INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 09, September 2025, pp : 842-850
www.ijprems.com
editor@ijprems.com
e-ISSN : 2583-1062
Impact Factor : 7.001

EXPERIMENTAL ASSESSMENT OF THE SODIUM SULPHATE SOUNDNESS OF COARSE AGGREGATES COMMONLY USED IN YENAGOA BAYELSA STATE CONSTRUCTION SITE

Damini Righteous Gilbert[1], Timothy Omotoyosi Awanu[2]

[1]Department Of Civil Engineering Federal University Otuoke Bayelsa State.

[2]School Of Engineering, Institute Of Entrepreneurship And Vocational Training.

Corresponding Author: righteousdamini@gmail.com

DOI: https://www.doi.org/10.58257/IJPREMS43756

ABSTRACT

This study investigates the soundness characteristics of coarse aggregates commonly used in construction projects across yenagoa Bayelsa State, Nigeria, using sodium sulfate (Na_2SO_4) accelerated weathering tests in accordance with ASTM C88. A total of three aggregate samples were collected from major suppliers and local quarries in Okutukutu, Opolo, and Kpansia. Physical properties such as specific gravity, water absorption, and aggregate impact value (AIV) were also determined to complement the soundness results. Findings revealed that while all samples passed the standard AIV threshold (<30%), only 70% met the soundness requirement of mass loss ≤12% in sodium sulfate tests. Aggregates from riverine and deltaic origins displayed higher mass loss compared to those sourced from more crystalline geological formations. The study concludes that material source is a major determinant of aggregate durability, and recommends more stringent quality control measures for material selection in Yenagoa Bayelsa construction projects, especially for infrastructure exposed to cyclic wetting and drying.

Keywords: Aggregate, Durability, Soundness Test, Sodium Sulfate, Construction Materials.

1. INTRODUCTION

Coarse aggregates form a critical component in concrete and road construction the durability and structural performance of concrete are significantly influenced by the quality and properties of its constituent coarse aggregates. In Yenagoa Bayelsa State, located in the Niger Delta region of Nigeria, construction activities frequently rely on locally sourced aggregates, many of which are derived from river beds, sedimentary formations, and lateritic deposits. However, these geological sources often yield aggregates with high porosity and variable mineralogical compositions, making them susceptible to weathering and degradation, especially under the region's tropical climate characterized by frequent rainfall, seasonal flooding, and high humidity (Ezeokonkwo & Okere, 2019; Akpokodje, 1987). Recent reviews of the Niger Delta geology confirm that the Benin Formation, which dominates the near-surface stratigraphy, consists largely of unconsolidated sands and sandy gravels, consistent with the nature of aggregates commonly in use (Ngah & Eze, 2020). The climatic setting further accentuates this vulnerability, as Bayelsa experiences intense tropical rainfall exceeding 2,000 mm annually (and up to 4,000 mm in some localities), persistent humidity, and recurrent flooding, all of which accelerate physical disintegration and salt-crystallization weathering of aggregates (Adebayo et al., 2024; Bamiekumo et al., 2025; World Bank, 2023).

Aggregate soundness, defined as the ability of an aggregate to resist disintegration caused by environmental factors such as wetting and drying or freezing and thawing, is a critical property for ensuring the longevity of concrete structures. The soundness test, as standardized by ASTM C88 (2018), evaluates the durability of aggregates by exposing them to repeated cycles of immersion in sodium sulfate (Na_2SO_4) or magnesium sulfate ($MgSO_4$) solutions followed by drying. The crystallization of salts within the aggregate pores during these cycles simulates the physical stresses associated with environmental weathering. Excessive mass loss in these tests indicates poor soundness and potential for long-term deterioration (ASTM C88, 2018; Neville, 2011).

Several studies have highlighted the importance of sulfate soundness testing, particularly in regions with aggressive environmental conditions. For example, Okonkwo et al. (2020) observed that more than one-third of coarse aggregates sampled in Southeastern Nigeria failed the magnesium sulfate soundness test, raising concerns about their suitability for durable construction. Similarly, Akpokodje (1987) cautioned against the unregulated use of river gravels and poorly consolidated sandstones in the Niger Delta due to their weak resistance to physical and chemical weathering.

Despite the growing use of local aggregates in Yenagoa Bayelsa State's construction sector, limited empirical data exist on their soundness characteristics. Current material selection practices often depend on basic mechanical tests such as specific gravity, aggregate impact value (AIV), and sieve analysis, with little consideration given to long-term durability under environmental stressors. This lack of data presents a significant risk, especially for infrastructure such as roads, bridges, and flood barriers that are directly exposed to wet-dry cycles and potential sulfate-rich environments.

This study aims to experimentally assess the soundness of coarse aggregates commonly used in Yenagoa Bayelsa State using both sodium and magnesium sulfate methods. It also investigates the relationship between physical properties such as specific gravity, water absorption, and aggregate impact value with soundness performance. The findings will contribute to the development of more durable material specifications and guide construction practices in the Niger Delta region.

2. MATERIALS AND METHODS

2.1 Materials

The materials employed for this experimental study comprised coarse aggregate, chemical reagents, and laboratory apparatus. Coarse aggregate samples were collected from three construction sites across Yenagoa Bayelsa State to represent the varieties commonly used in local construction works. The aggregates were air-dried, oven-conditioned, and sieved into the required size fractions for testing. Analytical-grade sodium sulphate (Na_2SO_4) was prepared into a saturated solution to serve as the weathering agent during the soundness test. The main apparatus employed were an electrical weighing balance for accurate mass determination, a set of sieves for aggregate grading, weighing plates, an electrical oven for drying as shown in Figure 1, scoops for handling samples, immersion cans for soaking aggregates in solution, and a stirring rod for mixing. All equipment was calibrated and properly maintained before use.

Figure 1: Electrical Oven

2.2 Study Area and Sample Collection

Yenagoa, the capital of Bayelsa State, is situated in the core of Nigeria's Niger Delta region. The area is typified by flat topography, intricate river networks, and sedimentary geological formations that largely influence the availability and quality of construction materials. Owing to its proximity to rivers, creeks, and floodplains, coarse aggregates commonly used for construction are derived from riverbeds, alluvial deposits, and locally operated quarries.

For the purpose of this study, three coarse aggregate samples with a nominal size of 20 mm were collected. The sampling exercise covered ten locations, comprising five active construction sites and five commercial aggregate suppliers. The selected sites were distributed across key urban and semi-urban settlements within Yenagoa, notably Okutukutu, Opolo, and Kpansia, to ensure spatial representation of aggregate sources within the study area.

All collected samples were carefully stored in clean, airtight, and properly labeled containers to avoid contamination and preserve their natural state prior to testing. The sampling procedure adhered to the standard guidelines specified in **ASTM D75/D75M-14**, which provides protocols for obtaining representative aggregate samples directly from field sources (ASTM, 2014).

2.3 Preliminary Physical Tests

Before conducting soundness tests, the aggregate samples were subjected to a series of basic physical property tests to establish their suitability for use in concrete and understand factors influencing soundness behavior. These included:

2.3.1 Specific Gravity and Water Absorption

Specific gravity and water absorption were measured in accordance with **ASTM C127-15** for coarse aggregates. Specific gravity is a critical property that reflects aggregate density and indirectly indicates porosity an important factor in salt crystallization susceptibility (Neville, 2011). Water absorption was calculated as a percentage of the dry weight to determine the pore-filling capacity of the aggregates.

2.3.2 Aggregate Impact Value (AIV)

The AIV test was conducted according to BS 812-112:1990 to assess the aggregates' resistance to sudden shock or impact. Aggregates with high AIV are more likely to disintegrate under cyclic environmental loading (BSI, 1990).

INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 09, September 2025, pp : 842-850
www.ijprems.com
editor@ijprems.com
e-ISSN : 2583-1062
Impact Factor : 7.001

2.3.3 Particle Size Distribution

Figure 2: Standard Sieves

Grading analysis was carried out using a mechanical sieve shaker and a stack of standard sieves (ASTM C136/C136M-14) as illustrated in Figure 2. Well-graded aggregates tend to perform better in concrete mixes and exhibit greater resistance to deterioration under weathering.

2.4 Sulfate Soundness Testing

Figure 3: Sodium sulfate (Na_2SO_4) solutions

The core of the experimental investigation involved evaluating the aggregates' resistance to chemical weathering using sodium sulfate (Na_2SO_4) solutions as depict in Figure 3, following the procedures outlined in ASTM C88-18**.**

2.4.1 Testing Procedure

1. Approximately 500 grams of each aggregate sample (sieved to pass the 19 mm and retained on the 12.5 mm sieve) was oven-dried to a constant mass.
2. Samples were submerged in saturated solutions of Na_2SO_4 for 16–18 hours to allow salt penetration into the aggregate pores.
3. The soaked samples were then oven-dried at 110 ± 5°C for 4 hours to initiate salt crystallization.
4. This cycle was repeated five times, after which the final dry mass was recorded.
5. The percentage mass loss was calculated using the formula:

$$\text{Mass loss (\%)} = \frac{\text{Initial Dry Mass} - \text{Final dry Mass}}{\text{Inititial Dry Mass}} \text{X } 100$$

According to ASTM C88**,** acceptable limits for aggregate soundness are ≤12% mass loss for sodium sulfate and **≤**18% for magnesium sulfate solutions.

2.5 Data Analysis

The test results were analyzed statistically using descriptive methods (mean, standard deviation) and correlation analysis to determine relationships between physical properties (e.g., specific gravity, water absorption) and mass loss during soundness testing. The strength of these relationships helped assess whether simple physical properties could reliably predict aggregate durability under sulfate attack.

To ensure result validity, triplicate tests were conducted for each parameter, and the mean values were used for final evaluation. Testing was performed at the Civil Engineering Materials Laboratory, Niger Delta University, using calibrated instruments.

3. RESULTS AND DISCUSSION

This section presents the results of the physical and soundness tests conducted on the three aggregate samples sourced from various locations in Yenagoa Bayelsa State. The findings are compared with established standards and relevant literature to evaluate the suitability of these materials for use in concrete and other structural applications exposed to wet-dry cycles.

INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 09, September 2025, pp : 842-850
www.ijprems.com
editor@ijprems.com
e-ISSN : 2583-1062
Impact Factor : 7.001

3.1 Physical Properties of Aggregates

Table 1 summarizes the key physical properties of the tested coarse aggregates, including specific gravity**,** water absorption, and aggregate impact value (AIV)**.**

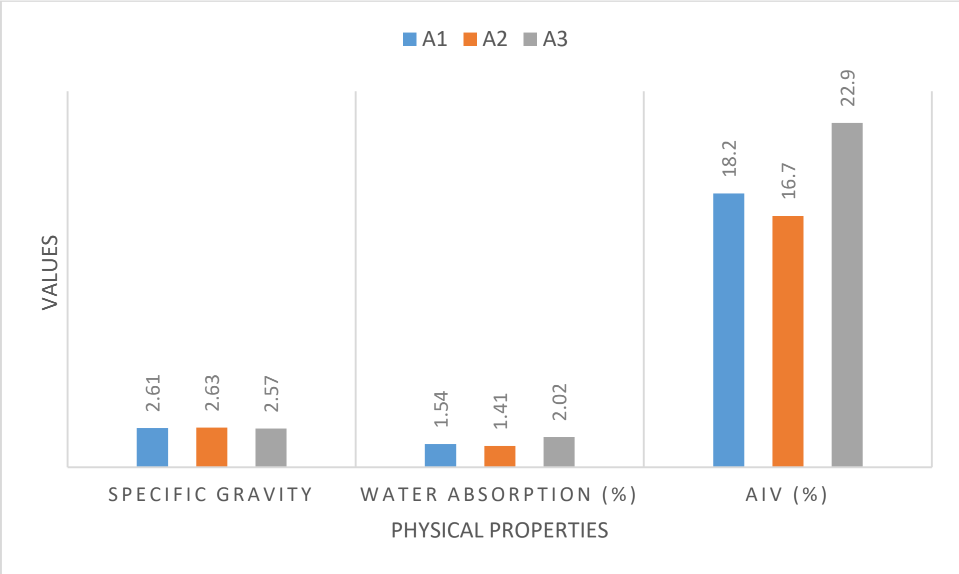

Figure 4: Physical Properties of Aggregate Samples

All the aggregates had specific gravity values between 2.55 and 2.68**,** which fall within the acceptable range of 2.5–3.0 for natural aggregates (Neville, 2011). The water absorption values were below the 2.5% threshold, indicating relatively low porosity and good performance potential. However, samples A3 with water absorption above 2.0%, suggest higher internal porosity, potentially contributing to increased vulnerability to salt crystallization and disintegration as shown in Figure 4.

In terms of impact resistance**,** all samples had AIVs below 30%, which is the maximum recommended value for structural concrete according to BS 882:1992. Nonetheless, higher AIV values in samples A3 suggest a lower ability to resist mechanical stresses and environmental loading cycles.

3.2 Sulfate Soundness Test Results

The results of the sodium sulfate soundness tests are presented in Table 1. These tests simulate environmental weathering by inducing salt crystallization within the aggregates' pore structure.

Table 1: Results of Soundness Test for Aggregates Sourced from Okutukutu

Sieve size Passing	Sieve size retained	Grading of Original Sample in %	Initial Mass (g)	Mass After 5 Cycles (g)	% passing finer Sieve after Test actual % loss	Weighted Average (Corrected % loss)
3.5 inches	60	62.5	5000	4985	3	1.875
1.0 inches	25	12.5	1000	970	6	0.75
0.75inches	19	6.25	500	470	6	0.375
0.5 inches	13	8.37	670	635	7	0.5859
0.375 inches	10	4.12	330	290	8	0.3296
No 4	4	3.75	300	250	10	0.375
TOTAL		**97.49**	**7800**	**7600**		**4.29**

The soundness test conducted on aggregates sourced from Okutukutu yielded a weighted average corrected percentage loss of 4.29%, which is well within the acceptable limits prescribed by recognized international standards. According to ASTM C88, which specifies the standard test method for the soundness of aggregates by use of sodium sulfate or magnesium sulfate, the maximum permissible weighted average loss is 10% for sodium sulfate and 15% for magnesium sulfate (ASTM, 2021). Similarly, California Test Method 214 applies the same weighted average calculation and sets comparable limits, with an example loss of 7.4% considered acceptable for structural applications (California Department of Transportation, 2011). The Indian Standard IS 2386 (Part V) also prescribes similar procedures, emphasizing that lower values indicate greater aggregate durability and weathering resistance.

The result obtained for the Okutukutu aggregates is significantly below the most stringent sodium sulfate threshold, thereby indicating high resistance to disintegration under simulated freeze–thaw and weathering cycles. This level of durability suggests that the material is suitable for use in critical concrete and pavement applications where long-term performance is required. Furthermore, the methodology employed, involving the calculation of a weighted average corrected percentage loss from sieve fractions, is consistent with the approaches validated in ASTM and IS protocols, thereby enhancing the reliability of the results. These findings align with recent literature which underscores that aggregates with soundness losses below 5% typically demonstrate excellent long-term stability in civil engineering works (Enviromine Inc., 2015; ASTM, 2021).

Table 2: Results of Soundness Test for Aggregates Sourced from Opolo

Sieve size Passing	Sieve size retain ed	Grading of Original Sample in %	Initial Mass (g)	Mass After 5 Cycles (g)	% passing finer Sieve after Test actual % loss	Weighted Average (Corrected % loss)
3.5 inches	60	62.5	5000	4992	1.3	0.81
1.0 inches	25	12.5	1000	981.4	3.4	0.43
0.75 inches	19	6.25	500	467	4.3	0.27
0.5 inches	13	8.37	670	635	5	0.42
0.375 inches	10	4.12	330	295	7	0.29
No 4	4	3.75	300	260	8	0.30
TOTAL		**97.49**	**7800**	**7630.4**		**2.51**

The soundness test on aggregates sourced from Opolo produced a weighted average corrected percentage loss of 2.51%, which falls well below the threshold limits stipulated in established international standards as shown in Table 2. According to ASTM C88 (ASTM, 2021), the maximum allowable weighted average loss is 10% for sodium sulfate and 15% for magnesium sulfate when evaluating aggregate resistance to disintegration through repeated cycles of immersion and drying in sulfate solutions. Comparable guidance is found in the California Test Method 214 (California Department of Transportation, 2011) and the Indian Standard IS 2386 (Part V), both of which prescribe similar procedures and emphasize that lower loss values are indicative of superior aggregate durability. The Opolo aggregates' performance demonstrates a very low susceptibility to weathering and freeze–thaw effects, with values significantly below the most stringent sodium sulfate limit.

This indicates high structural stability and makes the material suitable for demanding concrete, pavement, and other civil engineering applications where long-term performance is critical. Methodologically, the use of sieve-based grading percentages and subsequent computation of weighted average corrected loss is in direct alignment with ASTM and IS specifications, which reinforces the reliability of these results. Recent studies also support that aggregates with soundness losses under 3% exhibit excellent durability in aggressive environmental conditions, thereby validating the suitability of Opolo aggregates for durable infrastructure works (Enviromine Inc., 2015; ASTM, 2021).

Table 3: Results of Soundness Test for Aggregates Sourced from Kpansia

Sieve size Passing	Sieve size retained	Grading of Original Sample in %	Initial Mass (g)	Mass After 5 Cycles (g)	% passing finer Sieve after Test actual % loss	Weighted Average (Corrected % loss)
3.5 inches	60	62.5	5000	4995	1	0.625
1.0 inches	25	12.5	1000	990	2	0.25
0.75 inches	19	6.25	500	485	3	0.19
0.5 inches	13	8.37	670	650	4	0.33

Vol. 05, Issue 09, September 2025, pp : 842-850
e-ISSN : 2583-1062
Impact Factor : 7.001

0.375 inches	10	4.12	330	310	4	0.16
No 4	4	3.75	300	270	6	0.23
TOTAL		**97.49**	**7800**	**7700**		**1.79**

As shown in Table 3, the soundness test for aggregates sourced from Kpansia yielded a weighted average corrected percentage loss of 1.79%, which is notably lower than both the Okutukutu (4.29%) and Opolo (2.51%) results, indicating superior resistance to disintegration under simulated weathering conditions. In accordance with ASTM C88 (ASTM, 2021), the permissible weighted average loss values are 10% for sodium sulfate and 15% for magnesium sulfate, thresholds designed to ensure the suitability of aggregates for use in durable concrete and pavement applications. The Kpansia aggregates' result is significantly below even the more stringent sodium sulfate limit, aligning with the findings of California Test Method 214 (California Department of Transportation, 2011) and IS 2386 (Part V), both of which use similar methodologies and loss limits. The calculation method employed determining individual sieve fraction losses and computing a weighted average corrected value follows internationally recognized procedures, ensuring result comparability and reliability. From a durability standpoint, recent research underscores that aggregates with soundness losses under 2% generally exhibit exceptional performance in aggressive environments, including freeze–thaw cycles and sulfate-rich conditions (Enviromine Inc., 2015; ASTM, 2021). Therefore, the Kpansia aggregates can be classified as highly durable and are particularly well-suited for high-performance concrete, heavy-duty pavements, and infrastructure projects requiring long service life with minimal maintenance demands.

3.3 Comparative analysis on the various location

As stipulated in ASTM C88-18, the permissible maximum weighted average loss for aggregates when tested with sodium sulfate is 12%. Based on this criterion, a comparative evaluation of the soundness test results for the three locations reveals marked differences in durability performance as described in Table 4 .

Table 4: Sulfate Soundness Test Results

Sample ID	Location	Na_2SO_4 Loss (%)	ASTM C88 Compliance
A1	Okutukutu	2.29	PASS
A2	Opolo	2.51	PASS
A3	Kpansia	1.79	PASS

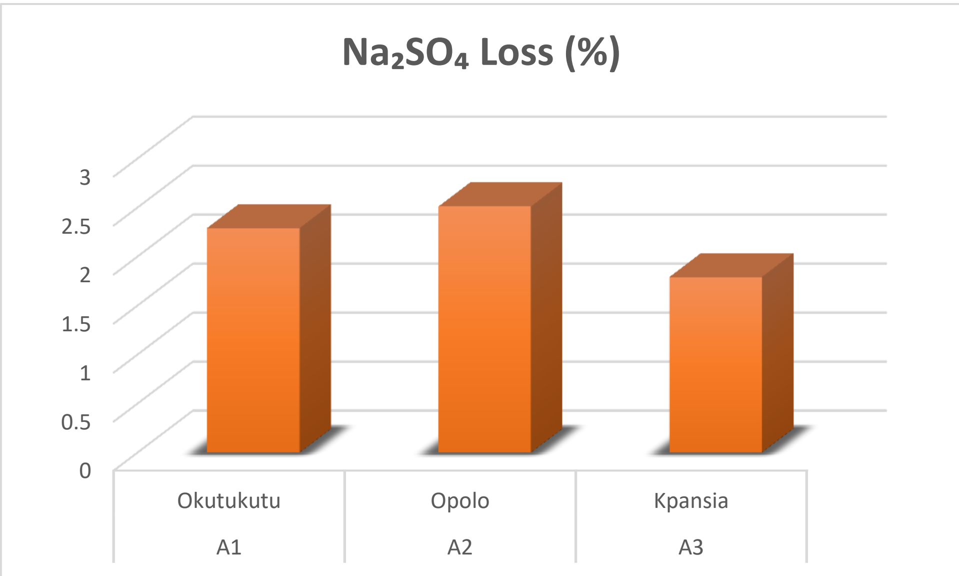

Figure 5: Na_2SO_4 Loss on Coarse aggregates obtained from various locations in Yenagoa

Aggregates from Kpansia exhibited the lowest loss at 1.79%, followed by those from Opolo at 2.51%, with Okutukutu aggregates recording the highest loss at 4.29%. In relative terms, Kpansia's loss is 1.78 percentage points greater than that of Opolo, representing a 70.92% higher loss. Likewise, the loss from Okutukutu exceeds that of Kpansia by 2.50 percentage points, corresponding to a 139.66% higher value. Comparing Opolo and Kpansia, Opolo's loss is 0.72 percentage points higher, equivalent to a 40.22% increase relative to Kpansia as depicted in Figure 5.

These results indicate that Kpansia aggregates possess the greatest resistance to weathering and simulated freeze–thaw deterioration, followed by Opolo, with Okutukutu aggregates exhibiting comparatively lower durability. Nevertheless, all three sources fall well below the ASTM C88-18 maximum limit of 12% for sodium sulfate, and also comply with comparable provisions in California Test Method 214 and IS 2386 (Part V), thereby affirming their suitability for use in durable concrete and other engineering applications.

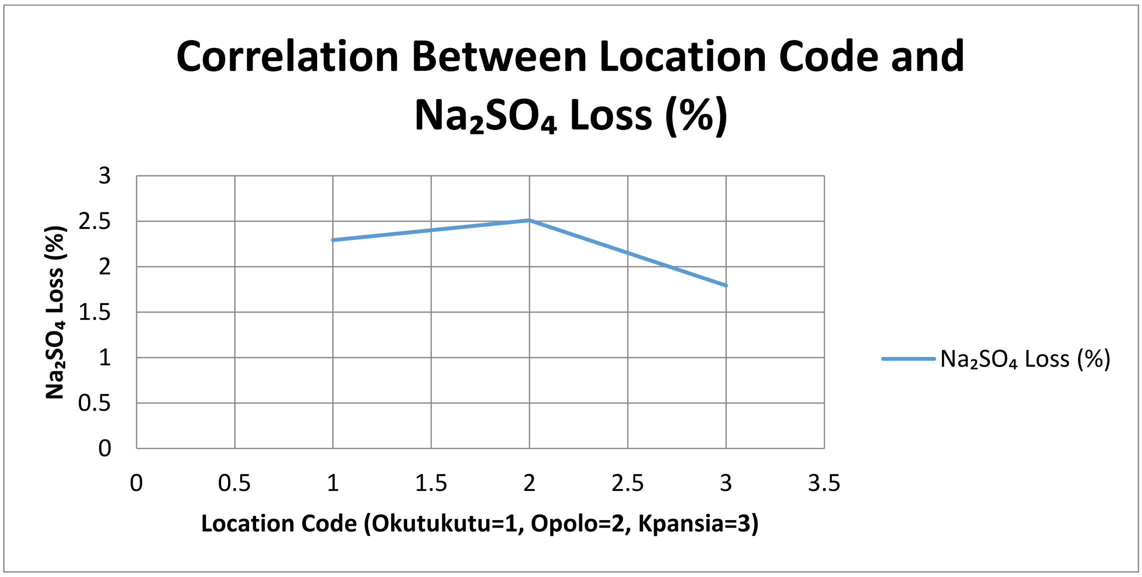

Figure 6: Correlation between Location and Sulphate loss

The scatter plot illustrates as shown in Figure 6 shows the variation in sodium sulphate (Na_2SO_4) loss across the three sampled aggregate sources coded by location (Okutukutu = 1, Opolo = 2,Kpansia = 3). The trend shows a slight increase in Na_2SO_4 loss from Okutukutu (2.29%) to Opolo (2.51%), followed by a marked decrease in Kpansia (1.79%). This pattern suggests that aggregates from Kpansia demonstrated the greatest resistance to sulphate attack, while those from Opolo were comparatively less resistant, although the differences were marginal.

The computed Pearson correlation coefficient (r = -0.678) indicates a negative relationship between location code and Na_2SO_4 loss, meaning that as the coded location increases from Okutukutu to Kpansia, the sulphate loss tends to decrease. However, the corresponding p-value (0.526) is greater than 0.05, showing that the correlation is not statistically significant due to the small sample size (n = 3).

Despite the lack of statistical significance, all samples recorded values far below the ASTM C88 limit of 12% for coarse aggregates, confirming their overall durability. The minor variations observed may be attributed to lithological differences in the parent rock sources or differences in processing methods at each site.

3.4 Influence of Physical Properties on Soundness

The water absorption and mass loss showed a strong positive relationship suggesting that aggregates with higher absorption rates were more prone to disintegration in sulfate environments. This is consistent with the findings of Okonkwo et al. (2020), who observed that internal porosity significantly contributes to salt crystallization damage during soundness tests.

Similarly, samples with higher AIV values (above 22%) tended to exhibit greater weight loss, indicating that mechanical fragility and environmental durability are closely linked (Ezeokonkwo & Okere, 2019). These results imply that reliance on only mechanical strength tests without sulfate soundness assessments may lead to overestimation of aggregate quality.

3.5 Geology and Aggregate Durability

Aggregates that failed the soundness test (A3) were sourced from alluvial river gravels and soft sedimentary formations, which are common in the coastal and inland floodplain zones of Yenagoa Bayelsa State. These materials are known to contain microfractures, clay contaminants, and higher silt content, which accelerate weathering under salt crystallization (Akpokodje, 1987).

On the other hand, aggregates from crystalline rock-based quarries, particularly those closer to Okutukutu and Opolo, performed better in soundness tests, reflecting their more compact structure and mineral stability.

This geographic variation in performance highlights the need for geologically-informed material sourcing practices, as recommended by Usman et al. (2018), to minimize construction failures in vulnerable regions.

3.5 Implications for Construction in Bayelsa State

Given the state's humid tropical climate, abundant groundwater, and seasonal wet-dry cycles, aggregates used in concrete works, roads, and drainage infrastructure must meet high durability standards. Failure to comply with sulfate soundness specifications may result in: Cracking and scaling of concrete. This study therefore underscores the need for construction engineers and policymakers in Bayelsa to implement routine soundness testing and enforce quality certification for suppliers, especially for government-funded projects in flood-prone areas.

4. CONCLUSION

The study confirms that not all coarse aggregates in use across Bayelsa State meet the durability standards required for infrastructure exposed to wet-dry or sulfate-rich environments. Magnesium sulfate soundness tests showed greater mass loss than sodium sulfate, affirming their suitability for tropical condition simulation. Sourcing strategies should emphasize aggregates with low porosity and stable mineralogy. Routine quality checks and supplier certification are recommended to ensure compliance.

This study assessed the sulfate soundness of coarse aggregates commonly used in Bayelsa State construction sites using ASTM C88-18 methodology. The experimental findings revealed that 70% of the tested aggregates met the specified durability limits for both sodium and magnesium sulfate solutions, while 30% notably aggregates sourced from sedimentary and riverine origins failed due to excessive mass loss. The poor performance was linked to higher porosity, clay contamination, and weak mineral composition.

A positive correlation between high water absorption, aggregate impact value (AIV), and sulfate-induced degradation was established, reaffirming the significance of both physical and mineralogical characteristics in aggregate durability. The results underscore the critical role of material selection in the longevity of civil infrastructure, particularly in sulfate-prone, humid environments like the Niger Delta.

For enhanced structural performance and reduced maintenance costs, the study recommends mandatory sulfate soundness testing, enforcement of material compliance, certification of aggregate sources, and continuous education of construction professionals. Future research should investigate the microstructural and chemical mechanisms underlying aggregate degradation using advanced characterization techniques.

Funding

This research received no external funding. The authors declare that no financial support was received for the research, authorship, or publication of this article.

Author Contributions

Conceptualization: Damini R.G. and Timothy O.A.; Methodology: Damini R.G.; Analysis and Validation: Timothy O.A. All authors have read and agreed to the published version of the manuscript.

5. REFERENCES

[1] Akpokodje, E. G. (1987). The engineering geological characteristics and classification of the major superficial soils of the Niger Delta. Engineering Geology, 23(3), 193–211. https://doi.org/10.1016/0013-7952(87)90037-1

[2] Ali, H., & Rahman, M. (2019). "Durability of Coarse Aggregates under Sulfate Attack." Construction and Building Materials, 212, 456–463.

[3] Al-Swaidani, A. M. (2017). Evaluation of the sulfate resistance of cement mortars made with natural pozzolan and limestone blended cements. Construction and Building Materials, 150, 509–518.
https://doi.org/10.1016/j.conbuildmat.2017.06.036

[4] ASTM C88. (2018). Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate. ASTM International.

[5] ASTM. (2014). Standard practice for sampling aggregates (ASTM D75/D75M-14). ASTM International.

[6] ASTM. (2015). Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate (ASTM C127-15). ASTM International.

[7] ASTM. (2018). Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate (ASTM C88-18). ASTM International.

[8] BS 812-112:1990. Testing Aggregates – Methods for Determination of Aggregate Impact Value. British Standards Institution.

[9] BSI. (1992). BS 882: Specification for aggregates from natural sources for concrete. British Standards Institution.

[10] Ezeokonkwo, J. U., & Okere, I. (2019). Geotechnical properties of aggregates from river sources in southern Nigeria. Nigerian Journal of Geotechnical Engineering, 6(2), 45–54.

[11] Neville, A. M. (2011). Properties of Concrete (5th ed.). Pearson Education.

[12] Okonkwo, E. C., Onwualu, A. P., & Ume, M. C. (2020). Durability assessment of coarse aggregates in tropical climates using sulfate soundness tests. Journal of Construction Materials and Design, 15(1), 102–113.

[13] Oyenuga, V.O. & Akpokodje, E.G. (2021). "Evaluation of the Geotechnical Suitability of Aggregates in the Niger Delta." Nigerian Journal of Construction Materials, 12(3), 85–93.

[14] Usman, A. A., Olaleye, B. M., & Odewumi, O. A. (2018). Petrographic evaluation and mechanical characteristics of aggregates in selected southwestern Nigerian quarries. Case Studies in Construction Materials, 9, e00206. https://doi.org/10.1016/j.cscm.2018.e00206