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MECHANICAL AND PHYSICAL PERFORMANCE OF LIGHTWEIGHT CONCRETE USING WASTE PUMICE AS COARSE AGGREGATE

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Abstract

The increasing demand for sustainable and lightweight construction materials has encouraged the utilization of industrial waste in concrete production. This study investigates the mechanical and physical performance of lightweight concrete produced by partially and fully replacing natural coarse aggregate with waste pumice obtained from the apparel industry. Concrete mixes were prepared with pumice replacement levels of 0%, 20%, 40%, 60%, 80%, and 100% while maintaining a constant water–cement ratio. Fresh concrete properties were evaluated through slump tests, whereas hardened concrete was assessed for dry density, self-weight, and compressive strength at curing ages of 7, 14, 21, and 28 days. The results indicate that increasing pumice content leads to a reduction in workability, density, and compressive strength due to the porous nature and high-water absorption of pumice aggregate. However, a significant reduction in self-weight was achieved, demonstrating the effectiveness of waste pumice in producing lightweight concrete. Concrete mixes containing low to moderate pumice replacement levels exhibited acceptable strength performance suitable for non-load bearing and lightweight structural applications. A strong correlation was observed between dry density and compressive strength, highlighting the predictable behavior of pumice-based concrete. The findings confirm that waste pumice can be successfully utilized as an environmentally friendly coarse aggregate alternative, contributing to sustainable construction and efficient waste management.

INTRODUCTION

Concrete is the most widely used construction material in the world due to its versatility, availability of raw materials, and relatively low cost. However, conventional concrete is characterized by high self-weight and intensive consumption of natural resources such as crushed stone and gravel. The continuous growth of infrastructure development has significantly increased the demand for aggregates, leading to depletion of natural resources and serious environmental concerns. In addition, the heavy self-weight of normal concrete contributes to higher dead loads, resulting in increased foundation sizes, reinforcement requirements, and overall construction costs[1], [2], [3]. These challenges have motivated researchers and practitioners to explore alternative materials and innovative approaches to produce lightweight and sustainable concrete without compromising essential mechanical performance.

Lightweight concrete has emerged as an effective solution to reduce the self-weight of structural and non-structural elements while maintaining acceptable strength and durability. By incorporating lightweight aggregates, lightweight concrete offers advantages such as reduced dead load, improved thermal insulation, enhanced fire resistance, and better acoustic performance compared to conventional concrete[4], [5], [6]. These properties make lightweight concrete particularly suitable for non-load bearing elements, precast components, partition walls, façade panels, and low-rise buildings. Despite these benefits, the widespread adoption of lightweight concrete remains limited due to concerns regarding strength reduction, workability issues, and availability of cost-effective lightweight aggregates[7], [8], [9].

Pumice is a naturally occurring volcanic material formed by rapid cooling of gas-rich lava, resulting in a highly porous structure with low density. Due to its cellular texture and low specific gravity, pumice has long been recognized as a potential lightweight aggregate in concrete. Traditionally, pumice has been used in construction applications such as lightweight blocks, insulation layers, and masonry units. In recent years, interest in pumice has increased because of its favourable physical characteristics, including low bulk density, high porosity, good thermal insulation, and resistance to fire and chemical attack. These properties make pumice a promising candidate for producing lightweight concrete with enhanced functional performance. In addition to natural pumice deposits, a significant quantity of pumice waste is generated by the apparel industry, where pumice stones are commonly used in stone-washing processes to give denim fabrics a faded appearance[10], [11], [12], [13]. After repeated use, these pumice stones lose their effectiveness and are discarded as industrial waste. Disposal of waste pumice poses environmental challenges, including landfill occupation and potential ecological impacts. The reutilization of this waste material in concrete production presents an opportunity to address waste management issues while simultaneously reducing the extraction of natural aggregates. Converting industrial waste pumice into a useful construction material aligns with sustainable development goals by promoting resource efficiency and minimizing environmental degradation[11], [12], [13].

The incorporation of waste pumice as a partial or full replacement for conventional coarse aggregate can significantly influence the mechanical and physical properties of concrete. Due to its porous nature, pumice aggregate generally exhibits higher water absorption and lower strength compared to natural crushed stone. These characteristics affect fresh concrete properties such as workability and slump, as well as hardened concrete properties including density, compressive strength, and overall structural performance. Understanding these effects is critical to determining suitable replacement levels that balance weight reduction with mechanical adequacy.

From a mechanical perspective, compressive strength is one of the most important parameters governing the applicability of lightweight concrete. While the use of pumice aggregate typically results in lower compressive strength compared to normal concrete, previous studies have demonstrated that pumice-based concrete can still achieve sufficient strength for non-load bearing and semi-structural applications. The reduction in strength is often attributed to the weaker interfacial transition zone between pumice particles and cement paste, as well as the intrinsic low strength of the porous aggregate. Nevertheless, proper mix design, controlled replacement ratios, and optimized water-cement ratios can help mitigate strength loss and improve overall performance. Physical properties such as density and self-weight play a crucial role in defining lightweight concrete. The replacement of conventional coarse aggregate with pumice significantly reduces concrete density, leading to substantial weight savings[14], [15], [16], [17],

[18]. This reduction in self-weight contributes to lower dead loads on structural systems, improved seismic performance, and reduced transportation and handling costs. Furthermore, the porous structure of pumice enhances thermal insulation properties, which can improve energy efficiency in buildings by reducing heat transfer through walls and panels. Workability is another critical aspect affected by the inclusion of pumice aggregate. Due to its rough surface texture and high-water absorption capacity, pumice can reduce slump and make concrete mixes less workable if not properly accounted for in mix design. Adequate moisture conditioning of pumice aggregates and careful control of mixing water are essential to ensure uniform mixing, proper compaction, and satisfactory finishing. Evaluating the relationship between pumice content and workability is therefore necessary to establish practical guidelines for field applications[19], [20]. The mechanical and physical performance of lightweight concrete incorporating waste pumice must be evaluated across different curing ages to capture strength development behavior over time. Early-age strength is particularly important for precast elements and construction scheduling, while long-term strength determines service performance. Investigating compressive strength at multiple curing intervals provides valuable insight into hydration characteristics and the long-term viability of pumice-based lightweight concrete. The use of waste pumice as a coarse aggregate replacement not only improves sustainability but also offers economic advantages. By reducing dependence on natural aggregates and lowering waste disposal costs for the apparel industry, pumice-based lightweight concrete presents a cost-effective alternative for specific construction applications. Moreover, the development of such eco-friendly materials supports the transition toward green construction practices and circular economy principles.

Methodology

Experimental Approach

The research adopted a laboratory-based experimental approach to evaluate the mechanical and physical performance of lightweight concrete incorporating waste pumice as a replacement for conventional coarse aggregate. The study focused on producing concrete mixes with varying proportions of waste pumice and assessing their behavior in both fresh and hardened states. A control mix using natural coarse aggregate was prepared to serve as a reference for comparison. The experimental program was designed to systematically observe changes in workability, density, self-weight, and compressive strength as the pumice replacement level increased.

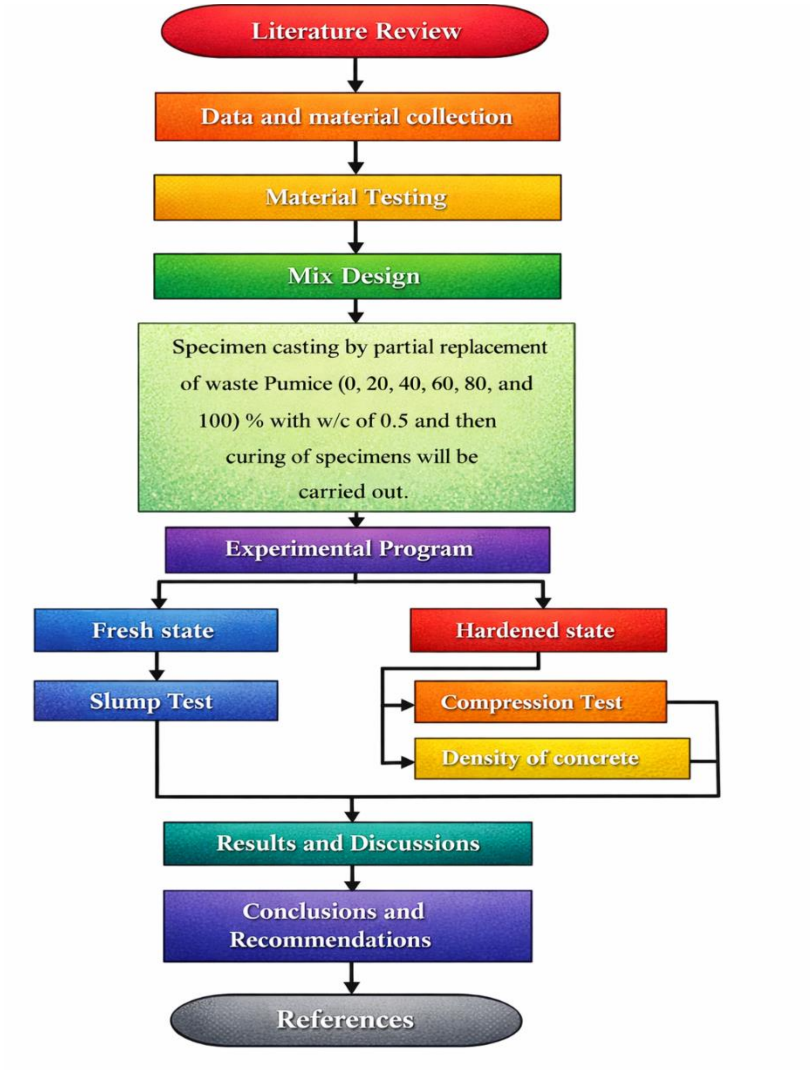


Figure 1 Flowchart of research

Concrete specimens were cast under controlled laboratory conditions to minimize variability and ensure repeatability of results. Standardized testing procedures were followed in accordance with ASTM and ACI guidelines to ensure reliability and comparability with previous studies. Multiple curing ages were selected to evaluate both early-age and later-age performance of the concrete. The experimental approach emphasized quantitative measurement and comparative analysis, allowing clear identification of trends related to pumice content. This approach enabled an objective assessment of the Feasibility of utilizing waste pumice for lightweight concrete applications.

Scope of Investigation

The scope of this investigation was limited to the use of waste pumice as a replacement for conventional coarse aggregate in non-load bearing and lightweight concrete applications. The study considered replacement levels of 0%, 20%, 40%, 60%, 80%, and 100% by weight of coarse aggregate while maintaining a constant water–cement ratio. Only ordinary Portland cement, natural river sand, crushed stone, and waste

pumice aggregate were used in the experimental program.
The research focused on evaluating workability through slump testing and assessing hardened concrete properties such as density, self-weight, and compressive strength at curing ages of 7, 14, 21, and 28 days. Durability-related properties, microstructural analysis, and long-term performance were outside the scope of this study. The investigation was conducted under controlled laboratory conditions, and field performance was not examined. The results are intended to support the use of waste pumice in lightweight, non-structural concrete elements such as blocks, panels, and partitions.

Material
Ordinary Portland Cement (OPC) was used as the primary binding material in this study due to its widespread availability and suitability for concrete production. Natural river sand served as fine aggregate and was clean, well-graded, and free from organic impurities, while crushed stone was used as the natural coarse aggregate in the control mix. Waste pumice aggregate was collected from an apparel industry where pumice stones are discarded after use in stone-washing operations. Prior to concrete production, all materials were tested in accordance with relevant ASTM standards to determine their physical properties, including fineness, specific gravity, water absorption, and bulk density. The waste pumice was cleaned, air-dried, and sieved to obtain particle sizes comparable to conventional coarse aggregate. Due to its highly porous structure and high-water absorption, special care was taken in preparing the pumice aggregate to ensure uniformity and consistency during mixing. Maintaining constant cement and fine aggregate contents across all mixes allowed the effects of waste pumice replacement on concrete performance to be accurately evaluated.

Characterization of Materials
The materials used in this study were characterized through standard laboratory testing to determine their physical properties and ensure suitability for concrete production. Ordinary Portland Cement was tested for fineness and specific gravity to confirm uniformity and compliance with standard requirements. Fine aggregate and natural coarse aggregate were evaluated for specific gravity, bulk density, water absorption, and grading characteristics, as these properties directly influence workability, strength, and mix proportioning. Waste pumice aggregate was subjected to similar tests, with particular attention to its bulk density and water absorption due to its highly porous structure. The significantly lower density and higher absorption capacity of pumice compared to natural aggregates were key factors affecting the mechanical and physical behavior of lightweight concrete. All tests were performed in accordance with relevant ASTM standards to ensure accuracy, repeatability, and comparability of results. The obtained properties formed the basis for mix design and performance evaluation of pumice-based lightweight concrete.

Table 1 Physical Properties and Standards of Materials

Material	Property Tested	Test Result (Typical)	Standard Followed
Cement (OPC)	Specific Gravity	3.15	ASTM C188
Cement (OPC)	Fineness (Sieve No. 100)	≤10% retained	ASTM C786
Fine Aggregate	Specific Gravity (SSD)	2.60	ASTM C128
Fine Aggregate	Water Absorption (%)	1.5	ASTM C128
Fine Aggregate	Bulk Density (kg/m³)	1650	ASTM C29
Fine Aggregate	Fineness Modulus	2.6–2.8	ASTM C136
Natural Coarse Aggregate	Specific Gravity (SSD)	2.65	ASTM C127
Natural Coarse Aggregate	Water Absorption (%)	0.8	ASTM C127
Natural Coarse Aggregate	Bulk Density (kg/m³)	1550	ASTM C29

Natural Coarse Aggregate	Fineness Modulus	6.5–7.0	ASTM C136
Waste Pumice Aggregate	Specific Gravity (SSD)	1.15–1.25	ASTM C127
Waste Pumice Aggregate	Water Absorption (%)	15–20	ASTM C127
Waste Pumice Aggregate	Bulk Density (kg/m³)	800–900	ASTM C29
Waste Pumice Aggregate	Fineness Modulus	6.0–6.5	ASTM C136

Concrete Mix Design

The concrete mix design was carried out in accordance with ACI 211.1 guidelines to ensure consistency and reliability. A control mix was prepared using natural coarse aggregate, while additional mixes were produced by partially and fully replacing the coarse aggregate with waste pumice. Replacement levels of 0%, 20%, 40%, 60%, 80%, and 100% by weight were considered to evaluate the influence of pumice content on concrete performance. A constant water–cement ratio of 0.50 was maintained for all mixes to allow direct comparison between different replacement levels. The cement and fine aggregate contents were kept unchanged across all mixtures, and mix proportions were adjusted only for coarse and pumice aggregates.

Table 2 Concrete Mix Proportions

Mix ID	Pumice Replacement (%)	Cement (kg/m³)	Fine Aggregate (kg/m³)	Natural Coarse Aggregate (kg/m³)	Waste Pumice Aggregate (kg/m³)	Water–Cement Ratio
M0	0	380	760	1140	0	0.50
M20	20	380	760	912	228	0.50
M40	40	380	760	684	456	0.50
M60	60	380	760	456	684	0.50
M80	80	380	760	228	912	0.50
M100	100	380	760	0	1140	0.50

Specimen Preparation, Curing Regime, and Testing of Fresh Concrete

Concrete specimens were prepared following a controlled laboratory procedure to ensure uniformity and repeatability of results. The mixing process involved dry mixing of cement, fine aggregate, and coarse aggregate or waste pumice aggregate to achieve a homogeneous blend, followed by gradual addition of water while mixing continued until a uniform consistency was obtained. Fresh concrete was immediately used to cast specimens in steel cube Molds of size 150 mm × 150 mm × 150 mm. The concrete was placed in Molds in layers and compacted properly to eliminate entrapped air. For each mix, a total of 16 cube specimens were cast to facilitate testing at different curing ages. After casting, the specimens were covered and kept undisturbed for 24 hours under laboratory conditions to prevent moisture loss.

Subsequently, the specimens were demoulded and cured in a water tank at a controlled temperature of 27 ± 2 °C until the designated testing ages. The curing durations considered were 7, 14, 21, and 28 days. Workability of fresh concrete was evaluated using the slump cone test in accordance with ASTM C143. The test was conducted immediately after mixing, and the slump value was recorded to assess the effect of waste pumice content on the consistency and flowability of fresh concrete.

Table 3 Details of Specimen Preparation, Curing, and Fresh Concrete Testing

Parameter	Description
Mixing Method	Manual/mechanical mixing in laboratory mixer
Specimen Type	Concrete cubes
Specimen Size	150 mm × 150 mm × 150 mm
Number of Specimens per Mix	16
Total Number of Specimens	96
Initial Curing	24 hours in Molds under laboratory conditions
Curing Method	Water curing
Curing Temperature	27 ± 2 °C
Curing Duration	7, 14, 21, and 28 days
Fresh Concrete Test	Slump test
Standard Followed	ASTM C143
Purpose of Slump Test	Evaluation of workability and consistency

Testing of Hardened Concrete, Experimental Matrix, and Data Analysis

The hardened concrete specimens were tested to evaluate density, self-weight, and compressive strength at different curing ages. Density and self-weight were determined by measuring the mass of each cured specimen using a digital weighing balance and dividing it by the known volume of the cube specimen. These measurements provided an assessment of the weight reduction achieved through the incorporation of waste pumice aggregate. Compressive strength tests were conducted using a calibrated universal testing machine in accordance with ASTM C39. The load was applied axially at a constant and controlled loading rate until failure, and the maximum load sustained by each specimen was recorded. Compressive strength was calculated by dividing the peak load by the cross-sectional area of the specimen. Tests were performed at curing ages of 7, 14, 21, and 28 days to evaluate strength development over time. The experimental matrix included six concrete mixes with waste pumice replacement levels ranging from 0% to 100%, with 16 specimens prepared for each mix. Experimental results were processed by calculating average values for each property, and comparative analysis was carried out between control and pumice-based mixes. Relationships between density and compressive strength were examined to identify performance trends and establish correlations useful for lightweight concrete applications.

Table 4 Hardened Concrete Testing, Experimental Matrix, and Data Analysis Summary

Parameter	Description
Density Measurement	Mass-to-volume ratio of cube specimens
Self-Weight Determination	Measured using digital weighing balance
Density Calculation	Density = Mass / Volume
Compressive Strength Test	Uniaxial compression
Testing Machine	Universal Testing Machine (UTM)
Loading Rate	Constant controlled rate (as per ASTM C39)
Specimen Size	150 mm × 150 mm × 150 mm
Testing Ages	7, 14, 21, and 28 days
Number of Mixes	6
Pumice Replacement Levels	0%, 20%, 40%, 60%, 80%, 100%
Specimens per Mix	16

Total Specimens	96
Data Analysis Method	Average values and comparative analysis
Correlation Study	Density vs. compressive strength relationship

Results

Workability and Density Results of Concrete with Waste Pumice Aggregate

The workability of fresh concrete was evaluated using slump tests for all mix proportions containing varying percentages of waste pumice aggregate. The control mix exhibited the highest slump value, indicating better workability due to the use of natural coarse aggregate with low water absorption. As the percentage of waste pumice increased from 20% to 100%, a gradual reduction in slump was observed. This decrease in workability can be attributed to the highly porous structure and rough surface texture of pumice aggregate, which absorbs a significant amount of mixing water and increases internal friction within the concrete mix. Compared to the control mix, concrete containing higher pumice content showed stiffer consistency, highlighting the need for careful water control or preconditioning of pumice aggregates in practical applications.

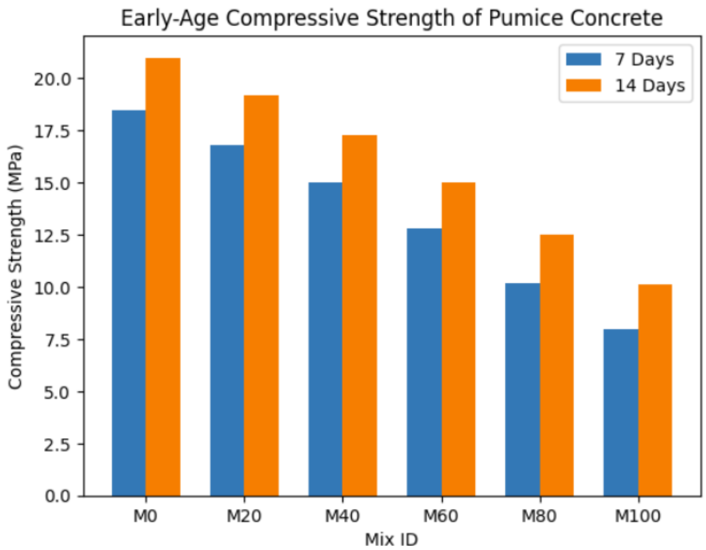
Table 5 Workability and Density Results of Concrete with Waste Pumice Aggregate

Mix ID	Pumice Replacement (%)	Slump (mm)	Dry Density (kg/m³)	Self-Weight Reduction (%)
M0	0	75	2400	0
M20	20	65	2100	12.5
M40	40	55	1850	23.0
M60	60	45	1600	33.3
M80	80	35	1300	45.8
M100	100	25	950	60.4

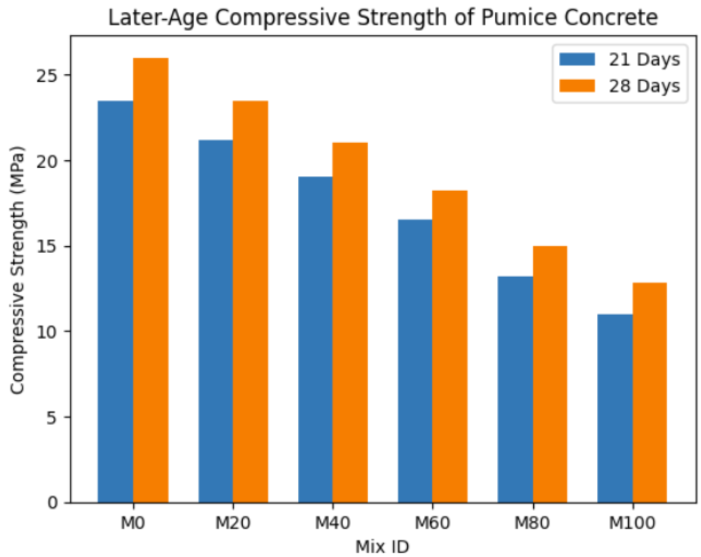
The density and self-weight of hardened concrete decreased noticeably with increasing waste pumice replacement. The control concrete showed the highest dry density, while mixes containing pumice exhibited progressively lower densities as the replacement level increased. This reduction is primarily due to the low specific gravity and high porosity of pumice aggregate. At higher replacement levels, a substantial percentage reduction in self-weight was achieved compared to conventional concrete, demonstrating the effectiveness of waste pumice in producing lightweight concrete suitable for non-load bearing applications.

Compressive Strength Results

The compressive strength of concrete mixes incorporating waste pumice aggregate was evaluated at curing ages of 7, 14, 21, and 28 days. At early ages, the control mix exhibited the highest compressive strength, while pumice-based mixes showed progressively lower strength values with increasing replacement levels. At 7 days, concrete containing 20% and 40% pumice demonstrated moderate strength reduction compared to the control, whereas higher replacement levels resulted in more pronounced reductions. By 14 days, all mixes exhibited strength gain, indicating continued hydration; however, the strength gap between control and high pumice-content mixes remained evident.

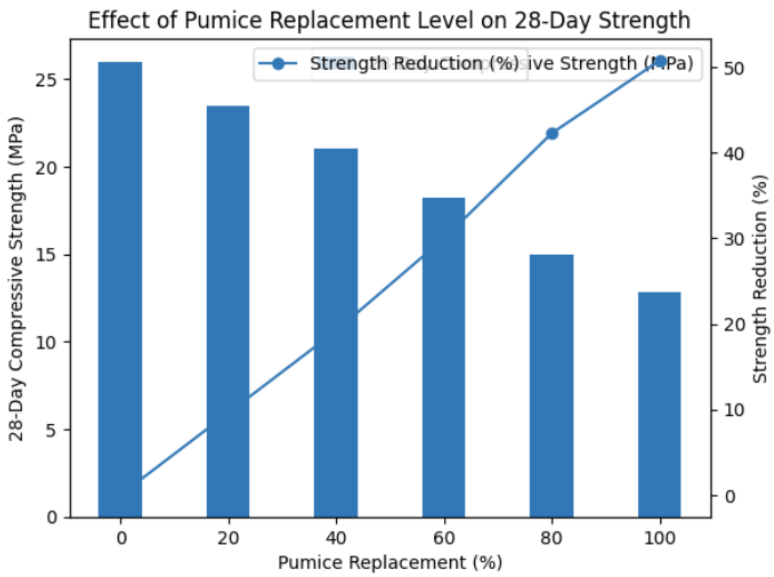


At later ages of 21 and 28 days, a similar trend was observed. The control mix achieved the highest compressive strength, while pumice-based concretes showed reduced values proportional to pumice content. Despite this reduction, mixes with lower to moderate pumice replacement levels continued to demonstrate steady strength development. Concrete containing very high pumice content exhibited comparatively lower strength, reflecting the influence of lightweight aggregate porosity on load-bearing capacity.



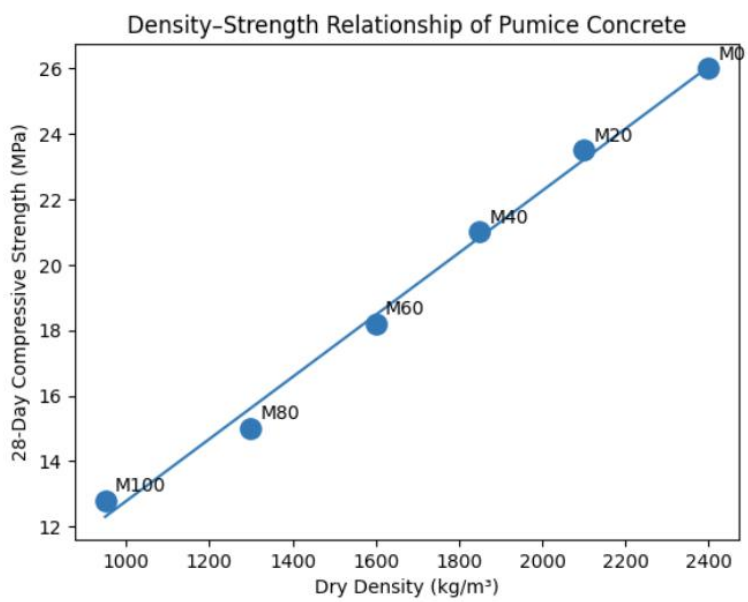
Effect of Pumice Replacement Level

Increasing the waste pumice replacement level from 0% to 100% resulted in a systematic decrease in compressive strength. Lower replacement levels showed relatively smaller reductions, while higher levels produced significant strength loss. Based on the observed results, mixes containing low to moderate pumice replacement maintained compressive strength suitable for lightweight and non-load bearing applications.



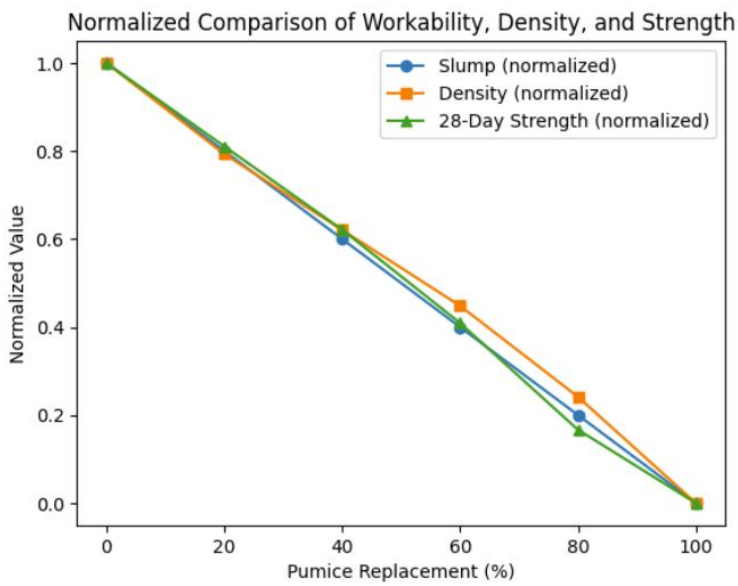
Relationship Between Density and Compressive Strength

A direct relationship was observed between dry density and compressive strength of concrete. As the dry density decreased with increasing pumice content, compressive strength also decreased. Regression analysis indicated a strong positive correlation between density and strength, confirming that lighter concrete mixes generally exhibited lower compressive strength values.



Failure Characteristics of Concrete Specimens

During compression testing, control specimens exhibited typical brittle failure characterized by vertical cracking and sudden crushing. In contrast, pumice-based concrete specimens showed more distributed cracking patterns and gradual failure, particularly at higher replacement levels. Lightweight specimens exhibited surface crushing around pumice particles, indicating weaker aggregate-paste bonding.



Discussion

The reduction in workability observed with increasing waste pumice content is primarily associated with the intrinsic physical characteristics of pumice aggregate. The highly porous structure and rough, irregular surface texture of pumice significantly increase water absorption during mixing, thereby reducing the amount of free water available for lubrication of the concrete matrix[21], [22], [23], [24]. As a result, concrete mixes with higher pumice replacement exhibited lower slump values and stiffer consistency compared to the control mix. This behavior is consistent across all replacement levels and highlights the need for moisture conditioning or water adjustment when pumice is used as a coarse aggregate. The decrease in workability became more pronounced at replacement levels above 60%, indicating that high pumice content can adversely affect handling and placement if not properly managed[25], [26], [27].

The substantial reduction in dry density with increasing pumice replacement demonstrates the effectiveness of waste pumice in producing lightweight concrete. The low specific gravity and high internal porosity of pumice aggregates directly contributed to lower unit weight of the hardened concrete. At higher replacement levels, the density fell within the range typically associated with structural and non-structural lightweight concrete[28], [29]. This reduction in density is particularly advantageous for applications where dead load minimization is critical, such as precast elements, partition walls, and non-load bearing components. The progressive decrease in density with increasing pumice content also indicates a consistent and predictable influence of pumice aggregate on concrete weight, which is beneficial for mix design optimization[30], [31], [32].

Compressive strength results revealed a clear dependency on the replacement level of waste pumice aggregate. At early curing ages, pumice-based concrete mixes exhibited lower strength compared to the control mix, although all mixes demonstrated continuous strength gain with time. The reduced early-age strength can be attributed to the weaker mechanical properties of pumice aggregate and its porous nature, which leads to stress concentration under load. Additionally, the interfacial transition zone between pumice particles and cement paste is relatively weaker than that of conventional aggregates, contributing to reduced load transfer efficiency. However, the steady increase in strength between 7 and 14 days indicates that hydration processes were not significantly hindered by the presence of pumice[33], [34], [35], [36], [37].

At later curing ages, the compressive strength trends remained consistent, with the control mix achieving the highest strength and pumice-based mixes showing progressively lower values as the replacement percentage increased. Despite this reduction, mixes with low to moderate pumice content maintained compressive strength levels suitable for lightweight and non-load bearing applications. The results suggest that replacement levels up to approximately 40% to 60% can provide a balance between strength retention and weight reduction. Beyond this range, the strength loss became more significant, limiting the applicability of high pumice-content mixes to applications where structural demands are minimal[37], [38], [39].

The observed relationship between dry density and compressive strength highlights the fundamental trade-off between weight reduction and mechanical performance in lightweight concrete. As pumice content increased, both density and strength decreased in a nearly linear manner, indicating a strong correlation between these parameters. This relationship confirms that density can be used as a reliable indicator of expected strength in pumice-based concrete. The strong correlation also suggests that strength prediction models based on density may be developed for practical design applications, enabling engineers to select appropriate pumice replacement levels based on performance requirements[26].

Failure characteristics observed during compression testing further support the influence of pumice aggregate on concrete behavior. Control specimens exhibited sudden and brittle failure marked by well-defined vertical cracking, typical of normal-weight concrete. In contrast, pumice-based concrete specimens showed more distributed cracking patterns and gradual failure, particularly at higher replacement levels. The failure surfaces of pumice concrete often revealed crushing of pumice particles rather than fracture of the cement matrix, indicating that aggregate strength governed the failure mechanism. This behavior suggests increased energy absorption and reduced brittleness in pumice-based concrete, which may be advantageous in certain applications[40], [41], [42], [43].

Conclusion and Recommendation

- The use of waste pumice aggregate as a replacement for natural coarse aggregate proved effective in producing lightweight concrete with significantly reduced density and self-weight, making it suitable for non-load bearing and lightweight construction applications.
- Increasing the pumice replacement level resulted in a consistent decrease in workability, primarily due to the high-water absorption and porous structure of pumice aggregate.
- Dry density of concrete decreased progressively with higher pumice content, confirming the suitability of waste pumice for lightweight concrete production.
- Compressive strength decreased as the proportion of pumice increased; however, all mixes exhibited continuous strength development with curing age.
- Concrete mixes with low to moderate pumice replacement levels (approximately 20–60%) achieved a favourable balance between strength retention and weight reduction.
- A strong correlation was observed between dry density and compressive strength, indicating that density can be used as a reliable predictor of strength for pumice-based concrete.
- Failure patterns of pumice concrete showed more gradual and distributed cracking compared to conventional concrete, indicating reduced brittleness at higher pumice contents.
- The reuse of waste pumice contributes to sustainable construction by reducing industrial waste disposal and conserving natural aggregate resources.
- For practical applications, preconditioning or moisture control of pumice aggregate is recommended to improve workability and consistency of concrete mixes.

- Future research is recommended to investigate durability properties, long-term performance, and microstructural behavior of pumice-based lightweight concrete.
- The use of chemical admixtures should be explored to enhance workability and strength at higher pumice replacement levels.

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