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# META-KAOLIN FROM SUDAN: A SUSTAINABLE ALTERNATIVE FOR CEMENT IN CONCRETE MIXTURES

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**Abstract- The search for alternative materials with reduced CO2 footprints, lower cost and eco-friendly cementitious properties have lately been a global concern. In search for such options in Sudan, Kaolinite clay (KC) was investigated to check its suitability as a sustainable cementitious material. Sudan has a diversified geological structure with a widespread minerals wealth of which kaolin deposits (KDs) are confirmed to be extensively available. The distribution and availability of KDs in Sudan were explored in this study and by using X-Ray Fluorescence and XRD tests, the clay's chemical composition was determined and compared to cement. Furthermore, the pozzolanic reactivity of meta-kaolin (MK), a thermally treated form of the clay, was affirmed through a chemical analysis, comparison to ordinary Portland cement (OPC) and the determination of the degree of the subsequent strength of the hydrated mixture. Three different scenarios were considered with MK included in partial replacement for cement to produce normal concrete, self-compacting concrete (SCC) and high strength concrete (HSC). Several mix designs were prepared, casted and cured for different ages to test the properties of fresh and hardened concrete.**

**The results confirmed that MK prepared from KDs from 4 different locations in Sudan exhibited similar chemical composition to OPC but with variable amounts of silica and alumina. In replacement for cement it reduced the workability of fresh concrete but increased the compressive strength of hardened concrete when compared to conventional concrete with the highest strength achieved at (10-20)% MK replacement by weight of cement. Test results showed conformity of MK included SCC to the internationally accepted classification criteria. 20% MK inclusion yielded a 63MPa compressive strength in 28 days confirming its suitability as a pozzolanic material. KCs are abundantly available in Sudan but not yet fully utilized. Satisfactory results in all the studied scenarios confirmed the clay's suitability as a sustainable cementitious alterative for many construction applications in Sudan.**

**Keywords – concrete, meta-kaolin, Sudan.**

## 1. INTRODUCTION

The worldwide construction industry is criticized for being a major threat to sustainable development due to its very high demand for concrete [1]. With wide-reaching increased urbanization, a parallel increased demand for concrete production has arisen making it the most commonly used man-made building material. Concrete is a composite material that consists of fine and coarse aggregates, cement as a binder in the mix, water and maybe other admixtures proportioned to meet specific design demands. The worldwide production of concrete is 10 times that of steel by tonnage while other construction materials such as polymers are more expensive and less common than concrete materials [2].

Cement, the main constituent of concrete, is a major industrial commodity whose production poses negative environmental impacts when CO2 is released through the stage of fossil fuels burning and the chemical conversion of limestone to lime. Recently, research trials have been geared towards alternatives with reduced CO2 footprints, lower cost and eco-friendly cementitious properties. This paper presents some research outcomes on the occurrence of the kaolinite clays (KC) in Sudan and their utilization in substitution for cement in concrete production. Owing to the fact that no national standards exist in Sudan to cover this material in its raw or treated form, as a cementitious addition for concrete, this study investigated the clay existence in Sudan and tested its chemical composition compared to cement. MK properties were studied and its pozzolanic activity in comparison to cement was investigated through a set of experiments measuring the extent of its usefulness as a sustainable alternative cementitious material.

## 2. LITERATURE REVIEW

*2.1 Alternative cementitious materials –*

The path to sustainability starts by adopting approaches that minimize the impact on the environment [3] [4] or providing greener materials characterized by less energy and resources consumption with high performance ability [5]. Thus, research and development of alternative cementitious materials (ACM) and supplementary cementing materials (SCM) become mandatory for the construction industry to manage the environmental threats entailed by the conventional cement technology [6]. SCMs are materials with an active amorphous SiO2 as the main component. To meet the demands of environment protection, several research activities recorded the use of industrial by-products or other wastes being utilized in concrete mix to compensate for partial cement replacement [7].

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Naik confirmed that since 1990s, industrial by-products such as coal fly ash, foundry sand slag from metal-casting industries, wood ash from pulp mills, sludge from primary clarifiers have been successfully used in concrete [8]. Reused concrete debris have been used in partial or full replacement of aggregates opening a new source for virgin aggregates preservation [9]. Recycled materials in the form of post-consumer wastes or the use of building demolition residues in partial or full replacement of some of the concrete constituents proved to offer a potential solution [10]. Trials cited in the literature gave evidence that materials which mainly contain silica and some part of reactive alumina were found to produce the same hydration products as OPC giving many positive effects regarding the production of eco-friendly concrete hence offering a promising sustainable solution to the construction industry [11] [12].

The use of SCM was pioneered by North America since 1970s [13] where various by-products such as calcined shale, silica fumes, which can be mixed with blended cement to enhance concrete strength. Suggested for use due to their vast availability, preliminary investigations have been performed to verify their potential usefulness in improving concrete quality and performance if used independently or in combination with two or even three ternary mixtures [14]. Coal fly ash, ground granulated blast-furnace slag and Silica fumes are classified as commonly used SCMs [15]. As the projected global future demand for concrete production is expected to rise to 5.8 billion tons, by the year 2050 [16], much of it is expected to be met through the combination of SMCs and clinker in order to meet the environmental restrictions [17].

Owing to the fact that in some countries, demand for SCMs exceed supply because traditional SCMs are not produced locally [18], there is a need to explore alternative SCMs to meet the increased demand [19]. [15] and [20] pointed that promising sources of alternative SCMs include natural mineral deposits and wastes from various industries, calcined clays, natural volcanic SCMs, municipal solid waste incinerator residues agricultural wastes. Despite the reported research findings on the enhanced feasibility, improved rheological properties, increased strength and durability, decreased permeability as advantageous improved properties when SCMs are used [14] [15] [16] [19], there are still many challenges facing the identification, characterization, production and adoptions of these materials [18].

*2.2 Pozzolanic materials and Pozzolanicity –*

“Pozzolans are materials containing reactive silica and/or alumina which on their own have little or no binding property but, when mixed with lime in the presence of water, can set and harden like a cement” [21]. Pozzolanic materials have been used in recent years as cement replacing materials for concrete with improved workability, strength and durability. The pozzolanic reactions change the microstructure of concrete and chemistry of hydration products by consuming the released calcium hydroxide Ca(OH) generating additional CSH resulting in increased strength, reduced porosity, hence a more compact concrete with increased durability [22] [23]. Using pozzolanic admixtures reduced CO2 emission and allows the structures longer service life thus lowering their environmental impact [24].

Analyzing the chemical composition of potential SCMs alone is insufficient to determine its reactivity hence other characteristics are required to be confirmed to determine the degree of the subsequent strength of the hydrated mixture. Evaluation of pozzolanic activity, pozzolanicity, falls in three categories, chemical, physical and mechanical. The literature revealed the presence of a number of standards for testing pozzolanicity but the most commonly cited were the Indian Standard Specifications for testing pozzolanic materials (IS 4098 – 1967), the American Society for Testing and Materials (ASTM) Standards (ASTM C311 – 77), and the British Standards Institute (BS EN 196-5:1995) were consulted [25][26][27].

*2.3. Geological structure and mineral wealth of Sudan–*

Republic of the Sudan is a vast plain lying in the subtropics of north-east Africa bordered by the Red Sea, Egypt and Libya to the north, Chad and Central African Republic to the west, South Sudan to the south, and Ethiopia and Eritrea to the east. It is located at the confluence of the Blue and White Nile and has a diversified geology [28]. [29] According to [30], the minerals potential and resources in Sudan are huge but yet to be evaluated and developed. They include natural gases, chrome, gypsum, mica, zinc, uranium, cobalt, kaolin, granite, nickel and tin. Most of the country’s economically valuable minerals are reported to be unexploited with an indication of massive deposits, radioactive, rare earth elements, industrial minerals, rocks and precious metals. The annual production of minerals in Sudan is variable where feldspar, fluorite, kaolin and talc amounts are not precisely identified.

*2.4. Chemical composition and distribution of Kaolinite Clays in Sudan–*

Kaolinite is a group of common clay minerals that are known as hydrous aluminum silicates. The principal ingredient is kaolin (China clay) [31] which is a mined material. In its natural state, kaolin is a white soft powder consisting principally of the mineral kaolinite. Under the electron microscope the latter is seen to consist of roughly hexagonal, platy crystals ranging in size from about 0.1 micrometer to 10 micrometers or even larger [32]. As found in nature, kaolin usually contains varying amounts of other minerals and is stained yellow by iron hydroxide pigments. When mixed with water it becomes plastic and with higher water amounts it forms a slurry or watery suspension. It occurs widely in nature and is used for making porcelain and china, as a filler in the manufacture of paper and textiles and as a medicinal absorbent.

Kaolinitic clay (KC) deposits are known to occur in several localities in the Sudan. Figure 1 shows the deposits which were geologically described including those deposits in the basement complex in Derudeb area in the Red Sea Hills, Jabal Hizam in Northern Kordofan, Jabal Nakashush North West Sudan, and kaolinitic paleosols at El Atrun area and Jabal Tawiga in North

West Sudan, Jabal Umm Ali North of Shendi, Markhiyat Hills North West of Omdurman and the Gedarif-Showak District in Eastern Sudan [33].

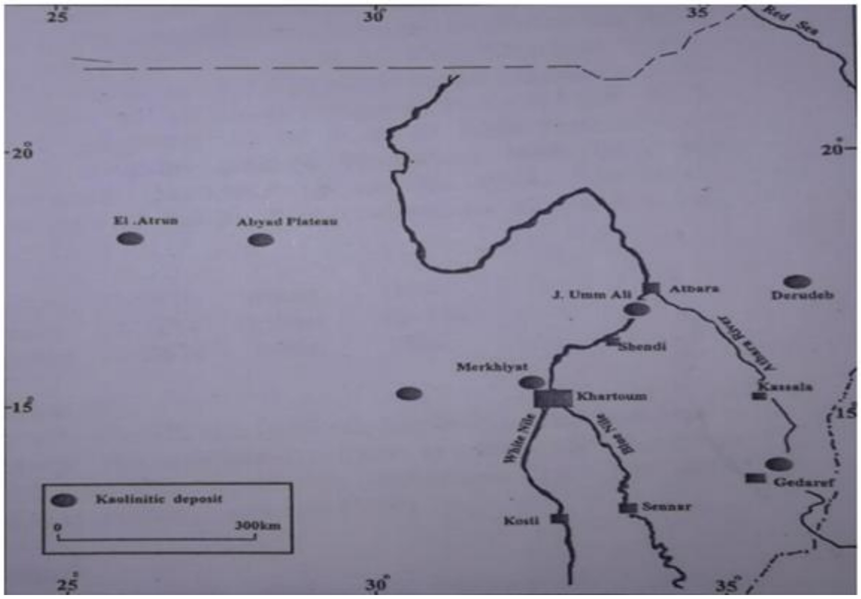



Figure 1. Kaolinite clays locations in Sudan

According to [33], the strongly indurated kaolinites are distributed over an area of 10,000 square kilometers. These deposits belong to the upper part of the Gedaref formation and are overlain by basaltic lava and smectite soil. Products of weathering have been found in mid to late cretaceous continental sediments mainly of Wadi El Milk and the equivalent Shendi-Omdurman formations, the Wadi Hower formation and the Kababish formation. In Northern Sudan, in situ weathered rocks and reworked weathering products of lateritic derivatives facies have been accumulated mainly in clastic sedimentary sequences as fluvial over-bank deposits. The fine-grained kaolintic sediments are considered to be over-bank deposits. The origin of the KDs of Gedaref-Showak area, occurring in a basalt interflow position, is unknown until now nevertheless, some preliminary results of chemical and X-ray diffraction investigations point to a polly-genetic alteration history and a mafic rock source.

## 3. EXPERIMENT AND RESULTS

Experimental work was conducted in 3 phases to achieve the stated research objectives. The first phase was concerned with the kaolinite clay (KC) samples which were randomly collected from four different locations in Sudan: Merowe, Kassala, Garre and Alsayal. The physical appearance of the clay was as shown in Figure 2.

(a) (b) (c)

Figure 2. The physical appearance of the raw Kaolin Clay from Sudan

The second phase considered a thermal treatment process where the clay was transformed to meta-kaolin (MK). This thermal activation of the KC took place in the range of 700-800℃ for 5 hours in simple furnaces to drive off the water from the clay through a chemical process known as calcination refer to Figure 3. This calcination process led to a breakdown and disorder of the clayey structure due to the loss of hydroxyls leading to the formation of an amorphous silica which is responsible for the pozzolanic activity. The resulting MK was ground and tested using X-Ray diffraction to determine the constituent components which were further compared to cement Refer to Figure 3.


Figure 3. (a) KC Burning Furnace (b) MK Grinding Mill (c) MK Grinding Mold (d) MK Powder

XRD was used to study the mineralogy of the crystal structure of the produced mineral Meta-Kaolin (MK) whereas, XRF was used to analyze the elemental composition of the clay and verify the major constituents of the sample (SiO2 and Al2O3) in addition to some other minor constituent oxides (TiO2, Fe2O3, Na2O, K2O, MgO and CaO). The MK was then tested according to the ASTM-C618 to determine its pozzolanicity. The evaluation of the pozzolanic activity of the MK was conducted via chemical and mechanical tests. The former comprised measurement of the amount of the three major oxides (SO2+Al2O3+Fe2O3), Loss on ignition percent, as shown in table 1, and the later was concerned with assessing the strength properties of the concrete samples containing MK.

Table 1 - Evaluation of the pozzolanic activity of the MK from Sudan in comparison to cement

| Elements | Meta-kaolin from different locations in Sudan | | | | Cement | | | Pozzolan-icity |
|---|---|---|---|---|---|---|---|---|
| | Major oxides (%) | | | | Oxides form Sudanese manufactures (%) | Oxides presence limits according to ASTM C150 (%) | Oxides presence limits according to BS EN 197-1 (%) | Limits according to ASTM C618 (%) |
| | Merowe | Kassala | Garre | Alsayal | | | | |
| SiO2 | 52.6 | 61.16 | 65.43 | 64.551 | 20.11-21.65 | 19-23 | 17-25 | - |
| Al2O3 | 36.2 | 22.7 | 30.29 | 31.471 | 4.44-5.11 | 2.5-6.0 | 3-8 | - |
| Fe2O3 | 4.25 | 4.12 | 1.67 | 1.575 | 3.01-3.68 | 0-6.0 | 0.5-0.6 | - |
| CaO | 0.1 | - | 0.85 | 0.818 | 60.44-65.02 | 61-67 | 60-67 | - |
| SiO2+Fe2O3+Al2O3 | 93.05 | 88.42 | 97.30 | 97.60 | - | - | - | ≥70% |
| MgO | 0.82 | 0.21 | 0.09 | 0.625 | 1.87-2.94 | 0-5.0 | 0.1-4.0 | ≤5% |
| LOI | 4.08 | 5.65 | 0.68 | 1.3 | | | 2 | ≤6% |

MK was then used in partial replacement for cement in concrete mixtures as a third phase in this study. For this phase, three different scenarios were considered as discussed below. Several mix trails were designed and concrete mixtures were prepared, casted and cured for different ages to test the effect of the inclusion of the treated kaolinite clay on some of the properties of fresh and hardened concrete.

*3.1 MK partially replacing cement to produce normal concrete*

The first scenario comprised MK added to concrete mixtures in (5,10,15,20,30) % replacement for cement. Workability of the fresh concrete samples was tested through the slump test where all results were conforming to the required limit (60-180mm) then a set of 56 (150×150×150) mm cubes were casted and cured for 7,28,90 days. The targeted compressive strength was 25 and 3MPa at 28 days and the recorded results are presented in table 2.

Table 2 - Compressive strength results for MK included concrete samples from different sources in Sudan

| | Compressive strength (MPa) | | | Compressive strength (MPa) | | | Compressive strength (MPa) | |
|---|---|---|---|---|---|---|---|---|
| | Targeted strength=30MPa | | | Targeted strength=25MPa | | | Targeted strength=30MPa | |
| | Merowe | | | Kassala | | | Garre | |
| MK (%) | 7 Days | 28 days | 90 days | 7 days | 14 days | 28 days | 7 days | 28 days |
| 0 | 25.07 | 27.3 | 35.9 | 17.5 | 20.2 | 25.1 | 24.0 | 30.05 |
| 5 | - | - | - | 22.5 | 24.2 | 32.6 | 27.3 | 31.7 |
| 10 | 24.0 | 29.3 | 31.5 | 9.6 | 15.4 | 26.4 | 22.2 | 28.0 |
| 15 | - | - | - | 16.6 | 17.9 | 27.6 | 25.5 | 26.7 |
| 20 | 31.9 | 35.8 | 40.1 | 12.6 | 12.1 | 24.8 | - | - |
| 30 | 28.7 | 31.0 | 35.8 | - | - | - | - | - |

*3.2 MK partially replacing cement to produce self-compacting concrete (SCC)*

When used to produce SCC, MK from Merowe KC was included in different proportions with 3 mix trials as described in table 3. SCC mix and preparation procedure followed the basic requirements for composition of concrete described in section A.5.2 of the ES206-1:2000 and the targeted compressive strength was 40MPa at 28 days.

Table 3 - SCC Trials with MK partially replacing cement

| Component (Kg) | Trial (1) | Trial (2) | Trial (3) |
|---|---|---|---|
| Cement | 7.275 | 7.275 | 7.275 |
| Water | 3.795 | 3.855 | 4.00 |
| Sand | 14.66 | 14.66 | 14.66 |
| Coarse aggregate | 8.415 | 8.415 | 8.415 |
| Super-plasticizer | 0.106 | 0.159 | 0.126 |
| MK | 2.025 | 2.425 | 2.225 |

Among several tests specified by the European Standards for fresh SCC properties measurement, the flowability was measured by means of the slump flow and V-Funnel testing methods as specified by EN 206-1: 2000, 5.4.2 to 5.4.4 while compressive strength was measured as required by EN 206-1: 2000, Clause 5.5 for hardened concrete. Conformity to the properties of SCC was then assessed depending on the stated criteria as described in EN 206-1 Table 6. The first trial was not acceptable according to the BS hence a second and third trials were conducted. The results are depicted in tables 4 through 7 where the obtained values for each test were presented together with the standard limits for classifications.

The results in table 4 indicate different classes, trial 1 (class SF1) which is considered as appropriate for unreinforced or slightly reinforced structures while trial 2 (class SF3) is suitable for use in vertical applications in very congested structures and trial 3 (class SF2) is considered suitable for many normal applications.

Table 4 - Slump flow test results for the fresh SCC samples

| Test | Flowability (Slump flow) | | |
|---|---|---|---|
| | Trial (1) | Trial (2) | Trial (3) |
| Values obtained | 520 | 790 | 650 |
| Limits for classification | 550-650 | 760-850 | 660-750 |
| Classification | SF1 | SF3 | SF2 |

The viscosity measurement, presented in table 5, showed medium rate of flow (VS2) for all trial mixes.

Table 5 - Viscosity tests results for the fresh SCC samples

| Test | Viscosity (T500 (seconds)) | | |
|---|---|---|---|
| | Trial (1) | Trial (2) | Trial (3) |
| Values obtained | 3 | 3 | 3 |
| Limits for classification | >2 | >2 | >2 |
| Classification | VS2 | VS2 | VS2 |

The V-funnel test results shown in table 6 indicate class (VF2) for Trial (1) and Trial (3) and class (VF1) for Trial (2)

Table 6 - V-funnel test results for the fresh SCC samples

| Test | V-Funnel (seconds) | | |
|---|---|---|---|
| | Trial 1 | Trial 2 | Trial 3 |
| Values obtained | 15 | 8 | 9 |
| Limits for classification | 9-25 | ≤8 | 9-25 |
| Classification | VF2 | VF1 | VF2 |

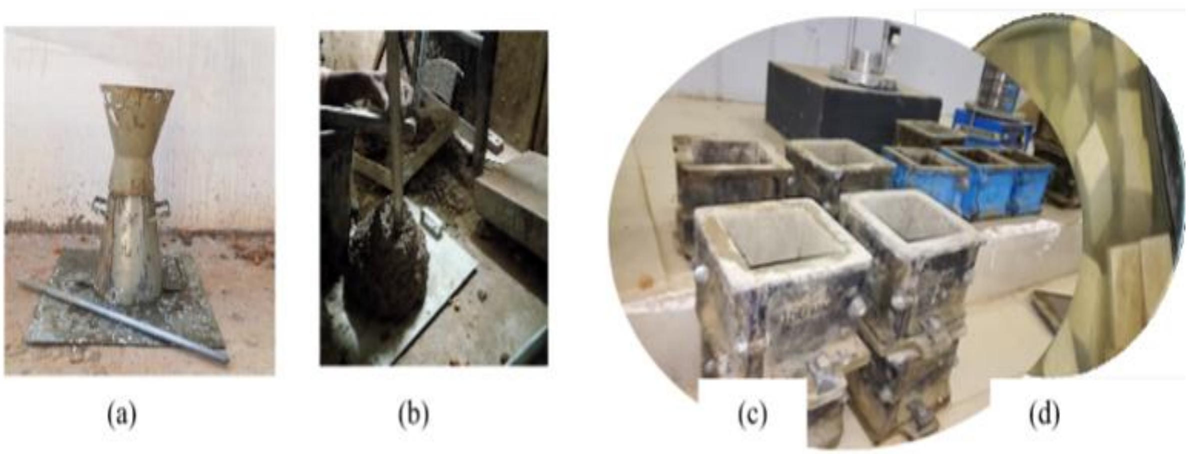
As depicted in table 7, the values obtained for both Trail (2) and Trial (3) were acceptable compared to the targeted strength (40MPa).

Table 7 - Compressive Strength for the hardened SCC samples

| Trials | 7 days | 14 days | 28 days |
|---|---|---|---|
| Trial (1) | - | - | - |
| Trial (2) | 29.6 | 33.4 | 41.3 |
| Trial (3) | 30.7 | 37.2 | 46.5 |

*3.3 MK partially replacing cement to produce high strength concrete*

For the third scenario, MK from Alsayal KC was added in different proportions to test its potentiality for producing high strength concrete. MK was used in 10,20,30% replacement of cement with a targeted compressive strength of 60MPa at 28 days. Workability was tested for the different mix trails and a total of 48 standard 150×150×150mm cubes were casted and cured for 3,7,14,28 days (refer to figure 4).



(a) (b) (c) (d)

Figure 4. (a) Slump Cone (b) Workability Test (c) Concrete Casting (d) Concrete cubes curing

The 28 days compressive strength results are depicted in table 8.

Table 8 - Compressive Strength for the hardened concrete samples

| MK (%) | 0% | 10% | 20% | 30% |
|---|---|---|---|---|
| 28-days Compressive Strength (MPa) | 59.5 | 60 | 63 | 53 |

The results confirmed that all samples with 10-20% MK inclusion it was possible to achieve the targeted high strength.

**4. CONCLUSION**

The results showed vividly the abundant presence of the KC in Sudan. The chemical characterization of the thermally treated form of the clay (MK) from the studied locations, showed the presence of high amounts of silica, alumina and iron oxides exceeding the limits set for cement by the Sudanese manufacturers, the ASTM and BS. According to the ASTM, the presence of the three major oxides ($SiO_2+Fe_2O_3+Al_2O_3$) exceeded, beyond a doubt, the set limits confirming high pozzolanicity. Moreover, the presence of MgO and the LOI values were all within the set limits for all the consulted standards. Thus, the vast availability of the natural mineral deposits makes it a promising source of alternative SCMs.

The results confirmed the possibility of producing normal concrete, high strength concrete and self-compacting concrete when MK is used in partial replacement for cement in concrete mixtures. Kassal's MK yielded the targeted strength in 28 days with the optimum amount of 5% while Garri's MK yielded a slightly higher than the targeted strength with the same amount of MK replacing cement. When MK was included in SCC mixtures, the slump flow test results confirmed their suitability for the different types of structures; slightly reinforced, vertical applications and normal applications while the viscosity measurements showed a medium rate flow whereas the 28-days compressive strength had further confirmed that the trail mixtures meet the targeted value. It was also possible to achieve a high strength value (63MPa) when MK was included in the range of 10-20% in replacement for cement in the concrete mix. These results offer a reasonable base to support the assumption that MK is a suitable sustainable option to replace cement in concrete mixtures. However, further investigation is recommended into its effect on the behavior of hardened concrete in long ages.

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