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Article

Improving the properties of alluvial sand, a potential alternative to standardized sand for geotechnical laboratory

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Abstract: Despite Cameroon's immense sand reserves, several enterprises continue to import standardized sands to investigate the properties of concretes and mortars and to guarantee the durability of built structures. The present work not only falls within the scope of import substitution but also aims to characterize and improve the properties of local sand (Sanaga) and compare them with those of imported standardized sand widely used in laboratories. Sanaga sand was treated with HCl and then characterized in the laboratory. The constituent minerals of Sanaga sand are quartz, albite, biotite, and kaolinite. The silica content (SiO_2) of this untreated sand is 93.48 wt.%. After treatment, it rose 97.5 wt.% for 0.5 M and 97.3 wt.% for 1 M HCl concentration. The sand is clean (ES, 97.67%–98.87%), with fineness moduli of 2.45, 2.48, and 2.63 for untreated sand and sand treated with HCl concentrations of 0.5 and 1 M respectively. The mechanical strengths (39.59–42.4 MPa) obtained on mortars made with untreated Sanaga sand are unsatisfactory compared with those obtained on mortars made with standardized sand and with the expected strengths. The HCl treatment used in this study significantly improved these strengths (41.12–52.36 MPa), resulting in strength deficiencies of less than 10% after 28 curing days compared with expected values. Thus, the treatment of Sanaga sand with a 0.5 M HCl concentration offers better results for use as standardized sand.

Keywords: standardized sand; HCl treatment; mortars; mechanical strength; Sanaga

1. Introduction

Every year, an estimated 4 billion cubic meters of concrete and mortar are used for infrastructure development through the construction of various buildings such as administrative structures, residential complexes, bridges, freeways, dams, airports, etc. [1,2]. For the formulation of concrete, aggregates (sand and gravel) are the most widely exploited solid materials in the world, with production estimated at between 25.9 and 29.6 billion tonnes per year [3]. According to a new report by the United Nations Environment Programme (UNEP), sand is the second most used resource in the world after water [4].

Despite the general development of infrastructure, numerous problems, such as the collapse of buildings, bridges, and pipes and the premature deterioration of infrastructure, have recently been observed in developing countries, particularly in Cameroon. These problems are very often linked to the poor quality of the materials used and the poor formulation of the concretes and mortars employed. In addition, there is insufficient monitoring of compliance with standards. These standards, sometimes of foreign origin, are costly and not always available on time. It is therefore essential to study the various physico-chemical and mechanical properties of the materials used in the manufacture of mortars and concretes to guarantee their quality and performance in construction. Sand is a granular material composed of fine rock and mineral particles [5]. Alluvial sands are naturally occurring sands resulting from the weathering of pre-existing rocks. Depending on its qualities, sand is the element with the greatest influence on concrete. Indeed, cleanliness, fineness modulus, and particle size distribution are the main physical characteristics used to control sand quality [5]. In the laboratory, standardized sand is generally used to test cement, concrete, and mortars. To date, studies on the development of standardized sand in the tropics are rare as many African countries continue to import standardized sand. It should also be noted that, given the long distances involved in obtaining standardized sand (mainly imported from outside the continent), this sand, although indispensable, is becoming very expensive and may be inaccessible to many individuals [6,7]. More recently, several crises, notably the coronavirus (COVID-19), have disrupted the global economy and transactions. This has led to a shortage of standardized sand in markets south of the Sahara and Cameroon in particular. It would therefore appear that sand exploitation is of great importance to the African economy [6] and to the quality of built structures. This underlines the need to study the possibility of valorizing and standardizing local materials, particularly sand, according to their geotechnical specificities, for use in construction. In Congo, some researchers [7] have carried out work to develop local standardized sand by selecting local sands with characteristics close to the required standards and determining their chemical compositions.

In Cameroon, there are large reserves of alluvial sands in rivers and valleys that could have the characteristics required for the design of standardized sands and bring undeniable added value to the local material that sand represents. However, very little work has been devoted to the characterization and development of standardized sand. The present study therefore aims to: (1) characterize the natural alluvial sands of the Sanaga, improve their non-conforming characteristics, and obtain mechanical strengths that meet geotechnical standards; (2) formulate recommendations for the production of standardized sand locally, in compliance with current standards. The ultimate objective is to eliminate the undesirable elements contained in these sands, notably by hydrochloric acid treatment.

2. Localization

The Sanaga River stretches from latitude 3°32′ N to latitude 7°22′ N, with its most westerly point at meridian 9°45; it reaches meridian 14°57′E and drains a succession of plateaus bounded to the west by the Cameroon ridge and to the north by the Adamawa plateau. The Sanaga River is 918 km long and 20 m deep, stretching over some 130,000 km^2. The section of the Sanaga studied, from which the samples were collected, concerns the locality of Nanga-Eboko, a division in the Central region of Cameroon, 166 km from Yaoundé. The middle part of the Sanaga corresponds to the portion of this river in the study area. **Figure 1** illustrates the location and hydrographic network of the Sanaga at the mouth of Nanga-Eboko. Geologically, the Sanaga watershed is made up of a vast ensemble of crystalline schists composed of ectinites, migmatite, and concordant ancient eruptive rocks represented mainly by syntectonic granites [8].

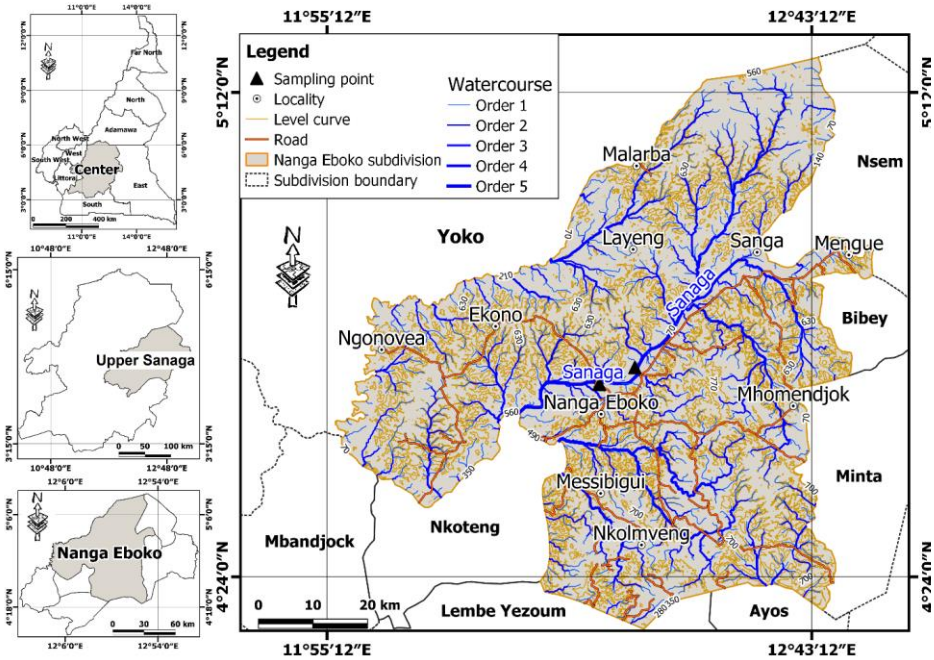

Figure 1. Localization map of the studied site.

3. Materials and methods

3.1. Materials

Figure 2. Representative sample of Sanaga sand.

Sanaga sand is in great demand and is used as aggregate for construction. The Sanaga sand reserve is the largest in Cameroon’s center region. The sand samples (**Figure 2**) used for this study were local sands (a representative sample obtained from a mixture of several samples taken along the river) and the EN 196-1 standardized sand more widely used in laboratory tests in Cameroon and the sub-region. Samples were taken along the watercourse. After macroscopic description, the two samples shown on the map were selected. On the basis of the similarities observed between the samples, these two samples represent the sands of this watercourse. These samples were then mixed to obtain a representative sample.

Class 52.5R compound Portland cement (CEM II) was also used in this project. This cement was chosen for the mortar samples because of its mechanical performance, reduced water content, and rapid setting.

3.2. Methods

3.2.1. Physical characterization

The water content is used in this work to determine the moisture content by weight of the sample. This test was carried out following standard NF P 94-050 [9], using a series of successive weightings before and after oven drying (24 h at 105 °C) of the representative sand sample.

Granulometric analysis consists of establishing a dimensional distribution of the different particles in the sand studied, expressed as a percentage by mass. The test consists of classifying the different grains making up a sample using a series of sieves nested one on top of the other, with openings decreasing in size from top to bottom. This test was carried out under standard NF P 94-056 [10].

The fineness modulus is obtained from particle size data. It expresses the fineness of sand. It is obtained by standard NF P 18-540 [11] and expressed as Equation (1).

$$\text{fm} = \frac{\%R_{1.25} + \%R_{0.63} + \%R_{0.315} + \%R_{0.16}}{100} \quad (1)$$

where:

fm is fineness modulus.

*R*x is refusal corresponding to a sieve opening *x*.

Sand equivalent (SE) is used to measure the degree of cleanliness of sand. It consists in measuring the quantity of very fine elements contained in the sand. The test was carried out by flocculation on the 0/2 sand fraction following standard NF P 18-598 [12]. The sand equivalent value is expressed as Equation (2).

$$\text{ES} = \frac{H_2}{H_1} \times 100 \quad (2)$$

where:

H_1 is flocculate height.

H_2 is height of clean sand.

Apparent density corresponds to the mass per unit apparent volume of the material, i.e., the volume made up of solid grains and voids. This test was carried out per standard NF EN 1097-3 [13]. Specific density does not take voids into account. It is obtained by the pycnometer method under standard NF P 94-054 [14].

Mortars were formulated from two different types of sands (sand extracted from the Sanaga River and standardized sand) using EN-196-1 [15] standard method. To determine compressive strength, specimens of formulated mortar were subjected to an increasing load until failure following NF EN 12390-3 [16] standard. The failure load is the maximum load recorded during the test, and the compressive strength is the ratio of the failure load to the cross-sectional area of the specimen; the results are obtained using Equation (3).

$$R = \frac{F}{S} \tag{3}$$

where:

R is compressive strength in MPa;

S is cross-sectional area of the specimen to which the compressive force is applied;

F is maximum load in Newtons.

Flexural strength is the limiting stress of a material before flexural failure. It is used to determine the relative variation in bond forces between particles of a material. This test was carried out following standard NF P 94-422 [17]. Flexural strength, in MPa, is given by Equation (4).

$$F = \frac{3}{2} \times \frac{Pd}{le^2} \tag{4}$$

where:

d is the distance between cylindrical supports in mm;

e is specimen thickness in mm;

P is the load applied at the failure in Newton (N);

l is the width of specimen in mm.

3.2.2. Chemical and mineralogical analysis

Chemical analysis by X-ray fluorescence (XRF) spectrometry

Chemical analysis by X-ray fluorescence (XRF) spectrometry was carried out in the laboratory of Société des Cimenteries du Cameroun (CIMENCAM). This technique aims to determine the mass content of major oxides such as SiO_2, Al_2O_3, Fe_2O_3, MgO, Na_2O, CaO, and K_2O. The chemical composition of the sand was obtained after heating and melting with a lithium tetraborate flux and analyzed using a Pan Analytical Axios Advanced PW4400. Loss on ignition is defined as the variation in mass resulting from heating a sample under specific conditions. It is used to assess the non-volatile organic matter content of waste, sludge, and sediment.

Sand treatment

The treatment aims to remove undesirable particles from Sanaga sand samples. The treatment consists mainly of removing oxides and alkalis by hydrochloric acid attack. Purification of sand with hydrochloric acid (HCl) is often preferred to simple washing with water for several scientific and technical reasons. Hydrochloric acid can dissolve certain mineral impurities present in sand, such as iron oxides, carbonates, and silicates. These impurities are not always soluble in water and may require chemical treatment to be effectively removed. Washing with water can remove surface particles and soluble contaminants. However, it is often insufficient to remove more stubborn contaminants or fine particles adhering to sand grains. Hydrochloric acid, on the other hand, can penetrate deeper and dissolve these contaminants for a more thorough cleaning. The procedure used for HCl treatment consisted of placing a 10 g mass of sand in a bath and adding 150 mL volumes of a hydrochloric acid (HCl) concentration corresponding to C = 0.5 M and C = 1 M. The mixture was homogenized and heated to 200 ℃ on a hot plate for 15 minutes. Finally, the hydrochloric acid solution was drawn off, and the sand was rinsed in a bath containing distilled water.

Mineralogical analysis by X-ray diffraction (XRD)

The mineralogical composition of the sample was carried out using an X-ray powder diffractometer, XRD (Bruker Advance D8), Cu-Kα radiation, and Ni filtered radiation (λ = 1.54184 Å). Radiation was generated by an electric current of 30 mA and at a voltage of 40 kV. Analysis of each powder sample ($\phi \leq 75$ µm) was performed in swept steps from 5° to 70° for random powder in 2θ range and integrated at the rate of 2s per step.

4. Results, interpretations, and discussions

4.1. Mineralogical and chemical composition

4.1.1. Mineralogical composition

The minerals identified by post-treatment diffractogram (XRD) analysis of studied sand samples include quartz, biotite, kaolinite, and albite (**Figure 3**). These minerals are thought to result from the disintegration of granites and similar rocks by natural weathering and erosion processes [18]. Quartz predominates the mineralogical composition (93% approx.) of the sand extracted from the Sanaga. The abundant presence of quartz is essential for the composition of standardized sands. Indeed, according to standard EN 196-1 [15], the most important and abundant mineral that a standardized sand must contain is quartz. It should be noted that the presence of clay minerals (kaolinite), even in small quantities, is not conducive to the manufacture of standardized sands; these sands should therefore be treated to effectively eliminate the level of fine clay particles.

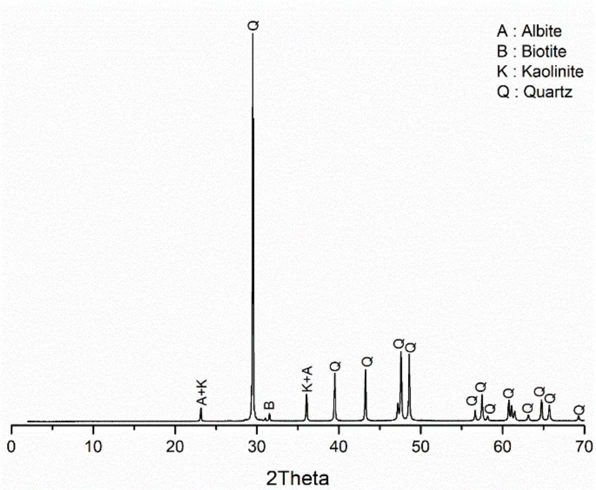

Figure 3. XRD pattern of Sanaga sand.

4.1.2. Chemical composition

Table 1 shows the results of the chemical analysis of untreated sand, sand treated with hydrochloric acid at different concentrations (0.5M and 1M), and reference sand.

Table 1. Major oxide composition of sands.

Oxides (%)	Untreated	Treated		Standard Sand
		0.5M	**1M**	
SiO_2	93.48	97.5	97.3	98.05
Al_2O_3	3.14	1.77	1.67	0.54
Na_2O	0.34	0.13	0.14	
MgO	0.13	0.03	0.08	
K_2O	0.89	0.13	0.12	
CaO	0.17	0.11	0.11	
TiO_2	0.3			
Fe_2O_3	1.55	0.33	0.57	0.07
LOI	3.01	1.31	1.43	0.16

The variations in chemical composition as a function of sand type are illustrated in **Figure 4.** The sands studied (treated and untreated Sanaga sand) have very high SiO_2 contents (93.48 wt.%–97.5 wt.%). These values are generally lower than those observed for standardized sand (98.05 wt%). Alumina content (Al_2O_3) is relatively low overall (1.67 wt.%–3.14 wt.%), with the highest value recorded for untreated Sanaga sand. Overall, iron oxide (Fe_2O_3) is also present in low proportions (0.33 wt.%–1.55% wt.%), with the highest value observed in the untreated Sanaga sand sample. The other oxides are present in very low proportions in both natural and treated Sanaga sand samples (cumulative percentage: <3 wt.%). Loss on ignition values is low (1.31 wt.%–3.01 wt.% by weight), with the highest value recorded in untreated Sanaga sand. This chemical composition of Sanaga sand is due to the petrographic, mineralogical, and therefore chemical composition of the basement rocks [8]. The Al_2O_3, K_2O, Na_2O, and Fe_2O_3 contents in the samples in **Table 1** are associated with the low presence of feldspar, clay, and micas (biotite) listed in **Figure 3**. High amounts of MgO, K_2O, and Na_2O are associated with high expansion [19]. Thus, HCl treatment resulting in a reduction of these oxides in Sanaga sand is a major advantage for the use of this sand in mortars. In addition, after hydrochloric acid treatment of local sand, it was found that the silica content of Sanaga sand increased between 3.82% and 4.02 wt.% compared to pure sand. The 0.5 M concentration offers better treatment than the 1 M concentration. These silica concentrations are very close to those recommended by reference standard EN 196-1 [15], which is 98.05 wt.%. The silica content shows a clear increase from 93.48 wt.% to 97.3 wt.% and 97.5 wt.% for the 1 M and 0.5 M concentrations, respectively. This increase is mainly due to a significant drop of alumina (Al_2O_3), magnesium (MgO), potassium (K_2O), and titanium (TiO_2).

The SiO_2/Al_2O_3 ratio of sand extracted from the Sanaga is 29.77% in its natural state, compared with 55.08% at 0.5 M and 58.26% at 1 M. This ratio, although lower than that of the reference standard EN 196-1 [15], would indicate an abundance of silica in Sanaga sand [20]. The results obtained after sand treatment are in line with Indian and Asian standards. This could be explained by the fact that the oxides present in the sand particles have been reduced by the attack of tetrachloro-silicate ions, as reported in certain works [21]. The purification equation is as follows:

$$SiO_2 + 4HCl \rightarrow SiCl_4 + 2H_2O.$$

This equation enabled considerable elimination of oxides such as Al_2O_3, Fe_2O_3, K_2O, CaO, etc., leading to an increase in silica content of the order of 3% to 4%. After treatment, the loss on ignition of the sand studied is down (1.31 wt.% for 0.5 M and 1.43 wt.% for 1 M) and relatively close to the recommendations of the European standard (0.1 wt.%–0.16 wt.%). This reduction also reflects the elimination of alumina, magnesium, and potassium oxides, mainly contained in clays.

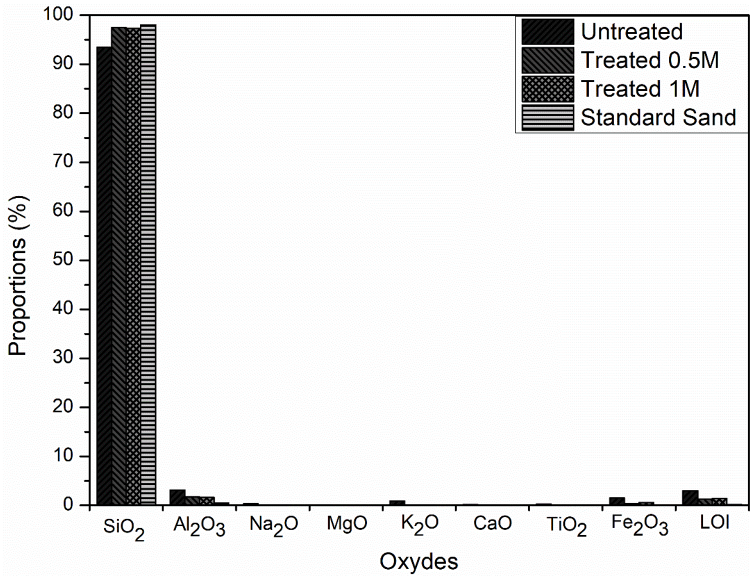

Figure 4. Chemical composition of untreated, treated, and standard sand.

4.2. Grain size distribution

The results of the particle size analysis of the various sands studied are shown in **Table 2** and presented in the particle size pattern in **Figure 5.**

Table 2. Physical parameters of sands.

Parameters	Untreated	Treated		Standard
		0.5M	1M	
cs (0.2mm < φ < 2 mm) (%)	95	98	99	86
fs (φ < 0.2 mm) (%)	5	2	1	14
fm	2.45	2.48	2.63	2.49
SE (%)	97.67	98.54	98.87	98.34
dh	1.49	1.38	1.41	/
dr	2.67	2.61	2.41	2.64
dd	1.46	1.34	1.37	/
W (%)	2.50	/	/	7.00
Cu	4.07	4.36	2.62	6.43
Cc	1.88	2.14	1.39	1.30

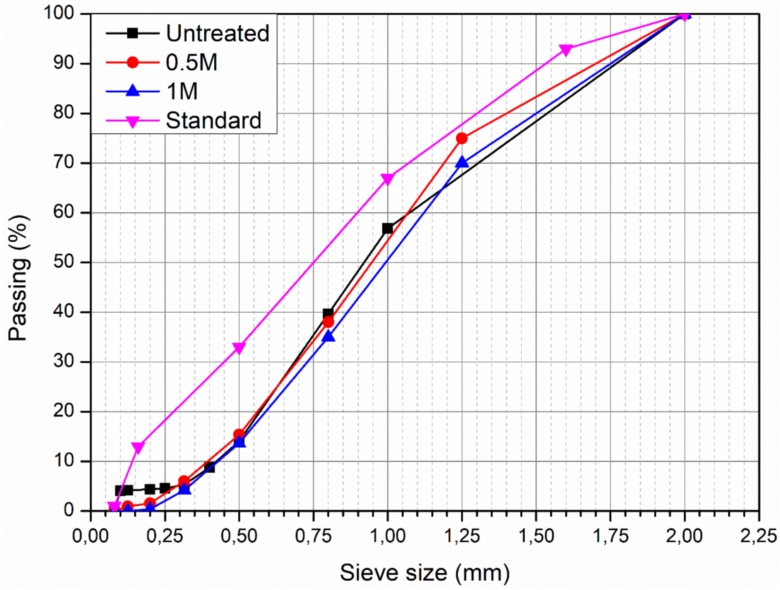

Figure 5. Particle size distribution pattern of Untreated, treated, and standard sand.

The sands studied show particle size distribution curves that follow an "S" shape (**Figure 5**). This curve is common for sands containing elements of different sizes [22]. The particle size patterns show that the particle sizes of the standardized sand and the sand extracted from the Sanaga River are globally continuous. Analysis of the sands' particle size curves shows that natural sand extracted from the Sanaga has a fine particle content ($\varphi < 0.2$ mm) of around 5% and a coarse particle content (0.2 mm $< \varphi < 2$ mm) of almost 95%. Research [23] has shown that particle size distribution in sand is crucial to both the workability and segregation of newly mixed concrete. According to various authors [24,25], the use of uniformly distributed mixes generally leads to better workability compared with discontinuously graded mixes. However, it should be noted that discontinuously graded mixes can lead to a greater slump. Analysis of the Sanaga sand grading curve clearly shows that the samples are made up of the main granular classes in varying proportions. The coefficients of uniformity (Cu) of the sands studied (2.62–6.43) are greater than 2, showing that these sands have spread or varied and continuous granulometries. The lowest value recorded on the sample treated with HCl at a concentration of 1 M reflects a more or less heterogeneous (i.e., less uniform) grain size, composed mainly of coarse elements. When mixtures are non-uniformly distributed, they tend to settle more, resulting in concrete of higher density and lower permeability [24].

The curvature coefficients of the Sanaga sand grading curves indicate that this sand has a well-graded grading (Cc < 3). The granulometric data show that Sanaga sand is coarse-grained (cs), with proportions ranging from 95% to 99%. The quantity of fine particles (fs) varies between 1% (1 M-treated sand) and 5% (untreated sand). Except for natural samples, all other samples can be classified as clean sands since their fine particle content ranges between 1% and 3.8%. However, the quantity of fine particles present has a significant impact on the amount of water required and the workability of the mortar [26]. According to standards [27–29], there is a limit to the amount of fine particles allowed. If the fine content exceeds 3 to 5%, it is advisable to treat the sand or reject it. Aggregate can contain fine particles in various forms. They may be present in the sand in the form of clay, silt, or stone dust. The presence of fines or silt can reduce the permeability of concrete. In addition, too much silt can reduce the workability of concrete and increase shrinkage. According to the European standard [30], sand is considered pure if particles larger than 2 mm account for no more than 20% of its total mass, and if particles smaller than 0.063 mm account for no more than 15% [31].

4.3. Fineness modulus

Table 2 shows that all fineness moduli (fm) are between 2.45 and 2.63. The fineness modulus of sand is one of the key factors affecting the workability, strength, durability, visco-plasticity, density, and permeability of fresh and hardened concrete [5,32]. Sand with a fineness modulus (fm) of 2.1 to 2.5 is considered too fine, while sand with an fm of 2.5 to 3.1 is considered medium, and sand with an fm of 3.1 to 3.5 is considered coarse. According to ASTM C 33 [27], the fineness modulus should be between 2.3 and 3.1. It is important to note that the use of very coarse or very fine sand can lead to poor-quality concrete mixes. Coarse sand can lead to hard concrete mixes that are more likely to bleed and segregate. To achieve the desired workability of concrete, a significant amount of water is required when using very fine sand. However, this type of sand can easily separate and may require a greater quantity of cement. According to some authors [5], optimizing fineness modulus can improve concrete strength by between 8% and 39%. The Ethiopian standard [29] specifies a slightly different range of 2 to 3.5, with a tolerance of ±0.2. If the fineness modulus is between 2.0 and 2.6, the material is fine sand. If it's between 2.6 and 2.9, it's medium sand. If it's between 2.9 and 3.5, it's coarse sand. If the sand's fineness modulus exceeds 3.5, it is considered unacceptable. The Sanaga sand samples meet the requirements of Ethiopian [29] and French [11], standards and the sand fineness modulus values show that all the sands are of good quality and suitable for construction.

4.4. Sand equivalent (SE) values

The sand equivalent results show that all the sands have the characteristics of very clean sand, due to the almost total absence of clay fines. Sand equivalent values for the material studied range from 97.67% to 98.87%. The best results were obtained after treatment of the sand with HCl. According to NF EN 933-8 [33], these sands are classified as very clean sands, with extremely negligible clay fines, which could however lead to plasticity defects in the concrete. Despite this, these sands can be used in conventional concrete structures if structural strength is required. In addition, high sand equivalent values have a positive impact on concrete properties [34]. When assessing the quality of fine particles in sand, a high sand equivalent value indicates positive effects of the fine fraction on concrete properties [34,35].

4.5. Densities

Table 2 shows the densities of sand samples before and after hydrochloric acid treatment.

The specific densities of the sands studied range from 2.41 to 2.67, as shown in

Table 2. The values are similar for the different samples. These results are comparable to those obtained in other studies carried out in the same region [36]. These results show that the densities of acid-treated sands extracted from the Sanaga River drop with reference to their initial state. Bulk and dry densities of Sanaga sand before and after HCl treatment vary between 1.38 and 1.49 and between 1.34 and 1.46 respectively. Like specific densities, bulk and dry density values also tend to decrease after treatment with HCL. These results mainly reflect a decrease in the oxides making up the clay minerals (alumina oxide, potassium oxide, and magnesium oxide) in terms of mass. It seems that the clay minerals acted as fillers (filler effect). Thus, before treatment, the volume of voids within the sand was occupied by clay particles.

However, although a decrease in density values was observed, the densities of the sand extracted from the Sanaga are within the range prescribed by EN 196-1 [15] (2.63–2.67), particularly for the 1 M concentration [22].

4.6. Water content

The average natural water content of the Sanaga sand sample is shown in **Table 2**.

The sand sample extracted from the Sanaga has a water content of 2.5%, which is very close to the water content of sand standardized to EN 196-1 [15]. The amount of water contained in the sand determines the effective water/cement ratio and the free water content. The water content value is attributed to the presence of clay minerals. Thus, a high amount of clay minerals may lead to high water content values for the sand. If the sand is dry or has a low water content, it requires a higher water/cement ratio for mix design, as the sand particles are quickly covered with cement paste. To calculate the amount of water required for the water/cement ratio, it is essential to know the water content of the sand. Standards [37–39] determine the water content of fine aggregates, which is generally between 2% and 6% for free water content. Fine aggregates can retain a maximum water content of around 2%–8%. Based on the water content results and the above description, Sanaga natural sand, and in particular treated sand, meets the free water content values prescribed by the standard.

4.7. Mechanical strength of mortars

Table 3 shows the different compressive strength results for sand mortars before and after treatment with hydrochloric acid at different concentrations.

Table 3. Mechanical strength of mortars.

Time	**Compressive strength (MPa)**				**Flexural strength (MPa)**			
	Untreated	**0.5M**	**1M**	**Standard**	**Untreated**	**0.5M**	**1M**	**Standard**
14 days	39.59	41.77	41.12	48.97	8.4	9.2	8.92	11.15
28 days	41.01	50.1	49.7	54.5	10.1	11.03	10.7	12
35 days	42.4	52.36	51.98	55.98	10.21	11.39	11.04	12.1

The compressive strength of mortar is the performance measurement most commonly used by engineers in the design of buildings and other structures. Mortar compressive strengths were determined at 14, 28, and 35 days. Compressive strengths obtained with treated and untreated Sanaga sand varied between 39.59–41.77 MPa, 41.01–50.1 MPa, and 42.4 and 52.36 MPa at 14, 28, and 35 days, respectively. In general, the compressive strengths of the various mortars show a relatively significant increase after hydrochloric acid treatment. Treatment of the sand with a concentration of 0.5 M hydrochloric acid gave the best results and most closely resembled the results obtained with the reference sand prescribed by standard EN 196-1 [15]. The graph in **Figure 6** shows this evolution between untreated sand mortar and sand treated with different concentrations.

The flexural strengths of the various mortars treated with hydrochloric acid also show increasing results close to the reference sand in standard EN 196-1 [15]. The graphs in **Figure 6** show this progression from untreated sand mortar to sand treated at different concentrations (0.5 M and 1 M), as well as that of sand, standardized in standard EN 196-1 [15], respectively. The strengths obtained with treated and untreated Sanaga sand varied between 8.4–9.2 MPa, 10.1–11.3 MPa, and 10.21 and 11.39 MPa at 14, 28, and 35 days, respectively. When the sand was treated with HCL, the 0.5 M concentration gave better results, close to those obtained with sand standardized to EN 196-1 [15].

Overall, the mortar strength histograms show that these values increase with time. The strength values of standardized sand remain higher than those of sand extracted from the Sanaga, whether treated or not; however, after HCl treatment, a significant overall increase is observed, with values in line with those expected and approaching those of standardized sand. As sand mainly acts as a reinforcing particle in a mortar [40], the nature (mineralogical and chemical composition) and particle size distribution of the sand are the main parameters influencing the mechanical behaviour of the mortar tested. The increase in strength after treatment is therefore justified by the greater or lesser reduction in the content of undesirable elements such as K_2O, Na_2O, etc. [41]. This slight difference in mechanical strength in favour of standardized sand may be due to a higher percentage of silica and therefore quartz (XRF and XRD results). Quartz had a positive effect on mechanical strength. Indeed, the abundant quartz in Sanaga sand reacts with calcium hydroxide from cement hydration to form hydrated calcium silicates (C-S-H), which constitute the main binding phase and ensure the long-term strength and durability of the materials [42]. Natural sand may have a higher organic matter content indicated by the LOI value (3.01%) than treated sand (LOI 0.5 M = 1.31% LOI 1 M = 1.43%), which is detrimental to cementitious matrices [41]. In the natural state, the compressive strength of mortars is lower than the 0.5 M compressive strength. This is attributed to the presence of clay in the natural sand, which, in contact with the binder, causes a loosening of the contacts and bonds between the aggregates and the cementitious matrix [41]. Furthermore, the presence of clay minerals can harm mechanical strength due to the reaction of the cement with the alumina silicates contained in the clays, producing hydrogen gas, which creates microcracks in the cementitious matrix [43]. Similarly, the finer particles of non-clay sand can also fill the pores of the mortar matrix, resulting in a denser material, leading to an increase in the mortar's mechanical properties.

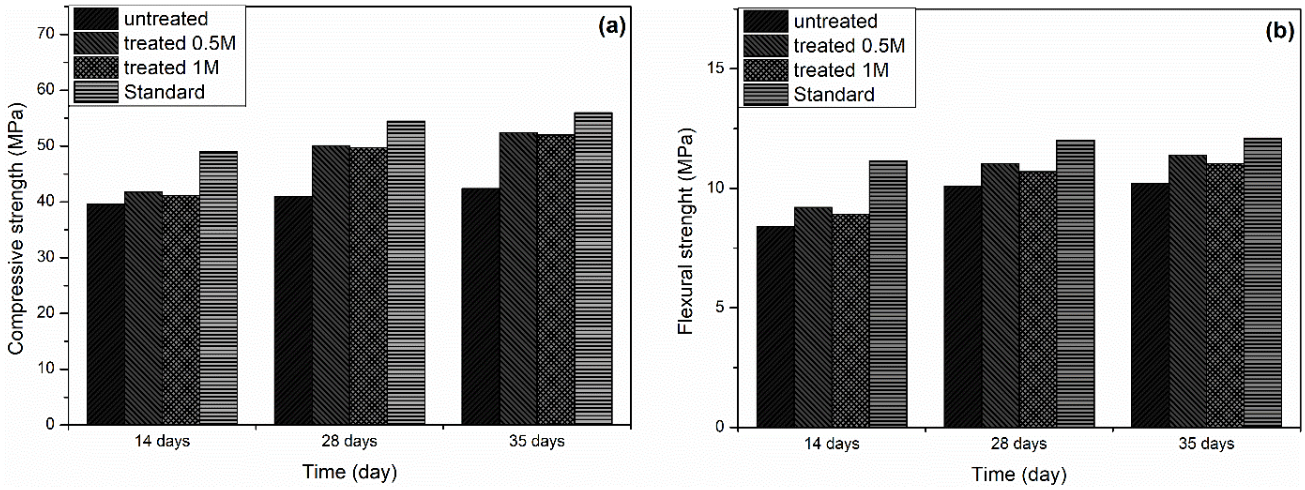

Figure 6. Evolution of mechanical properties according to time.

4.8. Statistics and comparative analysis of mechanical strength

Table 4. Comparative mechanical strength analysis.

	Compressive strength				Flexural strength			
	Untreated	**0.5M**	**1M**	**Standard**	**Untreated**	**0.5M**	**1M**	**Standard**
VR 14 days (%)	−19.15	−14.70	−16.03	/	−24.66	−17.49	−20.00	/
VR 28 days (%)	−24.75	−8.07	−8.81	/	−15.83	−8.08	−10.83	/
VR 35 days (%)	−24.26	−6.47	−7.15	/	−15.62	−5.87	−8.76	/
Min.	39.59	41.77	41.12	48.97	8.40	9.20	8.92	11.15
Max.	42.40	52.36	51.98	55.98	10.21	11.39	11.04	12.10
Mean	41.00	48.08	47.60	53.15	9.57	10.54	10.22	11.75
Std. dev.	1.41	5.58	5.73	3.69	1.01	1.17	1.14	0.52

Table 4 shows the rates of variation observed between the uniaxial compressive strengths of mortars made from standardized sand and those made from untreated Sanaga sand treated with HCl at different concentrations (0.5 and 1 M). In the natural state, compared with the values obtained with standardized sand, those obtained with Sanaga sand show a compressive strength deficit of −19.15, −24.75, and −24.26% at 14, 28, and 35 days of curing, respectively. These values highlight a very significant strength deficit of almost 25% compared with standardized values. However, mortars made from HCl-treated sand showed better variation rates. For a concentration of 0.5 M, the variation rates show a slight strength deficiency. The rates of change obtained at 0.5 M are −14.70, −8.07, and −6.47% respectively, at 14, 28, and 35 days of curing. For treatment with 1 M concentrated HCl, the rates of change obtained were −16.03, −8.81, and −7.15% respectively, at 14, 28, and 35 days of treatment. In general, at 28 days and beyond, the strengths obtained with Sanaga sand treated with 0.5 and 1 M concentrated HCl offer less than 10% difference compared with those obtained with standardized sand. According to some authors [5], this can be the result of optimizing the effect of fineness modulus by HCl treatment that can improve the mechanical strength. The strength results therefore show that treating Sanaga sand with a 0.5 M concentration of HCl results in higher mechanical strengths. These results are justified

by the disappearance of the clay mineral phase containing certain oxides whose presence is detrimental to the hardening reaction. In general, flexural (**Table 4**) strengths describe the same phenomenon as that observed for compressive strengths.

5. Conclusion

This study aimed to characterize and improve the geotechnical, chemical, and mechanical properties of sand extracted from the Sanaga River, for the production of standardized local sand and overcome the failure observed in mortars caused by the use of inappropriate sands. Imported EN 196-1 sand, with known characteristics, was used as the main reference for various comparisons. The ultimate aim was to improve the properties of local sand. Sanaga sand was therefore subjected to physical, mineralogical, and chemical characterization. The sand was also tested in mortar production to assess its mechanical resistance.

Physical parameters such as fineness modulus, which is 2.96 for sand extracted from the Sanaga River, have been corrected in the laboratory with HCl treatment to obtain a fineness modulus, which is now 2.45 after treatment and complies with standard EN 196-1 for imported standardized sands. Post-treatment densities were reduced from 2.67 to 2.61 for 0.5 M and 2.64 for 1 M in the case of Sanaga sand, in line with EN 196-1, which recommends a value of 2.6. Other physical parameters, such as water content and sand cleanliness, showed acceptable properties in line with current standards.

Chemical parameters showed 93.01% silica for sand extracted from the Sanaga River; HCl-based purification further enriched this sand in silica. The 0.5 M concentration gave a better result than that of 1 M since the silica content of the Sanaga sand is 97.5% at 0.5 M and 97.3% at 1 M. The silica content of Sanaga sand is therefore acceptable, as it meets Indian and Chinese standards, which require a silica percentage of around 97%.

The mechanical parameters of mortars made from sand extracted from the Sanaga are increasingly similar to those of EN 196-1 standard sand. This observation was confirmed by the rates of change in mechanical strength between local sand and imported EN 196-1 sand, which showed more interesting values when the local sand was treated with 0.5 M. Moreover, according to the Cameroon standard for standardized mortars, these strengths reached the expected threshold.

HCl treatment at 0.5 M of Sanaga sand eliminates efficiently sand defects, enabling it to be used as standardized sand in the building and public works industry.

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