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Engineering Characterization of Coarse Aggregates from Somalia for Structural Concrete: A Comparative Assessment with Imported Omani Aggregate

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Abstract

The engineering properties of coarse aggregates play a fundamental role in determining the strength, durability, and long-term performance of structural concrete. Although Somalia has experienced rapid growth in infrastructure and building construction over the past decade, the selection of coarse aggregates remains largely based on local availability and commercial practice due to the absence of a comprehensive engineering database for the country's principal aggregate sources. This study addresses this knowledge gap by presenting the first standardized comparative engineering characterization of coarse aggregates obtained from seven major aggregate-producing regions of Somalia (Mogadishu, Baidoa, Beledweyne, Dusamareeb, Kismayo, Bosaso, and Baledogle), using imported Omani aggregate as a benchmark. Laboratory testing was conducted at the SOMGEG Engineering Materials Laboratory in accordance with standardized ASTM and British Standard (BS) procedures. The investigation evaluated particle-size distribution, specific gravity, water absorption, bulk density, flakiness index, clay lumps and friable particles, Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), Los Angeles abrasion, and sodium sulphate soundness. Descriptive statistics, Pearson correlation, and linear regression analyses were employed to examine relationships among the measured engineering properties. The results revealed substantial variations in aggregate quality across the investigated sources. Oven-dry bulk specific gravity ranged from 2.041 to 2.603, while water absorption varied from 0.40% to 7.10%. Aggregate Crushing Value ranged from 22.0% to 40.0% for the Somali aggregates compared with 10.4% for the imported Omani aggregate, whereas Los Angeles abrasion loss ranged from 21.0% to 41.3%, compared with 11.3% for the imported benchmark. Strong statistical relationships were identified between water absorption and aggregate performance, including oven-dry bulk specific gravity ($r = -0.922$), Aggregate Impact Value ($r = 0.957$), Los Angeles abrasion loss ($r = 0.929$), and sodium sulphate soundness loss ($r = 0.906$), indicating that aggregate porosity is a key factor governing mechanical resistance and durability. Among the locally available materials, Bosaso, Baidoa, Baledogle, and Beledweyne exhibited the most favourable overall engineering performance, whereas the Mogadishu aggregate showed comparatively higher water absorption and lower mechanical resistance. The study establishes the first nationwide performance-based engineering database for the principal coarse aggregate resources of Somalia, providing a scientific basis for evidence-based aggregate selection, concrete mix design, quality assurance, and the future development of national aggregate specifications. The findings also demonstrate that several locally sourced Somali aggregates satisfy internationally recognized engineering requirements and can provide technically viable and more sustainable alternatives to imported materials for structural concrete applications.

Keywords: coarse aggregates; engineering characterization; structural concrete; engineering properties; Somalia; Omani aggregate.

1. Introduction

Concrete is the most widely used construction material worldwide and forms the backbone of modern civil engineering infrastructure. It is extensively employed in residential and commercial buildings, bridges, highways, ports, airports, dams, retaining structures, drainage systems, marine facilities, and industrial developments because of its versatility, durability, economic efficiency, and adaptability to a wide range of structural applications. The performance of concrete, however, depends not only on the quality of cement and water but also on the engineering characteristics of its constituent aggregates. Coarse aggregates generally occupy approximately 60–75% of the total concrete volume and constitute nearly 70–85% of its total mass. Consequently, they exert a dominant influence on the fresh and hardened properties of concrete, including workability, density, stiffness, dimensional stability, shrinkage, abrasion resistance, permeability, compressive strength, and long-term durability. Their characteristics also affect the quantity of cement paste required, the water demand of the mixture, and ultimately the economic efficiency of concrete production (ACI Committee E-701, 2007; Neville, 2011; Mehta & Monteiro, 2014; Mohanta & Murmu, 2022; Mohammed et al., 2023).

Because coarse aggregates constitute the largest proportion of concrete, their engineering quality must be evaluated using standardized laboratory procedures before they are incorporated into structural works. Reliance on visual inspection, commercial reputation, or historical usage alone cannot ensure satisfactory engineering performance because aggregates derived from different geological formations frequently exhibit considerable variations in mineralogical composition, particle morphology, density, porosity, strength, and durability. Such variations influence both the fresh and hardened behaviour of concrete and may significantly affect structural safety, serviceability, maintenance requirements, and overall life-cycle costs. International standards therefore recommend that aggregates intended for structural concrete should satisfy specified limits for grading, density, water absorption, particle shape, mechanical resistance, cleanliness, and durability before acceptance for engineering use (ASTM International, 2018; ASTM International, 2019).

The engineering behaviour of coarse aggregates is governed by a combination of physical, geometrical, mechanical, and durability-related properties that collectively determine their suitability for concrete production. Among these characteristics, particle-size distribution (gradation) is one of the most influential because it directly affects aggregate packing, void ratio, paste requirement, workability, segregation resistance, bleeding, and concrete density. Well-graded aggregates improve particle interlock and reduce the volume of cement paste required to fill internal voids, thereby enhancing both

the economy and mechanical performance of concrete. Conversely, poorly graded aggregates often increase paste demand, reduce workability, and may lead to segregation or excessive shrinkage. Consequently, sieve analysis remains one of the most fundamental laboratory procedures for evaluating aggregate quality and ensuring compliance with recognized engineering specifications (ASTM International, 2019).

The density and porosity of aggregate particles are equally important because they influence concrete weight, moisture behaviour, and mix design calculations. Specific gravity provides an indication of the relative density of aggregate particles and is an essential parameter in absolute-volume concrete mix design, while water absorption reflects the accessible pore structure within the aggregate and serves as an indirect measure of porosity and durability. Aggregates exhibiting high water absorption generally contain greater internal pore volumes and may require additional mixing water or moisture correction during batching. Excessive absorption may also indicate reduced resistance to weathering and long-term deterioration. Accurate determination of specific gravity and water absorption is therefore essential for achieving consistent concrete quality, minimizing batching errors, and ensuring reliable structural performance (ASTM International, 2024a; Telloli et al., 2021; Bayari et al., 2025). Similarly, bulk density provides practical information regarding the mass of aggregate occupying a given volume under stockpile and batching conditions and is widely used for estimating storage requirements, transportation efficiency, and material quantities during concrete production (ASTM International, 2023a).

Particle shape and surface texture further influence the performance of both fresh and hardened concrete. Angular and rough-textured aggregates generally provide improved mechanical interlock with the surrounding cement paste, contributing to higher compressive strength and better bond characteristics. However, highly angular or flaky particles may reduce workability, increase internal friction during mixing, and require larger quantities of cement paste to achieve satisfactory consistency. Conversely, rounded aggregates usually improve workability but may reduce inter-particle interlock and mechanical strength. The flakiness index is therefore widely employed as an indicator of particle geometry because excessive proportions of elongated or flaky particles may impair compaction efficiency, create weak zones within hardened concrete, and reduce structural performance under loading (British Standards Institution, 1990a). Several recent investigations have demonstrated that aggregate morphology significantly influences concrete rheology, packing density, and mechanical behaviour, emphasizing the importance of incorporating particle-shape evaluation within comprehensive aggregate characterization programmes (Çelik et al., 2021; Mohanta & Murmu, 2022; Hosen et al., 2024).

Aggregate cleanliness is another critical factor affecting concrete performance. Clay lumps, friable particles, dust coatings, and other deleterious materials can interfere with the bond between aggregate surfaces and hydrated cement paste, reducing strength development and increasing the susceptibility of concrete to cracking and durability-related deterioration. Fine clay coatings may also increase water demand and alter the effective water-cement ratio during batching. For these reasons, internationally recognized specifications impose strict limits on the allowable quantities of clay lumps and friable particles in coarse aggregates intended for structural applications (ASTM International, 2023b). Recent studies have similarly shown that washing and proper processing of aggregates can substantially improve concrete quality by removing excessive fines, improving particle grading, and enhancing aggregate–cement bond characteristics (Legamo & Sida, 2022).

In addition to physical characteristics, coarse aggregates must possess adequate mechanical strength to withstand crushing, impact, abrasion, transportation, concrete mixing, compaction, and service loads throughout the life of a structure. Mechanical resistance is commonly evaluated using the Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), and Los Angeles Abrasion (LAA) tests, each representing different modes of loading encountered during construction and service. ACV measures the resistance of aggregate particles to gradual compressive loading and provides an indication of their crushing strength, whereas AIV evaluates resistance to sudden impact loading resulting from repeated dynamic forces. The Los Angeles Abrasion test combines impact and abrasion within a rotating steel drum to assess aggregate toughness and resistance to mechanical degradation. These tests are widely recognized as reliable indicators of aggregate quality because they correlate closely with the long-term mechanical performance of concrete and pavement materials (ASTM International, 2020a; British Standards Institution, 1990c, 1990d; Köken, 2022).

Finally, durability-related properties are essential when aggregates are exposed to repeated cycles of wetting, drying, temperature variation, or chemically aggressive environments. Sodium sulphate soundness testing simulates the expansive stresses generated during salt crystallization within aggregate pores and provides an indication of the material's resistance to weathering and long-term disintegration. Aggregates demonstrating low mass loss during soundness testing generally possess superior durability and are better suited for structural concrete subjected to severe environmental exposure. Consequently, modern aggregate evaluation increasingly adopts an integrated laboratory approach in which physical, geometrical, mechanical, and durability properties are assessed collectively rather than independently. Such comprehensive characterization provides engineers with a scientifically robust basis for selecting

aggregate sources, optimizing concrete mix design, and ensuring durable, economical, and sustainable infrastructure development. This integrated approach forms the foundation of the present study and provides the basis for the comparative evaluation of coarse aggregates obtained from major quarry sources across Somalia and imported Omani aggregates used as a benchmark for structural concrete applications.

Over the past two decades, considerable research has been undertaken worldwide to evaluate the engineering characteristics of coarse aggregates and their influence on concrete performance. These investigations consistently demonstrate that aggregate quality is governed by geological origin, mineralogical composition, particle morphology, physical properties, mechanical strength, durability, and production practices. Although the engineering parameters used to evaluate aggregates are largely standardized through ASTM, British Standards, and other international specifications, significant variations exist among aggregate sources due to differences in parent rock, weathering processes, quarrying methods, and processing techniques. Consequently, comprehensive laboratory characterization remains indispensable for identifying aggregates suitable for structural concrete and for minimizing the risk of premature deterioration and structural failure.

One of the earliest comprehensive studies highlighting the importance of aggregate quality was conducted by Dinku (2005), who emphasized the need for standardized aggregate production and testing procedures in Ethiopia. The study demonstrated that even aggregates derived from high-quality basaltic formations may exhibit inconsistent engineering performance if quarry selection, processing, quality control, and laboratory verification are inadequate. Dinku further argued that sustainable infrastructure development requires systematic testing rather than reliance on traditional quarry reputation or commercial practice. These conclusions remain highly relevant to many developing countries where rapidly expanding construction industries frequently depend on locally available aggregate resources without comprehensive engineering evaluation.

Subsequent investigations further confirmed the importance of source-specific aggregate characterization. Ashraf et al. (2013) evaluated hard-rock aggregates used for high-strength concrete in Bangladesh and demonstrated that aggregates possessing relatively high specific gravity and low water absorption produced superior compressive and tensile strengths. Similarly, Barzangi et al. (2014) compared two natural gravel sources in Iraq using grading, specific gravity, water absorption, Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), Los Angeles Abrasion (LAA), flakiness, and elongation tests. Their results showed that although both sources satisfied ASTM and British Standard

requirements, measurable differences existed in abrasion resistance and crushing strength, confirming that aggregate source significantly influences engineering performance. These findings reinforce the importance of evaluating each aggregate source individually rather than assuming comparable performance among visually similar materials.

Attention has also been directed toward aggregate production, handling, and quality management. Tafa (2017) demonstrated that improper storage, handling, and processing practices may substantially reduce aggregate quality even when the parent rock possesses acceptable engineering properties. Likewise, Kumar et al. (2018) compared crushed rock aggregates with naturally occurring river and lag gravels in Ethiopia and reported that properly graded natural gravels could achieve compressive strengths comparable to, or even exceeding, those of crushed aggregates. Their findings emphasized that compliance with engineering specifications depends not only on aggregate origin but also on grading quality and processing practices. Recent investigations have increasingly focused on systematic laboratory characterization using internationally recognized testing standards. Mamo et al. (2019) demonstrated that comprehensive physical testing—including specific gravity, water absorption, Aggregate Impact Value, Aggregate Crushing Value, and Los Angeles Abrasion—provides an effective framework for comparing multiple quarry sources and identifying materials suitable for construction applications. Although their investigation focused primarily on road-base aggregates, the methodology provides an excellent model for comparative evaluation of coarse aggregates intended for concrete production. In another Ethiopian study, Warati et al. (2019) showed that locally available volcanic scoria could successfully replace conventional aggregates under appropriate mix proportions, illustrating the importance of scientifically evaluating indigenous materials before dismissing them in favour of imported alternatives.

More recent research has expanded beyond conventional physical testing by examining the interaction between aggregate engineering properties and concrete performance. Islam et al. (2020) evaluated several commonly used aggregate sources in Bangladesh and established strong relationships between aggregate strength, particle shape, mineralogical characteristics, and the compressive, tensile, and flexural strength of concrete. Their results confirmed that aggregate quality becomes increasingly important as concrete strength requirements increase, particularly for structural applications requiring enhanced durability and mechanical performance. At the same time, Assefa and Gebregziabher (2020) emphasized that sustainable aggregate production requires not only engineering quality but also

environmentally responsible quarry management practices that minimize landscape degradation, dust generation, and ecological disturbance.

Growing attention has also been given to the influence of mineralogy and petrography on aggregate durability. Telloli et al. (2021) investigated several natural aggregate types used in northern Italy and demonstrated that mineralogical composition and aggregate–cement interaction significantly influence concrete strength and long-term durability. Likewise, Çelik et al. (2021) characterized marble, basalt, and andesite aggregates in Türkiye and showed that clay-bearing minerals, higher water absorption, and unfavourable petrographic characteristics reduce aggregate durability despite acceptable grading characteristics. These studies demonstrate that physical properties alone are insufficient for evaluating aggregate quality and should be interpreted together with mineralogical and durability characteristics wherever possible. Other researchers have investigated methods for improving aggregate performance through processing and predictive evaluation. Legamo and Sida (2022) demonstrated that washing and blending aggregates significantly improve compressive strength by reducing silt content and optimizing particle-size distribution. Their findings indicate that aggregate sources initially considered unsuitable may become acceptable following appropriate processing procedures. Köken (2022) further introduced predictive modelling approaches using regression analysis, gene expression programming, and artificial neural networks to estimate Los Angeles Abrasion and magnesium sulphate soundness values from fundamental engineering properties. Although these models were developed for Turkish rock aggregates, they demonstrate the growing integration of data-driven approaches into aggregate characterization and suggest potential directions for future research using comprehensive laboratory datasets.

Recent international studies continue to reinforce the central role of aggregate engineering properties in determining concrete performance. Mohammed et al. (2023) demonstrated that maximum aggregate size significantly affects workability, interfacial transition zone (ITZ) development, and mechanical properties of concrete, while Hosen et al. (2024) showed that variations in specific gravity, water absorption, Aggregate Crushing Value, Aggregate Impact Value, and Los Angeles Abrasion among natural aggregate sources produce measurable differences in concrete strength and durability. Similarly, Bayari et al. (2025) demonstrated that local sedimentary rocks can provide suitable coarse aggregates for structural concrete when their mineralogical and engineering properties satisfy recognized specification limits. In Somalia, Muse et al. (2025) provided the first direct comparison between locally sourced and imported aggregates, demonstrating that aggregate origin significantly influences workability, water absorption, abrasion resistance, durability, and compressive strength of concrete.

Collectively, these investigations consistently demonstrate that aggregate selection should be based on comprehensive laboratory evaluation rather than assumptions regarding geological origin or commercial preference.

Comprehensive review studies further emphasize that aggregate characterization should adopt an integrated engineering approach encompassing physical, mechanical, geometrical, mineralogical, durability, and sustainability considerations. Mohanta and Murmu (2022) concluded that reliable aggregate selection requires simultaneous evaluation of grading, density, water absorption, particle shape, abrasion resistance, impact resistance, crushing resistance, and durability indicators together with responsible resource management practices. This integrated perspective is increasingly recognized as essential for producing durable, economical, and sustainable concrete infrastructure under diverse environmental conditions.

Despite the rapid growth of Somalia's construction industry, the selection of coarse aggregates for structural concrete remains largely based on local availability, transportation distance, commercial cost, contractor preference, and previous construction experience rather than comprehensive engineering evaluation. Although both locally quarried and imported aggregates are widely used, particularly imported Omani aggregates, their selection is generally influenced by market perception instead of standardized laboratory evidence. Consequently, engineers lack reliable engineering information for comparing aggregate sources, optimizing concrete mix design, and ensuring long-term structural performance. Furthermore, findings from international studies cannot be directly applied to Somalia because aggregate properties are strongly influenced by local geology, mineralogical composition, climatic conditions, quarrying methods, and production practices.

The construction industry in Somalia has experienced substantial growth over the past decade, driven by urban reconstruction, rapid population growth, expansion of transportation infrastructure, increasing private investment, and the rehabilitation of public facilities following prolonged periods of conflict. Large-scale developments including multi-storey buildings, highways, ports, airports, bridges, industrial facilities, and public infrastructure have significantly increased the demand for high-quality concrete and reliable construction materials. National economic reports also indicate continuing investment in infrastructure and urban development, highlighting the importance of establishing scientifically verified construction-material standards capable of supporting safe, durable, and sustainable engineering practice (Somalia National Bureau of Statistics, 2025).

Despite this rapid growth, the selection of coarse aggregates for concrete production in Somalia remains largely based on local availability, transportation distance, commercial cost, contractor preference, and previous construction experience rather than comprehensive engineering evaluation. While these practical considerations influence material procurement, they cannot replace laboratory characterization using internationally recognized testing standards. Aggregates originating from different regions frequently possess distinct geological characteristics that influence particle grading, density, porosity, mechanical strength, abrasion resistance, impact resistance, weathering durability, and long-term concrete performance. Consequently, selecting aggregates without adequate laboratory verification introduces uncertainty into concrete mix design, quality control, and structural reliability, particularly for projects requiring high-performance or durable concrete. Another important characteristic of the Somali construction sector is the widespread use of both locally quarried aggregates and imported aggregates, particularly those imported from the Sultanate of Oman. Imported aggregates are commonly regarded by engineers, contractors, and clients as premium construction materials because of their perceived consistency and quality. However, imported materials involve considerably higher transportation and procurement costs and do not necessarily provide superior engineering performance for every construction project. Conversely, many locally available Somali aggregates remain underutilized because their engineering characteristics have not been comprehensively documented. Consequently, material selection often depends on market perception rather than measured engineering evidence, potentially increasing construction costs while overlooking locally available resources capable of satisfying structural performance requirements. This situation demonstrates the urgent need for an objective engineering database that allows local and imported aggregates to be compared using standardized laboratory procedures rather than commercial reputation alone.

A review of previous studies indicates that most investigations have focused on individual aggregate sources, specific engineering properties, or concrete performance under local conditions. Although the recent study by Muse et al. (2025) compared locally sourced and imported aggregates, it evaluated only a limited number of aggregate sources and did not establish a comprehensive engineering database representing the principal aggregate-producing regions of Somalia. To the best of the authors' knowledge, no published study has systematically characterized coarse aggregates obtained from Mogadishu, Baidoa, Beledweyne, Dusamareeb, Kismayo, Bosaso, and Baledogle using a unified laboratory testing programme encompassing physical, geometrical, mechanical, and durability properties while simultaneously benchmarking their engineering performance against imported Omani aggregate. This absence of standardized nationwide engineering data limits evidence-based aggregate

selection, quality assurance, concrete mix optimization, and the development of national specifications for structural concrete in Somalia.

To establish the current state of knowledge and identify existing research gaps, a comprehensive review of recent studies on aggregate engineering properties and concrete production was undertaken. The reviewed investigations covered aggregate characterization, concrete performance, durability assessment, laboratory testing methods, and engineering applications from different countries. As summarized in Table 1, previous studies have generally focused on individual aggregate sources, specific engineering properties, or concrete performance under local conditions. Although these investigations have significantly advanced the understanding of aggregate behaviour, none has provided a comprehensive comparative engineering characterization of coarse aggregates collected from the principal aggregate-producing regions of Somalia using a unified laboratory testing program and an imported benchmark aggregate.is depicted in Table 1.

Accordingly, a significant knowledge gap remains regarding the comparative engineering characteristics of coarse aggregates obtained from the major quarry regions supplying the Somali construction industry. To date, no published study has systematically compared aggregates collected from Mogadishu, Baidoa, Beledweyne, Dusamareeb, Kismayo, Bosaso, and Baledogle using a consistent laboratory testing program covering particle-size distribution, specific gravity, water absorption, bulk density, particle shape, cleanliness, Aggregate Crushing Value, Aggregate Impact Value, Los Angeles Abrasion, and sodium sulphate soundness while simultaneously benchmarking their performance against imported Omani aggregates. The absence of such comprehensive information limits evidence-based aggregate selection, constrains optimization of concrete mix design, and reduces confidence in the long-term durability of concrete structures constructed using locally available materials.

The principal novelty of this study lies not in the application of standard laboratory tests, but in the development of one of the first comprehensive, source-based engineering characterizations of coarse aggregates representing the major aggregate-producing regions of Somalia using a unified testing methodology and a common imported benchmark**.** Unlike previous investigations that focused on individual aggregate properties, isolated quarry locations, or concrete strength alone, this research integrates physical, geometrical, mechanical, and durability-related properties into a single comparative engineering framework. This integrated methodology enables direct comparison among multiple Somali aggregate sources under identical laboratory conditions, thereby eliminating variations arising from differences in testing procedures and providing a consistent basis for engineering evaluation. A second

important contribution of this study is the establishment of a regional engineering database for coarse aggregates used in Somalia. Such a database has practical significance because it provides engineers, consultants, contractors, material suppliers, and regulatory authorities with scientifically verified information for selecting aggregates according to measured engineering performance rather than commercial perception or historical practice. The database also provides a technical foundation for improving quality assurance, optimizing concrete mix design, reducing unnecessary dependence on imported materials, and supporting the development of future national specifications and quality-control procedures for aggregate production within Somalia.

Furthermore, the study contributes to sustainable construction by identifying locally available aggregate resources capable of meeting internationally recognized engineering requirements. Demonstrating the suitability of locally sourced materials has the potential to reduce transportation costs, lower the environmental impacts associated with long-distance aggregate importation, strengthen domestic quarry industries, and improve the resilience of construction-material supply chains. Consequently, the findings contribute not only to engineering practice but also to broader national objectives related to sustainable infrastructure development and resource utilization.

Therefore, the objective of this study was to conduct a comprehensive engineering characterization of coarse aggregates collected from the principal aggregate-producing regions of Somalia using standardized ASTM and British Standard laboratory procedures. The engineering performance of locally sourced aggregates was evaluated and compared with imported Omani aggregate through comprehensive assessment of their physical, geometrical, mechanical, and durability properties. The study aims to establish a reliable performance-based engineering database to support evidence-based aggregate selection, optimize concrete mix design, improve quality assurance, and facilitate the future development of national aggregate specifications for structural concrete applications in Somalia.

Table 1. Literature review matrix for aggregate engineering properties and concrete production

No.	Authors / Year	Topic / Research Focus	Country / Study Area	Methodology	Analyses / Tests	Key Findings	Relevance to Present Study
1	Dinku (2005)	Aggregate standardization	Ethiopia	Review	Physical & geological properties	Need for national standards	Framework for Somalia
2	Ashraf et al. (2013)	Hard rock aggregate	Bangladesh	Experimental	SG, absorption, strength	High-quality aggregate improves concrete	Structural concrete
3	Barzangi et al. (2014)	Natural coarse aggregate suitability	Iraq	Experimental	ACV, AIV, LAA, SG	Both sources met standards	Similar comparison
4	Tafa (2017)	Aggregate handling	Ethiopia	Case study	Quality control	Handling affects quality	Quarry management
5	Kumar et al. (2018)	River vs crushed aggregate	Ethiopia	Experimental	ASTM tests	Aggregate source influences strength	Comparison
6	Mamo et al. (2019)	Basalt aggregates	Ethiopia	Experimental	LAA, ACV, SG	Suitable for construction	Laboratory comparison
7	Warati et al. (2019)	Scoria aggregate	Ethiopia	Experimental	Strength tests	Local aggregate feasible	Alternative materials
8	Islam et al. (2020)	Aggregate evaluation	Bangladesh	Experimental	ACV, LAA, petrography	Aggregate quality governs concrete	Methodology
9	Assefa & Gebregziabher (2020)	Aggregate sustainability	Ethiopia	Review	Environmental assessment	Need sustainable quarrying	Recommendations
10	Telloli et al. (2021)	Natural aggregates	Italy	Experimental	Petrography & mechanics	Mineralogy influences performance	Petrographic interpretation
11	Çelik et al. (2021)	Natural stone aggregates	Türkiye	Experimental	LAA, soundness	Durability varies by rock type	Durability discussion
12	Zhang et al. (2021)	Aggregate morphology and fresh concrete	China	Experimental	Morphology, rheology, compressive strength	Aggregate shape significantly influences workability and strength	Supports discussion of aggregate shape and flakiness. (ScienceDirect)
13	Legamo & Sida (2022)	Aggregate washing	Ethiopia	Experimental	Concrete strength	Washing improves strength	Processing recommendation
14	Köken (2022)	Prediction of LA abrasion	Türkiye	Experimental & AI	LAA, $MgSO_4$	Reliable prediction models	Future work
15	Mohanta & Murmu (2022)	Coarse aggregate review	Global	Review	Physical & durability properties	Comprehensive characterization required	Literature background
16	Mohammed et al. (2023)	Aggregate size	Bangladesh	Experimental	SEM, strength	Size influences ITZ	Grading discussion

17	Hosen et al. (2024)	Aggregate properties & concrete strength	Bangladesh	Experimental	SG, ACV, AIV, LAA	Source significantly affects concrete	Closest comparison
18	Bayari et al. (2025)	Sandstone aggregate	Ghana	Experimental	Petrography, ACV	Local rock suitable	Source evaluation
19	Muse et al. (2025)	Somali aggregates	Somalia	Experimental	LAA, absorption, strength	Imported and local aggregates differ	Direct comparison
20	De La Rosa et al. (2025)	Photogrammetric characterization of coarse aggregates	Spain	Experimental	Shape & particle size	Aggregate geometry affects concrete performance	Supports shape discussion. (ScienceDirect)
21	López Rojas (2025)	Aggregate morphology and concrete	Mexico	Experimental review	Morphology & strength	Angularity influences mechanical performance	Supports flakiness interpretation. (revistas.uaa.mx)
22	Subash & Parida (2025)	Aggregate gradation	India	Experimental	Gradation, durability, strength	Gradation significantly affects concrete performance	Supports grading discussion. (Springer)
23	AbdelMoaty et al. (2025)	Aggregate effects on concrete properties	Egypt	Experimental	Aggregate type & compressive strength	Aggregate characteristics strongly influence concrete behaviour	General comparison. (MDPI)
24	Piotrowska et al. (2014)	Aggregate shape under triaxial loading	France	Experimental	Aggregate morphology	Aggregate shape affects concrete response	Mechanics background. (revistas.uaa.mx)
25	Quiroga & Fowler (2004)	Aggregate characteristics and concrete performance	USA	Experimental	Aggregate characterization	Aggregate properties control concrete quality	Classic reference. (revistas.uaa.mx)
26	Neville (2011)	Properties of Concrete	UK	Reference book	Concrete technology	Fundamental aggregate behaviour	Background
27	Mehta & Monteiro (2014)	Concrete: Microstructure, Properties and Materials	USA	Reference book	Concrete materials	Aggregate role in concrete	Background
28	Mindess, Young & Darwin (2003)	Concrete	Canada	Reference book	Concrete engineering	Fundamental concrete behaviour	Background

2. Materials and Methods

2.1 Study Area

Somalia possesses diverse geological formations that provide abundant natural sources of construction aggregates for infrastructure development. To ensure representative coverage of the country's principal aggregate-producing regions, coarse aggregate samples were collected from seven active quarry locations distributed across northern, central, and southern Somalia. The selected sites comprise Bosaso, Dusamareeb, Beledweyne, Baidoa, Baledogle, Mogadishu, and Kismayo, which collectively supply aggregates for buildings, roads, bridges, and other civil engineering projects. **Figure 1** illustrates the geographical distribution of the investigated quarry locations across Somalia together with the country's location within the African continent. The selected quarries represent diverse geological environments, including limestone formations, sedimentary deposits, alluvial materials, and coastal deposits, thereby providing a representative basis for evaluating the engineering characteristics of coarse aggregates used for structural concrete.

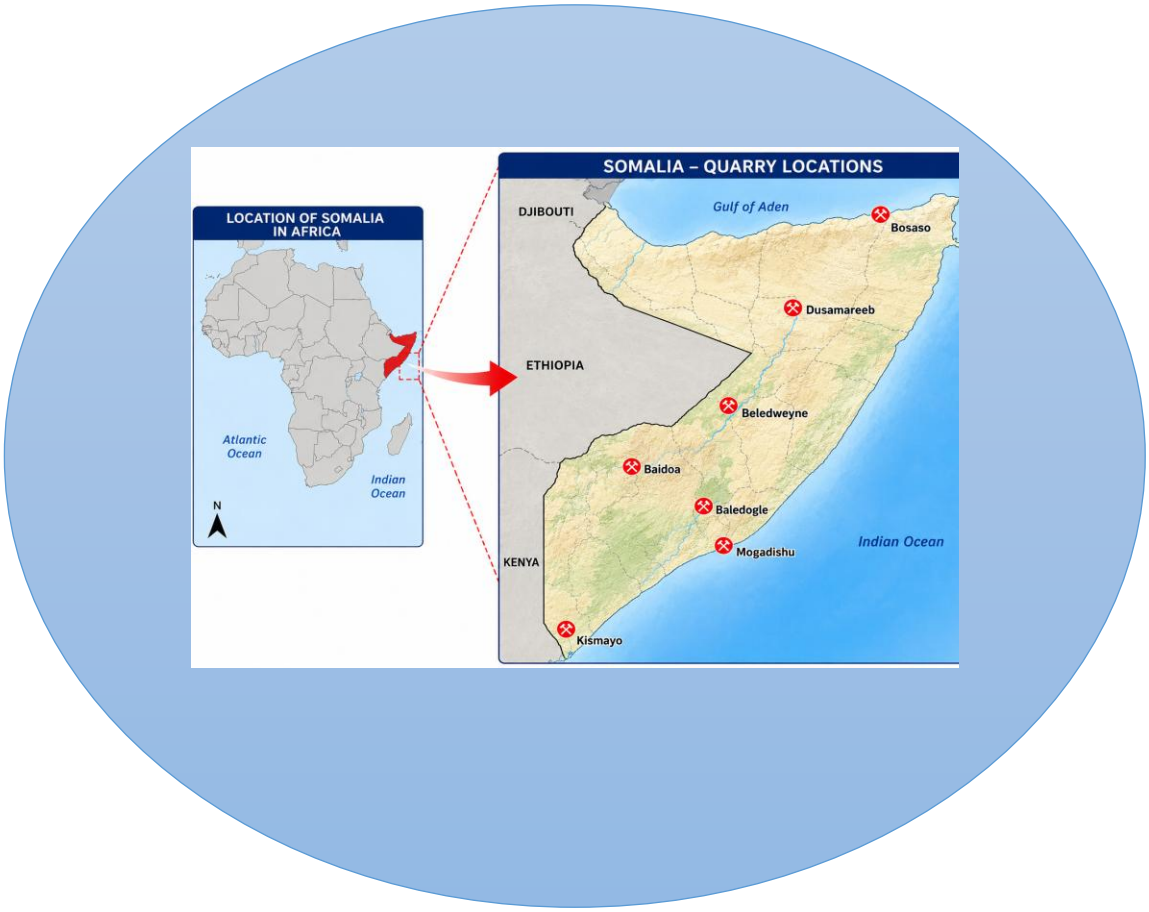


Figure 1. Location of the investigated quarry sites and aggregate sampling locations across Somalia.

The investigated quarry sites provide broad geographical coverage of the principal aggregate-producing regions of Somalia. This distribution captures variations in geological setting and aggregate origin, enabling a comprehensive comparison of aggregate engineering properties under a unified laboratory testing program. Representative samples were collected directly from active quarry production stockpiles in accordance with ASTM sampling procedures to ensure that the laboratory results accurately reflect materials currently used in engineering practice.

Representative coarse aggregate samples were collected from the principal aggregate-producing regions of Somalia to provide broad geographical and geological coverage of the materials currently used in structural concrete construction. The selected quarry locations represent the major sources supplying aggregates for buildings, roads, bridges, and other civil engineering infrastructure. **Table 2** summarizes the geographical location, administrative region, approximate geological formation, and sample identification code for each investigated aggregate source.

Table 2. Geographic characteristics of the investigated aggregate sources

Aggregate Source	***Region***	***Approximate Geological Formation***	***Sample Code***
Bosaso	Bari	Limestone/Coastal sedimentary rocks	BOS
Dusamareeb	Galgaduud	Limestone and sandstone	DUS
Beledweyne	Hiiraan	Alluvial deposits	BEL
Baidoa	Bay	Limestone	BAI
Baledogle	Lower Shabelle	Limestone	BAL
Mogadishu	Banaadir	Coastal limestone/coral deposits	MOG
Kismayo	Jubaland	Coastal sedimentary deposits	KIS

This study was designed as an experimental laboratory investigation to evaluate the engineering characteristics of coarse aggregates used for structural concrete production in Somalia. Representative bulk aggregate samples were collected from active quarry sites, crushing plants, stockpiles, and aggregate suppliers serving the seven regions listed in Table 2**.** In addition, imported Omani aggregate, which is widely used in Somalia for high-quality construction projects, was included as a benchmark material to facilitate a comparative assessment of the engineering performance of locally available and imported aggregates. All samples were collected, handled, and prepared using consistent procedures to

ensure representative laboratory testing and reliable comparison among the investigated aggregate sources.

2.2 Aggregate Sampling

Eight coarse aggregate sources were investigated, comprising seven locally produced Somali aggregates (Bosaso, Dusamareeb, Beledweyne, Baidoa, Baledogle, Mogadishu, and Kismayo) and one imported Omani aggregate used as a benchmark for comparison. All materials consisted of crushed coarse aggregates commonly used in reinforced concrete buildings, bridges, pavements, and other civil engineering infrastructure throughout Somalia. Bulk aggregate samples were collected directly from active quarry production stockpiles following standard aggregate sampling procedures to ensure that each sample was representative of the materials supplied for construction. The selected quarry sites represent the principal aggregate-producing regions currently serving the Somali construction industry. Each sample was labelled according to its source location, carefully packaged, and transported to the Somali Geotechnical Engineering Group (SOMGEG) Engineering Materials Laboratory in Mogadishu for laboratory evaluation.

Upon arrival at the laboratory, all samples were visually inspected to identify any damage or contamination that may have occurred during transportation. Where necessary, the aggregates were air-dried or oven-dried prior to testing and subsequently reduced to representative laboratory test portions using standard sample reduction procedures. Loose foreign materials and accidental contaminants were removed only when they did not constitute part of the representative aggregate sample. Identical sampling, handling, and preparation procedures were applied to all aggregate sources to minimize laboratory-induced variability and ensure that differences observed during testing reflected the intrinsic engineering characteristics of each aggregate source rather than variations in sample preparation.

Following sample preparation, the aggregates were subjected to a comprehensive laboratory testing programme conducted under identical laboratory conditions to evaluate their grading characteristics, physical properties, particle shape and cleanliness, mechanical resistance, and durability in accordance with the relevant ASTM and British Standard test methods.

2.3 Laboratory Testing Program

A comprehensive laboratory testing programme was undertaken to characterize the engineering performance of the investigated coarse aggregates. The laboratory investigation was organized into five principal categories: physical properties, shape and cleanliness properties, gradation properties, mechanical resistance properties, and durability properties. All laboratory tests were conducted using calibrated equipment at the SOMGEG Engineering Materials Laboratory in accordance with internationally recognized ASTM and British Standard test procedures.

2.3.1 Physical Properties

Physical characterization included determination of bulk specific gravity in the oven-dry condition, bulk specific gravity in the saturated surface-dry (SSD) condition, apparent specific gravity, water absorption, and bulk density. These properties provide important information regarding aggregate density, porosity, moisture absorption characteristics, and volumetric behaviour, all of which significantly influence concrete mix design, workability, and long-term structural performance.

2.3.2 Shape and Cleanliness Properties

Aggregate shape and cleanliness were evaluated by determining the flakiness index together with the percentage of clay lumps and friable particles. These properties influence aggregate interlocking, concrete workability, compaction, bond development, and the overall mechanical performance of hardened concrete. Flakiness Index testing was conducted in accordance with BS 812, while clay lumps and friable particles were determined following ASTM C142.

2.3.3 Gradation Properties

Aggregate grading was determined by sieve analysis following ASTM C136 using a standard series of sieves. The percentage passing each sieve size was calculated, and cumulative percentage passing curves were developed for every aggregate source. The gradation curves were subsequently compared with standard grading requirements to assess compliance with specification limits.

A gradation chart provides a graphical representation of aggregate particle-size distribution and is widely used to evaluate whether aggregate grading satisfies the requirements of relevant standards or project specifications. In this study, the horizontal axis represents sieve opening size arranged from smaller to

larger openings, while the vertical axis represents cumulative percentage passing. The laboratory grading results for all investigated aggregates are presented in Table 4 and illustrated in Figure 4.

2.3.4 Mechanical Resistance Properties

Mechanical performance was evaluated using the Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), and Los Angeles Abrasion (LAA) tests. The ACV test assesses the resistance of aggregates to gradually applied compressive loading, whereas the AIV test evaluates resistance to sudden impact loading. The Los Angeles Abrasion test measures resistance to abrasion, wear, and mechanical degradation under combined impact and grinding action. These tests collectively provide reliable indicators of aggregate strength, toughness, and suitability for structural concrete subjected to service loads.

2.3.5 Durability Properties

Aggregate durability was assessed using the Sodium Sulphate Soundness test in accordance with ASTM C88. The soundness test evaluates the resistance of aggregates to repeated cycles of salt crystallization that simulate weathering effects encountered under natural environmental conditions. Aggregates exhibiting lower soundness losses are generally considered more durable and more suitable for long-term structural applications, particularly in aggressive coastal and arid environments such as those found in Somalia. The sequence of aggregate preparation, weighing, sieve analysis, and laboratory testing conducted at the SOMGEG Engineering Materials Laboratory is illustrated in Figures 1 and 2**.** The laboratory testing program, applicable testing standards, measured engineering properties, and principal equations used in the calculations are summarized in Tables 3 and 4**.**

2.4 Statistical Analysis

The laboratory test results were statistically analyzed to summarize and compare the engineering characteristics of the investigated coarse aggregates. Since each aggregate source was represented by one final laboratory value for each engineering property, descriptive statistical methods were used to evaluate variability among aggregate sources rather than within-source laboratory repeatability. Descriptive statistical parameters, including the arithmetic mean, standard deviation (SD), minimum value, maximum value, and coefficient of variation (CV), were calculated for all measured engineering properties. Pearson correlation analysis was subsequently performed to examine the relationships among

selected physical, mechanical, and durability properties of the investigated aggregates. Linear regression analysis was then applied to quantify these relationships, and the coefficient of determination (R^2) was used to assess the goodness-of-fit of the regression models. Scatter plots with fitted regression lines were prepared to visualize the relationships between the principal engineering properties. All statistical analyses, regression models, correlation analyses, and graphical presentations were performed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA).

Table 3. Laboratory test program, standards and measured outputs.

Property group	***Property or test***	***Standard code***	***Main output***
Sampling and reduction	Field sampling of aggregates	ASTM D75/D75M	Representative bulk sample
Sampling and reduction	Reduction to laboratory test size	ASTM C702/C702M	Representative test portion
Gradation	Sieve analysis of coarse aggregate	ASTM C136/C136M	Cumulative percent passing
Physical properties	Specific gravity and absorption	ASTM C127/C127M	OD SG, SSD SG, apparent SG, absorption
Physical properties	Bulk density and voids	ASTM C29/C29M	Bulk density
Shape	Flakiness index	BS 812-105.1	Flaky-particle content
Cleanliness	Clay lumps and friable particles	ASTM C142/C142M	Clay/friable-particle content
Mechanical resistance	Aggregate crushing value	BS 812-110	ACV
Mechanical resistance	Aggregate impact value	BS 812-112	AIV
Mechanical resistance	Los Angeles abrasion	ASTM C131/C131M	Abrasion loss
Durability	Sodium sulfate soundness	ASTM C88/C88M	Weighted soundness loss

Table 4. Principal formulas used for aggregate-property calculations.

Measured property	*Formula used in analysis*
Bulk specific gravity, oven dry	G_OD = A / (B - C)
Bulk specific gravity, SSD	G_SSD = B / (B - C)
Apparent specific gravity	G_app = A / (A - C)
Water absorption	Absorption (%) = [(B - A) / A] x 100
Bulk density	rho = M / V
Cumulative percent passing	P_i = 100 - cumulative percent retained on sieve i
Flakiness index	FI (%) = mass of flaky particles / total sample mass x 100
Clay lumps and friable particles	C_f (%) = (M_initial - M_final) / M_initial x 100
Aggregate crushing value	ACV (%) = mass passing 2.36 mm after crushing / original test mass x 100
Aggregate impact value	AIV (%) = mass passing 2.36 mm after impact / original test mass x 100
Los Angeles abrasion loss	LA (%) = (M_initial - M_retained) / M_initial x 100
Weighted sulfate soundness loss	L_total (%) = sum of fractional mass share x percentage loss for each size fraction



Figure 2. (a) Aggregate preparation, (b) weighing,(c) sieving, and (d) equipment arrangement at the SOMGEG Laboratory.



Figure 3. (a) Mechanical resistance equipment, (b)-(c) coarse aggregate particles and (d) sample handling during laboratory testing.

3. Results and Discussion

This section presents and discusses the results of the laboratory investigation conducted on coarse aggregates collected from seven regions of Somalia and the imported Oman aggregate used as a reference material. The laboratory evaluation included particle grading, physical properties, shape and cleanliness characteristics, mechanical resistance, durability, and statistical analyses of the measured engineering properties. The results are interpreted in relation to the requirements of relevant ASTM and British Standard (BS) specifications and are compared to identify variations in aggregate quality, engineering performance, and suitability for structural concrete applications.

3.1 Gradation Properties and Sieve-Analysis Interpretation

Figure 4 and table 5 below show the gradation chart for sieve analysis of coarse aggregate from all tested regions in Somalia and from the imported Oman benchmark. The chart displays cumulative percentage passing for each sieve size. The curves make the differences between sources immediately visible and help identify whether a material is balanced, gap graded, too coarse, or too fine for a target aggregate size. This graphical check is important because a table of percent passing may hide local grading defects that become obvious when the data are plotted.

The tested materials generally exhibited a coarse aggregate grading pattern, with 100% passing the 28.0 mm sieve and very low percentages passing the 4.0 mm and 2.36 mm sieves for most aggregate sources. Mogadishu exhibited 91.5% passing the 20-mm sieve and 44.1% passing the 14-mm sieve, indicating a well-distributed coarse fraction with relatively limited fines. Baidoa showed a steeper reduction between the 20-mm and 14-mm sieves (86% to 39%), suggesting a relatively coarser particle-size distribution. Beledweyne exhibited the highest proportion passing the 20-mm sieve (96%) among the Somali aggregates, indicating a relatively uniform grading. Dusamareeb and Kismayo displayed intermediate grading characteristics, while Bosaso exhibited a balanced particle-size distribution suitable for structural concrete applications. Baledogle contained the greatest proportion of finer coarse particles, with 11% passing both the 6.3-mm and 4.0-mm sieves, indicating that additional screening or blending may be required where strict grading specifications apply.

Compared with the imported Oman aggregate, most Somali aggregates exhibited similar overall grading trends, although the Oman aggregate contained a greater proportion of particles passing the 14-mm sieve

(63%), indicating a slightly more uniform intermediate-size distribution. Nevertheless, the grading curves of the majority of Somali aggregates remained consistent with the general grading characteristics expected for structural concrete applications, suggesting that locally available aggregates can provide satisfactory particle-size distributions when appropriate quality-control and screening procedures are implemented. The shaded band in Figure 4 is an indicative ASTM C33/C33M No. 57 grading reference. It is shown only as a screening aid because the laboratory sieve series does not exactly match all ASTM control sieve openings. The practical conclusion is that most local sources have an acceptable coarse aggregate grading trend, but final acceptance must be based on the exact sieve series and grading envelope specified in the project. The chart therefore supports the main purpose of sieve analysis: to verify compliance with required particle size distribution and to guide source correction, stockpile blending, or screening before concrete production.

Table 5. Gradation properties of coarse aggregates, cumulative percentage passing by sieve size.

Sieve Size (mm)	Mogadishu	Baidoa	Beledweyne	Dusamareeb	Kismayo	Bosaso	Baledogle	Oman
28.0	100	100	100	100	100	100	100	100
20.0	91.5	86.0	96.0	83.0	75.0	90.0	76.0	97.0
14.0	44.1	39.0	42.0	53.0	41.0	48.0	37.0	63.0
10.0	4.1	0.0	7.0	10.0	11.0	5.0	14.0	1.0
6.3	0.9	0.0	1.0	0.0	1.0	0.0	11.0	0.0
4.0	0.7	0.0	0.0	0.0	0.0	0.0	11.0	0.0
2.36	0.6	0.0	0.0	0.0	0.0	0.0	0	0.0

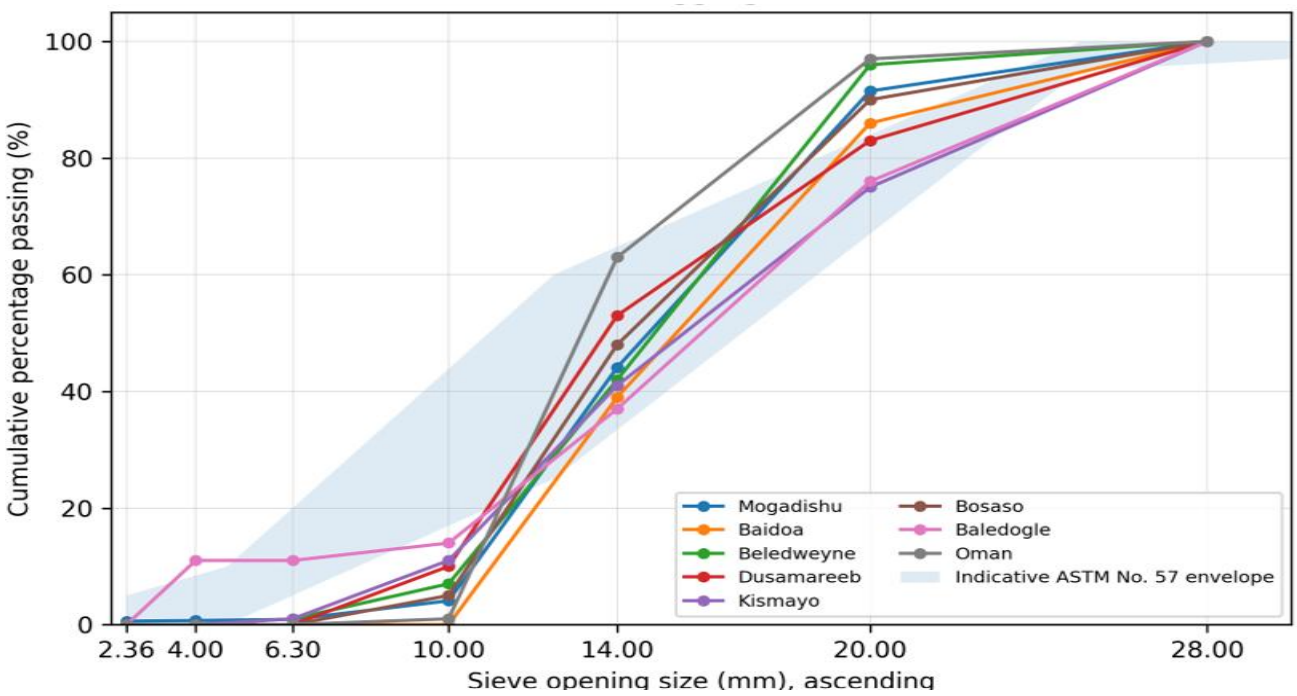


Figure 4. Gradation chart for sieve analysis of coarse aggregate from all tested Somali regions and the imported Oman benchmark. The x-axis is arranged from smaller to larger sieve openings.

3.2 Physical properties

The physical properties of the investigated coarse aggregates, including bulk specific gravity (oven-dry), bulk specific gravity (SSD), apparent specific gravity, water absorption, and bulk density, are summarized in Table 6, while Figures 5 and 6 illustrate the relationships among these properties. These parameters provide important information on aggregate density, porosity, moisture susceptibility, and packing characteristics, all of which influence concrete mix design, strength development, durability, and overall structural performance.

3.2.1 Bulk Specific Gravity

The specific gravity values varied among the investigated aggregate sources, reflecting differences in mineralogical composition and internal pore structure. Bosaso exhibited the highest bulk specific gravity (oven-dry) of 2.603, followed by Beledweyne (2.546) and Oman (2.490), indicating relatively dense aggregates with low internal porosity. Baidoa also demonstrated a comparatively high specific gravity (2.469), suggesting favourable aggregate quality for structural concrete applications.

In contrast, Mogadishu recorded the lowest bulk specific gravity (2.041), while Dusamareeb (2.329), Kismayo (2.356), and Baledogle (2.360) exhibited intermediate values. Lower specific gravity generally

reflects increased internal voids and lower particle density, which may influence concrete strength and durability if not properly considered during mix design. Overall evaluation, the bulk specific gravity results indicate that Bosaso, Beledweyne, Baidoa, and the imported Oman aggregate possess dense aggregates with relatively low internal porosity, making them well suited for structural concrete applications. In contrast, the lower specific gravity observed for Mogadishu indicates a more porous aggregate that may require greater attention during concrete mix design.

3.2.2 Water Absorption

Water absorption values exhibited considerably greater variation than specific gravity, indicating substantial differences in aggregate porosity. Mogadishu recorded the highest water absorption (**7.10%**), substantially exceeding all other investigated sources. Such high absorption indicates a highly porous aggregate requiring additional mixing water and closer control of moisture corrections during concrete production.

Conversely, Baidoa (**0.**40%) and Bosaso (0.70%) exhibited the lowest water absorption values, indicating dense aggregates with limited pore space and reduced moisture susceptibility. Beledweyne (1.50%) and the imported Oman aggregate (1.50%) demonstrated identical absorption values, whereas Dusamareeb (2.00%), Kismayo (2.30%), and Baledogle (2.40%) showed moderate absorption characteristics. The large variation in water absorption confirms that aggregate porosity differs considerably among the investigated sources and highlights the importance of moisture correction during concrete mix design. Aggregates with lower water absorption generally exhibit improved durability, lower permeability, enhanced resistance to weathering, and greater long-term dimensional stability under environmental exposure.

3.2.3 Apparent Specific Gravity

The apparent specific gravity values of the investigated aggregates ranged from **2**.386 to 2.732, reflecting variations in mineral composition and the density of the aggregate solid matrix, excluding permeable pore spaces. As shown in Table 6 and Figure 6, Bosaso exhibited the highest apparent specific gravity (2.732), followed by Beledweyne (2.645) and the imported Oman aggregate (2.602). These relatively high values indicate dense aggregate particles with low internal porosity, which are generally associated with improved mechanical strength and durability in concrete.

Among the remaining Somali aggregates, Baidoa (2.556) exhibited a relatively high apparent specific gravity, whereas Baledogle (2.518), Kismayo (2.495), and Dusamareeb (2.481) showed intermediate values. Mogadishu recorded the lowest apparent specific gravity (2.386), consistent with its comparatively high-water absorption and low bulk specific gravity, indicating a more porous aggregate structure.

The variation in apparent specific gravity among the investigated sources was smaller than that observed for water absorption, suggesting that differences in aggregate quality are influenced more by pore structure than by mineral composition alone. Engineering suitability, the apparent specific gravity results confirm that Bosaso, Beledweyne, Baidoa, and the imported Oman aggregate consist of relatively dense mineral particles suitable for high-performance structural concrete.

3.2.4 Bulk Density

Bulk density is an important engineering property because it reflects the packing characteristics of aggregate particles and influences concrete yield, void content, and cement paste demand. The measured bulk densities of the investigated aggregates ranged from 1.190 Mg/m³ to 1.608 Mg/m³, as presented in Table 6 and Figure 6.

The imported Oman aggregate exhibited the highest bulk density (1.608 Mg/m³), closely followed by Beledweyne (1.603 Mg/m³), indicating excellent particle packing and relatively low void content. Among the remaining Somali aggregates, Mogadishu (1.510 Mg/m³) and Bosaso (1.400 Mg/m³) also demonstrated comparatively high bulk densities, whereas Baidoa (1.353 Mg/m³) showed intermediate performance. Lower bulk densities were observed for Dusamareeb (1.260 Mg/m³), Baledogle (1.231 Mg/m³), and Kismayo (1.190 Mg/m³), suggesting slightly higher void ratios within the aggregate mass.

Although some variation exists among the investigated sources, all measured bulk density values fall within the range commonly reported for crushed coarse aggregates used in structural concrete. Higher bulk density generally indicates improved particle packing, reduced inter-particle voids, lower cement paste demand, and more economical concrete production. Conversely, aggregates with lower bulk density may require additional paste to achieve comparable workability and compaction.

Comparative engineering performance of the aggregates, the bulk density results indicate that Beledweyne, Bosaso, and Baidoa possess favourable packing characteristics comparable to those of the

imported Oman aggregate, whereas Kismayo, Baledogle, and Dusamareeb may require more careful optimization during concrete mix design to compensate for their relatively lower packing densities.

3.2.5 Engineering Interpretation

A comprehensive evaluation of the measured physical properties indicates that the Somali aggregates exhibit varying levels of engineering quality when compared with the imported Oman aggregate. Bosaso demonstrated the highest specific gravity together with very low water absorption, while Baidoa combined low absorption with favourable density characteristics. Beledweyne exhibited physical properties closely matching those of the Oman aggregate, suggesting its suitability for high-quality structural concrete.

In contrast, the Mogadishu aggregate exhibited significantly higher water absorption and lower specific gravity, indicating greater porosity and the potential need for stricter moisture control and mix-design adjustments. Comprehensive evaluation, the physical property demonstrates that significant variations exist among the investigated aggregate sources. Nevertheless, with appropriate material selection, moisture correction, quality-control procedures, and mix-design optimization, the majority of Somali aggregates satisfy the physical requirements for structural concrete and provide a practical alternative to imported aggregates for sustainable local construction Among the investigated Somali aggregates, Bosaso, Beledweyne, and Baidoa demonstrated the most favourable combination of density and moisture-related properties, whereas the Mogadishu aggregate would require stricter quality control and moisture adjustment during concrete production because of its relatively high porosity.

Table 6. Physical properties of coarse aggregates obtained from different regions of Somalia and the imported Oman aggregate.

Region	***Bulk SG OD***	***Bulk SG SSD***	***Apparent SG***	***Water Absorption (%)***	***Bulk Density (Mg/m³***
Mogadishu	2.041	2.186	2.386	7.10	1.510
Baidoa	2.469	2.479	2.571	0.40	1.353

Beledweyne	2.546	2.584	2.645	1.50	1.603
Dusamareeb	2.329	2.374	2.469	2.00	1.260
Kismayo	2.356	2.411	2.513	2.30	1.190
Bosaso	2.603	2.621	2.732	0.70	1.400
Baledogle	2.360	2.416	2.564	2.40	1.231
Oman	2.490	2.530	2.590	1.50	1.608

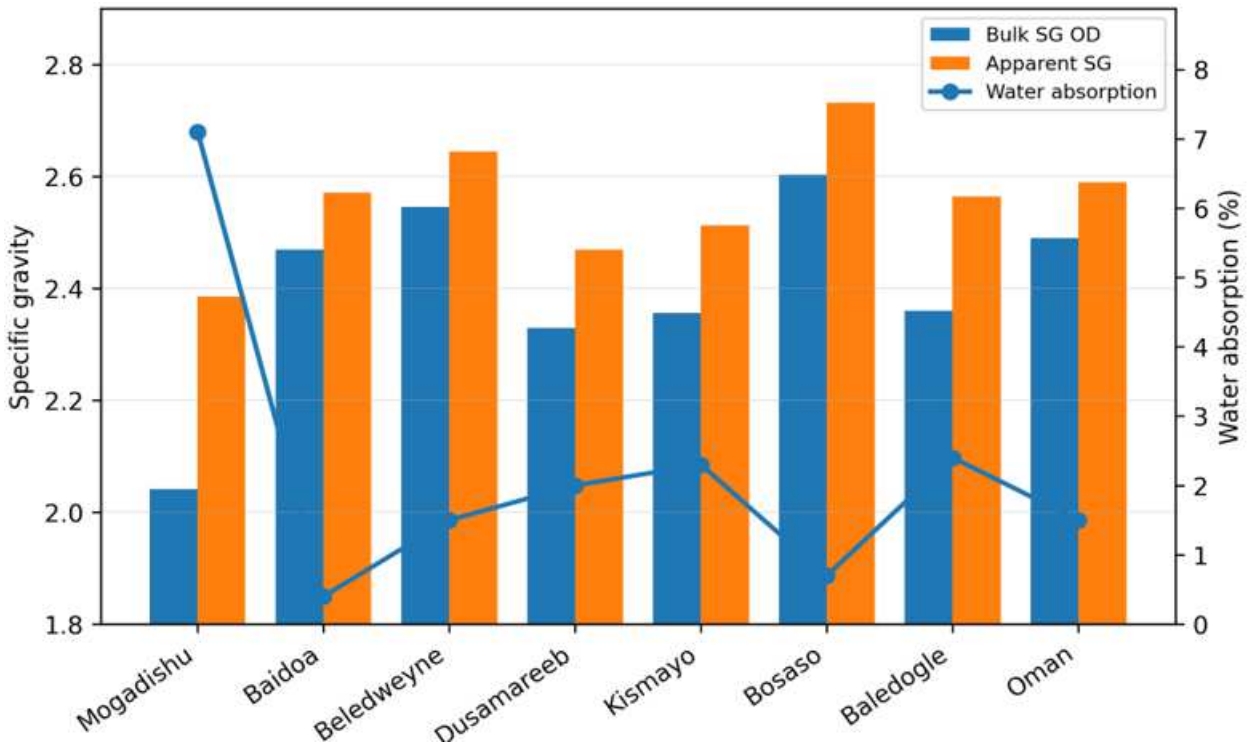


Figure 5. Specific gravity and water absorption of tested aggregate sources.

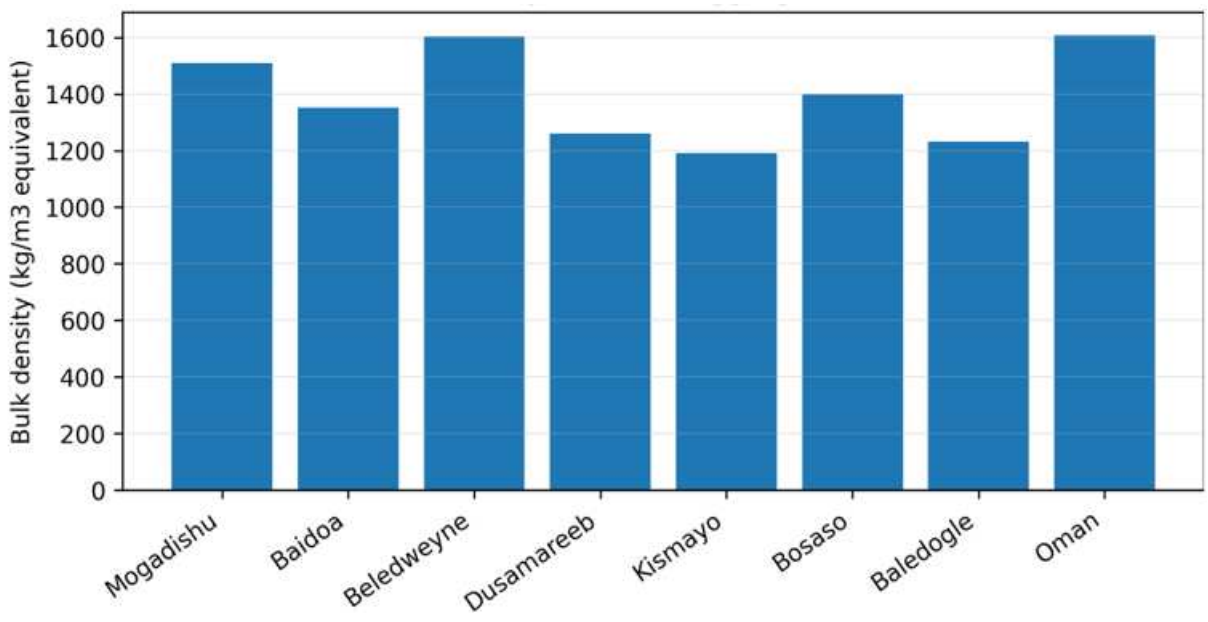


Figure 6. Bulk density of tested aggregate sources, shown as kg/m3 equivalent.

3.3 Shape and Cleanliness Properties

Particle shape and cleanliness are important aggregate characteristics that influence concrete workability, compaction, segregation resistance, particle packing, and the bond between cement paste and aggregate. Aggregates containing excessive flaky particles tend to increase void content, reduce packing efficiency, and adversely affect the mechanical performance of hardened concrete. Likewise, clay lumps and friable particles are undesirable because they may disintegrate during mixing, creating weak zones within the concrete matrix and reducing the effectiveness of the aggregate–paste interface.

3.3.1 Flakiness Index

The flakiness index values of the investigated aggregates ranged from 8.3% for the imported Oman aggregate to 12.8% for both Mogadishu and Beledweyne, as presented in Table 6 and Figure 7. Among the Somali aggregates, Bosaso exhibited the lowest flakiness index **(**9.4%**),** followed by Kismayo (10.2%), Baledogle (10.9%) and Baidoa (11.0%)**.** Dusamareeb recorded 12.1%**,** whereas Mogadishu and Beledweyne exhibited the highest values (12.8%**).** Although minor variations were observed among the aggregate sources, all flakiness index values remained relatively low, indicating that the investigated aggregates generally possess favourable particle shapes for structural concrete applications. Lower flakiness values improve aggregate packing, reduce void content, enhance concrete workability, and promote more efficient stress transfer within hardened concrete. The results therefore suggest that particle shape is unlikely to be a limiting factor for the use of these aggregates in structural concrete.

3.3.2 Clay Lumps and Friable Particles

The clay lumps and friable particles contents were generally very low, indicating good aggregate cleanliness across most sources. Bosaso, Baledogle, and the imported Oman aggregate each recorded the lowest value (0.1%), followed by Baidoa (0.2%), while Beledweyne and Dusamareeb each recorded 0.3%. Kismayo exhibited a slightly higher value (0.8%), although this remains relatively low for structural concrete applications.

In contrast, Mogadishu recorded the highest clay lumps and friable particles content (2.0%), indicating the presence of a greater quantity of weak or weathered particles. Although this value remains acceptable for many structural concrete applications, it indicates the need for closer quality control and, where necessary, washing or additional processing before use in durability-sensitive structures. Overall conclusion, the cleanliness results demonstrate that the majority of the investigated Somali aggregates exhibit levels comparable to those of the imported Oman aggregate, confirming that contamination by clay lumps and friable particles is generally low and unlikely to adversely affect concrete performance when appropriate material quality control is maintained.

3.3.3 Engineering Interpretation

The combined evaluation of particle shape and cleanliness indicates that the investigated aggregates are generally suitable for structural concrete production. Bosaso, Baidoa, Beledweyne, and Baledogle exhibited the most satisfactory combination of low flakiness and excellent cleanliness, closely matching the performance of the imported Oman aggregate. Dusamareeb and Kismayo also demonstrated satisfactory engineering characteristics despite slightly higher flakiness or clay lump contents. Although the Mogadishu aggregate recorded the highest flakiness index and clay lumps content, these characteristics can be effectively managed through improved aggregate processing, washing, and routine quality-control procedures. Overall, the results indicate that particle shape and cleanliness are unlikely to impose significant limitations on the use of the investigated Somali aggregates for structural concrete, provided that appropriate quality-control measures are maintained during aggregate production. These findings demonstrate that the investigated Somali aggregates generally satisfy the particle shape and cleanliness requirements for structural concrete and are comparable to the imported Oman aggregate in terms of these quality indicators.

Table 6. Shape and cleanliness properties of coarse aggregates.

Region	*Flakiness Index (%)*	*Clay Lumps & Friable Particles (%)*
Mogadishu	12.8	2
Baidoa	11.0	0.2
Beledweyne	12.8	0.3
Dusamareeb	12.1	0.3
Kismayo	10.2	0.8
Bosaso	9.4	0.1
Baledogle	10.9	0.1
Oman	8.3	0.1

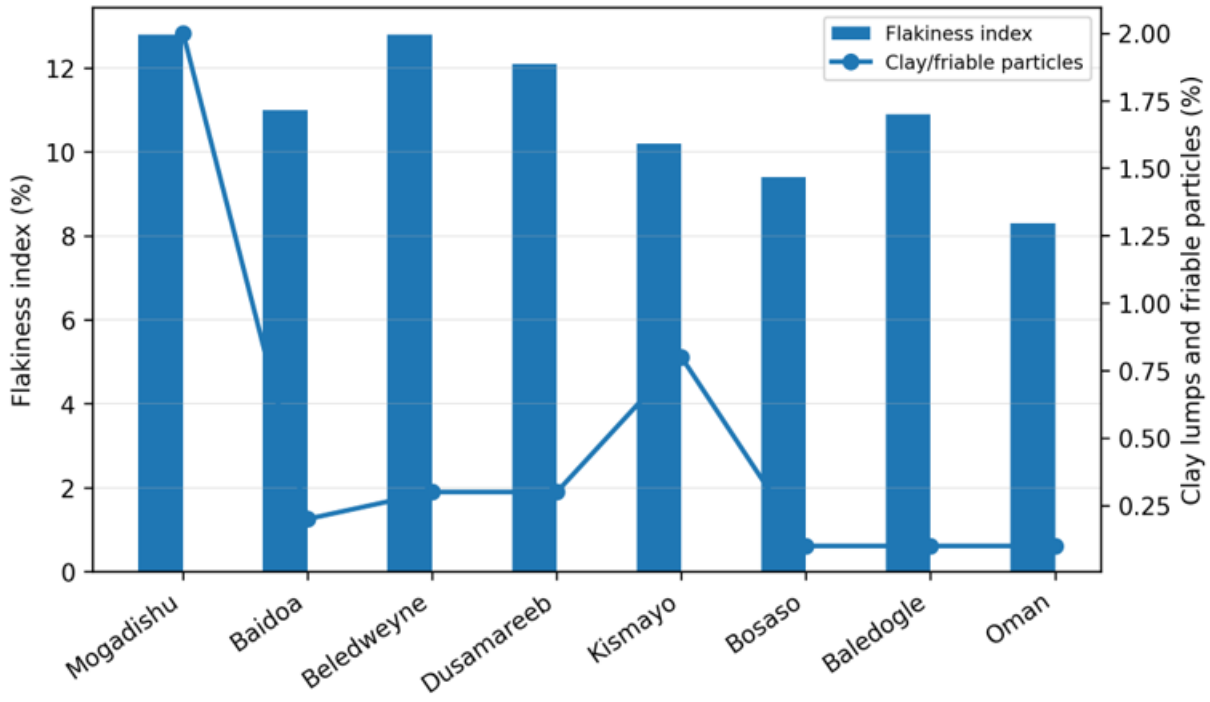


Figure 7. Flakiness index and clay lumps with friable particles for tested aggregate sources.

3.4 Mechanical Resistance Properties

The mechanical resistance of coarse aggregates is a critical factor in determining their suitability for structural concrete. Aggregate particles must resist crushing, impact, and abrasion during handling, mixing, compaction, and throughout the service life of concrete structures. The Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), and Los Angeles Abrasion (LAA) tests collectively evaluate aggregate strength, toughness, and resistance to mechanical wear under service conditions. The

results are presented in Table 7, while Figures 8 and 9 illustrate the mechanical performance and the relationship between water absorption and abrasion resistance.

3.4.1 Aggregate Crushing Value (ACV)

The ACV results indicate clear differences in crushing resistance among the investigated aggregate sources. The imported Oman aggregate exhibited the lowest ACV (10.4%), confirming its superior resistance to compressive crushing. Among the Somali aggregates, Baidoa and Baledogle recorded the lowest ACV values (22%), followed by Bosaso and Dusamareeb (23%), Beledweyne (25%), and Kismayo (26%). In contrast, Mogadishu recorded the highest ACV (40%), indicating comparatively lower resistance to crushing.

Despite these variations, all Somali aggregates except Mogadishu exhibited ACV values well below 30%**,** indicating good crushing resistance suitable for structural concrete. The comparatively higher ACV of the Mogadishu aggregate indicates lower resistance to compressive loading and suggests that it may be less suitable for heavily loaded or high-strength concrete unless appropriate quality-control measures are implemented.

3.4.2 Aggregate Impact Value (AIV)

The AIV results followed a trend similar to that observed for ACV, indicating consistency in aggregate toughness. The imported Oman aggregate recorded the lowest AIV (5%), confirming its superior resistance to sudden impact loading. Among the Somali aggregates, Baidoa**,** Dusamareeb**,** Bosaso, and Baledogle each recorded 9%, while Beledweyne and Kismayo recorded 10%**.** Mogadishu again exhibited the highest AIV (19%).

These relatively low AIV values demonstrate that most Somali aggregates possess satisfactory toughness and are capable of resisting impact during aggregate handling, transportation, and concrete production. The higher value observed for the Mogadishu aggregate is consistent with its lower specific gravity and higher water absorption, suggesting that greater porosity contributes to reduced impact resistance.

3.4.3 Los Angeles Abrasion Resistance

Los Angeles abrasion is widely regarded as one of the most important indicators of aggregate durability because it evaluates resistance to both abrasion and impact under repeated loading conditions. The

imported Oman aggregate exhibited the lowest abrasion loss (11.3%), demonstrating excellent resistance to mechanical degradation.

Among the Somali aggregates, Bosaso and Baledogle exhibited the lowest abrasion losses **(**21%**),** followed by Baidoa (23%)**,** Dusamareeb (24%)**,** Kismayo (24%)**,** and Beledweyne (26%)**.** Mogadishu recorded the highest abrasion loss (41.3%), indicating comparatively lower resistance to mechanical wear.

Although the abrasion loss of the Mogadishu aggregate remains below the commonly accepted maximum limit of 50% for concrete aggregates, its considerably higher value relative to the other investigated sources indicates reduced resistance to long-term mechanical wear. Consequently, its use in heavily trafficked pavements, industrial floors, or other applications subjected to severe abrasion should be carefully evaluated.

3.4.4 Engineering Interpretation

The combined evaluation of ACV, AIV, and LAA provides a comprehensive assessment of the mechanical performance of the investigated aggregates. Among the Somali aggregates, Baidoa**,** Bosaso**,** Baledogle**,** and Dusamareeb exhibited the most favourable combination of crushing resistance, impact resistance, and abrasion durability, indicating their suitability for structural concrete applications. Beledweyne also demonstrated satisfactory mechanical performance, with only slightly higher crushing and abrasion values.

In contrast, the Mogadishu aggregate consistently recorded the highest ACV, AIV, and LAA values, confirming that it is mechanically weaker than the other investigated aggregates. This behaviour is consistent with its higher water absorption and lower specific gravity discussed in Section **3.2**, indicating that increased porosity adversely influences its mechanical performance.

In engineering assessment, the mechanical resistance results indicate that the majority of the investigated Somali aggregates possess adequate strength and durability for structural concrete and compare favourably with internationally accepted engineering requirements. While the imported Oman aggregate demonstrated superior mechanical characteristics, several locally available aggregates provide comparable performance for most structural applications when appropriate quality-control procedures are maintained. These findings are consistent with the physical property evaluation presented in Section

3.2, confirming that aggregates with lower water absorption and higher specific gravity generally exhibited superior mechanical resistance. These findings are consistent with the physical property evaluation presented in Section 3.2, confirming that aggregates with lower water absorption and higher specific gravity generally exhibited superior mechanical resistance. Engineering suitability, the results demonstrate that several locally available Somali aggregates provide mechanical properties suitable for structural concrete and represent viable alternatives to imported aggregates when appropriate quality-control measures are maintained.

Table 7. Mechanical properties of coarse aggregates from different regions and the Oman benchmark.

Region	ACV (%)	AIV (%)	LAA Abrasion (%)
Mogadishu	40.0	19	41.3
Baidoa	22.0	9	23.0
Beledweyne	25.0	10	26.0
Dusamareeb	23.0	9	24.0
Kismayo	26.0	10	24.0
Bosaso	23.0	9	21.0
Baledogle	22.0	9	21.0
Oman	10.4	5	11.3

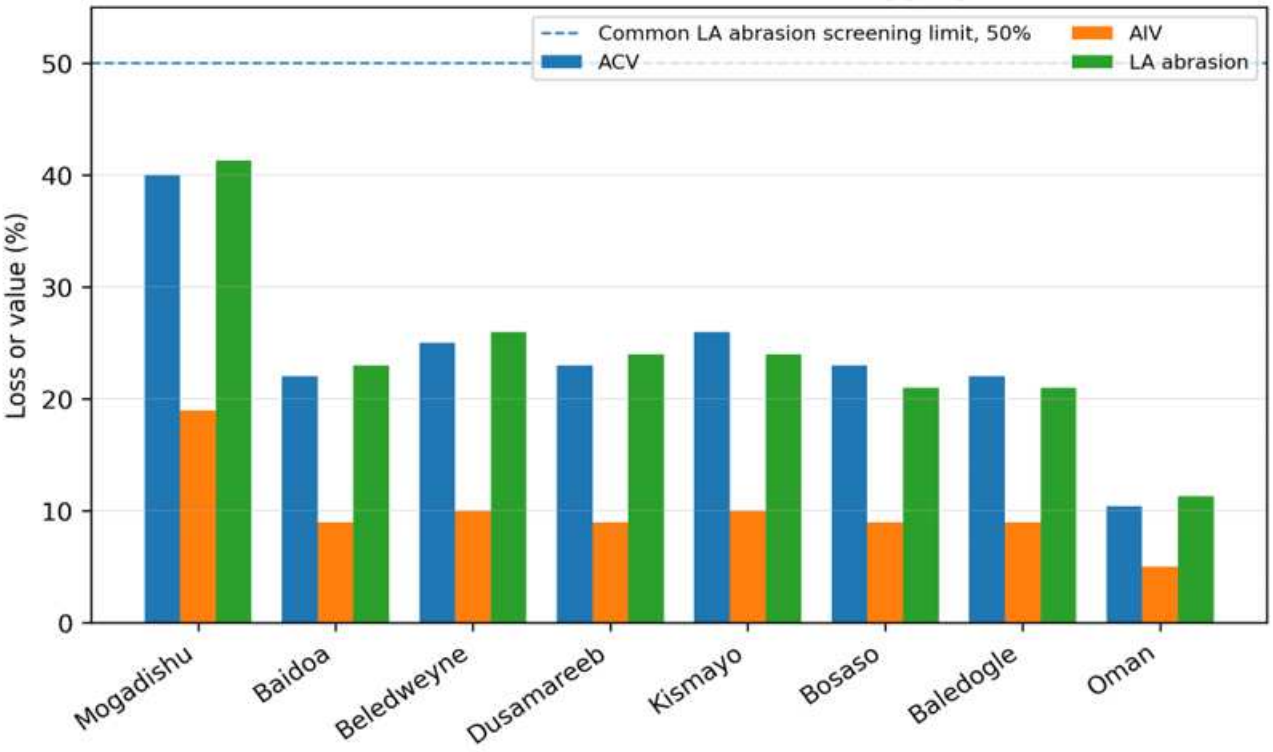


Figure 8. Mechanical resistance indicators of tested aggregate sources.

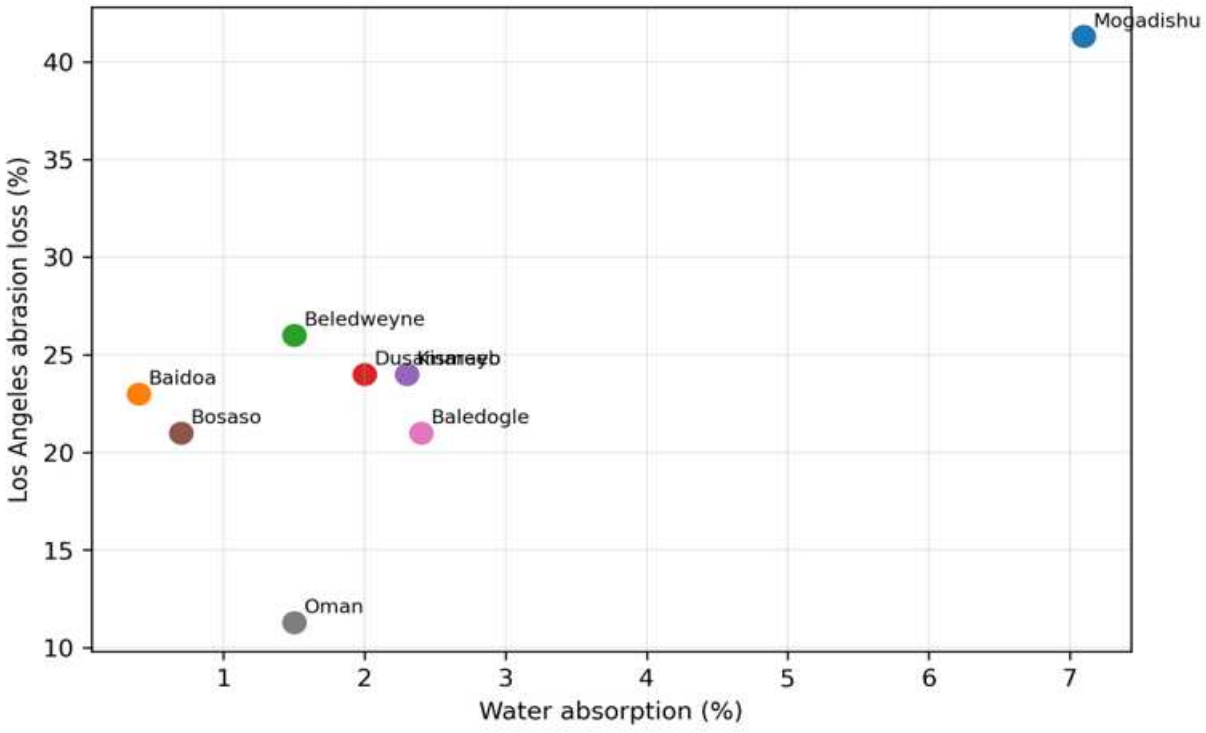


Figure 9. Relationship between water absorption and Los Angeles abrasion loss.

3.5 Durability and Sodium Sulfate Soundness

The durability of coarse aggregates is an important consideration for ensuring the long-term performance of concrete structures exposed to weathering and aggressive environmental conditions. Sodium sulfate soundness testing evaluates the resistance of aggregates to deterioration caused by repeated salt crystallization, which simulates the effects of natural weathering. The results are presented in table 8**,** while Figure 10 illustrates the sodium sulfate soundness losses of the investigated aggregate sources.

3.5.1 Sodium Sulfate Soundness Results

The sodium sulfate soundness results indicate excellent durability performance for all investigated aggregate sources. The imported Oman aggregate recorded a soundness loss of 0.80%, demonstrating excellent resistance to salt-induced weathering and serving as the benchmark for comparison. Among the Somali aggregates, Baledogle exhibited the lowest soundness loss (0.53%**),** indicating the highest resistance to sulfate crystallization among the local sources. Kismayo also demonstrated excellent durability with a soundness loss of 0.90%**,** followed by Baidoa (1.00%)**,** Dusamareeb (1.10%)**,** Bosaso (1.10%)**,** and Beledweyne (1.20%)**.** These values are all very low and indicate excellent resistance to weathering-related deterioration.

Mogadishu recorded the highest sodium sulfate soundness loss (4.70%). Although this value is considerably higher than those of the other investigated aggregates, it remains well below the maximum sodium sulfate soundness loss of 12% commonly specified in ASTM C33/C33M for coarse aggregates. Therefore, even the Mogadishu aggregate demonstrates acceptable resistance to sulfate-induced deterioration under normal service condition.

Engineering**,** performance-based**,** the results indicate that all investigated Somali aggregates possess satisfactory resistance to salt crystallization and are unlikely to experience significant deterioration due to sulfate weathering. The relatively small variation in soundness losses among most of the aggregate sources further suggests that weathering resistance is generally good regardless of geographical origin.

Table 8. Durability property of coarse aggregates, sodium sulfate soundness loss.

Region	*Sodium Sulfate Soundness Loss (%)*
Mogadishu	4.7
Baidoa	1
Beledweyne	1.2
Dusamareeb	1.1
Kismayo	0.9
Bosaso	1.1
Baledogle	0.53
Oman	0.8

5.2 Engineering Interpretation

The combined evaluation of durability, physical properties, and mechanical resistance demonstrates that aggregate suitability cannot be assessed using a single laboratory test. Although all investigated aggregates satisfied the sodium sulfate soundness criterion, differences in water absorption, specific gravity, crushing resistance, impact resistance, and Los Angeles abrasion resulted in noticeable variations in overall engineering performance. The comparatively higher soundness loss observed for the Mogadishu aggregate indicates slightly lower durability than the other investigated sources. However, its overall engineering limitations are primarily associated with its higher water absorption, lower specific gravity, and reduced mechanical resistance, as discussed in Sections 3.2 and 3.4, rather than sulfate soundness alone.

In contrast, Baledogle**,** Baidoa**,** Bosaso**,** Dusamareeb**,** Kismayo, and Beledweyne exhibited low soundness losses together with satisfactory physical and mechanical properties, indicating that these aggregates possess balanced engineering characteristics suitable for structural concrete applications. The imported Oman aggregate exhibited the best durability performance and remains an appropriate benchmark; however, several Somali aggregate sources demonstrated comparable durability characteristics. Consequently, aggregate selection for structural concrete should be based on a comprehensive evaluation that includes particle grading, physical properties, cleanliness, mechanical resistance, soundness, and concrete trial-mix performance. Such an integrated approach provides a more

reliable basis for ensuring long-term durability and structural performance than reliance on any single laboratory test.

In general, the sodium sulfate soundness results demonstrate that the investigated Somali aggregates exhibit durability characteristics comparable to the imported Oman aggregate, confirming that resistance to sulfate-induced weathering is generally adequate and is unlikely to be the primary factor governing their suitability for structural concrete applications.

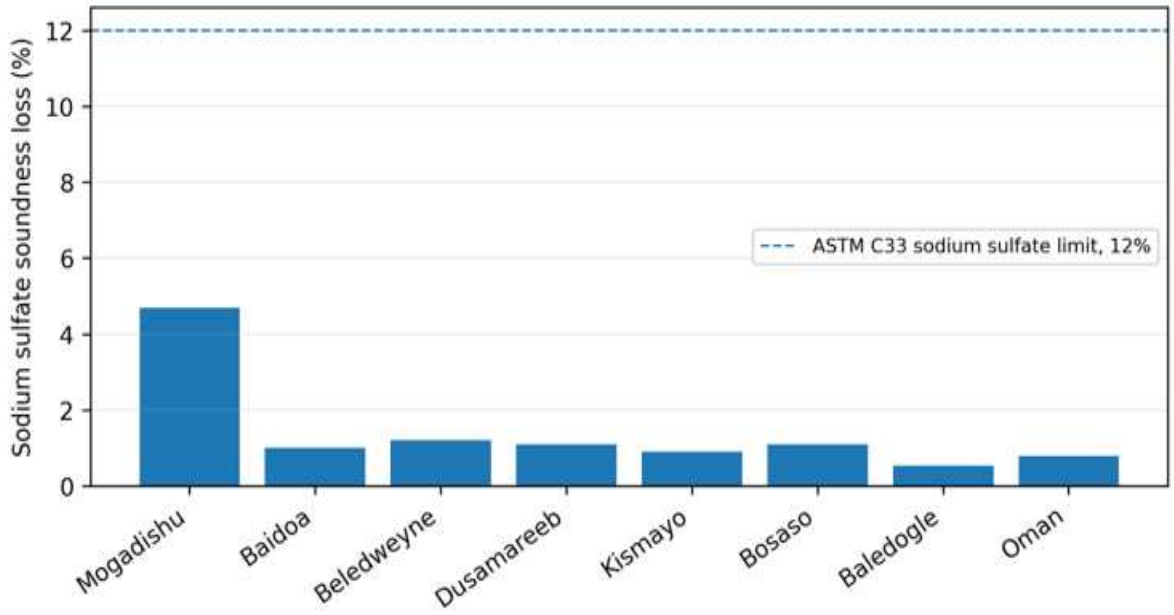


Figure 10. Sodium sulfate soundness loss of tested aggregate sources.

3.5.1. Engineering Interpretation

The combined evaluation of durability, physical properties, and mechanical resistance demonstrates that aggregate suitability cannot be assessed using a single laboratory test. Although all investigated aggregates satisfied the sodium sulfate soundness criterion, differences in water absorption, specific gravity, crushing resistance, impact resistance, and abrasion loss resulted in noticeable variations in overall engineering performance. Consequently, aggregate selection for structural concrete should be based on a comprehensive assessment that includes particle grading, physical properties, cleanliness, mechanical resistance, soundness, and concrete trial-mix performance. Such an integrated evaluation provides a more reliable basis for ensuring long-term durability and structural performance under field conditions. Overall, the sodium sulfate soundness results demonstrate that the investigated Somali aggregates exhibit durability characteristics comparable to the imported Oman aggregate, indicating that

weathering resistance is not expected to be the primary limiting factor governing their use in structural concrete.

3.6 Statistical Analysis of Aggregate Engineering Properties

Statistical analysis was performed to evaluate the variability and relationships among the engineering properties of the investigated coarse aggregates collected from seven regions of Somalia and the imported Oman aggregate. Descriptive statistical parameters, including the mean, standard deviation (SD), minimum value, maximum value, and coefficient of variation (CV), were calculated for all measured engineering properties. In addition, Pearson correlation and simple linear regression analyses were conducted to investigate the relationships among selected physical, mechanical, and durability properties.

3.6.1 Descriptive Statistical Analysis

The descriptive statistical results are presented in Table 9**.** The analysis indicates that the physical properties of the investigated aggregates generally exhibited relatively low variability. Bulk specific gravity (oven-dry) ranged from 2.041 to 2.603, with a mean value of 2.399 and a coefficient of variation of 7.27%**.** Similarly, bulk specific gravity in the saturated surface-dry (SSD) condition exhibited a mean value of 2.450 and a coefficient of variation of 5.62%**,** while apparent specific gravity showed the lowest variability with a coefficient of variation of only 4.14%**.** These results indicate that aggregate density was relatively consistent among the investigated sources. Bulk density also demonstrated relatively low variability, with a mean value of 1.394 Mg/m^3 and a coefficient of variation of 11.84%**,** suggesting comparable packing characteristics among most aggregate sources.

In contrast, water absorption exhibited substantially greater variability. Water absorption values ranged from 0.40% to 7.10%**,** with a mean value of 2.24%, a standard deviation of 2.09%, and a coefficient of variation of 93.38%**.** The high coefficient of variation was largely influenced by the comparatively high water absorption of the Mogadishu aggregate, whereas the remaining aggregate sources exhibited relatively low and comparable values. Similarly, clay lumps and friable particles exhibited the highest variability among all measured properties, with a coefficient of variation of 134.04%, indicating significant differences in aggregate cleanliness. Such variability reflects differences in production methods, source geology, and aggregate processing.

Table 9. Descriptive statistics of the investigated aggregate engineering properties

Engineering Property	*Mean*	*Standard Deviation*	*Minimum*	*Maximum*	*Coefficient of Variation (%)*
Bulk SG (Oven Dry)	2.399	0.174	2.041	2.603	7.27
Bulk SG (SSD)	2.450	0.138	2.186	2.621	5.62
Apparent Specific Gravity	2.559	0.106	2.386	2.732	4.14
Water Absorption (%)	2.238	2.089	0.400	7.100	93.38
Bulk Density (Mg/m³)	1.394	0.165	1.190	1.608	11.84
Flakiness Index (%)	10.938	1.611	8.300	12.800	14.73
Clay Lumps & Friable Particles (%)	0.488	0.653	0.100	2.000	134.04
Aggregate Crushing Value (%)	23.925	8.070	10.400	40.000	33.73
Aggregate Impact Value (%)	10.000	3.964	5.000	19.000	39.64
Los Angeles Abrasion (%)	23.950	8.311	11.300	41.300	34.70
Sodium Sulphate Soundness Loss (%)	1.385	1.352	0.530	4.700	97.63

The mechanical properties also exhibited moderate variability. Aggregate Crushing Value (ACV) ranged from 10.4% to 40.0%**,** with a mean value of 23.93% and a coefficient of variation of 33.73%**.** Aggregate Impact Value (AIV) varied between 5% and 19%**,** with a coefficient of variation of 39.64%**,** while Los Angeles Abrasion values ranged from 11.3% to 41.3%**,** with a coefficient of variation of 34.70%**.** These results indicate noticeable differences in aggregate resistance to crushing, impact, and abrasion depending on geological origin.

Although the coefficient of variation was relatively high (97.63%), this was primarily influenced by the comparatively higher soundness loss of the Mogadishu aggregate, while the remaining aggregate sources exhibited consistently low soundness losses. Overall, the descriptive statistical analysis demonstrates that although aggregate density remains relatively consistent among the investigated sources, aggregate porosity, cleanliness, mechanical resistance, and durability vary considerably. These findings emphasize

the importance of laboratory characterization before selecting coarse aggregates for structural concrete applications.

3.6.2 Pearson Correlation Analysis

Pearson correlation analysis was performed to investigate the relationships among selected engineering properties of the investigated aggregates. The correlation matrix is presented in Table 10**.**

Table 10. Pearson correlation matrix for selected aggregate engineering properties

Variable 1	***Variable 2***	***Pearson Correlation (r)***	***Relationship***
Water Absorption	Bulk SG (Oven Dry)	**−0.922**	Strong negative
Water Absorption	Aggregate Impact Value	**0.957**	Strong positive
Water Absorption	Los Angeles Abrasion	**0.929**	Strong positive
Water Absorption	Sodium Sulphate Soundness Loss	**0.906**	Strong positive
Clay Lumps & Friable Particles	Sodium Sulphate Soundness Loss	**0.934**	Strong positive

The analysis revealed a strong negative correlation between water absorption and bulk specific gravity (r = −0.922**),** indicating that aggregates with higher density generally exhibit lower water absorption due to reduced internal pore space. This inverse relationship is physically reasonable because denser aggregates generally contain fewer interconnected pores available for water absorption. Water absorption also exhibited strong positive correlations with Aggregate Impact Value (r = 0.957) and Los Angeles Abrasion value (r = 0.929). These results indicate that aggregates with higher porosity generally possess lower resistance to impact loading and abrasion. Consequently, increased water absorption is associated with reduced aggregate strength and mechanical durability.

A strong positive relationship was also observed between water absorption and Sodium Sulphate Soundness loss (r = 0.906), suggesting that aggregates with higher water absorption are generally more susceptible to weathering deterioration. Furthermore, clay lumps and friable particles demonstrated a strong positive correlation with Sodium Sulphate Soundness loss (r = 0.934), indicating that aggregate cleanliness was strongly associated with long-term durability performance. Overall, the correlation analysis confirms that density, porosity, strength, and durability are closely interrelated engineering characteristics governing aggregate performance in structural concrete.

3.6.3 Linear Regression Analysis

Simple linear regression analysis was performed to quantify the relationships between selected engineering properties of the investigated coarse aggregates. The resulting regression models are presented in Figures 11–15**,** together with their corresponding regression equations and coefficients of determination (R^2). Figure 11 illustrates the relationship between water absorption and bulk specific gravity (oven-dry). The fitted regression equation, Bulk SG = −0.077(WA) + 2.571 (R^2 = 0.850), indicates that aggregates with higher water absorption generally possess lower specific gravity. Approximately 85% of the variation in bulk specific gravity is explained by differences in water absorption, confirming the strong influence of aggregate porosity on density.

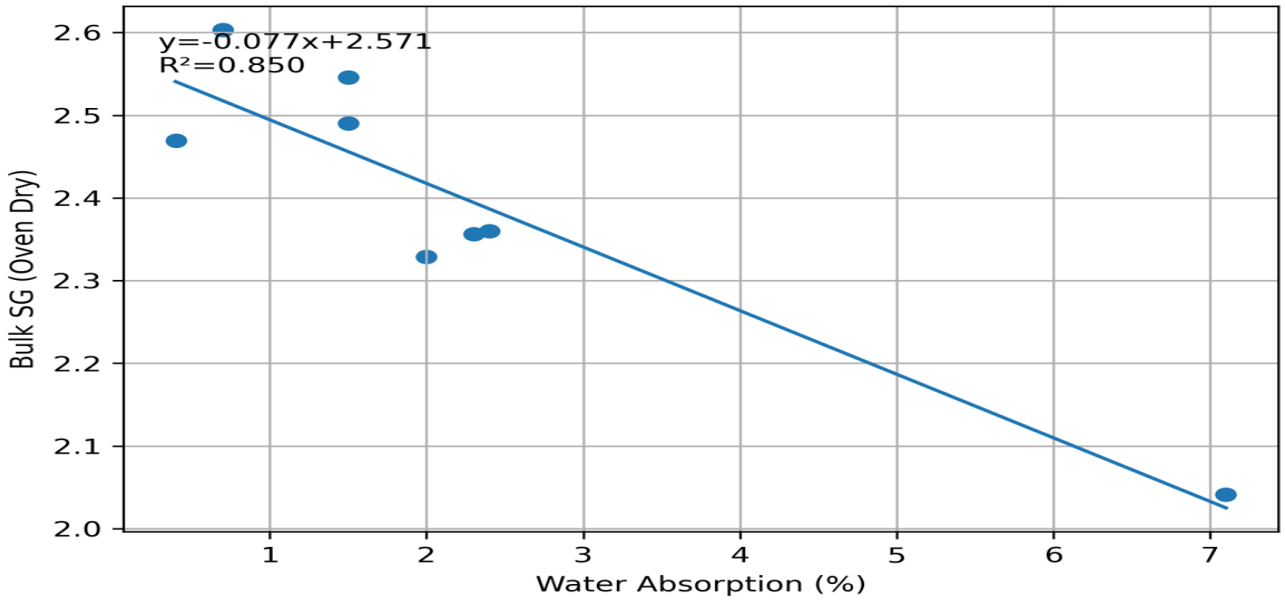


Figure 11. Linear regression relationship between water absorption and bulk specific gravity (oven-dry).

Figure 12 presents the relationship between water absorption and Los Angeles Abrasion (LAA). The regression analysis produced a positive correlation (R^2 = 0.650), demonstrating that aggregates with higher water absorption generally experience greater abrasion losses. This behavior suggests that porous aggregates are more susceptible to mechanical wear and degradation during service. The fitted regression equation LAA = 3.206(WA) + 16.776 indicates that Los Angeles Abrasion increases as water absorption increases, confirming that porous aggregates are generally more susceptible to abrasion damage. Although the correlation is moderate (R^2 = 0.650), the regression demonstrates that water absorption can be used as a practical indicator of abrasion resistance during aggregate quality assessment.

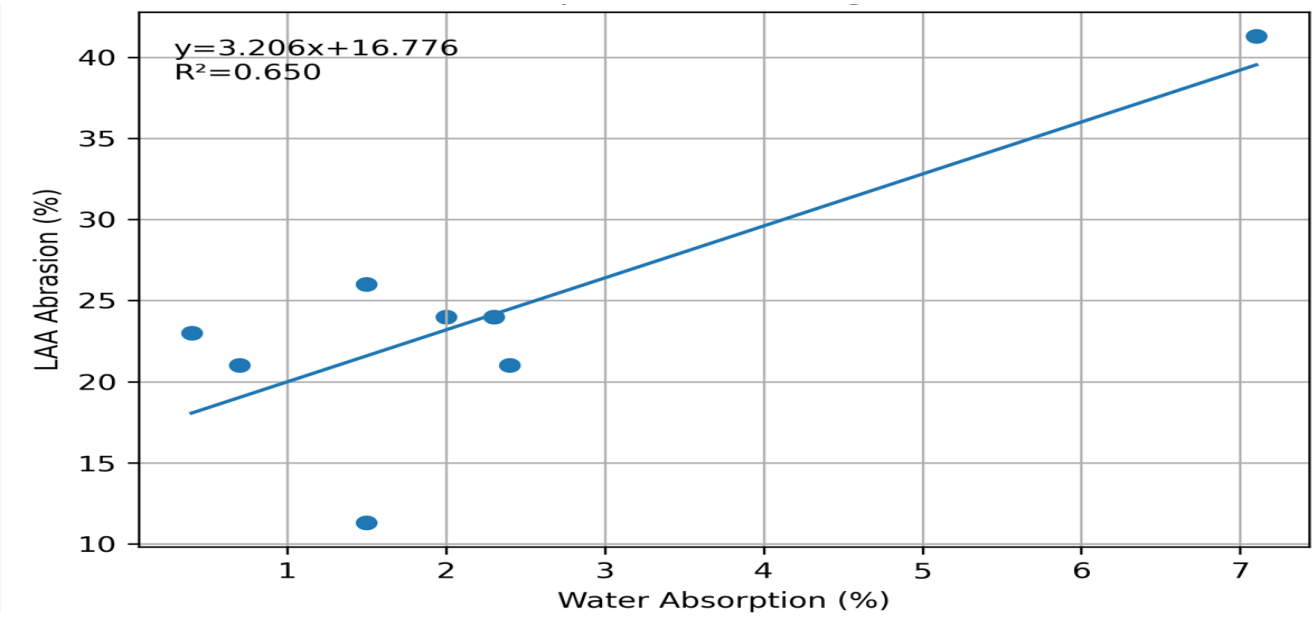


Figure 12. Linear regression relationship between water absorption and Los Angeles Abrasion.

The relationship between Aggregate Crushing Value (ACV) and Aggregate Impact Value (AIV) is shown in Figure 13**.** An excellent linear relationship was obtained (R^2 = 0.948), confirming that aggregates exhibiting higher resistance to crushing also demonstrate greater resistance to impact loading. The excellent agreement between these two independent mechanical indices confirms the consistency and reliability of the laboratory measurements. The regression equation AIV = 0.478(ACV) − 1.440 demonstrates the strong linear relationship between the two mechanical strength indices.

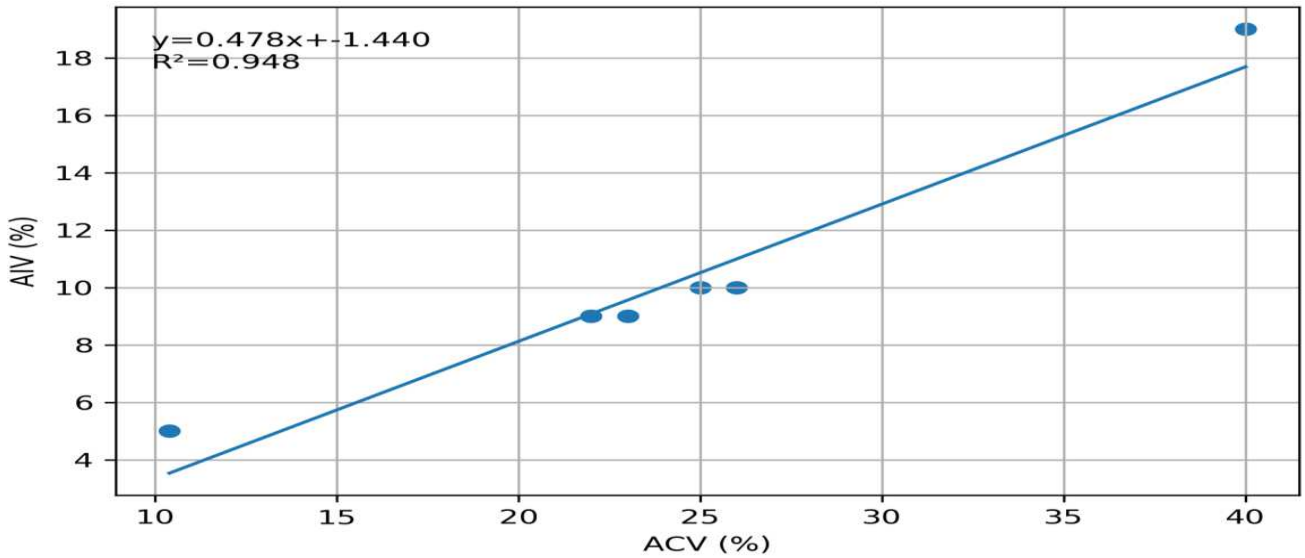


Figure 13. Linear regression relationship between Aggregate Crushing Value and Aggregate Impact Value.

Figure 14 illustrates the relationship between Aggregate Crushing Value and Los Angeles Abrasion. The regression analysis produced an exceptionally strong positive relationship ($R^2 = 0.970$), indicating that aggregates with higher crushing values also exhibit greater abrasion losses. This finding confirms that both tests evaluate similar aspects of aggregate mechanical performance and collectively provide reliable indicators of aggregate quality. The fitted equation LAA = 1.014(ACV) + 0.320 confirms that aggregates exhibiting higher crushing values also experience greater abrasion losses. The very high coefficient of determination demonstrates that Aggregate Crushing Value is an excellent predictor of Los Angeles Abrasion performance.

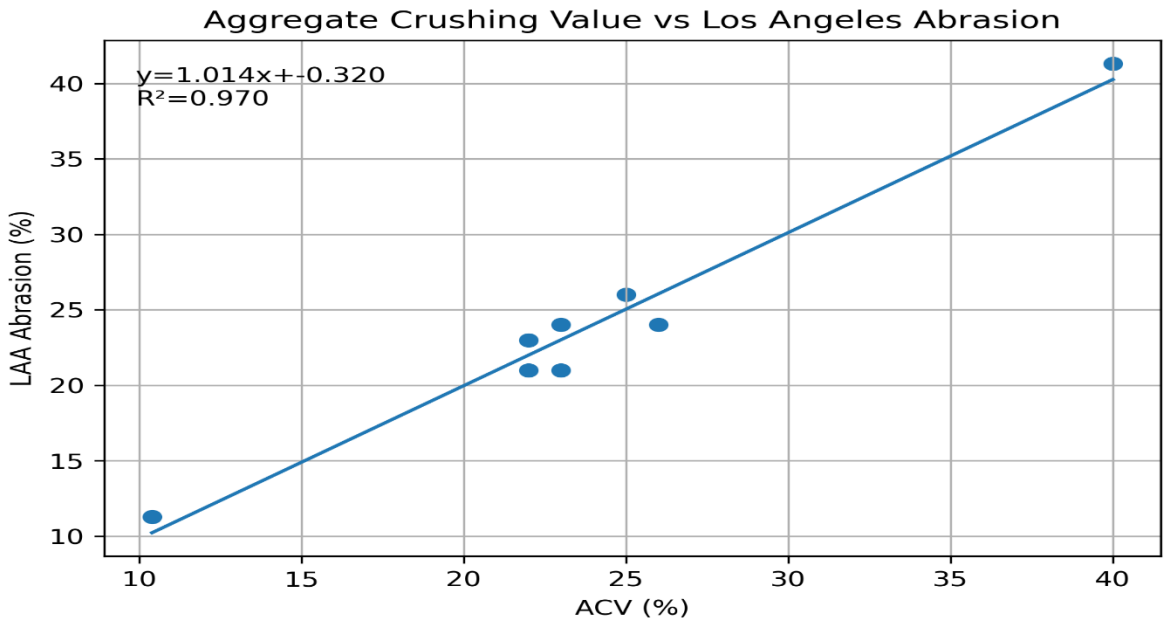


Figure 14. Linear regression relationship between Aggregate Crushing Value and Los Angeles Abrasion.

The relationship between water absorption and Sodium Sulphate Soundness Loss are depicted in Figure 15. A strong positive relationship ($R^2 = 0.821$) was observed, indicating that aggregates with higher water absorption generally experience greater soundness losses during repeated sodium sulphate cycles. This relationship confirms that water absorption is a useful indicator of aggregate durability because increased porosity facilitates salt penetration and accelerates weathering deterioration. This finding highlights the importance of controlling aggregate porosity when selecting materials for durable concrete structures exposed to aggressive environmental conditions.

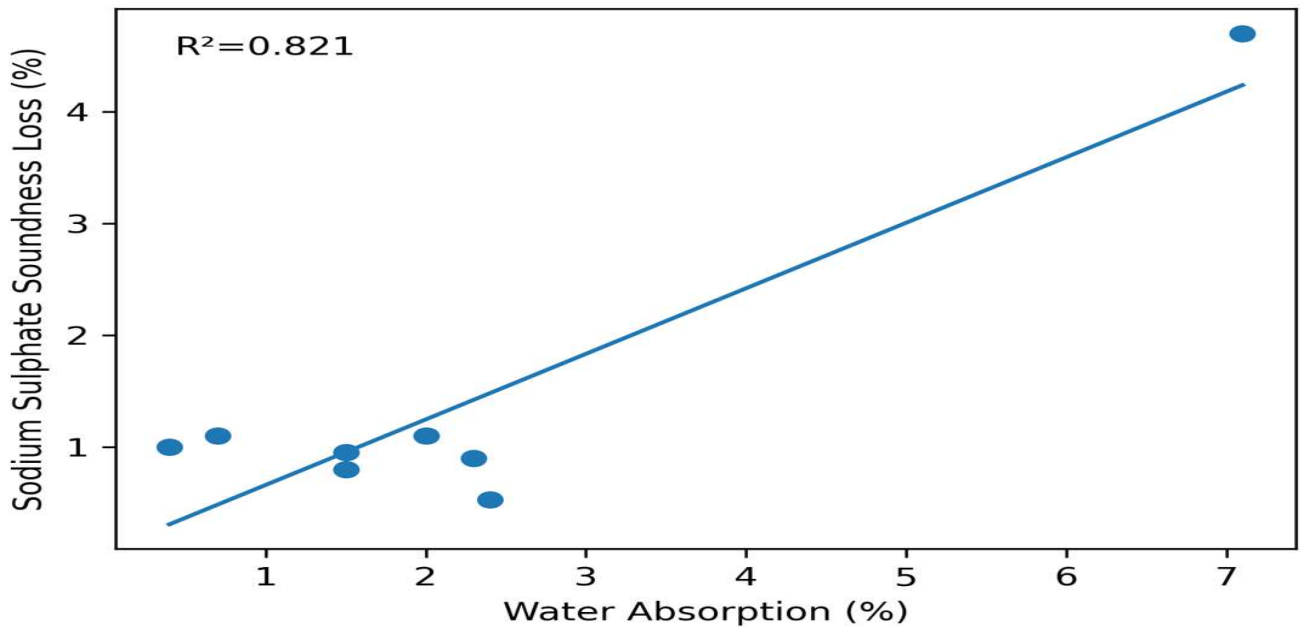


Figure 15. Linear regression relationship between water absorption and Sodium Sulphate Soundness Loss.

3.6.4 Engineering Interpretation

Overall, the regression analyses demonstrate that water absorption is an effective predictor of aggregate mechanical strength and durability. Aggregates with lower water absorption generally exhibited lower Los Angeles Abrasion values, lower Aggregate Impact Values, and improved soundness performance. Similarly, the inverse relationship between water absorption and bulk specific gravity confirms that denser aggregates tend to possess lower porosity and superior engineering performance. The high coefficients of determination obtained for several regression models indicate that a substantial proportion of the variation in aggregate strength and durability can be explained by changes in physical properties, particularly water absorption and specific gravity. These regression models therefore provide practical engineering tools for aggregate quality assessment, material selection, and quality control in structural concrete applications. Furthermore, the statistical analyses demonstrate that several locally available Somali coarse aggregates exhibit engineering properties comparable to those of the imported Oman aggregate, whereas others require careful evaluation before being considered for structural concrete production. Overall, the statistical analyses provide quantitative evidence supporting the engineering suitability of several Somali coarse aggregates for structural concrete applications. The strong correlations and regression relationships demonstrate that water absorption is a practical quality-control indicator because of its close association with aggregate density, mechanical resistance, and durability. Consequently, water absorption may be used as a rapid and reliable parameter for preliminary aggregate

evaluation and material selection in Somalia, although comprehensive laboratory testing remains essential for final acceptance.

3.7 Comparison with Previous Studies and Engineering Standards

The engineering properties obtained in the present study were evaluated in relation to internationally recognized ASTM and British Standard test procedures as well as previously published investigations conducted in Somalia and other countries. It should be noted that most ASTM and British Standards referenced in this study primarily prescribe standardized laboratory test methods rather than universal acceptance limits. Consequently, the measured values were interpreted in accordance with commonly adopted engineering practice and project-specific requirements rather than being classified using absolute pass-or-fail criteria. The comparison presented herein therefore focuses on the consistency of the measured engineering properties with values reported in the literature and their implications for structural concrete applications.

The specific gravity values determined for the investigated aggregates were generally comparable with those reported by Barzangi et al. (2014), Telloli et al. (2021), Bayari et al. (2025), and Hosen et al. (2024), indicating that the Somali aggregates possess density characteristics consistent with natural coarse aggregates commonly used for structural concrete. Similarly, the measured water absorption values fell within the range reported in previous investigations, although some regional variations were observed. Aggregates from Baidoa and Bosaso exhibited relatively lower water absorption, indicating lower porosity and potentially improved durability, whereas the Mogadishu aggregate recorded comparatively higher absorption. Nevertheless, the measured values remained consistent with those reported for natural aggregates in comparable geological environments and can be accommodated during concrete mix design through appropriate moisture correction procedures.

The grading characteristics obtained from sieve analysis demonstrated that the investigated aggregates generally complied with the specified grading envelopes for coarse aggregates. Well-graded particle-size distributions contribute to improved particle packing, reduced void content, and lower cement paste demand, thereby enhancing both the workability and mechanical performance of concrete. Similar observations have been reported by Islam et al. (2020), Mohammed et al. (2023), and Bayari et al. (2025), who concluded that proper gradation plays a fundamental role in achieving high-quality structural concrete irrespective of aggregate origin.

Particle shape and cleanliness also exhibited good agreement with previous investigations. The measured flakiness index values were generally comparable with those reported by Çelik et al. (2021) and Islam et al. (2020), indicating that the investigated aggregates contain acceptable proportions of flaky particles for concrete production. Likewise, the clay lump contents were relatively low across all investigated sources, suggesting that deleterious materials are unlikely to adversely affect the bond between aggregate particles and hydrated cement paste. These observations are consistent with the findings of Legamo and Sida (2022), who demonstrated that reducing clay contamination and improving aggregate cleanliness contribute to enhanced concrete strength and durability.

The mechanical resistance of the aggregates, as evaluated using the Aggregate Crushing Value, Aggregate Impact Value, and Los Angeles Abrasion tests, showed trends similar to those reported in previous international studies. Aggregates from Baidoa consistently exhibited lower crushing, impact, and abrasion values than several other Somali sources, indicating greater resistance to mechanical degradation. In contrast, the Mogadishu aggregate generally produced comparatively higher values, suggesting relatively lower resistance to crushing and abrasion. Nevertheless, all investigated aggregates exhibited engineering characteristics comparable with the ranges reported by Barzangi et al. (2014), Islam et al. (2020), Köken (2022), Hosen et al. (2024), and Bayari et al. (2025), confirming that variations among aggregate sources primarily reflect differences in geological origin, mineralogical composition, and weathering history rather than deficiencies in material quality. Durability assessment based on sodium sulphate soundness further demonstrated that the investigated aggregates possess satisfactory resistance to weathering-related deterioration. The measured soundness losses were comparable with values reported by Çelik et al. (2021) and Köken (2022), indicating that the aggregates are capable of withstanding cyclic environmental exposure without significant degradation. Although minor differences were observed among the investigated regions, these variations are expected because of natural differences in rock type, pore structure, and mineralogical composition.

Particular attention was given to comparing locally sourced Somali aggregates with the imported Omani aggregate, which is widely regarded as a premium construction material within the Somali construction industry. The results indicate that while the imported aggregate exhibited consistently favourable engineering characteristics, several locally sourced aggregates, particularly those obtained from Baidoa, Bosaso, and Kismayo**,** demonstrated physical, mechanical, and durability properties that were comparable with the imported benchmark. This finding is particularly significant because it challenges the widespread assumption that imported aggregates are inherently superior to locally available

materials. Instead, the results demonstrate that properly selected and quality-controlled Somali aggregates are capable of meeting engineering requirements for structural concrete while offering potential economic and logistical advantages through reduced transportation costs and improved local resource utilization. Overall, the comparison with previous investigations confirms that the engineering characteristics of the aggregates examined in this study are consistent with internationally reported values for natural coarse aggregates used in structural concrete. More importantly, the study extends existing knowledge by providing the first comprehensive comparison of the principal aggregate-producing regions of Somalia using a unified laboratory testing program and standardized evaluation procedures. The resulting engineering database provides a scientifically robust basis for aggregate selection, concrete mix design, quality assurance, and future development of national aggregate specifications, thereby supporting safer, more economical, and more sustainable concrete construction throughout Somalia.

Finally, the comparative analysis demonstrates that several locally sourced Somali aggregates possess engineering characteristics comparable with those reported internationally and, in several cases, with the imported Omani aggregate. These findings provide a scientific basis for promoting performance-based aggregate selection in Somalia and reducing unnecessary reliance on imported materials. The implications of these findings for engineering practice and sustainable infrastructure development are summarized in the following Conclusions section.

3.8 Engineering Suitability Ranking and Practical Recommendations

Table 11 presents a practical engineering ranking of the investigated coarse aggregates based on the integrated evaluation of particle grading, specific gravity, water absorption, flakiness index, clay lumps and friable particles, Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), Los Angeles abrasion, and sodium sulphate soundness. Unlike evaluations based on individual laboratory properties, this ranking combines the engineering performance of each aggregate source to provide practical guidance for material selection in structural concrete applications. The results indicate that Bosaso and Baidoa aggregates exhibited the most favourable overall engineering performance and were therefore classified as Excellent**.** Bosaso aggregate demonstrated the highest bulk specific gravity together with very low water absorption, excellent resistance to crushing, abrasion, and weathering, indicating a dense and durable aggregate suitable for demanding structural applications. Similarly, Baidoa aggregate combined low water absorption with favourable mechanical resistance and durability, making it highly suitable for reinforced and high-strength concrete. Beledweyne aggregate was classified as very good

because it consistently exhibited satisfactory physical, mechanical, and durability properties, although its performance was marginally lower than that of Bosaso and Baidoa in some engineering parameters. The imported Omani aggregate remained the benchmark material, demonstrating consistently excellent engineering characteristics across all laboratory tests. These findings are consistent with the comparative laboratory results presented in Sections 3.2–3.5. The aggregates from Kismayo**,** Dusamareeb**,** and Baledogle were classified as Good**,** indicating that they are suitable for most structural concrete applications when appropriate quality-control procedures are implemented. Although these aggregates exhibited slightly higher water absorption or moderately lower mechanical resistance than the highest-ranked materials, all satisfied the relevant engineering requirements and demonstrated acceptable durability.

In contrast, the Mogadishu aggregate was classified as fair because it exhibited comparatively higher water absorption together with lower resistance to crushing, impact, and abrasion. Nevertheless, the laboratory results indicate that the material remains suitable for general structural concrete provided that adequate moisture correction, quality control, and optimized concrete mix design are applied during production.

The engineering suitability ranking developed in this study provides a practical decision-support tool for engineers, contractors, consultants, and regulatory authorities involved in material selection for concrete construction in Somalia. More importantly, it establishes the first performance-based classification of the principal coarse aggregate sources used in the country and provides a scientific foundation for future national aggregate specifications, quality-control procedures, and sustainable utilization of locally available construction materials. By translating detailed laboratory results into practical engineering guidance, the ranking facilitates evidence-based aggregate selection while reducing unnecessary dependence on imported materials.

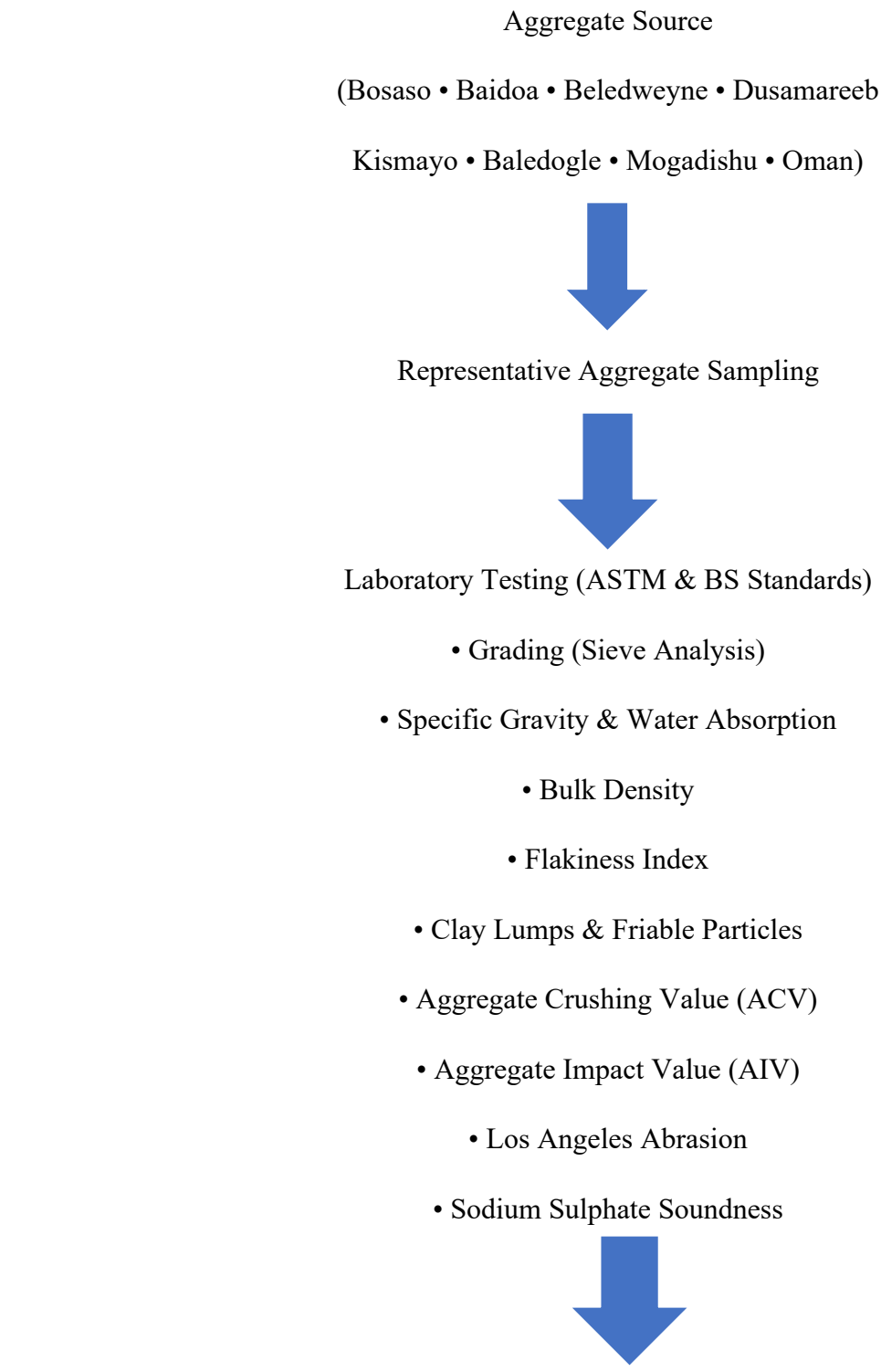
Table 11. Engineering suitability ranking and practical recommendations for the investigated coarse aggregate sources

Aggregate Source	*Overall Engineering Performance*	*Structural Concrete*	*High-Strength Concrete*	*Marine/Coastal Concrete*	*Practical Recommendation*
Bosaso	Excellent	Excellent	Excellent	Excellent	Highly recommended
Baidoa	Excellent	Excellent	Very Good	Very Good	Highly recommended
Beledweyne	Very Good	Very Good	Good	Good	Recommended
Oman (Imported)	Excellent	Excellent	Excellent	Excellent	Benchmark material
Kismayo	Good	Good	Fair	Fair	Recommended with quality control
Dusamareeb	Good	Good	Fair	Fair	Recommended with quality control
Baledogle	Good	Good	Fair	Fair	Grading improvement recommended
Mogadishu	Fair	Fair	Poor	Poor	Suitable only with careful mix design and moisture correction

3.9 National Engineering Implications

The findings of this study provide practical guidance for the selection of coarse aggregates in structural concrete construction across Somalia. The engineering suitability ranking can assist engineers, contractors, consultants, and regulatory agencies in selecting appropriate aggregate sources based on verified physical, mechanical, and durability properties. The results also support the adoption of standardized quality-control procedures consistent with ASTM and BS standards to improve construction quality and structural reliability. Furthermore, increased utilization of high-quality local aggregates can reduce dependence on imported materials, lower construction costs, and promote more sustainable infrastructure development. To the authors' knowledge, this study provides one of the first comprehensive engineering datasets comparing coarse aggregates from multiple regions of Somalia using standardized laboratory testing procedures, offering a valuable reference for future national aggregate specifications and engineering practice. To facilitate the practical application of the research

findings, Figure 19 presents a decision-making framework for selecting coarse aggregates for structural concrete based on the integrated laboratory evaluation conducted in this study. The framework demonstrates how standardized laboratory testing, compliance assessment, engineering evaluation, and performance ranking can be translated into practical recommendations for different construction applications.



Compliance with ASTM / BS Requirements



Integrated Engineering Evaluation

Physical + Mechanical + Durability

+

Statistical Performance Assessment



Engineering Suitability Ranking

Excellent → Very Good → Good → Fair



Engineering Recommendation for Use

High-strength reinforced concrete

Reinforced concrete buildings

Bridges and major infrastructure

Pavements

Marine and coastal structures

General structural concrete

General concrete works

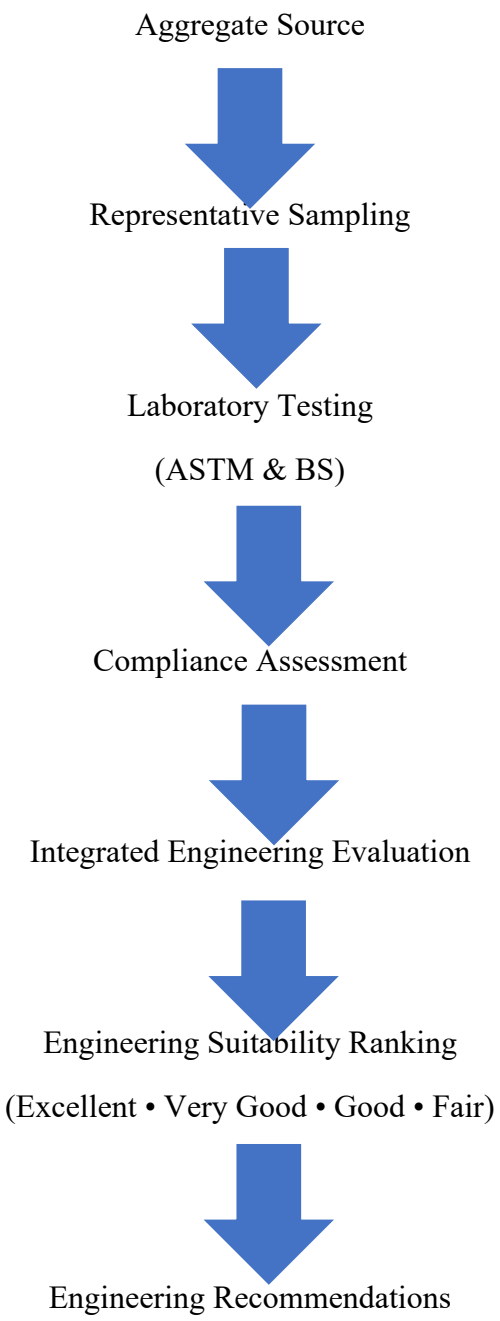


Figure 19. Engineering decision-making framework for aggregate selection

As illustrated in Figure 19**,** the proposed framework enables engineers, consultants, contractors, and regulatory agencies to select aggregate sources according to their measured engineering performance rather than availability or commercial perception. The framework also supports performance-based quality assurance and provides a practical foundation for the development of future national aggregate specifications for Somalia.

3.10 Limitations of the Study

The present investigation provides a comprehensive engineering characterization of coarse aggregates from the principal aggregate-producing regions of Somalia using standardized ASTM and British Standard laboratory procedures. However, the scope of the study was limited to the evaluation of aggregate engineering properties, including grading characteristics, physical properties, particle shape and cleanliness, mechanical resistance, durability, and statistical relationships among the investigated parameters. Petrographic characterization, mineralogical and chemical analyses, and microstructural investigations were beyond the scope of the present work. Furthermore, the study did not evaluate the performance of concrete produced using the investigated aggregates. Future research should therefore incorporate petrographic analysis, concrete mix performance testing, and long-term durability evaluation, including compressive strength, tensile strength, flexural strength, modulus of elasticity, permeability, shrinkage, creep, alkali–silica reactivity, and field performance under aggressive environmental conditions. Such investigations would complement the engineering database established in this study and further support the development of performance-based national specifications for sustainable concrete construction in Somalia.

4. Conclusions

This study presented a comprehensive engineering characterization of coarse aggregates obtained from seven major aggregate-producing regions of Somalia (Mogadishu, Baidoa, Beledweyne, Dusamareeb, Kismayo, Bosaso, and Baledogle) and compared their engineering performance with imported Omani aggregate using standardized ASTM and British Standard laboratory procedures. The investigation evaluated grading characteristics, physical properties, particle shape and cleanliness, mechanical resistance, durability, and statistical relationships among the investigated engineering parameters. The results provide a comprehensive engineering database for coarse aggregates used in Somalia and establish a scientific basis for performance-based aggregate selection for structural concrete. The laboratory investigation demonstrated considerable regional variations in aggregate engineering quality. Oven-dry bulk specific gravity ranged from 2.041 for the Mogadishu aggregate to 2.603 for the Bosaso aggregate, while saturated surface-dry specific gravity varied from 2.186 to 2.621, and apparent specific gravity ranged from 2.386 to 2.732. Water absorption varied substantially from 0.40% for the Baidoa aggregate to 7.10% for the Mogadishu aggregate, reflecting significant differences in aggregate porosity and mineralogical characteristics. Bulk density ranged from 1.190 Mg/m³ to 1.608 Mg/m³, confirming

differences in particle compactness and packing efficiency among the investigated aggregate sources. Evaluation of particle shape and cleanliness showed that all investigated aggregates satisfied the requirements for structural concrete production. Flakiness Index values ranged from 8.3% to 12.8%, while clay lumps and friable particles varied between 0.10% and 2.00%, indicating generally clean and well-shaped aggregates suitable for concrete production. Nevertheless, the observed regional variations emphasize the importance of proper aggregate processing, washing, stockpile management, and routine quality-control testing to ensure consistent concrete performance. Mechanical resistance testing revealed clear differences in aggregate strength and toughness. Aggregate Crushing Value ranged from 10.4% for the imported Omani aggregate to 40.0% for the Mogadishu aggregate, Aggregate Impact Value varied from 5% to 19%, and Los Angeles Abrasion loss ranged between 11.3% and 41.3%. Among the locally available aggregates, Bosaso, Baidoa, Baledogle, and Dusamareeb consistently demonstrated the most favourable mechanical performance, exhibiting comparatively lower crushing, impact, and abrasion values than the remaining Somali aggregate sources. Durability assessment using the Sodium Sulphate Soundness test demonstrated satisfactory resistance to sulphate-induced weathering for all investigated aggregates, with soundness losses ranging from 0.53% to 4.70%, well below the commonly adopted acceptance limit of 12%, indicating that sulphate weathering is unlikely to limit the long-term performance of these aggregates under normal service conditions. Statistical analysis demonstrated strong relationships among the investigated engineering properties. Water absorption exhibited a strong negative correlation with oven-dry bulk specific gravity ($r = -0.922$) and strong positive correlations with Aggregate Impact Value ($r = 0.957$), Los Angeles Abrasion loss ($r = 0.929$), and Sodium Sulphate Soundness loss ($r = 0.906$). Regression analysis further confirmed that water absorption is a reliable predictor of aggregate mechanical performance and durability, with coefficients of determination (R^2) ranging from 0.650 to 0.970. These findings demonstrate that aggregate porosity is one of the principal factors governing density, strength, abrasion resistance, and long-term durability. Comparison with previous international investigations demonstrated that the engineering characteristics of the Somali aggregates are generally consistent with those reported for natural coarse aggregates successfully used in structural concrete in Somalia, Ethiopia, Ghana, Bangladesh, Iraq, Italy, and Türkiye. Furthermore, the use of internationally recognized ASTM and British Standard laboratory procedures provides confidence in the reliability, reproducibility, and practical applicability of the reported engineering data. From an engineering perspective, the findings confirm that locally available Somali coarse aggregates are suitable for structural concrete when appropriately selected and subjected to routine quality-control procedures. Based on the integrated assessment of grading characteristics, physical properties, mechanical resistance, durability, and statistical analysis, Bosaso aggregate is recommended for high-

strength concrete, heavily loaded reinforced concrete structures, bridges, and major infrastructure projects because of its superior engineering performance. Baidoa aggregate is recommended for reinforced concrete buildings, foundations, bridges, and other major structural applications, exhibiting engineering characteristics comparable to the imported Omani aggregate. Beledweyne aggregate is recommended for general structural concrete and reinforced concrete construction, owing to its consistently favourable engineering properties. Baledogle aggregate is suitable for structural concrete, although improved particle grading and routine quality-control measures are recommended to optimize concrete performance. Dusamareeb and Kismayo aggregates are suitable for general reinforced concrete applications, provided that grading control, moisture correction, and standard quality-control procedures are implemented during concrete production. Although the Mogadishu aggregate satisfies the minimum engineering requirements for structural concrete, its relatively high-water absorption and comparatively lower mechanical resistance indicate that washing, moisture correction, optimized concrete mix design, and project-specific performance verification should be undertaken before its use in heavily loaded structures or severe exposure conditions. The principal scientific contribution of this research is the development of one of the first comprehensive standardized engineering datasets comparing coarse aggregates from multiple regions of Somalia using a unified laboratory testing program and an imported benchmark aggregate. Unlike previous investigations that evaluated individual aggregate sources or limited engineering properties, this study provides an integrated comparative assessment of grading, density, porosity, particle shape, cleanliness, mechanical resistance, durability, and statistical relationships under identical testing conditions. The resulting database provides engineers, consultants, contractors, researchers, and regulatory authorities with a scientific basis for performance-based aggregate selection, quality assurance, concrete mix design, and the future development of national aggregate specifications. The findings also demonstrate that dependence on imported aggregates is not always technically justified, as several locally available Somali aggregates exhibited engineering characteristics comparable to the imported Omani aggregate. Future research should investigate the behaviour of structural concrete produced using these aggregate sources through laboratory evaluation of compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, permeability, shrinkage, creep, alkali–silica reactivity, and long-term durability under aggressive environmental conditions. In addition, long-term field monitoring of concrete structures constructed with locally sourced Somali aggregates is recommended to validate the laboratory findings and support the development of performance-based national specifications for sustainable concrete construction in Somalia.

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Author Contributions

A.A.A.: Conceptualization, Investigation, Resources, Data Curation, Formal Analysis, Writing—Original Draft Preparation.
T.S.B.A.M.: Methodology, Formal Analysis, Writing—Review and Editing, Supervision.
A.A.A. and T.S.B.A.M.: Validation and interpretation of the results.
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Competing Interests

The authors declare that they have no known competing financial interests or personal **relationships** that could have appeared to influence the work reported in this paper.

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