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Potential use of coltan mining waste rock in road construction

Alinabiwe Nyamuhanga Ally[1,2], Manjia Marcelline Blanche[3], Ursula Joyce Merveilles Pettang Nana[3], Masika Muhiwa Grâce[1,2], Élodie Ruffine Zang[1], Ngapgue François[4] and Chrispin Pettang[3]

[1] *Laboratory Engineering Civil and Mechanics, Doctoral Research Unit for Engineering and Applications, University of Yaoundé I, Yaoundé, Cameroon*

[2] *Department of Civil Engineering, Faculty of Applied Sciences and Technologies, Free University of Great Lakes Countries, Goma, Democratic Republic of the Congo*

[3] *Department of Civil Engineering, National Advanced School of Engineering of Yaoundé, University of Yaoundé I, Yaoundé, Cameroon*

[4] *Department of Civil Engineering, Fotso Victor University Institute of Technology, University of Dschang, Bandjoun, Cameroon*

Corresponding author:
Alinabiwe Nyamuhanga Ally
ir.alny111@gmail.com

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Faculty of Civil Engineering and Architecture Osijek
Josip Juraj Strossmayer University of Osijek
Vladimira Preloga 3
31000 Osijek
CROATIA

Abstract:
The mining industry produces vast quantities of mine refuse, including waste rock and tailings, which pose a significant environmental problem. Mining residues, which are generated during ore extraction and mineral processing, are typically deposited near mines. This method of mine waste disposal can lead to environmental problems and land loss. This fact has prompted research into the utilisation of sediments as alternative materials to produce backfill and paving materials. The Democratic Republic of the Congo (DRC) possesses approximately 80 % of Africa's coltan reserves, which is geologically unsustainable considering its many mineral resources. When coltan is extracted, geologically heterogeneous debris spanning from fine particles to boulders is produced. The purpose of this study was to analyse the potential value of mine tailings in road embankments using coltan waste rock from the eastern DRC as a case study, in accordance with the French standard. To accomplish this, it was necessary to evaluate the coltan waste rock's chemical, mineralogical, and geotechnical properties. The coltan mining waste rock studied (SS1,i, SS2,i, and SS3,i) were found to be naturally clayey in nature, with characteristics for use in road construction. However, stabilised at 60 % by the SS4, classified as sand according to the Laboratoire Central des Ponts et Chaussées (LCPC) classification, the SS1,i, SS2,i, and SS3,i clayey waste rock possess the necessary characteristics for sub-base course materials.

Keywords:
coltan; mining waste; road construction; california bearing ratio; stabilisation

1 Introduction

The mining industry generates large volumes of tailings, sludge, and waste rock, which pose an enormous environmental problem. Mining waste (waste rocks and tailings) generated during ore extraction and mineral processing is typically deposited at or near mine sites. This method of mine waste management can lead to environmental problems and land loss. This has prompted research on waste as an alternative material for the production of concrete, backfills, pavements, and other materials. The use of mining waste as a construction resource helps conserve non-renewable natural resources, reduce mining waste, and reduce the environmental impact of mining. However, although it has been studied, the use of mining waste in road construction has not yet been developed on a large scale, and there is a significant lack of specific legislation. This shortcoming is due to the variety of mined rocks, diversity of tailings, mine waste rocks, valuable by-products intended for recovery, and environmental specificities [1].

Mining includes extraction, processing, and metallurgical processes. Underground or open-pit mining operations generate three main types of solid waste: waste rock in the form of rock fragments representing the non-commercial part of the extracted rock; concentrator tailings consisting of gangue, water, and sometimes chemical additives used during the ore processing phase; and sludge from the treatment of contaminated water [2]. In addition to waste rock and tailings, dead soil excavated during mining operations is also considered to be mining waste.

Geologically heterogeneous mining waste is composed of sedimentary, metamorphic, or igneous rock, soil, and loose sediments, ranging in size from fine particles to boulders. Approximately 250,000 million tonnes of solid waste are produced each year by mining activities in various forms [2]. In addition to occupying large areas, mining waste can cause serious environmental problems and major ecological disruptions, if not properly controlled. Due to its significant volume, mining waste is one of the primary sources of industrial waste and necessitates special consideration from the scientific community [3, 4]. The use of waste in construction materials, including concrete, road fills, fired bricks, and ceramics, has received increasing attention [5-7]. This application was motivated by the depletion of natural resources, promotion of sustainable development, and promotion of a circular economy [8].

Additionally, several factors must be considered before using waste or by-products as construction materials. In short, the use of industrial by-products as secondary and alternative materials in the infrastructure sector depends on their availability and transport cost, as well as their physical, geotechnical, and chemical properties [9]. This method offers several economic and ecological advantages. For example, when wastes with acceptable properties are available, it is possible to avoid the costs associated with extraction and minimise transport distance, energy consumption and, consequently, greenhouse gas emissions.

Although the conventional production of road materials requires extraction, crushing, and screening, the exploitation of mining waste as a material requires attention only for screening. However, the use of mining waste as a construction material must satisfy certain requirements. This must ensure that it represents a suitable application in terms of its technical and environmental properties, creates economic interest, preserves natural resources, and slows the consumption of natural resources.

Roads are subject to traffic constraints, climatic variations (precipitation, variations in the water table, and freeze-thaw cycles). In addition, the natural variability of soils, such as the presence of clay, and fines content, all of which require specific conditions in terms of the materials used. Depending on the geographical location of the supply and demand of road materials, compromises must be made between the various levels of requirements. Depending on the anticipated traffic (load and frequency), in situ bearing capacity of the soil (high or low), and climatic region, the total depth of the road structure can vary from 30 cm to over 1 m. Depending on the technology chosen, a road is generally made up of soil and four layers: subgrade, base course, and surface course. The surface course, also known as the wearing course, can be made of asphalt, concrete, or 95 % aggregates. Concrete can contain sand or fine particles. fine particles in the composition. This composition has the properties required for safe use by vehicles (uniformity rather than unity). They also play a role in waterproofing, and contribute to road durability.

Second, the base layer provides mechanical strength and distributes vertical stress over the subgrade to prevent excessive deformation. They are subject to elevated levels of stress; therefore, the materials they are made of must be of sufficient quality. The California bearing ratio (CBR) must be at least eighty to achieve a dry density of 95 % OPM [10]. The materials in the base course can undergo considerable attrition under traffic, particularly when the base course is not stiffened because the shear strength is entirely taken up by the friction between the grains.

Third, the sub-base layer plays the same role as the base layer. Regardless of the structure in which they are included, the materials for the sub-base layer must have a CBR greater than or equal to 30, which is obtained for a density corresponding to 95 % of the OPM [10]. To avoid segregation, materials with smaller grain sizes and maximum dimensions not exceeding 60 mm are recommended.

Fourth, the subgrade is used to adapt the characteristics of the in situ backfill materials or soil to the essential functions of the pavement support platform. The substitute or additional materials to be used in the subgrade to compensate for the inadequacy of natural soil and, if necessary, to allow site traffic must be selected; in any event, they must have a CBR greater than five [10].

Roads are among the structures that require the most materials for construction. In the United Kingdom, aggregate sources produce approximately 300 million tonnes per year, 30 % of which are used for road construction. In France, the construction of road and rail, including underground networks, absorbs approximately 60 % of the aggregates produced [1]. Therefore, the use of industrial by-products in road construction has been the subject of numerous studies. It has been shown that coal mine tailings correspond to very silty sands and gravels of medium hardness and can be used in the construction of pavements in compliance with the compaction table proposed by the French guide for road works. Because of their CBR (9 as CBR), they can be used as sub-base materials [11]. It has been established that phosphate mine waste rock can be used as an alternative material in the construction of dry, compacted embankments. Its insensitivity to water, its dry density of 17,9 kN/m^3 at 95 % of the Proctor, and its CBR of 13 at 4 days of immersion make it a material that can be used as a material layer [9].

Coal rejects have been used in backfill and pavement layers in Morocco. It has been established that coal rejects can be used as aggregates for road embankments with a density of 2,65 g/cm^3, CBR of 9 %, liquid limit of 41 %, plastic limit of 25 %, and plasticity index of 16 % [11]. Nevertheless, despite intensive research on the recycling of mining waste in road construction, none have addressed the use of coltan waste in construction materials. Considered a geological scandal in view of its numerous mineral resources, the Democratic Republic of Congo (DRC) holds approximately 80 % of Africa’s coltan reserves. Coltan is a black or reddish-brown mineral. It is formed by a combination of two minerals, columbite (niobium) and tantalite, in varying proportions and is derived from flow-sheeted pegmatite rock. Coltan waste exists in the form of coherent clay and/or powdered granules and is obtained throughout the mining process. When coltan is mined, it generates geologically heterogeneous waste products consisting of sedimentary, metamorphic, or igneous rock, soil, and loose sediments, ranging in size from fine particles to boulders. In addition to occupying large areas of heaps, these rejects constitute an unexploited resource for mining quarries.

The purpose of this study was to assess the potential use of coltan mine waste rock from the 4731-mining perimeter in North Kivu for road construction. In addition to the geotechnical tests recommended for road construction, the coltan waste rock was subjected to mineralogical and chemical studies to assess its use in road construction. The aim of this study was to assess the potential use of coltan mine waste rock from Kivu (Eastern DR Congo) in pavement layers and to contribute to the recovery of mining waste in road construction.

2 Materials and experimental methods

The coltan mine waste used in this study was mainly waste rock in the form of coherent clay ($SS_{1,i}$; $SS_{2,i}$; $SS_{3,i}$) and gravelly waste rock (SS_4). The experimental design of this study is shown in Figure 1.

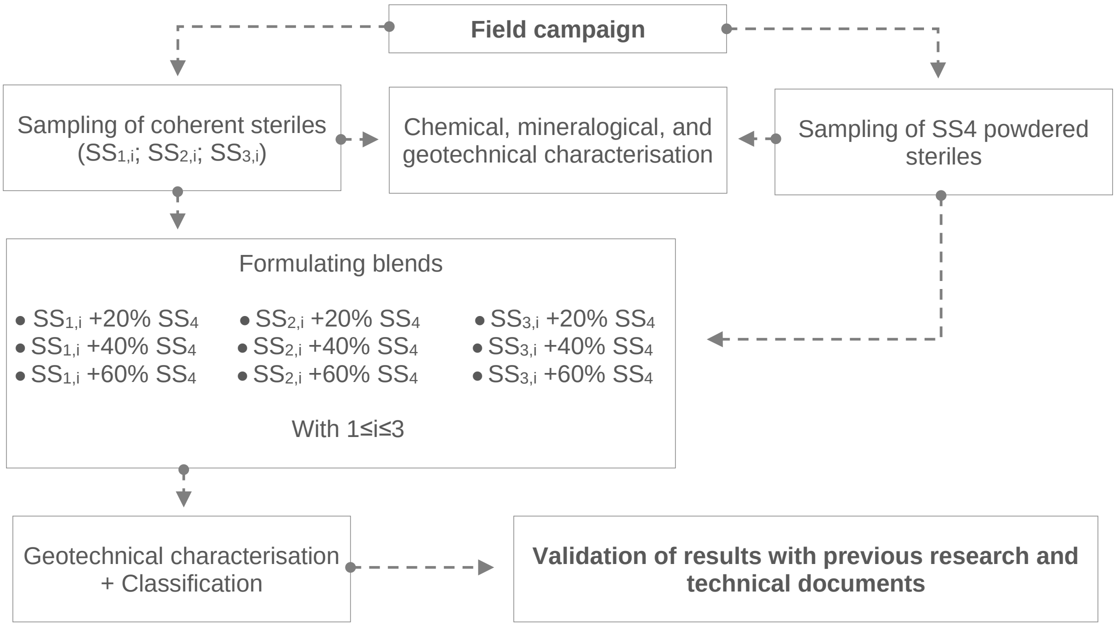

Figure 1. Experimental design

The raw materials studied were coltan mine waste rock from the Bisunzu region in the Masisi territory of North Kivu Province in the DRC (Figure 2). These materials were obtained from coltan extraction during mining operations. The first three samples ($SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$) consisted of coherent coltan waste rock, whereas the fourth sample (SS_4) consisted of gravelly coltan waste rock used as a stabilising material. Samples were gathered from stopes within Dédé Bibatama's 4731-mining boundary. $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$ were collected from three waste rock piles, each with three samples (i=1,...,3), while SS_4 was collected from a pile comprising waste rock in the form of sand and utilized as a stabilising element. Ten samples were collected from their natural states. Geotechnical tests were conducted on the waste rock extracted from each stockpile in its natural state and at 20 %, 40 %, and 60 % stabilisation using waste rock in coherent form. A total of thirty-six samples were tested for use in road construction.

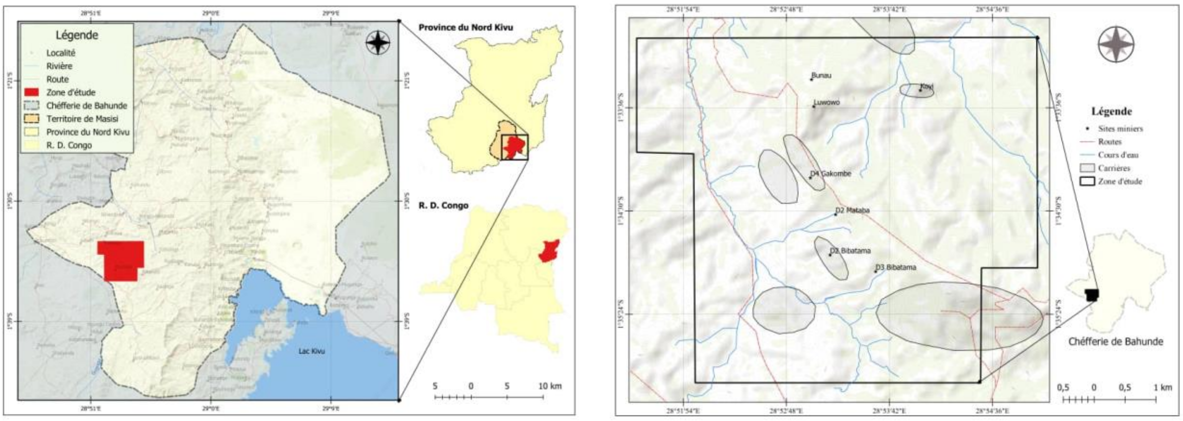

Figure 2. Study area location

Geological data (mineralogy and geochemistry) were obtained from oven-dried samples at 30 °C. The materials were crushed at the Civil Engineering Laboratory of Université Libre des Pays des Grands Lacs, Goma. Mineralogical analyses were performed by X-ray diffraction at the Kyungpook National University laboratory in South Korea. The chemical composition was determined by X-ray fluorescence after ignition at Wuhan Sample Solution Analytical Technology Co., Ltd., Hubei, China. Geotechnical and mechanical tests were performed at the Civil Engineering Laboratory of the Faculty of Applied Sciences and Technologies of the Université Libre des Pays des Grands Lacs in the DRC. The methods used to determine the density of the materials were those prescribed by the standard NF P 94-054 STANDARD [12] for coherent waste rock, and the standard [13] for pulverulent waste rock. The particle size distribution was examined by wet sieving, dry sieving, and sedimentation in accordance with standards [14], [15], and [16], respectively. The liquid limit (WL) was assessed using the Casagrande cup method, and the plastic limit (WP) was assessed using the roller method. These measurements were performed in accordance with the standard Norme NF P 94-051, 1993). The optimal water content (Wopt) and maximum dry density (γd) were determined according to standards [17]. The CBR test was performed after four days of immersion, in accordance with the standard [18]. The use of coltan mining waste in road materials was guided by the prescriptions of and, based on [10], the CBR classes listed in Table 1. The studied waste rock was classified by determining the positions of the materials studied in the Casagrande plasticity diagram.

Table 1. Material use according to their CBR [10]

CBR Class	Use in road construction
S1: 0<CBR<5	Not suitable for road construction
S2: 5<CBR<10	Sub-base layer
S3: 10<CBR<15	Sub-base layer and backfill
S4: 15<CBR<30	Sub-base layer for traffic T_1
S5: 30<CBR<60	Sub-base layer for traffic T_2/T_3 and base layer for traffic T_1
S6: 60<CBR<120	Sub-base layer for traffic T_3/T_4 and base layer for traffic T_2
S7: CBR>120	Base layer traffic T_3

3 Results and discussion

3.1 Mineralogical and chemical analysis

3.1.1 Chemical analysis

The chemical compositions of the samples are listed in Table 2. Quantitative analysis was performed to determine the mass compositions of various metal oxides in the four coltan mine waste samples. The data summarised in Table 2 highlight the chemical variability of the analysed coltan rejects. Analysis of the samples showed homogeneity in terms of the structure and mass proportion of various metal oxides in the waste. However, the chemical elements that were the most variable in the composition of waste rock were SiO_2, TiO_2, $Al2O_3$, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5. The SS_1, SS_2, and SS_3 waste rocks had almost identical chemical compositions in terms of metal oxides. The variability was pronounced in SS4, which had low percentages of Rb_2O (0,29 %) and F (0,49 %). The main feature was the high silicon oxide (SiO_2) content of the four wastes: approximately 57 % for the first three and 49 % for SS_4. Alumina or aluminium oxide (Al_2O_3) had a mass content of almost 21 %, with a variability of 3 %, compared with the fourth sample. Iron (III) oxide, also known as ferric oxide, has a mass content of approximately 10 %, which is much higher than the extremely low proportions of alkaline and alkaline earth oxides. The least abundant oxides are TiO_2, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5. From a semi-quantitative perspective, all four coltan releases had relatively high mass contents of silicon dioxide (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3). In addition, TiO_2, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5 were present in low proportions. The mass ratio of the first three samples, $\tau = \frac{m_{SiO2}}{m_{Al2O3}}$ was approximately 2,7; indicating high kaolinite content.

Table 2. Chemical composition of waste rock

Chemical elements	Chemical composition of waste rock (mass %)			
	$SS_{1,i}$	$SS_{2,i}$	$SS_{3,i}$	SS_4
SiO_2	57,25	57,25	57,26	49,07
TiO_2	0,95	0,94	0,95	1,34
Al_2O_3	21,12	21,11	21,12	24,18
Fe_2O_3	10,55	10,45	10,46	7,50
MnO	0,04	0,04	0,05	0,52
MgO	0,30	0,20	0,21	1,33
CaO	0,29	0,29	0,30	1,90
Na_2O	0,15	0,15	0,16	0,26
K_2O	0,51	0,41	0,42	2,09
P_2O_5	0,21	0,21	0,22	0,38
LOI	8,16	8,06	8,07	9,56
SUM	99,53	99,11	99,22	98,12
Remarks	-	-	-	Contains 0,29 % Rb_2O 0,49 % F

3.1.2 Mineralogy

Figures 3-6 show the diffractograms of the medium samples $SS_{1,i}$, $SS_{2,i}$, $SS_{3,i}$, and SS_4. Table 3 shows the results of the semi-quantitative analyses of mine waste rock.

Table 3. Semi-quantitative mineralogical composition of the coltan mine waste rock

Colltan mine waste rock	Kaolinite	Hematite	Magnetite	Quartz	Goethite	Ilmenite	Orthoclase
	$Al_2Si_2O_5(OH)_4$	Fe_2O_3	Fe_3O_4	SiO_2	FeO (OH)	FeTiO3	$KAlSi_3O_8$
$SS_{1,i}$	50,7	24,20	15,90	6,6	2,60	-	-
$SS_{2,i}$	50,2	24,45	16,15	6,6	2,60	-	-
$SS_{3,i}$	51,2	23,95	15,90	6,5	2,45	-	-
SS_4	-	-	-	11,4	-	25,3	63,4

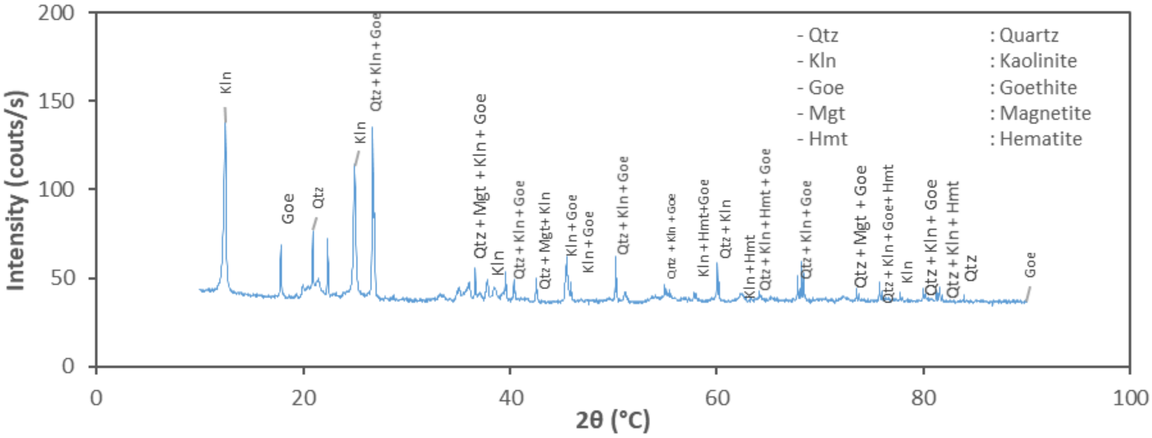

Figure 3. Diffractograms of the medium $SS_{1,i}$ sample

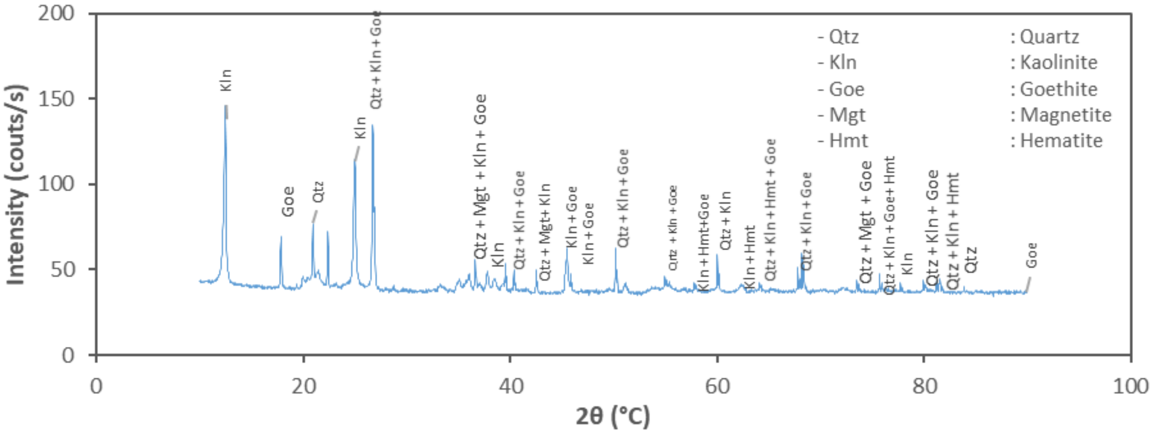

Figure 4. Diffractograms of the medium $SS_{2,i}$ sample

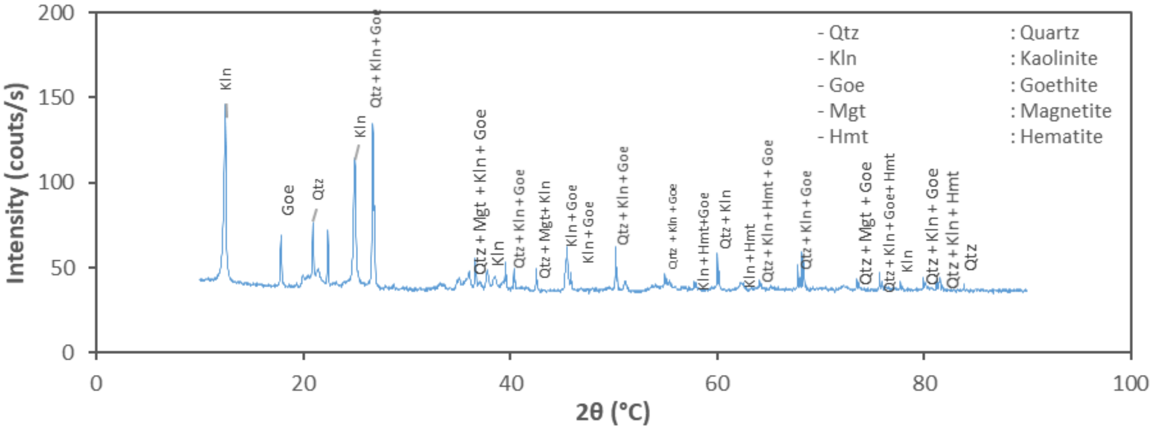

Figure 5. Diffractograms of the medium $SS_{3,i}$ sample

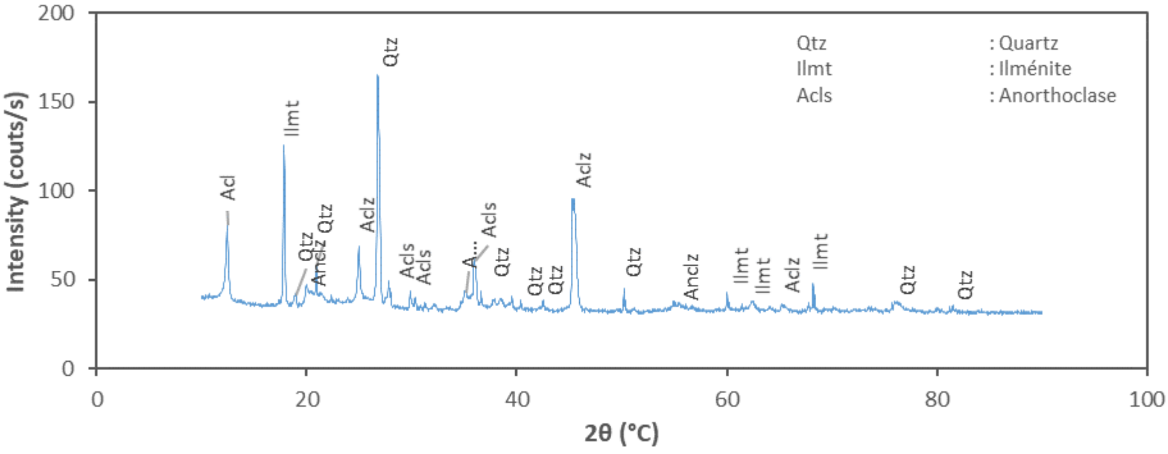

Figure 6. Diffractograms of the medium SS_4 sample

The mineralogical composition influences the mechanical behaviour of the material used in the pavement. The $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$ mine wastes showed remarkably similar mineral phase compositions, with a high percentage of kaolinite. These results are in perfect agreement with the chemical parameters, which indicate a kaolinite content of over 50 %. In addition, the sterile

SS_4 used as the corrective material contained 63,4 % orthoclase, 25,3 % ilmenite, and 11,4 % quartz.

3.2 Geotechnical characteristics

3.2.1 Specific density

Table 4 lists the specific densities of $SS_{1,i}$, $SS_{2,i}$, $SS_{3,i}$; and mine waste stabilised at 20 %, 40 %, and 60 % of SS_4, where SD is the standard deviation.

Table 4. Specific density of mine waste rock

Waste rock		γ (g/cm^3)	Waste rock		γ (g/cm^3)	Waste rock		γ (g/cm^3)
SS_1	SS_{11}	2,30	SS_2	SS_{21}	2,26	SS_3	SS_{31}	2,21
	SS_{12}	2,25		SS_{22}	2,13		SS_{32}	2,23
	SS_{13}	2,26		SS_{23}	2,27		SS_{33}	2,23
	Average	2,27		Average	2,22		Average	2,22
	SD	0,03		SD	0,08		SD	0,01
SS_1+20 %	SS_{11}	2,26	SS_2+20 %	SS_{21}	2,28	SS_3+20 %	SS_{31}	2,24
	SS_{12}	2,29		SS_{22}	2,18		SS_{32}	2,26
	SS_{13}	2,28		SS_{23}	2,29		SS_{33}	2,25
	Average	2,28		Average	2,25		Average	2,25
	SD	0,02		SD	0,06		SD	0,01
SS_1+40 %	SS_{11}	2,27	SS_2+40 %	SS_{21}	2,30	SS_3+40 %	SS_{31}	2,27
	SS_{12}	2,27		SS_{22}	2,21		SS_{32}	2,28
	SS_{13}	2,30		SS_{23}	2,32		SS_{33}	2,28
	Average	2,28		Average	2,28		Average	2,28
	SD	0,01		SD	0,05		SD	0,01
SS_1+60 %	SS_{11}	2,31	SS_2+60 %	SS_{21}	2,32	SS_3+60 %	SS_{31}	2,30
	SS_{12}	2,31		SS_{22}	2,26		SS_{32}	2,31
	SS_{13}	2,32		SS_{23}	2,33		SS_{33}	2,31
	Average	2,31		Average	2,30		Average	2,31
	SD	0,01		SD	0,04		SD	0,01

The average density of the SS_4 waste rock was 2,4 g/cm^3. The average specific density of natural samples $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$ is 2,27 g/cm^3, 2,22 g/cm^3 and 2,22 g/cm^3, respectively. These values are close to the specific density of phosphate rock (2,42-2,65) [19, 20] and slightly higher than that of coal waste rock (2,65) [11]. Mixing $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$ with SS_4 at different stabilisation percentages increased the specific density of the samples. Stabilising $SS_{1,i}$ at 20 %, 40 %, and 60 % yielded arithmetic mean densities of 2,28 g/cm^3, 2,28 g/cm^3 and 2,31 g/cm^3, respectively. Stabilising $SS_{2,i}$ at 20 %, 40 %, and 60 % yielded arithmetic mean densities of 2,25 g/cm^3, 2,32 g/cm^3 and 2,30 g/cm^3, respectively. Stabilising $SS_{3,i}$ at 20 %, 40 %, and 60 % yielded arithmetic mean densities of 2,22 g/cm^3, 2,25 g/cm^3 and 2,31 g/cm^3, respectively.

3.2.2 Granulometric composition

The particle size data recorded for the natural samples and the samples stabilised at 20 %, 40 %, and 60 % SS_4 are presented as particle size curves in Figures 7 and 8. The coltan waste rock samples exhibited similar grain sizes. The various particle size curves presented in Figures 7 and 8 show that all three samples were predominantly fine, except for SS_4. However, the addition of 20-60 % SS_4 waste rock and sand (0/5) gradually reduced the fine-particle content. However, the formed mortar quantity was high. Improvement in the particle size of the waste rock ($SS_{1,i}$, $SS_{2,i}$, $SS_{3,i}$) by the addition of SS_4 waste rock enabled an increase in the number of particles between 0,080 and 5 mm in the waste rock studied.

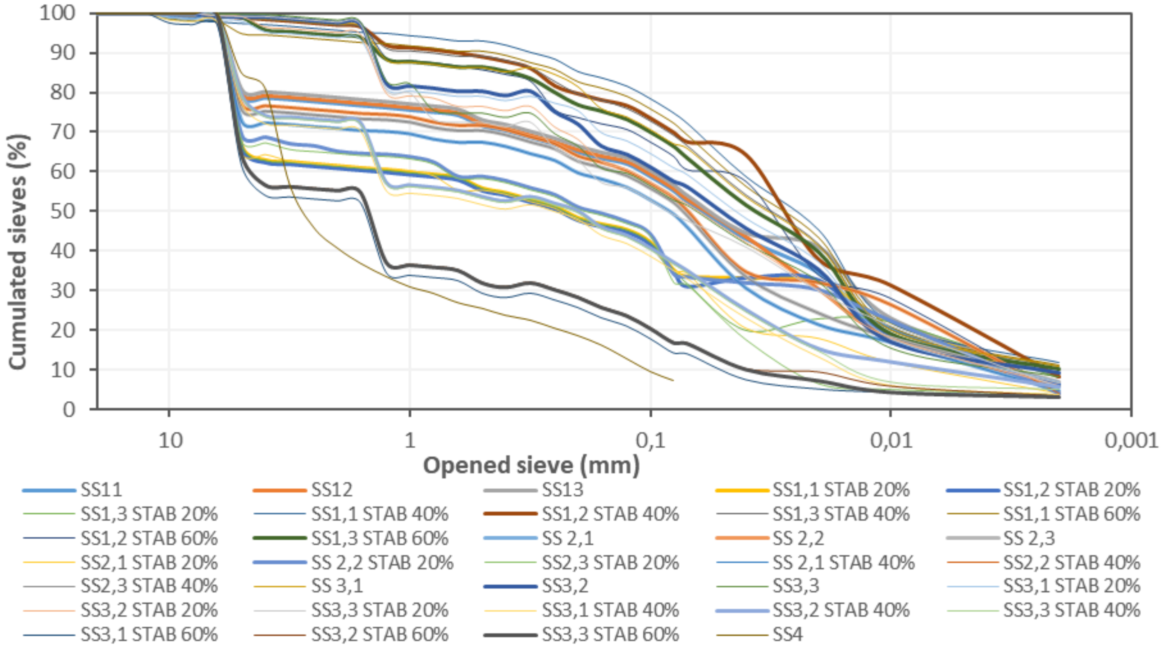

Figure 7. Granulometric composition of coltan mine waste rock

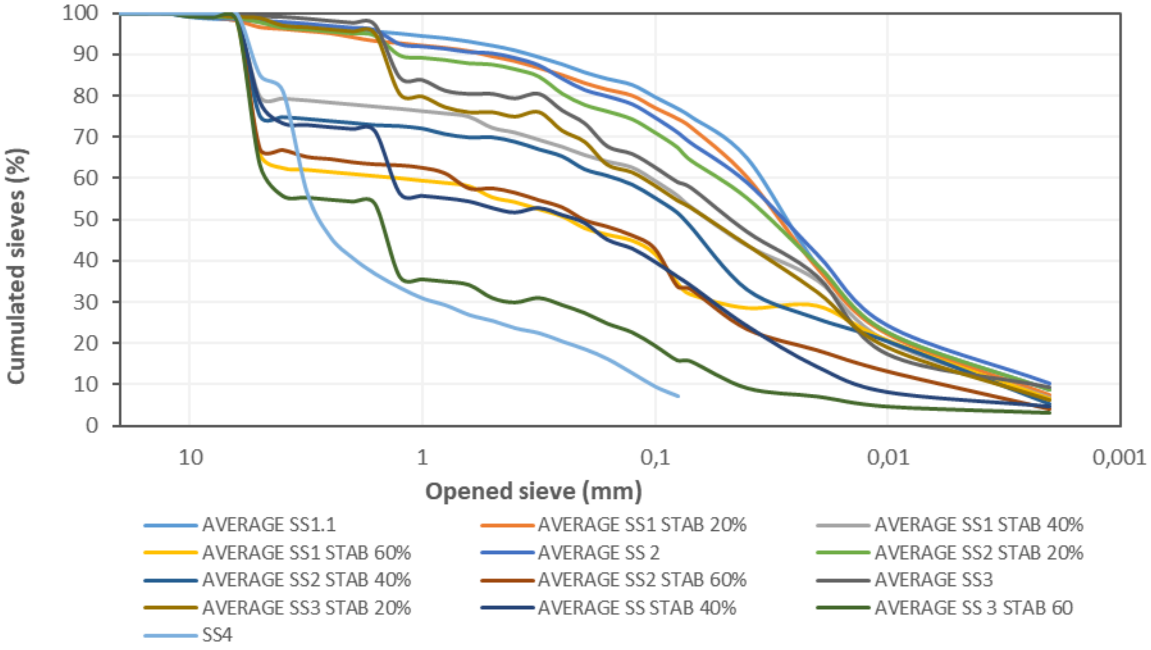

Figure 8. Average particle size composition of coltan mine waste rock

Compared to the particle size requirements laid down by [10] coltan waste rock in its natural state ($SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$), it has a fine-particle size that is not included in the range of materials used in road base courses. In addition, the stabilisation of the coltan waste rock studied at 60 % SS_4 resulted in a grain size that was acceptable for use in sub-base courses. This was justified by the particle size correction of the clayey tan waste rock due to the addition of gravelly particles from the SS_4 coltan waste rock.

3.2.3 Atterberg limits

The Atterberg limits were determined for the mortars, and their respective values are listed in Tables 5-7. The values for the liquidity limit, plasticity limit, and plasticity index are high in waste rock in its natural state because of the fine particles it contains, that is, an arithmetic mean for the liquidity limit (WL) of 39,63; 40,40 and 41,47 respectively for $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$.

Table 5. Atterberg limits for coltan waste rock SS_1

Mine Waste rock		WL	WP	IP
SS_1	SS_{11}	40,30	28,25	12,05
	SS_{12}	39,20	28,20	10,90
	SS_{13}	39,40	26,90	12,45
	Average	39,63	27,78	11,80
	SD	0,59	0,77	0,80
SS_1+20 % SS_4	SS_{11}	39,80	28,00	11,30
	SS_{12}	39,10	20,20	9,80
	SS_{13}	39,01	27,33	11,76
	Average	39,30	25,18	10,95
	SD	0,43	4,32	1,02
SS_1+40 % SS_4	SS_{11}	39,20	29,44	9,75
	SS_{12}	38,90	30,43	8,37
	SS_{13}	38,50	28,50	9,90
	Average	38,87	29,46	9,34
	SD	0,35	0,97	0,84
SS_1+60 % SS_4	SS_{11}	38,90	30,63	8,26
	SS_{12}	38,60	30,94	7,65
	SS_{13}	38,00	29,70	8,20
	Average	38,50	30,42	8,04
	SD	0,46	0,65	0,34

Table 6. Atterberg limits for coltan waste rock SS_2

Mine Waste rock		WL	WP	IP
SS_2	SS_{21}	38,20	29,66	8,53
	SS_{22}	41,40	25,20	16,16
	SS_{23}	41,60	28,86	12,70
	Average	40,40	27,91	12,46
	SD	1,91	2,38	3,82
SS_2+20 % SS_4	SS_{21}	38,00	29,90	8,05
	SS_{22}	40,80	26,31	14,48
	SS_{23}	41,10	29,51	11,58
	Average	39,97	28,57	11,37
	SD	1,71	1,97	3,22
SS_2+40 % SS_4	SS_{21}	36,60	28,67	7,90
	SS_{22}	40,00	26,56	13,43
	SS_{23}	40,00	30,13	9,80
	Average	38,87	28,45	10,38
	SD	1,96	1,79	2,81
SS_2+60 % SS_4	SS_{21}	36,20	29,04	7,15
	SS_{22}	39,20	29,07	10,12
	SS_{23}	39,00	29,50	9,50
	Average	38,13	29,20	8,92
	SD	1,68	0,26	1,57

The arithmetic means for the plasticity limits (WP) were 27,78; 27,91 and 24,14; for $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$, respectively.

The arithmetic mean for the plasticity index (PI) was 11,85; 12;49 and 17;33, for sterile $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$, respectively. The Atterberg limits obtained for coltan mine waste rock in its natural state were virtually identical to those obtained for coal in Morocco (WL=42, WP=25, and IP=17) [11]. Although the coltan mine waste rock exceeded the *Centre Expérimental de Recherche et d'Etudes du Batiment et des Travaux Publics* (CEBTP)requirements for the limit values, it must be improved to achieve the appropriate Atterberg limits.

The improvement of fine mine waste rock by the SS_4 coltan mine waste rock progressively reduced the liquidity limits, plasticity limit, and PI. This can be explained by the presence of particles smaller than 400 µm in the SS_4 waste rock, which are insensitive to water and function as degreasers in mixed materials. These regressive behaviours are similar to those reported in [21, 22]. Thus, at 60 % stabilisation of $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$ waste rock: an arithmetic mean for the liquidity limit (WL), respectively of 38,50; 38,13 and 38,27 for the sterile $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$, an arithmetic mean for the plasticity limit (WP), respectively of 30,42; 29,20 and 26,96; respectively for sterile $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$ and finally an arithmetic mean for the PI of 8,04; 8,92 and 11,27 respectively for coltan mine waste rock $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$. In addition, the addition of 60 % coltan mine waste rock SS_4 waste rock yields a liquidity limit (WL) of less than 60 and a PI of less than 15 for all samples, making these waste rocks suitable for use as sub-base materials in accordance with the requirements of [10].

Table 7. Atterberg limits for coltan waste rock SS_3

Mine Waste rock		WL	WP	IP
SS_3	SS_{31}	40,4	23,97	16,4
	SS_{32}	41	22,4	18,54
	SS_{33}	43	26,14	16,85
	Average	41,47	24,17	17,26
	SD	1,36	1,88	1,13
SS_3+20 % SS_4	SS_{31}	40	25,08	14,92
	SS_{32}	40	22,9	17,09
	SS_{33}	42	27,17	14,83
	Average	40,67	25,05	15,61
	SD	1,15	2,14	1,28
SS_3+40 % SS_4	SS_{31}	39,5	26,18	13,3
	SS_{32}	39	24,25	14,7
	SS_{33}	41	27,5	13,4
	Average	39,83	25,98	13,8
	SD	1,04	1,63	0,78
SS_3+60 % SS_4	SS_{31}	38	27,7	10,3
	SS_{32}	38,3	25,29	13
	SS_{33}	38,5	27,9	10,5
	Average	38,27	26,96	11,27
	SD	0,25	1,45	1,5

3.3 Classification of coltan mine waste rock studied

The classification of $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$ waste rocks was performed by determining the positions of the materials studied in the Casagrande plasticity diagram, as shown in Figure 9. The *SS4* classification was based on the *Laboratoire Central des Ponts et Chaussées* (LCPC) classification.

The position of the waste rock studied in the Casagrande plasticity diagram (Figure 9) shows that the samples studied were all medium-plasticity silts, except for sample SS_3 in its natural and stabilised state, which is a medium-plasticity plastic clay. SS_4 coltan mine waste rock is classified as gravel in accordance with the LCPC classification, with more than 50 % of its constituent elements larger than 0,08 mm and a diameter greater than 2 mm.

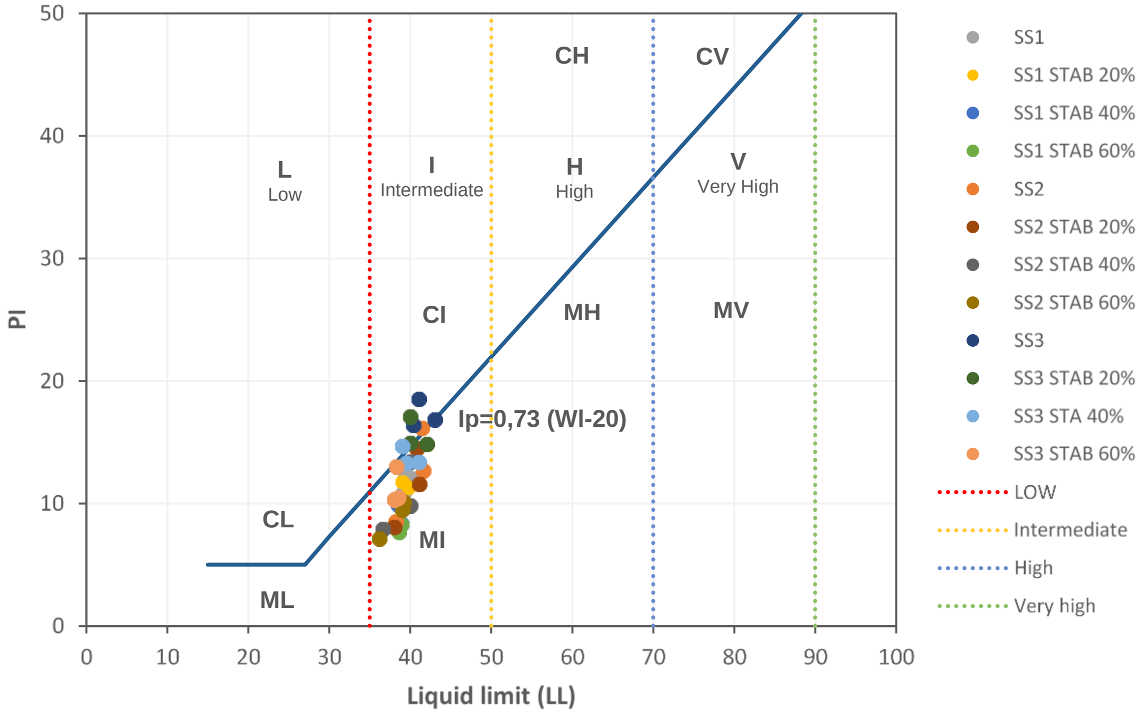

Figure 9. Material positions used in the Casagrande plasticity chart

3.4 Bearing capacity and compaction parameters

The results of the modified Proctor and CBR tests are summarised in Tables 8-10.

Table 8. Dry density, optimum moisture content and CBR for SS_1

Waste rock		γ_d	W_{opt}	CBR
SS_1	SS_{11}	1,80	15,50	0,00
	SS_{12}	1,80	15,30	0,00
	SS_{13}	1,84	14,30	1,00
	Average	1,81	15,03	0,33
	SD	0,02	0,64	0,58
SS_1+20 % SS_4	SS_{11}	1,82	15,20	1,00
	SS_{12}	1,82	15,00	3,00
	SS_{13}	1,89	14,00	7,00
	Average	1,84	14,73	3,67
	SD	0,04	0,64	3,06
SS_1+40 % SS_4	SS_{11}	1,84	14,50	10,00
	SS_{12}	1,85	14,50	9,00
	SS_{13}	1,89	13,50	20,00
	Average	1,86	14,17	13,00
	SD	0,03	0,58	6,08
SS_1+60 % SS_4	SS_{11}	1,90	14,00	27,00
	SS_{12}	1,91	13,30	33,00
	SS_{13}	1,93	13,00	37,00
	Average	1,91	13,43	32,33
	SD	0,02	0,51	5,03

Table 9. Dry density, optimum moisture content and CBR for SS_2

Waste rock		γ_d	W_{opt}	CBR
SS_2	SS_{21}	1,96	13,20	0,00
	SS_{22}	1,80	16,00	0,00
	SS_{23}	2,00	14,00	1,00
	Average	1,92	14,40	0,33
	SD	0,11	1,44	0,58
SS_2+20 % SS_4	SS_{21}	1,98	13,00	11,00
	SS_{22}	1,82	15,00	10,00
	SS_{23}	2,10	13,50	16,00
	Average	1,97	13,83	12,33
	SD	0,14	1,04	3,21
SS_2+40 % SS_4	SS_{21}	2,00	12,70	22,00
	SS_{22}	1,87	13,70	21,00
	SS_{23}	1,90	13,20	33,00
	Average	1,94	13,20	25,33
	SD	0,09	0,71	6,66
SS_2+60 % SS_4	SS_{21}	2,10	12,30	30,00
	SS_{22}	1,89	13,00	25,00
	SS_{23}	2,05	12,50	39,00
	Average	2,01	12,60	31,33
	SD	0,11	0,36	7,09

Table 10. Dry density, optimum moisture content and CBR for SS_3

Waste rock		γd	Wopt	CBR
SS_3	SS_{31}	1,98	13,00	1,00
	SS_{32}	1,90	15,00	1,00
	SS_{33}	1,89	15,50	2,00
	Average	1,92	14,50	1,33
	SD	0,05	1,32	0,58
SS_3+20 % SS_4	SS_{31}	2,00	12,50	19,00
	SS_{32}	1,95	14,50	14,00
	SS_{33}	1,90	15,00	15,00
	Average	1,95	14,00	16,00
	SD	0,05	1,32	2,65
SS_3+40 % SS_4	SS_{31}	2,04	12,00	28,00
	SS_{32}	1,97	14,20	25,00
	SS_{33}	1,90	14,50	26,00
	Average	1,97	13,57	26,33
	SD	0,07	1,37	1,53
SS_3+60 % SS_4	SS_{31}	2,07	11,70	35,00
	SS_{32}	1,99	14,00	38,00
	SS_{33}	1,93	14,00	30,00
	Average	2,00	13,23	34,33
	SD	0,07	1,33	4,04

These different densities were obtained at the average optimum water contents of 15,0 %, 14,4 %, and 14,5 % for $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$, respectively. The stabilisation of coltan mine waste $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$ 20 % coltan mine waste SS_4, gives an arithmetic mean optimum dry density of 1,8 g/cm^3; 2,0 g/cm^3 and 2,0 g/cm^3 respectively at optimum water contents of 14,7 %, 13,8 %, and 14,0 %, respectively. The stabilisation of coltan mine waste $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$ at 40 % SS_4, gives an arithmetic mean optimum dry density of 1,9 g/cm^3, 1,9 g/cm^3 and 20,0 g/cm^3 respectively at an optimum moisture content of 14,2 %, 13,2 %, and 13,6 %, respectively. Stabilising $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$ with 60 % SS_4 gives an arithmetic mean optimum dry density of 1,9 g/cm^3, 2,0 g/cm^3 and 2,0 g/cm^3 respectively, at an optimum moisture content of 13,4 %, 12,6 % and 13,2 %, respectively. The optimum water content values were the highest for natural sterilisers ($SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$), whereas their dry density values were the lowest. Treating these coltan mine wastes with different percentages of SS_4 (20-60 %) resulted in a decrease in the optimum water content values and an increase in dry density. These trends are similar to those found in the fine lateritic soils of Bafang in Cameroon [23].

The California bearing capacity (CBR) coefficient is an important parameter for pavement design and dimensioning (Tables 8-10). The average CBR values of all samples were less than 30 %, except for collagen mine waste, which stabilised at 60 %. The CBR values at 95% after four days of immersion were the lowest in the natural state, while the treatment of these coltan mine wastes with different percentages (20-60 %) of SS_4 coltan mine waste resulted in an increase in CBR values.

3.5 Analysis of the compliance of coltan waste rock with road-surfacing standards for tropical countries

Compliance of coltan mine waste rock with road-surfacing standards for tropical countries were analysed based on the prescriptions in [10]. This study focused mainly on the characteristics of coltan waste rock, particularly, the Atterberg limits (liquidity limit and PI), granulometry (20; 10; 5; 2 and 0,080 mm sieves), dry density, and CBR.

Table 11. Compliance of coltan waste rock with road surfacing standards for tropical countries based on Atterberg limits [10]

Engineering parameters			Liquid limit LL (%)	Plasticity Ratio PI (%)
Base Materials		Atterberg Limits	35 (max)	15 (max)
Sub-base materials			60 (max)	30 (max)
Samples (average values)	$SS_{1,i}$		39,63	11,80
	$SS_{1,i}$ STAB 20 %		39,30	10,95
	$SS_{1,i}$ STAB 40 %		38,87	9,34
	$SS_{1,i}$ STAB 60 %		38,50	8,04
	$SS_{2,i}$		40,40	12,46
	$SS_{2,i}$ STAB 20 %		39,97	11,37
	$SS_{2,i}$ STAB 40 %		38,87	10,38
	$SS_{2,i}$ STAB 60 %		38,13	8,92
	$SS_{3,i}$		41,47	17,26
	$SS_{3,i}$ STAB 20 %		40,67	15,61
	$SS_{3,i}$ STAB 40 %		39,83	13,80
	$SS_{3,i}$ STAB 60 %		38,27	11,27

In addition to its requirements [10] (Table 11), the natural state of coltan mine waste rock has a liquidity limit greater than 35 (maximum value for base materials) and less than 60 (maximum value for sub-base materials), and a PI of less than 15 (maximum value for base materials), with the exception of $SS_{3,i}$ (IP=17,26). Stabilised at 60 % SS_4, the liquidity limit of the waste rock studied remained above 35, with an arithmetic mean of 38,50 for $SS_{1,i}$, 38,13 for $SS_{2,i}$ and 38,27 for $SS_{3,i}$. The PI decreased with 60 % stabilisation of the SS_4. The arithmetic mean of the PI was 8,04; 8,92 and 11,27 for $SS_{1,i}$, $SS_{2,i}$, and $SS_{3,i}$, respectively. The decrease in landfall limits is thought to be due to the correction of granulometry by SS_4, which is sandy in nature. These results are consistent with those of fly ash-stabilised coal tailings [11]. With a liquidity limit above 35 and a PI below 15, the studied coltan mine waste rock stabilised with 60 % SS_4 can be used as a sub-base material.

In addition to the requirements of [10], sub-base materials must have a particle size in which the percentage of sieved material on the 20; 10; 5; 2 mm, and 0,080 mm sieves must be 75-100 %, 58-100 %, 40-78 %, 28-65 %, and 5-35 %, respectively. Table 12 shows that only the waste rock stabilised at 60 % SS_4 had a grain size that conformed to that of the sub-base materials.

Table 12. Compliance of coltan waste rock with road surfacing standards for tropical countries based on grain size distribution [10]

Engineering parameters		Grain size distribution (%)	20mm	10mm	5mm	2mm	0,08mm
Base Materials			60-100	35-90	20-75	12-50	4-20
Sub-base materials			75-100	58-100	40-78	28-65	5-35
Samples (average values)	SS$_{1,i}$		100	99,2	98,1	96,2	77,0
	SS$_{1,i}$ STAB 20 %		100	99,5	96,7	94,2	74,5
	SS$_{1,i}$ STAB 40 %		100	99,7	79,8	77,9	55,9
	SS$_{1,i}$ STAB 60 %		100	99,9	66,0	61,2	34,8
	SS$_{2,i}$		100	99,3	98,3	96,5	71,2
	SS$_{2,i}$ STAB 20 %		100	99,6	97,8	95,1	67,5
	SS$_{2,i}$ STAB 40 %		100	99,5	75,0	73,3	51,6
	SS$_{2,i}$ STAB 60 %		100	99,7	67,0	63,8	33,7
	SS$_{3,i}$		100	100,0	99,2	97,7	59,1
	SS$_{3,i}$ STAB 20 %		100	99,7	98,8	95,6	54,6
	SS$_{3,i}$ STAB 40 %		100	99,5	78,6	72,0	36,3
	SS$_{3,i}$ STAB 60 %		100	99,2	63,3	54,4	15,9

The stabilisation gradually reduced the fine-particle content. In addition, the studied coltan waste rock had a dry density varying between 1,8 and 2,08. Coltan waste rock stabilised at 60 % SS$_4$ has a dry density greater than or equal to the minimum density for sub-base materials (1,9) [10], as presented in Table 13.

In their natural state, the coltan waste rocks studied (SS$_{1,i}$, SS$_{2,i}$, and SS$_{3,i}$) had CBRs of approximately 5 %, whereas when stabilised at 20 %, they offered 95 % arithmetical mean CBR values of 3,7 %, 12,3 %, and 16,0 %, respectively. Stabilising at 40 % SS$_4$, coltan waste rock yielded 95 % arithmetic mean CBRs of 13,0 %, 25,3 %, and 26,3 %, respectively. Stabilising at 60 % SS$_4$, coltan waste rock yields 95 % arithmetical mean CBRs of 32,3 %, 31,3 %, and 34,3 %, respectively.

The CBR obtained in the natural and stabilised states were lower than those obtained for coal mine waste [11, 24, 25]. The lower CBR in the natural state was due to the nature of the coltan waste rock, 60 % of which had a grain size of less than 0,08 mm.

Furthermore, the increase in CBR as a function of the percentage of SS$_4$ is due to the mineralogical characteristics of the SS$_4$ waste rock (high percentage of orthoclase), as well as because of following the granulometric correction of SS$_{1,i}$, SS$_{2,i}$, and SS$_{3,i}$ by SS$_4$ [11, 26, 27].

Compared to the classification proposed by [28], the coltan waste rock investigated, stabilised with 20 % SS$_4$, is class S1 and therefore undesirable for road construction. SS$_{2,i}$ stabilised with 20 % SS$_4$ is class S3 and can therefore be used in road sub-bases and embankments. Coltan waste rocks SS$_{3,i}$ stabilised with 20 % SS$_4$ are class S4 and can therefore be used as T1 traffic sub-bases. Coltan waste rock SS$_{1,i}$ stabilised with 40 % SS$_4$ is class S3 and can therefore be used for road sub-bases and embankments, whereas coltan waste rock SS$_{2,i}$ and SS$_{3,i}$ stabilised with 40 % SS$_4$ are class S4 and can therefore be used for T1 traffic sub-bases. Coltan waste rocks SS$_{1,i}$, SS$_{2,i}$, and SS$_{3,i}$ stabilised with 60 % SS$_4$ are class S5 and can therefore be used for T2/T3 and T1 traffic base courses.

Table 13. Compliance of coltan waste rock with road surfacing standards for tropical countries based on Modified Proctor [10]

Engineering parameters			Maximum Dry Density	CBR (%)
Base Materials		Modified Proctor	2,0 min	80 min
Sub-base materials			1,9 min	30 min
Samples (average values)	SS$_{1,i}$		1,81	0,3
	SS$_{1,i}$ STAB 20 %		1,84	3,7
	SS$_{1,i}$ STAB 40 %		1,86	13,0
	SS$_{1,i}$ STAB 60 %		1,91	32,3
	SS$_{2,i}$		1,92	0,3
	SS$_{2,i}$ STAB 20 %		1,93	12,3
	SS$_{2,i}$ STAB 40 %		1,96	25,3
	SS$_{2,i}$ STAB 60 %		2,08	34,5
	SS$_{3,i}$		1,94	1,3
	SS$_{3,i}$ STAB 20 %		1,98	17,0
	SS$_{3,i}$ STAB 40 %		2,01	27,0
	SS$_{3,i}$ STAB 60 %		2,03	36,5

4 Conclusion

This study investigated the applicability of coltan mine waste for road construction located east of the DRC. To achieve this goal, chemical, mineral, and geotechnical tests were conducted. The study showed that coltan mine waste is naturally clayey and has poor characteristics for use in road construction. However, when stabilised at 60 % with another coltan mine gravel waste, the coltan mine waste meets the necessary characteristics of materials that can be used in sub-base courses. In particular, with an arithmetic mean liquidity limit of less than 60, a PI of less than 30 and 20 mm sieves of between 75 and 100 % (10 mm sieves between 58 and 100 %, 5 mm sieves between 40 and 78 %, 2 mm^2 sieves between 28 and 65 %, and 0,080 mm sieves between 5 and 35 mm), a dry density greater than or equal to 1,9 g/cm^3 and a CBR greater than or equal to 30 % is achieved.

Future studies could focus on the use of hydraulic binders to stabilise coltan mine waste rock and improve its load-bearing capacity.

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