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Geomechanical characterization of lateritic hardpans from Bamendjou (West-Cameroon)

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Abstract

This study reports on the physical, mechanical, mineralogical and geochemical analysis carried out on four lateritic hardpan specimens from quarries in the Bamendjou area in the Western Region of Cameroon using common prescribed procedures. The results indicate that values of the bulk density, specific gravity, total and open porosities are very variable from one specimen to another. Meanwhile, the value of the compressive strengths of both the dry and immersed specimens were also very variable from one specimen to another, with the F2 and F1 specimens having higher values than the A1 and A2 specimens. All the specimens immersed in water recorded lower compressive strengths than the dry specimens. The flexural strengths also varied from one sample to another, with the F2 specimen having the highest resistance. The X-ray diffraction patterns reveal that the major peaks were assigned to gibbsite, goethite, and hematite, while the minor peaks were assigned to kaolinite and anatase. The mineralogy and geochemistry influenced the physical and mechanical properties, with the iron rich specimens having higher values in both the physical and mechanical properties than the alumina rich specimens. The results of the compressive strengths obtained were higher than (1–4) MPa obtained in Burkina Faso and India where they have been using lateritic blocks for construction. Thus the hardpans of Bamendjou can also be exploited for building purposes conveniently.

Keywords: Bamendjou, Building purposes, Lateritic hardpans, Physical, Mechanical mineralogical, Geochemical characteristics

Introduction

Lateritic hardpans are residual products of the laterization process from the parent rock developed in humid, tropical and subtropical regions of the world having good drainage. The combination of certain pedogenetic factors such as precipitation, temperature, seasonal variation and land morphology leads to the development of a weathering mantle which results in the formation of hardpan horizons within the soil profile. Buchanan [1] was the first to identify and name this soil laterite from the latin word “later” meaning brick. Since it can be cut into bricks, it is often utilised as building stones in some tropical and subtropical regions of the world where it is readily available and it is economical compared to other natural stones [2]. In Cameroon, research on laterites and lateritic soil, started at the beginning of the twentieth century [3, 4] with many studies carried

out on laterite for mining purposes [5, 6] while for road construction [7, 8] have carried out some useful studies. However, very little work has been done on the utilization of the lateritic hardpans in masonry, meanwhile, in India and Burkina Faso, a good number of studies were carried out with the development of specifications for the use of lateritic hardpans in masonry [9–11]. In spite of the existence of many works related to the utilization of laterite for building applications in other areas of the world, there is no available information of similar utilization in Cameroon, in spite of its relative abundance in the country. Demographic pressure is now giving impetus to use non-conventional materials for building purposes and lateritic hardpans is among the plethora of these materials which can be utilized for sustainable construction practice. The Bamendjou vicinity contains one of the vast unexploited laterite deposits of Cameroon. It is therefore exigent to have relevant scientific knowledge of the characteristics of these hardpans if it is intended for building purposes.

Materials and methods

The site setting

The study area is located between longitudes 10°10' and 10°20' East and latitudes 5°20' and 5°30' North (Fig. 1). It belongs to Bamendjou subdivision which is located in the Hauts Plateaux Division of the West Region and has a surface area of 45 km². Geologically, Bamendjou falls within what is popularly referred to as the *Bamiléké* Plateau situated within the Western highlands of Cameroon and located in the central part of Cameroon Volcanic Line (CVL). In this region, the lateritic hardpans or duricrust were developed exclusively from the aphyric or porphyric basalts [12]. The vegetation is an anthropic savanna known as the Grassfield of Western Cameroon. The hydrography of the area shows a subparallel drainage pattern as shown in Fig. 2.

Materials and methods

Materials

The lateritic hardpans were obtained from three quarries located in Bamendjou as shown in Fig. 2. The Nkong-Kang (NK) quarry is located at an elevation of 1628 m at a latitude of 05° 21' 9" North and longitude 10° 08' 12" East. At this position the lateritic hardpans outcrop to the surface. The Nkong Dang (ND) is at an elevation 1633 m at a latitude of 05° 23' 22" North and longitude 10° 20' 14" East. The Nkong-T'honta (NT) quarry is located at an elevation of 1566 m at a latitude of 05° 22' 14" North and longitude 10° 20' 26" East. The specimens of each of the various lateritic hardpans obtained from the quarries are shown in Fig. 3. The lateritic blocks were hewn out with a combination of rudimentary equipment such as pick axes, shovels and an electric saw, after which they were then cut into blocks. Each of these blocks were rapped in cellophane paper then wax sealed and then rapped again with another layer of cellophane paper for transportation to the laboratory. In all four samples were collected, comprising two from Nkong-Kang (NK) quarry (A1 and F2) and one sample from each of the other quarries, Nkong-Dang (ND) and Nkong-T'honta (NT) which were labelled as (A2 and F1) respectively. Each of these were shipped to the Faculty of Applied Sciences of the University of Liege in Belgium, where they were further cut to the required sizes with the aid of diamond tipped saw.

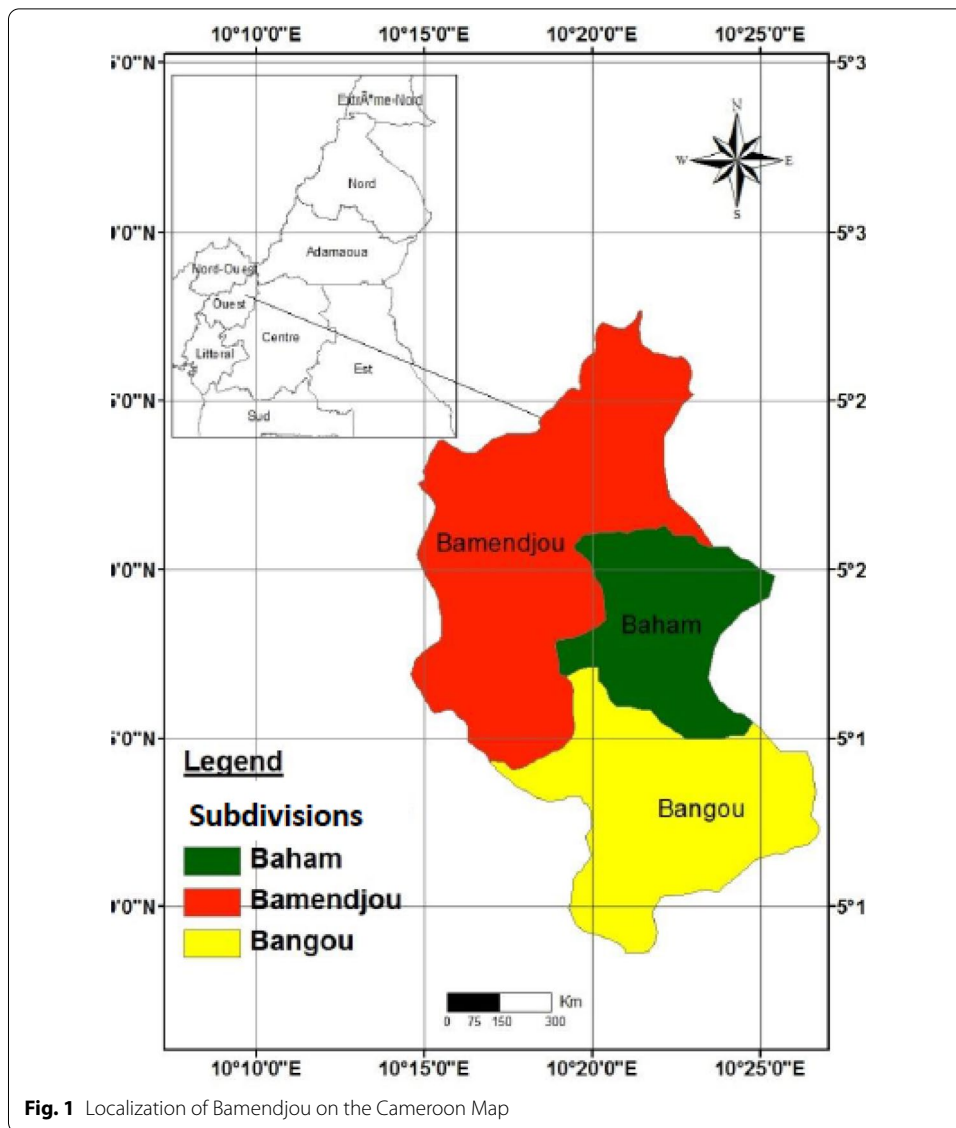


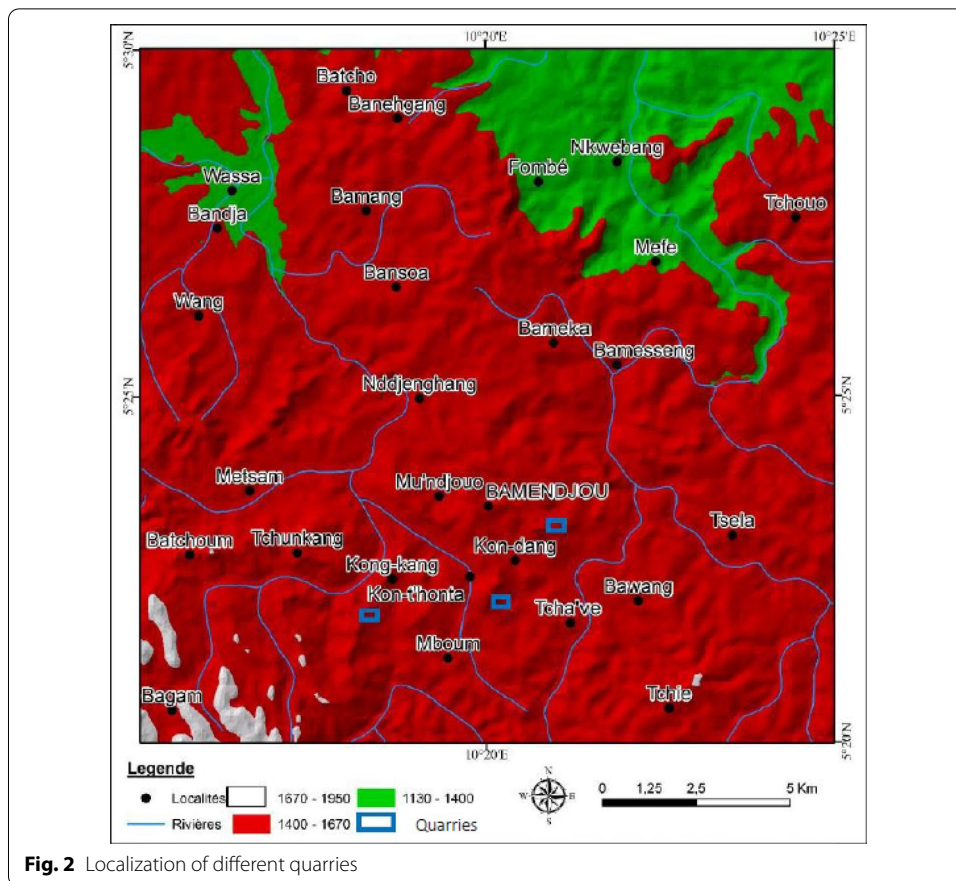
Fig. 1 Localization of Bamendjou on the Cameroon Map

Physical analysis

The following physical analysis were carried out on the specimens: water content, specific gravity, bulk density, total porosity, open porosity and the degree of saturation using different but prescribed techniques. The water content test was performed in accordance with the French standards NF P94-050 [13]. The specific gravity (G_s) was determined according to the standard NF EN ISO 8130-2 (2011) using the pycnometer with gas (Helium). The bulk density (ρ) and porosity (P_o) were calculated using the hydrostatic method in accordance with the EN 1936: [14] standard expressed as

$$\rho = \frac{m_0}{(m_s - m_h)} \rho_w \left(\text{g/m}^3 \right)$$

where " m_0 " is the dry weight of the specimen, " m_s " is the saturation weight, " m_h " is the hydrostatic weight (immersed in water) and " ρ_w " the density of water.



Total porosity (N), open porosity (N_0) and saturation ratio (S) were calculated as follows:

$$N = \left(\frac{G_s - \rho}{G_s} \right) * 100(\%)$$

$$N_0 = \left(\frac{m_s - m_0}{m_s - m_h} \right) * 100(\%)$$

$$S = \frac{N_0}{N} (\%)$$

Mechanical analysis

Compressive strength testing was performed on six specimens of dimensions 5 cm × 5 cm × 5 cm while flexural strength testing was carried out on specimens of dimensions 5 cm × 2.5 cm × 15 cm. Figure 4(a) shows the experimental set-up of the compressive testing device while Fig. 4(b) shows the flexural strength testing device and Fig. 4c–e are the various specimens to be tested. The compressive strength was performed on specimens that were dry as well as specimens that were immersed in water. The immersed samples were in water for 192 h after which they were air dried



Fig. 3 Samples of lateritic hardpans from the various quarries

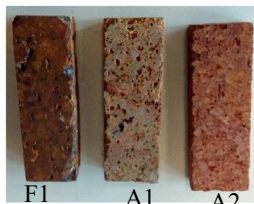
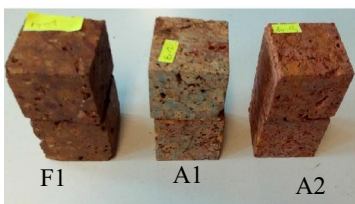
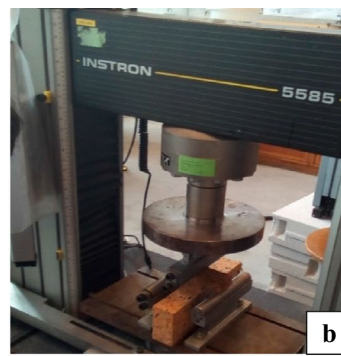


Fig. 4 **a** compressive strength device, **b** flexural strength device, **c-e** are the specimens for testing

for 48 ± 2 h (EN 13722 [15]) before testing, using a monoaxial compression method on an Instron 5585 universal testing machine, in accordance with the European norms EN 1926 [16]. The flexural strength was obtained using the same device as above, in accordance with the European norms EN 12372 [17].

Mineralogical and geochemical analyses

The mineralogical analysis was carried out by X-ray diffraction using the Bruker D8 Advance diffractometer. The crushed samples were scanned using monochromatic Cu K α radiation with 26 ranges of 2°–70° in steps of 0.020° operated at 40 kV and 25 mA using Cu-K α 1 radiation (I = 1.5406 Å). The interpretation of the mineral phases was carried out in accordance with [18] with the aid of the EVA software which contains a Powder Diffraction File for mineral identification.

Results and discussions

Physical properties

The results of the physical parameters determined in the laboratory comprising of the bulk density, specific gravity, natural water content, open and total porosity of the specimens are presented in Table 1. The values of the bulk density are very variable from one specimen to another ranging from 1.88 to 3.01 g/cm³. The specific gravity are also very high and variable from one quarry to another ranging from a value of 2.8 to 3.84. It was observed that the natural water content was very low in all the specimens as shown in Table 1. The porosity of a material, is a measure of the void or empty spaces available in a material. Two porosity terms are often utilized which are the total porosity and open porosity. In this study the both open and total porosity parameters of the specimens varied from one specimen to the other within the same quarry. Similar results were observed by Lawane et al. [19]; Vasquez et al. [20] and Kasthurba et al. [21] on blocks of laterites destined for construction purposes. The differences between values of total porosity may be due to differences in the porous system. The open porosity accounts for 30% to 63% of the total porosity resulting in the degree of saturation being much lower than 100%. This means that the material has a significant occluded porosity Brown [18]. Lawane et al. [19], reported that in laterites, occluded porosity plays an important role in the resistance of rocks as well as of its degradation, depending if the voids are connected or continuous.

Table 1 Mineralogical composition of the lateritic hardpans of Bamendjou

Quarry	Samples	Minerals (%)				
		Goethite	Hematite	Gibbsite	Anatase	Kaolinite
Nkong-Thonta	F1	60.96	6.90	16.66	1.94	13.54
Nkong-Kang	F2	13.13	48.04	26.66	2.37	6.79
	A1	10.45	1.53	81.58	3.69	2.58
Nkong-Ndang	A2	20.59	6.79	66.39	3.33	2.91

Table 2 Geochemical composition of the stone lateritic blocks of Bamendjou

Quarry	Samples	Geochemical elements										Total		
		Al ₂ O ₃	Fe ₂ O ₃	SiO ₂	TiO ₂	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅		SO ₃	LOI
Nkong-Thonta	F1	14.30	58.88	6.30	1.53	0.08	0.39	0.03	0.00	0.02	1.45	0.00	16.13	99.11
	F2	20.10	58.34	4.23	3.18	0.5	0.38	0.01	0.00	0.01	0.09	0.00	13.12	100.01
Nkong-Kang	A1	51.63	12.93	1.44	3.70	0.11	0.02	0.00	0.00	0.00	0.28	0.00	29.35	99.49
	A2	43.85	23.43	2.44	4.00	0.04	0.16	0.02	0.00	0.01	0.50	0.00	25.58	100.03

Mechanical properties

The results obtained from the uniaxial compressive strength tests and the three point flexural strength tests are presented in Table 2. The samples were tested dry as well as immersed in water. The values of the compressive strength tested dry as well as immersed were very variable from one specimen to another. The values of samples F2 (75.97 and 75.7) MPa and F1 (32.18 and 23.15) MPa, were very high compared with those of the specimen A1 (22.73 and 8.79) MPa and A2 (13.89 and 5.51) MPa. However, we also note very significant variables within the same specimen (Fig. 5a; b). The resistance of the specimens that were immersed in water decreased considerably in all the specimens except for the F2 specimens. The compressive strength of lateritic stone blocks (LBS) obtained in Burkina Faso and India gave strength values between 1.5–4.0 MPa [11, 21]. Meanwhile the European standards EN 777-1 [22] prescribes a minimum of 2.3 MPa for the compressive strength of bricks. Therefore all the specimens can be utilized safely for the construction of dwelling units since the minimum compressive strength of the hardpans tested dry was 13.89 MPa. The flexural strength also varied from one sample to another, with the F2 specimen having the highest resistance (15.51 MPa). The lowest value of flexural strength was observed in sample A1 (1.3 MPa). Moreover, we observe differences within the same specimen (Fig. 6). Both the results of the compressive and flexural strength showed some dispersion within the same quarry and from one specimen to another with very high standard deviations. Similar results were found by [9] in Burkina Faso.

The effect of immersion of the specimens in water on the durability of the material was evident when the compressive strength test was carried out. The results show that the compressive strength of specimens immersed in water decreased with the increase in water content.

Similar results were reported by [9, 10, 23]. A negative, but very strong and significant correlation was recorded between the compressive strength of the immersed specimens and the degree of saturation ($r = -0.90$). This means that when the degree of saturation increases, the compressive strength of the immersed specimens drops. In other words, the resistance decreases with the increase in the water content. The

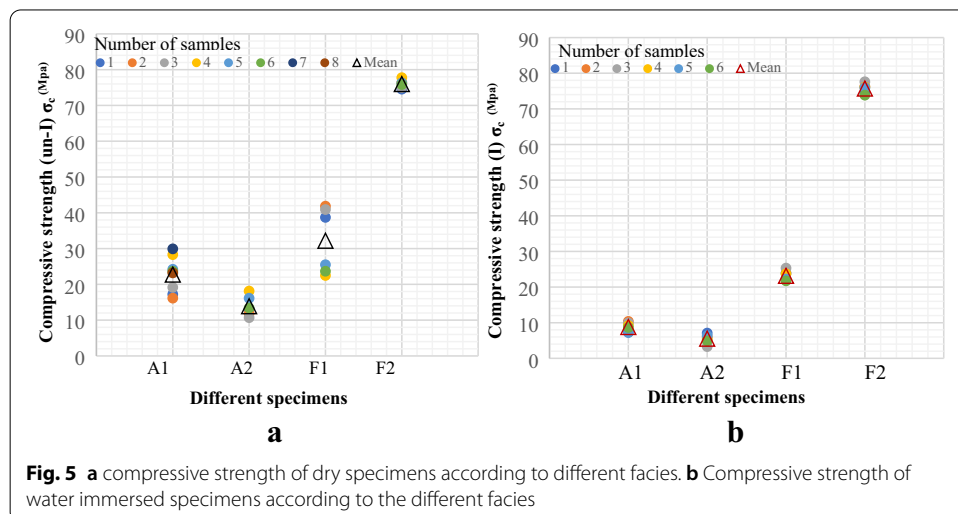
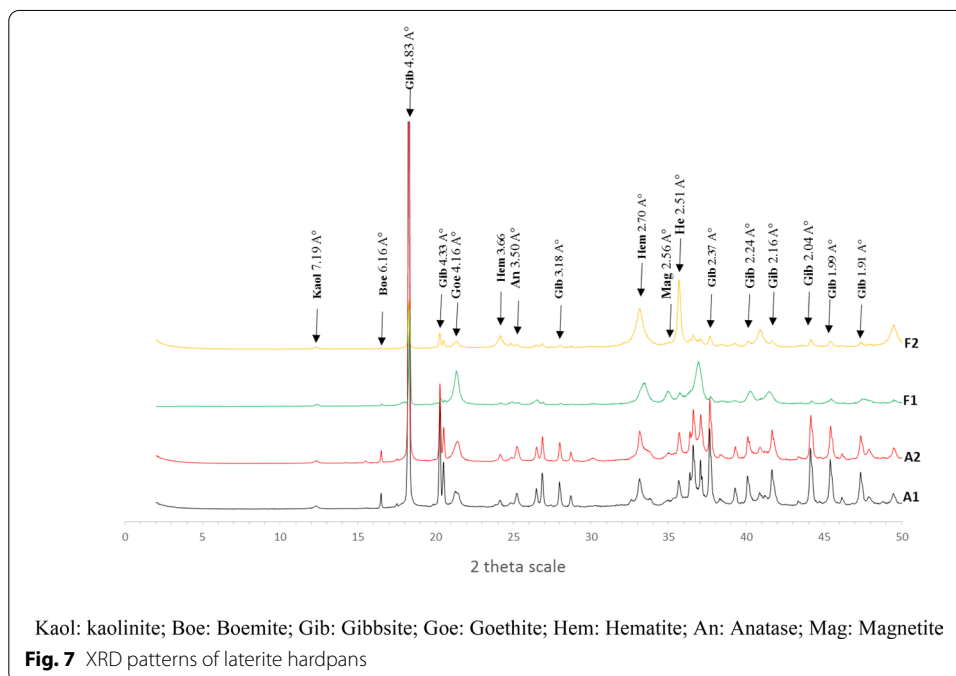
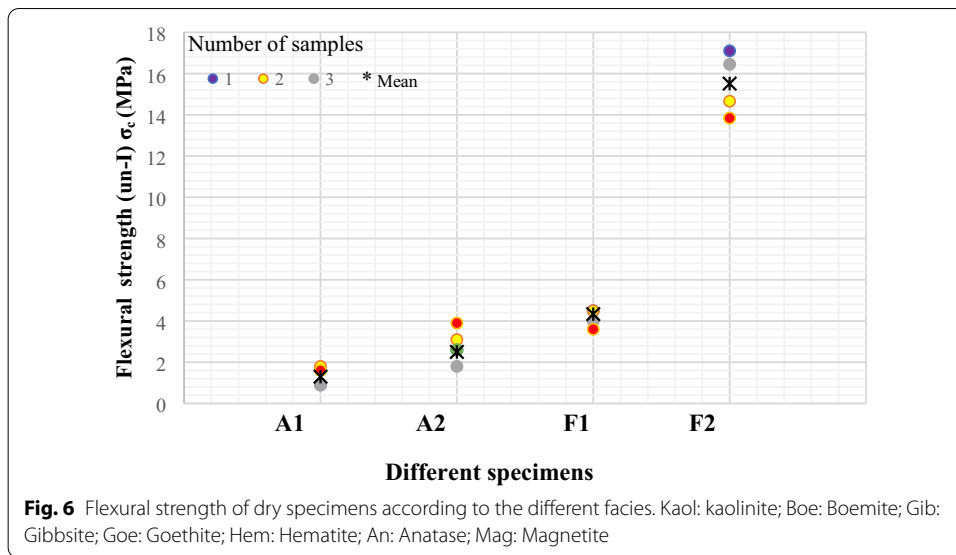


Fig. 5 a compressive strength of dry specimens according to different facies. b Compressive strength of water immersed specimens according to the different facies



only exception was with the F2 sample having a slight decrease, while the other samples present a remarkable reduction of resistance after immersion. The samples with high alumina content showed a drop in the compressive strength after immersion in water of between 60 and 61%. This could be due to the fact that the aluminous minerals are more hydrated than iron minerals [24] which would easily facilitate their hydration with water and subsequently decrease the material strength.

Table 3 Physical properties of the stone lateritic blocks of Bamendjou

Quarry	samples	Nbr	Parameters					
			P (g/cm ³)	Gs	W _w (%)	S (%)	N (%)	N _o (%)
Nkong-Thonta	F1	6	2.45 ± 0.01	3.69	1.17	54.16 ± 1.9	35.15 ± 1.11	19.04 ± 0.79
Nkong-Kang	F2	6	3.01 ± 0.04	3.84	1.12	30.4 ± 2.11	21.47 ± 1.11	6.57 ± 0.63
	A1	6	1.19 ± 0.02	2.8	0.4	52.08 ± 4.42	30.84 ± 0.7	16.06 ± 1.42
Nkong-Ndang	A2	6	1.88 ± 0.05	3.16	0.6	63.75 ± 1.01	37.48 ± 1.73	23.89 ± 1.20

Number of samples (Nbr)

Table 4 Mechanical properties of the lateritic hardpan specimens of Bamendjou

Quarry	Facies	Mechanical properties		
		State	Compressive (MPa)	Flexural (MPa)
Nkong-Thonta	F1	Un-Immersed	32.18 ± 9.20	04.33 ± 0.43
		Immersed	23.15 ± 1.40	
Nkong-Kang	F2	Un-Immersed	75.97 ± 1.13	15.51 ± 1.52
		Immersed	75.70 ± 1.35	
	A1	Un-Immersed	22.73 ± 4.96	01.30 ± 0.47
		Immersed	08.79 ± 1.30	
Nkong-Ndang	A2	Un-Immersed	13.89 ± 2.76	02.50 ± 0.69
		Immersed	05.51 ± 1.31	

Mineralogical and geochemical composition

The X-ray diffraction (XRD) patterns of the four lateritic hardpans from Bamendjou are presented in Fig. 7 while the mineralogical and geochemical characteristics are shown in Tables 3 and 4 respectively. It can be noted that all samples have their major peaks assigned to gibbsite (Gib), goethite (Goe), and hematite (Hem). The minor peaks were assigned to kaolinite (Kaol) and anatase (An). Goethite is the second most abundant mineral in these specimens, and represents 10.45 and 20.59% of minerals detected by X-ray. The results of the mineralogical analysis in Table 3 showed that lateritic hardpans exploited at three quarries in Bamendjou have significant proportions of iron oxide and hydroxide (goethite and hematite) and alumina (gibbsite). The A1 samples from the Nkong-Kang quarry and the A2 Nkong-Dang showed high levels of gibbsite (81.58% and 66.39% respectively), hence the high percentage of Al₂O₃ (51.63% and 43.85% respectively). On the other hand, F1 of the Nkong-Thonta quarry and F2 of Nkong-Kang have high Fe₂O₃ contents, resulting in 60.96% goethite and 48.04% hematite for the F1 and F2 samples, respectively. The high content in both the oxide and hydroxide is believed to be due to the humid tropical climate which occurs in the region which favors the allitization process. These hardpans have a different composition from the ones observed in Burkina Faso by Abhilash et al. [9] and in India by Kasthurba et al. [25]. The Al₂O₃ and Fe₂O₃ show opposing trends in the specimens while the SiO₂ and TiO₂ are almost constant as it is expected in most lateritic hardpans [4]. Meanwhile the following oxides P₂O₅, MnO, MgO and CaO were present only in small amounts. It was also observed that the geochemistry also influences the mechanical characteristics of the hardpans. For example the density and specific gravity though variable from from one

quarry to another clearly indicates that the specimens F2 and F1 which are iron rich have higher values than specimens A1 and A2 which are alumina rich. From the geochemical composition of the quarry it was also found that laterites which are rich in iron oxide were also less porous, and are therefore more resistant. A positive, strong and significant correlation was recorded between dry compressive strength and the level of iron ($r = +0.72$). The reverse was observed between dry compressive strength and total porosity ($r = -0.90$). While within the same quarry, the geochemical composition and porosity vary considerably. This could also explain the variation of resistance in Nkong-Kang quarry. In addition to the iron content, the mineralogical composition associated with low porosity is a very important factor. This could also be the difference between F1 and F2 specimens, because both contain the same value of iron oxide (58%), but the difference in mineralogical composition (F1 is rich in goethite 60.96% and F2 in 48.04% hematite). The hardness of goethite ($\text{FeO}(\text{OH})$) is 5–4.5, hematite (Fe_2O_3) is 5.5–6.5, gibbsite $\text{Al}(\text{OH})_3$ is 3.0 and kaolinite ($\text{Al}_4[\text{Si}_4\text{O}_{10}](\text{OH})_8$) is 2–2.5 [21, 26]. Linear correlations were established between natural compressive strength and hematite ($R^2 = 0.91$). The variation in strength of Bamendjou laterite suggests the need for a development of a suitable classification system for building applications similar to that adopted in the case of lateritic stone blocks (LBS) based on the strength requirements as given in Burkina Faso by Lawane et al. [19].

Correlation between the various parameters

The correlation between the mechanical and physical properties, then mineralogical and geochemical parameters is given by the Pearson coefficient shown in Table 5.

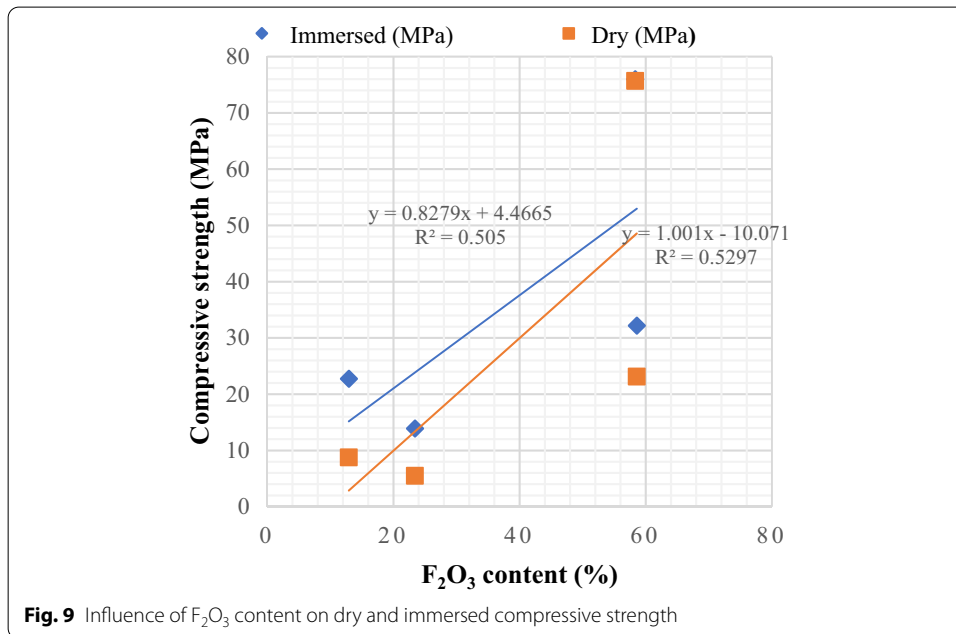
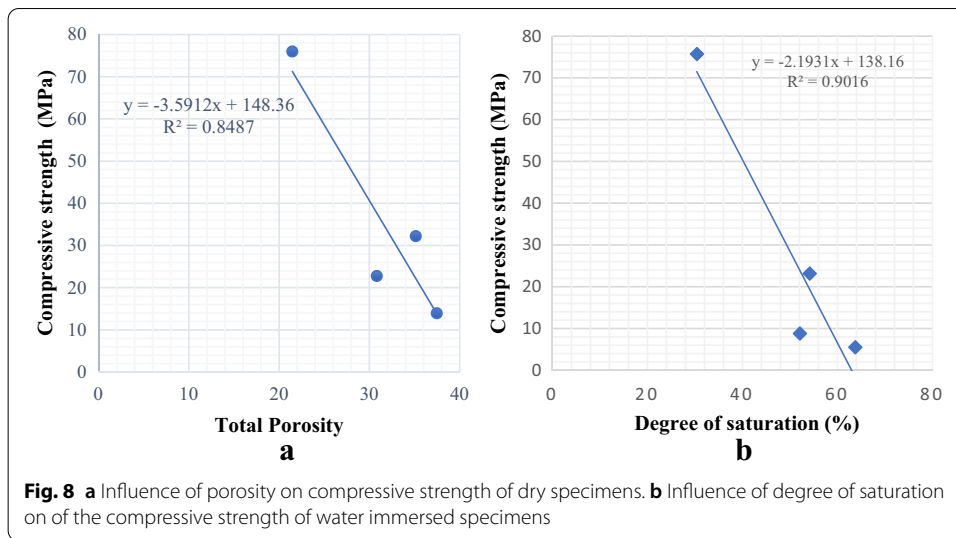
It is deduced from this table that

- A very negative correlation was found between the total porosity and the dry compressive strength ($r = -0.90$) at a significant threshold of $p < 0.05$. Similarly, strong negative correlations were obtained for the water immersed compressive strength ($r = -0.89$), and flexural strength ($r = -0.84$).
- A very negative correlation was found between the saturation ratio and the immersed compressive strength ($r = -0.94$) at a significant threshold of $p < 0.05$.
- A positive strong correlation was found between Fe_2O_3 and the dry compressive strength ($r = +0.72$) at a significant threshold of $p < 0.05$. Similarly, strong positive correlations were obtained for the water immersed compressive strength ($r = +0.69$), and flexural strength ($r = +0.70$).
- A negative strong correlation was found between Al_2O_3 and the dry compressive strength ($r = -0.64$) at a significant threshold of $p < 0.05$. Similarly, strong positive cor-

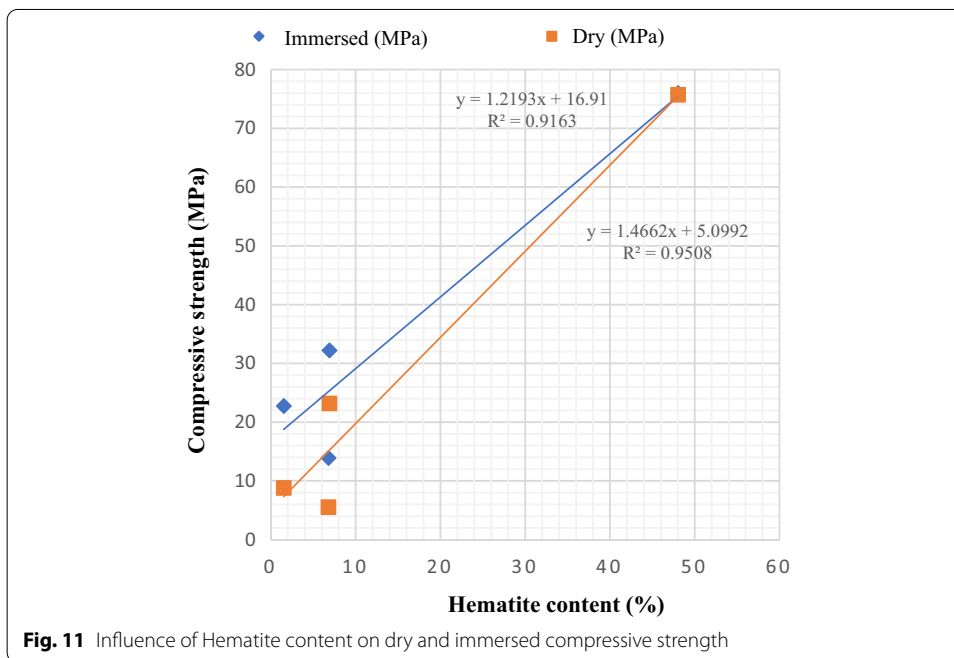
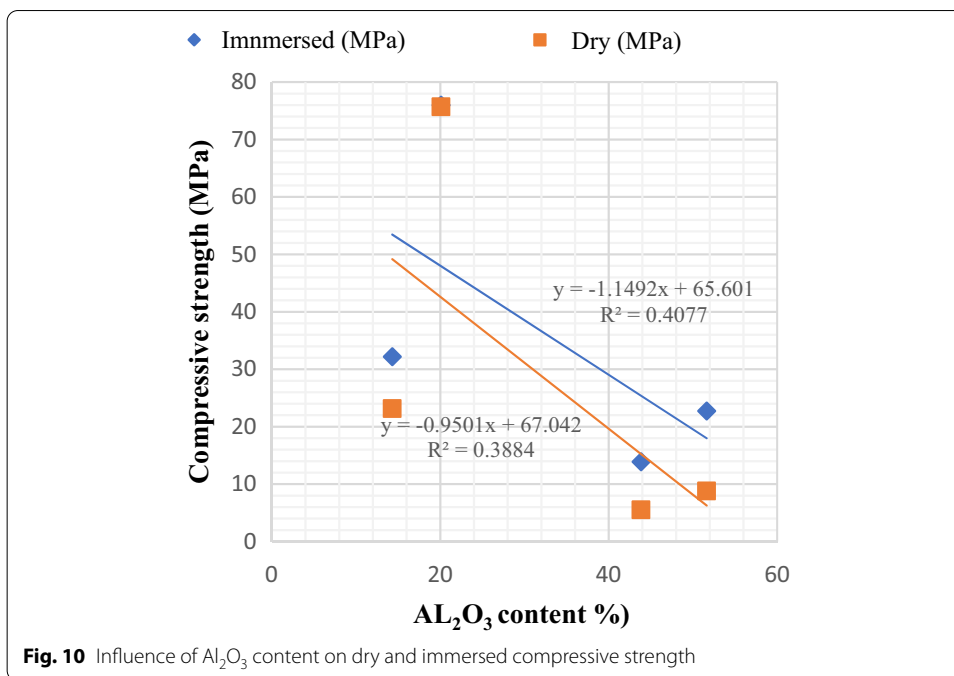
Table 5 Matrix of correlation between different parameters

Parameters	Total porosity	Saturation ratio	Fe_2O_3	Al_2O_3	Hematite
Mechanical properties					
Natural compressive strength	$r = (-0.90^b)$		$r = (+0.72^b)$	$r = (-0.64^b)$	$r = (+0.94^b)$
Saturated compressive strength	$r = (-0.89^b)$	$r = (-0.94^b)$	$r = (+0.69^b)$	$r = (-0.61^a)$	$r = (+0.97^b)$
Flexural strength	$r = (-0.84^b)$		$r = (+0.70^b)$	$r = (-0.66^a)$	$r = (+0.99^b)$

R, Coefficient of correlation; ^athreshold of significance ($p > 0.01$); ^bthreshold of significance ($p > 0.05$)



relations were obtained for the water immersed compressive strength ($r = -0.61$), and flexural strength ($r = -0.60$) at a significant threshold of $p < 0.01$. And finally, a positive strong correlation was found between Hematite and the dry compressive strength ($r = +0.94$) at a significant threshold of $p < 0.05$. Also, strong positive correlations were obtained for the water immersed compressive strength ($r = +0.97$), and flexural strength ($r = +0.99$).



The influence of the physical, mineralogical and geochemical properties on the mechanical properties

The influence of the physical, geochemical and mineralogical properties on the mechanical properties are shown in Figs. 8, 9, 10 and 11. It comes out from these figures that except for the lines from the Fig. 8 and 10, all the other figures present linear lines of average relationship with negative slope.

Table 6 Resistance of material lost after saturation and gibbsite content

Characteristics (%)	Specimens			
	A1	A2	F1	F2
Loss in resistance after immersion	13.94	8.38	9.03	0.27
Percentage loss in resistance after immersion (%)	61.32	60.00	28.60	0.35
Total porosity	30.84	37.48	35.15	21.47
Open porosity	16.09	23.89	19.04	6.57
Hematite (%)	6.79	1.53	6.9	48.04
Gibbsite level (%)	81.58	66.39	16.63	26.66

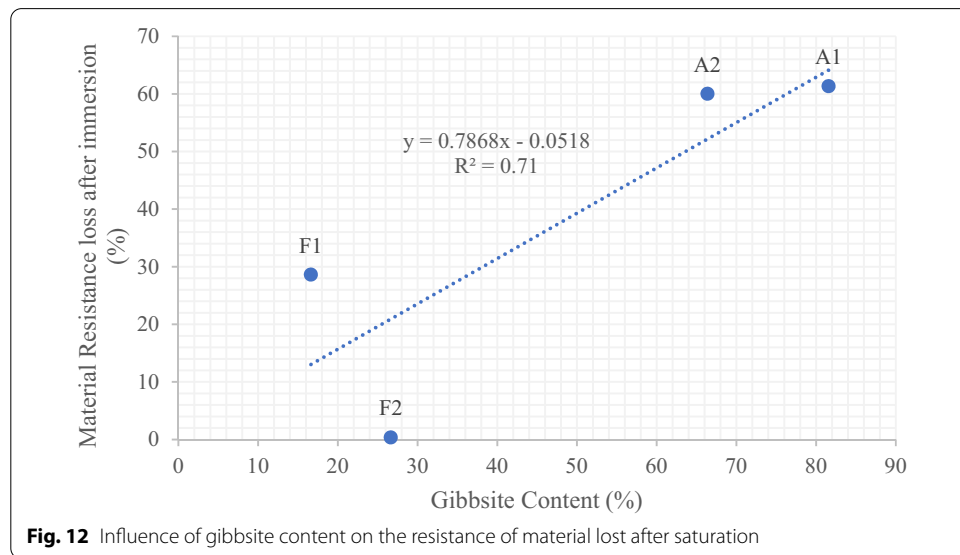


Fig. 12 Influence of gibbsite content on the resistance of material lost after saturation

Influence of gibbsite content on the compressive strength of material lost after water immersion

Table 6 presents the percentage of resistance in compression of material lost after immersion in water and the gibbsite content of material. It is deduced from this table that, the compressive strength of the A1 samples and A2 present a reduction of 61 and 60% respectively after immersion in water. The F2 sample is almost null because the load was not sufficient to cause the damage of material even after saturation. The A1 specimen presents a total porosity which is accessible to water and lower than F1 specimen, but which is more affected by water than F1 specimen (61.30% and 28.60%). The Influence of gibbsite content on the resistance of material lost after immersion in water is shown in Fig. 12. It comes out that, this figure present linear lines of average relationship with positive slope.

Conclusion

The aim of this study was to characterize four lateritic hardpan specimens coming from three quarries situated at Kong-Thonta; Kong-Kang and Kong Dang in Bamendjou sub-division of the West Region of Cameroon. The values of the bulk density are very variable from one specimen to another ranging from 1.88 to 3.01 g/cm³. The specific gravity are also very high and variable from one quarry to another ranging from a value of 2.8 to 3.84. Both open and total porosity parameters of the specimen varied from one specimen to the other within the same quarry. The total porosity of the F2 specimen from Kong-Kang quarry is lower than that of the other quarries. The results of the mechanical properties of the compressive strength tested dry were all above that Lateritic Block Stones (LBS) found in Burkina Faso and India with values ranging from 1 to 4 MPa. The minimum compressive strength of the hardpans was 13.89 MPa which is far superior to the ones found in Burkina Faso and India and therefore would be convenient for dwelling units. It is good to note that the European standard EN 777-1 [22] prescribes a minimum of 2.3 MPa for the compressive strength of bricks, while the French norms NFP 13-304 [27] prescribes values of 6–60 MPa for densely vibrated bricks and 1.5–7 MPa for lightly vibrated bricks. The flexural strengths of the specimens were different from each other with the minimum value of 1.3 MPa obtained for the A1 specimen. The F2 specimens gave the highest values of both the compressive and flexural strength followed by the F1 specimens. The predominant oxides in this laterite are Al₂O₃, Fe₂O₃ and SiO₂, as well as other oxides such as SiO₂, TiO₂, P₂O₅, MnO, MgO and CaO in minor quantities. The major minerals found in the hardpans were gibbsite, goethite and hematite. The mineralogical and geochemical composition are variable from one quarry to another and these both influenced the characteristics of the hardpans such as the physical and mechanical properties, with the iron rich hardpans giving better characteristics than the alumina rich hardpans.

Acknowledgements

We would like to thank the *Académie de Recherche pour l'Enseignement Supérieure* (ARES) for their partial support under the project : Stage en valorisation des ressources secondaires pour une construction durable.

Authors' contributions

All authors read and approved the final manuscript.

Declarations

Competing interests

The authors declare that there is no conflict of interest.

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Received: 12 January 2021 Accepted: 31 August 2021

Published online: 07 January 2022

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