Investigation and Comparative Analysis of Natural Moulding Sands from Five Deposits in Maiduguri, Nigeria

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Abstract

This study investigates foundry sands from samples deposits (A-E) to evaluate their uses for casting applications. Key properties analysed included chemical content, clay content, grain distribution (AFS-GFN), moisture content, bulk density, permeability, compression strength (CS), and refractoriness. Chemical analysis revealed high silica content (68.10% - 79.56% SiO_2) and aluminium oxide (2.68% - 20.52% Al_2O_3), meeting standards for aluminium casting. Impurities like FeO were present but within tolerable limits. Clay content varied significantly (11% - 44.5%), aligning with requirements for non-ferrous metals and specific ferrous alloys. Sieve analysis showed well-graded sands with a high percentage of fine grains (28.84% - 44.2% retained on the 63μm sieve), beneficial for surface finish. AFS-GFN values (60.55 - 90.5) were generally within the recommended range (35-90) for non-ferrous metals. Moisture content (1.9% - 5.6%) was suitable for low-temperature aluminium casting, with permeability (80.1 - 89.1) and Green Compression Strength (60.2 - 71.5 kN/m^2) fell within acceptable foundry ranges of. Refractoriness was high (1350°C – 1450 °C), indicating adequate thermal stability. The natural sands, particularly samples A, C, and D, possess suitable physico-chemical properties with high silica, adequate refractoriness with appropriate permeability, and strength for casting practice, especially for non-iron metals and specific ferrous alloys like light grey iron. Sample B's higher fines content and lower GFN suggest for small-scale and high precision casting.

Keywords: *American Foundry Society (AFS), Green Compression Strength (GCS), yield strength (YS), grain size (GS).*

1.0 Introduction

Foundry process, which involves creating products by pouring molten metal into a mould to create a casting, dates back to around 3600 BC. This old manufacturing method has proven highly successful and continues to progress, serving as a fundamental manufacturing process. Modern communication and lighting systems would be challenging without castings. Modern civilization would not be so far advanced as it is today if it were not for the foundry and its products. Foundry practice includes such basic production processes as melting of metal, manufacture of moulds, pouring of the metal into moulds, solidification, shakeout and fettling of the castings [3]. Castings with different features includes fabrication in cylinder blocks, mill rolls, machine tool bed, piston rings, connecting rods, wheels, housings and different automobile parts [2],[4],[5].

Natural moulding sand, primarily composed of silica (SiO_2) with clay and other additives, is important in foundry utilization. Its uses depend on the specific casting application and the desired properties of the final component. For a natural sand to be recommended for casting, it must be within a standard range for key attributes like strength, permeability, thermal stability, and collapsibility. This research focused on analyzing sands from selected deposits to evaluate if they possess these necessary characteristics for use in sand casting.

2.0 Materials and Methods

2.1 Materials

The materials used in this study as showing in Table 1 include foundry sands from study sites as indicated in Table 1.

Table 1: List of materials/sources

Material	Source/Location
Natural Moulding Sand Samples	Collected from 5 deposits in Maiduguri: Bulumkutu, Bulabulin Kasuwa, Maiduguri-Fariya, Ramat Polytechnic, and Mashidimami. Collected at 3 m depth with average distance of 1.28km

Table 2: Equipment and their sources

Equipment	Source
Moisture Teller	Ramat Polytechnic
Permeability Meter	Ramat Polytechnic (Ridsdale DieterT)
Sieve Shaker	Unimaid, Ramat (Advantech for some)
Lab Rammer	Ramat Polytechnic
Meter Rule	Ramat Polytechnic
Measuring Cylinder	Ramat Polytechnic
Stopwatch	Ramat Polytechnic
Thermometer	Ramat Polytechnic
Balance meter	Unimaid, Ramat Polytechnic (Ridsdale Digital Electronic Balance)
Oven	Ramat Polytechnic (Griffin and George Limited Electric Oven, M.L Furnace Model M5)
Shimadzu 720 X-ray Fluorescence (XRF) Spectrometer	Unimaid (Department of Geology)
Atomic Absorption Spectrophotometer (AAS)	Unimaid, Ramat Polytechnic
D-100KN Universal Testing Machine	Ahmadu Bello University (Civil Engineering Laboratory)
TH-170 Hardness Tester	Ahmadu Bello University (Civil Engineering Laboratory)

Table 3: longitude and latitude of the sand samples

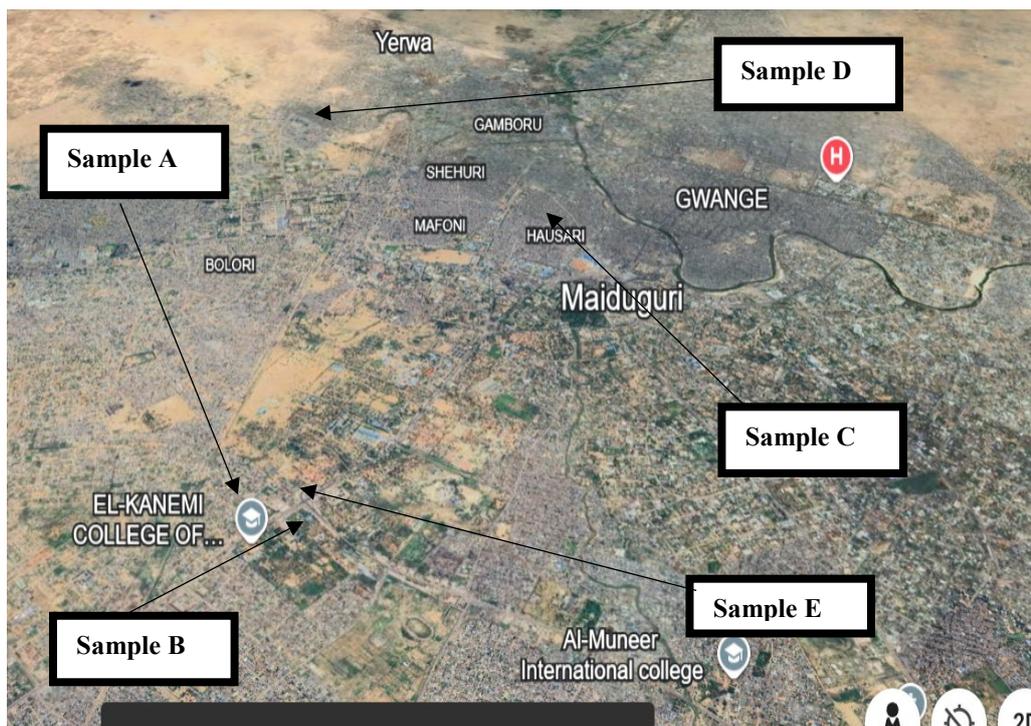| Location	Sample	Latitude (°N)	Longitude (°E)
Bulunkutu	Sample A	11.8300	13.1600
Mashidimami	Sample B	11.8350	13.1450
Bulabulin Kasuwa	Sample C	11.8354	13.1587
Maiduguri Fariya	Sample D	11.8400	13.1500
Ramat Polytechnic	Sample E	11.8250	13.1650

Fig 1: Map of Borno showing locations of the samples collected of study Area

2.2 Methods
2.2.1 Sample preparation
For this study, samples were retrieved from five designated sites (A, B, C, D, and E). Following the procedure outlined by [10], each sample was extracted from a depth of three meters. The analytical work was conducted at the laboratories of the Unimaid and Ramat Polytechnic in Maiduguri, Borno State.

2.2.2 Analysis of the sand chemical compositions
An X-Ray Fluorescence (XRF) analyser was employed to identify the elemental makeup of the sand samples, following established methods [5,8]. The procedure, conducted at the University of Maiduguri's Geology Department, involved placing a prepared sample into the instrument's chamber and reading the oxide composition results from its display.

2.2.3 Determination of physico-mechanical properties
To evaluate the sands suitability for casting, key properties such as grain fineness, permeability, moisture content, and compressive strength were tested. This investigation was performed at Ramat Polytechnic's Soil Testing Laboratory, adhering strictly to the standards of the AFS, ASTM, and British standards, as referenced in [10].

2.2.3.1 Grain fineness number
The grain number of the moulding sand was determined through a sieving analysis. Initially, a sample was weighed and subjected to a ten-minute vibration cycle in a sieve shaker. The residue on each sieve was then individually weighed on a digital beam balance. The data was used to compute the grain fineness number according to Equation 1 provided by [9].

$$\text{Grain fineness Number} = \frac{\text{Total Product}}{\text{Total \% Retained by Different sieves}} \qquad (1)$$

Plate 1: Standard sieve shaker

2.2.3.2 Permeability
Test To determine the sand's permeability, a test was conducted where de-aired water was passed through a saturated sample from a standpipe. The key measurement was the time taken for the water head in the standpipe to decrease from a fixed upper level to a fixed lower level. After repeating this process several times, the permeability was calculated using Equation 2.

$$\text{Permeability (k)} = 2.30 \frac{aL}{At} \log \frac{h_1}{h_2} \qquad (2)$$

K = Permeability constant (cm/sec)
L = Length of the specimen (cm)
A = sectional area of the specimen (cm²)
h1, h2 = head in the standpipe (cm)
a = sectional area of the standpipe (cm²)
t = Time (t2 - t1) for the head change (sec)

2.2.3.3 Moisture content test

50g of foundry sand were prepared and place inside an oven which was kept at a temperature of 110°C for 2 hours to allow for the escape of moisture. After which, it was taken out of the oven and reweighed. The moisture was obtained from the change in the weight of the before and given by equation 3

Moisture Content $= \dfrac{w1-w2}{w1}$ (3)

$W_1 =$ weight of moist sand specimen
$W_2 =$ weight of moist sand specimen

Plate 2: Electric oven (Griffin and George Limited)

2.2.3.4 Determination of clay content

The clay number was obtained using AFS, standard. A weighed sample of foundry sand was process in a wash bottle, and a solution of water and sodium hydroxide was added. The matrix was agitated for 10 minutes. After agitation, Water was incorporated into the mixture to fill the container, the mixture was stirred, and then allowed to settle. The clay-laden liquid was siphoned off, and the remaining sand was oven-dried at 105 °C. The procedure was repeated three times, and the average weight loss was used to calculate the clay content.

Plate 3: Digital balance (Griffin and George Limited)

2.2.3.5 Determination of dry compression strength

A standard AFS specimen was oven-dried at 110°C for two hours and allowed to cool. The dried specimen was then placed to a compressive load using a universal strength testing machine. The load was placed uniformly up to stage that specimen fractured. The maximum load recorded at the point of failure was reported as the dry compression strength.

2.2.3.6 Mould's green strength

Mould's **green strength** is defined as the maximum stress a moist sand mixture can withstand without fracturing under the forces of ramming and casting [16]. To measure this, cylindrical specimens (50mm diameter × 50mm height) were prepared and compressed in a testing machine until failure. Mould's **green strength** was

calculated by dividing the maximum compressive force at failure by the cross-sectional area of the specimen, as per Equation 4.

$$Pc = \frac{Fc}{Fs} \qquad (4)$$

Where: Fc -compressive force; As - total surface area of specimen.

2.2.3.7 Determination of refractoriness value

The refractoriness of the prepared specimens was evaluated by heating them to temperatures ranging from 700°C to 1300°C in 100°C increments. The samples were placed hours to maintain heat transformation, and their chemical condition was monitored for signs of fusion or degradation, following the method described by [8].

3.0 Results and Discussion
3.1 Elemental Composition

Chemical analysis of the foundry sand was important in determining the composition of the elements in its oxide form in that would make it appropriate for casting application.

Table 4: Elemental Composition of silica sand from five selected deposits

Elements	A	B	C	D	E
SiO_2	75.21	65.27	77.43	79.56	68.1
Al_2O3	16.35	20.52	3.77	2.68	18.11
Fe_2O3	1.02	0.56	1.49	4.37	0.68
TiO_2	0.20	1.01	2.9	0.45	1.20
CaO	3.69	1.87	2.17	1.59	2.66
MgO	1.53	1.81	1.91	2.93	2.11
NaO_2	5.11	1.96	5.2	2.46	2.20

Based on analysis in Table 3, the sand is predominantly composed of silica and alumina, with values ranging from 75% to 79.56% for Si and 16.35% to 18.11% for Al_2O_3. These major constituents are vital because they directly influence the sand's permeability and refractoriness [10]. The analysis confirms the sand complies with AFS standards for aluminium casting. As established by [4], the percentage of silica is a key indicator of refractoriness; a higher silica content corresponds to greater heat resistance, making it a desirable casting sand. The deposits also contained other elements, including Fe_2O_3, Na_2O, CaO, and MgO. However, impurities like CaO and Na_2O are detrimental as they reduce refractoriness and compromise the sand's quality. This underscores the importance of chemical testing to ensure sand properties are controlled to meet approved standards.

3.2 Clay Content

The measured clay content in the sand (11%, 20.5%, 44.5%, 15.6%, and 15%) aligns with the 8-15% range recommended for casting non-ferrous metals, light grey steel, malleable iron, and medium grey iron [4], [10]. This suitable clay level also implies that the sand will likely possess good compressive strength, flowability, and permeability, as these properties are highly dependent on clay content.

3.3 Sieve Analysis

The sieve analysis of the foundry sands is shown in Table 5 apparently there was variation in the grain sizes of the sands. The distribution of sand alters the quality of castings [10].
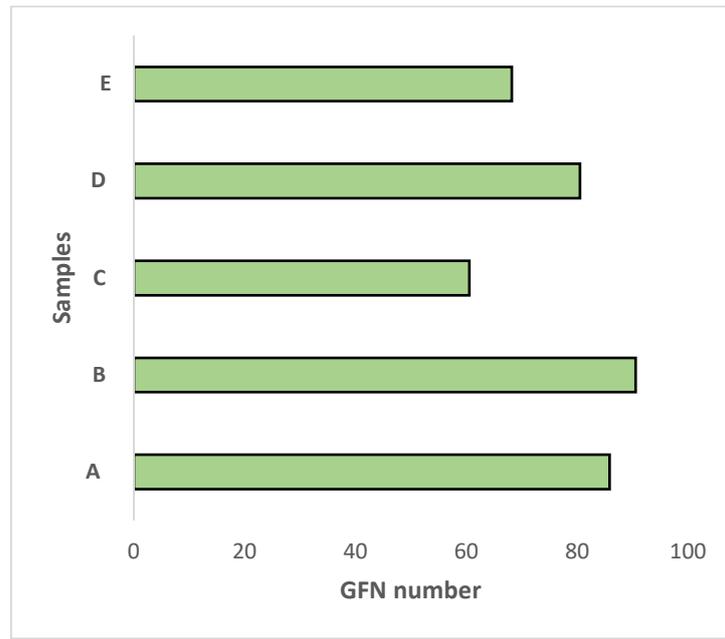
Figure 2: Grain size distribution

Table 5: GFN of Moulding sample A

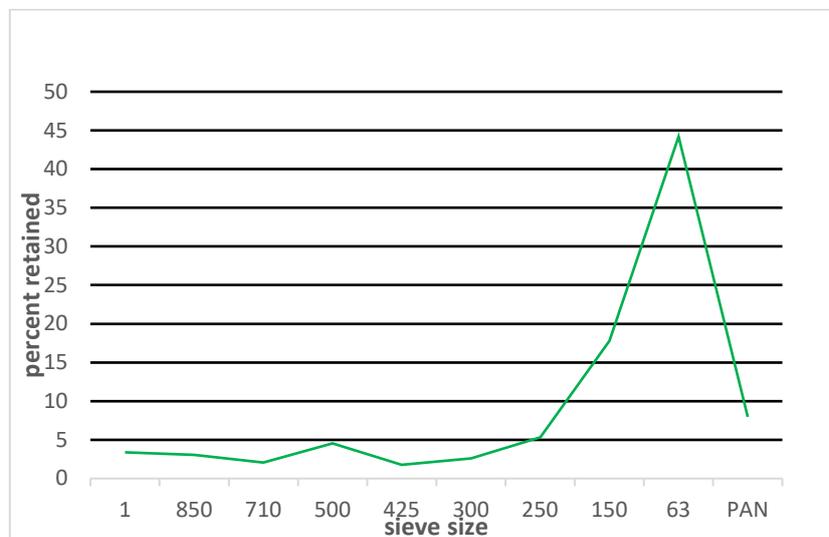| BS No	SS (Mm)	% Remained (A)	Factor (C)	(A X C)
18	1.00	3.39	0	0
20	850	3.04	18	54.72
25	710	2.08	20	41.6
35	500	4.56	25	114
40	425	1.77	35	61.95
50	300	2.58	40	103.2
60	250	5.33	50	266.5
100	150	17.8	60	1069.2
230	63	44.2	100	4417
	PAN	7.95	230	1828.5
Total		**92.75**		**7956.65**
Grain Fineness No		**85.84**		

Figure 3: Variation of mesh diameter with Percent retained for sample A

Table 6: GFN sample B

BS No	SS (Mm)	% Remained (B)	factor (C)	(A X C)
18	1.00	4.68	0	0
20	850	8.10	18	145.8
25	710	4.24	20	84.8
35	500	9.32	25	233
40	425	3.74	35	130.9
50	300	4 .00	40	160
60	250	9.65	50	482.5
100	150	20.02	60	1201.2
230	63	28.84	100	2884
	PAN	6.15	230	1414.5
Total		**98.74**		**6736.7**
GFN		*68.20*		

Table 7: GFN of sand C

BS No	SS	% Remained (A)	factor	Product (A X C)
18	1	2.39	0	0
20	850	1.96	18	35.28
25	710	2.08	20	41.6
35	500	4.1	25	102.5
40	425	1.77	35	61.95
50	300	2.58	40	103.2
60	250	5.33	50	266.5
100	150	16.5	60	990
230	63	43.55	100	4355
	PAN	7.95	230	1828.5
Total		**88.21**		**7784.53**
GFN		*88.25*		

Table 8: GFN of sample D

BS Sieve No	Sieve Size	% Retained (B)	factor (C)	Product (A X C)
18	1	4.66	0	0
20	850	7.9	18	142.2
25	710	4.11	20	82.2
35	500	9.22	25	230.5
40	425	3.88	35	135.8
50	300	3.99	40	159.6
60	250	9.55	50	477.5
100	150	20.11	60	1206.6
230	63	28.84	100	2884
	PAN	7.11	230	1635.3
Total		**99.37**		**6736.7**
Grain Fineness no		*67.7941*		

Table 9: GFN of sample E

BS No	SS	% Remained (B)	factor (C)	Product (A X C)
18	1	1.19	0	0
20	850	0.76	18	13.68
25	710	0.88	20	17.6
35	500	2.9	25	72.5
40	425	0.57	35	19.95
50	300	1.38	40	55.2
60	250	4.13	50	206.5

BS No	SS	% Remained (B)	factor (C)	Product (A X C)
100	150	15.3	60	918
230	63	42.35	100	4235
	PAN	6.75	230	1552.5
Total		**76.21**		**6736.7**
GFN		*88.39654*		

The GFN of the sand samples as in (Tables 5 and 6) indicates a well-defined grading, characterized by a high concentration (28.84% to 44.2%) of fine grains retained on sieves around 150µm. Sample B showed the lowest concentration at the finer 63 µm sieve size. A high concentration of fine, small grains is beneficial as it improves the surface quality of castings. Furthermore, the sand's particle shape and distribution contribute to good overall moulding properties [6].

3.4 AFS

The AFS Grain Fineness Number (GFN) is a key measure for moulding sand, directly influencing casting quality. For non-ferrous metals, the recommended GFN is between 35 and 90. Sample A (85.84) and Sample B (68.20) both fall within this range. However, an ideal GFN for a smooth surface finish with minimal binder is narrower, between 50 and 60. Generally, finer sand grains increase mould strength and hardness but reduce its permeability, which is the ability to let gases escape.

3.5 Moisture Content Number

Moisture number is a crucial factor in natural moulding sand, directly influencing the quality of the final casting [14]. The measured moisture values for samples A through E range from 1.9% to 5.9%. These values fall within the satisfactory range recommended by the AFS for casting low-temperature metals. For high-temperature metals, a higher moisture content of 6-8% is required [10]. Furthermore, moisture directly affects the sand's physical properties, particularly its permeability; as moisture value increases, permeability decreases.
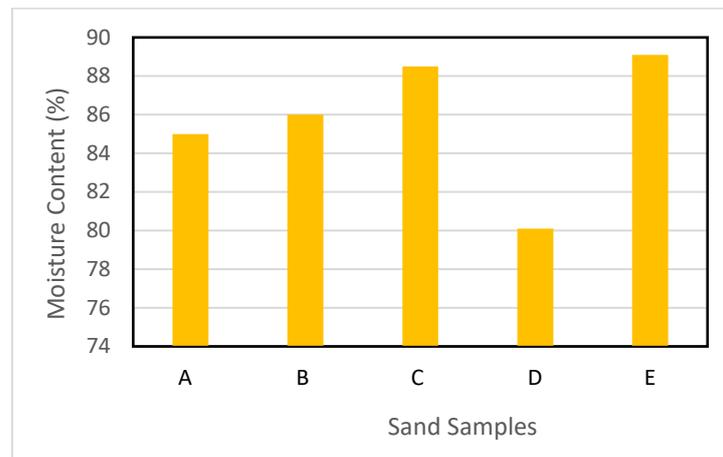

Figure 4: Moisture value of sands

3.6 Bulk Density

Bulk density, a key indicator of how tightly sand grains are packed, was evaluated for the moulding sand. The results, 1.011 g/cm³ and 1.122 g/cm³, fall within the acceptable range defined by AFS standards. This is confirmed by the recommended minimum bulk density of 1.49 g/cm³ for green moulding sand [10]. Achieving an appropriate bulk density is essential because it directly affects critical mould properties; a well-compacted sand with adequate density ensures better mould strength, reduced risk of mould wall movement, and improved surface finish on the final casting.

3.7 Permeability

Permeability refers to the capacity of moulding sand to allow gases, such as steam generated during metal pouring, to escape from the mould [7, 11]. The test results for the natural sand samples show permeability numbers of 85, 86, 88.5, 80.1, and 89.1. These results all fall within the recommended range of 80–110 for green sand [8].
The moisture content in the sand directly impacts this property; high moisture levels (above 8%) significantly reduce permeability. An optimal permeability value is critical: if it is too high, the sand's overly open structure can

cause rough castings and penetration defects. Conversely, if permeability is too low, indicating overly tight sand packing, it can lead to defects like blows and pinholes due to trapped gases
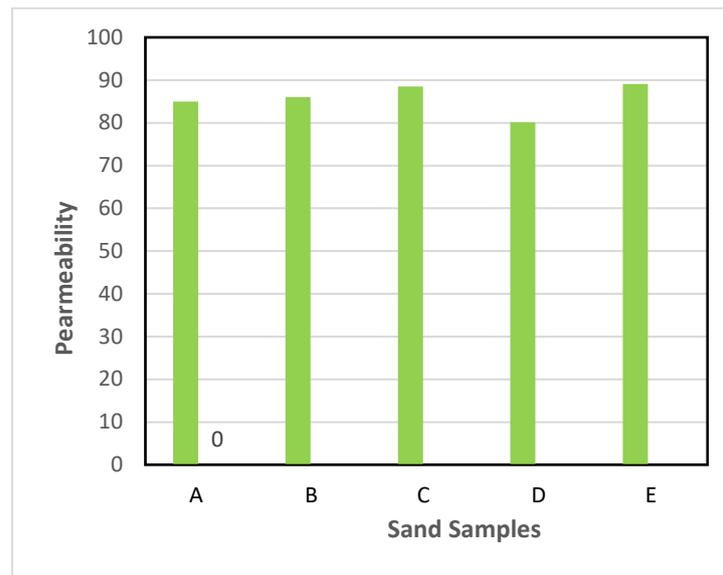

Figure 5: Moisture content of sand

3.8 Green Strength

Testing revealed that the sand samples possess compression strengths of 70.5, 71.5, 65.2, 66.8, and 60.2 kN/m². This parameter is vital for ensuring the mould retains its integrity throughout the casting process. As the recommended strength for green sand is between 70 and 100 kN/m² [10], the results confirm that the sand has the necessary mechanical strength to hold its shape without distorting or collapsing once the pattern is removed from the moulding box.
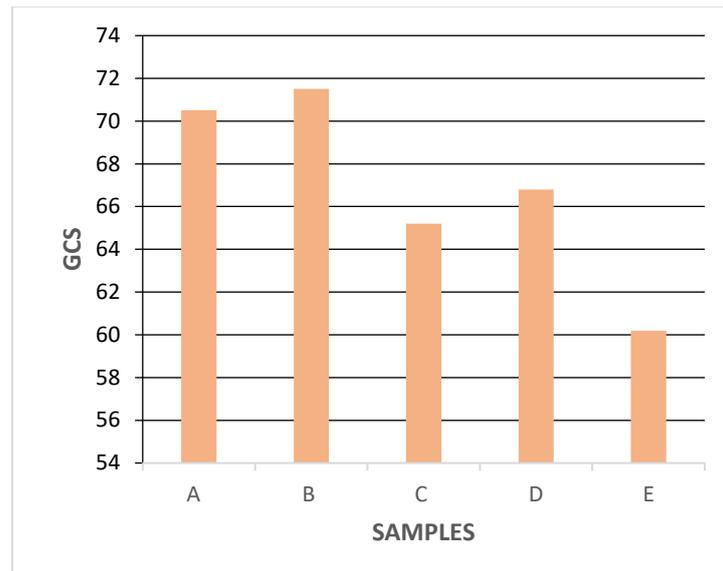
Figure 6: GFN of sand samples

3.9 Refractoriness

Refractoriness is the properties of foundry moulding sand to absorb high temperature. This indicate the foundry sand has sufficient moulding bonding strength properties to absorbs high temperature. For this research, each of the foundry sand had refractoriness higher than 1200°C. foundry sand with poor Refractoriness cause the casting to have poor quality and burn onto casting surface [10].
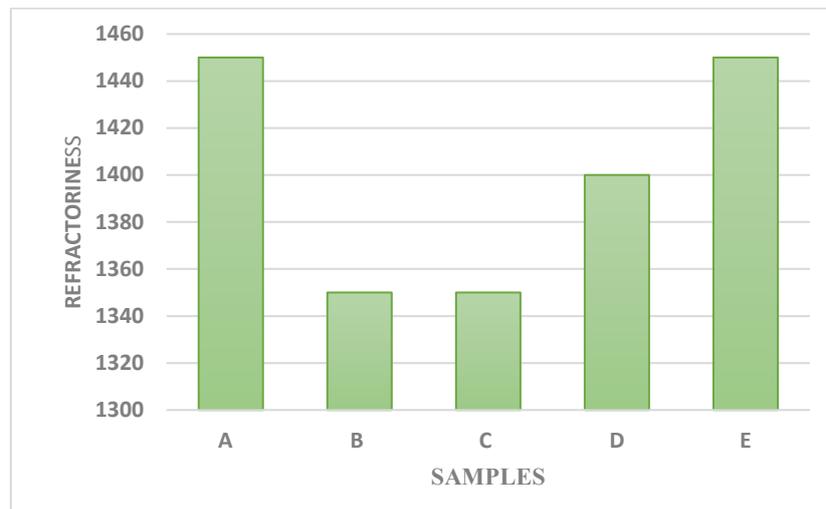
Figure 7: Refractoriness of sand samples

3.10 Moisture Content

Moisture content is a critical parameter in foundry sand, directly influencing the quality and integrity of the final casting, as established by research [6]. Its primary role is to activate the binding properties of clay, which is essential for developing the sand's green strength and plasticity, allowing it to hold a shape effectively.

The measured moisture content for the tested samples A through E was 5.6%, 3.9%, 3.85%, 1.9%, and 5.9%, respectively (Figure 4.2). All these values fall within the satisfactory range specified by AFS standards for casting low-temperature non-ferrous metals. However, it is important to note that the required moisture level is application-specific. For instance, casting high-temperature metals typically demands a higher moisture content, often between 6% and 8%, to ensure adequate thermal stability [14].

Furthermore, moisture content has a definitive and inverse relationship with a key mould property: permeability. As moisture content increases, the water vapor generated during the metal pouring process can occupy the pore spaces between sand grains. This phenomenon reduces the mould's permeability, potentially leading to casting defects such as gas holes if the gases cannot escape efficiently.
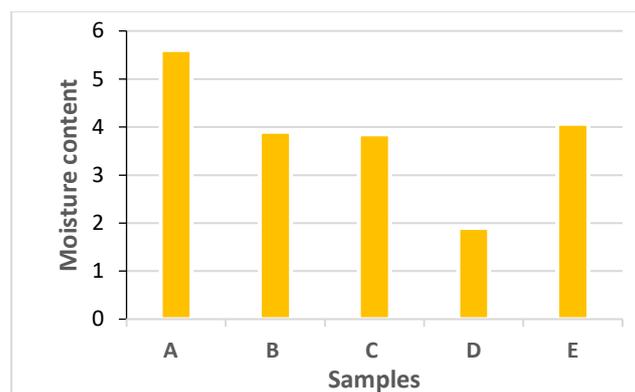

Figure 8: Moisture content of sand samples

3.11 Permeability

Permeability is a critical property of moulding sand that measures its ability to allow gases, such as steam generated during metal pouring [8, 10]. The tested natural sands showed permeability levels of 85, 86, 88.5, 80.1, and 89.1, all of which lies at AFS range of 80–110 [9].

This property is highly dependent on moisture content; sand with over 8% moisture will exhibit very low permeability. Maintaining the correct permeability is essential to avoid defects. Excessively high permeability indicates an overly open sand structure, which can lead to rough castings and penetration defects. Conversely, low permeability, resulting from overly tight packing, can trap gases and cause blows or pinholes [14].
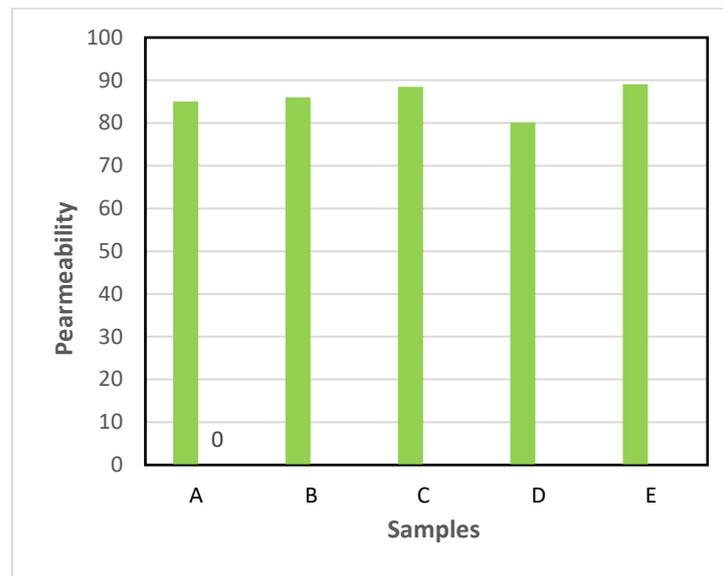
Figure 9: Moisture content of sand

3.12 Green Compression Strength

The green compression strength of the foundry sand samples was determined to be 70.5, 71.5, 65.2, 66.8, and 60.2 kN/m² . When compared to the established industry standard of 70–100 kN/m² for green sand [10], the results indicate that several samples meet or approach the recommended threshold.

This level of compressive strength is critical for mould integrity. It ensures that the sand mould possesses adequate structural stability to retain its precise shape without distorting or collapsing following the removal of the pattern from the moulding box. This characteristic is fundamental to producing dimensionally accurate castings, as a stable mould prevents defects such as mould wall shift or washouts during the pouring of molten metal.
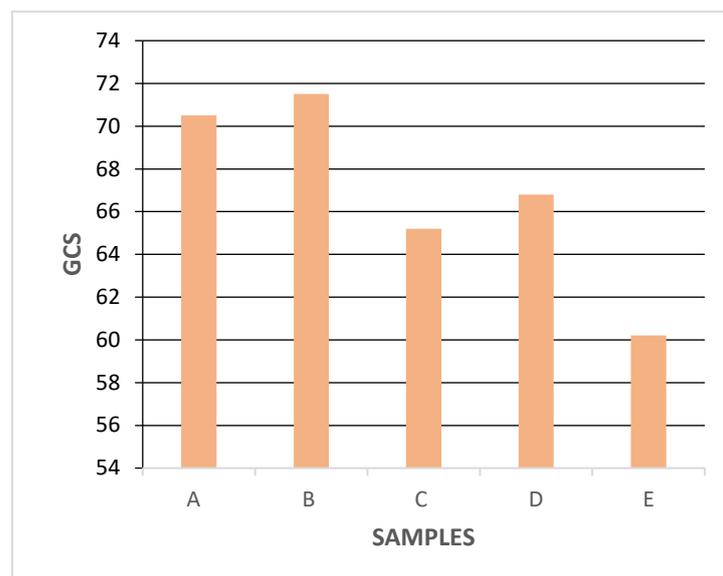

Figure 10: GFN of sand samples

4.0 Conclusions

Based on the investigation of hardness properties in aluminium casts produced from Maiduguri's natural moulding sands, the study concludes:

1. Suitability for Foundry Applications: The casting sands from the deposits (A, B, C, D, and E) possess physico-chemical properties acceptable for casting applications, particularly for non-ferromagnetic metals
2. (e.g., aluminum) and specific ferrous alloys such as light grey iron, malleable iron, and medium grey iron.
3. High Silica Content: The sands exhibit high silica content (68.10%–79.56% SiO_2), which ensures adequate refractoriness and chemical inertness, meeting (AFS) standards for aluminum casting.
4. Adequate Clay Content: Clay content varies significantly (11%–44.5%), aligning with AFS requirements for non-ferrous metals (8%–15%) and certain ferrous alloys. This supports good compressive strength,

flowability, and permeability, though high clay (e.g., sample C at 44.5%) may reduce permeability if not controlled.

5. Grain Size and AFS-GFN: The sands are well-graded with a high concentration of fine grains (28.84%–44.2% retained on 63 μm sieve), promoting excellent surface finish with GFN of (60.55–90.5) within the recommended range (35–90) for non-ferrous metals, with samples B and D (lower GFN) being particularly suitable for small-scale, high-precision castings.
6. Moisture Content Suitability: Moisture content (1.9%–5.9%) is appropriate for low-temperature casting (e.g., aluminium), within AFS of (2%–8%). This supports mould cohesion without compromising permeability.
7. Satisfactory Permeability: Permeability values (80.1–89.1) are within the AFS-recommended range (80–110) for green sand, ensuring effective gas venting during casting to prevent defects like blows or pinholes.

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