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Collaborative Effect of Fines on Changes in Grain Distribution in the Process of Improving the Geotechnical Properties of an Alluvial Gravel 0/14

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Abstract

The technical and economic optimization of road projects has led to research into the use of materials obtained by mechanical stabilization for pavement construction. This research has enabled us to outline a solution capable of giving the sub-base layer the necessary and sufficient capacity to support the induced loads forecast for the traffic. This work evaluates the effect of adding fine silty clay (Cl) and clayey silt (Csp), two corrective materials to alluvial gravel (0/14), the main material, in the process of improving its cohesion and geotechnical properties. The results obtained show that the optimum mix is obtained with 10% by weight of Cl and 15% Csp. The granulometry of the mixes is spread out, but poorly calibrated. The Ag-Cl mixtures made at 10%, 15%, 20%, 25% 30% and Ag-Csp at 15%, 20%, 25%, 30%, and 35%, do not obey the law of mixtures. Mixing with 10% Cl reduces the sand equivalent of alluvial gravel by 60.23%, while mixing with 15% Cl reduces the sand equivalent by 6.82%. The addition of correctors increases the optimum water content and fine sand content of the mixes. Increasing the fine sand content reduces the optimum dry density, CBR index and static modulus. Mixes containing 10% Cl and 15% Csp have CBR values of CBRCl (96%) and CBRCsp (84%) and are not suitable for pavement base layers. In fact, the hardness of the grains has a Los Anges value of 41%, higher than the maximum permitted by the standard of 35%. The mixes obtained can be used as pavement base layers for traffic levels in a cumulative number of heavy goods vehicles $5 \times 10^5 < \text{T1-T3} < 4 \times 10^6$ for an approximate life of 15 years.

Keywords

Alluvial Gravel, Cubitermes Sp Termite, Fines, Mechanical Treatment, Corrector

1. Introduction

The Republic of Congo, a developing country, is continuing to build its road network in order to open up its entire territory. This road network is characterized by its poor condition and low traffic density [1]-[3]. The development of a country's road infrastructure inevitably involves making the most of its natural resources, using appropriate methods that take into account the level of expertise of the specialists involved. The main obstacle to the development of infrastructure is the high cost of road construction and maintenance, recognized as two of the main barriers to development [4] [5]. However, reducing the cost of construction and its impact on the environment requires the use of local materials [6]-[8]. Unfortunately, natural materials suitable for road construction are not widely available and the cost of transporting them far from their source is sometimes prohibitive. In some departments of the country, the scarcity of conventional road materials suitable for road construction has led to the use of non-conventional materials such as lateritic gravelly soils, clay soils and cubitermes sp termite mound soils [7]-[10]. This shortage of road materials suitable for direct use on pavements has led to a search for alternative solutions that are both less costly and technically viable in road construction. The availability of alluvial gravel (0/14) in watercourses has led to its improvement with clay soil to give it cohesion [11]. A number of studies have shown that certain local materials have proved to be good in use, even if they do not always meet the specifications of current standards. The cubitermes sp termite mound soil has been used on a large scale for the construction of a 65 km earth road in the Republic of Congo. The scarcity of road materials suitable for direct use in the various layers of pavement has led to a search for alternative solutions to the recurring problem in certain departments of the Congo with watercourses rich in alluvial gravel. Mechanical stabilization between alluvial gravel (0/14), the main material, without cohesion and with a good skeleton [11], by adding silty clay and clayey silt as corrective materials to give it cohesion and improve its geotechnical properties. Despite its very high fine content, the material is very cohesive and compact. Mixtures of cubitermes sp termite mound soil-alluvial gravel (0/14) or clay soil-alluvial gravel (0/14) are mainly motivated by the availability of materials. Numerous studies have shown that the clay content of termite mound soils is generally higher than that of the surrounding soils [12] [13]. The cohesion of the alluvial gravel (0/14) is ensured by the fine fraction of the cubitermes sp termite mound soil or the clay soil. The influence of the proportion of fine particles on variations in particle size fractions has not yet been revealed. The aim of this work is to optimize mixes based on the addition of fines to alluvial gravel (0/14) in order to modify the particle size fractions and geotechnical properties of the material intended for road construction.

2. Materials and Methodology

2.1. Materials

Samples of alluvial gravel, cubitermes sp termite mound soil and clay soil were taken in the localities of Makoua and Ignié, in the Cuvette Centrale and Pool departments respectively, according to the geographical coordinates given in **Table 1**.

Table 1. Location of samples.

Type of materials	Locality	Location
Alluvial gravel	Makoua	015°35'23.1"E; 00°00'25.1"N
Clayey soil	Makoua	015°38'01.3"E; 00°00'04.9N
Soil of termite mound Csp	Ignié	15.35404°E; −4.02278°S

In the following text, alluvial gravels will be designated by the two letters (Ag), clay soil by the letters (Cl) and cubitermes sp termite soil by the letters (Csp).

Figure 1 shows samples of alluvial gravel (Ag), whitish clay soil (Cl) and grey-black cubitermes sp termite soil (Csp).

Figure 1. Views of alluvial gravel (Ag), clay soil (Cl) and cubitermes sp termite mound soil (Csp), respectively.

2.2. Methodology

Alluvial gravel (0/14) was taken from the Makoua river and transported to the civil engineering laboratory in Brazzaville. Before testing, the alluvial gravel was sampled to obtain a particle size of 0/14 mm. In this mechanical improvement, alluvial gravel is the main material, clay soil and cubitermes sp termite mound soil are two corrective materials to the alluvial gravel, used in the proportions (10%, 15%, 20%, 25%, 30%) and (15%, 20%, 25%, 30%, 35%), respectively.

Figure 2. Views of Ag-Cl and Ag-Csp mixtures.

In **Figure 2**, the alluvial gravel (Ag)-clay soil (Cl) and alluvial gravel (Ag)-cubitermes sp termite mound soil (Csp) mixtures were obtained by mixing the materials in the proportions chosen for this purpose. **Figure 3** shows the mechanical stabilization of mixtures, followed by laboratory tests.

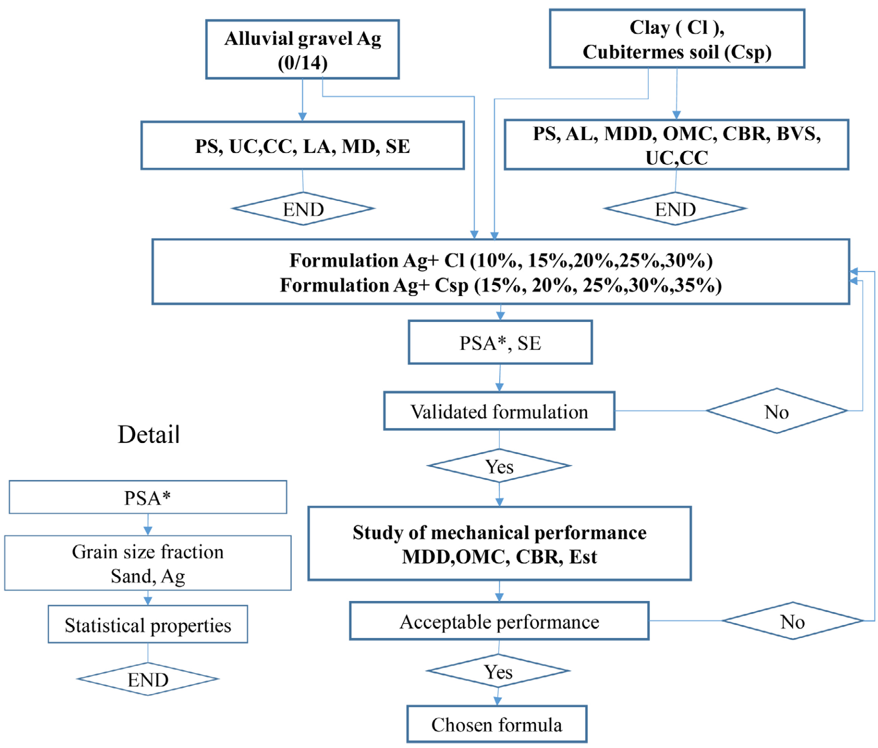

Figure 3. Flow chart for mechanical stabilization of mixtures (Ag-Cl) and (Ag-Csp).

In the laboratory, the analyses were carried out after passing the clay soil and the cubitermes sp termite mound soil through a 2 mm sieve. Pour la séparation des particules, deux types d'essais ont été réalisés: le tamisage pour les grains de taille ϕ > 80 µm selon la norme NFP94-056 [14] *et al.* sédimentation pour les grains de diamètre $\phi \leq$ 80 µm selon la norme NF P94-057 [15]. The particle size fraction is deduced from the recommendations of the particle size nomograms, which consider clays as particles < 0.002 mm, silts 0.002 - 0.06 mm, sands 0.06 - 2 mm, gravels 2 - 20 mm and pebbles 20 - 200 mm. The particle sizes corresponding to D_{10}, D_{30} and D_{60} by sieving weight are deduced from the particle size curves. The uniformity coefficient C_u and the curvature coefficient C_c were used to characterize the granulometry of Ag (0/14)-Cl (0/1) and Ag (0/14)-Csp (0/2) mixtures defined in accordance with the formulae below:

$$C_U = \frac{D_{60}}{D_{10}} \tag{1}$$

$$C_C = \frac{D_{30}}{D_{10} * D_{60}} \tag{2}$$

D_x is the particle size corresponding to x % by weight of the sieve.

For each fine content, three distribution tests of the granulometric fractions are determined and the average of the three tests is taken and plotted on the graph.

The Atterberg limits are determined in accordance with standard NF P 94-051 [16]. The liquidity (LL) and plasticity (PL) limits are determined by the fraction of soil passing through a 0.40 mm sieve. The plasticity index (PI) is expressed by the following relationship:

$$\text{PI} = \text{LL} - \text{PL} \tag{3}$$

Measuring the methylene blue adsorption capacity of a soil involves measuring the quantity of methylene blue absorbed by the 0/5 mm fraction of the clay soil and the cubitermes sp termite mound soil. This test characterizes the clay content of a soil, a parameter directly linked to the specific surface area of the soil, which reflects the overall quantity and quality (activity) of the clay fraction. The methylene blue value of a soil (BVS) is determined in accordance with the standard NF P 94-068 [17].

The maximum dry density and optimum moisture content were defined using the modified Proctor test, in accordance with standard NF P 94-093 [18].

The sand equivalent assesses the proportion of fine elements contained in the soil, defined in accordance with standard NF P 18-598 [19].

California Bearing Ratio (CBR) is a test used to determine the mechanical characteristics and compaction of materials in pavement layers. It measures the shear strength of the material and enables the bearing capacity of the material to be calculated, by estimating its resistance to punching. It is the essential parameter for geotechnical testing prior to construction and is defined in accordance with standard NF P 94-078 [20]. The static modulus of mixes has been defined by the relationship Est = 5CBR, provided that the CBR of all mixes is greater than 10 [21].

The resistance of the aggregate to fragmentation under the action of traffic and of the aggregates in terms of hardness, resistance to abrasion and resistance to polishing are defined according to the Los Angeles test procedure based on standard NF P18-573 [22].

The micro-Deval test determines the wear resistance of an aggregate sample. This wear resistance for certain rocks is not the same in dry conditions or in the presence of water. The test is defined according to the NF EN 1097-1 [23]. The flattening coefficient is one of the tests used to characterize the more or less massive shape of aggregates. Gravel grains that are closer to a sphere or cube are the best, and the test is defined according to the standard NF EN 933-3 [24].

Origin Pro 2019b software was used to determine the coefficient of determination and the correlations between the intrinsic parameters of the mixtures. The mathematical model selected was the one with a coefficient of determination R^2 greater than 0.8. Minitab 17 software was used to determine the statistical properties of the granulometric fractions of the mixtures.

3. Results and Discussion

3.1. Characterization of Alluvial Gravel (Ag), Clay Soil (Cl) and Cubitermes sp Termite Mound Soil (Csp)

The particle size distribution of alluvial gravel (0/14) as the main material and silty clay (0/1) and clayey silt (0/2) as corrective materials extracted from Figure 4 are shown in Table 2.

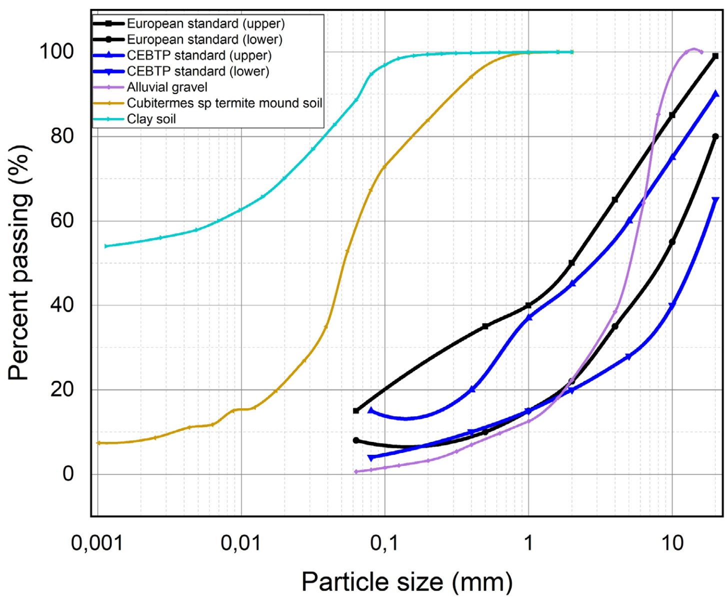

Figure 4. The granulometries Ag (0/14), Cl (0/1), Csp (0/2) and the normative spacing prescribed for 0/15 rock materials in the base layer of pavements defined in accordance with standard NF EN 13285 [25] and technical document [21].

Table 2. Grain size distribution of alluvial gravel (0/14), silty clay (0/1) and clayey silt (0/2).

Materials	Cl	Fsi	Msi	Csi	Fsa	Msa	Csa	Fg	Mg	Cg
Clay	51.7	16	11.86	10.01	10.33	0.1	0	-	-	-
Csp	32.8	20.5	9.9	10.96	16.24	8.47	1.13	-	-	-
G	-	-	-	-	3.22	6.25	12.84	22.31	38.55	39.14

Cl-clay, Fsi-fine silt, Msi-medium silt, Csi-coarse silt, Fsa-fine sand, Msa-medium sand, Csa-coarse sand, Fg-fine gravel, Mg-medium gravel, Cg-coarse gravel, Csp-cubitermes sp, G-gravel.

According to **Table 2**, alluvial gravel is a material with a good skeleton, lacking fine clay to ensure cohesion. Alluvial gravel is made up of smooth, whitish, rounded grains of size 0/14 [24]. The geotechnical properties of the alluvial gravel, the clay soil and the cubitermes sp termite mound soil are shown in **Table 3**.

Table 3. Geotechnical characteristics of materials.

Soils	Ag (0/14)	Csp (0/2)	Cl (0/1)
Clay (%)	-	32.8	51.7
Silt (%)	-	41.19	37.87
Sand (%)	22.31	10.43	26.01
Gravel (%)	77.69	0	0
D_{max} (mm)	14	0.2	0.1
D < 80 µm (%)	1	79.37	95.6
D < 2 mm (%)	22.39	100	100
BVS (g/kg)	-	0.3	-
SE (%)	88	-	-
LA (%)	41	-	-
MDE (%)	12	-	-
MDD (T/m^3)	-	16.26	19.23
OMC (%)	-	1.60	1.61
CBR	-	16	7
PI (%)	-	23.2	32.1
LL (%)	-	39	60.2
LP (%)	-	15.8	28.1
Cu	9.2	-	-
CC	2.3	-	-

MDD (T/m^3): maximum dry density, OMC (%): optimum moisture content, LA (%): Los Angeles, PI (%): plasticity index, LL (%): liquidity limit, PL (%): plasticity limit, SE (%): sand equivalent, MD: micro-Deval in the presence of water, UC: uniformity coefficient, CC: curvature coefficient.

According to the Unified Soil Classification System (USCS) [26], clay soil (Cl) is classified as silty clay (Cl) and cubitermes sp termite mound soil (Csp) is classified as clayey silt (Csp). The uniformity and curvature coefficients of silty clay and clayey silt are not measurable [26].

3.2. Characterization of Mixtures Ag (0/14)-Cl (0/1) and Ag (0/14)-Csp (0/2)

Figure 5 shows the particle size distribution of the Ag (0/14)-Cl (0/1) and Ag (0/14)-Csp (0/2) mixtures and the distribution of the grain size in the mixtures in accordance with standard NF EN 13,285 [25] and the technical document [21].

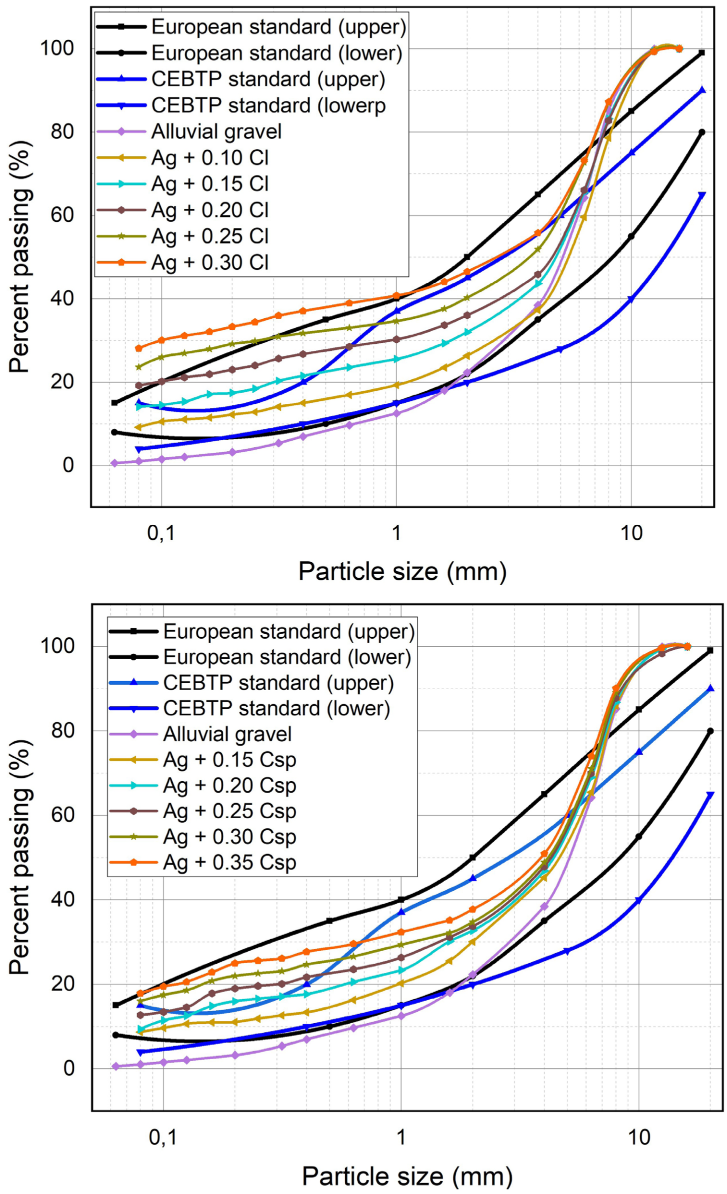

Figure 5. Distribution of grains in mixtures Ag (0/14)-Cl (0/1) and Ag (0/14)-Csp (0/2).

In **Figure 5**, the particle size curves between 0.08 and 2 mm remain spread out. In other words, the curves are oblique, meaning that the soils contain several classes of grain. These are good materials for building site tracks. The 30% silty clay (Cl) mixture does not integrate the grain distribution spindle defined by CEBTP 1984 [21]. Mixes with 15%, 20% and 25% Cl intermittently integrate the spindles. For the combination of alluvial gravels (Ag) and clayey silts (Csp), the 10% and 15% mixes incorporate both spindles for grain sizes below 6 mm. However, all the mixes incorporate the two spindles specified in European standard NF EN 13285 [25] for grain sizes below 7 mm. The geotechnical characteristics of the mixes are given in **Table 4** and **Table 5**.

Table 4. Geotechnical characteristics of mixtures Ag (0/14)-Cl (0/1).

Designation	10%	15%	20%	25%	30%
SE (%)	35	22	16	11	9
MDD (T/m^3)	2.19	2.15	2.11	2.07	2.03
OMC (%)	4	5.2	6.2	7	8
CBR (%)	96	62	40	35	29
Est (MPa)	480	310	200	175	145
Cu	70.7	-	-	-	-
Cc	11.6	-	-	-	-

MDD (T/m^3): maximum dry density, OMC (%): optimum moisture content, CBR (%): California Bearing Ratio, SE (%): sand equivalent, Cu: coefficient of uniformity, Cc: coefficient of curvature.

The 10% mixture has a spread particle size distribution Cu (70.7) > 6, but poorly calibrated Cc (11.6) > 3 [26]. The uniformity and curvature coefficients of the 15%, 20%, 25% and 30% mixes cannot be determined because of the high proportion of fines (over 10%), making it impossible to measure the diameter corresponding to 10% of the passings in these mixes.

Table 5. Geotechnical characteristics of mixtures Ag (0/14)-Csp (0/2).

Designation	15%	20%	25%	30%	35%
SE (%)	82	79	77	74	69
MDD (T/m^3)	2.18	2.15	2.11	2.07	2
OMC (%)	6.1	6.8	7.5	8.2	9.4
CBR (%)	84	49	36	30	24
Est (MPa)	420	245	180	150	120
CU	62.9	63.8	-	-	-
Cc	7.8	5.5	-	-	-

MDD (T/m^3): maximum dry density, OMC (%): optimum moisture content, CBR (%): California Bearing Ratio, SE (%): sand equivalent, Cu: coefficient of uniformity, Cc: coefficient of curvature.

The 15% and 20% mixtures have spread out particle size distributions (Cu > 6) but are poorly calibrated (Cc > 3) [26]. The coefficients of uniformity and curvature of the curves for mixtures with 25%, 30% and 35% clayey silt cannot be determined because of the high proportion of fines (over 10%), making it impossible to measure the diameter corresponding to 10% of the passages in these mixtures. The fractions of fine sand, medium sand, coarse sand, fine gravel and medium gravel extracted from **Figure 5** are shown in **Figure 6**.

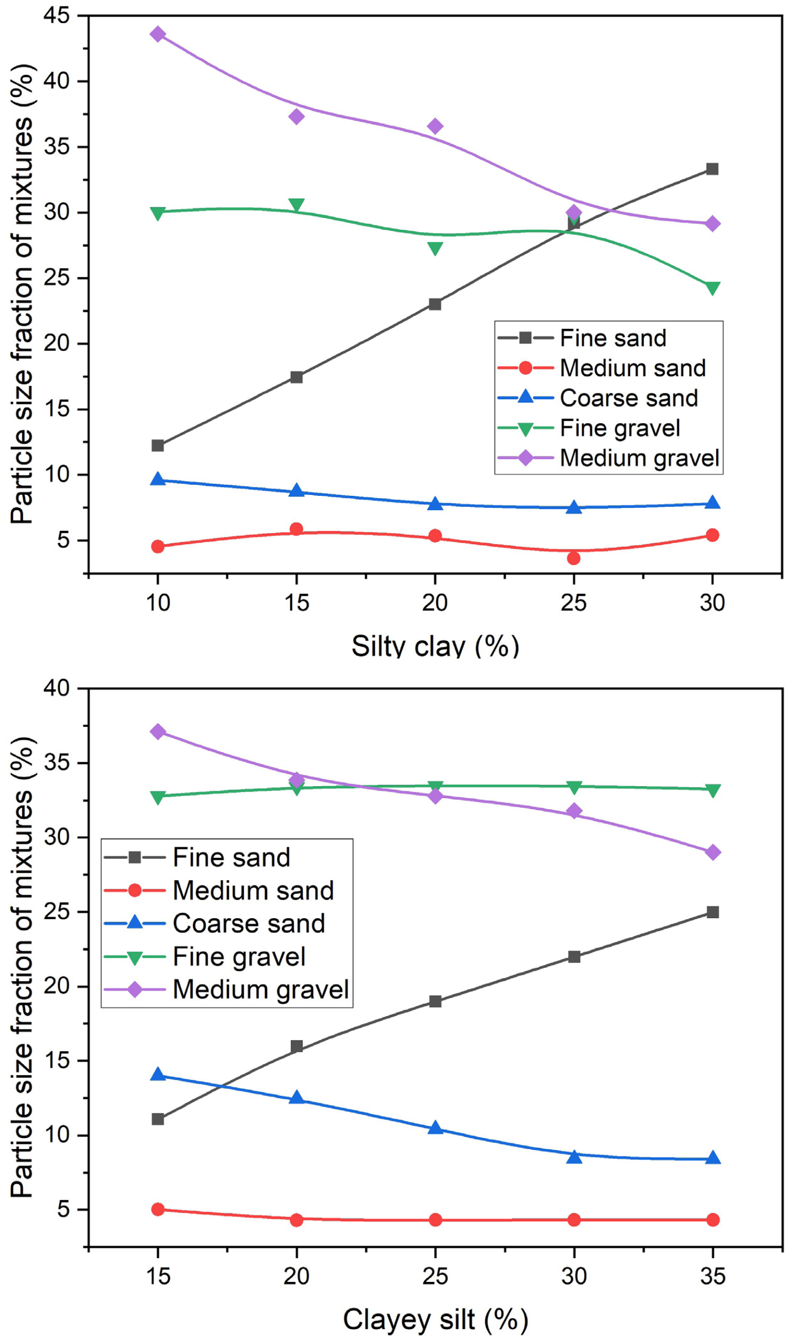

Figure 6. Distribution of particle size fractions in mixtures Ag (0/14)-Cl (0/1) and Ag (0/14)-Csp (0/2).

In **Figure 6**, for the alluvial gravel (Ag)-silty clay (Cl) mixture, the relationship obtained between the distribution of particle fractions in the mixtures as a function of the addition of sandy clay are polynomial fits:

$$Y_1 = B + B_1 X + B_2 X \tag{4}$$

Table 6. Determination of the constants B, B_1, B_2 and R^2 of polylinear.

Designation (Y_1)	B	B_1	B_2	R^2
Fine sand	−0.140 ± 2.379	1.262 ± 0.259	−0.005 ± 0.0064	0.998
Medium sand	4.826 ± 4.859	0.029 ± 0.528	−9.714E−4 ± 0.013	0.564
Coarse sand	13.468 ± 0.786	−0.473 ± 0.085	0.009 ± 0.002	0.976
Fine gravel	26.984 ± 8.393	0.484 ± 0.919	−0.018 ± 0.023	0.672
Medium gravel	54.862 ± 7.704	−1.301 ± 0.838	0.014 ± 0.021	0.946

From **Table 6**, the coefficients of determination R^2 for the particle size fractions (medium sand and fine gravel) of 0.564 and 0.672 respectively, are less than 0.8. In **Figure 6**, for the Alluvial Gravel (Ag)-Clayey silt (Csp) mixture, the relationship obtained between the distribution of particle fractions in the mixtures as a function of the addition of clay silt are polynomial fits:

$$Y_2 = B + B_1 X + B_2 X \tag{5}$$

Table 7. Determination of the constants B, B_1, B_2 and R^2 of polylinear.

Designation (Y_2)	B	B_1	B_2	R^2
Fine sand	−4.623 ± 2.920	1.225 ± 0.247	−0.011 ± 0.005	0.996
Medium sand	7.589 ± 1.160	−0240 ± 0.098	0.004 ± 0.002	0.839
Coarse sand	23.468 ± 3.594	−.749 ± 0.304	0.009 ± 0.006	0.974
Fine gravel	29.885 ± 0.615	0.271 ± 0.052	−0.005 ± 0.001	0.945
Medium gravel	43.681 ± 5.651	−0.509 ± 0.478	0.003 ± 0.009	0.955

In **Table 7**, the coefficients of determination R^2 for all the granulometric fractions are greater than 0.8.

According to **Figure 7**, the 95% confidence intervals for the particle size fractions of the Ag-Cl mixtures, the confidence interval for the fine sand content has a mean of (19.336 - 26.696), a median of (17.335 - 29.143) and a standard deviation of (5.98 - 11.484). Medium sand has a mean (4.551 - 5.304), median (4.455 - 5.388) and standard deviation (0.611 - 1.174). Coarse sand has a mean (7.821 - 8.573), median (7.635 - 8.708) and standard deviation (0.611 - 1.174). Fine gravel has a mean (27,290 - 29,538), median (27,355 - 30,090) and standard deviation (1826 - 3507). Medium gravel has a mean (32.796 - 37.862), a median (30.090 - 37.325) and a standard deviation (4.116 - 7.904). The statistical properties of the particle size fractions extracted from **Figure 7** are shown in **Table 8**.

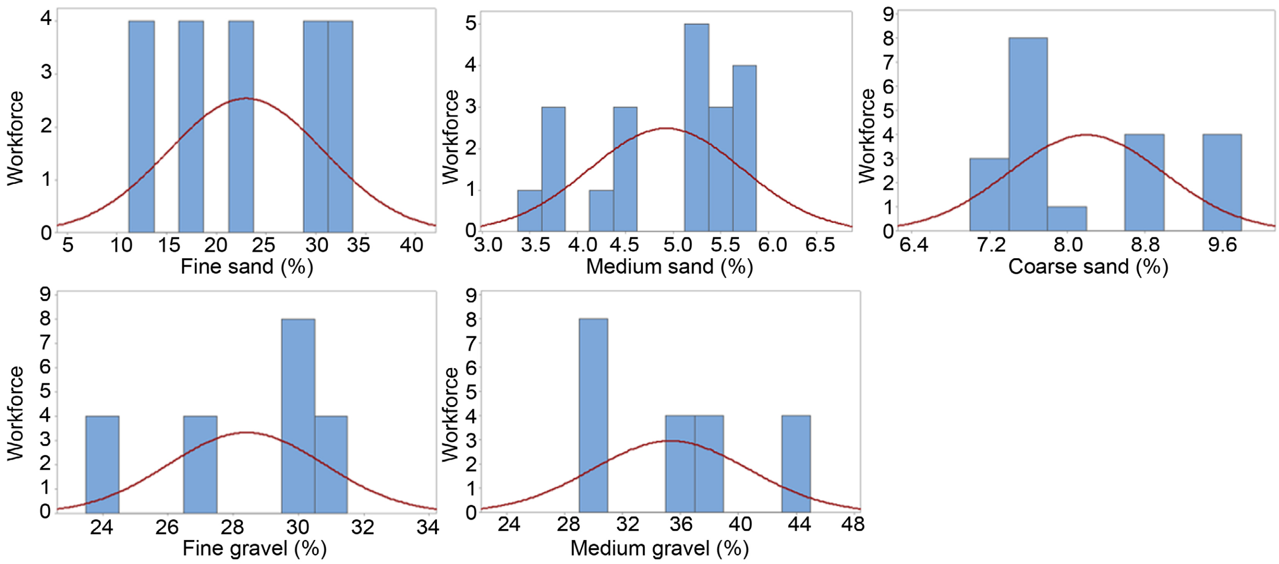

Figure 7. Statistical properties of the particle size fractions of mixtures of alluvial gravel (Ag) and silty clay (Cl).

Table 8. Statistical properties of particle size fractions (Anderson-Darling normality test).

Designation		FSa	MSa	CSa	FG	MG
Test of normality	A2	0.75	1.15	1.40	1.69	1.23
	P-value	0.042	<0.005	<0.005	<0.005	<0.005
Average		23.016	4.928	8.197	28.414	35.329
Standard deviation		7.863	0.804	0.804	2.401	5.412
Variance		61.823	0.646	0.646	5.767	29.286
Asymmetry		−0.060	−0.594	0.663	−0.892	0.274
Flattening		−1.455	−1.082	−1.182	−0746	−1.235
N		20	20	20	20	20
Minimum		12.150	3.610	7.350	24.270	29.110
1st quartile		17.270	4.383	7.608	27.313	30.038
Median		23.085	5.315	7.785	29.695	36.555
3rd quartile		29.188	5.398	8.718	30.113	37.345
Maximum		33.370	5.870	9.580	30.690	43.610

FSa: fine sand, MSa: medium sand, CSa: coarse sand, FG: fine gravel, MG: medium gravel.

According to **Table 8**, the normality of MSa, CSa, FG and MG is less than 0.005, with variances of 0.6460, 0.6463, 5.767 and 29.286 respectively.

According to **Figure 8**, the 95% confidence intervals for the particle size fractions of the Ag-Csp mixtures, the confidence interval for the fine sand content has a mean (15.146 - 19.734), a median of (15.850 - 21.82) and a standard deviation

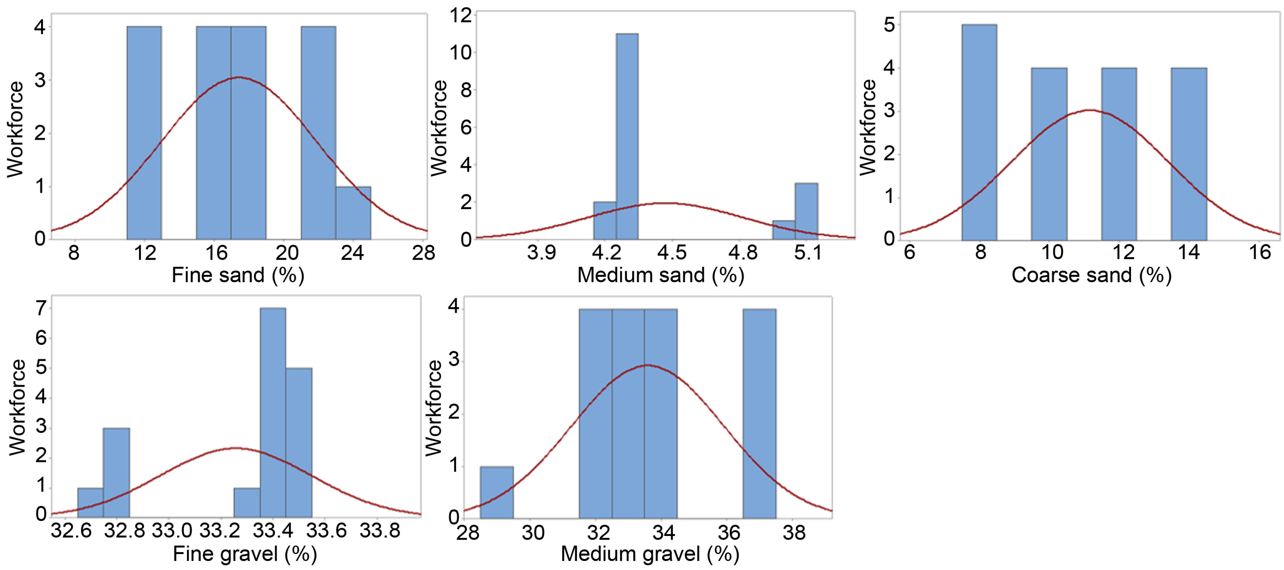

Figure 8. Statistical properties of the particle size fractions of Ag and Csp mixtures.

(3.323 - 6.790). Medium sand has a mean (4.291 - 4.650), median (4.28 - 4.33) and standard deviation (0.260 - 0532). Coarse sand has a mean (10.002 - 12.313), median (8.496 - 12.47) and standard deviation (1.674 - 3.42). Fine gravel has a mean (33.107 - 33.408), median (33.252 - 33.45) and standard deviation (0.218 - 0.446). Medium gravel has a mean (32.401 - 34.784), median (31.852 - 33.880) and standard deviation (1.26 - 3.527). The statistical properties of the particle size fractions extracted from **Figure 8** are shown in **Table 9**.

Table 9. Statistical properties of particle size fractions (Csp).

Designation		FSa	MSa	CSa	FG	MG
Test of normality	A2	0.61	2.91	0.83	2.29	0.86
	P-value	0.095	<0.005	0.025	<0.005	0.021
Average		17.44	4.471	11.158	33.258	33.592
Standard deviation		4.461	0.350	2.247	0.293	2.317
Variance		19.902	0.122	5.050	0.086	5.369
Asymmetry		−0.189	1.335	0.010	−1.269	0.289
Flattening		−1.007	−1.455	−1.551	−0.222	−0.233
N		20	20	20	20	20
Minimum		11.017	4.20	8.35	32.69	29.020
1st quartile		13.50	4.265	8.435	33.025	31.815
Median		18.87	4.31	10.43	33.41	32.82
3rd quartile		21.92	4.68	13.24	33.45	35.465
Maximum		24.99	5.13	14.11	33.49	37.130

FSa: fine sand, MSa: medium sand, CSa: coarse sand, FG: fine gravel, MG: medium gravel.

According to Table 9, the normality of the mean sand of the clayey silt (MSa) and that of the fine gravels is less than 0.005, with respective variances of 0.122 and 0.086.

Figure 9 shows the evolution of the sand equivalent of the alluvial gravel as a function of the addition of silty clay fines (Cl) and clayey silt (Csp).

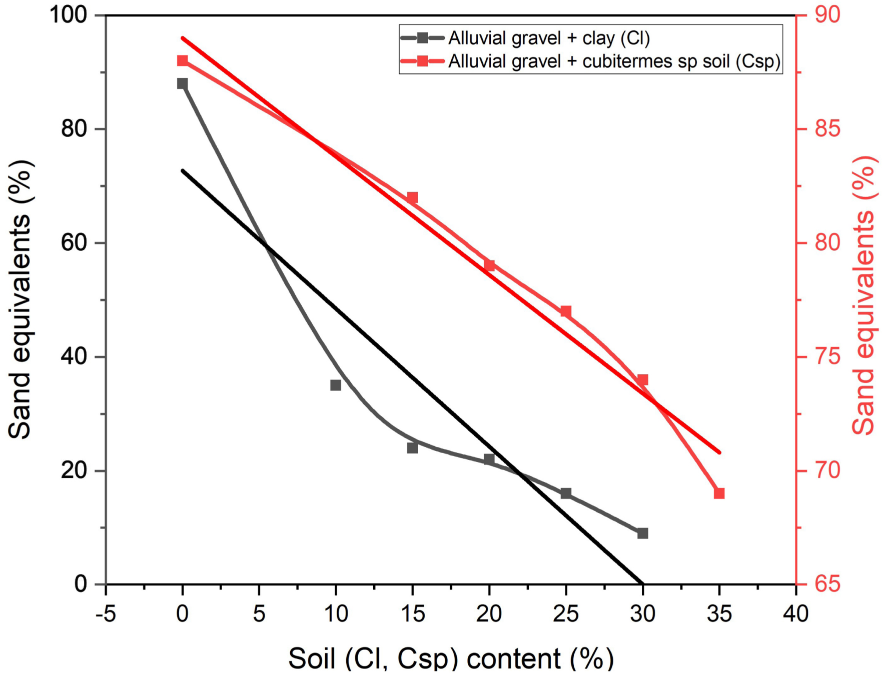

Figure 9. Evolution of sand equivalent as a function of the addition of fines (Cl, Csp).

Figure 9 shows the decrease in the sand equivalent of the mixture as a function of the content of silty clay (Cl) and clayey silt (Csp). The sand equivalent of the mixture is not really proportional to the contents (Cl, Csp) of the mixture (Figure 9). In fact, for silty clay (Cl), we have:

$$SE = (89 \pm 1.088) + (-0.52 \pm 0.046)\alpha_{Cl};\ R^2 = 0.970 \quad (6)$$

$$SE = (87.891 \pm 0.676) + (-0.274 \pm 0.079)\alpha_{Cl} \pm (-0.007 \pm 0.002)\alpha_{Cl}^2;\ R^2 = 0.993 \quad (7)$$

For clayey silt (Csp)

$$SE = (72.714 \pm 10.369) + (-2.423 \pm 0.535)\alpha_{Csp};\ R^2 = 0.837 \quad (8)$$

$$SE = (85.690 \pm 5.690) + (-5.537 \pm 0.806)\alpha_{Csp} \pm (0.104 \pm 0.026)\alpha_{Csp}^2;\ R^2 = 0.975 \quad (9)$$

where, *SE*: sand equivalent of the mixture, α_{Cl}: silty clay content (Cl) and α_{Csp}: clayey silt content (Csp) of the mixture.

The sand equivalent does not obey the law of mixtures unlike the sand content of the mixture. In other words, the sand equivalent is not proportional to the sand content of the mixture. In fact, the sand content of the mixture as a function of the silty clay content (Cl) and the clayey silt content (Csp) are given by the following relationships:

$$P_S^m = P_S^{Ag} + \left(P_S^{Cl} - P_S^{Ag}\right)\alpha_{Cl} \quad (10)$$

$$P_S^m = P_S^{Ag} + \left(P_S^{Csp} - P_S^{Ag}\right)\alpha_{Csp} \quad (11)$$

With: $P_S^m, P_S^{Ag}, P_S^{Cl}$ et P_S^{Csp} respectively the percentages of sand in the mixture, alluvial gravel (Ag), silty clay (Cl) and clayey silt (Csp); α_{Cl} et α_{Csp} respectively the silty clay content and the clayey silt content of the mixture.

If the sand equivalent of the mixture were proportional to the sand content of the mixture, it would also be proportional to the silty clay content (Cl) and the clayey silt content (Csp). Figure 10 shows the evolution of maximum dry density as a function of optimum moisture content.

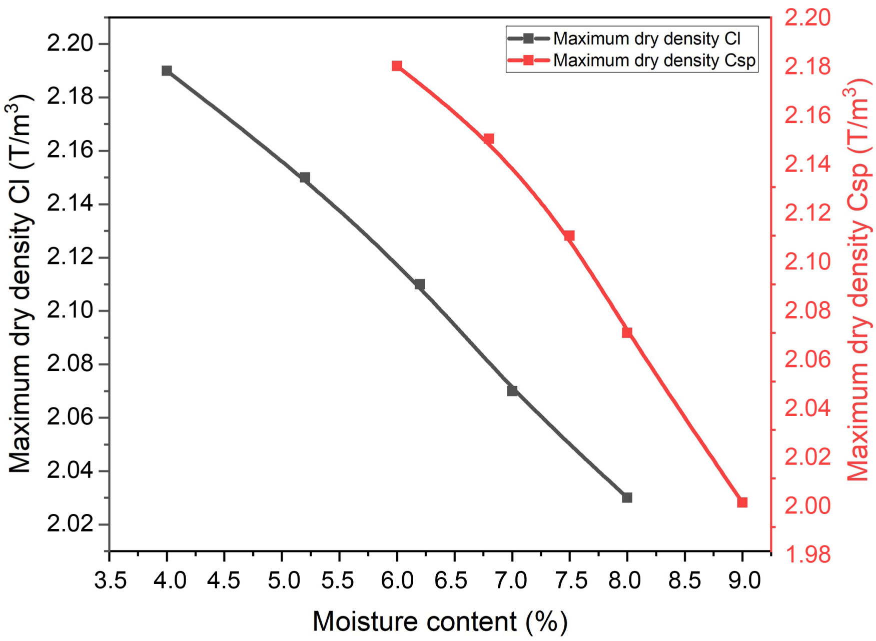

Figure 10. Evolution of maximum dry density as a function of optimum moisture content.

According to Figure 10, the maximum dry density decreases with increasing fine sand content and water content in the mixes (Figure 6). The addition of silty clay and clayey silt increases the optimum moisture content of the mix.

Dry density is not a direct indication of a material's mechanical strength. In a material that nevertheless has pores, the more interactions there are between the particles, the better the cohesion. The correlation between CBR index and maximum dry density as a function of silty clay (Cl) and clayey silt (Csp) is a polynomial fit:

$$Y_3 = B + B_1X + B_2X^2 \quad (12)$$

In Table 10, the coefficients of determination R^2 for determining the correlation between the CBR and the maximum dry density of the blends are greater than 0.8.

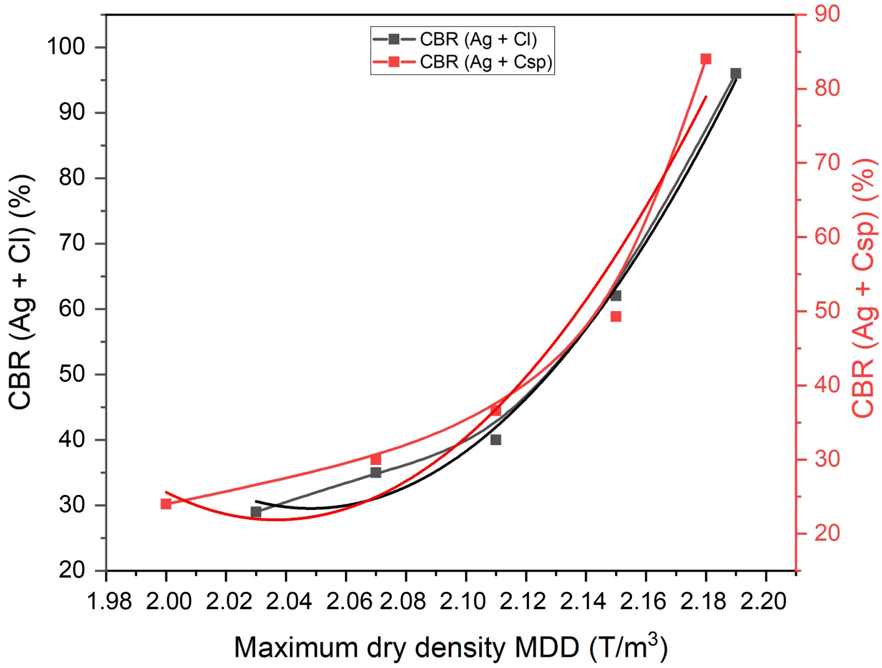

Figure 11. Change in CBR index as a function of maximum dry density.

Table 10. Determination of the constants B, B_1, B_2 and R^2 of polylinear.

Mixes	B	B_1	B_2	R^2
Ag-(Cl)	13701.77 ± 2599.36	−13350.18 ± 2465.15	3258.93 ± 584.12	0.984
Ag-(Csp)	11549.5 ± 4414.94	−11319.88 ± 4229.31	2778.97 ± 1012.09	0.893

3.3. Discussion

According to **Table 1**, the particle size distribution of alluvial gravel (0/14) is composed of sands (fine, medium, coarse) and gravels (fine, medium). Its particle size distribution is spread out and well calibrated, with uniformity coefficients Cu (9.2) > 4 and curvature coefficients CC (2.3) between 1 < Cc < 3 [26]. However, the uniformity and curvature coefficients for silty clay and clayey silt are not measurable. In other words, the particle size distributions of the two corrective materials are poorly calibrated. Its Los Angeles LA coefficient (41) is higher than the maximum of 35% required for the hardness of alluvial gravels to be used in the base layer of pavements [21]. Alluvial gravel integrates the two spindles in the range 2 - 8 mm and beyond that, the distribution of grains is outside the spindle.

According to the Unified Soil Classification System (USCS), the clayey soil and the soil of the cubitermes sp termite mounds are classified as highly plastic silty clay (Cl) and low plasticity clayey silt (Csp) respectively [26]. Mixe with Cl (10%) and Csp (15%) integrate the spindles and lie outside the two spindles for grain distribution greater than 8 mm (**Figure 5**). Both mixes are suitable for road construction [21]. In fact, the dislocation of the grains obtained after compacting the material means that the grain distribution completely integrates the two spindles (**Figure 5**). According to **Figure 6**, the addition of silty clay (Cl) and clayey silt (Csp) to alluvial gravels increases the content of fine sand (FSa) in the mixture. The distribution of Cl (coarse sand, medium gravel) and Csp (fine gravel) grains varies little. The distribution of Cl and Csp grains (coarse sand, medium gravel) and Csp (medium sand) decreases (**Figure 6**).

In **Table 6**, **Table 7** and **Table 10**, the equations used are those with coefficients of determination $R^2 \geq 0.8$.

The maximum CBR values (96%, 84%) **Figure 11** were obtained with Cl (10%) and Csp (15%) mixes, with sand equivalents of 35% (**Table 4**) and 82% (**Table 5**) respectively. All these values are within the authorised limits for road construction. Despite a CBR > 80% (CEBTP 1984) [21], mixtures with Cl (10%) and Csp (15%) cannot be used as base layer materials for pavements. In fact, alluvial gravel with a grain size (0/14) and LA value (41%) > 35% (CEBTP 1984) [21] is not suitable as a support for hammering tyres in a pavement base layer.

The addition of silty clay (Cl) and clayey silt (Csp) increases the fine sand content of the mix, which reduces the maximum dry density (**Figure 10**) and the CBR index (**Table 4** and **Table 5**). The increase in optimum moisture content is a function of the increase in Cl and Csp fines in the mix (**Figure 10**). The coefficients of determination as a function of grain distribution in the Ag-Csp mixtures (0.839 - 0.996) are greater than 0.8 (**Figure 12**).

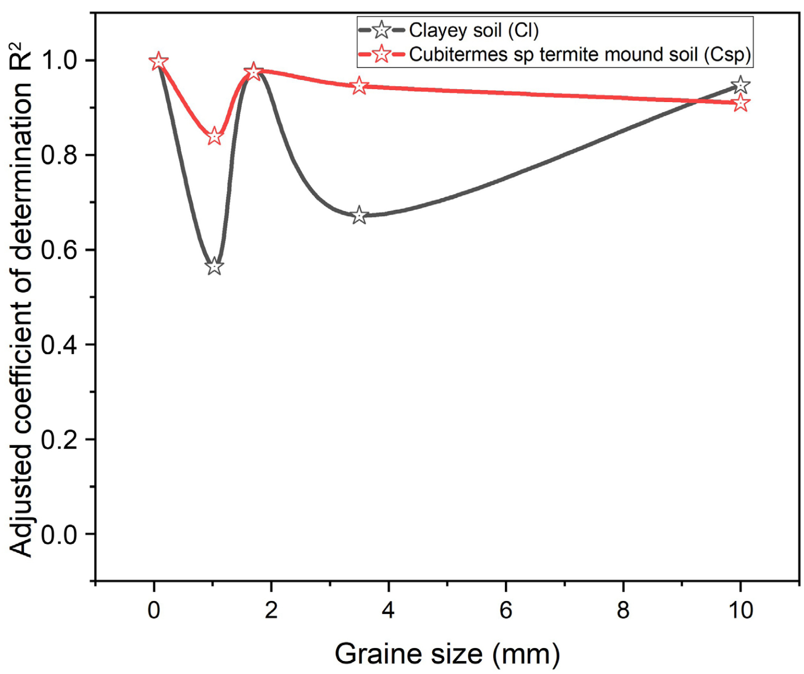

Figure 12. Coefficient of determination as a function of grain distribution.

In **Figure 12**, the coefficients of determination as a function of grain distribution in Ag-Cl mixtures for MSa and FG particles are less than 0.8 and those for

FSa, CSa and MG particles are greater than 0.8.

According to Figure 7 and Table 5, the Anderson-Darling normality test with the P value of the distribution of grains in the granulometric fractions (Msa, Csa, FG, MG), are less than 0.005, with A2 (1.15 - 1.69) and that of Fsa (0.042) with A2 (0.75) and the variance (0.646 - 61.823) by the addition of silty clay fines. According to Figure 8 and Table 6, the addition of clayey silt (Csp), the Msa and FG particle size fraction has a P value of less than 0.005, with A2 (2.91 - 2.29) respectively, and that of FSa (0.095), CSa (0.025), MG (0.021) has A2 (0.61 - 0.86) with a variance (5.050 - 19.902). The results obtained for each type of mixture (Ag-Cl and Ag-Cs) are disparate, which may be linked to the law of mixtures. Indeed, according to Figure 9, the sand equivalent does not seem to obey the law of mixtures, unlike the sand content of the mixture. In other words, the sand equivalent is not proportional to the sand content of the mixture. If the sand equivalent of the mixture were proportional to the sand content of the mixture, it would also be proportional to the silty clay content (Cl) and the silty clay content (Csp). All these changes can be explained by the fact that the distribution of grains in the mixtures may not obey the law of mixtures [27] [28].

4. Conclusion

Ag alluvial gravel (0/14) is the main material, which is cohesion less with a spread and poorly graded grain size, composed of sand (22.31%), gravel (77.69%), SE sand equivalent (88%), Los Angeles LA coefficient (41) and Micro Deval DM (12). Alluvial gravel is a material with clean sand that can be recommended for concrete. Silty clay (Cl) and clayey silt (Csp), two corrective materials for alluvial gravel, poorly graded, composed respectively of clay (51.7% - 32.8%), silt (37.87% - 41.19%) and sand (26.01% - 10.43%) with PI plasticity indices (32.1% - 23.2%). The normality of the particle size fractions of silty clays (MSa, CSa, FG, and MG) and clayey silts (MSa and FG) is less than P (0.005) and those of the Cl (FSa) and Csp (Fsa, MSa, and MG) fractions is greater than P (0.005). The addition of silty clay or clayey silt reduces the sand equivalent of the mixture. The reduction in the sand equivalent of the mix is not proportional to the silty clay or clayey silt content of the mix. From the above, we can say that the mixtures Ag (0/14)-Cl (0/1) and Ag (0/14)-Csp (0/2) do not obey the law of mixtures. The maximum dry densities, CBR indices and static moduli of the mixes decrease with the addition of corrective materials. The addition of fine silty clay and clayey silt increases the optimum moisture content of the modified Proctor test. These decreases in mechanical properties can be explained by the increase in the content of fine sand in the mixes. The mixtures Ag (0/14)-Cl (0/1) and Ag (0/14)-Csp (0/2) obtained from Cl (10%) and Csp (15%) respectively, have CBR (96% - 84%), Est (480 - 420 MPa), DDM (2.19 - 2.18 T/m^3) and SE (35% - 6%) mechanical properties which mean that the material can be used as a sub-base layer for T1-T3 traffic (5×10^5 - 4×10^6).

Conflicts of Interest

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

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