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Evaluation of Crushed Basaltic Rocks as Coarse Aggregate, at Selected Site South Sana'a, Yemen: Properties and Concrete Performance

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Abstract

Sana'a City has experienced rapid urban expansion, increasing the demand for high-quality construction materials. This study presents the first systematic engineering evaluation of crushed basaltic rocks from a selected economically significant site south of Sana'a, Yemen, assessing their suitability as coarse aggregate for concrete production. Comprehensive laboratory investigations were conducted, including chemical (XRF), physical, and mechanical tests in accordance with international standards. The basaltic aggregates exhibited excellent engineering properties, with low Aggregate Impact Value (AIV $\approx$ 8.96%), low Los Angeles Abrasion Value (LAV $\approx$ 12.22%), and low water absorption ($\approx$ 1.17%), indicating high strength, durability, and low porosity. All measured parameters complied with ASTM and BS specifications. Concrete produced using these aggregates achieved a 28-day compressive strength of 38.4 MPa, increasing to 45.9 MPa at 180 days, while the estimated modulus of elasticity ranged between 31.95 and 32.94 GPa. The results confirm that the South Sana'a basalt represents a high-quality and durable source of coarse aggregate for structural concrete production.

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1. INTRODUCTION

Crushed rock aggregates are essential raw materials in the construction industry and play a vital role in road and building construction, particularly in asphalt and cement–concrete works. Among the various raw materials, aggregates are the most durable and significant components of concrete mix, influencing the rigidity and overall performance of the final product [1]. Aggregates used in concrete must be free from deleterious substances and possess adequate strength and durability. Concrete should not contain soft, highly porous, chemically reactive, or excessively flaky particles, as these materials adversely affect the long-term serviceability of composite construction materials [2]. Concrete is one of the most widely used building materials. Concrete is produced by mixing coarse and fine aggregates, cement, water, and, if necessary, additives in a specific ratio. Aggregates constitute the primary granular material used in civil engineering applications [3]. The most important characteristics required of concrete are high resistance to physical and chemical effects and high compressive strength. Compressive strength is often used as a key indicator for classifying different types of concrete according to international standards [4]. Aggregates provide volume, stability, and weathering resistance. According to Tuğrul [4], Zerdi [5], and Langer [6], aggregates are generally considered inert fillers, representing approximately 70–85% of the total weight of concrete and approximately 70% of its volume.Therefore, aggregate selection is a crucial step in producing high-quality concrete. The construction quality largely depends on the properties of the coarse aggregate, which directly influences the durability and mechanical performance of concrete. Concrete is a fundamental structural material, and particular attention is given to the nature of the aggregates used, as they represent one of the most important components of modern construction [7]. Concrete

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is a composite material formed by the homogeneous mixing of aggregates, cement, and water in controlled proportions. From an engineering geology perspective, the quality of rock aggregates depends mainly on the mineralogical composition, texture, and structure of the source rock [8–12]. Šernas et al. [13] emphasized that the engineering properties of rock aggregates are key factors in selecting appropriate rock types for different construction purposes. Consequently, basaltic rocks are generally considered suitable for use in pavement and concrete applications because of their strength and durability [14–16]. Tuğrul [4] reported that concrete made with basalt aggregates exhibits excellent engineering properties and cost efficiency. Basalt is a dark-colored, dense, hard, and fine-grained volcanic rock with a wide range of industrial applications. It is commonly utilized in the manufacture of mineral-based insulation materials, glass ceramics, protective coatings [17], and as a dimension stone. Thin slabs of basalt are also cut and polished for use as building veneers, floor tiles, and monuments. Crushed basalt is frequently employed as an aggregate in concrete, asphalt pavements, road bases, railway ballasts, and as filter stones in drainage systems. Yemen is geologically rich in basaltic rock. The Sana'a region hosts several crushers that process basaltic rocks into coarse aggregates. Large quantities of basaltic aggregates are used in the region's construction industry, supplied by multiple crushers in and around southern Sana'a. Currently, four crushers operate in this area, producing significant quantities of coarse basaltic aggregates, with reserves considered nearly inexhaustible. However, their engineering properties have not been studied systematically. Although numerous studies have examined the use of basalt as a coarse aggregate in both normal and high-strength concrete, similar investigations in Yemen are scarce. To the best of our knowledge, the only published study is that of Al-Akhaly [18], who evaluated the engineering properties of coarse basaltic aggregates in the Hamdan area, northwest Sana'a. Therefore, this study provides the first systematic engineering evaluation of crushed basaltic aggregates from the economically significant South Sana'a region, particularly the Al-Dar Al-Bayda crusher site. Unlike previous investigations conducted in other geological settings in Yemen, such as Al-Akhaly [18], this study focuses on a different volcanic sequence characterized by distinct structural and geochemical features. In addition to evaluating the physical, mechanical, and chemical properties of the aggregates, this study further assessed their direct influence on concrete performance, including compressive strength development and modulus of elasticity. By integrating geological characterization with engineering testing and concrete behavior analysis, this study offers a comprehensive dataset that supports informed material selection for sustainable construction practices in the Sana'a region.

2. THE STUDY AREA

The selected crusher for this study is situated in the western part of Yemen, approximately 16 km south of Sana'a city (Figure 1). It is situated between latitudes 15°06'28" and 15°07'03" N and longitudes 44°14'46" and 44°15'11" E (Figure 1). Basaltic rocks were crushed into the size of coarse aggregates necessary for construction, and several crushers were used in the study area, although the area had not been studied before. This region has very rare vegetation and is characterized by low to moderately elevated hills, with altitudes varying from 1647 to 2838 m above sea level.The main rock for coarse aggregate production in the western part of Yemen is usually basalt, which is found in different regions.

Figure 1. Location map of the study area

3. GEOLOGICAL SETTING

The Cenozoic volcanics occupy a larger area in the study area, where the rocks are represented by Tertiary and Quaternary volcanics (Figure 2). The Tertiary volcanics show variations in thickness and lithology due to irregularities in the pre-volcanic topographic and volcanic activity conditions. They represent the lowest part of the Cenozoic volcanics, mostly overly the Cretaceous sandstone of the Tawilah Group, and were extruded during the Oligocene-Miocene. These volcanics occur as basal basaltic sheets, and stratoid pyroclastic rock is occasionally covered by dark basaltic flows. The basal basalt extends over a large area as a homogeneous blocking greenish-black rock with intense fracturing and weathering appearance. The stratoid volcanics comprise the main sequence of the Tertiary volcanics, consisting of alternating layers of alkalic flows and pyroclastic rocks. They include ignimbrite, rhyolite, dacite, basalt, and a large variety of tuffs of different colors [19]. The Quaternary volcanics in the study area are mainly represented by basaltic lava (Figure 2), which formed by extrusions and eruptions through many fissures [19]. Normal faults and joints are the most common structural features in

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the study area, affecting the Cenozoic volcanics. The dominant fault trends are NNW and NW, extending almost parallel to the Red Sea graben system (Figure 2). The basaltic rocks in the studied area have a dark gray color, fine grains, high compressive strength, and weathering range between fresh and slightly weathered on the surface outcrops only and show irregularly oriented columnar joint sets. Most of the joints are closed and unfilled, but in some cases, open joints with iron-oxide staining are observed. The joints were planar, curved, and closely spaced. In Yemen, basaltic blocks are usually used as dimension stones, and very strong and fresh basalt of very good quality is available in sufficient quantities for crushed coarse aggregate production. Concrete is the main use of coarse basaltic aggregates in the Sana'a region. Numerous basaltic crushers were found at different sites in the study area, south Sana'a. According to the field study, the basaltic intact rocks revealed no weathering and alteration signs in the hand samples. The basaltic rock is simply workable owing to systematic four to five columnar joint sets. Such polygonal jointing with a hexagonal columnar system of basaltic rocks may result from contraction during the cooling of lava flow.

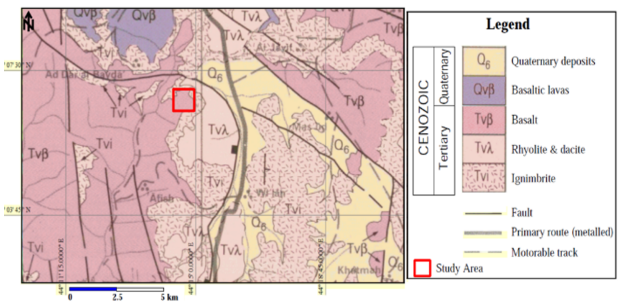

Figure 2. Geological map of the study area and its surroundings [20].

4. MATERIALS AND METHODS

4.1. SAMPLING AND SAMPLE PREPARATION

Representative bulk samples of crushed basalt aggregates were collected from the Al-Dar Al-Bayda crusher site in South Sana'a over three consecutive production days to ensure representativeness and minimize potential variability associated with daily operational changes. Approximately 150 kg of material was obtained directly from the crusher output, covering nominal aggregate sizes of 9.5, 12.5, and 19 mm.

The collected material was transported to the laboratory in sealed bags to prevent contamination and moisture variation from occurring. Upon arrival, the aggregates were air-dried under laboratory conditions and subsequently oven-dried at 105 ± 5 °C to constant mass where required by the relevant ASTM and BS standards. The material was then sieved into the required size fractions and prepared according to the specific procedures prescribed for each test. Representative subsamples were obtained using standard quartering methods to ensure the uniformity and repeatability of the results.

4.2. COARSE AGGREGATE TESTS

Crushed basaltic rocks from the southern Sana'a region, produced by the Al-Dar Al-Bayda crusher, are widely used by local construction companies as coarse aggregate. To evaluate the quality of these aggregates, a series of laboratory tests were conducted on representative samples of 9.5, 12.5, and 19 mm nominal sizes collected from the Al-Dar Al-Bayda crusher, which is one of the main aggregate production sites in southern Sana'a. The particle shape and surface texture of the samples were visually assessed according to ASTM D3398 [21] and BS 812: Part 1 [22], respectively. The flakiness index was determined by separating flaky particles using a metal thickness gauge, following BS 812: Part 105.1 [23], whereas the elongation index was measured using the appropriate gauge according to BS 812: Part 105.2 [24]. The specific gravity and water absorption were determined in accordance with ASTM C127 [25], and the density was calculated according to ASTM C29 [26]. The aggregate strength and durability were evaluated by determining the Aggregate Impact Value (AIV) according to BS 812: Part 112 [27] and the Los Angeles Abrasion Value (LAV) according to BS 812: Part 113 [28]. The soundness was tested using sodium sulfate (Na_2SO_4) as per ASTM C88 [29].

4.3. FINE AGGREGATE TESTS

Crushed sandstone, known locally as Zigan sand, was used as a fine aggregate in the concrete mixes. The fineness modulus was determined according to ASTM C136 [30], density according to ASTM C29 [26], and specific gravity and water absorption according to ASTM C128 [31]. The percentage of particles passing through a 75 μm sieve was measured according to ASTM C117 [32]. The presence of clay lumps and friable particles in both the coarse basaltic aggregate and Zigan sand was determined according to ASTM C142 [33]. This test was applied to the > 4.75 mm fraction of the coarse basaltic aggregate and the > 1.18 mm fraction of the Zigan sand. Chemical analyses of both coarse aggregates and Zigan sand were performed using an ARL 9800 XP SIM-SEQ X-ray fluorescence (XRF) unit at the Quality Laboratory of the Amran Cement Plant (ACP) in Amran, Yemen. This XRF instrument, manufactured by Thermo Electron Corporation, employs an Rh tube and UniQuant software. The sample preparation involved crushing the materials using a jaw crusher, followed by fine grinding in a disk

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vibration mill. During grinding, approximately 6–7 mL of hexane (C_6H_{14}) was added to reduce the temperature and prevent thermal alterations.

4.4. CEMENT CHARACTERIZATION

Amran Portland Cement (APC), CEM-I/42.5 N, was used in the concrete mix. The chemical composition was determined using XRF analysis. The insoluble residue (IR) percentage was measured according to the ASTM C114 standard [34]. Fineness was evaluated using BS EN 196-6 [35], based on Blaine fineness and the material retained on 45 μm and 90 μm sieves under vacuum conditions. The soundness was determined using the Le-Chatelier apparatus according to BS EN 196-3 [36]. Standard consistency, as well as the initial and final setting times, were measured using a Vicat apparatus in accordance with BS EN 196-3 [36]. The compressive strength of the cement was tested following BS EN 1015-11 [37]. The loss on ignition (LOI) percentages of the coarse basaltic aggregate, Zigan sand, and cement were determined according to ASTM D7348 [38].

4.5. CONCRETE MIX PREPARATION AND TESTING

The concrete mix was proportioned by weight and designed to achieve a target compressive strength of 30 MPa (C-30 grade), representing a commonly used structural concrete in local construction practices in Sana'a. The mix contained 350 kg/m$_3$ of cement, Zigan sand as fine aggregate, and basaltic coarse aggregates of 9.5, 12.5, and 19 mm sizes. A mix ratio of 1:2:3 with a water–cement (w/c) ratio of 0.60 was adopted, corresponding to a typical normal-strength concrete composition [39]. No chemical or mineral admixtures were used. The selected cement content was intended to simulate realistic field conditions and evaluate aggregate performance under practical application scenarios. Mixing was performed using a circular pan-type concrete mixer with a maximum capacity of 60 liters, equipped with three blades rotating about a vertical axis. The dry materials (cement and aggregates) were first mixed thoroughly, after which potable water was gradually added while continuously mixing until a uniform consistency was obtained. The slump of the fresh concrete was measured according to BS 1881: Part 102 [40]. Fifteen concrete cubes (150 × 150 × 150 mm^3) were cast according to ASTM C192 [41] under laboratory conditions at 21 ℃ and 80 ± 4% relative humidity. After casting, the specimens were covered with plastic sheets for 24 h to prevent moisture loss, then demolded, and cured by immersion in water at 21 ℃ for 7, 28, 56, 90, and 180 days. This testing schedule was adopted to evaluate both early age and long-term strength developments. The density and compressive strength of the hardened concrete were measured according to BS 1881: Parts 114 [42] and 116 [43]. The compressive strength was determined using a testing machine that applied a uniform axial load at a rate of 0.5 MPa/s, and the reported values represent the average of three specimens for each curing age (n = 3). The modulus of elasticity was estimated from the 28-day compressive strength and density of concrete using empirical equations provided by the American Concrete Institute (ACI 318) [44], European Standard (EN 1992-1-1) [45], and Architectural Institute of Japan (AIJ) [46]. All tests on coarse aggregates, fine aggregates, and cement were carried out at the laboratories of the Amran Ready-Mix Concrete Company (Sana'a) and the ACP. The aggregate and cement tests were repeated at least five times to ensure measurement consistency. The results were evaluated and compared with relevant international standards and previous studies that used basalt as a coarse aggregate.

5. RESULTS AND DISCUSSION

5.1. PROPERTIES OF COARSE BASALTIC AGGREGATE

5.1.1. Chemical Composition

The results of the geochemical analyses are summarized in Table 1. Chemical analysis indicated that coarse aggregate was mainly composed of SiO_2 (48.70 %), followed by Al_2O_3 (16.15 %) and Fe_2O_3 (11.55 %), a composition which reflects the basic rock quality. As shown in Table 1, the total Fe_2O_3 content is high for the samples (10.17–12.32 %) and high NaO_2 + K_2O content (4.31–6.06 %) is typical of alkaline basalts. LOI was very low (< 1 %), indicating that the samples were unaltered. When the chemical analysis results were classified based on SiO_2 and Na_2O+K_2O contents according to Le Maître [47], it was determined that the materials belonged to trachy-basalt and basalt rocks.

Table 1. Chemical composition of coarse aggregate

Sample No.	SB-1	SB-2	SB-3	Ave.
SiO_2	47.92	48.64	49.55	48.70
Al_2O_3	16.24	16.21	16.00	16.15
Fe_2O_3	12.32	12.15	10.17	11.55
CaO	7.62	7.73	9.52	8.29
MgO	6.22	5.13	7.30	6.22
K_2O	1.34	1.19	0.69	1.07
Na_2O	4.72	4.84	3.62	4.39
TiO_2	1.89	1.93	1.61	1.81
P_2O_3	0.52	0.43	0.44	0.46
SO_3	0.42	0.41	0.08	0.30
LOI	0.72	0.98	0.96	0.89
Total	**99.93**	**99.64**	**99.94**	**99.83**

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5.1.2. Physical Properties

5.1.2.1 Particle shape and surface texture

The particle shape significantly affects the performance of aggregates during both construction and service lives. The surface texture of aggregates also significantly influences the bond between the aggregate and cement paste. Generally, a rough surface texture enhances the bond strength, whereas a smooth or glassy surface results in poor bonding [48, 49]. Additionally, aggregates with a more angular shape and larger surface area provide better adhesion within the concrete matrix [49]. The shape and surface texture of crushed rock aggregates are fundamental parameters that influence the mechanical interlocking and bond strength between the aggregate and cement paste in concrete mix design [50]. Hence, bonding depends strongly on the surface texture, where smoother surfaces require less adhesion than rougher ones. The particles of the coarse aggregates were irregular, angular in shape, and possessed a rough surface texture. These features meet the requirements of the British Standard (BS) specifications for concrete aggregate.

5.1.2.2 Flakiness index (F_I) and elongation index (E_I)

The shape of aggregates is a critical factor influencing the workability and performance of concrete. The particle shape and size distribution affect the amount of water required to achieve the desired consistency, which in turn influences the compressive strength, drying shrinkage, and durability of the hardened concrete [51]. Each rock unit has its own shape characteristics, determined mainly by its mineralogical composition, texture, and structure, as well as the crushing method employed [51]. During aggregate production, rocks are fractured into particles of various shapes. According to the BS specifications, four categories are recognized: cuboidal, elongated, flaky, and flaky–elongated. Excessive amounts of flaky and elongated particles may weaken concrete mixes, as these particles are prone to breakage during handling, compaction, or under traffic loads.

A flaky particle is defined as one with a small thickness relative to its other dimensions, where the smallest dimension does not exceed 0.6 times the mean sieve size [23]. The F_I of the studied samples ranged from 7.83% to 18.33%, with an average value of 14.20% (Table 2). This feature provides information about the internal friction properties of the mixtures [17]. An elongated particle is one whose maximum dimension exceeds 1.8 times its mean dimension [23]. The E_I of the studied samples ranged from 4.87% to 11.07%, with an average of 7.83% (Table 2). Both F_I and E_I values conform to the BS 812: Part 105.1 and 105.2 specifications for aggregates used in concrete production.

5.1.2.3 Specific gravity (G_s) and Water Absorption (W_a)

The summary results of G_s are shown in Table 2. Three types of G_s were determined; the bulk G_s (dry) varies from 2.85 to 2.92, with an average of 2.88, bulk G_s (saturated surface dry, SSD) varies from 2.89 to 2.94, with an average of 2.92 and apparent G_s varies from 2.97 to 2.99, with an average of 2.98. The results in Table 2 indicates that the high values of G_s is related to the volcanic origin of the material. The G_s values of three types of G_s were 3 % higher than the results of Yilmaz [17] and Al-Baijat [52] for coarse basaltic aggregate in Jordan and Turkey, respectively.

The G_s of an aggregate is an important factor in mix design calculation because it relates the weight of aggregate to its volume. This property, give an idea of strength of rocks. There is generally a direct positive relationship between high G_s and high strength of aggregate [49, 53].

The W_a represents the water contained in aggregate in saturated surface dry condition. It varies from 0.70 to 1.50 %, with an average of 1.17 % (Table 2), similarly to the results of Engidasew [51] for the Miocene coarse basaltic aggregate in Ethiopia, 19 % lower than the results of Yilmaz [17] and 34 % lower than the results of Al-Baijat [52].

According to BS 8007 [55], ASTM C127 [25], and ASTM C33 [56] and BS 812 Part 2 [54] the maximum permissible W_a for concrete aggregates is < 3%, < 2.5%, and < 2%, respectively. Hence, the studied aggregates, with W_a values below 2%, are suitable for high-strength concrete production.

W_a is a useful property in evaluating durability of different rocks utilized as coarse aggregate for concrete Rocks with W_a values > 3 % are subject to freeze and thaw action [58, 59]. Aggregates having high W_a are naturally more porous and generally considered less resistant to mechanical forces and weathering [18].

The W_a of aggregate is a significant property in determining ratios of mixing. Hence, aggregate with low W_a values are in high request for quality concrete producing. High strength concrete can be produced through low W_a rock (< 2 %) [60].

The W_a impacts the G_S of the aggregate as well as in service behavior of concrete. It is reflected an indirect degree of aggregate permeability that influences other properties of aggregate, like soundness, durability and strength [49, 61, 62]. Aggregate having high W_a are more porous in nature and are usually considered improper [63]. In overall, less W_a aggregate frequently tend to be more resistant to weathering and mechanical forces.

5.1.2.4 Density (γ)

Loose γ of coarse aggregate ranges between 1481 and 1547 kg/m^3 with an average of 1514 kg/m^3, whereas compacted γ ranges between 1689 and 1939 kg/m^3 with an average of 1776 kg/m^3. Similar results were obtained

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Table 2. Engineering properties of coarse aggregate

Property		Min.	Max.	Ave.	Acceptance Limit for Concrete [standard used for evaluation]
Flakiness Index (%)		7.83	18.33	14.20	< 25 % [23]
Elongation Index (%)		4.87	11.07	7.83	< 25 % [24]
Specific gravity	Dry	2.85	2.92	2.88	> 2.6 [54]
	Saturated	2.89	2.94	2.92	
	Apparent	2.97	2.99	2.98	
Water absorption (%)		0.70	1.50	1.17	< 3 % [55]; < 2.5 [25]; < 2 % [56].
Density(kg/m^3)	Loose	1481	1547	1514	1200-1800 kg/m^3 [22]
	Compacted	1689	1939	1776	-
Clay lumps & friable particles (%)		0.04	1.74	0.62	< 3 % [56]
Aggregate impact value (%)		8.30	10.10	8.96	< 25 % [27, 57]
Los Angeles abrasion value (%)		10.50	14.20	12.22	< 35 % [28]
Soundness, (Na_2SO_4) (%)		0.50	2.80	1.63	< 10 % [29, 56]

by Engidasew [51] and 15 % lower than the results of Yilmaz [17] for loose γ, whereas compacted γ was 8 % lower than the results of Yilmaz [17]. Loose γ of coarse aggregate commonly used in normal weight concrete is varying from 1200 to 1800 kg/m^3 [22]. Hence, representative coarse aggregate satisfied the BS standard.

5.1.2.5 Clay lumps and friable particles

The clay lumps and friable particles present on the coarse aggregate could affect the water demand of the concrete mixes. After applying the test of substances finer than 75 μm, this test is applied to the fraction coarser than 4.75 mm sieve. The clay lumps and friable particles in coarse aggregate ranges between 0.04 and 1.74 % with an average of 0.62 %. This is very low value and lower than maximum allowable limit imposed by ASTM C33 [56] standard (3 %).

5.1.3. Mechanical Properties

The mechanical tests give factors for durability and strength of rock aggregate [49, 64]. The available BS, ASTM and EN standards need that the rock aggregate must not disintegrate during compaction or mixing. AIV and LAV are the fundamental strength parameters to assess the aggregate strength and durability, respectively.

AIV indicates relative measure of mechanical resistance of an aggregate to sudden shock [65]. A high impact value indicates that the aggregate is low resistance to fragmentation. The AIV test was stated to have the following advantages: it requires a small sample; it requires less expensive portable equipment; and samples may be tested in a wet condition [66].

In this study, the AIV value varies from 8.30 to 10.10 %, with an average of 8.96 ± 0.76 %. This value shows that the aggregate is highly durable and high resistance to fragmentation (dense and fine-grained). The AIV value is lower than the results of Engidasew [51].

The aggregate samples collected from the basaltic rocks which is fine grained and dense had revealed the highest strength in terms of AIV. BS and ASTM standards specified that AIV must be less than 25 % of its weight [27, 57]. All studied samples fall within the stated requirement. The results attained for AIV test is essentially influenced by geological factors; fabric, petrography and petrology [67].

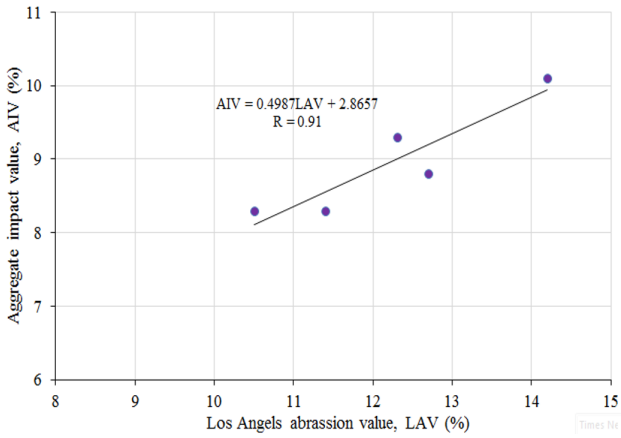

Figure 3. Los Angeles abrasion values versus aggregate impact values.

The LAV of the studied samples ranges from 10.50 to 14.20 %, with an average of 12.22 ± 1.40 %, lower than the results of Engidasew [51]. The EN standards identify the maximum acceptable value is 35 %. Thus, the studied aggregate samples have revealed good quality in terms of LAV test results (< 35 %).

As it has been seen in Figure 3, LAV and AIV display a very strong positive linear relationship (with R = 0.91) demonstrating these characteristics are significant mechanical properties of the characterization of aggregate as far as this study is concerned. Apart from testing aggregate with relate to its LAV and AIV, testing the aggregate with relate to its resistance to wear is a significant test for aggregate to be utilized for building floors and pavement and road constructions.

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5.1.4. Chemical Properties

5.1.4.1 Soundness

The soundness test evaluates the resistance of aggregates to disintegration when subjected to salt crystallization and freeze–thaw cycles that simulate extreme weathering conditions [68]. The test procedure involves repeatedly immersing the aggregate in a sulfate solution, drying it, and then re-immersing it in the same solution. During this process, expansive forces develop as sulfate crystals within the aggregate pores rehydrate. The resulting expansion reproduces the stresses that occur when water freezes inside the aggregate pores.

The permissible range of mass loss differs among testing standards, depending on the type of sulfate solution used. Typical limits are 18% for magnesium sulfate and 10% for sodium sulfate.

In this study, all tested samples demonstrated excellent soundness performance, with mass loss values ranging from 0.50% to 2.80% and an average of 1.63%. These results fall well within the ASTM C33 [56] requirement (<10%), indicating high durability of the basaltic aggregates. Comparable results were reported by Engidasew [51].

5.1.4.2 Alkali silica reaction (ASR)

ASR is a deleterious chemical process that occurs between reactive silica present in aggregates and the alkalis in cement paste [69]. The reaction is driven by three primary factors: (1) a significant amount of reactive silica in the aggregate, (2) high alkalinity of the pore solution within the concrete, and (3) the presence of external moisture [70].

This reaction produces a swelling gel that can generate internal stresses, leading to expansion, cracking, and, over time, potential loss of structural integrity [48]. The susceptibility of volcanic rocks to ASR is typically related to their content of volcanic glass, altered minerals, and overall SiO_2 composition [71, 72].

According to Katayama et al. [73], basaltic rocks with bulk silica contents exceeding 50% may exhibit potential reactivity toward ASR. However, the chemical analyses of the studied samples indicate that all contain less than 50% SiO_2, suggesting a very low potential for alkali–silica reactivity.

5.1.4.3 Geological Factors Controlling Aggregate Performance

The high physical and mechanical performance of the investigated basaltic aggregates is directly related to their volcanic origin and dense mineralogical texture. The basalt belongs to Cenozoic volcanic sequences and is characterized by a fine-grained structure and a compact crystalline groundmass with very low porosity, as well as a clear absence of weathering features (LOI < 1%). This interlocking crystalline texture enhances the internal cohesion of the rock and limits the propagation of microcracks, which explains the low values of both AIV and LAV.

The relatively high specific gravity (Gs ≈ 2.9) and low water absorption (< 2%) reflect the dominance of dense minerals and low effective porosity, contributing to improved durability and resistance to environmental effects. The columnar joints formed during lava cooling facilitate quarrying operations without significantly compromising the integrity of aggregate particles after crushing.

Regarding ASR, the predominance of crystalline phases and the absence of significant volcanic glass reduce the potential reactivity, despite the relatively high total silica content.

Accordingly, the superior engineering properties of the studied aggregates are not incidental but are controlled by the geological and mineralogical characteristics of the South Sana'a basalt, confirming its suitability as a high-quality source of coarse aggregate for concrete production.

5.2. CONCRETE MIX DESIGN

5.2.1. Materials

5.2.1.1 Coarse aggregate

In the concrete mix, crushed basaltic aggregates of 9.5 mm, 12.5 mm, and 19 mm nominal sizes were used in this study. The physical, mechanical, and chemical characteristics of these aggregates were previously described in the earlier sections.

5.2.1.2 Fine aggregate

Crushed sandstone, locally known as Zigan sand, with a maximum particle size of 4.75 mm, was employed as the fine aggregate. Testing was performed according to ASTM standards, and all the measured properties satisfied the specified requirements [74]. The corresponding results are presented in Table 3.

Table 3. Physical properties of Zigan sand

Property		Value	Acceptance limit for concrete and reference
Specific gravity (dry)		2.58	2.4-3.0 [31]
Fineness modulus		2.42	2.1-3.1 [56]
Density (kg/m^3)	Loose	1469	1200-1750 kg/m^3 [26]
	Compacted	1613	
Water absorption (%)		1.39	0.2-4.0 % [74]
Clay lumps and friable particles (%)		3	< 3 % [56]
Materials < 75 μm (%)		2.94	< 3 % [56] for wadis sand < 7 % [56] for crushed sand

The chemical composition of the Zigan sand, listed in Table 4, shows that it is predominantly composed of silica (SiO_2) at 97.04%, with smaller proportions of alumina (Al_2O_3, 1.11%), ferric oxide (Fe_2O_3, 0.51%), and calcium oxide (CaO, 0.31%). This composition confirms the purity and inert nature of the fine aggregate, making it suitable

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for high-quality concrete production.

5.2.1.3 Cement

The concrete mix was prepared using Amran Portland Cement (APC), supplied by the ACP in 50 kg bags and stored in a dry environment until mixing. This cement is widely used throughout Yemen for structural concrete works.

The properties of the cement comply with the requirements of the American standard ASTM C150 [75] for Ordinary Portland Cement (Type I) and with EN 197-1 [75, 76] specifications for CEM I 42.5 N. The chemical composition of the cement is provided in Table 5, while its physical properties and compressive strength are summarized in Table 6.

Table 4. Chemical composition of Zigan sand used in the study

Sample No.	ZS-1	ZS-2	ZS-3	Ave.
SiO_2	97.18	96.61	97.32	97.04
Al_2O_3	1.09	1.13	1.12	1.11
Fe_2O_3	0.37	0.51	0.66	0.51
CaO	0.49	0.19	0.25	0.31
MgO	0.06	0.03	0.05	0.05
K_2O	0.03	0.02	0.02	0.02
TiO_2	0.11	0.12	0.12	0.12
P_2O_3	0.03	0.03	0.02	0.03
Cr_2O_3	0.06	0.07	0.05	0.06
SO_3	0.05	0.03	0.05	0.04
Total	**99.47**	**98.74**	**99.66**	**99.29**

Table 5. Chemical composition of Amran Portland cement used in the study.

Compound	Mass (%)	Specification [76, 77]
SiO_2	21.55	17 - 25
Al_2O_3	6.52	3.0 - 8.0
Fe_2O_3	4.27	0.5 - 6.0
CaO	60.92	60 - 67
MgO	2.48	0.5 - 4.0
K_2O	0.76	0.5 - 1.3
Na_2O	0.36	0.5 - 1.3
Mn_2O_3	0.11	minor
TiO_2	0.20	minor
P_2O_5	0.19	minor
SO_3	1.71	$\leq$ 3.50*
Cl	0.01	$\leq$ 0.10*
LOI	0.78	$\leq$ 5.0*
IR	0.36	$\leq$ 5.0*

** [76]*

The mix was designed to achieve a target strength of C-30 grade concrete, corresponding to an average compressive strength of 30 MPa at 28 days. This grade is commonly employed in the Yemeni concrete industry. The mix design included w/c ratio of 0.60 and a cement content of 350 kg/m^3, with a maximum coarse aggregate size of 19 mm. The resulting slump value was 110 mm, indicating medium workability. A single mix proportion was used, and the detailed mix composition is presented in Table 7.

Table 6. Physical properties and compressive strength of Amran Portland cement

Physical Tests	Obtained results	Specification [76, 77]
Fineness (%)		
Retained on 90 μm sieve	1	
Retained on 45 μm sieve	6	< 10
Blaine (cm^2/gm)	3300	> 2800*
Specific gravity	3.10	-
Consistency (%)	28.80	26 - 33
Soundness (mm)	1	$\leq$ 10
Setting time (min)		
Initial	60	$\geq$ 60
Final	140	< 600
Compressive strength (MPa)		
2 days	21	$\geq$ 10
7 days	34	$\geq$ 16
28 days	54	$\geq$ 42.5

*[77]

Table 7. Mix ratios of concrete mix

Mix materials		Mass
Cement (kg/m^3)		350
Water (Liter/m^3)		210
w/c ratio		0.60
Fine aggregate (kg/m^3)		790
Coarse basaltic aggregate (kg/m^3)	9.5 mm	410
	12.5 mm	440
	19 mm	280

5.2.2. Density

Figure 4 presents the density results of the concrete specimens. The density of each sample was measured after water curing and prior to the compressive strength test. Before weighing, surface moisture was carefully removed from the cube specimens using a towel. The density of each cube was calculated as the ratio of its mass to its volume.

The bulk density of normal-weight concrete typically ranges between 2200 and 2600 kg/m^3 [78]. The density values of all tested specimens fall within this range, confirming that the produced concrete belongs to the normal-weight category.

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An increase in density was observed with longer curing durations, where the 7-day specimens exhibited the lowest density and the 180-day specimens achieved the highest. The density increased by approximately 2% between the 7-day and 180-day curing periods. This gradual increase is attributed to the progressive compaction and densification of the internal concrete matrix resulting from the continued hydration process during curing.

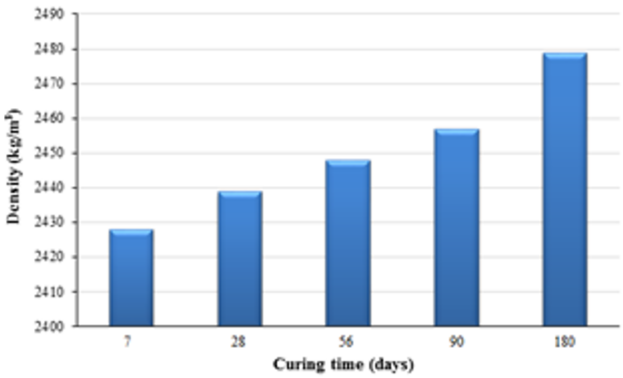

Figure 4. Density development of concrete specimens with age of curing

5.2.3. Mechanical Behavior of Concrete

5.2.3.1 Compressive strength (σ_c)

σ_c is one of the most essential mechanical parameters used to evaluate the performance of concrete, and concrete grades are commonly defined based on this property. The compressive strength of a specimen corresponds to the maximum load it can sustain before failure, divided by the cross-sectional area of the cube.

In this study, the σ_c of concrete mixes prepared with crushed basaltic rock as coarse aggregate and Zigan sand as fine aggregate was measured after curing periods of 7, 28, 56, 90, and 180 days. The variation of σ_c with curing time is illustrated in Figure 5. The compressive strength increased from 30 MPa at 7 days to 45.90 MPa at 180 days, showing a clear exponential growth trend with curing age. This continuous increase is attributed to the progressive formation of hydration products over time.

At 28 days, the concrete achieved a σ_c of 38.4 MPa, with the 7-day strength representing approximately 78% of the 28-day strength. This ratio aligns well with the findings of Rajput et al. [79], which used similar w/c and mix ratios. For normal concrete cured under standard conditions, 7-day strengths typically range between 60% and 80% of the 28-day strengths [78], confirming the sound performance of the mix used in this study.

Beyond 28 days, the compressive strength continued to increase by approximately 12%, 17%, and 20% at 56, 90, and 180 days, respectively, compared to the 28-day

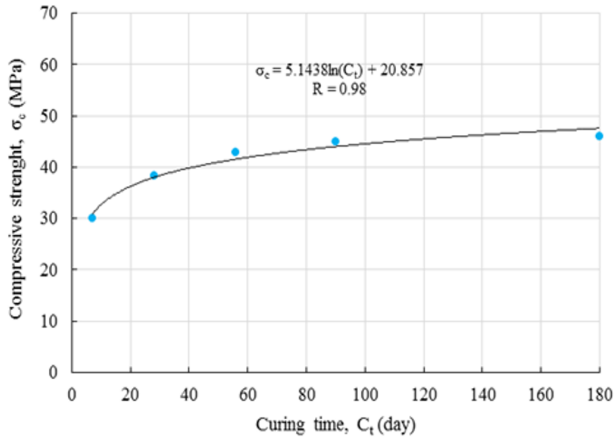

Figure 5. Compressive strength development of concrete specimen with age of curing.

value. The 28-day strength of 38.4 MPa was slightly lower than those reported in previous studies. This may be due to the presence of greater proportions of fine sand and a slight amount of very fine particles (clay and silt) in the Zigan sand [80].

When comparing the influence of coarse basaltic aggregate from the Al-Dar Al-Bayda crusher on the 28-day compressive strength (for a cement content of 350 kg/m^3), the obtained σ_c value was approximately 8% lower than that reported by Tuğrul [4] and 5 % lower than the σ_c of the concrete sample consisting of coarse basalt aggregate used in Al-Baijat study [52].

The rock strength is a basic property, but the effective strength of an aggregate particle is modified by its shape and size [67]. The σ_c of concrete mostly depends on the aggregates strength. The parameters that affect concrete strength include aggregate shape, size, grading, texture, weathering, cement content, and curing conditions.

The observed compressive strength development can be directly related to the physical and mechanical characteristics of the investigated basalt aggregates. The relatively high specific gravity and low water absorption indicate a dense and low-porosity aggregate structure, which enhances interfacial bonding between the aggregate and cement paste. Furthermore, the low AIV and Los Angeles Abrasion Value LAV reflect strong resistance to crushing and abrasion, contributing to improved load transfer within the concrete matrix. These characteristics collectively explain the steady strength gain up to 180 days and the satisfactory modulus of elasticity values. The dense crystalline texture of the basalt aggregates also supports improved stiffness, which is consistent with the calculated elastic modulus based on international models.

5.2.3.2 Modulus of elasticity (E_c)

The E_c is an important mechanical property of concrete required for the design of reinforced concrete structures. Evaluating the influence of coarse aggregate type on E_c is essential, as this property is highly dependent

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on the mineralogical and physical characteristics of the aggregate [64, 81, 82]. Various building codes provide empirical equations for estimating E_c, formulated primarily for design purposes and expressed as functions of parameters known during the design phase [83].

According to ACI 318 [44], the 28-day E_c of concrete (in GPa) can be estimated from the average compressive strength.

$$E_c = \gamma^{1.5} \times 0.043 \times \sigma_c^{0.5} \quad (1)$$

Likewise, the EN 1992-1-1 [45] estimates the 28 day E_c from σ_c by:

$$E_c = 22000 \times (\sigma_c/10)^{0.3} \quad (2)$$

Also, the AIJ [46] states the next formula to evaluate the concrete E_c:

$$E_c = 21000 \times (\gamma/2300)^{1.5} \times (\sigma_c/20)^{0.5} \quad (3)$$

(σ_c, in MPa) and the density (γ, in kg/m^3) of hardened concrete as follows By applying these equations to the 28-day σ_c values of the tested concrete samples, comparable results were obtained for all standards, ranging from 31.95 to 32.94 GPa (Table 8). This consistency is attributed to the irregular, angular particle shape, rough surface texture, high stiffness, and low (W_a) of the basaltic coarse aggregates used in this study.

Table 8. Estimated values of elasticity modulus at 28 days according to ACI, EN and AIJ

Property	value	Standard
Density of hardened concrete, (kg/m^3)	2448	-
Compressive strength, σ_c (MPa)	38.40	-
Modulus of elasticity, E_c (GPa)	32.27	[51]
	32.94	[45]
	31.95	[46]

Similar findings were reported by Abi Farraj [84] for concrete mixes with the same cement content and w/c ratio, and the obtained E_c values were approximately 29% higher than those reported by Siddique [85]. It is well established that concrete produced with crushed coarse aggregates generally exhibits higher E_c values compared with concrete made using rounded aggregates [86]. Moreover, the modulus of elasticity is influenced by the toughness and volumetric proportion of the coarse aggregates within the mix [87].

6. CONCLUSION AND RECOMMENDATIONS

In this study, the engineering properties of coarse basaltic aggregates produced from the Al-Dar Al-Bayda crusher, located south of Sana'a, were evaluated. The performance and durability of civil engineering structures largely depend on the quality of the aggregates used. Therefore, the mechanical strength and physical characteristics of the aggregate must satisfy the relevant standard specifications for construction applications.

The selection of suitable aggregates is of great importance, as they constitute more than 75% of the total concrete volume. The coarse basaltic aggregates from the southern Sana'a region are widely utilized due to their excellent production quality, characterized by high G_S, high γ, low clay and friable particle content, low F_I and E_I, low water absorption (Wa), low aggregate impact and abrasion values (AIV and LAV), and superior soundness.

The σ_c of the concrete samples ranged from 30 MPa at 7 days of curing to 45.90 MPa at 180 days, exhibiting an exponential increase with curing age. This enhancement is attributed to the continuous formation of hydration products over time. The 7-day strength represented approximately 78% of the 28-day strength, which falls within the expected range (60–80%) for normal concrete cured under standard conditions.

All test results indicate that the basaltic rocks in the study area are highly suitable for producing high-quality coarse aggregates for concrete manufacturing. In particular, the AIV, LAV, and sodium sulfate (Na_2SO_4) soundness values confirm the potential of these materials to yield durable and superior-quality aggregates.

Currently, crusher sites surrounding Sana'a city are selected without systematic engineering geological assessment. To improve production quality and ensure long-term sustainability, close collaboration between geologists and civil engineers is strongly recommended. Furthermore, producers of coarse aggregates should consistently comply with international and local standard specifications and maintain strict quality control to ensure reliable and high-performance concrete materials.

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REFERENCES

[1] Y. Sarfraz, M. Basharat, M. T. Riaz, M. A. Khan, A. Shahzad, and K. S. Ahmed, "Evaluation of physico-mechanical properties of crushed rock aggregates: A case study from the sub-himalaya, pakistan," *Acta Montanistica Slovaca*, vol. 26, no. 3, pp. 466–480, 2021. DOI: 10.46544/AMS.v26i3.07.

[2] P. N. Quiroga and D. W. Fowler, "The effects of aggregate characteristics on the performance of portland cement concrete," International Center for Aggregates Research, Austin, TX, USA, Tech. Rep., 2004.

[3] R. Přikryl, "Geomaterials as construction aggregates: A state-of-the-art," *Bull. Eng. Geol. Environ.*, vol. 80, pp. 8831–8845, 2021. DOI: 10.1007/s10064-021-02488-9.

[4] A. Tuğrul, "Effects of basalt aggregates on concrete properties," *Qual. Stud. (NWSAQS)*, vol. 13, no. 2, pp. 68–79, 2018. DOI: 10.12739/NWSA.2018.13.2.E0043.

[5] T. A. Zerdi, "Effects of using washed basalt coarse aggregates on strength characteristics of concrete," *Glob. J. for Res. Anal.*, vol. 4, no. 12, pp. 64–65, 2015.

©2026 The Author(s). This article is licensed under CC By 4.0

[6] W. Langer, "Sustainability of construction materials," in *Sustainability of Construction Materials*, 2nd ed., Cambridge, UK: Woodhead Publishing, 2016, pp. 181–200.

[7] F. G. Blyth and M. H. de Freitas, *A Geology for Engineers*, 6th ed. London, UK: Edward Arnold, 1977.

[8] C. O. Okogbue and O. P. Aghamelu, "Performance of pyroclastic rocks from abakaliki metropolis (southeastern nigeria) in road construction projects," *Bull. Eng. Geol. Environ.*, vol. 72, pp. 433–446, 2013. DOI: 10.1007/s10064-013-0489-0.

[9] R. Ajalloeian and M. Kamani, "An investigation of the relationship between los angeles abrasion loss and rock texture for carbonate aggregates," *Bull. Eng. Geol. Environ.*, vol. 78, pp. 1555–1563, 2019. DOI: 10.1007/s10064-017-1209-y.

[10] S. Adomako, C. J. Engelsen, R. T. Thorstensen, and D. A. Barbieri, "Review of the relationship between aggregate geology and los angeles and micro-deval tests," *Bull. Eng. Geol. Environ.*, vol. 80, pp. 1963–1980, 2021. DOI: 10.1007/s10064-020-02097-y.

[11] P. Strzałkowski and U. Kázmierczak, "Wear and fragmentation resistance of mineral aggregates—a review of micro-deval and los angeles tests," *Materials*, vol. 14, p. 5456, 2021. DOI: 10.3390/ma14185456.

[12] P. Strzałkowski et al., "Evaluation of the structure and geometric properties of crushed igneous rock aggregates," *Materials*, vol. 14, p. 7202, 2021. DOI: 10.3390/ma14237202.

[13] O. Šernas, V. Vorobjovas, L. Šneideraitiene, and A. Vaitkus, "Evaluation of asphalt mix with dolomite aggregates for wearing layer," *Transp. Res. Procedia*, vol. 14, pp. 732–737, 2016. DOI: 10.1016/j.trpro.2016.05.340.

[14] A. Ibrahim, S. Faisal, and N. Jamil, "Use of basalt in asphalt concrete mixes," *Constr. Build. Mater.*, vol. 23, pp. 498–506, 2009. DOI: 10.1016/j.conbuildmat.2007.10.026.

[15] S. Jalasutram, D. R. Sahoo, and V. Matsagar, "Experimental investigation of the mechanical properties of basalt fiber-reinforced concrete," *Struct. Concr.*, vol. 18, pp. 292–302, 2017. DOI: 10.1002/suco.201500216.

[16] A. Karasin, M. Hadzima-Nyarko, E. Işık, M. Doğruyol, I. B. Karasin, and S. Czarnecki, "The effect of basalt aggregates and mineral admixtures on the mechanical properties of concrete exposed to sulphate attacks," *Materials*, vol. 15, p. 1581, 2022. DOI: 10.3390/ma15041581.

[17] A. Yilmaz, "Engineering properties of basalt aggregates in terms of use in granular layers of flexible pavements," *Case Stud. Constr. Mater.*, vol. 17, e01182, 2022. DOI: 10.1016/j.cscm.2022.e01182.

[18] I. A. Al-Akhaly, "Engineering properties of basalt coarse aggregates in hamdan area, nw sana'a, yemen," *J. Geol. Eng.*, vol. 42, no. 2, pp. 159–174, 2018. DOI: 10.24232/jmd.486021.

[19] A. M. Al-Anweh, "Geology and cement industrial applications on carbonate and clay deposits around sana'a basin, republic of yemen," M.S. thesis, Cairo University, Cairo, Egypt, 2010, p. 240.

[20] Robertson Group Plc., "Satellite mapping programme: Technical report for yemen joint project for natural resources," Ministry of Oil and Mineral Resources, Sana'a, Yemen, Tech. Rep., 1992.

[21] *Astm d3398: Standard test method for index of aggregate particle shape and texture*, West Conshohocken, PA, USA: ASTM International, 2000.

[22] *Bs 812 part 1: Methods for determination of particle size and shape*, London, UK: British Standards Institution, 1975.

[23] *Bs 812 part 105.1: Determination of aggregate particle shape (flakiness index)*, London, UK: British Standards Institution, 1989.

[24] *Bs 812 part 105.2: Determination of aggregate particle shape (elongation index)*, London, UK: British Standards Institution, 1989.

[25] *Astm c127: Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate*, West Conshohocken, PA, USA: ASTM International, 2001.

[26] *Astm c29: Standard test method for bulk density (unit weight) and voids in aggregate*, West Conshohocken, PA, USA: ASTM International, 2009.

[27] *Bs 812 part 112: Methods for determination of aggregate impact value (aiv)*, London, UK: British Standards Institution, 1990.

[28] *Bs 812 part 113: Methods for determination of aggregate abrasion value (aav)*, London, UK: British Standards Institution, 1990.

[29] *Astm c88: Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate*, West Conshohocken, PA, USA: ASTM International, 1999.

[30] *Astm c136: Standard test method for sieve analysis of fine and coarse aggregates*, West Conshohocken, PA, USA: ASTM International, 2006.

[31] *Astm c128: Standard test method for relative density (specific gravity) and absorption of fine aggregates*, West Conshohocken, PA, USA: ASTM International, 2015.

[32] *Astm c117: Test method for materials finer than 75-μm (no. 200) sieve in mineral aggregates by washing*, West Conshohocken, PA, USA: ASTM International, 2004.

[33] *Astm c142: Standard test method for clay lumps and friable particles in aggregates*, West Conshohocken, PA, USA: ASTM International, 2017.

[34] *Astm c114: Standard test method for chemical analysis of hydraulic cement*, West Conshohocken, PA, USA: ASTM International, 2004.

[35] *Bs en 196-6: Methods of testing cement – part 6: Determination of fineness*, London, UK: British Standards Institution, 2018.

[36] *Bs en 196-3: Methods of testing cement – part 3: Determination of setting times and soundness*, London, UK: British Standards Institution, 2016.

[37] *Bs en 1015-11: Methods of test for mortar for masonry – part 11: Determination of flexural and compressive strength of hardened mortar*, London, UK: British Standards Institution, 2019. DOI: 10.3403/BSEN1015.

[38] *Astm d7348: Standard test methods for loss on ignition (loi) of solid combustion residues*, West Conshohocken, PA, USA: ASTM International, 2021.

[39] R. O. Asiedu, "Using lateritic gravel as all-in aggregate for concrete production," *J. Eng. Des. Technol.*, vol. 15, pp. 305–316, 2016. DOI: 10.1108/JEDT-01-2016-0001.

[40] *Bs 1881 part 102: Method for determination of slump*, London, UK: British Standards Institution, 1983.

[41] *Astm c192: Standard practice for making and curing concrete test specimens in the laboratory*, West Conshohocken, PA, USA: ASTM International, 2016.

[42] *Bs 1881 part 114: Methods for determination of density of hardened concrete*, London, UK: British Standards Institution, 1983.

[43] *Bs 1881 part 116: Method for determination of compressive strength of concrete cubes*, London, UK: British Standards Institution, 1983.

[44] *Aci 318: Building code requirements for reinforced concrete*, Farmington Hills, MI, USA: American Concrete Institute, 1995.

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[45] *En 1992-1-1: Eurocode 2 – design of concrete structures – part 1-1: General rules and rules for buildings*, European Committee for Standardization, 2004.

[46] *Standard for structural calculation of reinforced concrete structures, chapter 2*, Tokyo, Japan: Architectural Institute of Japan, 1995.

[47] R. W. L. Maitre, *Igneous Rocks: A Classification and Glossary of Terms*. Cambridge, UK: Cambridge University Press, 2002.

[48] D. J. Harrison and A. J. Bloodworth, "Construction materials: Industrial minerals laboratory manual," British Geological Survey, Keyworth, UK, Tech. Rep. WG/94/12, 1994.

[49] A. M. Neville, *Properties of Concrete*, 4th ed. Edinburgh, UK: Pearson Education Asia Ltd., 2000.

[50] A. Adanikin, A. Olutaiwo, and A. Ashamo, "Mechanical strength determination of crushed stone aggregate fraction for road pavement construction (case study: Selected quarries in western nigeria)," in *Proceedings of FUOYE First International Engineering Conference (FICE2018)*, Ikole, Nigeria, 2018. [Online]. Available: https://repository.elizadeuniversity.edu.ng/handle/20.500.12398/287.

[51] T. A. Engidasew, "Engineering geological characterization of volcanic rocks of ethiopian and sardinian highlands to be used as construction materials," Ph.D. dissertation, Università degli Studi di Cagliari, Cagliari, Italy, 2013.

[52] H. M. Al-Baijat, "The use of basalt aggregates in concrete mixes in jordan," *Jordan J. Civ. Eng.*, vol. 2, pp. 63–70, 2008.

[53] P. S. Kandhal and D. Y. Lee, "An evaluation of the bulk specific gravity for granular materials," *Highw. Res. Rec.*, vol. 307, 1970.

[54] *Bs 812 part 2: Determination of relative densities and water absorption of coarse aggregates*, London, UK: British Standards Institution, 1975.

[55] *Bs 8007: Code of practice for design of concrete structures for retaining aqueous liquids*, London, UK: British Standards Institution, 1987.

[56] *Astm c33: Standard specification for concrete aggregates*, West Conshohocken, PA, USA: ASTM International, 2001.

[57] *Astm c131: Standard test method for resistance to degradation of small size coarse aggregate by abrasion and impact in the los angeles machine*, West Conshohocken, PA, USA: ASTM International, 1996.

[58] R. E. Goodman, *Introduction to Rock Mechanics*, 2nd ed. New York, USA: Wiley, 1989.

[59] M. S. Shetty, *Concrete Technology: Theory and Practice*, 6th ed. New Delhi, India: S. Chand Publishing, 2012.

[60] P. G. Fookes, "An introduction to the influence of natural aggregates on the performance and durability of concrete," *Q. J. Eng. Geol.*, vol. 13, pp. 207–229, 1980.

[61] M. R. Smith and L. Collis, *Aggregates* (Geological Society Engineering Geology Special Publication). London, UK: Geological Society, 1993, vol. 9.

[62] M. Korkaç and A. Tuğrul, "Evaluation of selected basalts from niğde, turkey, as source of concrete aggregate," *Eng. Geol.*, vol. 75, pp. 291–307, 2004.

[63] R. J. Schmidt and P. E. Graf, "The effect of water on resilient modulus of asphalt treated mixes," in *Proceedings of the Association of Asphalt Paving Technologists*, vol. 41, 1972, pp. 118–162.

[64] P. C. Aïtcin and P. K. Mehta, "Effect of coarse aggregate characteristics on mechanical properties of high-strength concrete," *ACI Mater. J.*, vol. 87, pp. 103–107, 1990.

[65] M. R. Smith and L. Collis, *Aggregates—Sand, Gravel and Crushed Rock Aggregates for Construction Purposes*, 3rd ed. London, UK: Geological Society, 2001.

[66] P. S. Kandhal, C. Y. Lynn, and F. Parker, "Tests for plastic fines in aggregates related to stripping in asphalt paving mixtures," *J. Assoc. Asph. Paving Technol.*, vol. 67, 1998.

[67] D. M. Ramsay, R. K. Dhir, and I. M. Spence, "The role of rock and clast fabric in the physical performance of crushed-rock aggregate," *Eng. Geol.*, vol. 8, pp. 267–285, 1974.

[68] Y. Wu, F. Parker, and K. Kandhal, "Aggregate toughness/abrasion resistance and durability/soundness tests related to asphalt concrete performance in pavements," National Center for Asphalt Technology, Auburn University, Auburn, Alabama, USA, Tech. Rep. Report 98-4, 1998.

[69] J. Farny and S. Kosmatka, "Diagnosis and control of alkali-aggregate reactions in concrete," Portland Cement Association, USA, Tech. Rep. IS413.01T, 1997.

[70] N. T. Fatt and Y. E. Beng, "Potential alkali-silica reaction in aggregate of deformed granite," *Bull. Geol. Soc. Malays.*, vol. 53, pp. 81–88, 2007.

[71] Y. Wakizaka, "Alkali-silica reactivity of japanese rocks," *Eng. Geol.*, vol. 56, pp. 211–221, 2000. DOI: 10.1016/S0013-7952(99)00144-1.

[72] M. Korkaç and A. Tuğrul, "Evaluation of selected basalts from the point of alkali-silica reactivity," *Cem. Concr. Res.*, vol. 35, pp. 505–512, 2005.

[73] T. Katayama, D. A. S. John, and T. Futagawa, "The petrographic comparison of rocks from japan and new zealand—potential reactivity related to interstitial glass and silica minerals," in *Proceedings of the 8th International Conference on Alkali-Aggregate Reaction in Concrete (ICAAR)*, Kyoto, Japan, 1989, pp. 537–542.

[74] *Astm c566: Standard test method for total evaporable moisture content of aggregates by drying*, West Conshohocken, PA, USA: ASTM International, 2013.

[75] *Astm c595: Standard specification for blended hydraulic cements*, West Conshohocken, PA, USA: ASTM International, 2017.

[76] *Bs en 197-1: Cement: Composition, specifications and conformity criteria for common cements*, London, UK: British Standards Institution, 2011.

[77] *Astm c150: Standard specification for portland cement*, West Conshohocken, PA, USA: ASTM International, 2018.

[78] A. M. Neville and J. J. Brooks, *Concrete Technology*, 2nd ed. Essex, UK: Pearson Education, 2010.

[79] V. S. Rajput, S. Pandey, D. Jain, and A. K. Saxena, "Use of quarry fine as partial replacement of fine aggregate in concrete (evaluation of workability and compressive strength)," *Int. J. Sci. Res. Dev.*, vol. 2, pp. 161–164, 2014.

[80] I. A. Al-Akhaly and A. M. Al-Anweh, "Engineering properties of crushed sand derived from kawkaban member (tawilah group), zigan area, ne sana'a, yemen," *Sultan Qaboos Univ. J. for Sci.*, vol. 30, pp. 68–82, 2025. DOI: 10.53539/2414-536X.1396.

[81] W. Baalbaki, B. Benmokrane, O. Chaallal, and P. C. Aïtcin, "Influence of coarse aggregate on elastic properties of high-performance concrete," *ACI Mater. J.*, vol. 88, pp. 499–503, 1991.

[82] P. A. Gutierrez and M. F. Canovas, "The modulus of elasticity of high-performance concrete," *Mater. Struct.*, vol. 28, pp. 559–568, 1995.

[83] H. K. Hilsdorf and W. Brameshuber, "Code-type formulation of fracture mechanics concepts for concrete," *Int. J. Fract.*, vol. 51, pp. 61–72, 1991.

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[84] F. A. Farraj, "Assessment of fresh and hardened properties of concrete made of crushed aggregates containing no natural sand," Ph.D. dissertation, Université Paul Sabatier – Toulouse III, Toulouse, France, 2021. [Online]. Available: https://theses.hal.science/tel-03343018.

[85] R. Siddique, G. D. Schutter, and A. Noumowe, "Effect of used-foundry sand on the mechanical properties of concrete," *Constr. Build. Mater.*, vol. 23, pp. 976–980, 2009. DOI: 10.1016/j.conbuildmat.2008.05.005.

[86] C. G. Rocco and M. Elices, "Effect of aggregate shape on the mechanical properties of a simple concrete," *Eng. Fract. Mech.*, vol. 76, pp. 286–298, 2009. DOI: 10.1016/j.engfracmech.2008.10.010.

[87] A. Makani, T. Vidal, G. Pons, and G. Escadeillas, "Time-dependent behaviour of high performance concrete: Influence of coarse aggregate characteristics," *EPJ Web Conf.*, vol. 6, p. 03 002, 2010. DOI: 10.1051/epjconf/20100603002.

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