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Physicomechanical Properties of Mortars Based On Ordinary Portland Cement with Bauxite as Mineral Additives

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ABSTRACT

Guinea has one of the world's main reserves of bauxite that can be used as an industrial mineral to produce low-cost building materials and other parts to address the housing and industrial development difficulties in this country. In this line, mortars were manufactured by replacing 5–25 wt.% of Portland cement with raw and 600 °C calcined. Workability and setting time of fresh mortars were measured. Hard products were characterized by linear shrinkage, porosity, and structural and microstructural investigations. The two mineral additives are chemically active since they favored the reduction of the workability and setting time of mortars. In the case of calcined bauxite, ettringite and monosulfoaluminate coexisted regardless of the rate of substitution due to the higher reactivity of alumina, whereas, for raw bauxite, ettringite is only found at 5 and 10 wt.%. Heterogeneous microstructures and increased porosity were revealed with the rate of cement replacement for raw bauxite, whereas for calcined bauxite, the porosity decreased. Even the minimum compressive strengths of both series of mortars, 13 MPa for raw bauxite and 17 MPa for calcined one, enabled their application as construction materials. Favouring the porosity increase, raw bauxite is more appropriate for applications using porous materials.

Keywords: Bauxite, Mineral Additives, Mortars, Portland Cement.

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I. INTRODUCTION

The use of mineral additives as partial cement replacements has emerged as a promising method for developing hybrid cements or alternative binders. Upon the reduction of the quantity of cement in compositions, the benefits of minerals additives relate to the fresh state and hardening properties of cement and concrete. Regarding their role in the fresh state, mineral additives can be classified as chemically active for those who generally decrease workability and setting time but increase the heat of hydration and reactivity. For another class, microfiller minerals being can increase the workability and setting time but decrease the heat of hydration and reactivity [1]–[4]. It is also interesting to consider some initial characteristics of the additives, such as particle size and specific surface area, which generally influence the properties of the mixture even during the blending process. Typically, finer particles and higher specific surface area of mineral additives are favourable to low porosity with however low workability and high water demand even though the latter could be offset by adding superplasticizer [3]. It is therefore essential to establish a good compromise based on the initial properties of the minerals to optimise their positive effect in the mixtures.

Other benefits of incorporating mineral additives in cementitious materials include satisfactory improvement of the mechanical properties and durability in term of resistance to sulphate attack, chloride penetration, alkali-aggregate reaction and corrosion of embedded steel to just name a few [1]–[5]. Mineral additives are diversified, with each of them characterised by some specific characteristics through which they influence the properties of their mixture with Portland cement differently. Numerous works in the literature have investigated the effects on cement compositions of mineral additives, including fly ash, silica fume, ground granulated blast furnace slag, metakaolin, rice husk ash, bauxite residue, and so on. In virtually all cases, satisfactory improvements have been demonstrated [1], [5]. Definitively, by substituting a part of cement with these materials, cement consumption and subsequently CO_2 emission can be reduced as the cement industry produces significant amounts of CO_2 [2], [5]–[15].

The use of mineral additives, however, faces some limitations, such as pre-treatment and unavailability, which compromise their contribution to sustainable development [13]–[15]. In this view, locally available source is an opportunity that must be grasped. Bauxite is the most important current mineral resource in Guinea, which has the world's largest reserve [16]–[19]. In this work, this abundant and available bauxite is used as an additive in Portland cement compositions. The other interesting concern in this study is the exploitation of raw minerals to produce low-cost construction materials as a cost-effective and sustainable solution to the acute shortage of adequate housing in this country. For this purpose, two series of mortar formulations are investigated by partially replacing cement with bauxite quarried from Débélé in the crude state and also after calcination at 600 °C.

II. Methods

A. *Materials sampling*

Bauxite from Débélé, Kindia (Guinea) with the chemical and mineralogical characteristics presented in Table I [20], was dried at room temperature, crushed, and sieved with a 75 µm mesh to obtain a powder with a red colour corresponding to 2.5YR4/8, according to the Munsell code [21]. This powder was considered as a mineral additive and denoted as RB, it was then calcined at 600 °C in a muffle furnace with a heating rate of 5 °C/min to obtain another sample of mineral additive denoted as CB. The Portland cement used, CEM II 42.5 R, was purchased from CIMENCAM, a local cement manufacturing company, which provided properties as reported in Table I. The standard sand used was reconstituted from a local river and fine sands by dry sieving using a set of sieves, which also give the size distribution. On this basis, the fineness modulus, sand equivalent, and class index were estimated according to the ASTM C33 and ASTM D2419-95 standards [22], [23] (Table I).

TABLE I: Physico-Chemical and Mineralogical Characteristics of the Starting Materials [20]

Materials	Bauxite		Cement	Sand
	Raw	Calcined	CEM II 42.5	
Chemical composition (%)				
Al_2O_3	46.06	61.91	–	–
Fe_2O_3	23.80	31.99	–	–
SiO_2	1.74	2.34	–	–
TiO_2	1.74	2.34	–	–
CaO	0.06	0.08	–	–
P_2O_5	0.06	–	–	–
Cr_2O_3	0.18	0.24	–	–
SO_3	0.09	–	2.5–3.5	–
Cl^-	–	–	0.02–0.04	–
MgO	<0.01	<0.01	2.5–3.0	–
$Na_2O + K_2O$	< 0.02	<0.02	1.2–1.5	–
Insoluble	–	–	8–12	–
LOI	25.6	–	–	–
Semi quantitative composition (%)				
Gibbsite	69.5	–	–	–
Hematite	23.80	–	–	–
Quartz	1.74	–	–	–
Anatase	1.74	–	–	–
Gypse	–	–	3.5	–
Clinker	–	–	65 - 79	–
Pozzolan	–	–	21 - 35	–
Amorphous phase (%)	30.8	–	–	–
Pozzolanicity (mg (CH)/g)	748	–	–	–
Physical Properties				
Specific surface area (m^2/g)	3.60	4.32	3.8–4.1	–
Density (g/cm^3)	2.66	–	3.06	2.63
Sieve < 45 µm (%)	–	–	> 94	–
Water demand (WD)(%)	–	–	28–31	–
Setting time (min)	–	–	≥ 60	–
Fineness modulus (%)	–	–	–	2.30
Sand equivalent (%)	–	–	–	89.61
Class index	–	–	–	0/2

B. *Mortar Formulation and Characterisation*

Mortars were prepared by mixing standard sand (S), binder (B) and demineralised water (W). The binder was either 100 wt.% Portland cement (control mortar, CM) or a mixture of 95–75 wt%. Portland cement + 5–25 wt.% of one of the abovementioned mineral additives (RB or CB), as indicated in Table II. The mass ratio of sand to binder (S/B) was three, as indicated by the EN F 196-1 standard [24]. The water to binder mass ratio (W/B) corresponded to good workability and then the normal consistency of 0.6±0.1 cm given on the Vicat apparatus used, as indicated by the EN F 196-3 standard [25]. The good workability, which is the ease and homogeneity with which the fresh blend of starting materials can be mixed, placed, consolidated and finished according to the EN F 196-1 standard, was obtained after many trials. The W/B mass ratio, which was finally retained for its satisfactory fulfillment, was equal to 0.5 for the CM, 0.58 for hybrid mortars with RB and varied from 0.58 to 0.64 for hybrid mortars with CB.

For each formulation, the mixture was homogenized in an automatic mixer of the CONTROLAB type, branded MIX MATIC, fresh pastes were characterized by the measurement of the setting time and the consistency using the Vicat apparatus according to NF EN 196-3 Standard. Furthermore, fresh mortars were shaped into parallelepiped test specimens of 4×4×16 cm^3 in a plastic mould and then vibrated for 15 s on an electrical vibrating table (M & O. type 202, N° 106) in order to remove entrapped air bubbles before storing under a plastic film in a wardrobe at 100 wt.% humidity at 20 °C for 7, 28, 45, and d for setting. At each said age, specimens after demoulding were subjected to linear shrinkage measurements using a digital caliper, the determination of water absorption rate, apparent density, and open porosity through Archimedes' test, the compressive strength test using an electrohydraulic press, type ENERPAC 3R according to NF EN 1015-11 Standard. For the latter, the result presented was the average of six tests; whereas, for the former tests, it was the average of three.

TABLE II: COMPOSITION OF MORTARS

Types of mortar	%PC	%RB or CB
CM	100	0
RB5	CB5	95
RB10	CB10	90
RB15	CB15	85
RB20	CB20	80
RB25	CB25	75

CM: Control Mortar; PC: Portland cement; RB: Raw Bauxite; CB; Calcined Bauxite.

Structural phases were determined from X-ray powder diffraction (XRD) on ground samples at 40 μm using a Bruker D8 Advance diffractometer equipped with a copper anode (λ= 1.5418 Å) and a graphite monochromator. The models were acquired with a step size of 0.01° (2θ) and a time per step of 0.1 s. Crystalline phases were identified by comparing the models with the standards of the powder diffraction file. This analysis was completed by Fourier transform infrared spectroscopy using a Bruker spectrometer in absorbance mode between wavenumbers of 4000 and 400 cm^{-1}. Samples were obtained by the KBr cap method. Microstructural observations on broken species were carried out using an optical microscope equipped with a stereomicroscope (Ceramics Instruments Model 101T - M7) with a binocular head and a Tablet 7 with an integrated micro camera.

III. RESULTS AND DISCUSSION

A. *Fresh Mortars Characteristics*

1) *Workability*

As observed during the preparation of mortars, the W/B mass ratio remained constant and equalled to 0.58 for mortars with RB as mineral additive, while for mortars with CB, it increased with the amount of additive, from 0.58 to 0.66 for 5 to 25 wt.% (Fig. 1). This ratio is also the measure of the demand in water of the blend; it is related to the nature of the sand used. However, at an equal amount of aggregate, the effect of the reactivity of the mineral additive can be noted since the chemical reaction of cement with water are responsible for the setting and hardening of mortar. The high demand of water can then be considered as an indicative of high reactivity of the binder with the consequently high performance of issued products. The presence of the bauxite increases the hydration capacity of the blended cement, it includes alumina, which is one of the two main components along with silica involved in formulating C-(A)-S-H gels with calcium during hydration. It is therefore obvious why the CB that provides activated alumina promoted more the reactivity of the mixture compared to the RB.

The higher activated character of the CB can be related to its greater rate of amorphous and specific surface area (51.2% and 4.32 m^2/g) compared with those of the RB (30.8% and 3.6 m^2/g) respectively, as indicated in Table I. For both series, the W/B ratio is above that of the control mortar, which is 0.5. This can be explained based on the results of some previous works, which demonstrated that larger particle size inclusions in cement lead to higher water requirements of the hybrid binder [10], [26]. Furthermore, Laoufi *et al.* [26] found that the great demand for water is linked to the higher pozzolanic activity, this is one of the typical cementitious activities of minerals. On this basis, the high W/B mass ratio is an advantage from the point of view of durability, while conversely, a low W/B ratio often causes auto dehydration, which presents drawbacks, like the appearance of cracked products [27].

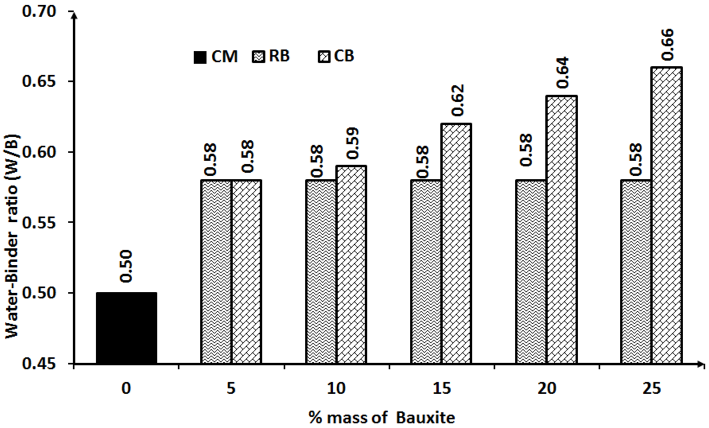

Fig. 1. Water to binder (W/B) mass ratio as a function of the amount of mineral additive:
RB: Raw Bauxite, CB: Calcined Bauxite; CM: Control Mortar.

2) *Setting time*

Fig. 2a and b showed the evolution of the initial and final setting times of mortars as a function of the number of mineral additives. In comparison to those of the control mortar, the setting times decrease with increasing additive for both series, but the reduction is more significant in the case of CB. It can then be admitted that the addition of bauxite, either at the crude state or calcined tended to accelerate the setting process of the hybrid cement. This effect may be explained by the presence of aluminum oxide, which is holistically the component that controls the setting time when its pair silica role is to alter the mechanical strength of the cement composition.

It can be noticed that the decrease in setting times, initial and final, is in good agreement with the increase of W/B ratio discussed above. When the amount of additive increases, the quantity of alumina naturally increased, the relative amount of water to ensure the workability of mixture also increased, and the hardening process is accelerated. This is due to the fact that part of the water is used for alumina species thus competing with cement [28]–[30], the remaining free portion available for combination with cement particles was consumed rapidly. Correspondingly, this caused the slowing of setting as shown on Fig. 2b, the acceleration of the hydration process and the decrease of workability. Assuming that for each parameter and in comparison with RB, the effect is more intensive in the case of calcined bauxite due to its activated character as mentioned above. The two additives, RB and CB, can however be both classified as chemically active mineral additives since they reduce the workability and setting time in agreement with some authors [1]–[4].

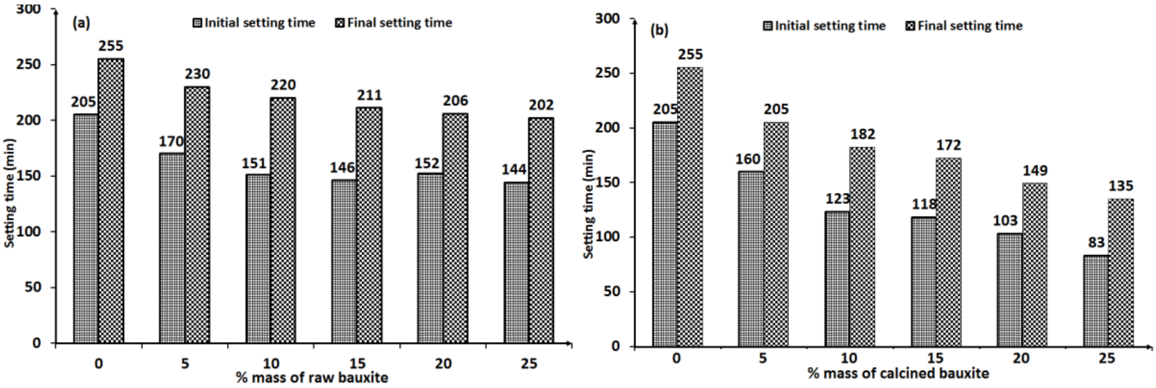

Fig. 2. Evolution of the setting time of pastes as a function of bauxite percentage: (a) Raw bauxite; (b) Calcined bauxite.

B. *Hardened Mortar Characteristics*

1) *Mineralogy and microstructure*

The XRD patterns of mortars at 90 d of age (Fig. 3a-b) revealed the presence of quartz and Portlandite in all the mortars, as well as ettringite (E) and calcium monosulfoaluminate (Afm) in the case of the hybrid mortars. However, in the case of RB, E was found in only mortars with 5, 10 and 15 wt.% additions, it was no more identified in the RB 15, RB20 and RB25 hybrid mortars with 15, 20 and 25 wt.%, respectively.

Quartz mainly originated from the sand added as filler in the binder pastes. The other phases are known as secondary hydrated products besides the main compound C-S-H/C-A-S-H type gel. E is actually an early-age product formed after mixing cement and water. Its amount decreases gradually with continued hydration depending on the starting material composition among other parameters. This favored the formation of other phases, such as Afm, based on the balance between alumina and sulphate. In fact, the presence of more alumina than sulfate would eventually favor the Afm, an explanation that is applicable in the case of mortars with raw bauxite. In the case of calcined bauxite, the higher reactivity of alumina may be considered since E and Afm coexisted no matter the rate of mineral additive in the mixture.

The above mineralogical composition of the mortars was confirmed by Fourier transform infrared spectroscopy (Fig. 4a-b). The spectra of both series of hybrid mortars and those of control mortar displayed similar bands of absorption. Characteristic absorption bands of O–H in portlandite can be observed at ~1400 and ~1000 cm^{-1}, whereas those of S–O in ettringite are at 700 cm^{-1} and also at ~1100 cm^{-1} [31]-[33]. The shape of bands between 1000 and 1100 cm^{-1} is almost identical to that of bands in the control mortar, suggesting the prevalence of O–H in Portlandite absorption in this area. This corroborates the absence or the presence at the non-detectable limit (in 15–25 wt.% RB) and the low amount (5 and 10 wt.% RB) of ettringite, as deduced from XRD (Fig. 3a).

In the case of calcined bauxite, where portlandite and ettringite co-exist in all the formulated mortars, as seen from the XRD patterns (Fig. 3b), the superposition of absorption bands O–H (in portlandite) and S–O (in ettringite) led to splitting form that is increasingly visible as the amount of mineral additive increased. It can then be concluded that the calcined bauxite favoured the stability of ettringite in the mixtures, ability, which is limited with raw bauxite. Furthermore, O–H in hydration groups can be exhibited by the bands at 3400, 1500 and 700 cm^{-1}. C–O stretching vibration bands also known as C–O as triplet bands were also observed at 1400, 870 and 700 cm^{-1}, carbonate group can be pointed even though none was identified by XRD [31], [33]-[34]. The bands at 780, 530 and 450 cm^{-1} are due to S–O of quartz.

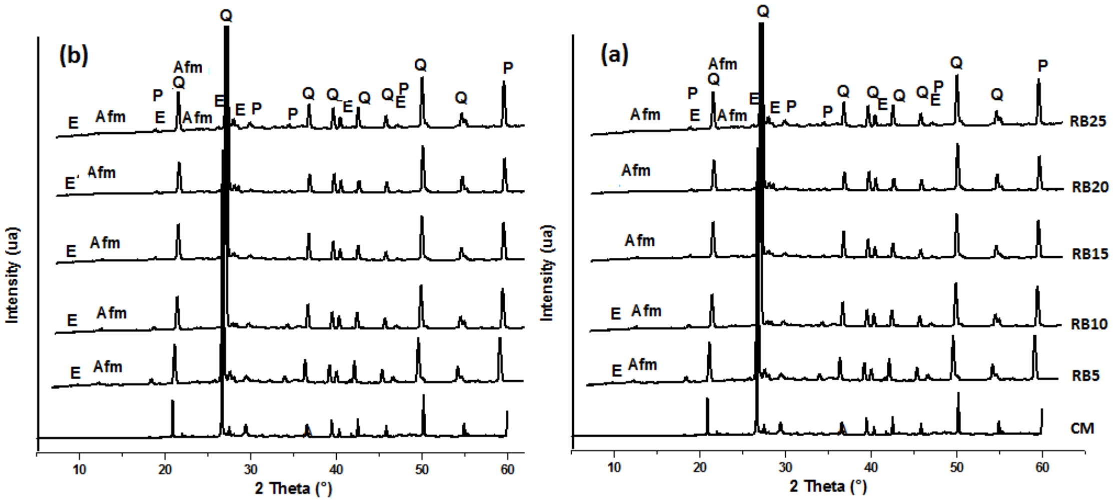

Fig. 3. X-rays patterns of mortars after 90 days (a) with raw bauxite; b) with calcined bauxite. P: Portlandite $Ca(OH)_2$ (PDF: 44-148); E: Ettringite $Ca_6Al_2(SO_4)_3(OH)_{12}.26H_2O$ (PDF: 41-1451); Afm: Monosulfoaluminate $Ca_4Al_2SO_{10}.12H_2O$ (PDF: 45-158); Q: SiO_2 (PDF 89-8934).

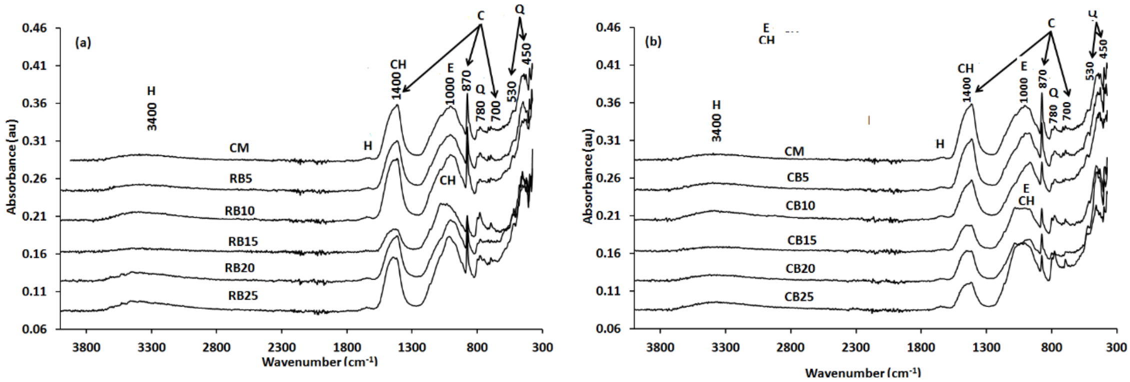

Fig. 4. Infrared spectra of mortars after 90 days: a) with RB; b) with CB H: hydrogen; CH: Portlandite; C: Calcite; E: Ettringite; Q: Quartz.

Images from optical microscopy of test discs with 0, 5, 10 and 15 wt.% mineral additives (Fig. 5) revealed heterogeneous morphology for all mortars. The sole difference is at the level of compactness, distribution and interconnection of different visible granular phases within the continued matrix phase, giving a three-dimensional-like network. This morphology appeared less compact with a high occurrence of pores in the control mortar, with increasing mineral additives for raw bauxite, whereas for calcined bauxite, there is a pore reducing trend. The hydrated phases formed during hydration, as demonstrated XRD analyses, reduced the space between the particles, resulting in the rearrangement of particles and obviously to less porosity. Referring to the conclusions drawn by Dalod *et al*. (2014), it can be inferred that the change in microstructure is closely linked to the formation process of ettringite and hydrated monosulfoaluminate, which were found to be responsible for partial pore clogging [35]. Accordingly, the progressive compactness with the amount of mineral additive from the control mortar can be established as a noticeable response to the relative presence of the abovementioned secondary phases.

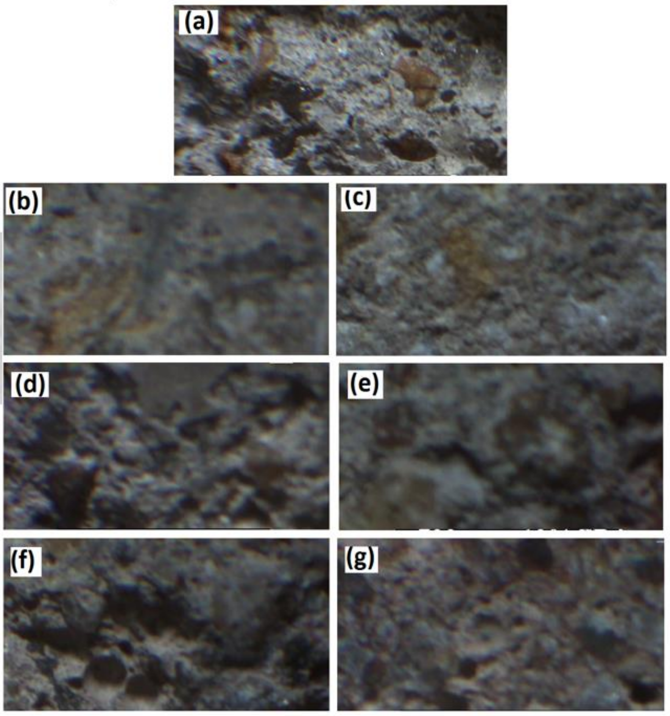

Fig. 5. Morphology of mortars obtained by optical microscopy.

2) *Physical properties and compressive strength*

The linear shrinkage of test-discs, Fig. 6a, and b, increased with the age both in the raw bauxite and calcined bauxite series. In the former case, a systematic decrease is observed with increasing RB in the mortar formulations, whereas in the latter case, a slight increase was observed at 5 wt.% of additive and then the decrease was followed with increasing CB. Furthermore, values are lower in mortars based on raw bauxite than those of the control mortar, whereas those of calcined bauxite series are generally greater. In general, the linear shrinkage is a reduction in structure dimensions related to the capillary surface. This is after the departure of free water from moisture and physicochemical transformations occurred in the system [36]-[38]. Since these transformations are mainly the hydration which proceeds with water and binder continuous consumption and the formation of new phases, it can be concluded that the shrinkage is related to the degree of chemical binding of water in the hydrated phases. The low bonds obviously lead to high shrinkage. Even though it is theoretically admitted that these new phases occupy almost the same volume as the original binder and water, the occurrence of structural readjustment remains due to the relative steric hindrance.

Moreover, one of the more likely formed phases is actually an amorphous gel with a highly variable stoichiometry, mainly depending on mix design, thus on the initial materials. An upward trend of shrinkage is generally observed with the increase of the amount of activators in the formulation [39]. RB and CB have been thereby shown earlier to be active additives, i.e., activators. In accordance, CB, much more active given its larger amount of amorphous phase and specific surface area compared to RB, led to greater linear shrinkage values. The overall trend of shrinkage remained at low values, the greatest values corresponding to 90 d of age ranged from 0.8% for control mortar to 0.7% for the RB5 series and to 0.8% for the CB5 series. It is important to note that shrinkage is an undesirable property from the technological point of view; the possible least values are hence preferred as the stability of the product is concerned. The reduction of shrinkage obtained can then be quoted as an advantage to the addition of the raw bauxite and much more than the calcined bauxite.

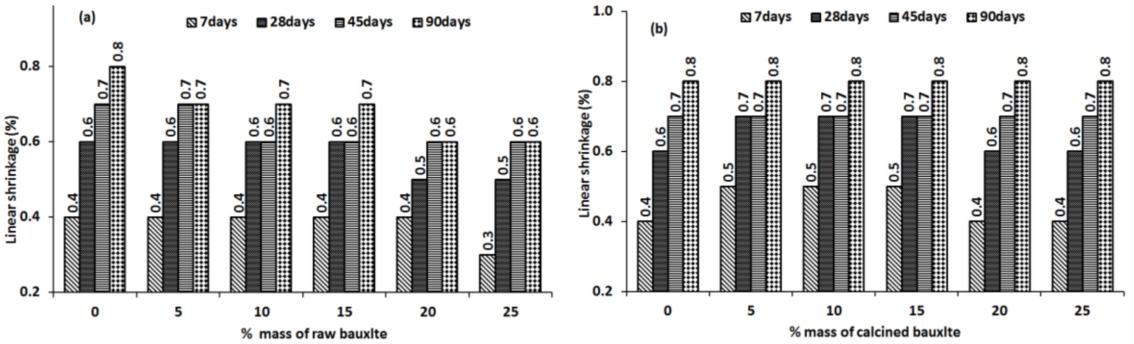

Fig. 6. Evolution of linear shrinkage as a function of bauxite percentage: a) with raw bauxite; b) with calcined bauxite.

As shown in Fig. 7a and 7b, the apparent density of control mortar test discs is close to 2.1 g/cm^3, it remained unchanged with age. Those of the mortars with raw and calcined bauxite additives were somewhat lower, a slight increase with age can be noticed but the increment is small. Values are greater in mortars with calcined bauxite compared to those of mortars with raw bauxite. In general, the values of apparent density for the control mortar and mortars with either raw bauxite or calcined bauxite are close. The structuring role of sand as aggregate is predominant since its amount is the same in all the compositions; it has a similar effect inducing a levelling-up effect of the density values.

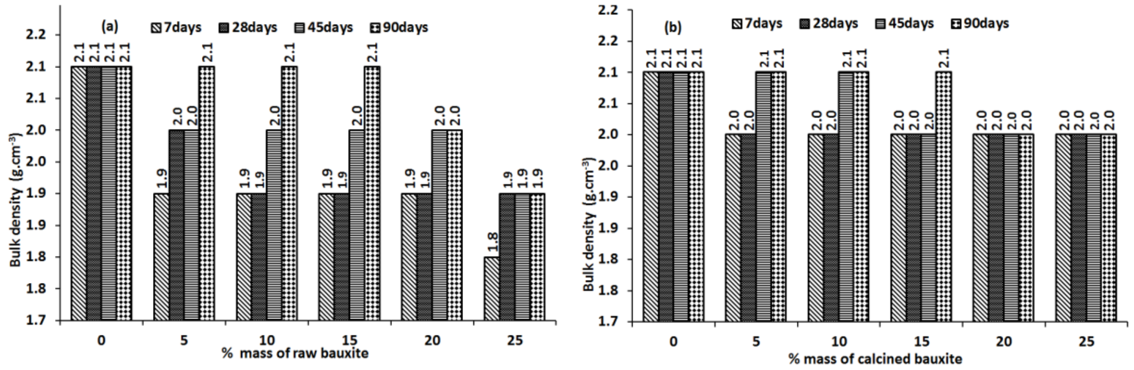

Fig. 7. Evolution of bulk density as a function of bauxite percentage: a) with raw bauxite (RB); b) with calcined bauxite (CB).

The open porosity (Fig. 8) decreased with age and increased with the amount of the additive in the mixes. At the given amount of mineral additive, test discs with raw bauxite showed higher values compared to those of the control mortar, in reverse with calcined bauxite series values remained lower. For instance, the highest value of open porosity is 22.5% corresponding to the highest rate of substitution (25 wt.%) of raw bauxite at 7 d, it lessened to 17.5% and 17% at 45 and 90 d, respectively. For the same amount of calcined bauxite, the highest value is ~16.9% at 7 d, which fell to 13.3 and 6.6% at 45 and 90 d, respectively.

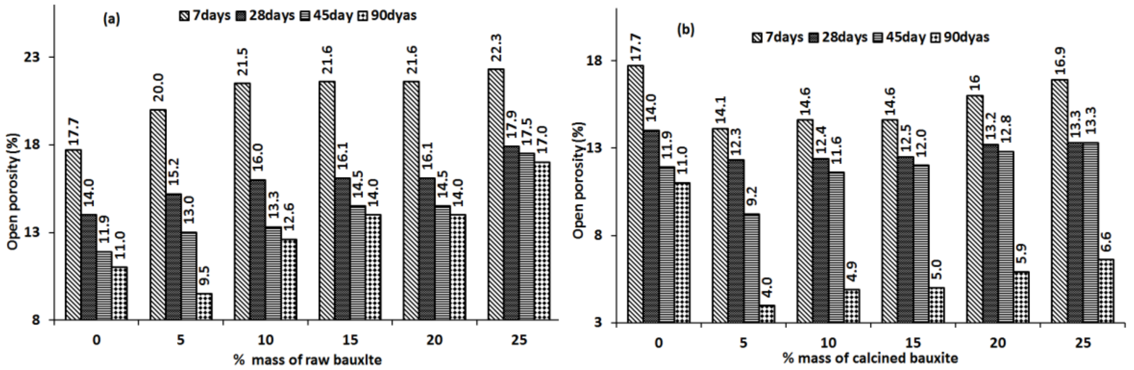

Fig. 8. Evolution of open porosity as a function of bauxite percentage: a) with raw bauxite (RB); b) with calcined bauxite (CB).

For the same amount of calcined bauxite, the highest value is ~16.9% at 7 d, which fell to 13.3 and 6.6% at 45 and 90 d, respectively. This is an indication of the continued hydration, which gradually yielded hydrated phases. The change in quality and quantity of these phases produce a progressive reorganisation of the structure following the variation of physical and mechanical properties of product. With the assumption that cementitious products are typically used for both structural and sewer applications such as construction material, the low value of porosity is indicative of good performance and even a good durability of the formulated mortars which are prone to be chemical resistant [40]–[41]. Mortars with raw bauxite exhibited an increase in open porosity, whereas those of calcined bauxite increased with the rate of mineral additives. However, the rate of decrease remained low for calcined bauxite, leading values close to those of the control mortar for the same age. In reverse, the rate of increase is big for raw bauxite resulting to more high values. The water absorption rate of mortars (Figs. 9a-b) displayed increase with bauxite additives in comparison to the control mortar, exception equally occurred in the case of 5 wt.% calcined bauxite where reduction was observed.

Like open porosity, water absorption rate is a basic parameter for porosity evaluation. In this view, formulation containing 5 wt.% of calcined bauxite is interesting as the additive allow to reduce the porosity required for sewing application. Elsewhere, it can be pointed out that calcined bauxite provided very little increase in porosity in reverse to raw bauxite that favored higher porosity. Similar observation was drawn with the used of metakaolins that had reduce effect on the porosity, but further investigation showed a reduction in the proportion of macropores and then to finer porous structure [42]-[44]. Porous structures are also interesting for many other applications, such as depollution via adsorption of undesirable substances and heavy metals [40], [41], [45]. According to some authors [40], [43], [44], porosity could have a dual role within materials. The first is to provide additional space to accommodate expansive phases formed, thus a positive effect on durability. The second is to help reduce the penetration of aggressive agents, such as sulphates and improve the strength of mortars at limited porosity values. We can therefore conclude that the use of raw bauxite additive favours the increase of porosity, whereas that of calcined bauxite promoted low porosity.

Although both additives are aluminium base compounds, structural difference exists concerning the structure which is crystalline for raw bauxite (gibbsite) and instead amorphous for calcined bauxite (metastable alumina). It can then be inferred that structure has determinant role on the reactivity of the added compounds, depending on the treatment performed on bauxite, it is possible to reduce the porosity in comparison to that of the control mortar, but with raw bauxite, value remained high in contrary to calcined bauxite [46]-[47]. The reduction of the porosity with the increase of mineral additives was previously observed on the microstructure discussed above regards the increased compact matrix and particles connexion. Still in the assumption that the use of cement is for sewer, regarding the variation of rate of water absorption (Fig. 9a-b), a similar development to that of open porosity was observed. It can be seen that the mortars containing raw bauxite have high values compared to those of the control mortar at each age, whereas those with calcined bauxite are relatively low. The highest absorption at 90 d corresponding to 25 wt.% raw bauxite is 7.9%, for mortars containing calcined bauxite, the greatest absorption at 90 d is 5.6% for 25 wt.% calcined bauxite. These observations on water uptake correlate well with those already made with the open porosity. In addition, these results corroborate those of previous studies which have shown that mineral additives can either contribute to the reduction of absorption [48] or maintain the pore network at the same level as the cement they replaced [45] through the development of the pozzolanic reaction. The progressive decrease in absorption, like porosity, could be linked to the precipitation of hydration products, CSH on the one hand, and on the other hand, the formation of ettringite known for its expansive character [32], [45], [49] and which contributes to the reorganisation and sometimes the decrease of pores in the hybrid mortars. Meanwhile, the decrease of the absorption rate with age is linked to the increase of the durability of products obtained as it corresponds to the accentuation of the densification and the mechanical strength of the material [50].

Regarding the compressive strength of mortars (Fig. 10), there is an increase with the age in all formulations, which is consistent with ongoing continued hydration process. For each series, the compressive strength showed decrease with the increase amount of mineral additives for both series of mortars, but the values remained higher for calcined bauxite than for raw bauxite. Exemption is noticed on the formulation with 5 wt.% of calcined bauxite which exhibited, from 28 days of age, values of compressive strength higher than those of the control mortar. The decrease observed with the increase amount of additives is almost linear for both series but the rate of decreasing is speedy for raw bauxite series, 13.3% at 5 wt.% to 51.5% at 25 wt.%. Whereas for calcined bauxite, the decrease stated instead at 10 wt.% with a rate of 16.5% till only 32.6% at 25 wt.%. A systematic decreasing effect of the two additives with the difference at the level of intensity can be suggested, pointing their common pozzolanic property and amount of amorphous phase. Referring to Table I, the pozzolanic activity and the amount of amorphous phase are respectively 748 mg (CH)/g and 30.8% for raw bauxite against 999.9 mg (CH)/g and 51.2% for calcined bauxiteThis is an indication of the continue hydration, which gradually yielded hydrated phases. The change in quality and quantity of these phases produce a progressive reorganisation of the structure following the variation of physical and mechanical properties of product. With the assumption that cementitious products are typically used for both structural and sewer applications such as construction material, the low value of porosity is indicative of good performance and even a good durability of the formulated mortars which are prone to be chemical resistant [40]–[41]. Mortars with raw bauxite exhibited an increase in open porosity, whereas those of calcined bauxite increased with the rate of mineral additives. However, the rate of decrease remained low for calcined bauxite, leading values close to those of the control mortar for the same age. In reverse, the rate of increase is big for raw bauxite resulting to more high values. Water absorption rate of mortars (Figs. 9a-b) displayed increase with bauxite additives in comparison to the control mortar, exception equally occurred in the case of 5 wt.% calcined bauxite where reduction was observed.

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These two properties are all-inclusive parameters that contribute to the mechanical strength evolution since they control the diverse hydrated phases formation. In this work, the role of the pozzolanic activity of the additive is very important to evaluate its behaviour in the mixture. The raw bauxite has a pozzolanic activity close to the standard limit value of 700 mg(CH)/g whereas that of calcined bauxite is closer to those of high cementitious materials like metakaolin. Nonetheless, the decrease in mechanical strength observed is similar to some results found in the literature [52]–[54], especially when replacing Portland cement with alumina compounds [15], [28], [29]. It is noteworthy that the obtained values are all satisfactory from a technological point of view, the lowest value of 13 MPa for 25 wt.% of raw bauxite is still acceptable for non-demanding structural applications and secondary construction activities according to many standards [55]–[58].

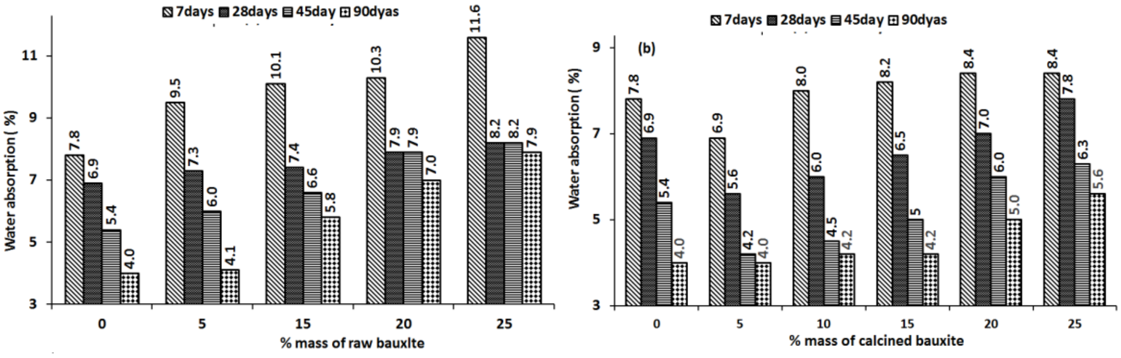

Fig. 9. Evolution of the water absorption rate as a function of the bauxite percentage:
a) with raw bauxite (RB); b) with calcined bauxite (CB).

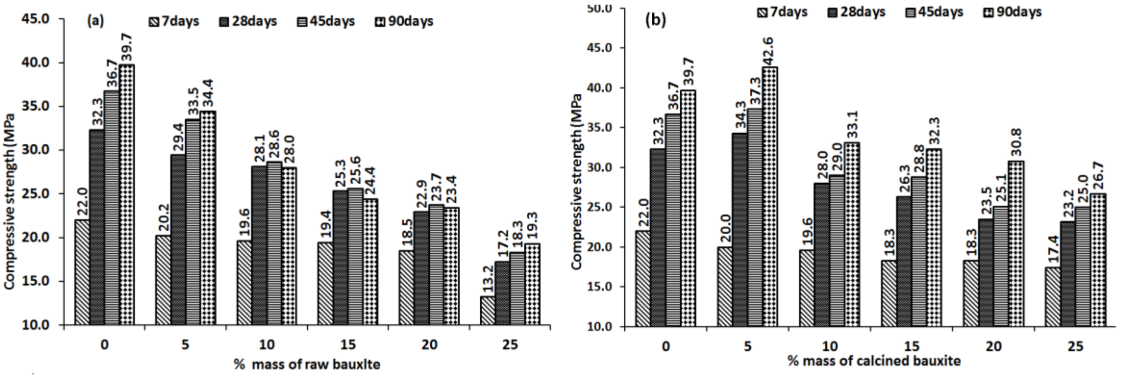

Fig. 10. Evolution of the compressive strength as a function of the percentage of bauxite:
(a) with raw bauxite (RB); (b) with calcined bauxite (CB).

IV. CONCLUSION

The characterisation of mortars formulated with 5–25 wt.% Portland cement replaced by raw bauxite and calcined at 600 °C, respectively, resulted in the following conclusions:

1) Mortars with raw or calcined bauxite additives hardened faster than the control mortars;

2) The two types of mineral additives favoured limited linear shrinkage of the test specimens, less than 1% after 90 d;

3) Raw bauxite favoured high porosity, orientating the application of hybrid mortars obtained to more appropriate porous material applications. Whereas calcined bauxite is prone to obtained low porosity for both structural and sewer applications such as construction materials;

4) The minimum compressive strength is higher than 13 MPa for the two types of hybrid series of mortars. This value is still acceptable for non-demanding structural applications and secondary construction activities according to many standards. For high performance, 5 wt.% of calcined bauxite is recommendable since the strength is higher than those of the control mortar.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest.

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