

# The Effect of Natural Pozzolana (Bayoda Desert) Volcanic Ash as Partial Replacement of Ordinary Portland Cement on the Compressive Strength and Workability of Concrete

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Publication Date: 2026/05/26

**Abstract:** This study investigates the feasibility of producing high strength concrete through the partial replacement of ordinary Portland cement with pozzolana at substitution rates of 10%, 20%, and 30% by weight of cement. The primary objective was to assess the effect of pozzolana addition on the compressive strength development of concrete at curing ages of 7, 28, and 90 days. Standard cubic specimens (150 mm × 150 mm × 150 mm) were prepared and cured under water for each mix, including a reference (control) mix containing no additives. Compressive strength tests were conducted in accordance with standard procedures at the SEA PORTS CORPORAT (SUDAN) ENGINEERING TEST LAB. The results demonstrated that all mixes achieved high strength classification (above 40 N/mm<sup>2</sup>), with the 20% pozzolana mix yielding the highest average 90 days compressive strength of 46.6 N/mm<sup>2</sup>, compared to 40.3 N/mm<sup>2</sup> for the reference mix representing an improvement of approximately 16%. These findings confirm that locally available pozzolana can be effectively utilized as a cement replacement material to enhance concrete compressive strength, offering both structural and economic benefits.

**Keywords:** Cement, Pozzolana, Chemical Composition, Compressive Strength, Workability.

**How to Cite:** Mona Adam Gumma Rabih; Eltahir Elshaikh; Ehdaa Mohammed Osmani (2026) The Effect of Natural Pozzolana (Bayoda Desert) Volcanic Ash as Partial Replacement of Ordinary Portland Cement on the Compressive Strength and Workability of Concrete. *International Journal of Innovative Science and Research Technology*, 11(5), 1610-1617. <https://doi.org/10.38124/ijisrt/26may737>

## I. INTRODUCTION

Concrete is one of the most extensively used construction materials in the world, owing to its favourable mechanical properties, relatively low cost, and versatility in forming complex structural shapes. It is a composite material composed of cement, coarse and fine aggregates, and water, with the option of incorporating chemical or mineral admixtures to achieve specific performance targets.[1][2]

The primary strength parameter governing the structural design of concrete elements is compressive strength. While ordinary concrete typically exhibits adequate performance for general construction, the demands of modern infrastructure including high-rise buildings, bridges, marine structures, and nuclear power facilities necessitate materials with superior mechanical and durability characteristics. High-strength concrete (HSC), defined as concrete with a compressive strength exceeding 40 N/mm<sup>2</sup>, has emerged as a viable solution to meet these demands. A key strategy in the production of (HSC) is the incorporation of mineral admixtures collectively referred to as supplementary

cementitious materials (SCMs) such as pozzolana, fly ash, silica fume, and ground granulated blast furnace slag. Pozzolanic materials, while lacking inherent cementitious properties, react with the calcium hydroxide (Ca (OH)<sub>2</sub>) liberated during cement hydration to form secondary calcium silicate hydrate (C-S-H) compounds, which contribute significantly to long term strength and durability.[1], [3], [4]

### ➤ Significance of the Study

Concrete produced locally under conventional practice often fails to achieve high strength specifications due to inconsistencies in material quality, mix proportioning, and curing conditions. The significance of this study lies in demonstrating that high strength concrete can be reliably produced using locally available raw materials and a controlled mix design procedure, thereby reducing dependence on imported materials and lowering construction costs without compromising structural performance. [5]

### ➤ Availability of Natural Pozzolanic Materials in Sudan

Natural pozzolanic materials are widely distributed across various regions of Sudan, with the Bayoda Desert

Volcanic Ash (BDVA) representing one of the most significant documented deposits. Located west of Atbara city in the Northern State, the (BDVA) is characterized by the presence of pozzolanic materials in the form of volcanic ash within its northern volcanic field. The principal volcanic field extends approximately 50 km in length and 20 km in width,

with the volcanic ash deposits oriented in a north-westerly direction between coordinates N 18°15'–E 32°27' and N 18°32'–E 32°02'. The nearest urban centres to the study area are the cities of Merowe and Atbara, and the estimated extent of the pozzolana deposit covers an area of approximately 1,000 km<sup>2</sup>, as illustrated in Figure 1.[6] [7], [8], [9]

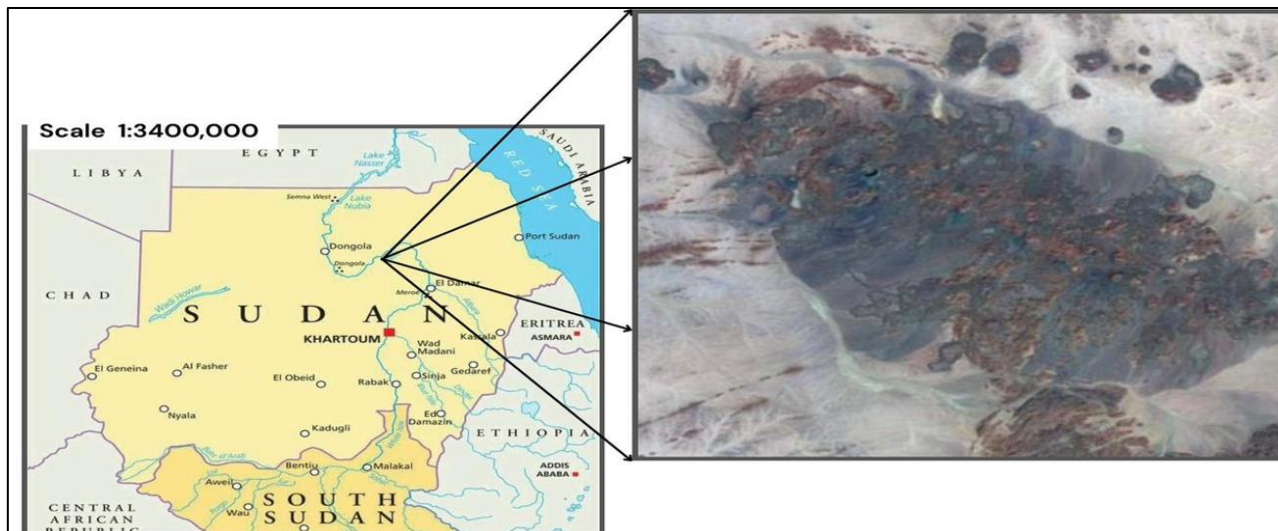


Fig 1 A Map of Sudan with a Satellite Image Showing the Location of the Pozzolana in the BayOda Desert.

## II. RESEARCH METHODOLOGY

### ➤ Materials

To achieve the objectives of this study, a systematic experimental program was designed and conducted using locally sourced materials from Red Sea State. The following sections provide a detailed description of the constituent materials and the testing methodologies employed throughout the investigation. Precise material characterization is fundamental to accurately evaluating the mechanical behaviour and performance of the concrete mixtures examined. Accordingly, each test method was deliberately selected to generate reliable and reproducible data. The rationale for incorporating each test is discussed to affirm its

relevance in substantiating the study's objectives and ensuring the validity of the experimental findings.

- *Cement:*

Ordinary Portland Cement (OPC) of strength class 42.5, procured from Alnahda Cement Company, was used throughout this investigation. The cement conforms to the requirements of EN 197-1:2011 and ES 4756-1:2013. Key physical properties, including fineness, standard consistency, initial and final setting times, were determined in accordance with BS 12:1996–2003, and the results are presented in Table 1. [10]

Table 1 Results of Cement Tests

Fineness (%)	2.4	not more than 10%
Consistency (%)	31	26% — 33%
Initial Setting Time (min)	138	not less than 45 min
Final Setting Time (hrs)	4:50	Not more than 10 hours
Soundness	1 mm	Not more than 10 mm
2 Days	19.8	Equal or Greater Than 10
28 Days	46.5	Equal or Greater Than 42.5

- *Water:*

Potable water obtained from the main supply network was utilized for both the mixing and curing of all concrete specimens throughout the testing period.

The material exhibited a specific gravity of 2.51 and a water absorption of 0.88%, as determined in accordance with ASTM C128. [11]

- *Sand:*

Natural fine aggregate was sourced from Khor Salloum Truck Quarry, Port Sudan. Prior to use, the sand was thoroughly washed, oven dried, and sieved into designated fractions to ensure compliance with graduation requirements.

- *Coarse Aggregate:*

Crushed coarse aggregate was obtained from Seaport Crusher, located in Port Sudan City. The aggregate had a nominal maximum particle size of 20 mm, a specific gravity of 2.83, and a water absorption of 0.53%. All aggregate

samples were tested and standardized in accordance with BS 812 and ASTM C127. [12]

• *Volcanic Ash (VA):*

The Pozzolana samples used in this investigation were collected from (BDVA) Ashes from the sources were first studied for chemical composition. Then, the ash from pulverized quartering process, grounded and sieved to grain size of less than 45 µm, and then characterized using chemical, physical analysis.

Four concrete mixes were designed and investigated in this study. A reference control mix was proportioned at a 1:2:4 cement to fine aggregate to coarse aggregate ratio by weight, with a water to binder ratio of 0.47, utilizing OPC exclusively as the binder. In the remaining three mixes, natural pozzolana was incorporated as a partial replacement of OPC at substitution levels of 10%, 20%, and 30% by mass, while all other mix parameters were maintained constant. The detailed mix proportions for all four mixes are presented in Table 2. The workability of the fresh concrete mixes was assessed using the slump test, conducted in accordance with the relevant standard specifications.

Table 2 Concretely Mix Details

Percentage Replacement (%)	Mass of Constituents (Kg)			
	Cement	Pozzolana	Sand	Course Agg
0	12	0	19.5	42.4
10	10.8	1.2	19.5	42.4
20	9.6	2.4	19.5	42.4
30	8.4	3.6	19.5	42.4



Fig 2 Materials Used to Produce Concrete

Concrete specimens were cast in steel moulds with internal dimensions of (150 mm × 150 mm × 150 mm). A total of thirty-six cubic specimens were prepared across all mix proportions. Immediately following casting, the moulds were covered with polyethylene sheeting to minimize moisture loss through evaporation. Demoulding was carried out after 24 hours, whereupon the specimens were transferred to a water-filled curing tank containing clean water and submerged for the designated curing periods. Water curing was adopted to promote hydration and enhance both the physical and mechanical properties of the hardened concrete. [13]

Compressive strength testing was performed at curing ages of 7, 28, and 90 days using an ELE (UK) Auto Test 2000 KN compression testing machine. Prior to testing, specimens were removed from the curing tank and allowed to surface-dry under laboratory ambient conditions for approximately two hours. The reported compressive strength values represent the mean of three replicate specimens for each mix and curing age. All tests were conducted at the Sea Ports Corporate (SUDAN) Engineering Tests Laboratory.

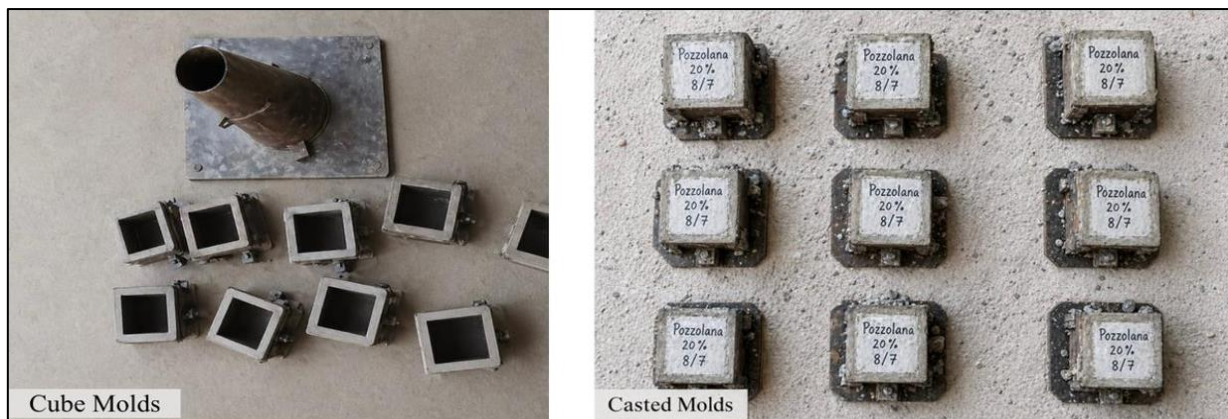


Fig 3 Cube Specimens

### III. RESULTS AND DISCUSSION

This section presents and interprets the results obtained from the experimental program, encompassing both material characterization and concrete performance evaluation. The chemical compositions of OPC and (BDVA) were determined and analysed as a basis for understanding the observed material behaviour. The performance of the four concrete mixes was subsequently evaluated based on two primary indicators, workability, assessed through the slump test on fresh concrete, and compressive strength, determined at curing ages of 7, 28, and 90 days on hardened concrete specimens. The influence of partial OPC replacement with (BDVA) at substitution levels of 0%, 10%, 20%, and 30% by mass on these performance parameters is systematically examined and interpreted in the following subsections.

#### ➤ Chemical Composition:

Chemical Properties of OPC, and (BDVA) The results of the chemical analyses, shown in Table 3 with OPC results, indicated that the principal oxides: Silica oxide (SiO<sub>2</sub>), Alumina oxide (Al<sub>2</sub>O<sub>3</sub>) and Iron oxide (Fe<sub>2</sub>O<sub>3</sub>) were substantially present in the samples investigated give good indication for good Pozzolanic activity. The analyses also showed the presence of minor elements, within the limitations of ASTM-C618 for Pozzolana. The composition of volcanic ash suitable for use as a Pozzolana according to ASTM C618. Is (Silica = 45 - 65%), (Alumina + Iron oxide = 15 - 30%), (Calcium + Magnesium oxide + Alkalis < 15%). the sample give good indication for good Pozzolanic activity. [14], [15]

Table 3 Chemical Properties of OPC, BDVA

SiO <sub>2</sub>	AL <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	SO <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	LOI
19.53	4.57	5.21	61.64	1.91	2.52	0.38	0.26	3.38
59.68	8.12	8.33	3.92	1.51	0.177	0.241	0.19	12.70

#### ➤ Slump Test Result

The results of workability test are presented in Table 4 and Fig 4.

Table 4 Result of Workability Test

0	10	20	30
25	45	55	60



Fig 4 The Effect of BDVA Replacement on Workability

The results demonstrate a consistent increase in fresh concrete workability with increasing levels of OPC replacement by natural pozzolana. This trend can be attributed to the distinct physical characteristics of pozzolanic materials in comparison to OPC particles. The relatively smooth surface texture and spherical morphology of pozzolanic particles reduce interparticle friction within the mix, producing a ball bearing effect that enhances paste fluidity and improves overall workability. Furthermore, the lower specific surface area demand of pozzolana compared to

OPC results in a greater availability of free water within the mix, contributing to the observed improvement in consistency. These findings are consistent with the well documented role of pozzolanic materials as workability enhancing agents in blended cement concrete systems. [16]

#### ➤ Compressive Strength:

The results of compressive strength tests are presented in (Table 5 and Figure 5)

Table 5 Compressive Strength (N/mm<sup>2</sup>) of Mixes

Age at Testing(days)	Pozzolana Replacement %			
	0	10	20	30
7	22	22.6	24	21.6
28	33	34.5	37.8	29.6
90	40.3	42.5	46.6	38.4

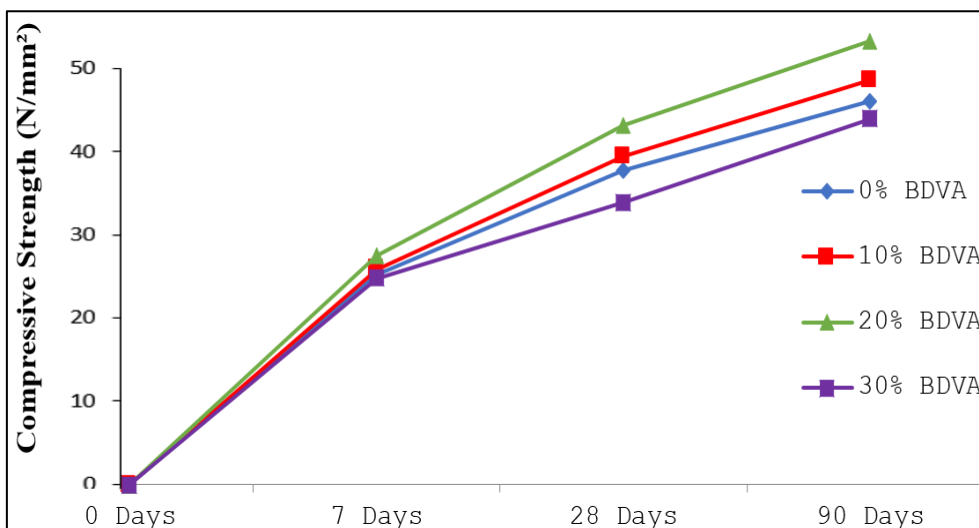


Fig 5 Compressive Strength of Mixes

The development of compressive strength with curing age for all four concrete mixes is illustrated in Figures 5 and 6. The control mix exhibited the highest rate of strength gain during the first seven days, after which the rate of strength development stabilized at a relatively lower but consistent level. In contrast, the mix incorporating 20% (BDVA) as a partial OPC replacement demonstrated the highest overall rate of strength gain across all tested ages, attributed to the optimum pozzolanic reaction conditions achieved at this replacement level.

As presented in Figure 5, compressive strength increased with curing age across all mixes, exhibiting a consistent trend with respect to (BDVA) replacement level. Strength increased progressively with increasing replacement percentage up to a maximum at 20% substitution, beyond which further increases in replacement level resulted in a reduction in compressive strength. This behaviour was observed consistently at all curing ages of 7, 28, and 90 days.

At a 20% (BDVA) replacement level, concrete attained its maximum compressive strength, corresponding to strength increases of 9%, 14%, and 16% at 7, 28, and 90 days, respectively, relative to the control mix, see Figure 6. The

continued strength gain observed at later ages is attributed to the progressive nature of the pozzolanic reaction, which commences upon cement hydration and persists over an extended period, contributing to long-term strength development.

The mechanistic basis for the observed strength behaviour can be explained through the pozzolanic reaction between the reactive silica present in (BDVA) and the calcium hydroxide  $[Ca(OH)_2]$  liberated during OPC hydration, resulting in the formation of additional calcium silicate hydrate (C-S-H) gel, which densifies the microstructure and enhances mechanical strength. At low replacement levels, the quantity of reactive silica available is insufficient to consume the relatively large amount of  $Ca(OH)_2$  produced, limiting C-S-H formation. Conversely, at high replacement levels, the reduced OPC content yields a diminished quantity of  $Ca(OH)_2$ , constraining the extent of pozzolanic reaction despite the abundance of reactive silica. Consequently, an optimum replacement level exists identified in this study as 20% at which the balance between reactive silica supply and  $Ca(OH)_2$  availability is most favourable, yielding maximum compressive strength development

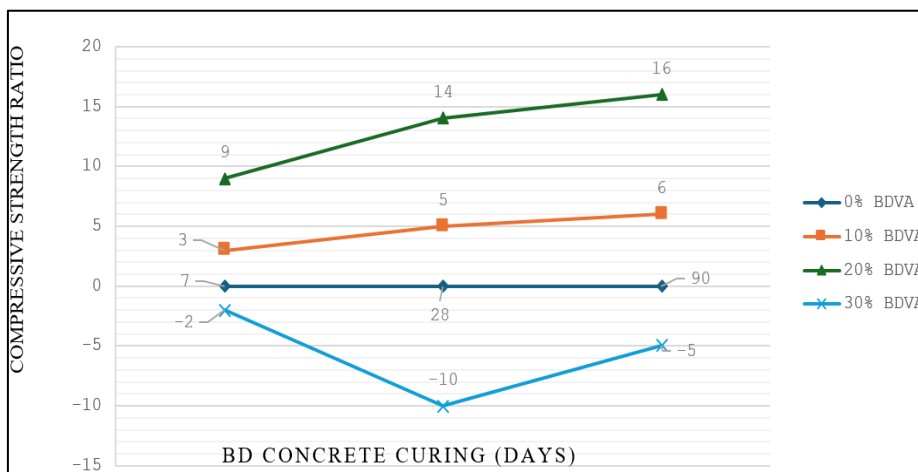


Fig 6 Variation of Relative Compressive Strength of Concrete

➤ *Failure Modes*

The failure patterns of cubic specimens were examined following compressive strength testing, as illustrated in Figure 7. The control mixes 0% of (BDVA) exhibited a brittle failure mode characterised by sudden explosive cracking, pronounced spalling, and visible disintegration at the aggregate-paste interface, indicative of a rigid and less ductile cementitious matrix. In contrast, specimens incorporating

(BDVA) at 10%, 20%, and 30% replacement levels displayed more gradual and distributed cracking patterns, with well-defined vertical and diagonal crack propagation and limited spalling, suggesting enhanced ductility and energy absorption capacity. The progressive crack widening observed in these mixes is attributed to microstructural refinement induced by the pozzolanic reaction, which densifies.



Fig 7 Failure Modes of Cube Specimens

➤ *Statistical Analysis*

A probability plot was generated to evaluate the normality of the compressive strength data. This framework was crafted utilizing the preceding experimental data from Table 6 harnessed the capabilities of a versatile statistical software program [Minitab (version 19.0)]. As illustrated in Figure 8, the plotted data points closely follow the reference line and remain well within the 95% confidence intervals, indicating a satisfactory agreement with the normal distribution. The dataset is characterized by a mean value of 32.74 N/mm<sup>2</sup> and a standard deviation of 8.703, reflecting a moderate dispersion around the central tendency. Statistical validation further supports this observation, as the obtained p

value of 0.384 is substantially higher than the commonly accepted significance level ( $\alpha = 0.05$ ), thereby confirming the absence of any statistically significant departure from normality. In addition, the relatively low Anderson Darling statistic reinforces the suitability of the normality assumption. The strength of the relationship between the observed data and the corresponding theoretical normal quantiles is evidenced by a high correlation coefficient ( $R = 0.90$ ), indicating a strong linear association. Collectively, these results confirm that the compressive strength data are well approximated by a normal distribution, thereby justifying the application of parametric statistical techniques in subsequent analyses.

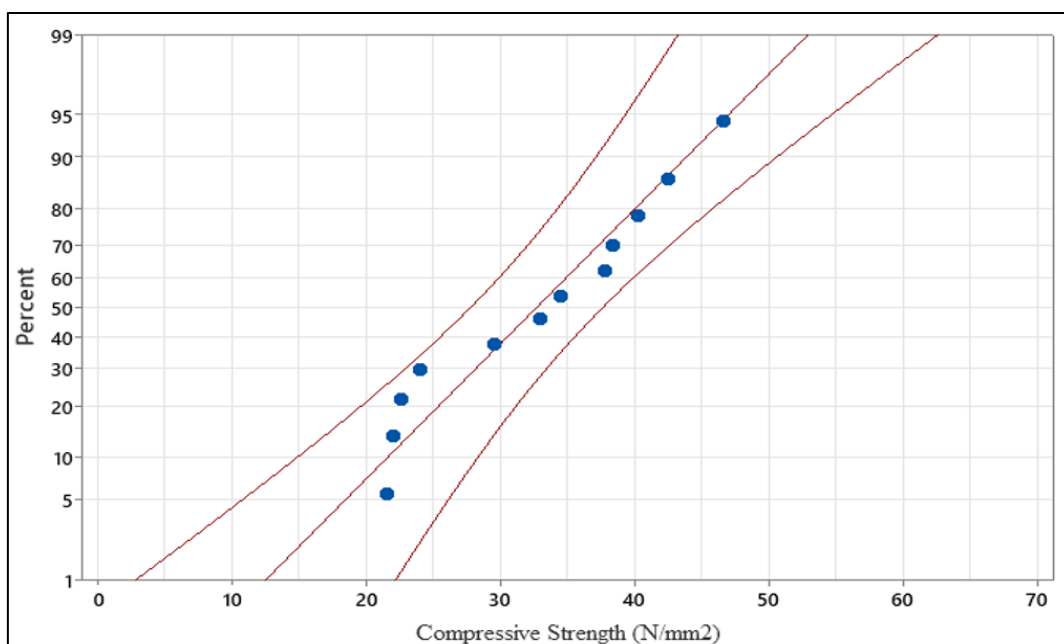


Fig 8 A Probability Plot of Compressive Strength

#### ➤ Novelty in Comparison with Related Research

Several investigations have examined the utilization of natural pozzolanic materials as partial OPC replacements in cementitious systems. Studies conducted in Sudan demonstrated that (BDVA) at substitution levels of 10%–30% yielded favorable compressive strength results, with the 10% replacement level achieving the highest strength when used alone [8], while pozzolana from three different locations within the same deposit achieved compressive strength ratios of 0.83–0.96 relative to plain OPC alongside improved workability [9]. Investigations on Jebel Marra volcanic ash confirmed its pozzolanic classification through XRF and XRD analyses, with combined SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub> content of 83.75%, and identified 20% as the optimum replacement level beyond which compressive strength declined [7] [17]. Similarly, natural clay pozzolana at a 30% replacement level yielded the highest compressive strength across all tested ages, further supporting the viability of partial cement substitution [16].

More recently, a comprehensive review by Fode et al. [18] concluded that a 5%–20% replacement range of volcanic-source natural pozzolana yields the most favorable compressive strength results in concrete with water to cement ratios of 0.35–0.55, identifying 15% as the most reported optimum level [18]. Játiva and Etxebarria (2024) evaluated volcanic ash as a partial OPC replacement in mortar production using calcination as an activation method, reporting that even at 75% VA replacement, an adequate 28-day compressive strength of 33 MPa was achieved, confirming the broad applicability of volcanic ash in construction applications. Investigations on eco high performance concrete incorporating natural pozzolana at up to 20% replacement [19] (2025) demonstrated a 28-day compressive strength of 63.8 MPa, only marginally lower than the control mix at 68.5 MPa, affirming the potential of natural pozzolana in high-performance blended cement systems. [20]

#### IV. CONCLUSIONS, LIMITATIONS, AND OUTLOOK

The following conclusions are drawn from the experimental results of this study:

(BDVA) satisfies the pozzolanic classification requirements of ASTM C618, with combined SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub> oxides, confirming its viability as a supplementary cementitious material. Workability improved consistently with increasing BDVA replacement levels, attributed to the spherical morphology of pozzolanic particles and increased free water availability. The high increase in workability with replacement indicates the possibility of production of self-compacting concrete using (BDVA). A 20% (BDVA) replacement level yielded the maximum compressive strength at all curing ages, with increases of 9%, 14%, and 16% at 7, 28, and 90 days, respectively, relative to the control mix. Replacement levels exceeding 20% resulted in progressive strength reduction due to insufficient Ca (OH)<sub>2</sub> availability for complete pozzolanic reaction. Partial replacement of

Ordinary Portland Cement with about 20% (BDVA) in concrete enhances both workability and strength.

The study was limited to a single (BDVA) source and three replacement levels. Durability properties, microstructural characterization, and field environmental conditions were not investigated, representing areas requiring further attention.

Future research should investigate a wider range of replacement levels, assess long term durability performance, and employ microstructural analysis techniques such as SEM and XRD. Field scale trials and the exploration of ternary blended systems incorporating (BDVA) with other locally available SCMs are also recommended.

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