base layer soil should range between 1.80 and 2.10 g/cm^3, and the optimum moisture content between 8% and 12%. Thus, the clayey sands from the studied sites comply with the technical requirements.

4.2.2. CBR Bearing Index of Clayey Sands

The soils from Cocody, Dabou, and Samo exhibit the highest CBR values at 95% of the Modified roctor Optimum after 4 days of water immersion, with values of 54%, 44%, and 38%, respectively. In contrast, the soils from Songon and Grand-Lahou show significantly lower values of 18% and 19%, indicating insufficient bearing capacity (see **Table 4**).

Table 4. CBR values at 95% of optimum moisture content after 4 days of water immersion for the different clayey sands.

Soils from the Localities	CBR
Samo	**38**
Cocody	**54**
Dabou	**44**
Songon	18
Grand-Lahou	19

The Cocody soil stands out with the highest CBR index (54%), confirming its good dry density and balanced particle size distribution. This soil demonstrates favorable mechanical properties.

The Dabou soil also shows a strong CBR value (44%), consistent with its natural compaction and low plasticity.

The Samo soil, with a CBR of 38%, could benefit from the addition of coarser materials to enhance its bearing capacity.

On the other hand, the soils from Songon and Grand-Lahou, with CBR values below 20%, are unsuitable for direct use as base layers. Stabilization using lime, cement, or gravel is required to meet the specifications of the CCTP.

Moreover, the CBR values of Songon and Grand-Lahou fall below the 30% threshold typically required for pavement base layers.

Overall, the analysis of clayey sands from the five study sites indicates that these soils require treatment before being used in road infrastructure. Rather than relying on conventional binders such as cement or lime, this study proposes the use of demolition debris as a sustainable and cost-effective alternative.

4.3. Influence of Demolition Debris Content on the Bearing Index (CBR) at 95% of Optimum Moisture Content after 4 Days of Water Immersion in Clayey Sands

Table 5 below shows the variation in CBR values at 95% of the Optimum Moisture Content (OMC) after 4 days of water immersion, as a function of the percentage of demolition debris added.

Table 5. Variation of CBR at 95% of OMC.

	CBR of the clayey sand mixed with demolition debris						
	0%	**2%**	**4%**	**6%**	**8%**	**10%**	**12%**
Samo	38	45	55	62	80	87	99
Cocody	54	65	73	85	91	93	112
Dabou	44	48	67	80	100	120	142
Songon	18	23	29	34	48	57	75
Grand-Lahou	19	23	38	42	60	70	87

A general increase in the CBR of the soils is observed as the content of demolition debris rises. The CBR in Zone 1 (Samo) increases from 38% to 99%, Zone 2 (Cocody) from 54% to 112%, and Zone 3 (Dabou)

A generally linear increase in CBR values is observed as the proportion of demolition debris in the soil increases.

Zone 1 (Samo): Initially moderate with a CBR of 38%, the value rises steadily to 99%. The soil shows good improvement with debris, though it remains less performant than Cocody or Dabou. It could be used for subgrade and base layers, with dosage optimization recommended.

Zone 2 (Cocody): Exhibits excellent mechanical behavior from the outset, with a CBR of 54% at 0% debris, reaching 112% at 12% debris content. The resulting mix appears well-structured and likely well-graded. It is suitable for base layers and meets the demands of high-performance road structures.

Zone 3 (Dabou): Achieves the highest CBR value at 12% debris an exceptional

142%. A sharp increase is noted from 4% onward. The Dabou material is highly responsive to debris addition, indicating excellent bearing capacity, ideal for base or foundation layers.

Zones 4 and 5 (Songon and Grand-Lahou): Initially very low CBR values of 18% and 19%, respectively, indicating poor natural bearing capacity. Although a notable improvement is observed with debris addition, values remain below 90% at 12%. These soils may be used for subgrade layers but would require additional treatment or blending with stronger materials.

The observed improvement in CBR can be attributed to the debris particles filling voids within the clayey sand matrix, thereby increasing material density. This rearrangement enhances the mechanical properties of the clayey sand-demolition debris mixture. The most significant gains occur between 4% and 10% debris content, suggesting this range as an optimal dosage.

At 12% debris content, some mixtures particularly those from Dabou and Cocody achieve performance levels exceeding those of treated natural gravels, which is promising for the valorization of demolition waste.

Certain road projects require a base layer CBR of 120%. Therefore, the Dabou soil, with 12% added debris, could be used effectively as a base layer material.

The curves are progressive, indicating a continuous particle size distribution. They show no abrupt breaks or horizontal plateaus, meaning the materials have no marked discontinuities between grain size classes. The curve for the Samo Z1 material reveals a very fine texture with a high proportion of particles smaller than 0.1 mm, likely rich in clay or silt. It indicates a poorly graded material, making it less suitable for compaction without treatment. The soils from Cocody Z2 and Dabou Z3 display a balanced and well-spread granulometry, with a mix of fines and medium-sized grains. The interlocking of grains of different sizes suggests good potential for compaction. The soils from Songon Z4 and Grand-Lahou Z5 show a significant presence of coarse particles (>2 mm), which could enhance bearing capacity but reduce cohesion. The fine content for Samo (28.55%), Dabou (29.24%), Songon (30.04%), and Grand-Lahou (22.54%) complies with LBTP standards, which recommend a maximum of 30% fines for base layer soils. Cocody, however, has a fine content of 41.38%. Petrographically, the demolition debris is predominantly silico-calcareous, with a variable presence of natural and artificial aggregates. The fines content, measured by sieving, remains below 17%, which meets the recommended thresholds for subgrade or foundation layers in road construction. No hazardous components (asbestos, heavy metals, hydrocarbons) were detected during environmental compliance testing.

5. Conclusions

This study highlights the potential of clayey sands from southern Côte d'Ivoire to be valorized in road base layers, despite their initial limitations in bearing capacity and plasticity. The gradual addition of demolition debris significantly improves their mechanical properties, particularly the CBR index, with optimal performance observed at 12% incorporation. This approach offers a sustainable and cost-effective alternative to conventional soil treatment methods, while aligning with the principles of circular economy. It not only enhances the bearing capacity of local materials but also reduces the environmental impact associated with construction waste management.

These results confirm that incorporating demolition debris into clayey sands significantly improves soil bearing capacity and enables the valorization of local and recycled materials within a sustainable development framework. This provides an economical and technically viable alternative to natural gravels, especially in areas where such resources are scarce.

Although the results obtained demonstrate a significant improvement in the mechanical properties of clayey sand–demolition debris mixtures, certain uncertainties remain. In particular, the effects of wet-dry cycles, which may alter the cohesion and bearing capacity of the material, were not evaluated in this study. Additionally, the potential release of leachates from demolition debris especially in the presence of urban pollutants could pose environmental risks.

These aspects represent important limitations that warrant further investigation through complementary studies, notably accelerated durability tests and chemical analyses of percolation water. Such an approach would help confirm the environmental and structural suitability of the material under varying climatic and hydrological conditions.

Moreover, no exploration was conducted beyond the 12% threshold, leaving open the question of possible mechanical saturation or negative effects on the compaction or cohesion of the mixture. Similarly, the lower limits of 2% and 4%, although slightly improving the CBR, may not be sufficient to meet technical requirements in certain contexts.

Therefore, it would be relevant to deepen this analysis through additional tests beyond 12% to identify a saturation threshold, and to perform statistical modeling of performance based on the initial characteristics of the soils. This variability highlights the importance of a contextual and adaptive approach in the valorization of recycled materials for road infrastructure.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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