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Use of Benin Laterites for the Mix Design of Structural Concrete

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***Abstract*—**This paper presents a mixed design trial of structural concretes with laterites from Benin. These materials are often the only granular resources readily available in many tropical regions. In the first step concretes were designed with raw laterites, but the performances obtained were rather disappointing in spite of high cement dosages. A detailed physical characterization of these materials then showed that they contained a significant proportion of fine clays, and that the coarsest fraction (gravel) contained a variety of facies, some of which were not very dense or indurated. Washing these laterites, and even the elimination of the most friable grains of the gravel fraction, made it possible to obtain concretes with satisfactory properties in terms of workability, density and mechanical strength. However, they were found to be slightly less stiff than concretes made with more traditional aggregates. It is therefore possible to obtain structural concretes with only laterites and cement but at the cost of eliminating some of their granular constituents.

***Keywords*—**Laterites, aggregates, concretes, mix design, mechanical properties.

I. Introduction

In many tropical regions of Africa, Australia, India, South East Asia and South America, laterites are the only granular mineral resources which are readily available for construction purposes. These materials result from the weathering of various outcropping source rocks under the effect of climate and vegetation [1], [2]. Benin has an abundance of this type of resource [3].

Currently, laterites are mainly used to make up the foundation and base layers of roadways, in the form of natural gravel or cement-treated gravel. In the building sector, in addition to traditional earthen constructions (laterites), they are also beginning to be used locally to make cement-stabilised bricks or blocks for the construction of infill walls or load-bearing walls of individual houses [1]-[6]. In the current context of scarcity of traditional granular resources, this material could also represent an interesting ecological and economic solution on a local scale for the manufacture of (reinforced) concrete intended for use in the structures and framework of current buildings (slabs, lintels, posts, beams, slabs etc.).

The rare attempts to design laterite concretes (see Section II) have given inconclusive results. These concretes very often present implementation difficulties in the fresh state (workability, etc.) and weak mechanical performances (resistance, elasticity) in the hardened state. It is therefore important to try to identify the causes of these difficulties and to propose possible simple technological solutions aimed at overcoming this obstacle. This is the objective of the present study, which firstly consisted in finely characterising the properties of a Benin laterite. The results made it possible to propose various treatments to improve the quality of aggregates from this resource. The concretes manufactured with the aggregates resulting from these treatments show that it is actually possible to obtain laterite concretes that respond to the overall requirements for a structural concrete of current quality.

II. State of the Art

This section briefly reviews the literature on the physical properties of aggregates derived from African and other laterites, and the use of laterites in concrete mix design.

A. Physical Characteristics of African Laterites

Van Ganse (1957) [7] was one of the first to study laterites from the former Belgian Congo. He described this material as a discontinuous sandy-clay gravel with a deficiency of elements between 0.25 mm and 1 mm in size.

Laquerbe et al. (1995) [8] studied "lateritic gravels" from Senegal for use in concrete with dune sand. They showed that they contain 10-35% fines (passing at 80 µm) and 20-60% grain sizes greater than 2 mm. These materials have a real density of 2,680 kg/m^3, a bulk density of 1,500 kg/m^3 and a water absorption coefficient of 7.15%.

Ndiaye (2013) [9] studied different "lateritic gravels" in Senegal. He also found that laterites comprise up to 35% fine (< 80 µm) and 20-60% coarser particles (> 2 mm).

Lawane (2014) [10] characterised laterites from three quarries in Burkina Faso for use in housing as stabilised earth blocks. He found that their real density varies between 2,720 kg/m^3 and 2,840 kg/m^3.

In [11], on the characterisation and valorisation of laterites used in road construction in Niger, Issiakou (2015) indicated that the real density of these materials is between 2200 kg/m^3 and 2800 kg/m^3. He proposed to classify them as materials of good bearing capacity if their fine particle content is around 12% or low bearing capacity if the same content is around 25%.

In [12], on the geotechnical characterisation of laterites from Cameroon (Batoufam Region) intended for road construction,

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Takala (2017) showed that these materials were "lateritic gravels" composed of three quarters of grains of sizes greater than 2 mm, the remainder being fine sand, silt and clays (approximately 10%).

B. Use of Laterite for Concrete Formulation

Raju and Ramakrishnan (1972) [13] experimentally investigated the behaviour of concrete made exclusively with laterite from the south-west coast of India. The mixes had a water/cement ratio between 0.4 and 0.6 and an aggregate/ cement ratio between 4 and 6. The compressive strengths obtained were between 5 MPa and 10 MPa, which were much lower than those of the crushed granite aggregate concrete of the same composition which was used as a reference.

Balogun and Adepegba (1982) [14] studied the effect of varying the optimum proportions of Nigerian laterite in lateritic concrete (concrete in which all the aggregates are of lateritic origin), using a constant water/cement mass ratio of 0.65. The maximum aggregate size was 19 mm and the fine fraction consisted of lateritic sand and lateritic fillers. They showed that the proportions of cement, fine and coarse aggregates that lead to better mechanical strength are respectively 1/1.5/3. They went on to recommend that the optimum lateritic filler content in laterite concrete should not exceed 50% of the total volume of fine aggregate.

Falade (1994) [15] studied the influence of the water/cement ratio and the laterite/cement ratio on the workability and mechanical properties of concretes where conventional sand is replaced by laterite sand. It shows that the workability increases with the increase of both ratios, but that the compressive strength decreases concomitantly. The optimum mix for a water/cement ratio of 0.5 is thus 1/1/2 (cement/sand/coarse aggregate).

Osunade (2002) [16] studied the compressive and tensile strength of laterite concrete where lateritic sand is progressively replaced by crushed granitic sand. The lateritic sand used came from Osun State in Nigeria (Ife-Ifewara site). The substitution was found to increase the compressive strength, at least to a maximum of 50% laterite sand. Laterite concrete containing 40% granitic sand can be used for pouring massive foundations without vibration, while 20% to 40% granitic sand is recommended for manually compacted pavements.

Ukpata et al. (2012) [17] investigated the compressive strength of concrete using laterite sand and quarry fines as fine aggregates and crushed granite as coarse aggregates. These materials were obtained from different sites in Cross River State, Nigeria. By varying the proportions of laterite and quarry fines from 0% to 100% in 25% increments and the water/ cement ratio from 0.5 to 0.7, they obtained hardened concretes with a density of between 2,293 kg/m^3 and 2,447 kg/m^3 and compressive strengths of between 17 MPa and 34.2 MPa. However, the strength was found to decrease as the amount of laterite increases. They conclude that the combination of quarry fines and laterite can replace conventional sand in structural concrete, provided that the amount of laterite does not exceed 50%.

Kamaruzaman and Muthusamy (2012) [18] investigated the mechanical characteristics of concrete where crushed coarse aggregates were substituted with laterite nodules from the state of Pahang in Malaysia. The sand and river coarse aggregates used were sourced from two regions in the same state of Pahang. They found that the compressive and flexural strengths, as well as the modulus of elasticity, decreased as the volume of lateritic nodules increased. They conclude that a substitution of 10% of the crushed coarse aggregates by lateritic nodules can give a concrete with mechanical properties comparable to those of normal concrete. Substitution of up to 30% can produce concrete with a compressive strength of around 30 MPa.

Ephraim et al. (2016) [19] in Nigeria measured the properties of concretes with different water/cement ratios where the coarse aggregates were gradually replaced by lateritic nodules. For concrete with a water/cement ratio of 0.6 and respective proportions of cement, sand and coarse aggregates of 1/2/4, the compressive strength obtained is 19.1 MPa. For concrete with a water/cement ratio of 0.55 and proportions of 1/1.5/3, the strength reaches 24.7 MPa. The authors conclude that lateritic nodule concrete can be used for structures with small bearing.

C. Summary

This bibliographic inventory shows that most of the work carried out to date has aimed at the partial substitution of traditional sands or gravels by lateritic sands or gravels (nodules). Only Raju and Ramakrishnan (1972) [13] have used just (raw) laterites for concrete formulation. The present work is in line with this objective, namely to study the complete substitution of traditional aggregates by laterites in order to produce concretes suitable for common building structures.

III. Materials and Methods

A. Laterites

1. Origin

The laterites used in this study come from the Attotinga quarry, commune of Allada, district of Agbannou in Benin (Fig. 1). This quarry is located in the "Guinean" zone of Benin. It is a plateau covered largely by tropical ferruginous soils and weak ferralitic soils ("Terre de Barre"). Several laterite quarries are exploited in this area, mainly for road construction purposes. A representative sample of several tons of raw laterite was taken for this study, from samples taken at different locations in the quarry stock. The sample was mechanically stirred several times to obtain a homogeneous mixture (Fig. 2).

Fig. 3 shows the appearance of the grains of the 10-20 mm fraction, after washing. The presence of various facies can be seen, ranging from indurated rock fragments to more or less porous and friable sandy or marly agglomerates.

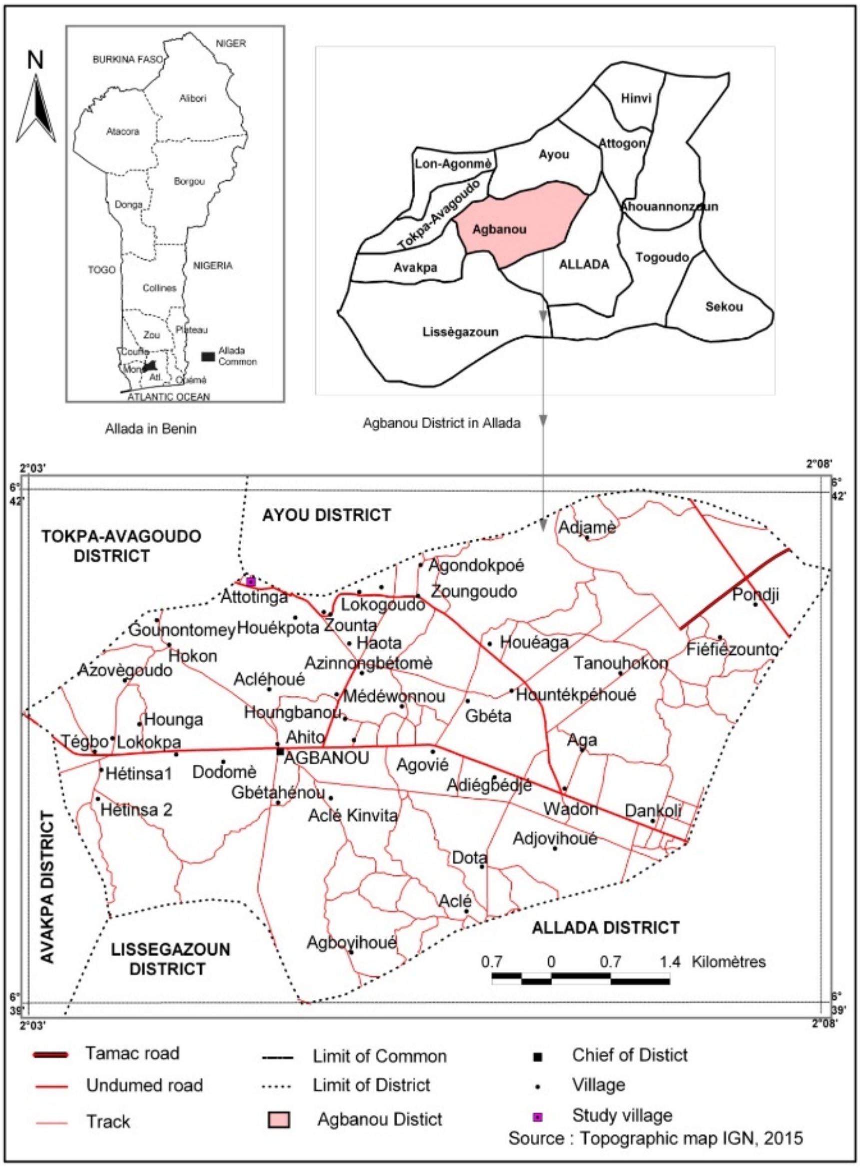


Fig. 1 Location of the Attotinga quarry, Agbanou district, Allada commune, Benin, where the laterites in the study were obtained [35]

Fig. 2 Appearance of raw laterite collected from the Attotinga quarry (Benin)

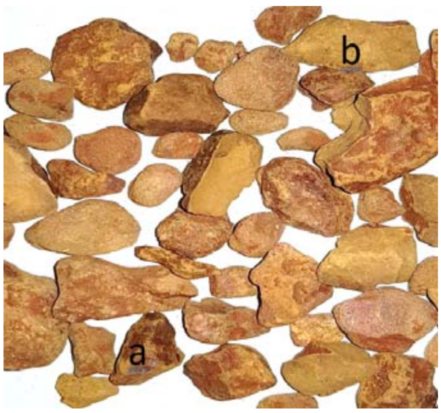


Fig. 3 Appearance of washed laterite nodules (fraction 10-20 mm); (a) indurated elements (b) more friable elements

2. Physicochemical Characterisation

The granulometric analysis of the raw laterite was carried out using a wet method on a representative sample, according to standard NF P 94-056 [20]. The granulometry of the fine fraction (passing 80 µm) was determined by sedimentometry according to standard NF P 94-057 [21].

The chemical composition of the laterite was analysed by X-ray fluorescence on both the sandy fraction and the gravel (mixture of the different facies).

The absolute density (Ad) (i.e. that of its constituent solid matter) was measured with a helium pycnometer on finely ground samples of raw laterite, according to standard NF EN 1097-7 [22]. The measurements were made on the sandy fraction and on grains representative of the two populations of grains present in the gravel (indurated grains and more friable grains).

The real density (Rd) and the water absorption (Wab) (considering the water-accessible porosity of the grains) were measured according to NF EN 1097-6/A1 [23]. These tests were not carried out on whole sand and gravel, but on different granular classes belonging to the fine fraction (< 4 mm) and on individual grains from the coarse fraction. These measurements were decided in view of the heterogeneous aspect of the grains (Fig. 3), the aim being to define the variability and extent of these properties within the material. Specifically, the washed sample used for the particle size analysis was separated into four fractions covering the sandy part (lateritic sand 0/4) (< 0.08, 0.08-0.16, 0.16-1.25, 1.25-4) and into seven elementary classes covering the coarse fraction (lateritic nodules 4/25) (5-6.3, 6.3-8, 8-10, 10-12.5, 12.5-16, 16-20, 20-25). For the latter, the grains were placed individually in stainless steel trays and their position was marked (Fig. 4).

Fig. 4 Individual characterisation of the real density and water absorption of grain sizes larger than 5 mm, Arrangement in stainless steel bins (grain size class 8-10)

They were weighed on a precision balance several times, being placed in the same position each time: i) after drying for 24 hours in an oven at 110 °C; ii) after imbibition for 24 hours under several centimetres of distilled water, in the air after wiping the surface with a damp cloth (imbibed mass dry surface) and then in water (hydrostatic weighing); iii) again in the air after drying at 110 °C for 96 hours (the distilled imbibition water present in the trays having been eliminated beforehand by siphoning off). These weighings made it possible to determine the real density and water absorption of each cut less than 5 mm and each grain larger than 5 mm. Weighing the dry grains before and after imbibition also made it possible to determine the percentage of disintegration of certain grains. Finally, given the sensitivity of these measurements, only those deemed viable were retained *a posteriori* by comparing the measured water absorption (W_{ab}) with the theoretical one (Wt_{ab}) determined from the measured densities (real and absolute), according to the relationship:

$$Wt_{ab} = \frac{1}{R_d} - \frac{1}{A_d} \quad (1)$$

Results that showed a theoretical Wt_{ab} value that deviated by ± 10% from the measured W_{ab} value were not included in this analysis.

Another special test was carried out for the quantification of grain disintegration. It consisted in collecting at regular intervals the d_{i-1} sieve passing from an immersed d/D sample which had been previously dried and weighed. At each interval, the sieve was shaken for a long time under water, rinsed and re-immersed in another container. After decanting and siphoning, the passing was collected, dried to a constant mass and weighed. This test was carried out on two samples from the 5-25 mm gravel (d_{i-1} = 4 mm sieve), one raw, the other previously washed.

Finally, the impact resistance (Los Angeles test), the cleanness of the sands and the methylene blue value test were measured according to standards NF EN 1097-2 [25], NF EN 933-8+A1 [26] and NF P94-068 [27] on the 10/14 fraction, on the 0/4 sand and on the fine fraction, respectively.

B. Concrete

Concretes were made with the raw laterites, with the washed laterites and with washed and sorted laterites (see Table II), in order to measure the effect of each treatment on the properties.

1. Constituents

The raw laterite sample taken from the quarry was dry split into FA 0/4 fine aggregate and CA 4/25 coarse aggregate (nodules). Subsequently, these two fractions were mixed in different proportions CA/FA to form the granular skeleton of the different concretes made. Initially, the aggregates were used as is. They were also used washed, then washed and sorted for the CA 4/25 fraction. In each case, the aggregates were stored in sealed bags and their water content and water absorption were taken into account in the calculation of the effective water W_{eff} of the mixtures.

To wash the laterites, the quantities of 0/4 FA and 4/25 CA required for the production of the concrete specimens were placed in turn in a large drum in order to undergo an initial vigorous washing with a water jet, until the tank was almost full. After a resting period to obtain relatively clear water, the upper volume of the tank was poured out to remove the supernatant elements (twigs, etc.). The material was then washed several times using the same principle, but each time the turbid water containing the fine fractions in suspension was immediately removed through a 63 µm sieve (removal of clays). The material was then washed in small quantities over the 63 µm sieve and the reject material was stored in sealed bags.

For sorting, several attempts were made to separate the lighter grains from the denser ones using upward water currents or water jigging techniques [28], but these proved to be ineffective given the laboratory resources available and the small quantities to be processed. Manual sorting of the 4/25 CA was then selected, based on the colour of the grains (see Fig. 3). Only the densest grains were thus recovered and used to make the washed and sorted laterite concretes.

The concretes were made with a Portland cement with limestone CEM II/B-LL 42.5 R [29] from the Beninese cement company NOCIBE. This cement contains up to 35% limestone. The mineralogical composition of its clinker is: C3S 63%, C2S 10%, C3A 8%, C4AF 7%. Its generic properties are given in Table I.

TABLE I
GENERIC PROPERTIES OF CEM II/B-LL 42.5 NOCIBE CEMENT

Compression at 2 days	20 MPa
Compression at 7 days	36.5 MPa
Compression at 28 days	46.4 MPa
Water demand (normal consistency)	31%
Setting time	230 min
Density	3.04 g/cm^3
Blaine fineness	4110 cm^2/g
> 90 µm	3.2%

The concretes were made with drinking water from a tap.

2. Mix Design

In a first step, the proportions of 0/4 FA and 4/25 CA (unwashed) forming the granular skeleton of the concrete were defined according to the Dreux-Gorisse method [30]. It is worth recalling that this method is based on a reference granular curve (not including cement) determined from the maximum size of the aggregates and tabulated parameters integrating consistency, shape, vibration, fineness of the sand, cement dosage, etc. For raw laterite and plastic consistency, with a cement dosage of 400 kg/m^3, the relative proportion of aggregate found is CA/FA = 2.5. With the washed materials, this proportion is 1.8. The experimental plan carried out with the raw materials then consisted of varying the granular proportions (CA/FA = 2.2, 2.5, 2.8), the quantity of cement (350, 400, 450 kg/m^3) and/or the quantity of water (W_{eff}/C ratio 0.4 - 0.5 - 0.6 - 0.7) around these initial values, as shown in Table II. For the washed materials, only a cement dosage of 350 kg/m^3 and a ratio W_{eff}/C = 0.55 were retained (Table II). To establish the mass composition of each mixture in the reference of the unit volume (1 m^3), the real density of the components, the water absorption of the aggregates and their water content at the time of manufacture, as well as a standard air content of 1.5% were taken into account.

The concretes were produced with a laboratory mixer (50-litre capacity) by successively introducing the aggregates, cement and water. The mixing time was 1.5 minutes. The consistency of the concrete was measured with an Abrams cone (Slump test S). The concrete was then poured into cylindrical moulds of 11 cm diameter and 22 cm height, in two layers vibrated with a 25 mm needle. The density of the concrete was determined by weighing the moulds. The specimens were demoulded at 24 hours and stored in airtight bags at 20 °C until the mechanical tests.

3. Mechanical Tests

The mechanical tests were carried out at 28 days. They consisted of the normal centred compression test Rc according to standard NF EN 12390-3 [31] and, on certain mixes, the measurement of the modulus of elasticity Ec according to standard NF EN 12390-13 [32] (Table II).

TABLE II
PROGRAMME OF THE TESTS CARRIED OUT

Laterites	CA/FA (%)	Different W_{eff}/C	C, kg/m^3	Tests
Raw	2.2	0.4 – 0.5 – 0.6 – 0.7	400	Rc
			350	
	2.5		400	Rc - Ec
			450	Rc
	2.8		400	
Washed Washed sorted	1.8	0.55	350	Rc - Ec

Finally, it should be noted that the Bolomey formula (2) usually used to predict the compressive strength of ordinary concretes provides the values in Table III for the different mixes, considering at first sight a rather poor granular coefficient G of 0.45.

TABLE III
PREDICTED VALUES OF THE COMPRESSIVE STRENGTH OF THE DIFFERENT MIX DESIGN, ACCORDING TO BOLOMEY'S RELATION

C/E_{eff}	Rc
0.4	41.8
0.5	31.3
0.55	28.1
0.6	24.4
0.7	19.4

It is worth recalling, in this relationship, the granular coefficient G describes the contribution of the aggregate to the compressive strength and that the proposed values range from 0.35 to 0.65 depending on the size and "quality" of the aggregate.

$$Rc_{28} = G.\sigma'_{c28}\left(\frac{C}{E_{eff}} - 0.5\right) \quad (2)$$

with σ'_{c28} the true class of cement (46.4 MPa, Table I); C and E_{eff}, the mass proportions of cement and water.

IV. RESULTS AND DISCUSSION

A. Aggregates

The particle size distribution of the raw laterite is shown in Fig. 5. It contains about 45% of particles smaller than 0.2 mm and 40% of grains larger than 4 mm. It is therefore a material with a rather discontinuous granularity, since there are few grains in the intermediate 0.2-4 mm range. This is one of the recurrent characteristics of African laterites, as described for example by [7]-[9] and [12]. This raw laterite contains about 30% of particles smaller than 80 µm. These fines were removed well by the washing process, as the particle size distribution of the washed 0/4 FA shows (Fig. 5). This figure also shows the particle size distribution of the washed CA.

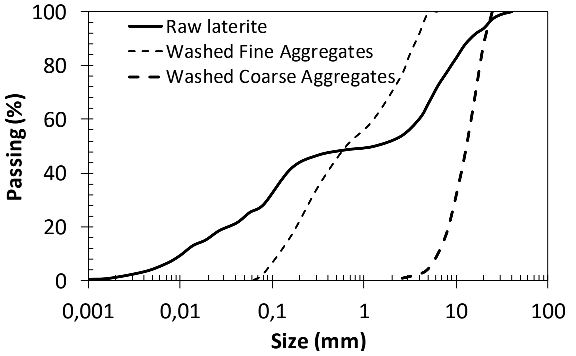


Fig. 5 Grain size of raw laterite, washed 0/4 FA and washed 4/25 CA

The chemical analysis of the sand and gravel by X-ray fluorescence is given in Table IV. Calcium is absent in both materials and significant differences appear in silica and iron, the FA being richer in silica and the CA richer in iron. This difference can also be seen in the absolute density, measured with a Helium pycnometer on finely ground samples. Indeed, the density of the FA is 2,660 kg/m^3 on average, whereas that of the CA is (much) higher, with a value of 2,980 kg/m^3 on average for the more porous grains and 3,130 kg/m^3 on average for the more indurated grains. These measurements confirm the "polyphasic" character of laterite.

TABLE IV
CHEMICAL ANALYSIS BY X-RAY FLUORESCENCE OF LATERITIC SAND AND GRAVEL

	FA	CA
LOI	7.61	9.02
Na_2O	0.06	0.07
MgO	0	0
Al_2O_3	10.13	7.76
SiO_2	60.84	40.71
P_2O_5	0.27	0.68
SO_3	0.27	0.26
K_2O	0.07	0.06
TiO_2	0.58	0.39
MnO	0.02	0
Fe_2O_3	19.82	40.90
SrO	0.01	0.01

The statistical results of the real density and water absorption measurements carried out on the three fractions of the washed lateritic FA (0/4) and on the individual grains of the seven elementary classes of CA (4/25) are reported in Table V. For the CA, more than 420 grains were retained for 600 grains processed, i.e., more than 70% of measurements considered reliable ((1), in which an average absolute density of 3,075 kg/m^3 was considered). These individual measurements also made it possible to study the distribution of the two properties, all classes combined. Thus, Fig. 6 shows the amplitude and frequency of these two properties (real density discretised in steps of 0.1 kg/dm^3 and water absorption in steps of 2%).

The real density properties of the three FA cuts can be seen to be rather similar to each other, but nevertheless higher than the average real density of the CA and the average value of each of its elementary classes. Conversely, the water absorption of the FA is (much) lower than that of the CA. Within the same elemental class of CA, these two properties also show very large contrasts of the same relative magnitude. This contrast can be seen clearly in Fig. 6, where the measurements for all grains of all classes of CA are combined and classified. Thus, grains with a real density of about 2,400 kg/m^3 and a water absorption of about 10% are the most represented. However, many grains have a much lower or higher real density and water absorption, ranging from 2,000 kg/m^3 and 3,000 kg/m^3 and conversely from 18% and 2%, respectively. In relative terms, the real density and water absorption of the grains thus vary by about 50% within the same laterite CA.

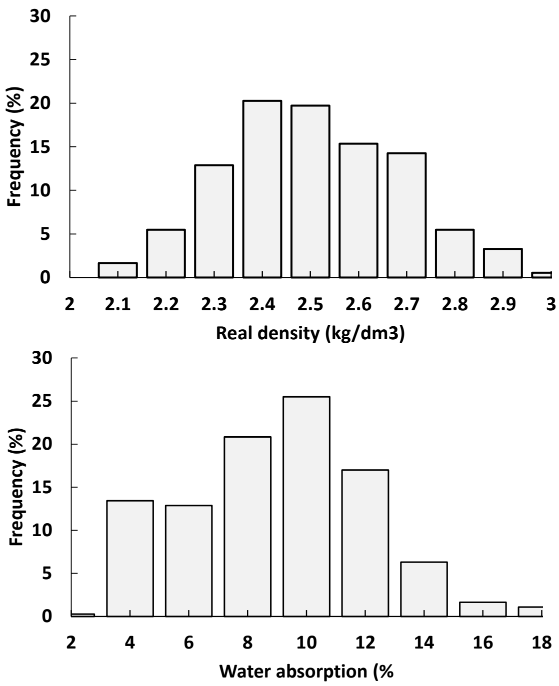


Fig. 6 Amplitude and extent of the real density and water absorption of lateritic CA grains

The differences are due to the presence of grains of different aspects within the CA. Some were being particularly indurated and compact while others were particularly friable and porous (Fig. 3). Furthermore, it can be assumed that the alteration of the most porous and friable grains gave (will give) a large majority of fine particles that are (will be) found in the fine fraction of the sand (< 80 µm), without any significant production of grains of intermediate sizes. This hypothesis is corroborated by: i) the high proportion of fines in the raw laterite (Fig. 5); ii) the discontinuous shape of the particle size curve (almost no grains between 0.2 mm and 2 mm, Fig. 5); iii) an average real density of the three sand cuts (less provided with friable grains) higher than the average real density of the different gravel classes (better provided with friable grains); iv) an average loss of mass of 0.3%, reaching up to 6.5% (class 5/6.3) after imbibition for 24 hours in distilled water (Table V). these results incidentally reveal the difficulty of measuring the physical properties of these materials and their representativeness.

TABLE V
STATISTICAL STUDY OF LATERITE GRAIN PROPERTIES

		FA washed 0/4				CA washed 4/25							
		0.08/0.16	0.16/1.25	1.25/4	**0/4**	5/6.3	6.3/8	8/10	10/12.5	12.5/16	16/20	20/25	**4/25**
Rd (kg/m^3)	Min					2.046	2.043	2.074	2.032	1.992	2.026	2.103	2.045
	Ave	2,54	2,524	2,562	**2.542**	2.315	2.328	2.499	2.455	2.371	2.387	2.465	**2,403**
	Max					2.600	3.020	3.045	2.857	2.79	2.983	2.635	2.847
Ab (%)	Min					5,4	2.7	0,9	2.01	2.69	2.04	2.84	2.65
	Ave	2,74	3,02	5,9	**3.89**	9.77	9.27	7.28	7.95	8.03	7.74	6.22	**8.04**
	Max					17.24	14.9	14.19	16.31	14.29	14.39	12.72	14,86
Mass loss	Min					0	0	0	0	0	0	0.1	0
	Ave					0.7	1	0.2	0.2	0.1	0.1	0.2	**0.3**
	Max					6.5	4.3	1.8	2.2	1.1	0.3	0.5	2.3

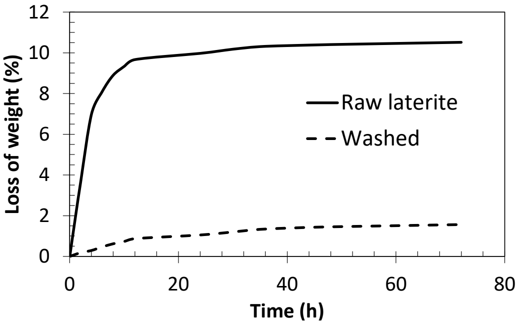


Fig. 7 Mass loss of immersed CA over time

The test which consisted in following the loss of mass of the immersed 4/25 CA over time also confirms the loss of physical integrity of certain grains (Fig. 7). Indeed, after 3 days of immersion, nearly 1% of the mass of the previously washed chippings had disintegrated (a value rather comparable to those found with the measurements on individual grains). However, this loss of mass reaches much higher values (of the order of 10%) when the test is carried out on the unwashed grains, thus confirming a strong presence of finer particles that are simply attached to or poorly adherent to the CA. The presence of this fraction and/or friable grains is most probably a fatal obstacle to obtaining good performance in cementitious (or even bituminous) composites. Furthermore, the individual tracking of the grains allowed us to distinguish those with the poorest properties in terms of density and porosity from those with the best properties. The former was found to almost always have a light beige colour which is distinct from that of the latter. Visual sorting (in the absence of a more automated method) thus made it possible to separate these two populations of grains manually, in order to be able to manufacture a concrete incorporating the best quality CA.

The geotechnical tests carried out on the raw laterite give respectively:

- for the FA fraction 0/4, a blue value of 0.7 and a sand cleanliness value of 22;
- for the 6/10 CA fraction, a Los Angeles value of 75.

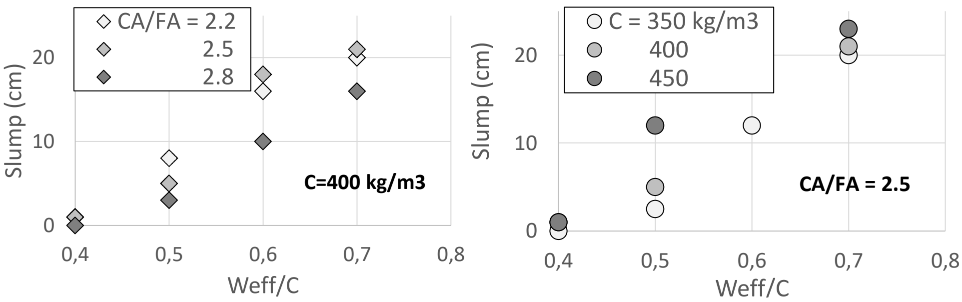
These values are all below or above the normative values for good concrete aggregates according to article 10 of standard XP P 18-545 [33], indicating that raw laterite is not a material that can be used a priori for this purpose.

B. Laterite Concretes

The properties of concretes made with unwashed, washed and sorted laterite FA 0/4 and CA 4/25 are given in Table VI.

1. Raw Laterites

These concretes were the subject of the first test campaign where the CA/FA, Weff/C and C ratios were varied.

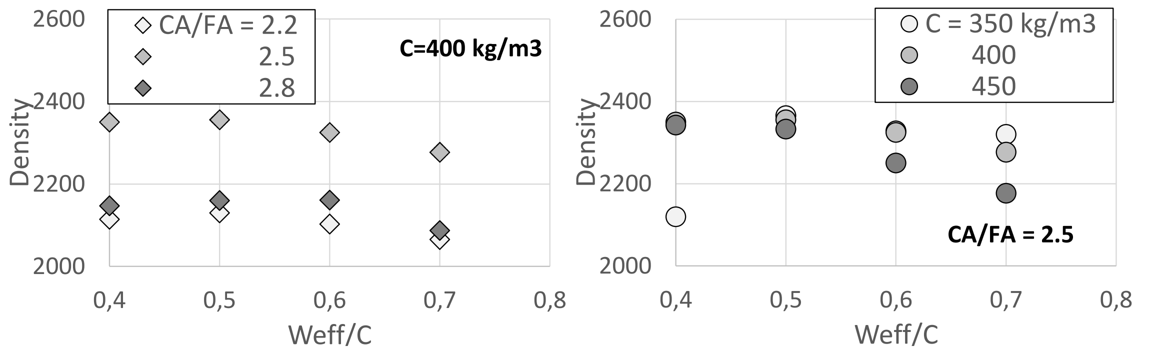


(a) (b)

Fig. 8 Abrams cone slump of raw laterite concretes as a function of W_{eff}/C ratio: (a) same cement dosage and different CA/FA ratio; (b) same CA/FA ratio and different cement dosage

TABLE VI
PROPERTIES OF LATERITE CONCRETES

Laterites	CA/FA	W_{eff}/C	C kg/m^3	Slump S cm	Density kg/m^3	Mechanical properties	
						Rc, MPa	Ec, GPa
Raw	2.2	0.4	400	1	2114 ± 99	14.6 ± 1.4	
		0.5		8	2130 ± 44	16.8 ± 1.8	
		0.6		16	2103 ± 49	15.8 ± 0.6	
		0.7		20	2065 ± 68	10.9 ± 0.4	
	2.5	0.4	350	0	2120 ± 12	7.6 ± 0.4	
		0.5		2,5	2366 ± 14	12.5 ± 0.2	
		0.6		12	2329 ± 14	13.1 ± 0.4	
		0.7		20	2320 ± 31	13.0 ± 0.3	
		0.4	400	1	2350 ± 12	13.5 ± 1.4	
		0.5		5	2356 ± 12	11.4 ± 1.2	7.8 ± 0.8
		0.6		18	2325 ± 26	11.4 ± 0.9	
		0.7		21	2277 ± 11	11.1 ± 0.5	
		0.4	450	1	2343 ± 11	16.4 ± 1.6	
		0.5		12	2333 ± 16	22.7 ± 2.7	
		0.6		20	2251 ± 18	15.7 ± 0.3	
		0.7		23	2177 ± 10	10.5 ± 0.6	
	2.8	0.4	400	0	2147 ± 68	21.2 ± 1.2	8.9 ± 0.4
		0.5		3	2160 ± 41	17.3 ± 1.6	
		0.6		10	2161 ± 43	16.7 ± 1.4	
		0.7		16	2087 ± 42	13.3 ± 1.2	
Washed	1.78	0.55	350	8	2487 ± 49	27.5 ± 0,3	17.9 ± 0.3
Washed sorted	1.78	0.55	350	3,5	2471	32.3 ± 3.2 (29-35.7)	18.4 ± 0.3

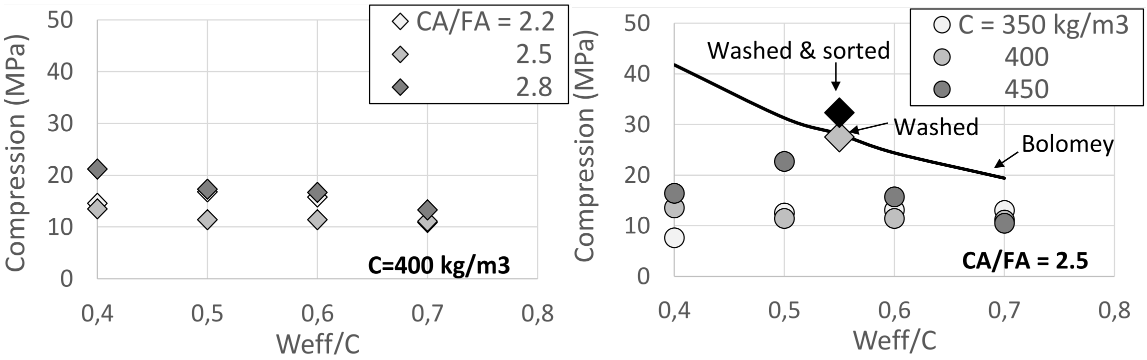


(a) (b)

Fig. 9 Density of raw laterite concretes as a function of the W_{eff}/C ratio: (a) same cement dosage and different CA/FA ratio; (b) same CA/FA ratio and different cement dosage

Fig. 8 shows the evolution of the consistency (slump S at the Abrams cone) as a function of the W_{eff}/C ratio, firstly for the three concretes dosed with 400 kg/m^3 of cement and having a different CA/FA ratio (Fig. 8 (a)), and secondly for the three concretes with the same CA/FA ratio of 2.5 and a different cement dosage (Fig. 8 (b)). The consistency can be seen to have logically decreased as the W_{eff}/C ratio increased, ranging from very firm concretes for a W_{eff}/C ratio of 0.4 (S = 0) to very fluid concretes for a W_{eff}/C ratio of 0.7 (S = 20 cm). However, for the same W_{eff}/C ratio, concretes rich in CA and/or poor in cement have a poorer consistency than concretes rich in FA and/or rich in cement. This is because these "non-optimised" concretes generate more friction between grains, which increases the shear threshold of the concrete and therefore reduces the slump [24]-[34]. Conversely, when these unwashed laterite concretes contain more FA and/or cement, they are more plastic and fluid, with the same W_{eff}/C ratio. This is similar to traditional ordinary concretes.

Fig. 9 shows the evolution of the density of the concretes (kg/m^3) in the same reference frame as before. The CA/FA ratio can also be seen to play an important role here (Fig. 8 (a)), since concretes with a high proportion of FA (CA/FA = 2.2) or a high proportion of CA (CA/FA = 2.8), compared to the theoretical value given by the Dreux method (CA/FA = 2.5), have (significantly) lower densities (Fig. 9 (a). The "granular unbalance" of these concretes means that they obviously trap more occluded air, despite the vibration. Concretes with a low W_{eff}/C can also be seen have a low density, which logically should be higher since they contain less water (Fig. 9 (b)). However, these concretes have a firm consistency, which slows down or prevents the departure of entrapped air, despite the vibration. On the other hand, as the W_{eff}/C ratio increases, the density of the concretes logically decreases as they contain more water. Generally speaking, raw laterite concretes, if they do not contain an excess of air, have a rather high in-place density, due to the high density of some of the CA they contain.



(a) (b)

Fig. 10 Compressive strength of raw laterite concretes as a function of the W_{eff}/C ratio: (a) same cement dosage and different CA/FA ratio; (b) same CA/FA ratio and different cement dosage

Fig. 10 shows the evolution of the compressive strength of concretes based on washed and sorted aggregates and washed aggregates (same marks). This property was found to remain poor for the same cement dosage of 400 kg/m^3 (Fig. 10 (a)), even when the concrete contains little water (low W_{eff}/C), whatever the CA/FA ratios tested. However, CA-rich concretes perform (slightly) better, despite their lower density (Fig. 10 (a)). A maximum strength of 21 MPa is obtained with 400 kg/m^3 of cement and a W_{eff}/C = 0.4 ratio. However, this concrete is unsuitable for use in construction because it has zero slump (S = 0). By increasing the cement dosage to 450 kg/m^3 and the effective water dosage (W_{eff}/C = 0.5), a concrete of acceptable consistency (S = 12 cm) and strength of 22.7 MPa at 28 days can be obtained (Fig. 10 (b)). However, like all other raw laterite concretes, this concrete was found to have a much lower performance level than that predicted by the Bolomey formula (black curve in Fig. 10 (b)). In order to predict their performance with this relationship, raw laterite aggregates would have to be assigned a grain size coefficient G lower than the most pessimistic value proposed by Dreux (< 0.35). This poor qualification is related to the particular characteristics of the FA (high fines and clay content, granularity, etc.) and the CA (wide range of density, large quantity of easily dissociable elements, disintegration of certain facies, poor mechanical performance, etc., see Section IV *A*). They result in a particularly pronounced "limiting effect" (high Los Angeles coefficient) which alters the strength of the composite subjected to stress (some grains are less resistant than the hardened paste and they break prematurely when the load is increased). The adhesion between the hardened cement paste and the aggregates is also poor, mainly due to the poor cleanliness of the sand and gravel. Furthermore, the modulus of elasticity of these concretes, measured on the mixture characterised by a W_{eff}/C = 0.5 ratio, a CA/FA ratio of 2.5 and a cement dosage of 400 kg/m^3, is particularly low (about 8 GPa), indicating particularly high instantaneous deformation and creep. These results show that raw laterite aggregates are poor materials that cannot be used to produce structural concrete of satisfactory quality, even with a (very) high cement dosage.

2. Washed Laterites

Following the poor results obtained with the raw laterites, it was decided to wash both aggregates according to the protocol described in Subsection III *B* 1. The resulting materials have an appearance more "in line" with traditional concrete aggregates. The FA is free of (clay) fines and the CA have a clean surface.

The concrete obtained with these aggregates (CA/FA ratio = 1.78) is also more suitable for use (Fig. 10). For a W_{eff}/C ratio = 0.55 and a cement dosage of 350 kg/m^3, it has a plastic consistency (S = 8 cm), a density close to 2,500 kg/m^3 and a compressive strength at 28 days of 27.5 MPa on average (Table VI). This concrete therefore complies with the predictions of the Bolomey relation (Fig. 10 (b)), considering here an ordinary granular coefficient G = 0.45.

The modulus of elasticity of this concrete (18 GPa) is much higher than that of unwashed laterite concrete, but it is still lower than that of traditional concrete of common structures.

Fig. 11 Appearance of washed laterite concrete and its mode of failure in compression

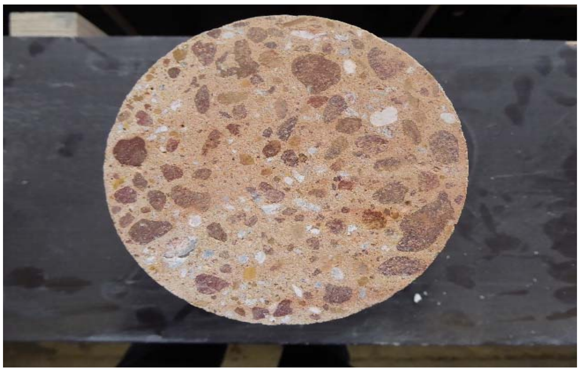


Fig. 12 Appearance of washed laterite concrete before and after compression crushing

3. Washed and Sorted Laterites

In a final step, the beige coloured grains, identified as the most porous and friable within the washed CA (see Figs. 3 and 11), were removed visually (attempts at separation by physical methods, such as the water jigger, proved inconclusive at the laboratory stage). The removed fraction corresponds to approximately one third of the CA (mass proportion). The CA sample obtained was used to cast six cylindrical specimens 11 x 22 cm. The concrete still had the same CA/FA and W_{eff}/C ratios and the same quantity of C cement as before. The mechanical tests carried out at 28 days showed (further) improved performance (Fig. 10 (b), Table VI), with an average compressive strength of 32.3 MPa (values ranging from 29 MPa to 35.7 MPa). However, the modulus of elasticity is only slightly improved, reflecting the rather low stiffness of laterite aggregates, even of good quality.

4. Summary

The work carried out in this study shows that it is possible to obtain structural concretes of satisfactory quality from an entirely lateritic granular skeleton. This result was obtained thanks to better knowledge of the physical properties of the different classes of grains (fine and coarse aggregate), in order to select the least altered facies within the resource. This treatment consisted of effective washing of the raw material, followed by separation of the lightest and most friable grains using an appropriate technique. It should be noted, however, that washing these laterites results in the removal of a significant proportion of the resource, which can be estimated from the particle size curve of the raw laterite (Fig. 5) at around 30%. This treatment would then require the management of water (recycling) and the sludge produced (which could be recovered elsewhere). Similarly, the removal of the poorest grains from the coarse aggregates would result in a mass loss of about 30% of this fraction. It is therefore possible to use laterite in structural concrete of satisfactory quality, but at the cost of this severe selection.

V. Conclusion

The objective of this work was to produce structural concretes for common structures from laterites mined in Benin. The tests carried out showed that the use of this granular resource without prior treatment did not make it possible to obtain concrete of satisfactory quality, even at the cost of very high cement dosages. A detailed characterisation of the physical properties of this material showed that the high content of fine elements (clay) was a real handicap. However, this obstacle could be overcome by washing the resource. Structural concretes of satisfactory quality, both in terms of workability and strength, can then be obtained, their only 'defect' being a rather low modulus of elasticity. The quality of these concretes can however be further improved by eliminating the most friable grains contained in the coarse fraction by sorting. However, these treatments have the disadvantage of discarding part of the resource and generating residues which could nonetheless be used elsewhere. Similarly, it would be interesting to test the interest of using a superplasticizer to increase the resistance of these laterite concretes as much as possible by reducing the water content. Therefore, these approaches are required to obtain quality structural concretes with laterites from Benin.

References

[1] A.K. Kasthurba, M. Santhanam, M.S. Mathews, Investigation of laterite stones for building purpose from Malabar region, Kerala state, SW India – Part 1: Field studies and profile characterisation, Constr. Build. Mater. 21 (2007) 73–82. https://doi.org/10.1016/j.conbuildmat.2005.07.006
[2] F.H. Buchanan, A Journey from Madras Through the Countries of Mysore, Canara, and Malabar, Performed Under the Orders of the Most Noble the Marquis Wellesley, Governor General of India..., Cadell, 1807.
[3] I. Youssouf, M. Lawani, Les sols beninois : classification dans la Base de référence mondiale, (2002) 29–50 (in French). http://agris.fao.org/agris-search/search.do?recordID = XF2016060395 (accessed March 2, 2020).
[4] G. Mohamad, P.B. Lourenço, H.R. Roman, Mechanics of hollow concrete block masonry prisms under compression: Review and prospects, Cem. Concr. Compos. 29 (2007) 181–192. https://doi.org/10.1016/j.cemconcomp.2006.11.003.
[5] A. Kasthurba, V. Reddy, Use of Laterite as a Sustainable Building Material in Developing Countries, Int. J. Earth Sci. Eng. 07 (2015) 1251–1258.
[6] A. Lawane, A. Pantet, R. Vinai, J.H. Thomassin, Etude géologique et géomécanique des latérites de Dano (Burkina Faso) pour une utilisation dans l'habitat, XXIXe Rencontres Universitaires de Génie Civil. Tlemcen, 29 au 31 Mai 2011. (2011) 206–215 (in French).
[7] R.V. Ganse, Propriétés et applications des latérites au Congo beige, (n.d.) 52 (in French).
[8] M. Laquerbe, I. Cisse, G. Ahouansou, Pour une utilisation rationnelle des graveleux latéritiques et des sables de dunes comme granulats à béton Application au cas du Sénégal, Mater. Struct. 28 (1995) 604–610 (in French).
[9] M. Ndiaye, Contribution à l'étude de sols latéritiques du Sénégal et du Brésil, PhD Thesis, Paris Est, 2013 (in French).
[10] A. Lawane Gana, Caractèrisation des matériaux latéritiques indurés pour une meilleure utilisation dans l'habitat en Afrique, PhD Thesis, Le Havre, 2014 (in French).
[11] M.S. Issiakou, Caractérisation et valorisation des matérieux latéritiques utilisés en construction routière au Niger, (n.d.) 350 (in French).
[12] H.B. Takala, Caractérisation géotechnique et évaluation en construction routière des latérites de Batoufam, ouest Cameroun, (n.d.) 16 (in French)
[13] N.K. Raju, R. Ramakrishnan, Properties of laterite aggregate concrete, Mater. Constr. 5 (1972) 307–314.
[14] L.A. Balogun, D. Adepegba, Effect of varying sand content in laterized concrete, Int. J. Cem. Compos. Lightweight Concr. 4 (1982) 235–240.
[15] F. Falade, Influence of water/cement ratios and mix proportions on workability and characteristic strength of concrete containing laterite fine aggregate, Build. Environ. 29 (1994) 237–240.
[16] J.A. Osunade, The influence of coarse aggregate and reinforcement on the anchorage bond strength of laterized concrete, Build. Environ. 37 (2002) 727–732.
[17] J.O. Ukpata, M.E. Ephraim, Flexural and tensile strength properties of

concrete using lateritic sand and quarry dust as fine aggregate, ARPN J. Eng. Appl. Sci. 7 (2012) 324–331.
[18] N.W. Kamaruzaman, K. Muthusamy, Engineering Properties Of Concrete With Laterite Aggregate As Partial Coarse Aggregate Replacement, Int. J. Civ. Eng. Geo-Environ. 3 (2012) 47–50.
[19] M. Ephraim, E. Adoga, E. Rowland-Lato, Strength of laterite rock concrete, Am. J. Civ. Eng. Archit. 4 (2016) 54–61.
[20] NF P 94-056, Soil: investigation and testing - Granulometric analysis - Dry sieving method after washing (1996), Afnor, La-Plaine-Saint-Denis.
[21] NF P 94-057, Soils investigation and testing - Granulometric analysis - Hydrometer method, Afnor, La-Plaine-Saint-Denis
[22] EN 1097-7, Tests for mechanical and physical properties of aggregates - Part 7: Determination of the particle density of filler - Pyknometer method, Afnor, La-Plaine-Saint-Denis
[23] NF EN 1097-6/A1, Tests for mechanical and physical properties of aggregates, - Part 6: Determination of particle density and water absorption, Afnor, La-Plaine-Saint-Denis
[24] F. de Larrard, Concrete Mixture-Proportioning: a scientific approach, Modern Concrete Technology series No. 9, A. Bentur and S. Mindness editors, E & FN SPON (1999), 420 p., ISBN 0-419-23500-0
[25] NF EN 1097-2, Tests for mechanical and physical properties of aggregates - Part 2: Methods for the determination of resistance to fragmentation, Afnor, La-Plaine-Saint-Denis
[26] NF EN 933-8+A1, Tests for geometrical properties of aggregates - Part 8: Assessment of fines — Sand equivalent test, Afnor, La-Plaine-Saint-Denis
[27] NF P94-068, Soils: Investigation and testing — Measuring of the methylene blue adsorption capacity of a rocky soil — Determination of the methylene blue of a soil by means of the stain test, Afnor, La-Plaine-Saint-Denis
[28] C. Hendrix, W. Xing, Suitable separation treatment of stony components in construction and demolition waste (CDW), Proceedings of the International RILEM Conference on the Use of Recycled Materials in Building and Structures, RILEM Publication SARL, 166-172 (2004)
[29] EN 197-1, Cement - Part 1: Composition, specifications and conformity criteria for common cements, Afnor, La-Plaine-Saint-Denis
[30] G. Dreux, Nouveau guide Du Beton-3e edition, Collect. UTI-ITBTP. (1981).
[31] NF EN 12390-3, Testing hardened concrete - Part 3: Compressive strength of test specimens, La-Plaine-Saint-Denis
[32] B. EN, 12390-13, Test. Hardened Concr.-Part. 13 (2013).
[33] XP P 18-545 - Aggregates- Defining elements, conformity and coding, (2011), Afnor, La-Plaine-Saint-Denis
[34] F. De Larrard, T. Sedran, Mixture-proportioning of high-performance concrete, Cem. Concr. Res. 32 (2002) 1699–1704.