Geological, geotechnical and mechanical characterization of charnockites – derived lateritic gravels from Southern Cameroon for road construction purposes

Caratérisation géomécanique des charnokites issues de graves latéritiques pour la construction routière des régions du Sud-Cameroun

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Abstract: Geological analyses have been associated to geotechnical and conventional mechanical tests to study charnockite – derived lateritic gravels from southern Cameroon for road construction purposes. The results show that the studied lateritic gravels consist of quartz (9 – 31 wt.%), kaolinite (15 – 28 wt.%), muscovite (13 – 30 wt.%), goethite (10 – 24wt.%), hematite (7.43 – 14 wt.%), gibbsite (9 – 16 wt.%), ilmenite (2.84 – 3.26 wt.%) and anatase (4.31 – 5.47 wt.%). These ferrugino–silico–aluminous materials are moderately to highly altered, averagely indurated and constituted of either "true" laterites, lateritic materials, or non lateritic materials, depending on the site. Values of the chemical index of alteration (98 – 100) and that of the relative potential index of lixiviation (77 – 94 %) consistent with the mineralogical determinations indicate that kaolinite is the only clay mineral in these materials, which excludes any swelling phenomenon. Geotechnical and mechanical tests conducted on these materials, present the investigated parameters in the following ranges: fine particles (16.20 – 44.10%), plasticity index (26 – 55%), Californian bearing ratio (31 – 68%), compressive strength (0.88 – 1.20 MPa), indirect tensile strength (0.07 – 0.15 MPa). Results of geotechnical and mechanical tests combined to that of geological analyses showed that in road construction, the studied lateritic gravels are suitable as sub–base layers for all volume traffic and, as base layers for low volume traffic. Nevertheless, one should be very cautious when (1) using silica/sesquioxide ratio, (2) deducting the swelling potential ε_s from clay fraction vs. plasticity index diagram or from the liquid limits and the percentage of fines. These relations are not verified with southern Cameroon lateritic gravel materials.

Keywords: Lateritic gravels, geological analyses, Geotechnical and mechanical tests, Road construction, Cameroon

Résumé: Geological analyses have been associated to geotechnical and conventional mechanical tests to study charnockite – derived lateritic gravels from southern Cameroon for road construction purposes. The results show that the studied lateritic gravels consist of quartz (9 – 31 wt.%), kaolinite (15 – 28 wt.%), muscovite (13 – 30 wt.%), goethite (10 – 24wt.%), hematite (7.43 – 14 wt.%), gibbsite (9 – 16 wt.%), ilmenite (2.84 – 3.26 wt.%) and anatase (4.31 – 5.47 wt.%). These ferrugino–silico–aluminous materials are moderately to highly altered, averagely indurated and constituted of either "true" laterites, lateritic materials, or non lateritic materials, depending on the site. Values of the chemical index of alteration (98 – 100) and that of the relative potential index of lixiviation (77 – 94 %) consistent with the mineralogical determinations indicate that kaolinite is the only clay mineral in these materials, which excludes any swelling phenomenon. Geotechnical and mechanical tests conducted on these materials, present the investigated parameters in the following ranges: fine particles (16.20 – 44.10%), plasticity index (26 – 55%), Californian bearing ratio (31 – 68%), compressive strength (0.88 – 1.20 MPa), indirect tensile strength (0.07 – 0.15 MPa). Results of geotechnical and mechanical tests combined to that of geological analyses showed that in road construction, the studied lateritic gravels are suitable as sub–base layers for all volume traffic and, as base layers for low volume traffic. Nevertheless, one should be very cautious when (1) using silica/sesquioxide ratio, (2) deducting the swelling potential ε_s from clay fraction vs. plasticity index diagram or from the liquid limits and the percentage of fines. These relations are not verified with southern Cameroon lateritic gravel materials.

1. INTRODUCTION

Cameroon, like other tropical countries has a huge resource of lateritic gravels. In sub–Saharian Africa, these materials are widely used in road construction as subbase or base layers naturally or cement improved material (Gidigasu, 1974; Bagarre, 1990; Nwaiwu et al., 2006; Adeyemi and Wahab, 2008; Millogo et al., 2008; Paige–Green et al., 2015). This is justified by their availability and an operability easier than that of certain crystalline formations (Sikali and Djalal, 1987; Meissa, 1993). Their use in road construction is based on grain size analyses, Atterberg limits, Modified Proctor and CBR tests (Lompo, 1980; Ekodeck, 1984; Bagarre, 1990; Millogo et al., 2008). However, it was found that lateritic gravels chosen solely on the basis of their geotechnical and mechanical properties poorly behaved when used as pavements (Tockol, 1993). Genetic features have considerable influence on geotechnical properties and on the behavior of these materials in pavement structures (Gidigasu, 1991). Given the evolving nature of lateritic gravels, some researchers have suggested to associate mineralogical and chemical analyzes to conventional geotechnical and mechanical tests for an efficient choice of road construction materials (Tockol, 1993; Adeyemi, 1995; Mahalinga–Iyer and William, 1997; Nzabakurikiza et al., 2012; Kamtchueng et al., 2015; Onana et al., 2015). In the southern Cameroon region, lateritic gravels are for the most part developed on charnockitic rocks. Geological, geotechnical and mechanical properties of these lateritic gravels in Cameroon are yet to be fully known.

The aim of this study is to assess the suitability of charnockites–derived lateritic gravels as raw material for road construction in order to improve the quality of the road network between Cameroon, ~~and~~ Equatorial Guinea, and Gabon. It is also aimed at increasing knowledge on Cameroon lateritic gravels.

2. RAW MATERIAL AND EXPERIMENTAL METHODS

The studied materials come from the alteration of charnockites of the Southern Cameroon region. The climate of this region is equatorial with rainfall varying between 1500 and 2000 mm per year. The average annual temperature is 24.4°C. The southern region is part of the South Cameroon plateau. Geological formations of Southern Cameroon region belong to the Ntem group inside the Congo craton (Bessoles et Trompette, 1980). The soils are ferrallitic, red or yellow, acid and highly desaturated (Vallerie, 1995). These soils are characterized by the presence of a very thick regolith, more or less thick indurated horizon and superficial clayey horizon essentially made up of kaolinite associated with hematite and goethite (Nguetnkam et al., 2006). The studied materials were collected in five (05) areas. In each area, 70 kg of material were taken on two or three road cuts for chemical and mineralogical analyzes and for geotechnical and mechanical testing. The colour was obtained using a Munsell soil color chart. The studied lateritic gravels are yellowish red (5YR 5/8), yellow 10 YR 8/8) or red (2.5YR 5/8). Their average operable thickness is 1.5 m (Fig. 2). Geological data were obtained by mineralogy and chemistry from materials dried in an oven at a temperature of 30°C. Raw materials have subsequently been ground at the Laboratory of Engineering Geology and Alterology of the University of Yaounde I (Cameroon). The mineralogical and chemical analyses were performed at the Geosciences laboratories (Geo Labs) at Sudbury (Canada). The X–ray diffraction patterns were obtained using a PAN Analytical X 'PERT PRO. The chemical composition was determined by X–ray fluorescence after sample ignition. Sample powders were ignited and then melted with lithium tetraborate flux before analysis using a PAN analytical Axios Advanced PW 4400. The dosage of the ferrous iron FeO was performed titrimetrically. A two-step loss of ignition (LOI or H_2O) determination was employed. Powders were first heated at 105°C under nitrogen to drive off adsorbed H_2O, before being ignited at 1000°C under oxygen to eliminate the remaining volatiles and oxidize Fe. The rock alteration parameters were determined using the OSCAR program (acronym of the French expression ‘‘Outils de Systématique et de Caractérisation Altérologique des Roches’’ ie Tool for Alterological Systematics and Characterization of Rocks of Ekodeck and Kamgang (2011). These parameters are the Relative Rock Virtual Weathering Degree (RRVWD), Relative Potential Lixiviation Index (RPLI), the Relative Potential Toughness Index (RPTI), potential Importance of Free Alumina (IFA) and potential Importance of free Ferric Iron (IFI).

Geotechnical and mechanical tests were carried out at the National Civil Engineering Laboratory of Cameroon (LABOGENIE). The determinations of specific gravity of the materials are those prescribed by the NF P 94 – 054 standards. The grain size analysis by dry sieving and sedimentation has been achieved according to NF P 94 – 56 and NF P 94 – 057 standards respectively. The liquid limit (LL) was measured using the Casagrande apparatus and the plasticity limit (PL) by squeezing and rolling a soil sample into an ellipsoidal mass till it reaches a thread of 3 mm thick. These tests were performed according to NF P 94 – 051 standards. The methylene blue value (MBV) characterizing the sample clay content was determined according to NF P 94 – 068 standard. The optimum moisture content (OMC) and the maximum dry density (MDD) were determined according to NF P 94 – 093 standard. The CBR test after 4 days soaking was achieved according to NF P 94 – 078 standards. The punching was achieved with a universal press type LaboTest coupled to a pressure gauge. The compressive strength test was performed by applying a vertical pressure on cylindrical specimens (diameter = 8 cm, height = 12.2 cm) compacted in the Duriez dilated mold and kept for 4, 7 and 28 days at room temperature (30°C) and, gradually increased until failure (NF P 94 – 420). The indirect tensile test was performed using the same principle as that of compression, except that, the specimen ~~is~~ was positioned transversely (NF P 94 – 422).

3. RESULTS AND DISCUSSION

3.1 Geological identification

The charnockites – derived lateritic gravels from southern Cameroon) are finer (1.5 m) than those derived from granites in western Cameroon (5 m) (Wouatong et al., 2013). Their mineralogical assemblage is made up of quartz (9.04 – 31.37 wt.%), kaolinite (15.23 – 27.66 wt.%), muscovite (13.19 – 30.21 wt.%), goethite (10.35 – 24.03 wt.%), hematite (7.43 – 14.87 wt.%), gibbsite (9.02 – 15.84 wt.%). Ilmenite (2.84 – 3.26 wt.%) appears only at Ngoulemakong, Ebolowa and Sangmelima sites, and anatase (4.31 – 5.47 wt.%) only in Djoum site. This mineralogical assemblage is usually found in this type of humid tropical climate materials (Nguetnkam et al., 2006; Kamgang Kabeyene et al., 2012). Moderate to high proportion of kaolinite (15.23 wt% – 27.66 wt.%) in the studied lateritic gravels is the result of intense alteration by hydrolysis of abundant feldspars observed in the charnockites. These kaolinite contents are lower than those obtained in eastern Cameroon (Kamgang et al., 2001). Bulk fractions are silico–ferrugino–aluminous while fine ones are silico–alumino–ferruginous. However, bulk fractions of E2, D1 and D2 samples are ferrugino–silico–aluminous. This is justified by high contents in ferric iron (39.52 – 42.26 wt.%) in these materials. Moderate to average concentrations of gibbsite (9.02 – 15.84 wt.%), goethite (10.35 – 24.03 wt.%) and hematite (7.43 – 14.87 wt.%) are due to ferromagesian mineral transformation by hydrolysis, and/or, degradation of the ancient ferruginous cuirasses overlying lateritic gravels. Similarly, values of the loss on ignition LOI which are ranging between 10 and 30 wt.%, show that the bulk fractions of these materials are more ferruginous than aluminous (Bohi, 2008). This ferruginous nature of the material is confirmed by the low quartz content (9.04 – 31.37 wt.%) and the predominance of goethite and hematite (12 – 36 wt.%) on gibbsite (0 – 16 wt.%). However, the toughness of these lateritic gravels remains average (35 < RPTI (%) < 55). The average amount of quartz (9.04 – 31.37 wt.%) comes directly from the parent rock and confirms that the studied lateritic gravels are moderately to highly altered (49 < RRVWD (%) < 66). Quartz, iron oxides and oxyhydroxides abundance in these materials improve their geomechanical properties (Bohi, 2008; Millogo et al., 2008). Values of the controversial silica/sesquioxides (S/R) ratio ranging between 0.97 and 3.52, indicate that the studied raw materials are of three types “true laterites” (S/R < 1.33), "lateritic materials" (S/R > 1.33) and "non lateritic materials" (S/R > 2). The mean value of S/R (1.90) less than < 2, according to the Brazilian specification (DNIT 098/2007) indicates that these materials are good for base layer. Values of the Chemical Index of Alteration (CIA) ranging between 98 and 100% and that of the relative potential index of lixiviation (RPLI) varying between 77 and 94%, suggest according respectively to Nesbitt and Young (1984) and Ekodeck et Kamgang (2011), the presence of kaolinite and gibbsite. This agrees with the mineralogy of the studied materials. The presence of kaolinite and the absence of smectite group minerals in these materials; which excludes any swelling phenomenon.

3.2 Geotechnical and mechanical characterization

The specific gravity values (2,69 – 2,89) indicate that these materials have good to excellent performance in road construction (Nwaiwu et al., 2006; De Graft Johnson et al., 1972 in Paige–Green et al., 2015). The grain size distribution curves of most of the studied samples fit within the particle size distribution specification envelope for base layer but not for sub–base layer specification envelope (Fig. 4) (CEBTP, 1984). Liquid limit values are higher than those obtained on granite – derived lateritic gravels (22 – 44 wt.%) from northern Nigeria (Chuka Osadebe et al., 2011). The position of the studied lateritic gravels samples in the Casagrande plasticity chart indicates the presence of clayey and highly plastic materials (Fig. 5). However, lateritic gravels from south eastern of Côte d'Ivoire are moderately clayey and plastic (Bohi, 2008). Weakly to moderately plastic lateritic gravel materials with low clay contents were found in northern Nigeria (Nwaiwu et al., 2006; Chuka Osadebe et al., 2011) and in southern Burkina Faso (Millogo et al., 2008). High degree of plasticity and ~~clayness~~ high clay content can be explained by the kaolinite contents of the studied raw materials (24.00 wt.%). Similarly, the low swelling potential ($\varepsilon_s \sim 0.024$) is consistent with the type of clay (kaolinite) contained in these materials. On the contrary, figure 6 and table 5 show that the studied samples have a high swelling potential despite the fact that swelling clay species such as smectites are absent from the mineralogical assemblage of the studied materials. Consequently, one should be very cautious when deducting the swelling potential ε_s from the plasticity index and clay fraction or from the liquid limit and the percentage of fines like in Djedid et al. (2001) and Millogo et al. (2008). These relations are not verified with southern Cameroon lateritic gravels. The average value of MBV (6.05g / 100g) indicates that they are clayey soils. The contribution of the plasticity of fines to the overall performance of the material, which depends on the fines proportion, is represented by derived parameters such as described by Charman (1988). These parameters have been suggested in the selection of materials for the construction of paved and unpaved roads sub–base and base layers in the tropics (Charman, 1988). The studied lateritic gravels have grading modulus (Gm) values varying between 1.46 and 2.57. This result indicates that these materials can be used as sub–base and base layers for low volume traffic roads ($< 0.3 \times 10^6$ esa). The average value of Gm (2.04) is in the range 1.65 – 2.70, required by the Brazilian standard DNIT 098/2007 for use as base layer. Skempton activity (Ac) average value is equal to 2.30. The studied lateritic gravels are thus of class 4. Materials of class 4 are known to be very active but kaolinite, the only clay mineral presents in the raw materials is not active. This is explained by the fact that the mineralogy of a material has very little influence on the activity coefficient. It is not the case with organic materials and the fraction above 2 µm (Pilot et al., 1970). Lateritic gravels from southern Cameroon materials cannot be used in base layer for all types of traffic due to their very high values of plasticity modulus (457 – 2226). In the equatorial zone, for paved roads, Pm ≤ 150 is recommended for base layer. However, for sub-base layer, only materials with Pm ≤ 500 can be used. Within the ten (10) studied samples, only Z1 meets the required specifications. According to AASTHO classification, the studied materials are of class A–2–7(0) or A–2–7(2). These materials have good performance in road construction. However, E1 (A–7–5(9)) and N2 (A–7–5(4)) materials have low to tolerable performance in road construction. These poor performances are linked to their high amount of fines (> 34%). The studied materials have an average MDD of 2.07. This value is higher than the minimum (1.90) recommended by DEGN (1987) for use in sub–base. The MDD value (2.07) is low compared to that (2.17) of southern Burkina Faso lateritic gravels (Millogo et al., 2008, 2012). However, the average amount of hematite contained in the studied materials (11.03 wt.%) is higher than that obtained in Burkina Faso (3 wt.%). These differences could be explained by the fact that Burkina Faso lateritic gravels are located in savanna and those of the southern Cameroon in forest. Therefore, geotechnical and geological properties of lateritic gravels overlying similar substrata differ depending on the biology (vegetation) and climate. The relative high amount of clays (kaolinite) and muscovite are indicative of the average degree of compactness of the lateritic gravels. The average optimum moisture content (11.79 %) is higher than that obtained in Burkina Faso (6.6 %) and lower than that of northern Nigeria (13.00 %) on granite-derived lateritic gravels. This is due to the abundance of the clay fraction in the studied materials (19.49 wt.%).

CBR is one of the most important criteria for the selection of natural gravel in road construction (Paige–Green et al., 2015). The CBR average value (42) is in the range of that normally encountered (53 ± 17) in Cameroon (Bagarre, 1990). This value is higher than that obtained by Chuka Osadebe et al. (2011) in Nigeria (36) and comparable to that obtained by Millogo et al. (2008). Minimum values of CBR at 95% MDD accepted for subbase and base layers for T3 traffic are 30 and 80 respectively (CEBTP, 1984). The studied materials are suitable for sub–base layers construction. Only the material S1 (CBR > 60) can be used as base layers for low volume traffic roads (CEBTP, 1984; DNIT 098/2007). This is in contradiction with the S/R ratio values. Therefore, one should be cautious when using this ratio for choosing a road construction material. Nkoumou et al. (2004) state that CBR values increase with the rise of ferric oxides contents and the drop of silica in Senegal. This is consistent with data obtained in lateritic gravels from southern Cameroon.

The mean compressive strength (Rc) values of the southern Cameroon lateritic gravels are 1.20, 1.04, 0.88 MPa respectively at 4, 7 and 28 days of cure. These values decrease with curing time (Fig. 7), except for E2 material and are lower than those obtained in Burkina Faso (1.26 MPa) and Cameroon (1.27 MPa), respectively on granites and gneiss (Millogo et al., 2008; Onana et al., 2015). The fact is due to the high clay contents of the studied lateritic gravels. Clays contribute to the decrease of compressive strength because of their high plasticity. Decreasing values of this parameter is due to the decrease of water content in the specimens with curing time. In contrast, for E2 sample which presents the highest clay content, water is retained in the specimen, causing Rc values increasing. The average compressive strength values are in the range 0.5 – 1.5 MPa presented by Messou (1980). The studied materials are thus suitable as sub–base layers.

The mean values of tensile strength (Rt) are 0.07, 0.09 and 0.15 MPa respectively at 4, 7 and 28 days of curing. These values below 0.2 MPa are consistent with the work of Bagarre (1990). The values of this parameter have two trends, increasing as a function of curing time (E2 and N1) and depleting in the other materials (Fig. 8). The average indirect tensile strength values at 4 days and 7 days of curing time are similar to those obtained in Burkina Faso (0.09 MPa) and Cameroon (0.08 MPa). Those values of Rt are lower than that at 28 days of cure (0.15 MPa).

4. CONCLUSION

The following conclusions can be drawn from the geological, geotechnical and mechanical characterization of charnockites–derived lateritic gravels from southern Cameroon.

a) The borrow pit of the studied yellow to yellowish and reddish lateritic gravels have 1.5 m of thickness, made up of kaolinite, quartz, muscovite, gibbsite, goethite, hematite, anatase and ilmenite. These ferrugino–silico–aluminous materials are moderately to highly altered, averagely indurated and constituted of either “true” laterites, lateritic materials, or non lateritic materials, depending on the site. Values of the chemical index of alteration and that of the relative potential index of lixiviation consistent with the mineralogical determinations indicate that kaolinite is the only clay mineral in these materials, which excludes any swelling phenomenon.

b) The studied lateritic gravels are clayey and highly plastic materials according to Casagrande plasticity chart. These high degree of plasticity and high clay content are due to the high kaolinite content. The low swelling potential of these materials is consistent with the presence of kaolinite. Consequently, one should be very cautious when deducting the swelling potential ε_s from clay fraction vs. plasticity index diagram or from the liquid limits and the percentage of fines. These relations are not verified with southern Cameroon lateritic gravel materials.

c) Southern Cameroon lateritic materials are clayey gravel (GC) or silty gravel (GM) of very low compressibility. These materials can be used as sub–base layers for all traffic volume and, as base layers only for low volume traffic in road construction.

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