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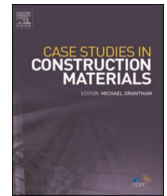
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## Case study

# Re-use in road construction of a Karal-type clay-rich soil from North Cameroon after a lime/cement mixed treatment using two different limes

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## ABSTRACT

Swelling clays characterized by their shrinkage and swelling phenomenon are known to be the main cause of cracking of paved roads. So, the road construction on swelling soils require knowledge and specific techniques, including the chemical stabilization with lime or cement addition. This technique favors the sustainable development by avoiding waste production especially soils. Indeed a maximum reuse of materials located in the building project area allows reaching the "zero loan, zero deposit" objective.

In this paper, the efficiency of mixed treatment with lime and cement tested was tested on swelling karal-type soils collected at Pitoa in the North Cameroon region. The soil samples were characterized by applying microstructural and geotechnical tests (XRD, SEM, Particle Size Analysis, Atterberg Limits, Modified Proctor, CBR test, and Unconfined Compressive Strength (UCS)). The results showed that the mixed treatment of karal soils using a 2% of hydrated lime mixed with CaO or a 3% of low carbonated hydrated lime and 3, 5 or 7% of cement, reduced drastically the soil volume variation under water content change and improved the soil physico-mechanical properties. Finally, soils after treatment reached the minimum characteristics required for recovery in road construction.

## 1. Introduction

The clay-rich soils found specifically in Northern and Far North Cameroon are called Karal soils and are known to be the main causes of pathologies in road construction [1]. For example, the Garoua-Pitoa road section constructed in 2009 underwent deformation of the platform barely a few months after inception. The observed degradations were cracks on the road shoulders and rutting on the carriage way. In order to better understand the origin of the phenomenon and reduce pathologies, Karal soils properties have been investigated [2–5] and the results obtained show their similarities in terms of chemical and physico-mechanical characteristics. For example, Karal soils from Dabanga, Logone Valley, Maroua and Kousseri or Maroua and Fotokol contained mainly aluminosilicates with the presence of quartz, kaolinite and montmorillonite clays as well as illite/mica, feldspars, iron oxides and bayerite in lower

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quantities [3,4,6,7]. The Karal soil fraction smaller than 2 μm appeared mainly higher than 30 %, reaching 45 % in the soil studied by Baana et al. [3], which is the characteristic of clays according to Mouroux et al. [8]. Furthermore, the particles passed through the 80 μm sieve have been estimated between 85 to 97 %. The plasticity index of Karal soils ranging between 15 and 40 agreed with soil mineralogy as well as the measured fine content, and allowed to classify Karal soils among plastic soil with moderate to strong swelling properties [9].

Because of the volume change of compacted soils in road layers under moisture variation, the Karal soils are considered as harmful material for road durability, leading building and public works companies to purge in situ soils and to replace it by material with good quality such as laterite. However, in the current context of sustainable development, the use of in situ Karal soil is strongly encouraged in order not only to achieve the "zero loan, zero deposit" objective, but also to minimize the cost of pavement construction while

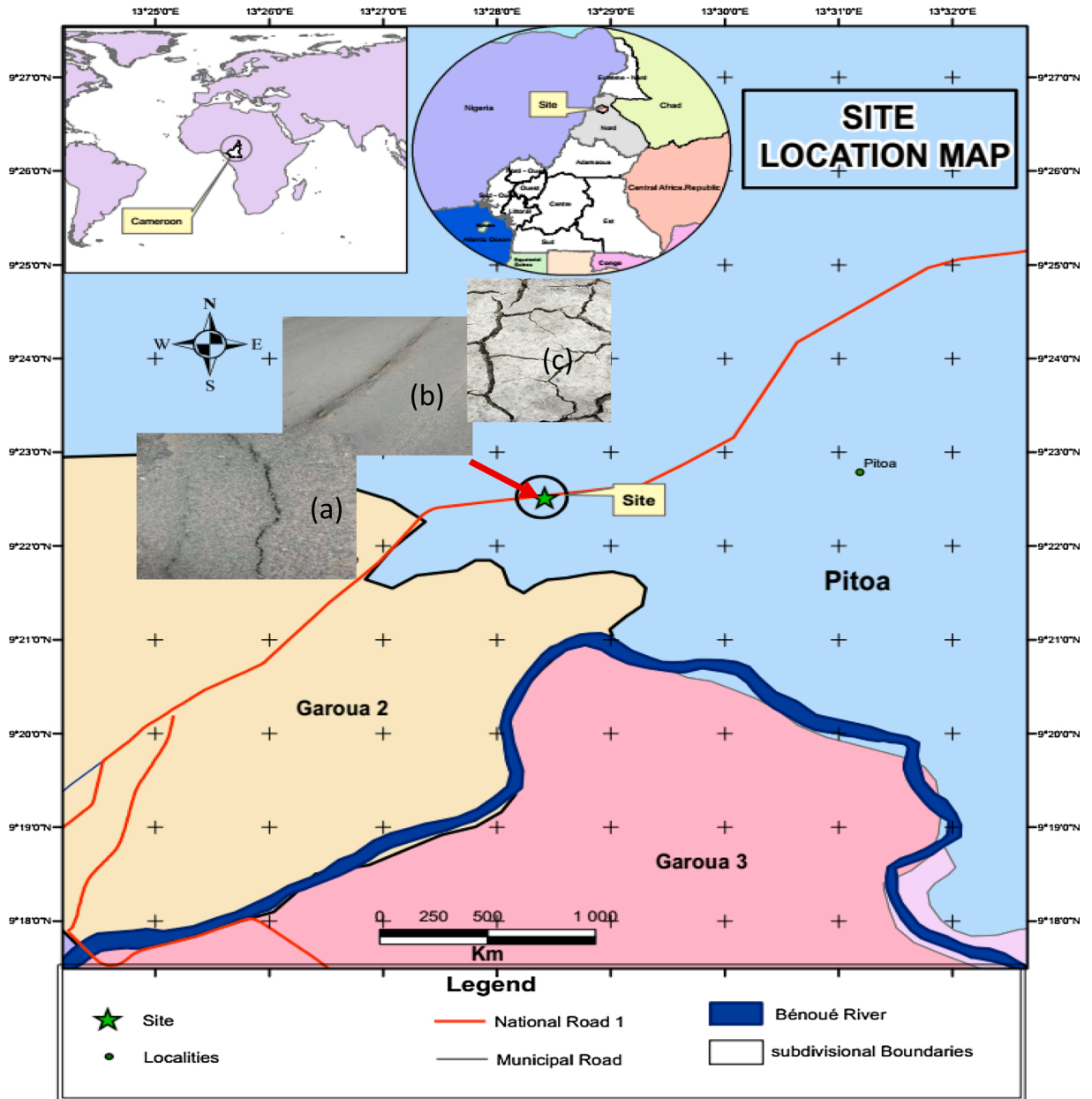


Fig. 1. Location of sampling site localized with a green star. The black lines are administrative boundaries between different municipalities represented by various colored areas, the blue lines are the rivers, the red lines represent the road. Source: Limite administrative INC2013, Réseau routier MINTP, Schéma Régional d'Aménagement et de développement durable du territoire du Nord Cameroun, www ESRI2008/ArcMap10.7, GoogleEarth) Embedded photos: (a) and (b) Cracks on bitumen concrete pavement after the swelling/shrinkage Karal soil under moisture variation. (c) The desiccation cracks on soils near the road.

remaining within acceptable safety limits. In this context, the stabilization of swelling soils using hydraulic binders (cement or lime type) or other more environmentally friendly binders represents a good alternative to achieve the objective [10]. For Ismael and al. [11], the use of electric arc furnace slag in Soil improvement has also given interesting results while treatments such as enzyme-based soil stabilizers [12–17], fiber stabilizers [18,19], liquid ionic stabilizer [20–23] are also experimented nowadays to fight against the production of CO<sub>2</sub>, as is the case during the production of hydraulic binders (lime or cement) in factories. For the specific case of Cameroonian Karal materials, most researchers focused on litho stabilization, i.e. the stabilization with non swelling minerals addition such as sand which produces a dilution effect reducing the clay effect. The efficiency of this technique to reduce the soil shrinkage was demonstrated [3] while a slight increase in CBR after adding sand was observed [1,24]. Temga et al. [5] stabilized the Karal soils with lime that induced a clear improvement of compressive strength that reached a 0.4–5.1 MPa value for a lime content varying between 4 to 12 %. A satisfactory effect after 10 % quicklime addition was also observed by Amadi and Okeiyi [25] who found a reduction of swelling from 8.75 % to 0.4 % for clay-rich lateritic soil.

Concerning the cement treatment applied on Karal soils, Diop [26] mentioned the usual appearance of cracks in road layers containing clays with strong swelling properties. The origin of this phenomenon was attributed to the absence of lime addition (coupled with cement) that induces flocculation and pozzolanic reaction in clay-rich material. Considering the absence or the scarcity of carbonates (calcite or dolomite) extractable from quarries in some parts of the world especially in North Cameroun, as well as the high energy consumption to produce quicklime with high purity, the use of hydrated lime was considered in several regions. If the literature is abundant on soil treated with efficient quicklime, the soil stabilization with hydrated lime or lime with various degree of carbonation was rarely presented. Quicklime has a particular advantage compared to hydrated lime considering its ability to hydrate in situ in contact with the soil moisture producing heat, and then acting as a strong drying agent for soil. After quicklime hydration producing portlandite Ca(OH)<sub>2</sub>, such lime become similar to hydrated lime and both by Ca(OH)<sub>2</sub> dissolution provide the abundant Ca<sup>2+</sup> required to react with silica and alumina from clay dissolution in contact with alkalized water [27]. In usual case, a 1% quicklime addition is enough to lower the water content of a soil by 1% until 2–4 % in hot and windy season [28]. Indeed, the drop in water content depends strongly on the weather conditions during earthwork period. Amadi and Okeiyi [25] also showed the lowering of the optimum water content of soils treated with quicklime and against all expectations, an ‘almost’ similar effect with hydrated lime was mentioned. However, quicklime addition induced higher engineering properties such as soil strengthening compared to those developed by hydrated lime.

For many authors, the addition of 3% quicklime could be equivalent to 4% hydrated lime [29,30] and in countries with non availability of quicklime, hydrated lime appears as a interesting alternative. However, the coupling of cement and lime (especially hydrated lime) in mixed treatment for swelling soils was rarely explored with Karal soils. In order to favor the reuse of the swelling Karal soils, the present work aims to compare the effect of soil treatment using two different types of coupled to cement addition. The efficiency of treatments with various contents of additives was tested on a Karal, clay-rich soil collected in Pitoa, a locality in North Cameroon. After the physico-chemical characterization of the studied soil as well as its mineralogical description using X-ray diffraction, the changes in the Atterberg limits were described considering the amounts of additives in soil treatment. Then, the results of linear shrinkage measurement (or swelling reduction) as well as the soil mechanical behavior given by Proctor test (compaction behavior), the CBR test (showing the soil penetration resistance) and the Unconfined Compressive Stress measurement were discussed and correlated to the soil treatment parameters.

## 2. Materials and methods

### 2.1. Materials and preparation

#### 2.1.1. The tested Karal soil

A total of 1600 kg of black coloured Karal soil were sampled at 1 meter depth and packed in 50 kg plastic bags. The studied soil was collected in Pitoa municipality (N9°22'31.4" / E13°28'25.2") localized in Northern Region of Cameroon, not far from the national road as observed on Fig. 1. The site of collect localized with green star was close to the road portion where usual longitudinal cracks were observed as well as some cracking on soils on both sides of road. The site located near the Benue River corresponds to a plain mainly composed by alluvial deposits and conducive to the clays formation. The local climate corresponds to the tropical Sudanese type with a dry season lasting six months characterized by important irregularities.

#### 2.1.2. Cement

The cement supplied by the CIMENCAM Company located in Figuil in Northern Cameroon was a Multi X type Portland cement CEM II with a 32.5 MPa resistance class and with slow setting properties. This local manufacturer was chosen because of its proximity to

**Table 1**

Chemical compositions of quicklime QL, hydrated lime HL and cement C given by EDX probe (based on X-ray fluorescence principle) coupled with SEM observation in Fig. 2.

% atomic	Na	Mg	Al	Si	K	S	Ca	Fe	others
<b>Cement</b>	0.15	0.39	0.49	1.69	0.14	0.24	6.54	0.3	Trace of Y (0.05 %)
<b>Quicklime</b>	–	0.8	0.16	0.2	0.08	–	10.46	0.1	Trace of Cu (0.04 %) and Y or Os (0.1 %)
<b>Hydrated lime</b>	–	0.63	0.05	0.12	0.08	–	13.82	0.07	

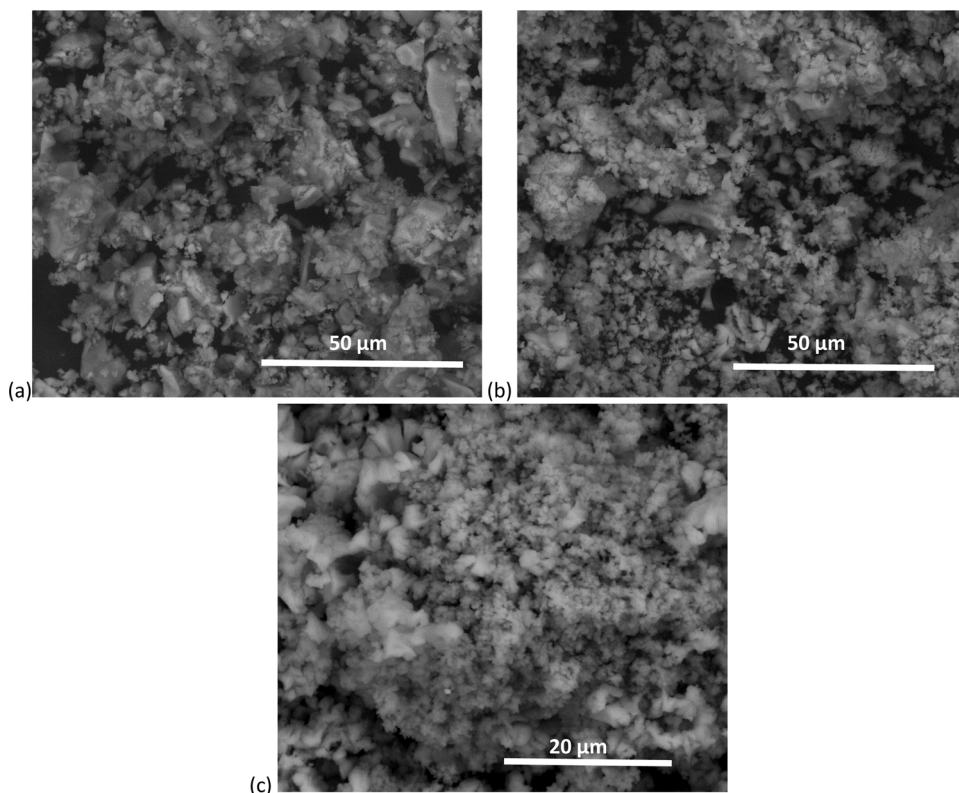
areas rich in Karal soil. The chemical composition of cement in Table 1 was given by local analysis by Energy Dispersive X-ray spectroscopy (EDX) coupled with environmental scanning electron microscopy (Env. SEM) used to observe the grain size of cement powder on Fig. 2. Images demonstrated that cement had a homogeneous chemical composition without pollutants such as heavy metals or iron-rich particles that should appear in white coloured among the uniform grey coloured calco-siliceous particles. The cement composition revealed the presence of calcium as major element (6.54 at%) followed by silicon (1.69 at%) while Mg, Al and Fe appeared with similar concentrations (around 0.3–0.5 at%). Such chemical composition reflected the geology of the local quarry. SEM observation confirmed also the fine grinding of cement particles from 1  $\mu\text{m}$  to 25  $\mu\text{m}$ .

X-ray diffraction pattern on cement powder (on Fig. 3) revealed the presence of quartz, calcite (remaining carbonates after calcination in the factory, additives of limestone and/or carbonated cement phases under  $\text{CO}_2$  during storage), C2S (cementitious phases), wollastonite and C3S as well as (Mg, Al, Fe) carbonate hydrates, biotite/mica (or illite/muscovite), clinocllore (chlorite type clay), kaolinite (remaining phases after calcination in the factory or added phase).

### 2.1.3. Lime

The two types of lime used in this study correspond to hydrated lime  $\text{Ca}(\text{OH})_2$  (hydrated lime or HL) and a lime called in this paper Quicklime (or QL) whose characteristics are not far from those met for hydrated lime according to NF EN 459-1 [31] standard. Both types were supplied by the company ROCA, located in Figuil near the CIMENCAM cement factory and was produced from the same mother calcareous rock. Considering the needs by building workers, the usual commercial production of lime concerns hydrated lime. Exceptionally, the so-called quicklime was produced on demand by the factory and appeared on bullets form with diameters of several millimetres to centimeter mixed with powder. Such heterogeneity in particle size was kept for soil treatment application because it was considered as representative of local products potentially used for soil treatment for road construction in Far North Cameroon. The fine fraction of HL lime coming from the industrial grinding of the bullets was composed by fine more or less aggregated particles as observed on Fig. 2(b). If the HL lime presented some particles from micrometer to 10  $\mu\text{m}$  with typical faces obtained after material fracture, the so called QL lime showed a very fine particle size distribution in Fig. 2(c) with mainly particles less than 5  $\mu\text{m}$ . Such fine particles size distribution allows a better coating of soil aggregates during treatment by mixing as well as its high efficiency and hydration speed in contact while water. At the opposite, the bigger size of partially carbonated HL lime particles played a role as a filler as explained in further paragraph.

After grounding and homogenization of particles and bullets, the HL lime appeared composed by portlandite  $\text{Ca}(\text{OH})_2$  (93 %) and calcite  $\text{CaCO}_3$  (7%). Carbonates may come from a partial calcination of calcareous rock in factory or a partial re-carbonation of initial



**Fig. 2.** Observation by environmental scanning electron microscopy (in backscattered electron mode at 20 kV) of materials as received and deposited on carbon scotch. (a) cement, (b) hydrated lime, (c) quicklime.

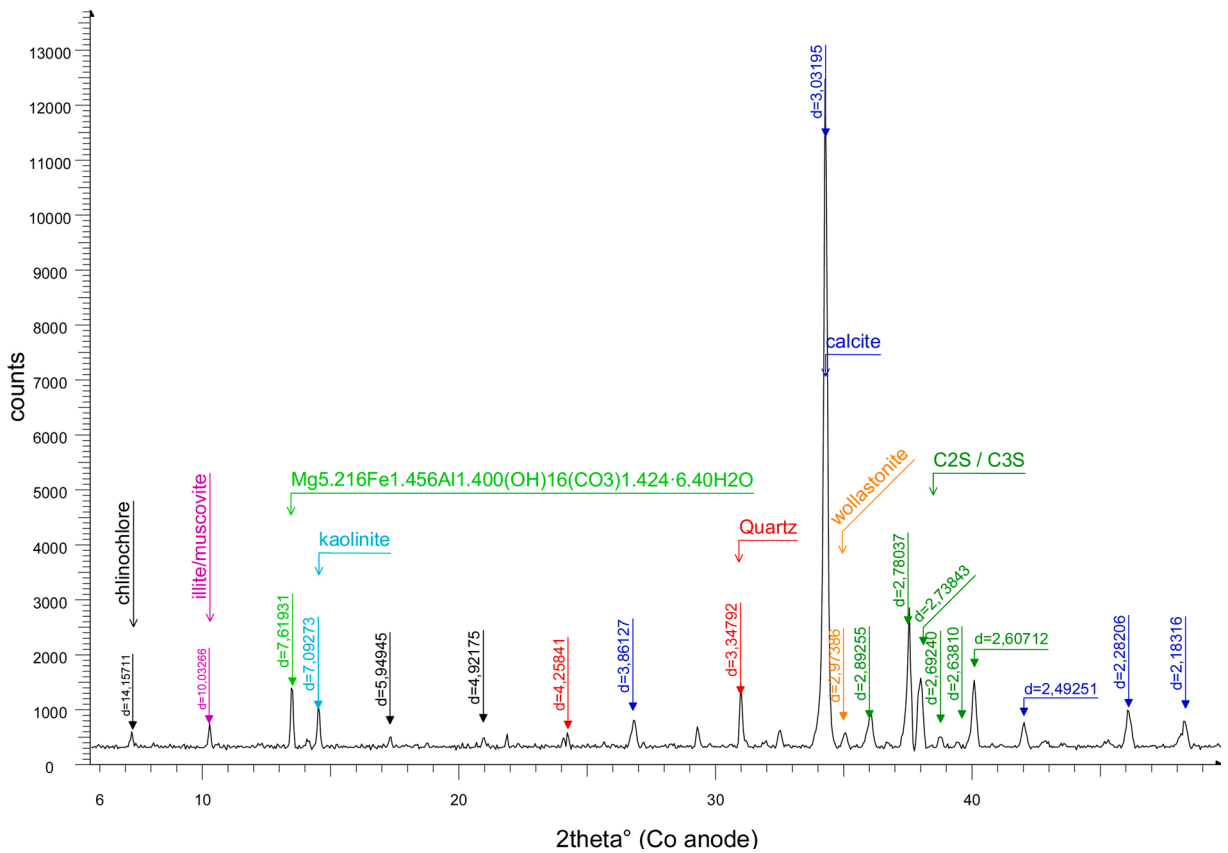


Fig. 3. X-ray diffraction pattern of powdered cement (after correction of the background).

portlandite under CO<sub>2</sub> in air (such phenomenon depends especially on the storage conditions). The chemical composition of hydrated lime given by local EDX measurement coupled with SEM in Table 1 confirmed the presence of Ca as main component with a 13.8 at%. Magnesium associated to carbonates remained very low with only 0.6 at% while all the other elements were under trace form with lower content than 0.1–0.2 at%

The QL lime used for tests in this study is composed mainly by portlandite Ca(OH)<sub>2</sub> with a low content in CaO (calcium oxide) and calcite CaCO<sub>3</sub> (< 3%). The potential of reactivity of QL lime was considered more elevated than the totally hydrated HL lime. A rapid test (ASTM D6276-99a [32] standard) of optimum lime dosage on studied Pitoa Karal soil confirmed a higher reactivity of QL lime compared to HL lime as shown on Fig. 4 above all at low content. From 5% of addition, both limes imposed a quite similar pH to the soil suspension. According to this method, a 5% of lime dosage should be an optimum value to reach a pH of 11.5, which seemed to be the

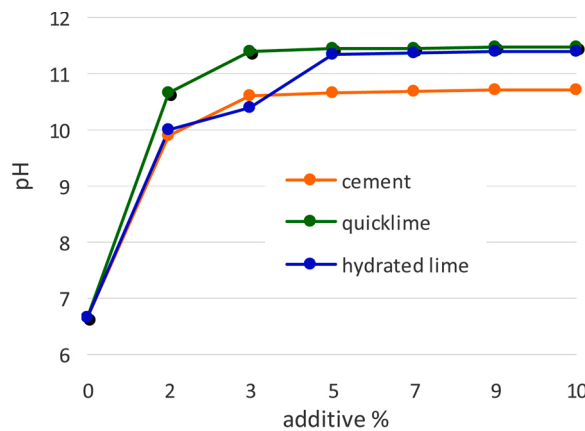


Fig. 4. The pH values tests according ASTM 6276-99a [32] standard, of suspensions composed by Pitoa Karal soil, water and various amounts of additives (cement, quicklime or hydrated lime).

maximum possible pH for these two limes. It is interesting to notice that between 2 and 5%, the quicklime is more efficient than the hydrated lime.

The optimum lime dosage was also determined using the Hill and Davidson [33]'s method. The minimum percentage  $L_m$  given by "lime fixation point" method is given by the empirical expression  $L_m = [\text{clay content} (< 2 \mu\text{m}) / 35] + 1.25$ . Considering the Pitoa Karal soil,  $L_m$  was equal to  $2.45 = \frac{\text{Clay content}(<2\mu\text{m})}{35} + 1.25 = 2.447$ . Considering the high efficiency of quicklime, a 2% quick lime addition was chosen while a 3% addition was selected for the hydrated lime.

## 2.2. Experimental methods

Prior to analysis, the Pitoa soil was oven dried for two days at 105 °C. After gentle manual grounding to pass through the 2 mm sieve (soil disaggregated more or less easily into powder form), the soil was sub-sampled using manual division method and stored in hermetic closed bags. Six lime/cement mixed treatments were selected. Then, a 3% hydrated lime was mixed with the soil and a 3, 5 or 7 % of cement C, respectively. Concerning quicklime with a higher reactivity, a 2% addition was mixed with soil and a 3, 5 or 7 % cement addition, respectively too.

The tests carried out in the laboratory on natural Karal soil concerned the particle size distribution, methylen blue value  $V_{bs}$ , cation exchange capacity CEC and organic matter content MO. The Atterberg limits (PL, LL, PI) as well as the Proctor test, the Californian Bearing Ratio (CBR) test and the Unconfined Compressive Strength UCS were applied on both natural and treated soils.

The particle size analysis used the sieving method according to the NF EN ISO 17892-4 [34] standard. The Atterberg limits were measured according to NF EN ISO 17892-12 [35] standard. The liquid limit (LL) was determined with the Casagrande cup, while the plasticity limit (PL) was assessed using the roll method. The Atterberg limits measurement on treated soils required the soil preparation: after the mixture of lime with the Pitoa soil and water, a 2 h30 rest in hermetic bag was applied before the cement powder incorporation. Mixtures were molded by compaction and cured 7 days prevented from drying. Then, pieces of treated soils were collected for standardized Atterberg limit.

The methylen blue absorption value  $V_{bs}$  was measured according to NF P 94-068 [36] standard. The method consists in adding a concentrated methylen blue solution to a soil suspension until the saturation of soil particles surface. As the clay fraction is characterized by the highest specific surface among the soil minerals, high  $V_{bs}$  are associated to clay-rich soils especially montmorillonitic soil. To complete the soil characterization, the natural water content was given by NF P 94-050 [37] standard whose principle consists in weighing the wet soil as taken on site and after its oven drying at 105 °C until a constant mass corresponding to the dry mass of material. The organic matter content was measured according to the NF P 94-055 [38] standard based on the reaction between soil and an oxidizer. The chemical analyzes by ICP-OES technique applied on totally dissolved soil after acid attack or alkaline fusion, and the mineralogical analyzes by X-ray diffraction on powder and oriented glass slides coupled with Rietveld quantitative method, completed the soil characterization. The loss on ignition at 1100 °C added to the chemical analysis represents the volatile part of sample after calcination (such as water and organic matter or other organic compounds composed by  $\text{CO}_2$ ).

The optimum water moisture  $w_{opt}$  and the maximum dry density  $\gamma_{d,max}$  of the untreated and treated Karal soils was established by applying the NF P94-093 [39] standard. The modified Proctor test (OPM) was applied instead of the normal Proctor test (OPN) following the recommendations formulated by CEBTP [40] for road construction and commonly used in sub-Saharan Africa. The value of optimum water content (at OPM) associated to each lime/cement treatment was applied to prepare compacted samples for the CBR test according to NF P94-078 [41] standard. For each treatment, the CBR values were collected on specimens prepared with a compacting energy corresponding to 10, 25 and 56 strokes, respectively. Before the application of a loading producing the penetration of a cylinder plunger into specimen at uniform speed (1.27 mm/min) until it reached a 2.5 and 5 mm depth, samples were immersed during 4 days to simulate the worst conditions on site. At the end of the specimen immersion and before penetration, the linear swellings of specimens were recorded too. In order to

Required criteria imposed by CEBTP [40]	
Platform	PI < 40
	LL < 70
	LS* < 2%
	MO < 3%
Subgrade layer	CBR > 5
	PI < 20
	F <80 $\mu\text{m}$ < 35%
Foundation layer	1.9 g/cm <sup>3</sup> < $\gamma_{d,max}$ < 2.1 g/cm <sup>3</sup>
	7% < $w_{opt}$ < 13 %
	CBR <sub>95%OPM</sub> > 30
	10% < F <80 $\mu\text{m}$ < 30%
	5 < PI < 20

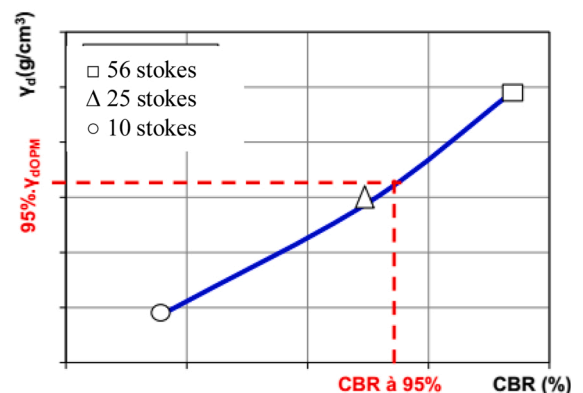


Fig. 5. The criteria imposed by the CEBTP guide [40] for road layers and graphic explaining the determination of  $\text{CBR}_{95\% \text{OPM}}$ . \*LS: linear swelling measured during immersed CBR test on sample compacted at 25 strokes.

compare CBR results to the criteria given by CEBTP [40] for foundation layer design, the CBR value for a compaction corresponding to 95 % of the OPM density was also determined graphically as described on Fig. 5.

The unconfined compressive strength (given by NF EN 13286-41 [42] standard) was applied in order to study the mechanical behavior of soil before and after various soil treatments. The soil samples were prepared at the optimum water moisture associated to each applied mixed treatments and then compacted into 8 per 16 cm specimens ( $H/D = 2$ ) for unconfined compressive strength tests. A static compaction with a hydraulic press was used to apply a controlled compaction speed of 0.02 mm/s to compact the soil to reach the maximum dry density of modified Proctor. After demolding, specimens were wrapped into plastic film and put in hermetic bag until test. The hardening of specimens during endogen cure was done at room temperature ( $20 \pm 2$  °C) and the mechanical performance were collected at 7, 28, 60 and 90 days, respectively. Concerning the determination of the unconfined compressive strength after a step of immersion, the specimens were submitted first to an endogen cure followed by a soaking in water to reach the equivalent total curing days of 7, 28 and 60 days. The curing periods corresponded to 3 + 4 days, 21 + 7 days and 28 + 32 days for respectively the endogen cure and the immersed cure. The Unconfined Compressive Strength (UCS) was given by the formula  $UCS = F_{c,max}/S$ , where  $F_{c,max}$  is the maximum load in compressive test and S the average cross-section area of the specimen.

### 3. Results

#### 3.1. Geotechnical and physical soil identification

The geotechnical and physical properties of the natural Karal soil from Pitoa are given in Table 2.

The Pitoa Karal soil sample presented a low gravel fraction (0.1 %) with a 6 % sandy fraction, a high fraction less than 63  $\mu\text{m}$  (93.9 %), and 41.9 % of < 2  $\mu\text{m}$  particles. According to Mouroux et al. [8], the soil could be classified among clays with a 2  $\mu\text{m}$  passing percentage higher than 30 %. The plasticity index and the methylen blue value equal to 31.1 and to 7.2 g/100 g, respectively, showed that the Pitoa Karal soil could be classified among plastic soil with high swelling properties according to Seed [9], with moderate one for Snethen [45], with moderate to high swelling according to the BRE [46] classification or with high to very high swelling properties if the Chen's classification [47] was applied.

The low natural moisture content ( $w_i = 8.4$  %) was correlated to the dry season of soil sampling. This value increases during the year depending of the rain frequency until high moisture content ( $w_{max} = 31.1$  % as shows on Fig. 6). The Karal soil presents not only a variable water content depending on the season, but also a high water retention capacity throughout the year which explains the ability to grow sorghum on Karal soils even during the dry season.

From the low CBR value equal to 0.66 and the high clay content (41.9 %) resulting in high swelling potential, the guide from CEBTP [40] concluded that it was not recommended to use Karal soils for pavement layers and that soil treatment before use is required.

#### 3.2. Chemical and mineralogical identification of Pitoa Karal soil

The X-ray diffraction pattern (XRD) of powdered Pitoa Karal soil is shown in Fig. 7. Pattern revealed in the natural Karal soil the presence of quartz (19 %), montmorillonite (15.6 %), illite/muscovite (5.6 %), and kaolinite (20.5 %) (or 26.6 % estimated from thermo-gravimetric analysis) with K-feldspars and Na-feldspars (10.5 %), anatase (1.6 %) and around 3% of amorphous phases usually assimilated to silica. The quantitative analysis given by Rietveld method with corundum addition showed a Rwp value equal to 6.22 (lower than 10) which validates the calculated amounts. The presence of such minerals has been also observed by other authors [2,3]. The oriented glass slide confirmed the presence of kaolinite with the disappearance of the peak at  $d = 7$  Å on calcined oriented glass slide while the (001) plan of illite/muscovite at  $d = 10$  Å didn't appeared probably because of a selective sedimentation in clay

**Table 2**  
Geotechnical and physical characteristics of the Pitoa Karal soil.

Standards	Parameters	Results
NF EN ISO 17892-12 [35]	Liquid limit LL	67.1
	Plasticity limit PL	36
	Plasticity index PI	31.1
	Gravel < 2 mm	0.1 %
NF EN ISO 17892-4 [34]	Sandy fraction 63 $\mu\text{m}$ - 2 mm	6%
	Silty fraction 2 - 63 $\mu\text{m}$	52 %
	Clay < 2 $\mu\text{m}$	41.9 %
NF P 94-068 [36]	V <sub>bs</sub>	7.2 g/100 g
NFX31-130 [43]	Cations exchange capacity CEC	107 g/100 g
NF P 94-050 [37]	Initial water content $w_i$	8.4 %
–	pH	6.65
NF P 94-055 [38]	Organic matter content (MO)	0.71 %
NF P 94 093 [39]	Optimum water content $w_{opt}$	17 %
NF P 94 078 [41]	Maximum dry density $\gamma_{d,max}$	1.66 t /m <sup>3</sup>
NF P11-300 [44]	CBR	0.66
	GTR class	A3
	HRB class	A-7-6(19)

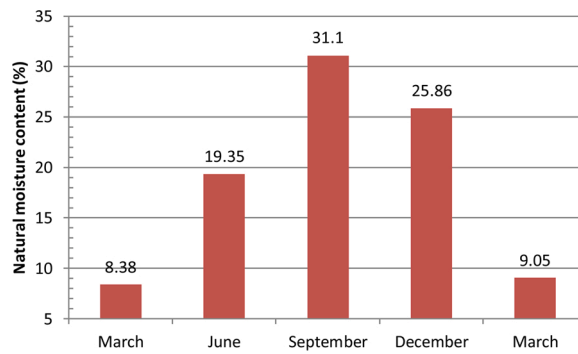


Fig. 6. Variation of the natural moisture content of Pitoa Karal soil during the year (test on natural soil samples collected on site at different periods of the year).

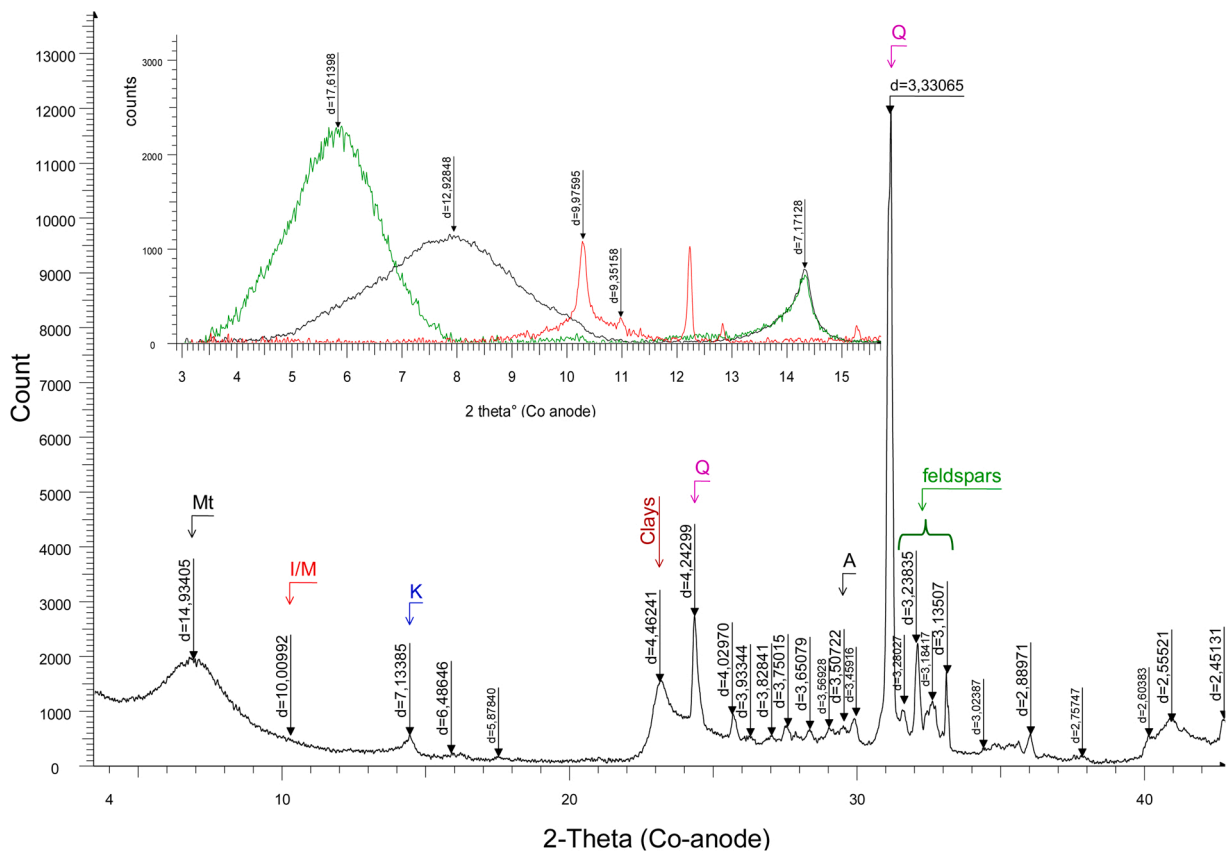


Fig. 7. X-ray diffraction pattern on powdered (< 80  $\mu\text{m}$ ) Pitoa Karal soil. Embedded figure corresponds to XRD patterns on oriented glass slides (OGS) obtained by the sedimentation of < 2  $\mu\text{m}$  suspension on glass slide after exchange with Na (in black: air dried OGS, in green: OGS after ethylene glycol treatment at 55  $^{\circ}\text{C}$  during one night, in red: OGS after burning at 550  $^{\circ}\text{C}$  during 2 h). Mt: montmorillonite; I/M: Illite/muscovite; K: kaolinite; Q: quartz; A: Anatase.

suspension that prevented the collect of the low dispersive illite/muscovite when the < 2  $\mu\text{m}$  fraction was extracted from soil. However, the presence of a high peak at  $d = 4.46 \text{ \AA}$  on powder XRD pattern confirmed the presence of such potassic clay. Finally, the large peak at  $d = 12.92 \text{ \AA}$  on air-dried glass slide was associated to montmorillonite (the position was specific Na-exchanged montmorillonite).

Such peak shifted toward higher  $d$  value (around 17.6  $\text{ \AA}$ ) after ethylene glycol contact, which demonstrated the ability of such clay type to swell. However, the required Na homoionisation of clay for freeing the crystalline swelling of clay suggested that natural compensating cations in clay interlayer fight against swelling in natural soil. The presence of iron in high amount (6.9 %) could hypothetically explain such result while no iron oxy-hydroxydes were clearly identified. Except iron, the chemical analysis of Karal soil

in Table 3 showed the presence of silicium and aluminum associated to the presence of quartz, clays and feldspars. A part of iron and magnesium entered in the montmorillonite composition. The amount of Na (0.89 %) related to Na-feldspars while the K amount referred to illite/muscovite and K-feldspars. Calcium such as a part of K and Na played the role of exchangeable cations in montmorillonite interlayer. The titanium amount (1.28 %) is related to anatase also observed on XRD powder pattern. The chemical composition as well as the loss on ignition LOI (from thermal analysis) and the cations exchange capacity (CEC) of 107 g/100 g agreed with the mineralogical composition.

### 3.3. Effect of mixed treatments on Atterberg limits

The lime/cement mixed treatment showed a clear effect on Atterberg limits (Liquid Limit LL, Plastic Limit PL and Plasticity Index PI). Concerning the plastic limit (PL), a strong reduction was observed on Fig. 8 when the cement percentage increased for both hydrated lime and quicklime additional treating agents. After 7 days curing, the Atterberg values of the treated Karal soil were strongly reduced (except for PL after a 3% cement addition with hydrated lime). It means globally that the soil mixture became less sensitive to water, due to the clay flocculation at particles aggregates scale and the partial cementation of particles considering the short time of curing. Oza et Gundaliya [48] observed also a 23.9 % decrease of PL after a cement dust/lime mixed treatment applied on a Black Cotton Soil from Rajko (India), similar to the tested Karal soil from physico-chemical and mechanical point of view. The liquid limit (LL) showed also a decrease, similarly to the Al-Rawas et al. [49] or Bourokba et al. [50]'s results obtained on soil treated with lone treatment (lime or cement). Whatever the protocol applied to measure the change of Atterberg limits after soil treatment (with or without a curing period after lime or cement addition), the Atterberg limits seemed globally to decrease.

In agreement with such observation, a significant reduction of the plasticity index was observed in Fig. 8 after the application of the mixed treatment whatever the cement quantities added. These results were confirmed by Al-Rawas et al. [49] or Oza et Gundaliya [48] on soil/cement, soil/lime or mixed treated soil, Khattab et al. [51] on lime/soil mixture and Phanikumar et al. [52] on lime and lime/cement treated soils. The decrease of PI that reached a minimum of 12.8 with a 2% QL lime addition remained higher than the decrease observed when HL lime was added. A higher efficiency of cation exchange between the natural Karal soil and the  $\text{Ca}^{2+}$  cations released by higher reactive QL lime may explained such result. At the opposite, the addition of cement over 3% had a small impact on the modification of the plastic index while LL and PL were slightly reduced for an addition higher than 5%. The LL and PL at 3% cement addition presented an unexpected behavior as no or small decrease compared to untreated soil, which could be attributed to the difficulty of measurement especially with the roll manufacture. The Portland cement also produced a  $\text{Ca}^{2+}$  release when the C2S and C3S phases dissolved during the cement hydration. So, a flocculation-aggregation of clays produced by cement hydration is possible [53,54] but such process seemed to impact similarly LL and PL producing an almost constant PI when the cement content increased.

### 3.4. Effect of mixed treatment on the compaction characteristics of mixtures

The Modified Proctor test produced curves in Fig. 9. Curves illustrated the short time effects of the mixed lime/cement treatment on the soil compaction characteristics and allowed to evaluate the optimum moisture content  $w_{\text{opt}}$  and the maximum dry density  $\gamma_{\text{d,max}}$  for Karal soil with or without treatment

The mixed treatment increased clearly the optimum moisture content from 17 % for natural soil to 18.2 % (20 %), 19.8 % (20.4 %) and 20.5 % (20.5 %) for soils with 3% hydrated lime (or 2% quicklime) and 3, 5, 7% cement additions, respectively. Curves of the optimum water content evolution versus the cement addition in Fig. 9a indicated that the  $w_{\text{opt}}$  was stabilized after a low quicklime addition, while the addition of increasing hydrated lime induced a continuous increase of  $w_{\text{opt}}$  not stabilized even after a 7% addition of cement. If the  $w_{\text{opt}}$  appeared similar after 7% QL or HL lime addition, the effect of quicklime remained more efficient at low cement content addition compared to hydrated lime, as observed previously on treated clay suspension in Fig. 4.

Not only the optimum water content increased with increasing cement addition, but also the maximum dry density  $\gamma_{\text{d,max}}$  of Karal soil. Such result disagreed with the usual trend of proctor parameters after treatment. While lime alone usually increases the  $w_{\text{opt}}$  and decreases the  $\gamma_{\text{d,max}}$ , the only cement addition produced no  $\gamma_{\text{d,max}}$  variation or its increase with a decreasing optimum water content. Only Bekki et al. [55] found similar results as in the present study. Indeed the values of  $w_{\text{opt}}$  and  $\gamma_{\text{d,max}}$  after a lime and/or cement treatment applied on a low plastic silt were higher than the ones for untreated soil.

More surprisingly in the present study, the quicklime addition produced a lower increase of the dry density compared to the hydrated lime addition. Indeed, the hydration process of quicklime not only rose the soil temperature which induced the consumption of soil water but also created a strong flocculation effect accompanied by the clay dissolution especially the montmorillonite. However, the protocol applied for proctor curve didn't impose a long curing before testing, which prevented the soil from the strengthening effect of CSH formation and  $\text{Ca}^{2+}$  effects on clay surfaces. Portlandite in both limes (initially present in hydrated lime or created after the quicklime or Portland cement hydration in contact with water) dissolved so slowly that the so-called flocculation effect is not enough efficient (as for a reactive lime) to create an intra-aggregates microporosity [56]. The flocculation that should transform the

**Table 3**

Chemical composition of Karal soil obtained from ICP/OES analysis. D.L.: detection limit. LOI: loss on ignition at 1100 °C.

Chemical composition	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	LOI	Tot
%	54.1	17.4	6.9	0.09	1.31	1.54	0.89	2.00	1.28	< D.L.	13.9	99.5

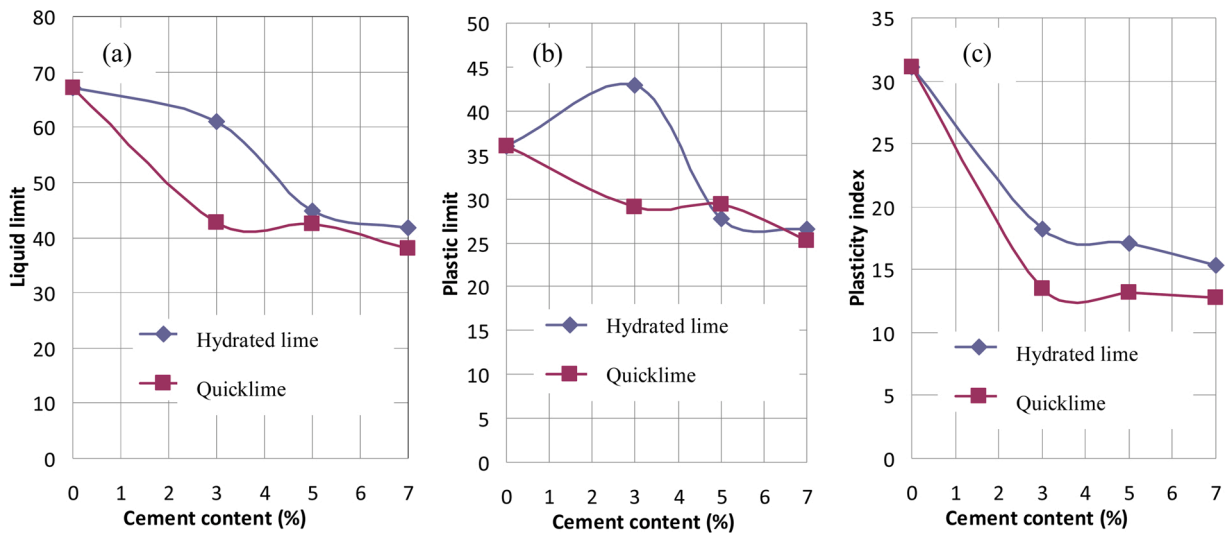


Fig. 8. Effect of mixed treatments on (a) the plastic limit, (b) the liquid limit and (c) the plasticity index of the Karal soil.

clay particle in contact with the  $\text{Ca}^{2+}$  leads usually to a decrease of the dry density, explained by the increasing of the microporosity in the aggregates. Such change of porosity should probably be stronger and faster (kinetic effect of a higher temperature) with a more reactive quicklime addition and less compensated by the cement addition. What we observe here can be explained with the role of an additive filler compared to the case of an active hydrated lime addition. Furthermore, hydrated lime was characterized by a lower purity compared to quicklime because of its higher content of fines grained carbonates whose size was estimated around the micrometer based on the observation on Fig. 2. Carbonates probably played also the role of filler as well as the cement particles whose hydration was low considering the lower  $w_{\text{opt}}$  of mixtures with hydrated lime. So the soil skeleton with 3% hydrated lime was supposed denser than with 2% quicklime due to a lower porosity after compaction, which explains the higher optimum dry density. The result of the Proctor test conducted with addition of lime and cement shows an increasing of the dry density well correlated to the amount of additive fillers, lime or cement. The more the hydraulic binders are added, the more the density increases because of the characteristics of the lime and cement we used in this study. This result is well correlated to the CBR tests as discussed below.

### 3.5. Effect of mixed treatment on the soil penetration resistance from CBR test

The Fig. 10 shows the effect of lime/cement mixed treatment on the CBR values at different compaction energies (corresponding to 10, 25 and 56 strokes) and after 4 days of immersion.

Whatever the treatment, the higher the compaction energy was, the higher the CBR values appeared as shown by Baana et al. [24]. This usual observed increase was attributed to the reduction of voids during compaction. Furthermore, the CBR values obtained at 95 % of the maximum dry density corresponding to Optimum Modified Proctor, clearly increased with the cement content added to the mixture containing quicklime or hydrated lime. The lower CBR value in the 3%HL + 3%C varied between 42.3 to 75.5 when the stokes number increased from 10 to 56 which represents a 78.5 % improvement. But the increase is only 32.9 % if the variation between 25 and 56 stokes was only considered. Such last rate of increase was closed to the rate measured after 3%HL + 5%C or 2%QL + 3%C treatment. It reached a rise of 47.9 % for 3%HL + 7%C, and 45.8 % for 2%QL + 5%C or 39.3 % for 2%QL + 7%C. The increase of the CBR value with the amount of hydraulic binder was well correlated to an increase of dry density after compaction. The addition of fine powder had a strong effect on the macroporosity, increasing the dry density by filling the voids and allowing a better placement of the particle and a better compaction. In fact, the more the soil was enriched with fine particles, the better the soil is compacted.

Now if the effects of HL and QL lime additions are compared, the quicklime treatment gave higher values of CBR by producing a more effective improvement of the penetration resistance compared to hydrated lime, even if the soil dry density (at very short term) appeared lower in presence of quicklime as observed on Proctor curve. In applied CBR test, the gradual formation of cementitious compounds during the four days of curing in immersed conditions [57] combined to the flocculation of clays produced by calcium from the  $\text{Ca}(\text{OH})_2$  dissolution contributed also to the enhancement of the soil bearing capacity. Considering the short time contact between additives and soil before the penetration step of the CBR test, the effect of pozzolanic reactions between clays and the released OH from the dissolution of the  $\text{Ca}(\text{OH})_2$  (brought by cement or lime), was considered as negligible. If a microporosity was promoted by quicklime addition, the strengthening by binding creation was also more efficient with QL lime considering its high and more rapid reactivity.

Moreover, the immersed conditions didn't limit the water content in samples that could reduce the ion mobility. So, the conditions allowed to be sure that all quicklime reacted. The compaction before penetration also induced a higher density inducing a voids decrease and consequently a higher saturation degree of the compacted soil. As the quantity of free water inside voids was not limited, the mineral dissolution required to create the binding phases such as hydrates was optimized.

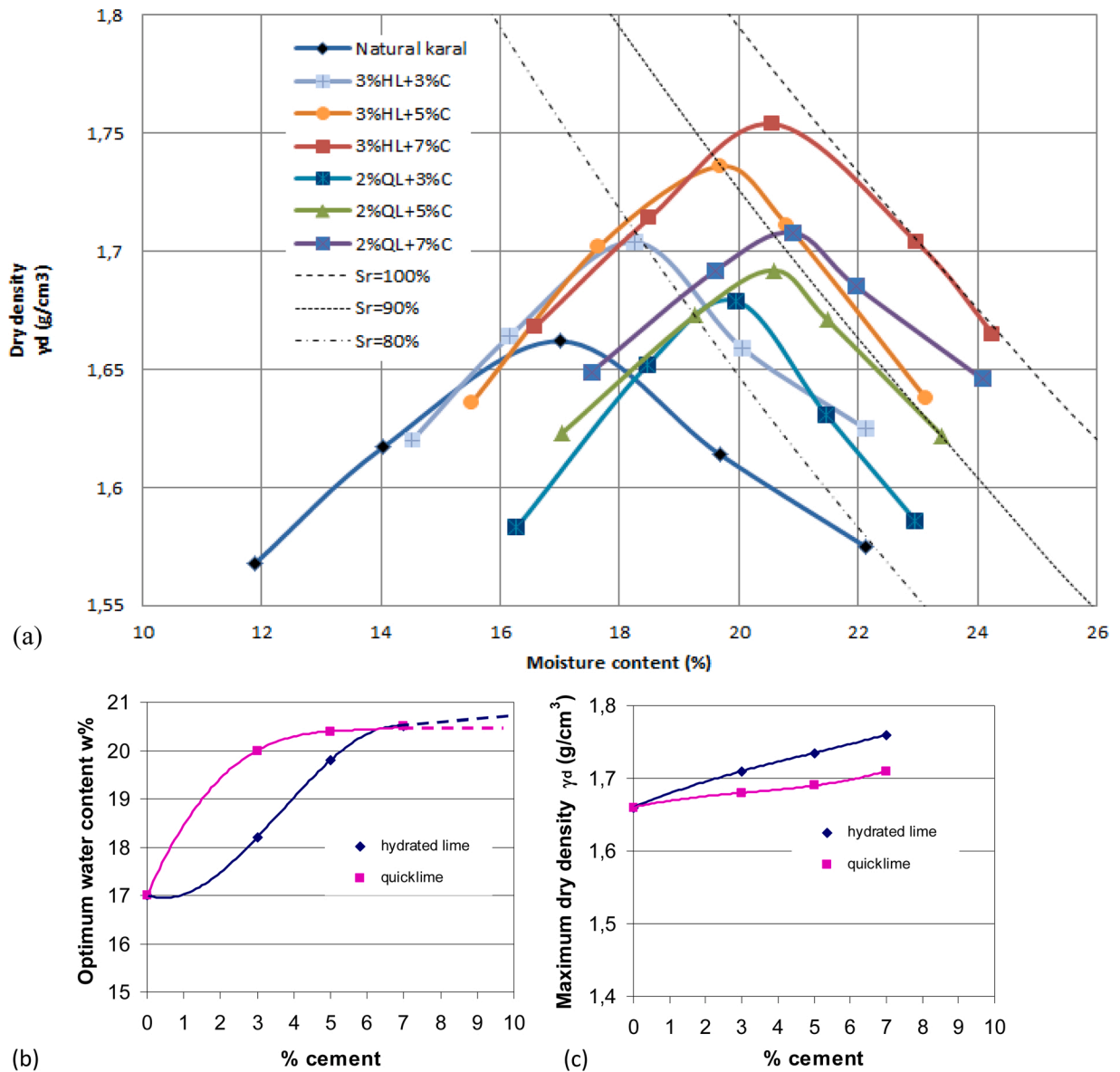


Fig. 9. (a) Effect of mixed treatments on the compaction characteristics of Pitoa Karal soil. The saturation curves were calculated with a particles density equal to 2.8 g/cm<sup>3</sup>. (b) The change of  $w_{opt}$ ,  $\gamma_{d,OPM}$  and (c) of  $\gamma_{d,max}$ ,  $\gamma_{d,OPM}$  versus the cement addition coupled with lime addition. The point at 0% cement content corresponds to the natural soil.

Compared to natural soil with almost zero CBR value (around 0.66) obtained at 95% of the Optimum Proctor Modified on Fig. 10b, the soil after 3%HL or 2%QL additions combined to 3% cement addition reached a 58.2 and 66 CBR values (in immersed conditions), respectively. If a 3% to 5% cement addition didn't change the CBR values at 95%  $\gamma_{OPM}$ , the additional amount of cement to the soil produced the CBR value enhancement. This non continuous increase of the CBR with the cement content could be associated to the filler effect of cement (above all at short curing time) combined to the void ratio in compacted soil at 95%  $\gamma_{OPM}$ . By increasing the cement content, the thickness of the cement coating around the soil aggregates (during the soil/cement/lime mixture) increased which promoted the formation of stronger cemented and connected skeleton. At low cement addition (until a particular content depending to the size of initial ground soil blocks corresponding in the present study to a  $D_{max} = 2$  mm), the cement didn't cover all the dispersed soil blocs or aggregates. Such image of the cement repartition at the soil aggregates surface may explain the shape of the curve with a plateau at low cement content.

Considering now the practice on site, the guide from CEBTP [40] imposes for road layers composed by natural soil, the conditions detailed in the table of the Fig. 5. Clearly, if the natural soil without treatment was unqualified, the soil after treatment became compatible with the threshold value of 30 for CBR<sub>95%OPM</sub>. This comparison remains only indicative because the CEBTP guide was not written for treated soils and a new guide should be produced for such type of soil associated the performance required for soil after

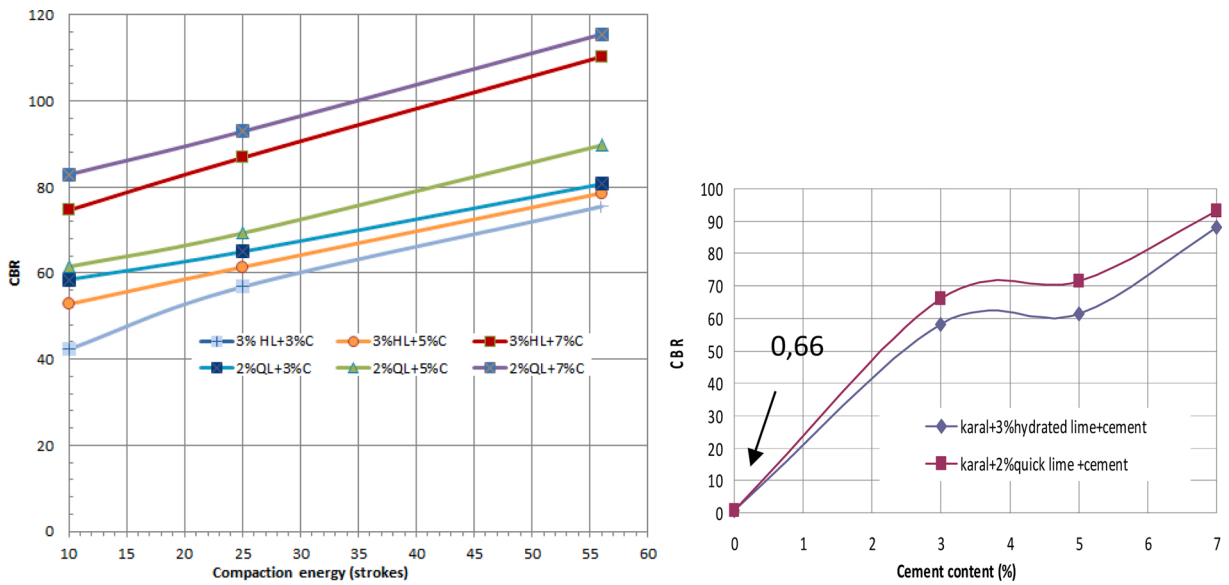


Fig. 10. (a) Effect of mixed treatment on CBR values for different compaction energies (b) CBR values obtained at 95 % of the  $\gamma_{OPM}$ .

treatment.

### 3.6. Effect of mixed treatments on the linear swelling

The effect of the lime/cement mixed treatment on the linear swelling measured on specimens during the CBR test appears on Fig. 11.

The swelling properties of the natural Karal soil decreased with the compaction energy from 9.1 % at 10 strokes, to 8.75 % at 25 strokes and 8.6 % at 56 strokes, similarly to the reduction measured by Baana [58]. The more compacted the soil was, the higher the dry density became and the lower the linear swelling appeared. Such results didn't agree with the common idea that a highly compacted sample with low density swells more compared to looser soil. Indeed, after compaction, the voids decrease and the swelling clay do no longer have enough space to swell locally in pore (at aggregate scale) without inducing a global swell at specimen scale. However, an increase of the dry density with the cement addition considered as a filler at short time contact (in other terms a decrease of voids) produced also a decrease in the vertical hydraulic conductivity [59,60]. In immersed CBR test, the water could only vertically and by gravity infiltrates the compacted soil. The results observed in Fig. 11 seemed in agreement with a hydraulic conductivity decrease.

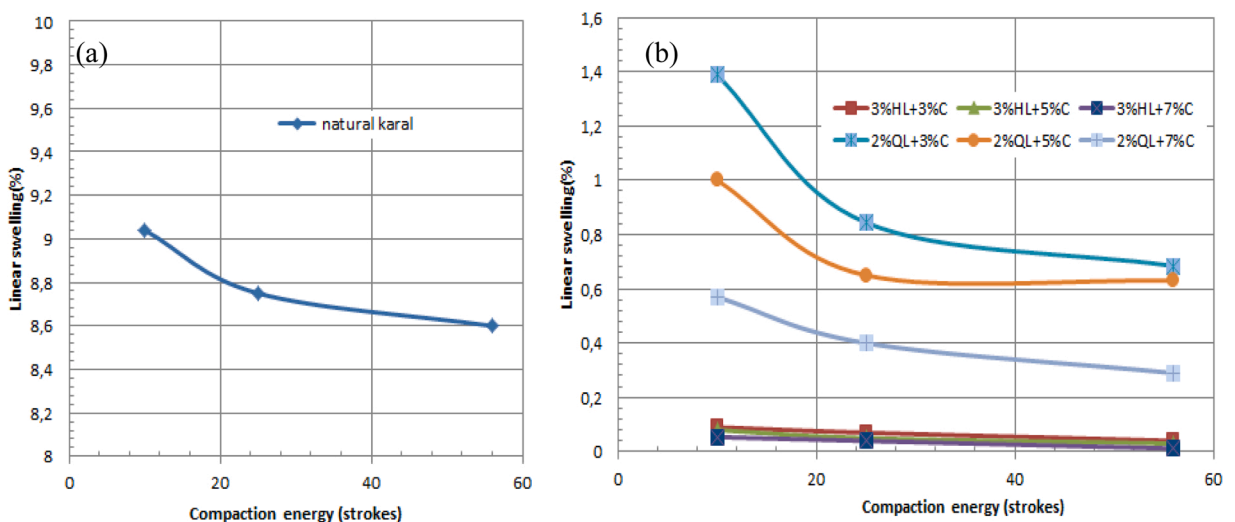


Fig. 11. Effect of compaction energy on the linear swelling of (a) the natural Karal soil compacted at  $w_{opt}$  and of (b) the mixed treated Karal soil compacted at  $w_{opt}$ .

In practice, the CBR values on natural soil higher than 2% were not acceptable considering the CEBTP [40] rules applied for the pavement layers construction. Fortunately, a strong reduction of swelling occurred after treatment. For treatments with hydrated lime whatever the cement content, the swelling properties were almost totally annihilated with linear shrinkage less than 0.1 % reaching 0.01 % at high compaction, in agreement to the observations made by Guettala et Guenfoud [61]. At the opposite, while quicklime induced a higher resistance to the penetration by soil strengthening, the linear shrinkage with such additive varied between 1.4 % and 0.3 % for low/high cement content and low/high compaction, respectively. Globally, the best results were obtained at low additives content and high compaction, preferentially with hydrated lime compared to quick lime. The stronger filler effect of hydrated lime compared to quicklime, resulting in a denser soil as observed on Proctor curve imposed a lower water penetration in specimen after a 4 days immersion and then to a lower swelling.

### 3.7. Effect of mixed treatment on the unconfined compressive strength (UCS)

The effect of lime/cement mixed treatment on the unconfined compressive strength (UCS) of Pitoa Karal soil is drawn on Fig. 12 after 7, 28, 60 and 90 days of curing. The UCS values increased with the addition of cement and with the curing time. The UCS values varied between 0.6 MPa and 2.6 MPa with a 3% hydrated lime addition combined with a 3% to 7% cement addition, which represented a 4.3 factor of improvement (FI). In comparison, the addition of quicklime in agreement with CBR test (at short curing time) induced higher UCS values that varied from 1.1 to 3.7 MPa corresponding to a 3.3 FI. Globally the curing time induced a more rapid increase of UCS value with quicklime especially at higher cement content. However, any of the growing tendencies reached a maximum effect (no stabilization of UCS) even after 90 days of cure and better properties were expected at longer curing time. Considering the rising tendencies drawn on Fig. 12 with a higher slope of the curves associated to quicklime, the UCS maximum should be achieved faster with quicklime lime compared to hydrated lime.

In term of trafficability criterion based on UCS value, the 1 MPa threshold was overspread from a 7 days curing for Pitoa Karal soil whatever the treatment except with 3%HL + 3%C corresponding to the lowest additives content that was tested and the less reactive lime. For such treatment, the trafficability criterion was obtained after a 26 days curing. In addition, a 2% of quicklime gave clearly better results than a 3% hydrated lime at long term (90 days) and high cement content (7%). However, some mixtures with 3% hydrated lime reached the performance of the 2% quicklime coupled with the lowest cement addition. The addition of higher quantities of less reactive lime (compensated by cement addition) could replace the use of quicklime but such choice should be validated based on technical efficiency, environmental parameters (energy consumption).

UCS results could be explained considering the long-term curing coupled to the hydration process of cement as well as the pozzolanic reaction of lime with the clay soil particles leading to the formation of cementitious products like CSH or CAH [56,62–64]. Both processes were responsible for the strength development even in presence of swelling clays known to degrade the efficiency of soil treatment. The lime addition with the Ca release reduced the swelling properties of clays while the cement supplied resistance by void filling and binding development especially with long curing time.

Concerning the effect of immersion on unconfined compressive strength (UCS), the UCS' values were collected in Table 4. The UCS'<sub>60</sub>/UCS<sub>60</sub> ratio allowed to estimate changes after immersion (UCS'<sub>60</sub> = UCS after 28 days of endogen curing followed by 32 days of immersion and UCS<sub>60</sub> = UCS after 60 days of endogen curing). In practice, according to the GTS/GTR approach [65] indicating the favorable conditions to obtain an immersion resistance, the UCS'<sub>60</sub>/UCS<sub>60</sub> ratio had to be higher than 0.6 or 0.8 for soils with Vbs < 0.5 g/100 g or Vbs ≤ 0.5 g/100 g.

As the Pitoa Karal soil Vbs was estimated to 7.2 g/100 g and considering that all the UCS'<sub>60</sub>/UCS<sub>60</sub> ratios of specimens treated with lime and cement given in Table 4 were higher than 0.6 (or very close to 0.6), the treated Karal soil whatever the treatment were considered as resistant to immersion. Such properties were essential considering the climate (see Fig. 6) in North Cameroon and for the design of sustainable platform.

## 4. Conclusion

The present work compared the effect on a Karal-type swelling soil of a mixed treatment composed by cement and two types of lime: a low carbonated hydrated lime and a second lime called "quicklime" which contained hydrated lime enriched by little CaO. Indeed, in order to favour the use of the swelling Karal soils in North Cameroon, a mixed treatment with hydrated or quicklime combined with cement addition demonstrated good performances. The tested soil as most of Karal soil in North Cameroon was identified as a plastic clays of low bearing capacity (the CBR at w<sub>opt</sub> was equal to 0.66 for soil from the Pitoa locality) with a medium to strong swelling due to the presence of montmorillonite combined to high water content variations considering the local climate. The use of mixed lime/cement treatment not only considerably reduced the swelling phenomenon (reduction of the linear swelling measured on CBR test and decrease of the soil plasticity index), but also increased the bearing capacity of soil (increase of the CBR value especially at high compaction rate and high additives contents). The lime/cement mixed treatment also increased the maximum dry density and the optimum moisture content of the Pitoa Karal soil as well as the unconfined compressive strength while producing a resistance to immersion considering patricians' rules.

After comparison of both limes, they showed a short time effects as observed on Proctor curves: after incorporating the lime and the cement, an increase of the dry density revealed that there was no short time effect for the treatment, few hours after incorporating the hydraulic binders. A lack of flocculation can explain an increasing of the density with the two tested limes. The amount of cement or lime only filled the macroporosity and has proportional effect on the dry density. Nevertheless, the Plasticity Index measured on the treated and compacted soil shows that the cohesive properties of the Karal are strongly reduced after 7 days curing. This shows that the

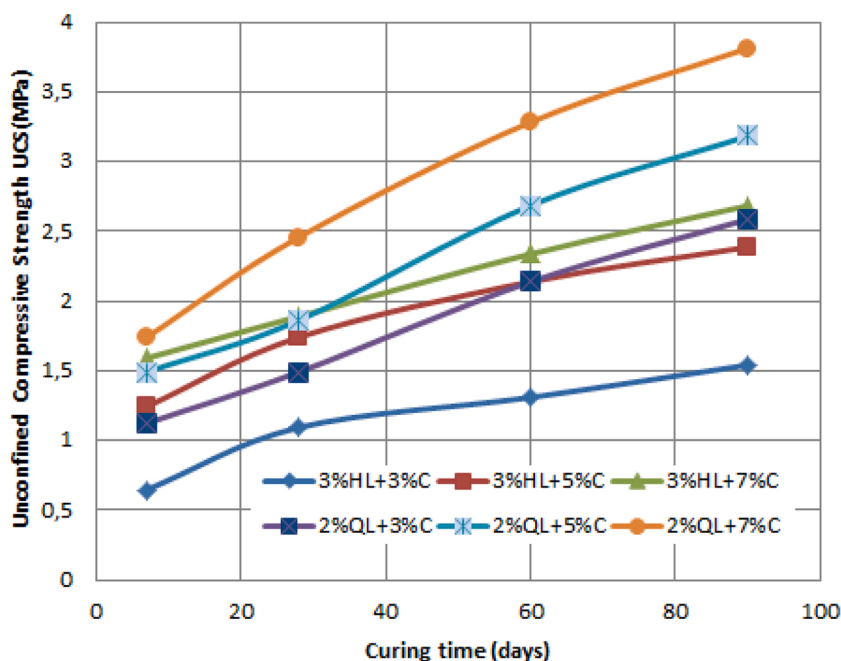


Fig. 12. Effect of mixed treatment on the unconfined compressive strength (UCS) of Pitoa Karal soil.

Table 4

UCS and UCS' values after treatments.

Parameters	Curing time (days)	3%HL +3%C	3%HL +5%C	3%HL +7%C	2%QL +3%C	2%QL +5%C	2%QL +7%C
UCS (MPa) (endogen cure)	7 d	0.64	1.24	1.59	1.12	1.49	1.74
	28 d	1.09	1.74	1.89	1.49	1.86	2.46
	60 d	1.31	2.14	2.34	2.14	2.68	3.28
	90 d	1.54	2.39	2.68	2.58	3.18	3.81
UCS' (MPa) (with endogen cure noted 'e' followed by soaking noted 's')	3 d <sub>e</sub> +4 d <sub>s</sub>	0.55	0.89	1.15	0.66	1.09	1.40
	21 d <sub>e</sub> +7 d <sub>s</sub>	0.89	1.19	1.79	0.99	1.39	2.19
	28 d <sub>e</sub> +32 d <sub>s</sub>	1.19	1.31	1.89	1.39	1.66	2.62
UCS' <sub>60</sub> / UCS <sub>60</sub>	-	0.91	0.61	0.81	0.65	0.62	0.80

lime (quick or hydrated) has a positive reaction with the swelling clay during this delay of 7 days curing. This is confirmed with the very good values of UCS obtained with both hydrated and quicklime. The so-called quicklime allows better results than the hydrated lime, with higher values and a better trend for the increasing of the UCS in the time, even if the dry density was lower and with lower contents than with the hydrated lime.

In practice, the coupled treatment made the soil suitable for traffic as soon as young age and normal curing for a designed road. The global results make us confident with a use in a capping layer, as done in other countries. The guide for using soils in Cameroon could be enriched with new practice if in situ tests could be used to validate such studies. However the durability of the treatment efficiency above all under repeated wetting-drying cycles should be demonstrated to validate the use of mixed treatment.

#### Declaration of Competing Interest

The authors report no declarations of interest.

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