EFFECT OF PARTIAL REPLACEMENT OF CEMENT WITH METAKAOLIN ON THE PHYSICO-MECHANICAL PROPERTIES OF EXCAVATED SOIL REINFORCED WITH NATURAL BORASSUS FRUIT FIBRE.

A thesis presented to the Department of Materials Science and Engineering
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In partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE IN
MATERIALS SCIENCE AND ENGINEERING

By;
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Supervised by;
Dr. Assia Aboubakar Mahamat
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JUNE, 2023

CERTIFICATION

This is to certify that the thesis titled “Effect of Partial Replacement of Cement with Metakaolin on the Physico-Mechanical Properties of Excavated Soil Reinforced with Natural Borassus Fruit Fibre” submitted to the school of postgraduate studies, African University of Science and Technology (AUST), Abuja, Nigeria for the award of the Master’s Degree is a record of original research carried out by **Olanipekun Khadijat Adeola** in the Department of Materials Science and Engineering.

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OLANIPEKUN, KHADIJAT ADEOLA

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DECLARATION

I hereby declare that this thesis work entitled **“EFFECT OF PARTIAL REPLACEMENT OF CEMENT WITH METAKAOLIN ON THE PHYSICO-MECHANICAL PROPERTIES OF EXCAVATED SOIL REINFORCED WITH NATURAL BORASSUS FRUIT FIBRE”** is the result of studies carried out by me, OLANIPEKUN KHADIJAT ADEOLA under the supervision of Dr. Assia Aboubakar Mahamat of the Department of Civil Engineering, Nile University of Nigeria and Professor Peter Onwalu, Department of Materials science and Engineering of African University of Science and Technology, Abuja-Nigeria.

There has been no previous submission of this thesis for a degree or diploma of this university or elsewhere. As in reporting scientific observation, other investigations that served as sources have been duly acknowledged.

…………………………………………

OLANIPEKUN, KHADIJAT ADEOLA

DEDICATION

I dedicate this work to my entire family, especially my late father of blessed memory.

ACKNOWLEDGEMENT

I am most grateful to Almighty Allah for his blessings and mercy to make this project possible. I am entirely blessed with loving people around me, my parents, siblings and my husband. Thank you for your help throughout this journey. May Almighty Allah continue to bless you all.

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ABSTRACT

Large amounts of excavated soil, both clean and polluted, are frequently produced during construction projects which are typically disposed of in landfills. This research explored a method to re-use the excavated soil as a construction material through partial replacement of cement with metakaolin and reinforcing with 0.2% Natural Borassus fruit fibre. The tests conducted were Moisture content, Particle size distribution, Material density, Atterberg Limit test, Linear shrinkage, Compressive strength test, Water absorption and FTIR while observing several material characterization methods such as; SEM, XRD, XRF from previous research. The average compressive strength results obtained after 28 days curing at room temperature for Mortar cubes with fibres and Mortar cubes with no fibre reinforcement were 7.5 MPa and 7.6 MPa respectively. Their failure pattern was satisfactory, there was about 6% increase in the water absorption from its 7th day result to its 28 days. The functional group did not show any significant change over the curing period and fibre content as observed with the FTIR. This shows a possibility in the usage of the constituents' materials for sustainable construction.

KEYWORDS: Excavated soil, Metakaolin, Natural Borrasus fibre, Compressive strength, Water absorption, FTIR

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Surplus excavated soils from infrastructure development and demolition may end up in landfills. It is necessary to device approach to reduce soil waste and lessen its negative environmental impact by devising ways to increase the reuse of excavated soil from construction sites in order to promote circular economy.

Urbanization has increased the demand for our natural resources for infrastructure development. Cities need to intensify their efforts to incorporate new concepts for sustainable urban development to reduce demands for natural resources (Huang et al., 2010). It was commonly acknowledged that recycling materials will lower the demand for finite virgin natural resources while also lowering the amount of this waste material sent to landfills (Arulrajah et al., 2011; Hoyos et al., 2011).

(Hale et al., 2021) stated that the European union is striving towards being a sustainable, smart and inclusive economy and increasing the reuse of excavated soils in a way that it doesn't endanger the environment or people's health is a necessity to achieve the UN Sustainable Development Goal 11 (Make cities inclusive, safe, resilient and sustainable). This will advance the use of more sustainable engineering techniques that will benefit the economy, environment, and society.

Increase in infrastructure development in rapid growing cities has made the construction industry to be one of the major sources of carbon emissions through the production of cement and its growing adoption. There is an urgent need to produce earth-based construction materials that require less energy for production and reduce the usage of cement in construction for sustainability.

Several studies have shown that Alkaline-activated metakaolin is a possible replacement for Portland cement because it has proven to be detrimental to the environment and contribute to global warming (Ayeni et al., 2021).

(Rashad, 2013) researched extensively on the usage of Alkaline activated metakaolin and confirmed that it is a prospective material towards this replacement strategy as it is more resistant to acid, saltwater attack, and sodium sulfate than Portland cement. They have a very good heat resistant up to 1200^{o}C-1400^{o}C and incorporating short fibres can improve the material's flexural, strength and impact energy.

Fiber reinforcement is a strengthening technique that is frequently employed to enhance the mechanical capabilities of a composite (Aboubakar et al., 2022). Natural fibre reinforcement should be considered to build new generational fibre reinforced composites that are environmentally friendly and safe service life. They possess distinctive quality that makes them great soil conservation materials (Gurunathan et al., 2015).

Environmentally friendly production method was adopted by Aboubakar et al., 2022 to evaluate the mechanical performance of an alkali activated Borassus fiber reinforced earth-based bio composite which helped achieve increase in compressive and flexural strength.

1.2 STATEMENT OF PROBLEM

Cement production has increased more than 30-fold since 1950, and almost four-fold since 1990, with significantly faster growth than the last two decades' global production of fossil fuels, making it the third-largest source of anthropogenic carbon dioxide emissions, behind fossil fuels and land use change. Large volumes of CO_2 are released during its production accounting for about 5-8% of the world's yearly CO_2 emission (Andrew, 2017).

The rate of increase in infrastructure development means more natural resources such as rocks are depleted and more soils are excavated and discarded and the increase in the usage of cement in construction has led to more carbon emission. The recycling rate of the discarded excavated soil for high quality purpose is very low.

The increasing scarcity of natural resources and the rising costs of disposal into landfills in many countries is a global concern driven by environmental considerations (Aatheesan et al., 2010; Hoyos et al., 2011).

Synthetic fibres adoption has witnessed a major drawback in utilization, due its sensitivity and negative environmental impact. They are non-biodegradable and require high cost and energy for production.

1.3 AIMS AND OBJECTIVES

This research aims to study the effect of partial replacement of cement with metakaolin on the physico-mechanical properties of excavated soil reinforced with natural Borassus fruit fibre.

The objectives are as follows:

- To promote resources management and development of earth-based construction material with natural fibre reinforcement.
- To optimize the use of discarded excavated soil for high quality purpose in construction.
- To reduce usage of cement for construction through partial replacement with Metakaolin.
- To test their compressive strength, water absorption, linear shrinkage and check conformity with the required standard for Mortar cubes.

CHAPTER 2

LITERATURE REVIEW

2.1 Reuse of Excavated Soils from Construction Projects

A lot of excavated soils from construction may end up in landfills which is not a sustainable practice. (Hale et al., 2021) outlined major obstacles such as; regulatory, organizational, logistical, and material quality affecting the reuse of excavated soils. It was stated that the rigid geotechnical requirement for soil usage in construction could be a barrier to the usage of excavated soil and it is highly recommended to study their geotechnical properties to determine the area for it best use and how they can be improved. Moreso, regulatory and planning process should be improved to optimize the re-use of excavated soil in a way that they do not pose a greater risk to the environmental and human health.

(Magnusson et al., 2015) conducted a review on the sustainable management of excavated soil, they emphasized the need to evaluate the potential of excavated soil as construction material and concluded that its' usage in construction could save up to 85% in terms of climate impact, save cost and lessen environmental effect by reducing transportation, landfilling and quarry material consumption.

(Xu et al., 2022) explored solution to utilize excavated soil waste as a partial replacement of construction material constraint for high-value purpose by examining its properties as fine and coarse aggregates in unfired clay bricks after dry-wet cycles. Their manufacture process is shown in figure 2.1 and 2.2. Compressive strength of four different categories were obtained for the samples produced; Grade I (higher than 20 MPa), Grade II (15–20 MPa), Grade III (10–15 MPa) and Grade IV (5–10 MPa) with respect to their mix ratio.

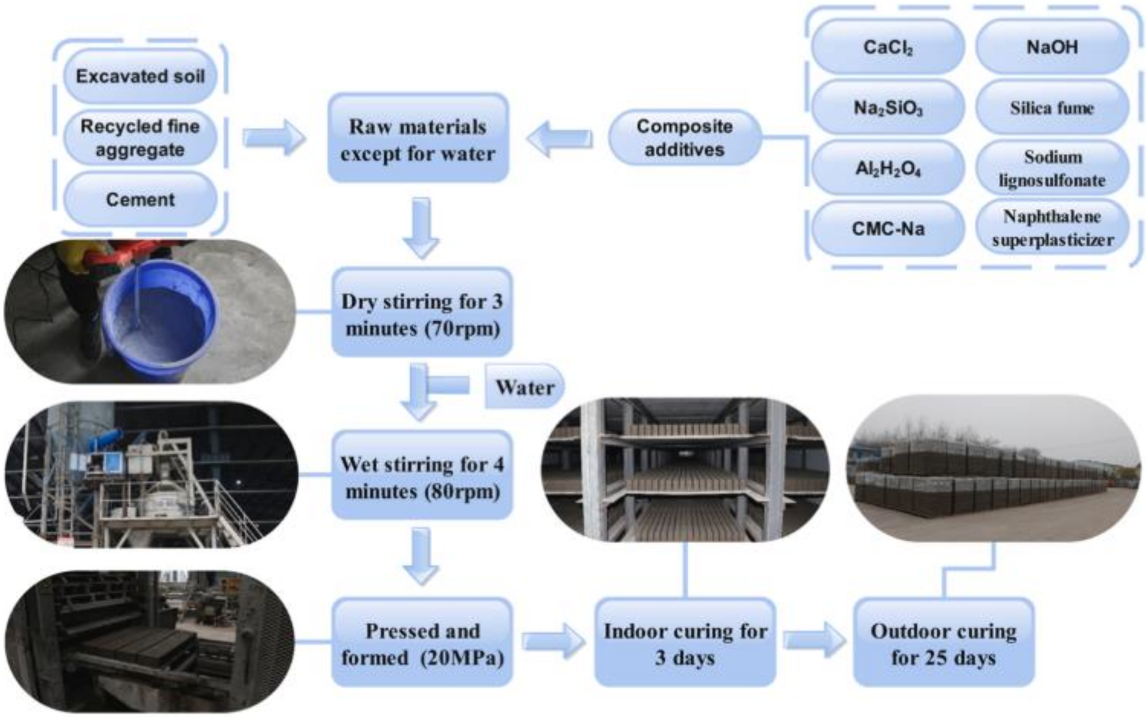


Figure 2.1. Manufacturing process of bricks from Excavated soil (Xu et al., 2022)

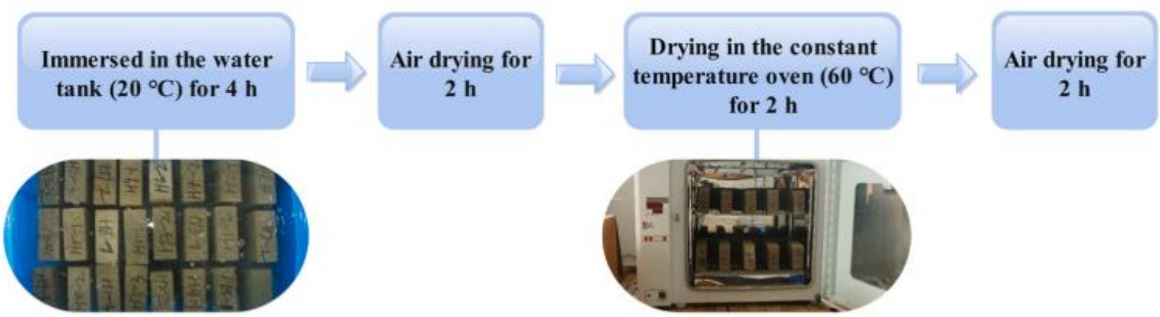


Figure 2.2. Dry-Wet cycle of bricks (Xu et al., 2022).

The study made by (Katsumi, 2015) showed that the Japanese legal system doesn't categorize excavated soil as waste. They were standardized by their Ministry of construction and fixed by 2008 in to 5-level system based on their soil type, strength and water content. Their applications included; Back filling, Road base and embankment, Elevated land construction, reclamation, river dyke, etc.

Excavated soil and rock make up about 28.6% of construction and demolition waste as indicated by (Blengini & Garbarino, 2010). The study proves that the usage of the waste can play an important role in the sustainable supply mix of aggregates for construction as it comprises of a blend of natural aggregates, quarry by-products and recycled waste in order to maximize economic, environmental and social benefits.

The reuse of excavated soils guidelines was provided by (Jürg et al., 2001) as shown in figure 2.3 gives details on handling excavated soils before reuse by assessing their exposure limits based on the environmental condition and testing the soils to determine their pollution level and categorized them to three impact categories; uncontaminated, weakly contaminated and heavily contaminated excavated soil. The uncontaminated soil can be used for playgrounds sites, recreational and agricultural purposes. The weakly contaminated could be used for traffic purposes; noise barriers and embankments, while the heavily contaminated soil must either be treated or deposited safely.

The sustainable reutilization of excavated materials was studied by (Chittoori et al., 2012) considering an integrated pipeline project as a way to cutdown material cost, wastage and CO_2 emissions from transportation. The research analyzed the geotechnical properties of the excavated soil samples and they were identified for potential reuse in bedding and backfilling which helped reduce the material management cost of the project and climate impact by 85%.

Enough space is required in construction site in order to reuse excavated soil for sorting and temporary storage before use. But the space required are often unavailable in densely populated region as studied by (Hao et al., 2007) in Hong Kong.

(Magnusson et al., 2015) proposed transporting excavated soil considered as wastes to recycling facilities, to be treated for use in other construction projects.

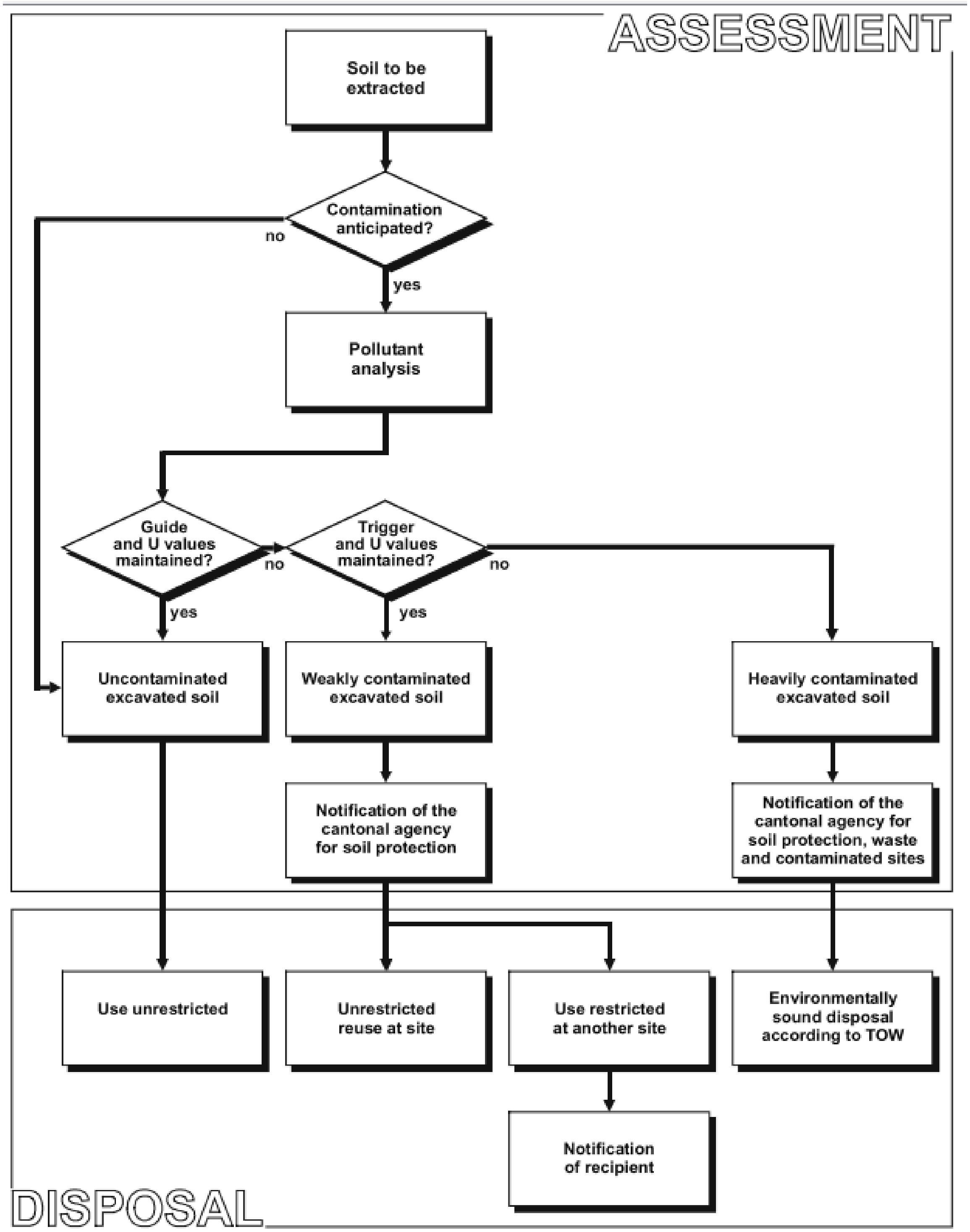


Figure 2.3. Flow diagram on Reuse of excavated soil guidelines. (Jürg et al., 2001)

2.2. Geotechnical requirement of soil for Construction purpose.

Technical criteria flowchart to screen excavated soil for best use was presented by (Teixeira et al., 2019) based on their geotechnical properties is shown in figure 2.4 in order to increase recovery the potentials of excavated soils for construction applications such as backfilling trenches, containing walls, etc. They provided the main geotechnical criteria to consider for the reuse of excavated soil as shown in Table 2.1.

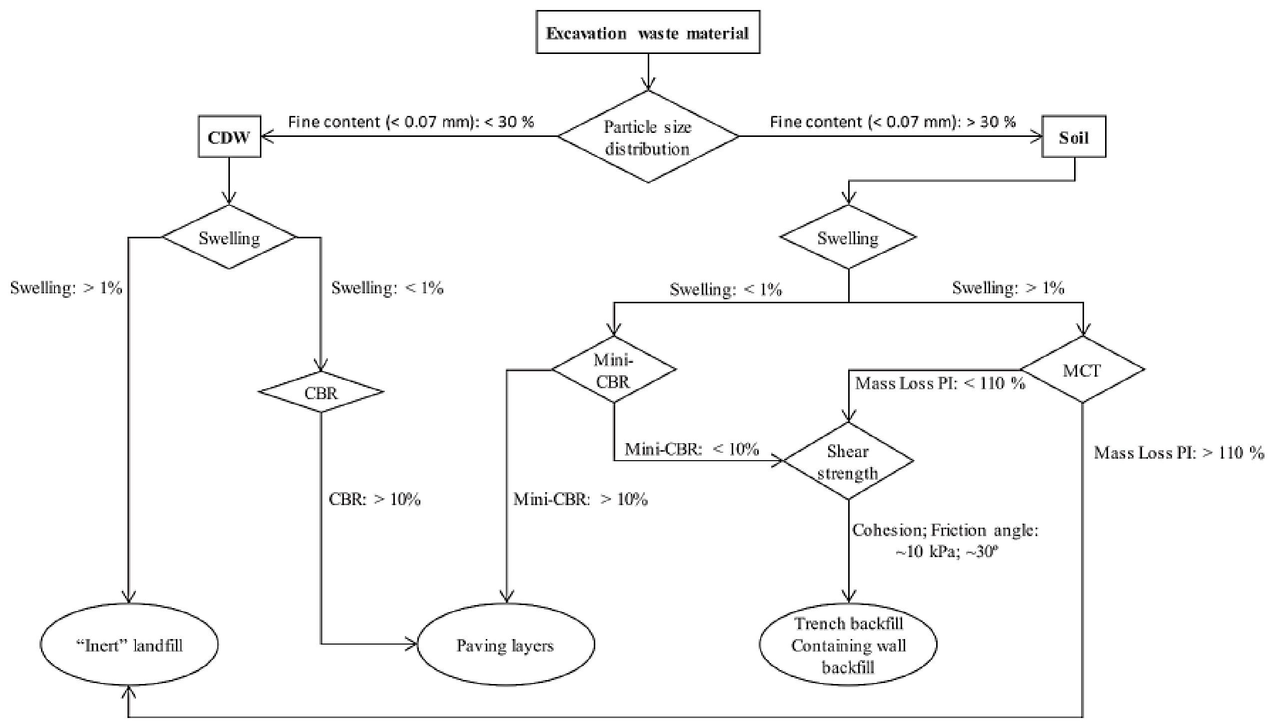


Figure 2.4. Flowchart for potential reuse of excavated soil and construction and demolition waste (CDW). CBR: California Bearing Ratio. MCT: miniature, compacted, tropical classification. Mass Loss PI: mass loss after immersion (Teixeira et al., 2019).

Table 2.1. Geotechnical criteria for the reuse of excavated soil (Teixeira et al., 2019).

Earthworks	Technical Criteria
Trench Backfill	• Cohesion and friction angle (shear strength). • Swelling and loss of strength by wetting.

	• Compaction degree (dry density and moisture content)
Walls with reinforced soil	• Grain size distribution • Swelling and loss of strength by wetting. • Cohesion and friction angle (shear strength)
Paving Layers	• Swelling • Penetration resistance (California Bearing Ratio) • Grain size distribution
Drainage	• Hydraulic conductivity • Loss of strength by wetting • Grain size distribution
Vegetation over replacement	• Clay content • pH • Organic matter • Permeability coefficient • Cation exchange capacity

(ASTM D2487 -00, 2000) identifies three major soil divisions: coarse-grained soils, fine-grained soils, and highly organic soils which are further subdivided into 15 soil groups for engineering purposes. They were classified based on the particle size distribution, liquid limit and plastic index to evaluate their significant properties for engineering use which has correlated generally with the engineering behavior of the soils from any geographic location. The standard provided method of sampling, preparation and procedures for classification of fine grained and coarse-grained soils.

(ASTM D2488 -00, 2000) provides procedures for describing soils for engineering purposes base on ASTM D2487 and identifying based on visual examination which is limited to natural occurring soils.

2.3 Replacement of Portland cement with Metakaolin

Researchers are very much interested in the development of ecofriendly new binders in place of Portland cement to promote sustainable and low carbon construction. Alkaline activated metakaolin belong to the prospective material that has been used in several studies as a replacement for Portland cement (Rashad, 2013).

(Dubey et al., 2015) prepared concrete by varying replacement at 0%, 5%, 10%, 15% and 20% by mass of cement with Metakaolin. About 21.67% increase in the 28-day compressive strength was observed in samples with 10% replacement of cement with Metakaolin.

The partial replacement of cement with metakaolin was experimented with high strength concrete by (Chaitanya et al., 2016). The samples were prepared at with metakaolin replacement at 0%, 10%, 15%, 20%, 25% and 30% in M70 concrete. The compressive strength, split tensile strength and flexural strength were maximum at 15% replacement of cement with metakaolin.

(Rao, 2016) also studied partial replacement of cement with metakaolin at 10% and fine aggregate with waste foundry sand varying from 0 – 40% by weight. The compressive, split tensile and flexural test at 7, 28 and 56 days showed optimum result of samples with metakaolin replacement at 10% and 30% replacement of sand with waste foundry soil which proves that the mechanical properties of concrete were improved with the metakaolin and waste foundry soil.

The study from (Ayeni et al., 2021) showed that metakaolin based geopolymer serves as a potential sustainable construction material as an alternative to Portland cement. The highest recorded compressive strength was 17.10MPa at 28days with samples prepared with 10M concentration of alkaline solution with the metakaolin powder and fine aggregate cured with 60ºC temperature.

(Dong et al., 2022) studied the effect of metakaolin on mechanical properties which showed that metakaolin addition to cement at 10% replacement effectively increased the density of the Portland cement, it demonstrated an excellent compressive performance by curing with humidity at varying percentages.

2.4 Natural Fibre reinforcement of Geopolymer composite

Natural fibre reinforcement should be considered to build a new generational fibre reinforced composites that are environmentally friendly, safe service life and they can serve as an efficient solution to the waste disposal problem of polymer-based materials (Gurunathan et al., 2015).

(Ayeni et al., 2022) used fibres from coconut husks at different weight percent from 0.5% - 2% in the production of a metakaolin based geopolymer composite with improved mechanical properties and stability. The highest compressive strength of 21.25N/mm^2 was observed at 0.5% fibre which makes them suitable for paving and building bricks. The fibre incorporation did not change the crystal structure or form new chemical bonds in the composite.

The mechanical performance of natural fibres reinforced geopolymer composites was studied by (Correia et al., 2013) by using Sisal fibre extracted from the leaves of the plant and pineapple leaf fibre. The fibre composition was 3%, cut to 25mm length and added to the geopolymer paste and was cured at 55^{o}C for 24 hours. The result showed that the use of these fibres improves the impact and traction performance of the material with sisal fibre reinforced composite performing better.

(Aboubakar et al., 2022) assessed mechanical performance of alkali activated Borassus fibre reinforced earth-based bio composite using eco-friendly manufacturing technique. The fibre reinforcement inclusion helped achieve improved mechanical properties (compressive and flexural strength) which showed some fluctuations over the curing period.

CHAPTER 3

MATERIALS AND RESEARCH METHODOLOGY

3.1 Materials and Sample Preparation

The materials used for this research are; Metakaolin, excavated soil, Portland cement, Natural Borassus fibre and water as shown in figure 3.2 (a) – (d) respectively

3.1.1. Metakaolin

The metakaolin was obtained by thermal treatment of the raw kaolin as done by (Ayeni et al., 2022). Metakaolin was used as a partial replacement of the cement. The Original source of the Kaolin clay used was Kankara, Katsina state. But it was obtained from Ushafa pottery in bags.

The Kaolin was then pulverized and sieved to remove larger size particles and impurities. Then wet beneficiation was also done to remove soluble impurities.

The Kaolin paste was later air dried in the oven at 105^{o}C for 24 hours and kept in a sack for further pulverization. The calcination of the beneficiated kaolin was done in an electric furnace at 700^{o}C for 2hours in air to form Metakaolin. It was sieved and particles passing through sieve size 150µm were used for this study. The processes are shown in figure 3.1 (a) – (i)

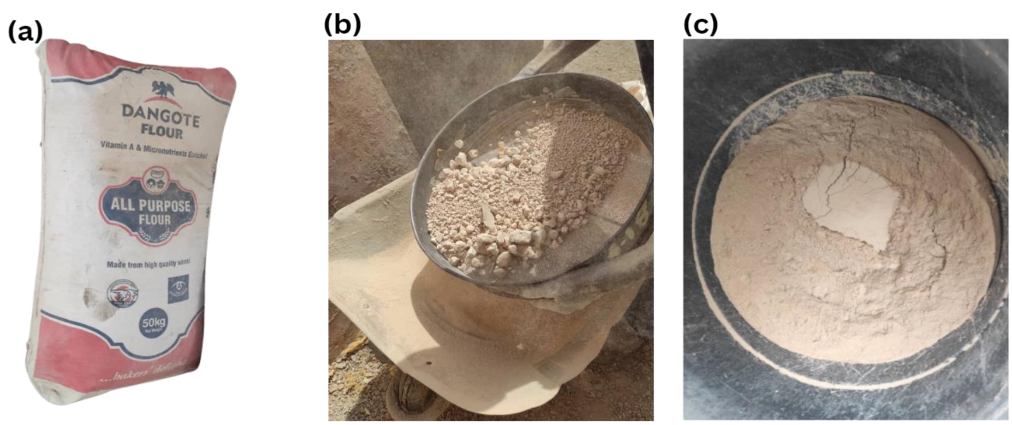


Figure 3.1. (a) Kaolin (b) Sieving of Kaolin (c) Fine Kaolin Particles

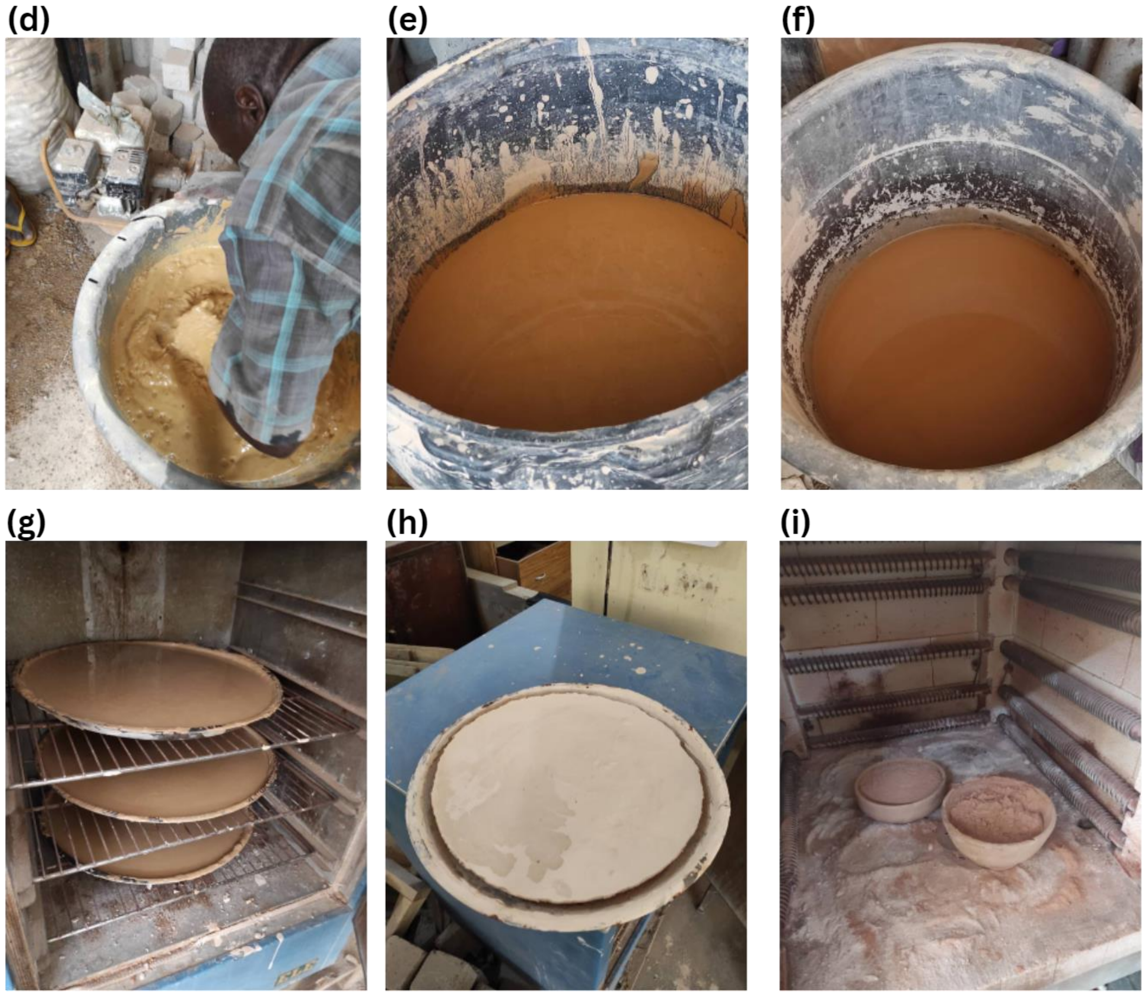


Figure 3.1. (d)Wet Beneficiation of Kaolin. (e) Decantation and Replacement of water. (f) Decantation and Replacement of water. (g) Kaolin pastes in oven (h) Dried Kaolin (i) Calcination of beneficiated Kaolin in furnace.

3.1.2. Excavated Soil

The excavated soil used were obtained from a field at Nile University Nigeria, there were heaps of them abandoned on the field as they were excavated from some construction site in the school premises. The soil has been left on the field for more than a month and provided habitat for weed germination. They were dried and compact, they had to be loosed with hand trowel vigorously to enable fetching of the soil particles.

The excavated soil was sieved and particle size retained and passing through sieve size 600µm only were used for this experiment. The soil was slick and sticky with water. Sieve Analysis and Atterberg limit test were don on the soil to further classify the soil.

3.1.3. Cement

Dangote Portland limestone cement was used for this experiment. It was manufactured by Dangote Cement Plc at Obajana, Kogi state, Nigeria. The particles were mostly fine-sized and there few crumbs and large particles which were crushed during mixing. The cement served as a binder in the mixture. They were used alongside metakaolin as a partial replacement in the mixture and compressive test and water absorption test was conducted to determine sample properties.

3.1.4. Natural Borassus Fibre

These fibres were extracted from ripe Borassus fruit manually. They had uniform diameter ranging from 100µm to 365µm (Aboubakar et al., 2022). The strands of fibres were separated from each other and cut in to pieces of about 1cm to enable proper binding with other constituents of the mixture.

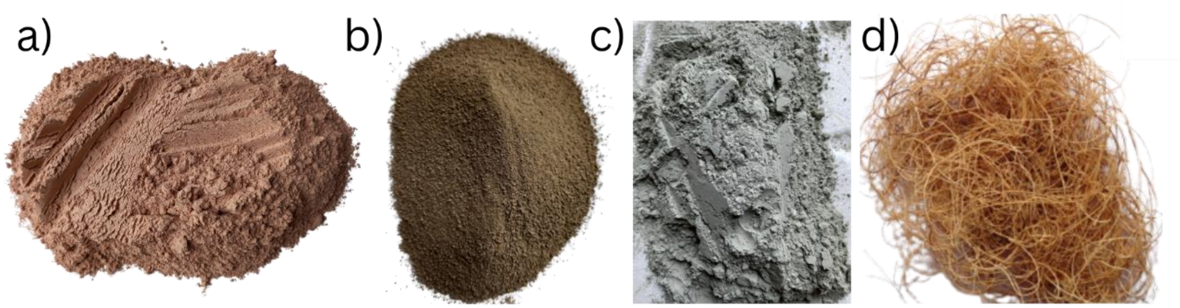


Figure 3.2. (a) Metakaolin (b) Excavated Sand (c) Cement (d) Natural Borassus Fibre.

3.2. EXPERIMENTAL PROCEDURES

Several laboratory tests were conducted on the materials, their mixtures and samples produced in order to effectively classify them and understand their properties. The test conducted were; Sieve Analysis, Moisture content test, Density, Atterberg limit test, Linear Shrinkage, Water Absorption test, Compressive strength test and FTIR in accordance to their relevant standards.

The samples were produced using 35% excavated soil, 15% Metakaolin, 20% Cement and 30% water. There was 0.2% Borassus fibres in some samples in order for us to examine their effect on the mixtures and compare results of Compressive strength, water absorption test at 7days, 14days and 28 days room temperature curing of the samples without Borassus fibres and the sample with 0.2% Borassus fibres.

The materials were mixed with water in the UTEST laboratory mixer till a homogenous slurry mixture was achieved and poured in Steel Three Gang, 5cm Cube Mould. They were vibrated using the UTEST Vibrating table to eliminate air bubbles and placed in the oven at $60^{o}C$ for 24hrs to allow for complete drying of moisture. The samples were demolded and cured at room temperature for 7days, 14days and 28days

Table 3.1. Material composition and samples produced

Mix Type	Material	Percentage composition (%)	Weight (g)	No. of samples
No Fibre	Excavated soil	35	1575	15
	Metakaolin	15	675	
	Cement	20	900	
	Water	30	1350	
Samples with fibre	Excavated soil	35	1575	15
	Metakaolin	15	675	
	Cement	20	900	
	Water	30	1350	
	Fibre	0.2	9	

A total number of 30 samples were produced and cured at room temperature and sun dried occasionally for 7 days, 14 days and 28days. Compressive test, water absorption test and FTIR Analysis were conducted for the samples after specific curing days.

Figure 3.3. (a) Materials mixing with UTEST laboratory mixer
(b) Vibrating samples with UTEST fixed amplitude vibrating tables
(c) Drying samples with UTEST laboratory oven

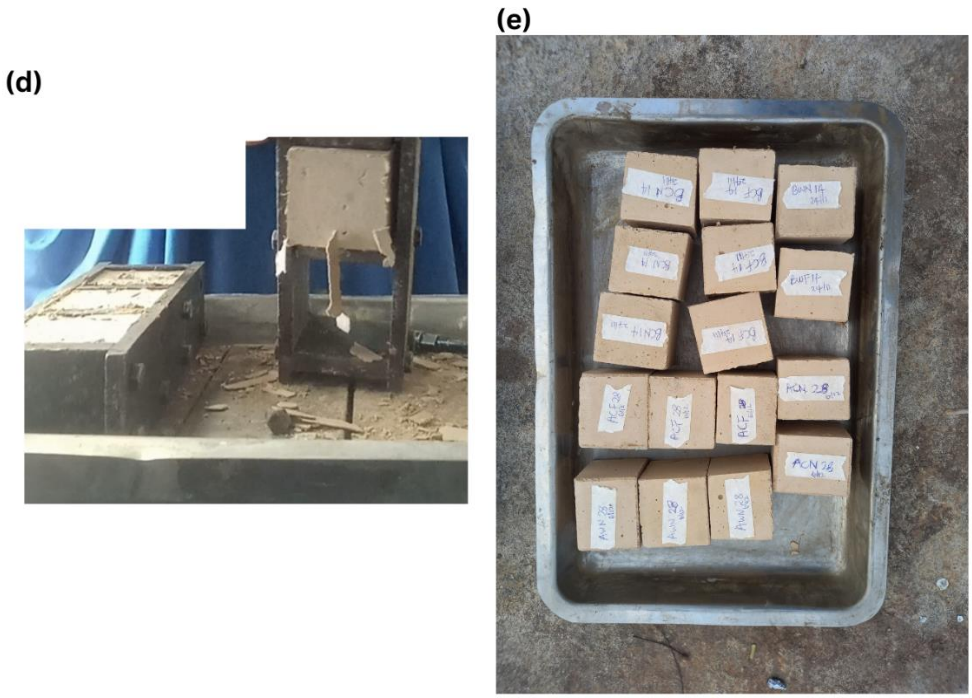


Figure 3.3. (d) Demolding of samples
(e) Labelled Samples during Sun drying curing

3.3 LABORATORY TESTS

The tests were conducted to enable us understand and effectively classify our samples are Moisture content test, Bulk Density, Sieve Analysis, Atterberg Limit test, Linear shrinkage, Water absorption and Compressive strength.

3.3.1. Moisture Content Test

The moisture content was carried to determine the water content present in the Excavated soil and Metakaolin and for this experiment. It was carried out in accordance to the BS 1377 – 2: 1990 (Methods of tests for soils for Civil engineering purposes) using the oven drying method for fine grained soils.

The samples were weighed with the known weight of the can. They were now placed in the oven for 24hrs at 110ºC to allow for complete drying of moisture content. The weight of the dry sample and can was also recorded and the moisture content was estimated in percentage using the equation below. The moisture content was carried out on three different specimens of the sample in order to estimate the average moisture content of the sample.

Moisture Content $= \frac{M_2 - M_3}{M_3 - M_1} \times 100$ (BS1377-2, 1990) ------------------ (i)

M_1 is the mass of container (in g);

M_2 is the mass of container + wet soil (in g);

M_3 is the mass of container + dry soil (in g).

3.3.2. Bulk Density, Unit weight and Dry Density.

The bulk density of the sample is the ratio of its total mass to the total volume. The test was carried out in accordance to BS 1377 – 2: 1990 using the linear measurement method.

Cylindrical containers were used and their volume was calculated using Diameter, D and mean length of sample, L. The mass of the empty cylinder was taken as M_1 and the mass of the cylinder when filled with the samples were also recorded as M_2 in order to obtain the mass of sample required, M for the cylinder volume, V.

The bulk density, ρ is expressed as; $\rho = \frac{M}{V} = \frac{M_2 - M_1}{\pi^{D^2}/_{4} L}$ in kg/cm^3 ------------------ (ii)

The Unit weight of the samples is the ratio of the total weight to the total volume. It is used when estimating the force exerted by the mass of the sample.

Unit weight, $\gamma = \rho \times g$ expressed in kN/m^3 (BS1377-2, 1990) ------------------ (iii)

Where; g is the acceleration due to gravity (=9.81 m/s^2)

The Dry density is mass of dry soil contained in a unit volume. It is also expressed in kg/cm^3 and can be calculated from the equation below if the moisture content, mc and bulk density, ρ of the sample is known.

Dry density, $\rho_d = \frac{100\rho}{100+mc}$ (BS1377-2, 1990) ------------------ (iv)

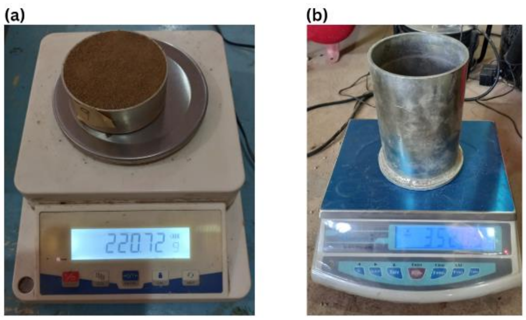


Figure 3.4. (a) Weighing Excavated soil and Cylindrical can for Bulk density
(b) Weighing cylinder for Metakaolin Bulk Density

3.3.3. Sieve Analysis

The sieve analysis was done to determine the particle size distribution of the excavated soil sample used for this experiment which retained and passing through 600µm sieve size.

The experiment was carried out using the BS 812 part 103, methods for determination of particle size distribution using the dry sieving method. The samples were prepared by drying in the oven at a temperature of 105°C to achieve a dry mass and it was weighed after cooling and recorded and M_1. The set of sieves to be used were cleaned, weighed and stacked together in descending order from top. A UTEST mechanical sieve shaker was used to sieve the samples vigorously for about 30minutes.

The samples retained on each sieve were weighed and the percentage retained and cumulative percentage passing on each sieve was also calculated. The graph of the cumulative percentage passing was plotted against the Nominal aperture size of test sieve.

The percentage retained and cumulative passing was estimated as shown below;

% Retained $= \frac{Mass\ Retained\ on\ Sieve}{Mass\ of\ Sample} \times 100$ ------------------------- (v)

% Passing @600 µm = $100\% - \%\ Retained\ @600\ \mu m$ ------------------------- (vi)

Cum. % Passing @300 µm = $\%\ Passing\ @600\ \mu m - \%\ Retained\ @300\ \mu m$

Cum. % Passing @200 µm = $Cum.\%\ Passing\ @300\ \mu m - \%\ Retained\ @200\ \mu m$

Cum. % Passing @150 µm = $Cum.\%\ Passing\ @200\ \mu m - \%\ Retained\ @150\ \mu m$

Figure 3.5. Sieve Analysis with UTEST Mechanical Sieve Shaker

3.3.4. Atterberg Limit

The Atterberg limit test was carried out to determine the Liquid Limit (LL), Plastic Limit (PL) and Plastic Index (PI) of the excavated soil sample, mortar cube mixture with fibre and without fibres in order to classify the samples in accordance with the Unified Soil Classification System or AASHTO.

The Liquid limit test was carried out in accordance to BS 1377-2: 1990 using the cone penetrometer method. It is the empirically moisture content where the sample goes from the liquid state to the plastic state. This helps us identify and classify our soil sample and variation in their moisture content have effects on its shear strength with known plastic limit. (BS1377-2, 1990)

The cone penetrometer method was carried out with the UTEST Semi-Automatic Cone Penetrometer which is made up of; A frame with leveling screws, a screw gear assembly with a handwheel for vertical adjustment, a digital penetration measurement gauge with 0.01 mm resolution/readability, a digital timer, a magnifying lens, and a low voltage illuminator mounted on a flexible arm.

The samples were prepared by mixing thoroughly with water to form a homogenous paste and later poured in to the penetrometer cup. They were leveled smoothly in the cup and excess soil was removed. The penetration cone was lowered to touch the surface of the soil in the cup centralized. The initial reading of the penetrometer was recorded. The timer was started and the cone penetrated the sample, after a period of 5secs, the dial gauge was lowered to the cone shaft to measure the final reading. The difference between the readings were recorded as cone penetration. The cone was lifted out carefully and cleaned. A portion of the sample was taken from the penetration area to the moisture can and weighed then placed in to the oven to determine its moisture content. The penetration test was repeated three more times, water and dry samples were added to maintain a penetration range of 15mm – 25mm for the experiment.

The moisture content was calculated for each specimen and a graph of Penetration against moisture content was calculated. The Liquid limit of the soil is the moisture content corresponding to a penetration of 20mm.

The Plastic Limit of the soil is the established moisture content at which the soil becomes too dry to be plastic. The remaining paste used for Liquid limit was used but more dry samples were added to allow it to be shaped to a ball. A portion was cut out to roll the sample to thread like continuously till it reached about 3mm diameter and crumbled. The pieces were gathered in a moisture can to determine the moisture content at this point. The procedure was repeated for a second sample and the mean of both moisture content is the Plastic limit. The moisture content of both samples should not differ by 0.5% else it will be discarded.

The Plasticity Index (PI) is the measure of plasticity, the moisture content at which the soil displays plastic properties. It is the difference between the Liquid limit and the Plastic Limit. Soil samples that are slightly plastic have PI < 7, medium plastic PI ranges from 7–17, and extremely plastic's PI >17. A high PI indicates that the soil is typically clay, a low PI indicates that the soil is frequently silt, and a zero PI indicates that the soil is non-plastic

Plastic Limit (PL) = $\frac{w_B + w_Z}{2}$ ---------------------------- (vii)

Where; w_B and w_Z are the moisture content for the respective samples at plastic limit.

Figure 3.6. Liquid Limit with UTEST Cone Penetrometer and Moisture Cans

3.3.5. Linear Shrinkage (LS)

The linear shrinkage (LS) helps to quantify the amount of shrinkage of our sample after drying process is extended after plastic limit is reached. The LS was conducted on our samples mix with the Borassus fibres and without the Borassus fibres in accordance to BS 1377-2:1990.

The samples used for this experiment were the same mix used for making our mortar cubes with fibres and without fibres whose moisture content coincides with the liquid limit of the sample mix.

The LS test moulds were cleaned and greased properly. The sample was poured and levelled in the mould. The original length was recorded as L_o, they were allow to airdry for 2 days and placed in the UTEST drying oven to dry completely at 110°C for about 16hours. The length of the oven-dried sample was recorded as L_D.

Percentage of Linear Shrinkage is expressed as;

$$LS = \left(1 - \frac{L_D}{L_O}\right) \times 100$$ -------------------------------- (viii) (BS1377-2, 1990)

Figure 3.7: Linear shrinkage Mould with sample after drying

3.3.6. Compressive strength Testing

The test was conducted to determine the compressive strength of the mortar cubes cured at room temperature and sometimes sundried within their 7days, 14 days and 28days. The compressive test was conducted for the sets of samples containing and not containing the Borassus fibres at these curing days. The test was conducted in accordance to BS EN 12390-3:2009 for compressive strength of test specimen. The test equipment used was CONTROLS WIZARD AUTO conforming to the BS EN 12390-4:2009 specification for the compressive testing machine

The machines surfaces were cleaned to remove dirt and moisture. The cubes were weighed and measured with the digital vernier caliper for actual dimensions upon testing. The cubes were positioned and the parameters were set on the testing equipment specifying the size to be 5 x 5 x 5cm. The equipment is digitally controlled, the load value, time taken and compressive strength were on its screen display as more is applied on the sample till it fails. The test was conducted on 3 numbers of a particular type of sample and their average compressive strength was estimated. The mode of these specimen failures was examined if its satisfactory or not satisfactory according to the standard.

The compressive strength, f_c *is* calculated by;

$$f_c = \frac{F}{A_C} \quad \text{---------------------------------} \quad \text{(ix)} \qquad \text{(BS EN 12390-3, 2009)}$$

where ;

f_c is the compressive strength in MPa

F is the maximum load at failure

A_c is the cross-sectional area of the specimen.

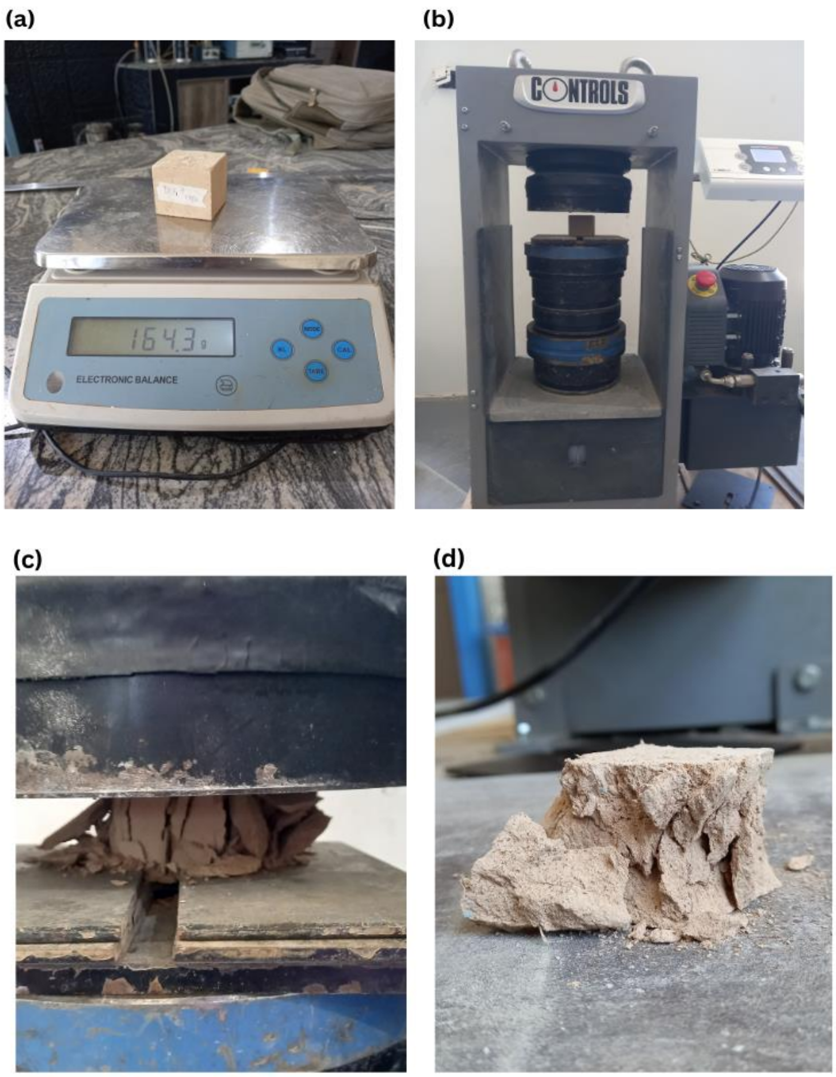


Figure 3.8. (a) Weighing of sample. (b) Placing sample in the Equipment for testing (c) Sample at Failure upon testing. (d) Failed sample

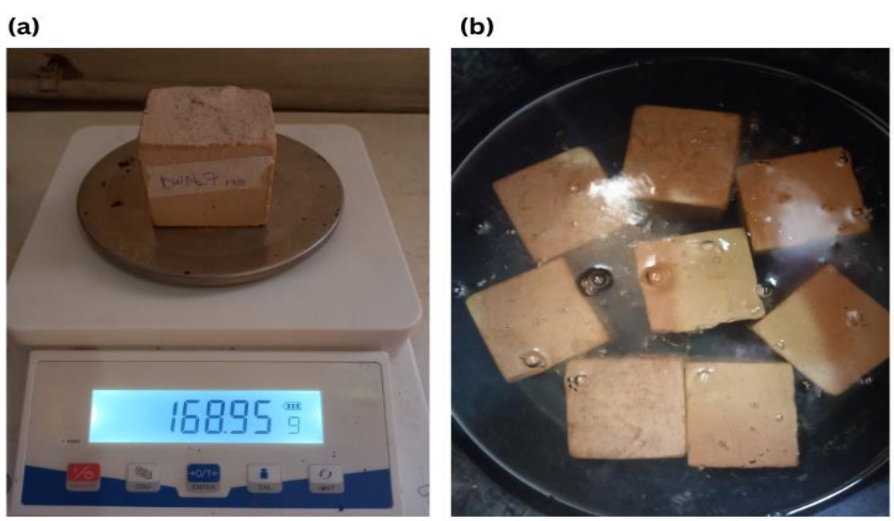
3.3.7. Water Absorption Test

The Water Absorption test was carried out in accordance in to BS 1881 – 122, Method for determination of water absorption. It is the measure of the moisture content absorbed by the specimen when immersed in water for a specified period of time, usually 30 minutes. The tests were conducted for samples cured at room temperature for 7 days and 28days in order to check their difference in their Absorption

The samples were oven dried for about 72hours after which they were placed in dry airtight wrap for 24 hours. The mass of the specimen was recorded as M_1, they were now immersed in water for 30 minutes. The samples were removed and surface dried quickly with a piece of clothes. The samples new weight after surface drying were also recorded as M_2. The process was repeated for three specimen of the same type as shown in figure 3.9 and the average Water Absorption was estimated. (BS 1881-122, 1983)

The Water Absorption (WA) is expressed as the percentage of the ratio of water content upon immersion to the dry mass of the specimen.

$$\text{WA} = \frac{M_2 - M_1}{M_1} \times 100 \quad \text{--------------------------------} \quad (x)$$



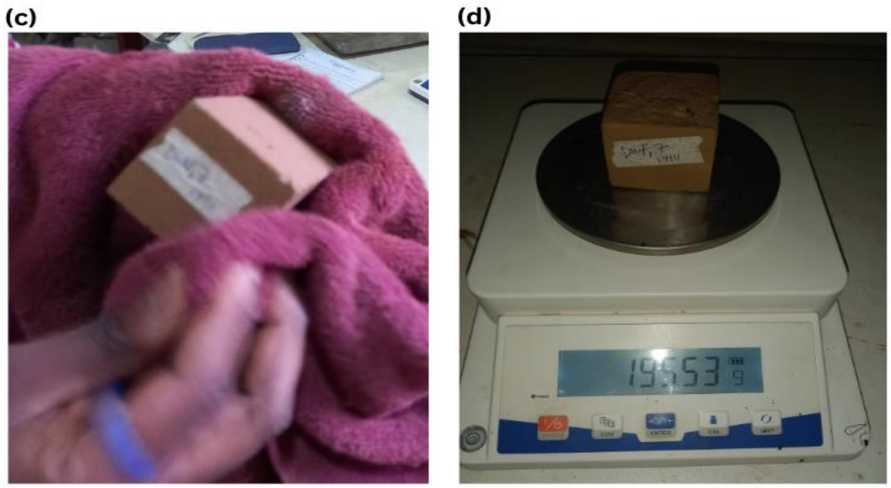


Figure 3.9. (a)Weighing of dry sample. (b) Sample Immersed in water
(c) Surface drying of sample. (d) Weighing of surface dried sample

3.4 MATERIAL CHARACTERIZATION

3.4.1 X-ray Diffraction (XRD) and X-ray Florescence analysis (XRF)

XRD and XRF analyzers are nondestructive method that offer quantitative and qualitative material characterization. They use X-ray source and detector by measuring the response to X-rays while interacting with the substance which helps with their identification. XRD and XRF helps with process control, screening, quality control and regulatory compliance for metals, mining and geology, scrap and recycling, education and research, and general manufacturing. (Michaud, 2015)

(Ayeni et al., 2022) examined the chemical composition of the Metakaolin used in this experiment with XRF, where the result showed that silica and alumina of 60.5% and 34.3% respectively were major constituents of the Metakaolin. The research also investigated the mineralogy of the Metakaolin with XRD by using a D-5000 PSC-8 X-ray diffractometer. The major minerals found were kaolinite, quartz and illitte.

3.4.2 Scanning Electron Microscope (SEM)

SEM provides a highly magnified image of the sample surface by scanning it with a high-energy beam of electrons in a raster scan pattern, which helps to simplify image interpretations. It provides information on the sample's topography, composition and electrical properties. SEM's measurement of surface topography is accurate over nanometer to millimeter range. It operates at higher and adjustable magnification from 10x – 300,000x. SEM's images are formed on a cathode ray tube with a raster synchronized with the raster of an electron beam moving over the sample. (Kaliva & Vamvakaki, 2020)

(Aboubakar et al., 2022) used the SEM on the natural Borassus fibres which showed that the fine and coarse fibres had uniform diameters throughout their length which varied from 100 μm to 365 μm respectively.

3.4.3 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR provides vibrational frequencies of chemical bonds which are used to identify the functional groups present in a sample. They are used for qualitative and quantitative determination of chemical species for solids and thin films, both trace and bulk, their stress and structural inhomogeneity. (Kaliva & Vamvakaki, 2020).

The FTIR was conducted on the sample mix with fibres and without fibres cured at 7 days and 14 days after the destructive compressive strength testing.

The samples were prepared by mixing a very small amount of the sample thoroughly with about a quarter teaspoon of Potassium Bromide (KBr) in a mortar with the pestle till it forms a homogenous mixture. Enough mixture was placed in a compacting die. They were transferred to the OFITE Automated compressive load frame, and the Enerpac hydraulic hand pump was used to exact pressure on the compacting die in the load frame. The compacting die was removed on the release of pressure in the OFITE equipment and the pellet was carefully removed and placed in the sample holder of Nicolet™ iS™ 5 FTIR Spectrometer used as shown in figure 3.10. The instrument sends infrared radiation of about 4,000 to 400 cm^{-1} through the sample. The system generates a plot of the radiation absorbed against its wavelength for the sample.

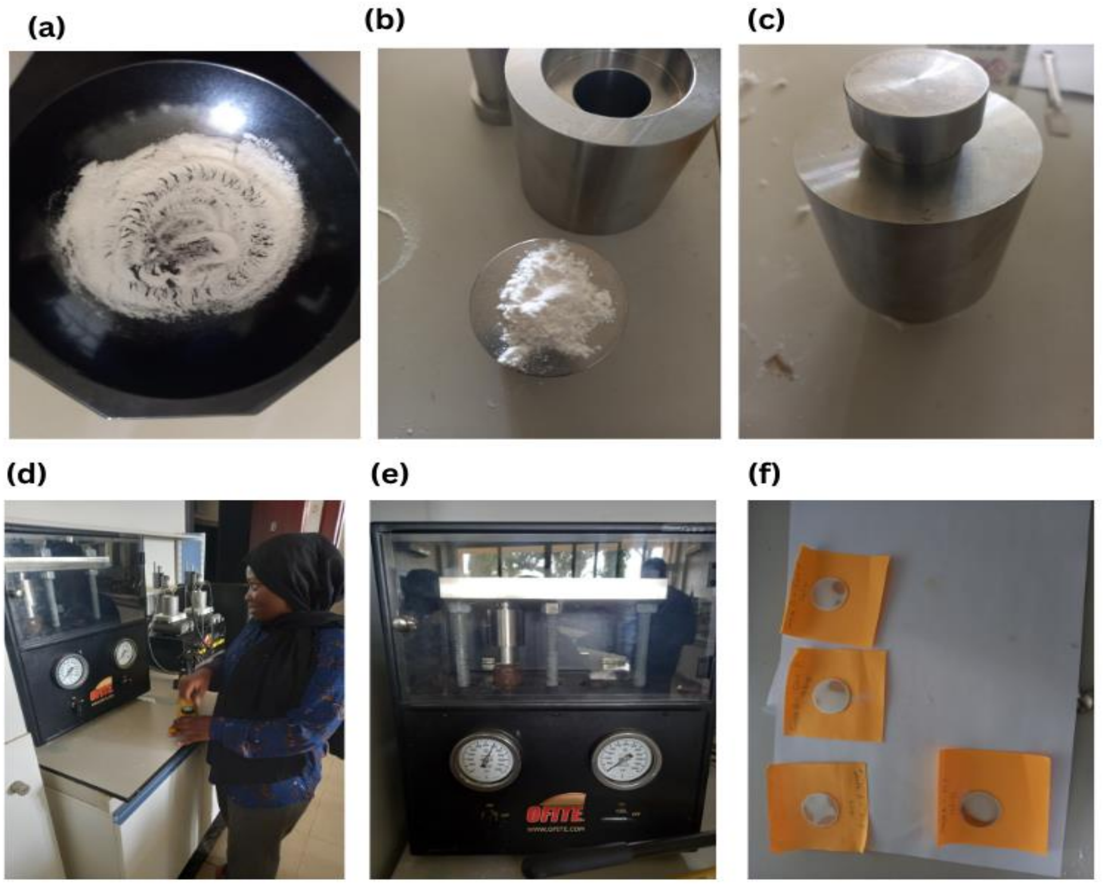


Figure 3.10. (a)Mixing of Sample with KBr in mortar. (b) Mixture poured in bottom die
(c) Compacting die with mixture. (d) Applying pressure with hydraulic pump
(e) Compacting die placed in OFITE equipment (f) Pellet formed and labelled per sample

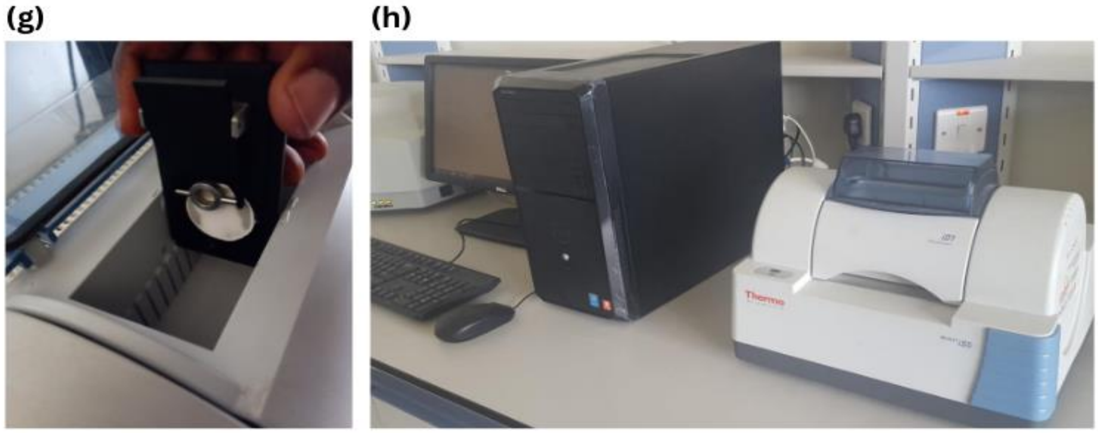


Figure 3.10. (g) Pellet placed in the sample holder of the FTIR instrument
(h) FTIR Instrument setup

CHAPTER 4

RESULTS AND DISCUSSION

4.1. LABORATORY TESTS RESULTS

4.1.1 Moisture content test

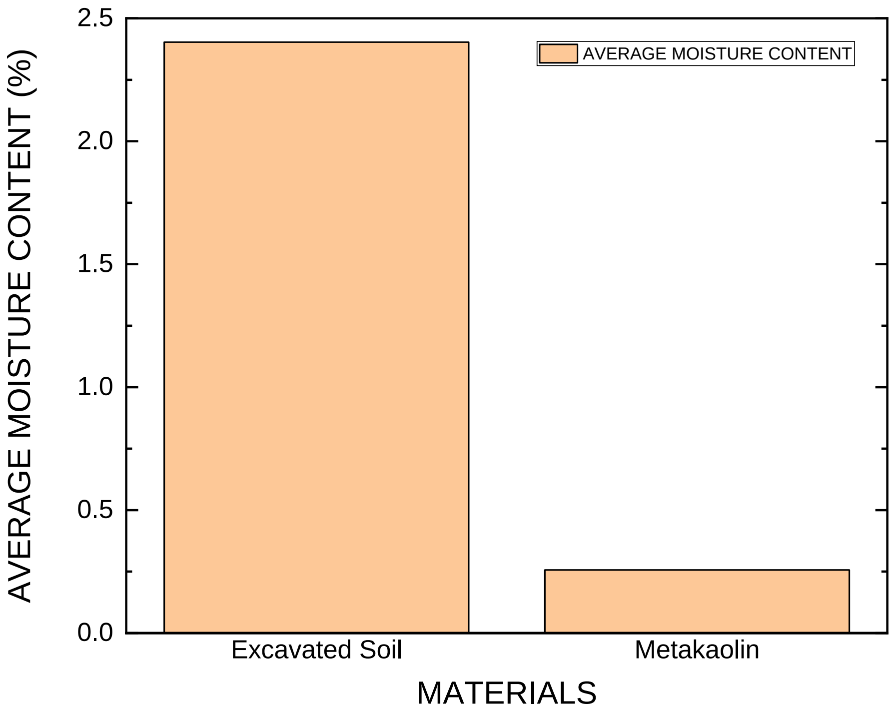


Figure 4.1. Average Moisture content for Excavated soil and Metakaolin

The figure above shows the natural average moisture content for Excavated soil sample used is 2.4% and Metakaolin is 0.26% which gives a hint on the state of the samples used for this experiment. The excavated soil used for this experiment has been discarded for up to 6months and exposed to direct sunlight which could be the reason for the low moisture content. The Metakaolin had gone through oven drying through the temperature of about 700^{o} C during formation process which resulted in it very low moisture content.

4.1.2 Bulk Density, Unit weight and Dry Density.

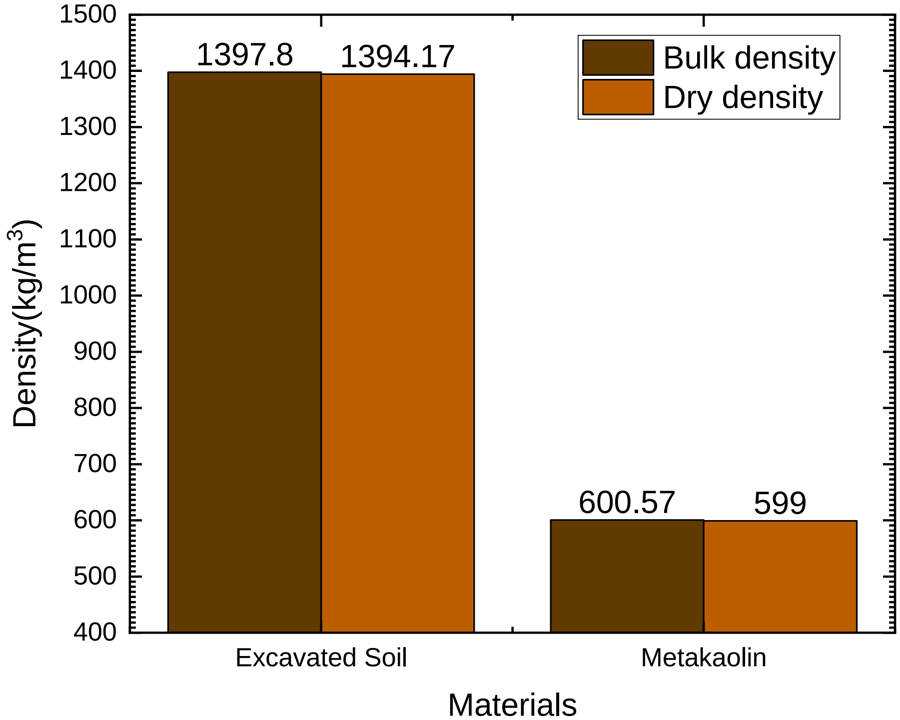


Figure 4.2. Graph showing Bulk Density and Dry density of Excavated soil and Metakaolin.

The difference in the values of the dry density and bulk density for the samples of Excavated soil and Metakaolin further proves the average moisture content level obtained for both samples. The Unit weight of Excavated soil and Metakaolin was estimated to be 13.7 kN/m3 and 5.89 kN/m3 respectively.

4.1.3 Sieve Analysis.

Metakaolin sample passing through 150µm sieve and Excavated soil retained and passing through 600µm sieve were used for the experiment. Figure 4.2 shows the particle size distribution of the excavated soil on the sieve sizes 600µm, 300µm, 200µm and 150µm which explains that our Excavated soil sample used can be classified as Fine Well-graded sand[H] (SW) according to ASTM D2487-00. (ASTM D2487 -00, 2000)

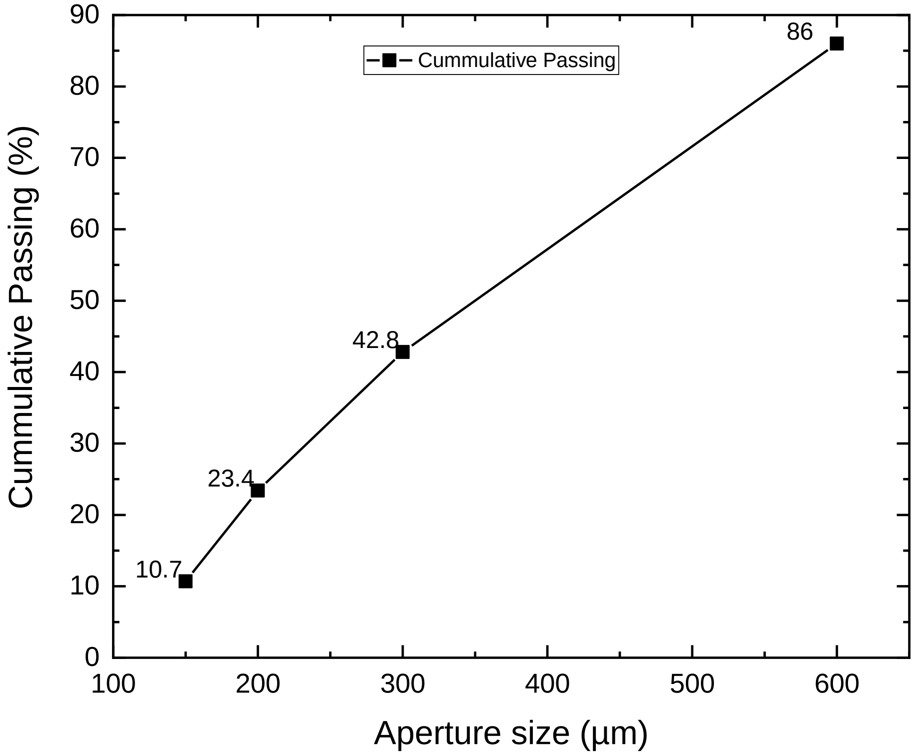


Figure 4.3. Particle size distribution of Excavated Soil.

4.1.4. Atterberg Limit Test and Linear Shrinkage

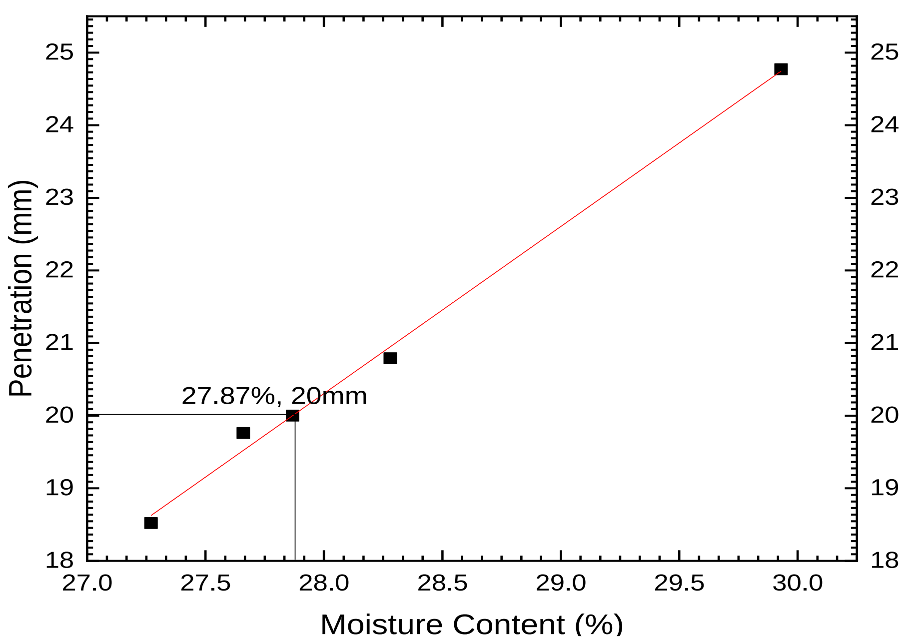


Figure 4.4. Graph of Penetration against Moisture content for Excavated Soil

Liquid Limit (LL) is approximately 27.87% as shown on the graph in Figure 4.4 above, Plastic Limit (PL) is 15% and Plasticity Index (PI) is 12.87% for Excavated soil samples.

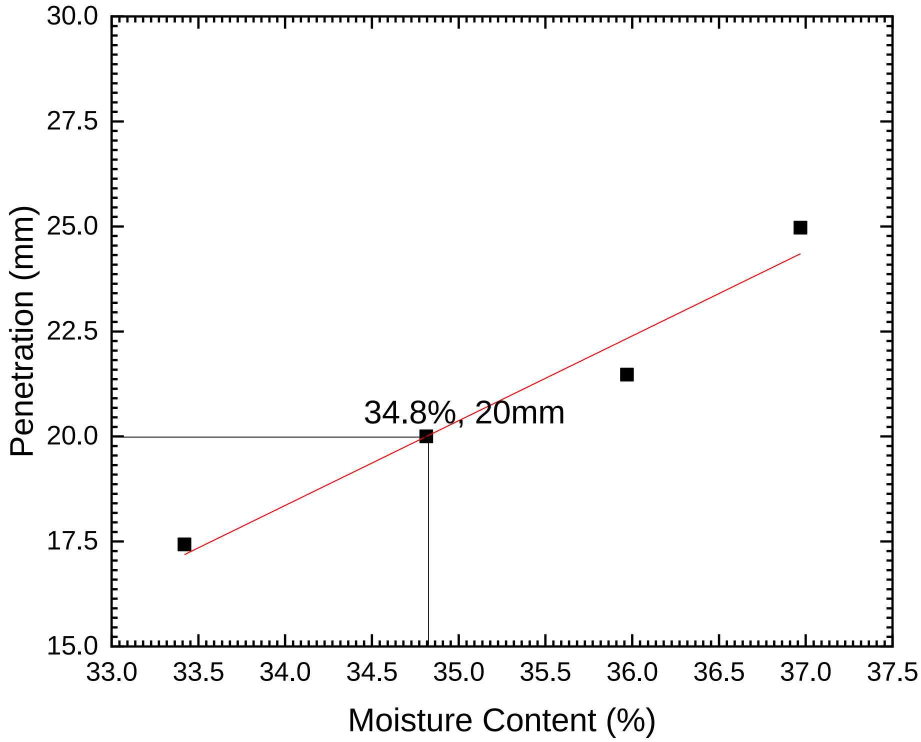


Figure 4.5. Graph of Penetration against Moisture content for Sample mix without Fibre.

Liquid Limit (LL) is approximately 34.8% as shown on the graph in Figure 4.5, Plastic Limit (PL) is 26.34% and Plasticity Index (PI) is 8.46% for samples without fibre.

Samples with 0.2% fiber's Liquid Limit (LL) is approximately 36.38% as shown on the graph in Figure 4.6, Plastic Limit (PL) is 24.61% and Plasticity Index (PI) is 11.77%

The average linear shrinkage for both samples with no fibre and 0.2% fibre is 2%. Both samples shrink in the same ratio when placed the linear shrinkage mould and dried.

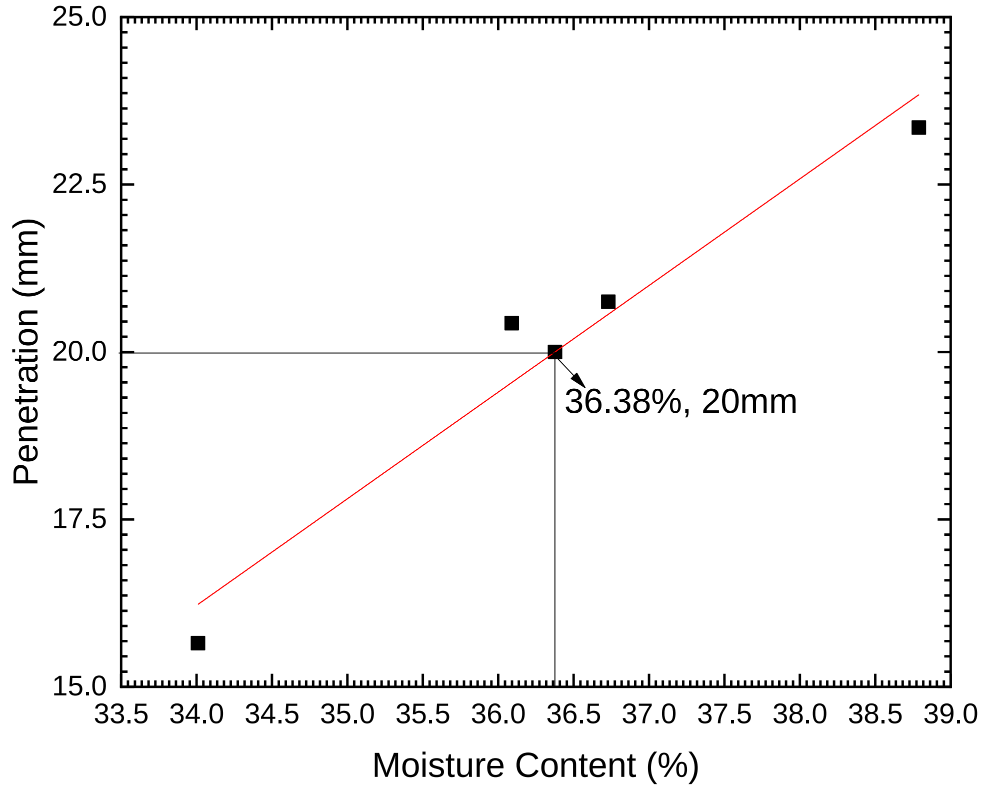


Figure 4.6. Graph of Penetration against Moisture content for Sample mix with 0.2% Fibre

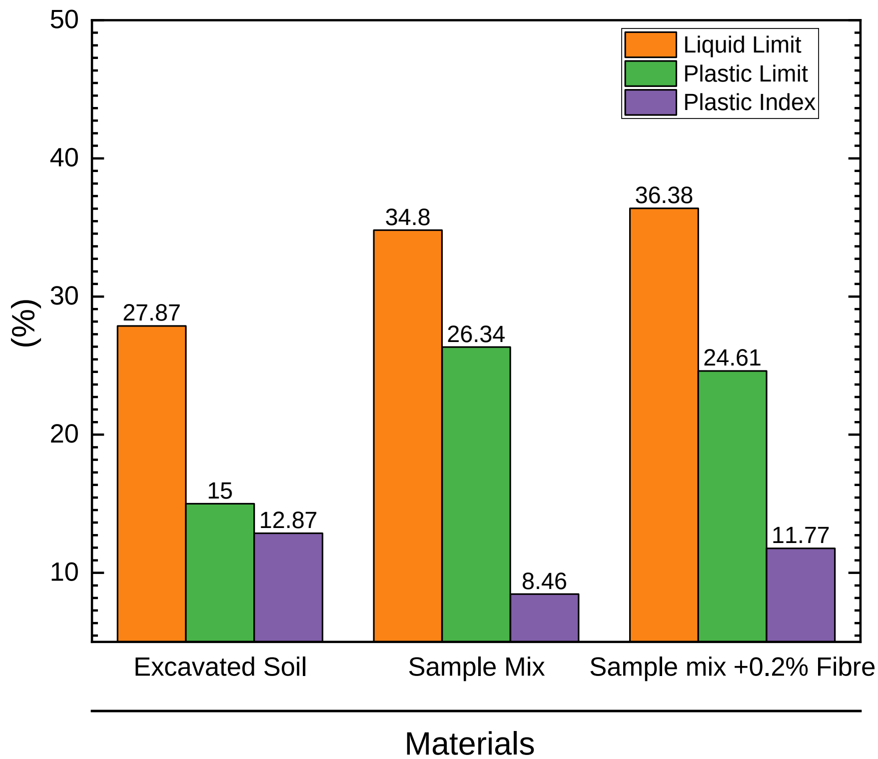


Figure 4.7. Atterberg Limits of Excavated Soil, Sample mix and Sample mix with Fibre.

The graph above shows the LL, PL and PI of the fine-grained excavated soil which can be used to classify the sample according to ASTM D2487-00. The Excavated soil sample can be classified under Lean clay[K,L,M] (CL) as Lean clay with sand because of the Plastic Index, PI is greater than 7%, Liquid limit less than 50% and their particle size distribution (ASTM D2487 -00, 2000).

The Atterberg limits and particle size distribution helps us to describe our soil sample in order to aid the evaluation of its properties for best usage in the best fit area applicable (ASTM D2488 -00, 2000).

The Excavated soil samples used identified as lean clay, is an example of inorganic fine-grained soils with soft consistency, possess medium toughness and plasticity, medium to high dry strength and no or slow dilatancy; which means it can maintain its original volume when subjected to shear deformations. (ASTM D2488 -00, 2000).

The sample mixtures with 0.2% fibre have a higher Liquid limit and Plastic index but lower Plastic limit compared to the sample mix with no fibre and same value for linear shrinkage. These consistency limits correlate well with engineering properties of the mixture. Hence it provides details on their transition from solid phase to liquid phase, compressibility, dry strength and toughness.

The higher the liquid limit the higher the compressibility of mixture. Greater values of plasticity index signify greater dry strength and toughness at plastic limit. The sample mixture with 0.5% fibres possesses slightly greater compressibility, dry strength and toughness, compared to sample mixtures with no fibres.

4.1.5. Compressive strength Testing.

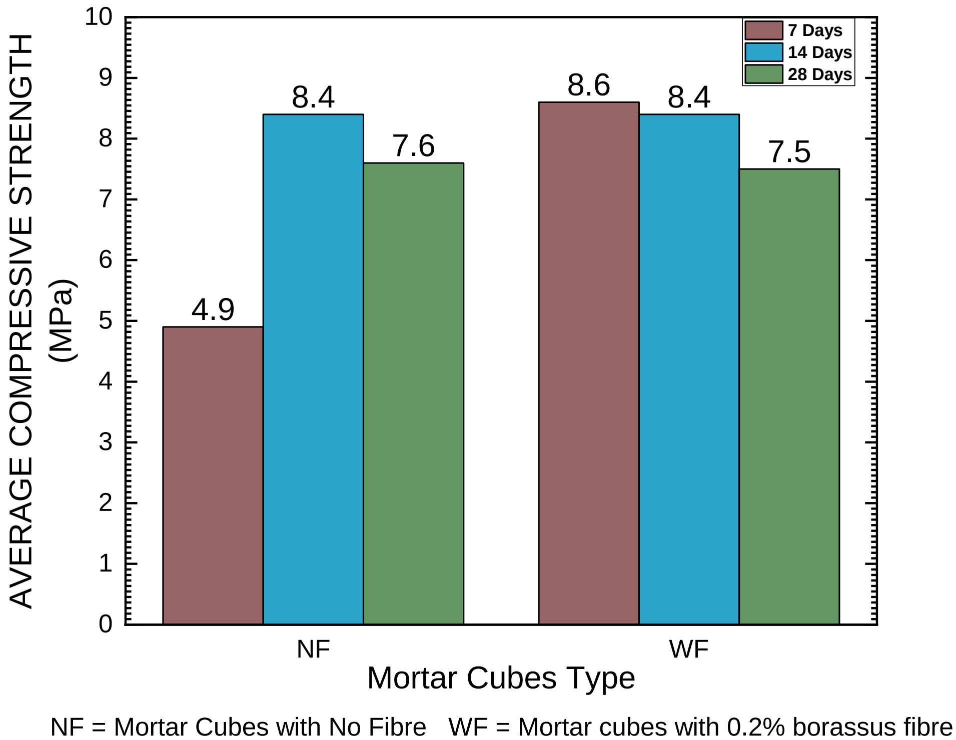


Figure 4.8. Average Compressive strength of Mortar cubes with their curing Days.

The graph in figure 4.8 above shows the compressive strength of the mortar cubes while curing at 7days, 14days and 28days. The Mortar cubes with 0.2% Borassus fibre shows the highest early strength more than 75% of what the mortar cubes without fibres could achieve at Day 7. More so, the Mortar cubes without fibres highest compressive strength was at Day 14 whose result coincide with the result of the samples with fibre.

Then again. Mortar cubes with 0.2% Borassus fibre has the highest compressive strength at Day 7 while it reduces gradually with 2% by Day 14 and further reduced with up to 10% at Day 28. Unlike the Mortar cubes with no Fibre, there was more than 70% increase in compressive strength for from day 7 to day 14. Making the day 14 compressive strength the highest. Both samples experienced up to 10% decrease in compressive strength from Day 14 to Day 28.

This decrease in compressive strength could be likened to the clay content in the mortar cube mixture. (Désiré & Léopold, 2018) researched on impact of clay particles on concrete compressive strength and discovered strength reduction with the number of curing days.

According to (Gawatre & Vairagade, 2014) the minimum compressive strength of brick shall not be less than 7.5 MPa when tested which our Mortar cubes passed under open aired curing condition.

(BS EN 998-2, 2016) classified hardened mortar with respect to their compressive strength and the mortar cubes from this research exceeds the M 5 class with 5 MPa compressive strength but not up to M 10 with compressive strength of 10 MPa. This signifies that the mortar cubes from this research can be improved or used as it is for relevant construction purpose.

4.1.5.1 Examining the mode of failure during compressive strength testing.

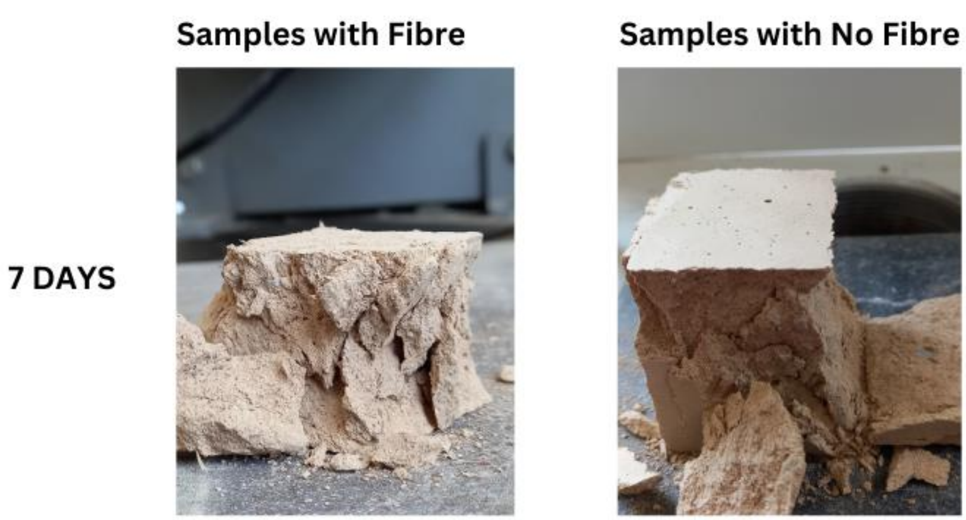


Figure 4.9a. Failure mode of samples at 7 days compressive strength test.

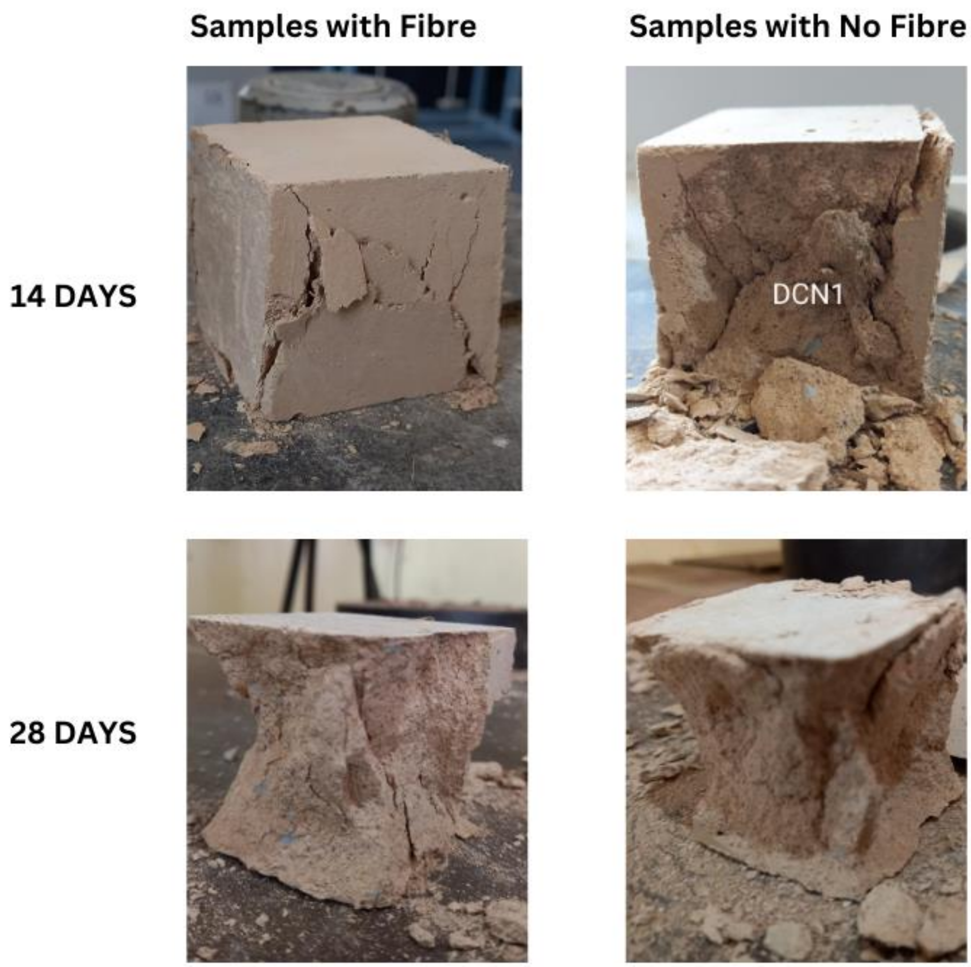


Figure 4.9b. Failure mode of samples at 14 days and 28 days compressive strength test.

According to BS EN 12390-3 on testing hardened concrete, the figure 4.9 a and b above showed that the failure of the Mortar cubes specimen were satisfactory as the four exposed faces were cracked approximately with little damage to the specimen faces in contact with the platens (BS EN 12390-3, 2009).

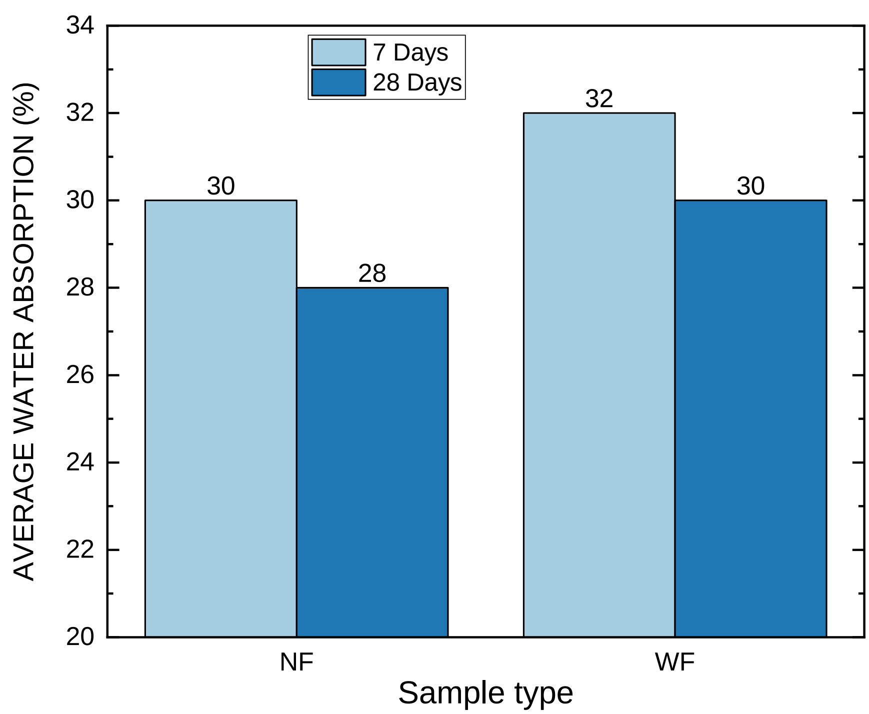
4.1.6. Water Absorption Test

The graph below in figure 4.10 shows the water absorption of the mortar cubes when cured at 7 days and 28 days.

It can be observed that Mortar cubes with 0.2% fibres average water absorption is slightly above Mortar cubes with no fibre. This means that they are more porous than the Mortar cubes with no fibre addition.

The average water absorption of the Mortar cubes is high due to presence of voids which made the samples absorb water quickly within 30 minutes of immersion. The higher value of water absorption in the Mortar mix with fibres samples could be because of the weak binding of the Mortar mix with the fibres thereby creating more voids for water absorption.

Then again, the graph shows constant increase of about 6% in the water absorption for both samples tested at 7days and 28 days. This could be because they were cured in similar conditions. Material loss of Mortar cubes during curing as visually inspected due to environmental conditions could lead to increase in voids in sample which increases its water absorption.



NF = Mortar Cubes with No Fibre   WF = Mortar cubes with 0.2% borassus fibre

Figure 4.10. Water Absorption Test Result of Mortar cubes with their curing Days.

4.2. STRUCTURE, COMPOSITION AND CHARACTERIZATION OF SAMPLES.

4.2.1 X-ray Diffraction (XRD) and X-ray Florescence analysis (XRF) of Metakaolin

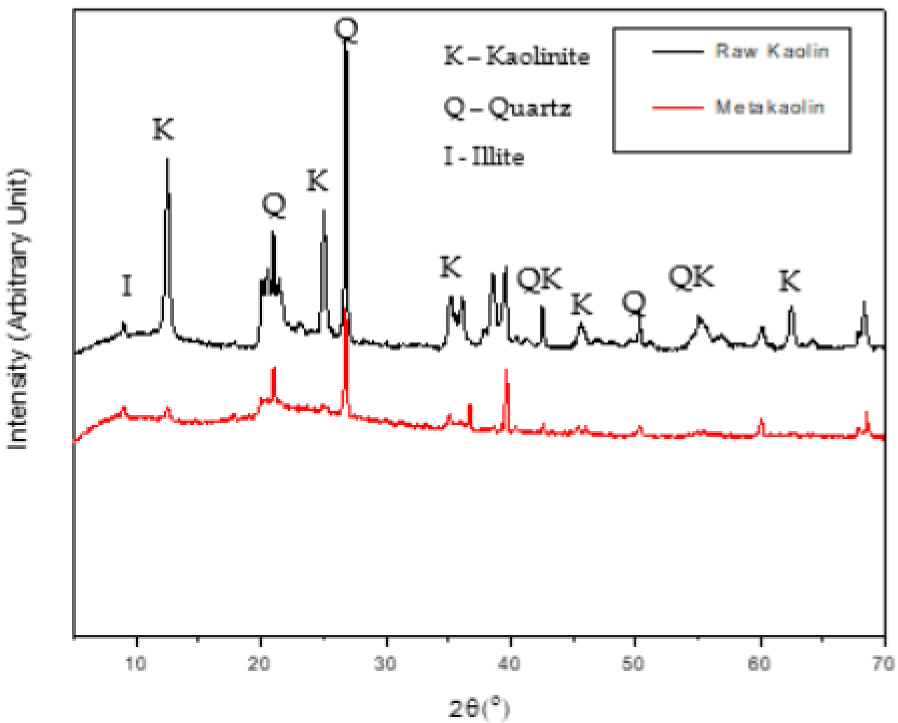
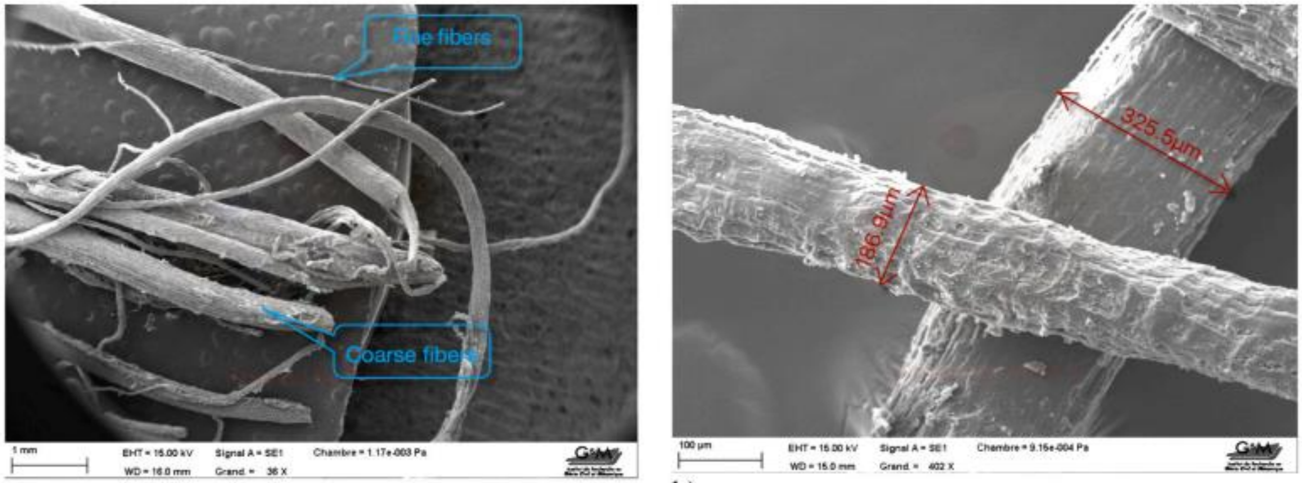


Figure 4.11. XRD Diffractogram of Raw kaolin and Metakaolin (Ayeni et al., 2022)**.**

Table 4.1. Chemical Composition of Metakaolin with XRF Analyzer (Ayeni et al., 2022)

Mass Ratio (%)	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	K_2O	MnO	ZrO_2	CaO	BaO	LOI
Metakaolin	60.50	34.30	2.41	0.15	0.20	0.15	0.09	0.04	0.01	2.15

4.2.2 Scanning Electron Microscope of Natural Borassus fibres



a) b)

Figure 4.12. (a) SEM Image of coarse and fine Borassus fibres (b) SEM Image showing uniform fibre diameter throughout the length of the Borassus fibre. (Aboubakar et al., 2022)

4.2.3 Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectra recorded from a wavenumber of 400 to 4000 cm^{-1} for the samples at their respective curing days after compressive strength test are shown in figure 4.13.

The identified functional groups are C-H group with sharp peaks at the range of 3029 – 2851cm^{-1} and at 762cm^{-1} of the fingerprint region with weaker peak. Overlapping OH acid group with broad peak within 3029 – 2926cm^{-1} was also observed in between the C-H group. Aromatic ring weak peak was observed at 1611cm^{-1} and strong peaks were observed almost at 1500 and 1455cm^{-1} of the finger print region. Alkanes were identified at the Fingerprint region and Halogen hydrocarbon with its sharpest peak at 699 cm^{-1}. The functional groups did not show any significant change over the curing period and fibre content, this shows the material chemical composition remained intact which was also observed by (Aboubakar et al., 2022) with 0.5% borassus fibres.

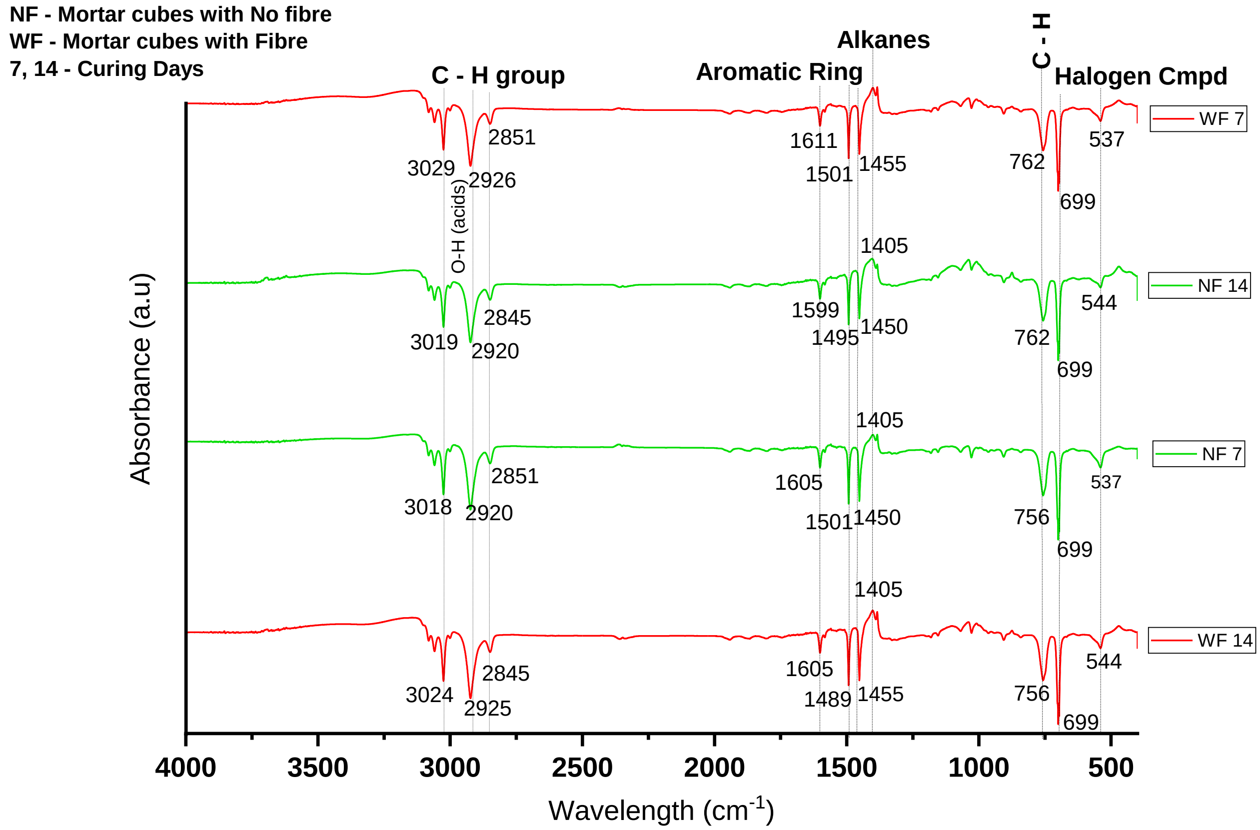


Figure 4.13. FTIR Spectra of Mortar cubes

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1. CONCLUSION

- The low natural moisture content of the discarded excavated soil sample used was as a result of the weather condition and prolonged exposure to it. On fetching the samples, it was a heap abandoned on the site very compact and we had to use shovel to lose them for usage.
- The sample mixtures enhanced the liquid limit and Plastic limit of the excavated soil sample used, their properties were enhanced and made them suitable to consider for construction purpose. The very fine particles of the Mortar cube mixture were used to achieve more plasticity.
- 0.2% Borassus Fibre increased the Liquid limit and Plastic index of the sample mix which signifies greater compressibility, dry strength and toughness at plastic limit.
- The compressive strength of the Mortar cubes from this research signifies they can be relevant and improved for construction purpose and their mode of failure was satisfactory in accordance to BS EN 12390-3 on testing hardened concrete.
- The water absorption is slightly high in Mortar cubes due to presence of voids in sample. It increased by 6% from 7 days to 28days curing days. It is slightly higher in mortar cubes with 0.2% Borassus fibre addition.
- The functional groups identified did not show any significant change over the curing period and fibre content, this shows the material chemical composition remained intact.

5.2. RECOMMENDATION

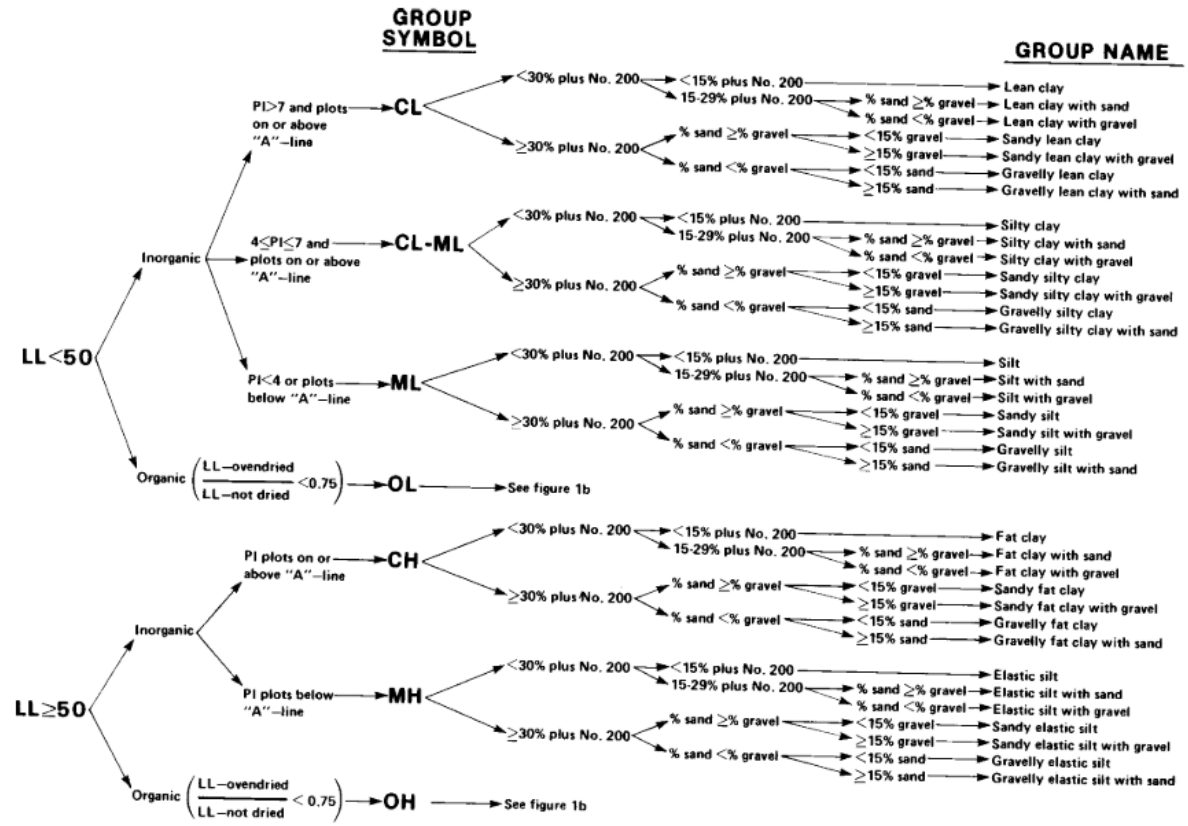
- Excavated soil in construction site should not be abandoned or discarded but rather tested and employed for relevant usage.
- Exploring other Curing Methods such as Oven drying, Humidity, etc, to discover if it enhances the compressive strength of the mortar cubes
- Alkaline activation of the Metakaolin could also be done to see if it enables the sample achieve higher strength.
- Stabilizers such as lime, fly ash can also be experimented to stabilize the clay content and avoid reduction in compressive strength with curing days.
- Several methods of eliminating surface voids can be deployed to reduce the water absorption of mortar cubes and make them suitable for usage such as adjusting material mix proportions with their water content and increasing vibration time to eliminate voids.
- Other material characterization technique such as the SEM, EDX, XRD and XRF can also be employed to test the materials and samples produced. SEM can be used to examine the failure of the mortar cubes after destructive testing to check its adhesion to the Borassus fibre reinforcement.

APPENDIX

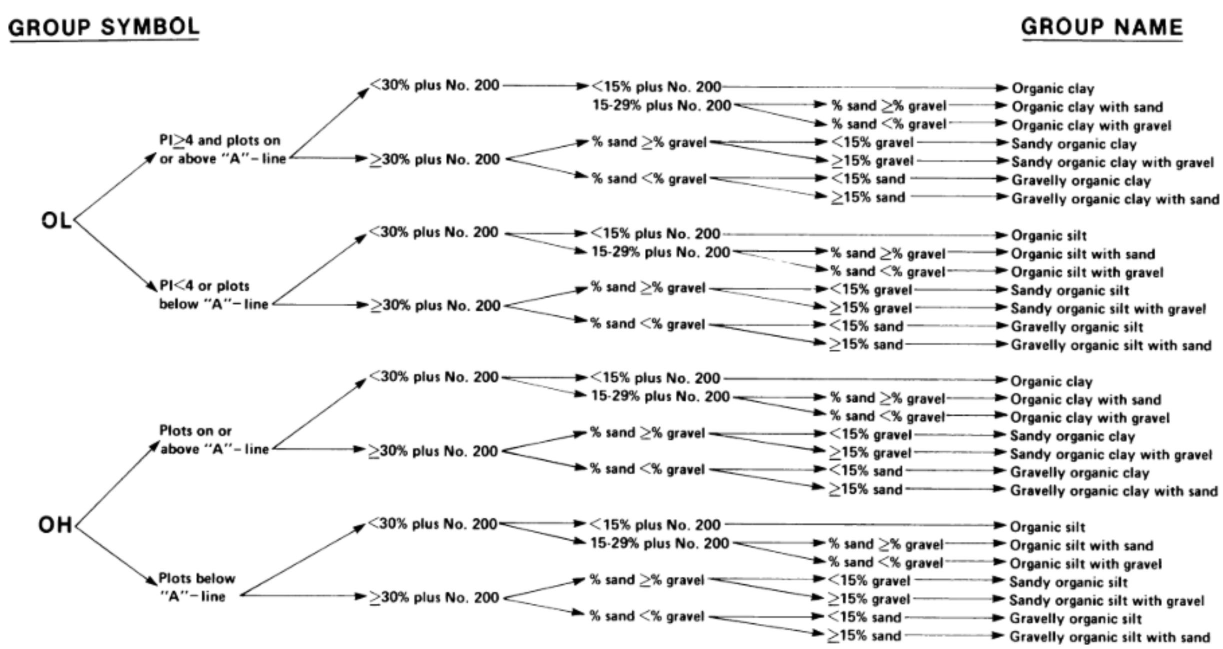
Soil Classification chart. (ASTM D2487 -00, 2000)

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests[A]				Soil Classification Group Symbol	Soil Classification Group Name[B]
COARSE-GRAINED SOILS	Gravels	Clean Gravels	Cu ≥ 4 and 1 ≤ Cc ≤ 3[C]	GW	Well-graded gravel[D]
More than 50 % retained on No. 200 sieve	More than 50 % of coarse fraction retained on No. 4 sieve	Less than 5 % fines[E]	Cu < 4 and/or 1 > Cc > 3[C]	GP	Poorly graded gravel[D]
		Gravels with Fines	Fines classify as ML or MH	GM	Silty gravel[D,F,G]
		More than 12 % fines[E]	Fines classify as CL or CH	,urule;1>GC	Clayey gravel[D,F,G]
	Sands	Clean Sands	Cu ≥ 6 and 1 ≤ Cc ≤ 3[C]	SW	Well-graded sand[H]
	50 % or more of coarse	Less than 5 % fines[I]	Cu < 6 and/or 1 > Cc > 3[C]	SP	Poorly graded sand[H]
	fraction passes No. 4 sieve	Sands with Fines	Fines classify as ML or MH	SM	Silty sand[F,G,H]
		More than 12 % fines[I]	Fines classify as CL or CH	SC	Clayey sand[F,G,H]
FINE-GRAINED SOILS	Silts and Clays	inorganic	PI > 7 and plots on or above "A" line[J]	CL	Lean clay[K,L,M]
50 % or more passes the No.	Liquid limit less than 50		PI < 4 or plots below "A" line[J]	ML	Silt[K,L,M]
200 seive		organic	Liquid limit – oven dried> < 0.75	OL	Organic clay[K,L,M,N]
			Liquid limit – not dried	OL	Organic silt[K,L,M,O]
	Silts and Clays	inorganic	PI plots on or above "A" line	CH	Fat clay[K,L,M]
	Liquid limit 50 or more		PI plots below "A" line	MH	Elastic silt[K,L,M]
		organic	Liquid limit – oven dried < 0.75	OH	Organic clay[K,L,M,P]
			Liquid limit – not dried		Organic silt[K,L,M,Q]
HIGHLY ORGANIC SOILS	Primarily organic matter, dark in color, and organic odor			PT	Peat

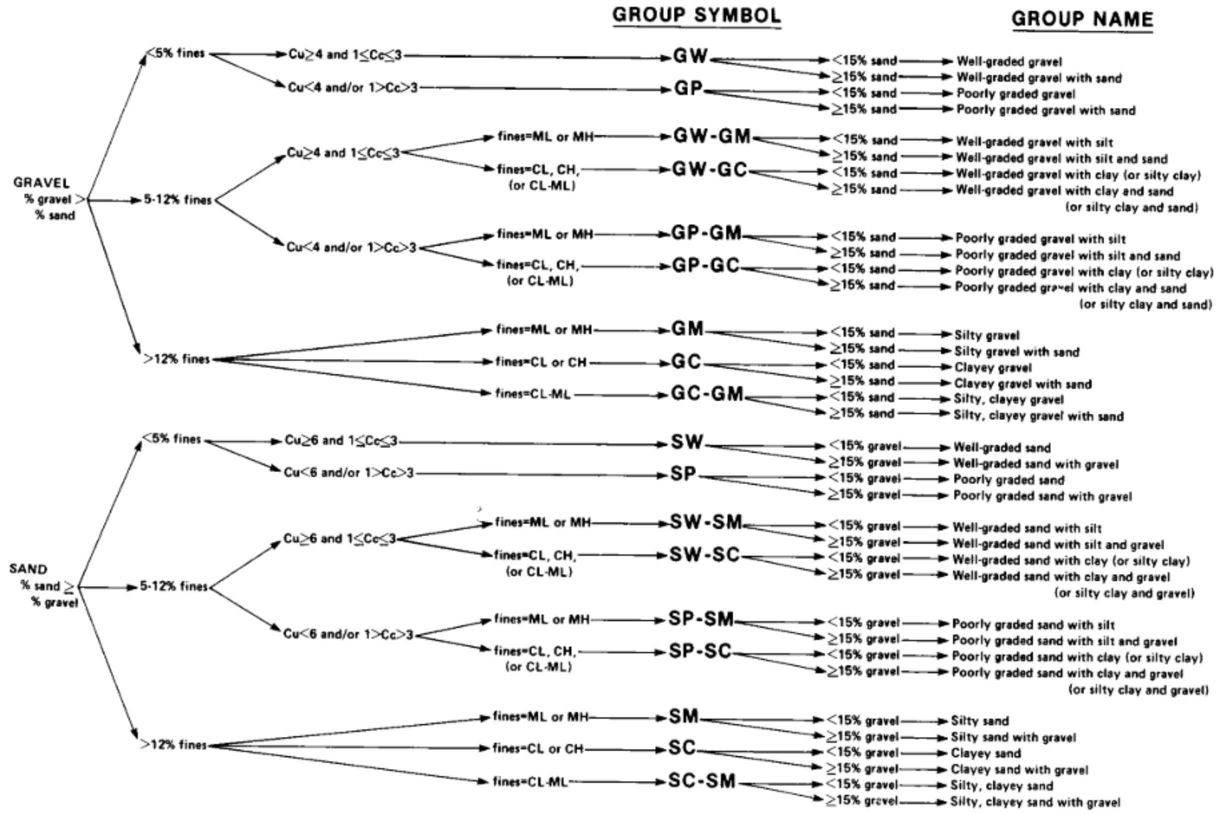
[A] Based on the material passing the 3-in. (75-mm) sieve.
[B] If field sample contained cobbles or boulders, or both, add "with cobbles or boulders, or both" to group name.
[C] $Cu = D_{60}/D_{10}$ $\quad Cc = (D_{30})^2 / D_{10} \times D_{60}$
[D] If soil contains ≥15 % sand, add "with sand" to group name.
[E] Gravels with 5 to 12 % fines require dual symbols:
GW-GM well-graded gravel with silt
GW-GC well-graded gravel with clay
GP-GM poorly graded gravel with silt
GP-GC poorly graded gravel with clay
[F] If fines classify as CL-ML, use dual symbol GC-GM, or SC-SM.
[G] If fines are organic, add "with organic fines" to group name.
[H] If soil contains ≥15 % gravel, add "with gravel" to group name.
[I] Sands with 5 to 12 % fines require dual symbols:
SW-SM well-graded sand with silt
SW-SC well-graded sand with clay
SP-SM poorly graded sand with silt
SP-SC poorly graded sand with clay
[J] If Atterberg limits plot in hatched area, soil is a CL-ML, silty clay.
[K] If soil contains 15 to 29 % plus No. 200, add "with sand" or "with gravel," whichever is predominant.
[L] If soil contains ≥30 % plus No. 200, predominantly sand, add "sand " to group name.
[M] If soil contains ≥30 % plus No. 200, predominantly gravel, add "gravelly" to group name.
[N] PI ≥ 4 and plots on or above "A" line.
[O] PI < 4 or plots below" A" line.
[P] PI plots on or above "A" line.
[Q] PI plots below "A" line.



Flowchart for classifying fine-grained soil (50% or more passes No. 200 Sieve) (ASTM D2487 - 00, 2000)



Flowchart for classifying organic fine-grained soil (50% or more passes No. 200 Sieve) (ASTM D2487 -00, 2000)



Flowchart for classifying coarse-grained soil (50% or more passes No. 200 Sieve) (ASTM D2487 -00, 2000).

Checklist for Description of soils (ASTM D2488 -00, 2000)

1. Group name
2. Group symbol
3. Percent of cobbles or boulders, or both (by volume)
4. Percent of gravel, sand, or fines, or all three (by dry weight)
5. Particle-size range:
   Gravel—fine, coarse
   Sand—fine, medium, coarse
6. Particle angularity: angular, subangular, subrounded, rounded
7. Particle shape: (if appropriate) flat, elongated, flat and elongated
8. Maximum particle size or dimension
9. Hardness of coarse sand and larger particles
10. Plasticity of fines: nonplastic, low, medium, high
11. Dry strength: none, low, medium, high, very high
12. Dilatancy: none, slow, rapid
13. Toughness: low, medium, high
14. Color (in moist condition)
15. Odor (mention only if organic or unusual)
16. Moisture: dry, moist, wet
17. Reaction with HCl: none, weak, strong

For intact samples:

18. Consistency (fine-grained soils only): very soft, soft, firm, hard, very hard
19. Structure: stratified, laminated, fissured, slickensided, lensed, homogeneous
20. Cementation: weak, moderate, strong
21. Local name
22. Geologic interpretation
23. Additional comments: presence of roots or root holes, presence of mica, gypsum, etc., surface coatings on coarse-grained particles, caving or sloughing of auger hole or trench sides, difficulty in augering or excavating, etc.

Criteria for Describing soils (ASTM D2488 -00, 2000)

TABLE 3 Criteria for Describing Moisture Condition

Description	Criteria
Dry	Absence of moisture, dusty, dry to the touch
Moist	Damp but no visible water
Wet	Visible free water, usually soil is below water table

TABLE 4 Criteria for Describing the Reaction With HCl

Description	Criteria
None	No visible reaction
Weak	Some reaction, with bubbles forming slowly
Strong	Violent reaction, with bubbles forming immediately

TABLE 5 Criteria for Describing Dilatancy

Description	Criteria
Very soft	Thumb will penetrate soil more than 1 in. (25 mm)
Soft	Thumb will penetrate soil about 1 in. (25 mm)
Firm	Thumb will indent soil about ¼in. (6 mm)
Hard	Thumb will not indent soil but readily indented with thumbnail
Very hard	Thumbnail will not indent soil

TABLE 6 Criteria for Describing Toughness

Description	Criteria
Weak	Crumbles or breaks with handling or little finger pressure
Moderate	Crumbles or breaks with considerable finger pressure
Strong	Will not crumble or break with finger pressure

TABLE 7 Criteria for Describing Dilatancy

Description	Criteria
Stratified	Alternating layers of varying material or color with layers at least 6 mm thick; note thickness
Laminated	Alternating layers of varying material or color with the layers less than 6 mm thick; note thickness
Fissured	Breaks along definite planes of fracture with little resistance to fracturing
Slickensided	Fracture planes appear polished or glossy, sometimes striated
Blocky	Cohesive soil that can be broken down into small angular lumps which resist further breakdown
Lensed	Inclusion of small pockets of different soils, such as small lenses of sand scattered through a mass of clay; note thickness
Homogeneous	Same color and appearance throughout

Criteria for Describing soils (ASTM D2488 -00, 2000)

TABLE 8 Criteria for Describing Toughness

Description	Criteria
None	The dry specimen crumbles into powder with mere pressure of handling
Low	The dry specimen crumbles into powder with some finger pressure
Medium	The dry specimen breaks into pieces or crumbles with considerable finger pressure
High	The dry specimen cannot be broken with finger pressure. Specimen will break into pieces between thumb and a hard surface
Very high	The dry specimen cannot be broken between the thumb and a hard surface

TABLE 9 Criteria for Describing Dilatancy

Description	Criteria
None	No visible change in the specimen
Slow	Water appears slowly on the surface of the specimen during shaking and does not disappear or disappears slowly upon squeezing
Rapid	Water appears quickly on the surface of the specimen during shaking and disappears quickly upon squeezing

TABLE 10 Criteria for Describing Toughness

Description	Criteria
Low	Only slight pressure is required to roll the thread near the plastic limit. The thread and the lump are weak and soft
Medium	Medium pressure is required to roll the thread to near the plastic limit. The thread and the lump have medium stiffness
High	Considerable pressure is required to roll the thread to near the plastic limit. The thread and the lump have very high stiffness

TABLE 11 Criteria for Describing Plasticity

Description	Criteria
Nonplastic	A ⅛-in. (3-mm) thread cannot be rolled at any water content
Low	The thread can barely be rolled and the lump cannot be formed when drier than the plastic limit
Medium	The thread is easy to roll and not much time is required to reach the plastic limit. The thread cannot be rerolled after reaching the plastic limit. The lump crumbles when drier than the plastic limit
High	It takes considerable time rolling and kneading to reach the plastic limit. The thread can be rerolled several times after reaching the plastic limit. The lump can be formed without crumbling when drier than the plastic limit

Criteria for Describing soils (ASTM D2488 -00, 2000)

TABLE 12 Identification of Inorganic Fine-Grained Soils from Manual Tests

Soil Symbol	Dry Strength	Dilatancy	Toughness
ML	None to low	Slow to rapid	Low or thread cannot be formed
CL	Medium to high	None to slow	Medium
MH	Low to medium	None to slow	Low to medium
CH	High to very high	None	High

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