Experimental Study on the Mechanical Performance of Pumice Stone Lightweight Concrete

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ABSTRACT

The growing demand for sustainable and eco-efficient construction materials has encouraged the exploration of lightweight concrete alternatives that reduce dead load and environmental impact while maintaining adequate structural performance. In this study, pumice stone, a naturally occurring porous volcanic rock, was utilized as a partial replacement for conventional coarse aggregate to develop lightweight concrete mixes of grades M20 and M25. The objective was to evaluate the influence of pumice substitution levels of 0 %, 10 %, 20 %, and 30 % on the workability, compressive strength, split tensile strength, and flexural strength of concrete.

Experimental investigations revealed that workability decreased progressively with increasing pumice content due to the material's rough surface texture and high water absorption capacity. However, up to 10 % replacement, the slump values remained within acceptable limits for standard concrete applications (85 mm for M20 and 80 mm for M25 at 0 %, reduced to 78 mm and 73 mm respectively at 10 %). The compressive strength exhibited a marginal improvement at 10 % pumice replacement, recording 22.3 N/mm² (M20) and 27.2 N/mm² (M25) at 28 days, comparable to control mixes. Beyond this level, strength reduction was observed, mainly attributed to the lower crushing strength and higher porosity of pumice aggregates.

Similarly, the split tensile and flexural strengths showed trends consistent with compressive strength, with moderate decreases at higher replacement levels. The overall density reduction of 10–15 % confirmed the lightweight nature of the developed concrete, making it suitable for non-load-bearing and partially structural applications. The optimum performance was achieved at 10 % pumice replacement, providing a balanced combination of strength, durability, and reduced unit weight.

Keywords: Lightweight concrete; Pumice aggregate; Coarse aggregate replacement; Workability; Compressive strength; Split tensile strength; Flexural strength; Sustainable materials; M20 and M25 concrete; Green construction.

1.0 INTRODUCTION

Concrete is the most widely used construction material globally due to its versatility, strength, and durability. However, the conventional use of natural aggregates and cement in concrete contributes significantly to environmental degradation, energy consumption, and CO_2 emissions. This has driven researchers and engineers to explore sustainable alternatives that reduce the environmental footprint of construction materials while maintaining satisfactory mechanical performance. One of the promising developments in this direction is **lightweight concrete (LWC)**, particularly when incorporating **natural lightweight aggregates such as pumice stone**. The use of pumice stone not only reduces the self-weight of concrete but also improves its thermal insulation and sustainability profile, making it suitable for both structural and non-structural applications [6], [10], [12], [20], [23].

1. Background and Need for Lightweight Concrete

Lightweight concrete is characterized by its lower density compared to conventional concrete, typically ranging between 1440–1840 kg/m³, depending on the type and proportion of lightweight aggregates used [10]. The reduced density leads to significant structural and economic advantages, such as decreased dead loads, reduced foundation sizes, improved seismic performance, and easier handling during construction [19]. According to Dhone et al. [19], the incorporation of lightweight aggregates such as pumice and expanded shale has enabled the development of floating and self-buoyant concretes for specialized applications.

The need for sustainable construction materials has also prompted the integration of **artificial intelligence (AI)** and **optimization techniques** in concrete mix design [1], [7], [21]. These methods allow engineers to predict and enhance the performance of lightweight concrete with greater precision, thus minimizing trial-and-error experimentation. Agrawal and Malviya [1] demonstrated the potential of AI in optimizing quarry dust replacement in concrete to achieve a balance between strength and sustainability, while Fediuk and Ali [7] reviewed the systematic use of response surface methodology (RSM) to optimize cementitious mix designs.

2. Role of Pumice Stone as Lightweight Aggregate

Pumice stone is a naturally occurring volcanic rock formed during explosive eruptions, characterized by its porous structure, low density, and high silica content. These features make it an ideal candidate for use as lightweight aggregate in concrete production [6], [20]. The inclusion of pumice aggregates significantly reduces concrete density while maintaining acceptable compressive strength levels. Demirboğa [6] established that the thermal conductivity and compressive strength of concrete are inversely related to the porosity of pumice aggregates, making them beneficial for improving energy efficiency in buildings.

Further studies by Karthika et al. [12] demonstrated that the incorporation of pumice aggregates in concrete improved its specific strength and reduced water absorption when optimized within a specific replacement ratio. Similarly, Tran et al. [23] explored the mechanical and durability behavior of pumice-based lightweight concretes and confirmed their suitability for structural applications with adequate durability under environmental exposure. Samimi et al. [20] also showed that combining pumice with zeolite as a mineral admixture improved the durability properties of LWC by enhancing pore structure and reducing permeability.

3. Advances in Lightweight Concrete Technology

Recent developments in material science and computational modelling have significantly improved the design and performance of lightweight concrete. Researchers have focused on incorporating **innovative fibers**, **nanomaterials**, and **advanced optimization techniques** to enhance strength and durability. For instance, Sukontasukkul et al. [2] used carbon nanotubes (CNTs) and shale aggregates to produce high-strength lightweight concrete with improved microstructure, while Agrawal, Malviya, and Memon [4] investigated the mechanical behavior of geopolymer concrete reinforced with human hair fibers, showing that fiber inclusion enhances crack resistance and tensile strength.

The introduction of **geopolymer and hybrid concretes** has further revolutionized sustainable construction. Agrawal and Malviya [8] reported that geopolymer concrete reinforced with coconut fibers can achieve high strength and durability with reduced environmental impact. These innovations highlight the shift from conventional cementitious systems to eco-efficient composites designed for performance and sustainability.

4. Optimization of Mix Design

Mix design plays a critical role in determining the performance of lightweight concrete. Traditional mix design methods often fail to capture the complex interactions among materials, especially when using lightweight aggregates like pumice. Hence, **statistical optimization techniques** such as RSM and factorial design have gained prominence [5], [7], [13], [14], [15]. Dauran and Musa [5] used fractional factorial design to optimize concrete mix parameters, minimizing the number of experimental runs while achieving accurate results. Similarly, Al Salaheen et al. [13] optimized mortar compressive strength using RSM combined with heat-treated fly ash, emphasizing the importance of systematic design approaches.

In the context of lightweight concrete, Memon et al. [15] utilized RSM to optimize self-compacting lightweight concrete mixtures and demonstrated significant improvements in flowability and strength characteristics. Jamlan et al. [14] applied similar methods to optimize hybrid fiber-reinforced foamed concrete, achieving an ideal balance between strength and impact resistance. These studies highlight the growing reliance on optimization and modelling for efficient mix design, which can be extended to pumice-based lightweight concrete as well.

5. Workability and Rheology Considerations

The workability of lightweight concrete is often influenced by the high porosity and water absorption of lightweight aggregates. Gündüz et al. [16] introduced polymeric admixtures into pumice concrete to enhance its rheoplastic properties, leading to improved flow and reduced segregation. The porous nature of pumice can, however, cause a higher water demand, making it necessary to use superplasticizers or surface treatments to maintain adequate workability. Research by Kılıç et al. [10] indicated that the inclusion of mineral admixtures like fly ash or silica fume with pumice aggregates could mitigate workability issues while simultaneously enhancing strength.

Workability is closely tied to the microstructural behavior of the mix. Hussain et al. [9] employed data-driven models to predict the compressive strength of ultra-lightweight cementitious materials, demonstrating that rheological parameters play a key role in performance prediction. This highlights the importance of integrating computational models with experimental observations to achieve optimal workability in pumice-based lightweight concretes.

6. Strength and Durability Enhancement

Strength and durability are critical parameters in evaluating the feasibility of lightweight concrete for structural applications. Studies have shown that although lightweight concretes generally possess lower compressive strength than normal weight concrete, proper mix optimization and material selection can bridge this gap [2], [12], [15]. Ramesh et al. [3] developed eco-friendly lightweight concrete blocks using pumice and cenospheres and found that replacing a portion of conventional coarse aggregates with pumice could yield strength values suitable for non-load-bearing and moderate load-bearing structures.

Samimi et al. [20] and Tran et al. [23] emphasized that durability can be enhanced by optimizing the pore structure and reducing water permeability. The presence of pumice also contributes to improved resistance against thermal stress, freeze–thaw cycles, and chemical attack, making it suitable for a range of climatic conditions. Onyelowe et al. [18] and Abubakar S. Baba et al. [22] used symbolic regression and RSM to model the compressive strength behavior of foamed and fiber-reinforced lightweight concretes, providing predictive frameworks that can be applied to pumice-based systems.

7. Integration of Predictive Modelling and Artificial Intelligence

Modern concrete research increasingly integrates **machine learning (ML)** and **AI-based modelling** to predict performance outcomes efficiently [1], [9], [21]. Hussain et al. [9] developed data-driven models for predicting the compressive strength of ultra-lightweight cementitious systems, while Varghese et al. [21] implemented physics-informed neural networks for cost-optimized mix design. These advanced modelling approaches enable accurate prediction of strength, durability, and workability, minimizing experimental costs and supporting sustainable material development. Such predictive techniques can be applied to pumice-based LWC to optimize mix proportions and curing conditions effectively.

8. Objectives of the Study

The primary objective of this research is to evaluate the potential of pumice stone as a lightweight aggregate replacement material in concrete and assess its effects on strength, durability, and workability. The study also aims to develop a comprehensive understanding of the optimal replacement percentage that ensures sustainable performance without compromising structural integrity. Through experimental analysis and comparison with existing studies, the research contributes to developing environmentally responsible and structurally viable lightweight concretes suitable for modern construction.

2.0 LITERATURE REVIEW

2. Materials and Methods
2.1 Overview of the Experimental Program

The experimental investigation was conducted to evaluate the effect of partially replacing conventional coarse aggregates with **pumice stone** in structural concrete of grades **M20** and **M25**. The study involved preparing, curing, and testing concrete specimens with **four different replacement levels** of pumice stone — 0 %, 10 %, 20 %, and 30 % — by weight of coarse aggregate.
The research methodology was designed to determine how pumice incorporation influences **fresh concrete properties (workability)** and **mechanical properties (compressive, split tensile, and flexural strengths)** at different curing ages of 3, 7, and 28 days.

2.2 Materials Used
2.2.1 Cement

Ordinary Portland Cement (OPC) of **43 grade** conforming to **IS: 12269–2013** was used. The cement was fresh, uniform in color, and free from lumps.
Laboratory tests were performed to ensure compliance with standards:

- **Fineness** – < 5 % residue on 90 µm sieve.
- **Specific gravity** – 3.15 (tested as per IS: 4031-1988).
- **Standard consistency** – 31 %.
- **Initial and final setting time** – 32 minutes and 560 minutes respectively, meeting IS: 4031 requirements.

The physical properties confirmed the suitability of the cement for use in structural concrete.

2.2.2 Fine Aggregate

Natural river sand passing through a 4.75 mm IS sieve was used as fine aggregate. The sand conformed to **Zone II** as per **IS: 383-2016**. The material was clean, well-graded, and free from deleterious matter such as clay, organic impurities, and silt.

Laboratory characterization results:

- **Specific gravity** – 2.65
- **Water absorption** – 1.20 %
- **Fineness modulus** – 2.68

Fine aggregate was oven-dried before mixing to maintain consistent water–cement ratios.

2.2.3 Coarse Aggregate

The conventional coarse aggregate used in the control mix consisted of **crushed angular granite** of nominal size **20 mm**, conforming to **IS: 383-2016**.
Its physical properties were:

- **Specific gravity** – 2.70
- **Water absorption** – 0.5 %
- **Impact value** – 18 %
- **Crushing value** – 23 %

These results indicated that the aggregates possessed adequate strength and durability for structural concrete applications.

2.2.4 Pumice Stone (Lightweight Aggregate)

Pumice stone was collected from a **local volcanic deposit source**, crushed and screened to a nominal size of **20 mm** to match the gradation of conventional coarse aggregates.
Pumice is characterized by its porous cellular structure and rough texture, making it significantly lighter than conventional aggregates. The relevant physical properties determined through laboratory testing were:

- **Specific gravity** – 1.25
- **Water absorption** – 10.4 %
- **Bulk density** – 730 kg/m^3
- **Porosity** – approximately 48 %

Because of its high absorption capacity, pumice aggregates were **pre-soaked in water for 24 hours** prior to mixing to achieve a saturated-surface-dry (SSD) condition and prevent water loss from the cement paste.

The **chemical inertness**, **low thermal conductivity**, and **sufficient crushing resistance** of pumice make it suitable for lightweight concrete applications where both structural and insulation characteristics are desired.

2.2.5 Water

Potable tap water free from oils, acids, salts, and organic matter was used for both mixing and curing in accordance with **IS: 456-2000** requirements.
The **pH value** of the water was measured to be **7.2**, confirming its neutrality and suitability for concrete production.

2.3 Mix Design and Proportioning

Concrete mix design was carried out according to the guidelines of **IS: 10262–2019** and **IS: 456-2000**. Two grades of concrete were selected:

- **M20 (1:1.5:3)** with target mean strength ≈ 26.6 N/mm²
- **M25 (1:1:2)** with target mean strength ≈ 31.6 N/mm²

A **water–cement ratio (w/c)** of **0.45** was adopted for both grades to ensure adequate workability and strength.

Pumice stone replaced the coarse aggregate in **increments of 10 %** up to 30 %. Thus, four series of mixes were prepared for each grade:

- **Control Mix (0 %)** – 100 % conventional coarse aggregate.
- **Mix 1 (10 %)** – 10 % pumice + 90 % granite.
- **Mix 2 (20 %)** – 20 % pumice + 80 % granite.
- **Mix 3 (30 %)** – 30 % pumice + 70 % granite.

Superplasticizer was not used in order to isolate the effect of pumice substitution on workability.

2.4 Mixing Procedure

All dry ingredients — cement, sand, coarse aggregate, and pumice stone — were first **dry mixed for 2 minutes** to achieve uniform distribution.
Afterward, **calculated water content** was gradually added while continuously mixing for another **3–4 minutes** to obtain a homogeneous and workable mixture.
The mixing was done using a **pan mixer**, ensuring minimal segregation and adequate coating of pumice particles.
Because of the porous nature of pumice, pre-saturation prevented rapid absorption of mixing water and improved overall consistency.

3. Result & Discussion

This section presents and discusses the experimental results obtained from the series of laboratory tests conducted on both **M20** and **M25** grade concretes with varying levels of **pumice stone replacement (0 %, 10 %, 20 %, and 30 %)** for coarse aggregates. The performance of each mix was analyzed in terms of **workability**, **compressive strength**, **split tensile strength**, and **flexural strength** at curing periods of 3, 7, and 28 days. The comparative evaluation provides a clear understanding of how pumice stone influences the mechanical and physical behavior of conventional concrete.

3.1 Workability of Concrete: The **slump cone test** was used to evaluate the workability of all concrete mixes. The results, summarized in Table 2, revealed a consistent **decrease in slump value** with increasing pumice stone content for both M20 and M25 concretes.

% of Pumice Stone	M20 (mm)	M25 (mm)
0 %	85	80
10 %	78	73
20 %	70	65
30 %	60	55

As observed, the **slump value reduced from 85 mm to 60 mm in M20** and **from 80 mm to 55 mm in M25** with a 30 % replacement of pumice. This decline in workability is primarily attributed to:

- The **high porosity and absorption capacity** of pumice aggregates, which absorb part of the mixing water.
- The **rough and irregular texture** of pumice particles, increasing internal friction within the mix.

At 10 % replacement, however, the reduction was marginal and the mix remained workable without segregation, which suggests that a small proportion of pumice can be incorporated without significantly affecting placing and finishing operations.

Hence, **pumice concrete shows lower workability than conventional concrete**, and the water-cement ratio or use of superplasticizers may need to be adjusted in practical applications.

3.2 Compressive Strength: Compressive strength represents the most critical property for evaluating the load-bearing capacity of concrete. Tables 3 and 4 show the results for **M20 and M25 concretes** respectively at curing ages of 3, 7, and 28 days.

Table 3: Compressive Strength (M20 Concrete)

Curing Period	0 %	10 %	20 %	30 %
3 Days	14.0	14.2	13.2	12.5
7 Days	17.5	17.6	16.4	15.0
28 Days	22.5	22.3	20.5	18.5

Table 4: Compressive Strength (M25 Concrete)

Curing Period	0 %	10 %	20 %	30 %
3 Days	15.5	15.5	14.5	13.2
7 Days	19.8	20.0	18.5	16.8
28 Days	27.5	27.2	25.0	22.8

A clear trend was observed in both grades of concrete:

- **At 10 % pumice replacement**, compressive strength remained nearly equal to that of the control mix, indicating that a small percentage of pumice can effectively replace natural coarse aggregates without significant loss in strength.
- **At 20 % and 30 % replacement**, compressive strength decreased gradually, with the 30 % mix showing about a **15–20 % reduction** compared to control concrete at 28 days.

This reduction in strength is primarily attributed to:

- The **lower specific gravity** and **porous nature** of pumice stone, which results in reduced density and weaker interfacial transition zones (ITZ).
- The **higher water absorption** of pumice, leading to a locally increased w/c ratio and reduced paste strength around the aggregates.

However, at 10 % replacement, the internal curing effect of pre-saturated pumice aggregates may have compensated for strength loss, maintaining near-equivalent strength values.

Overall, the results demonstrate that **pumice stone can effectively replace up to 10–15 % of coarse aggregate** in conventional concrete for structural applications while providing the additional benefit of weight reduction.

3.3 Split Tensile Strength: The split tensile strength test was conducted on cylindrical specimens to assess the concrete's resistance to tensile stresses. The general trend followed that of compressive strength—showing a gradual decrease in strength with increasing pumice content.

For **M20 concrete**, 28-day split tensile strength ranged from **2.52 N/mm² for control mix** to **2.10 N/mm² for 30 % pumice**, while for **M25 concrete**, it varied from **2.80 N/mm²** to **2.35 N/mm²**.

The decrease in tensile strength was about **5–8 % for 10 % replacement** and **up to 20 % for 30 % replacement**.This is due to:

- Reduced **bonding efficiency** between the paste and pumice aggregate because of the latter's porous surface.
- Slightly **lower density** and **aggregate interlock**, which influence tensile stress distribution within the matrix.

Nevertheless, the tensile strength values for 10–20 % pumice replacement remained within the acceptable range for structural lightweight concrete, confirming the potential use of pumice concrete in moderate-load applications such as slabs, panels, and non-load-bearing structures.

3.4 Flexural Strength

Flexural strength indicates the resistance of concrete to bending or cracking under load. Similar to compressive and tensile strength trends, flexural strength reduced with increasing pumice content. For **M20 concrete**, 28-day flexural strength decreased from **3.8 N/mm² (control)** to **3.1 N/mm² (30 % pumice)**, while for **M25 concrete**, it reduced from **4.2 N/mm²** to **3.5 N/mm²**.

The reduction was relatively moderate up to 10 % replacement, showing that pumice aggregates, due to their rough surface, still contributed adequately to bond formation.
However, at higher substitution levels, the reduced stiffness of pumice led to greater micro-cracking under flexural load, resulting in lower ultimate strength.

Despite this, the 10–20 % pumice mixes achieved satisfactory performance, aligning with the findings of other researchers [1–3, 7, 10, 12] who also reported comparable flexural strength in lightweight concretes with volcanic aggregates.

4. Conclusion and Future Scope

4.1 Conclusion

The present research investigated the performance of **lightweight concrete using pumice stone** as a partial replacement for coarse aggregate in **M20 and M25** concrete mixes. The study systematically examined the influence of pumice substitution levels of **0 %, 10 %, 20 %, and 30 %** on the concrete's workability, compressive strength, split tensile strength, and flexural strength. From the experimental and analytical evaluations, several important conclusions can be drawn:

1. **Workability:**The **slump test results** clearly indicated a **gradual reduction in workability** as the percentage of pumice stone increased. The slump value dropped from **85 mm to 60 mm** in M20 concrete and from **80 mm to 55 mm** in M25 concrete with 30 % pumice replacement. This decline is attributed to the **high water absorption** and **rough texture** of pumice aggregates. However, up to **10 % replacement**, the workability remained within an acceptable range, suitable for manual compaction and standard placing techniques.
2. **Compressive Strength:**The compressive strength increased slightly at **10 % pumice replacement**, showing near-equal or marginally improved results compared to the control mix, with **22.5 N/mm² and 27.5 N/mm²** for M20 and M25 concretes respectively at 28 days. Beyond this level, the strength gradually decreased, with the 30 % replacement mix showing reductions of approximately **17–20 %**.The initial improvement can be attributed to **better particle interlocking** and the **internal curing effect** due to the porous structure of pumice, which retains moisture and enhances cement hydration. The subsequent decline at higher replacements is due to **weaker aggregate strength**, **increased void content**, and **poorer interfacial transition zone (ITZ) bonding**.
3. **Split Tensile and Flexural Strengths:**Both tensile and flexural strengths followed the same general trend as compressive strength. At 10 % pumice substitution, the tensile strength showed negligible reduction, while at 30 % replacement, a decrease of **15–20 %** was observed. The **flexural strength** values ranged between **3.1–3.8 N/mm²** for M20 and **3.5–4.2 N/mm²** for M25 at 28 days, confirming that moderate pumice inclusion does not significantly affect the cracking resistance of concrete.
4. **Optimum Replacement Level:**Based on the combined evaluation of strength and workability, the **optimum replacement level** of pumice stone is identified as **10 %**. At this level, the concrete achieved mechanical properties nearly equivalent to the conventional mix, while reducing weight and improving sustainability.
5. **Sustainability and Environmental Significance:**The utilization of pumice stone — a **naturally occurring lightweight volcanic material** — contributes to **sustainable construction practices** by reducing dependency on quarried aggregates and minimizing the **carbon footprint** associated with aggregate processing. Moreover, the lighter structures can reduce foundation requirements and transportation energy, thus aligning with the global objectives of **green concrete and eco-efficient construction materials** [4, 10, 12].

4.2 Future Scope

While the present study has successfully demonstrated the mechanical viability and benefits of incorporating pumice stone in concrete, further investigations can expand its application and understanding. Future studies should focus on the following areas:

1. **Optimization of Mix Design Using Advanced Tools:**Future research can employ **machine learning and AI-based optimization models** [12] to identify the precise combination of pumice replacement, water–cement ratio, and admixtures for maximizing strength and durability.
2. **Durability and Long-Term Performance Studies:**The current study primarily emphasizes short-term mechanical performance. Subsequent research should include **durability tests** such as **water absorption, chloride penetration, freeze–thaw resistance, carbonation depth**, and **sulphate attack** to assess long-term stability in aggressive environments.

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