# The Response of Pumice Lightweight Concrete to Low Velocity Impact Loading

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## ABSTRACT

**Each year, engineers face significant sustainability challenges due to the large-scale production of concrete for buildings and infrastructure. To address this issue, alternative materials are being used. In this study, volcanic pumice, a lightweight material, was used to replace traditional coarse aggregate. Additionally, Glass Fibers (GFs) and Fiberglass Mesh (FGM) were incorporated to enhance the concrete's performance. The research experimentally examined the ability of lightweight concrete to absorb shocks, using volcanic pumice as the coarse material. The impact resistance was assessed by applying frequency impacts on a concrete plate caused by a falling weight, a 3.4 kg iron ball with a diameter of 9.5 cm, dropped from a height of 1.5 m. The number of strikes at the first fracture as well as the number of blows needed to cause failure, was recorded. An average of three specimens measuring 50 cm × 50 cm × 5 cm were tested at the ages of 28, 60, and 90 days. The study evaluated five pumice lightweight mixes: a reference mix without fiber, a 1% GF mix, a 1-layer FGM mix, a 3-layer FGM mix, and a hybrid mix (M hybrid) incorporating both GF and a 3-layer FGM. The results showed that the hybrid mix performed best in resisting repeated impact loads and absorbing energy. The performance improved by 350% compared to the reference mixture at 90 days. Identifying the impact resistance of lightweight aggregate concrete made with sustainable pumice aggregate could open new opportunities for using this type of concrete in structures exposed to low-velocity impact loads.**

***Keywords-lightweight concrete; pumice; glass fiber; fiberglass mesh; mechanical properties; low velocity impact***

## I. INTRODUCTION

Pumice is a lightweight, porous volcanic rock with a smooth, glassy appearance. Although it shares the same mineral composition as rhyolite, its structure is different [1]. The use of volcanic scoria as a coarse aggregate in lightweight concrete has been explored. It has been found that while scoria-based concrete had adequate strength and density for structural use, it also exhibited drawbacks, such as lower elastic modulus, increased permeability, and higher early surface absorption compared to the conventional concrete [2]. Research on volcanic pumice from Papua New Guinea demonstrated its suitability for producing insulating building materials, like lightweight concrete and masonry blocks. Similarly, a study in Tanzania evaluated pumice and volcanic scoria for lightweight construction. It concluded that scoria was more appropriate for structural applications, while pumice was better suited for non-structural uses [3, 4]. Another investigation integrated basaltic scoria and fly ash into concrete mixtures, resulting in concrete with good compressive and tensile strength—making it viable for structural purposes. This approach also offered environmental and economic benefits. Despite the extensive research on lightweight aggregates in concrete, few studies have examined their behavior under dynamic or impact-related stresses, particularly when pumice or scoria serve as coarse, energy-absorbing components [5]. It has been found that replacing traditional cement and coarse gravel with volcanic pumice produces structurally sound concrete, though, with reduced workability. Pumice's low elastic modulus makes it especially effective in applications requiring energy absorption, such as the buffer zones in check dams, which must withstand impacts from debris, like rocks or logs. This study investigates the performance of lightweight concrete made with raw volcanic pumice as a coarse aggregate under impact loading. It also evaluates how the addition of GFs and pumice fibers affects the concrete's mechanical properties, including bending, tensile, and compressive strength.

## II. MATERIALS

Cement: Ordinary Portland cement (CEM I, 42.5R) was utilized, according to the findings in [6]. Tables I and II illustrate the physical and chemical characteristics of the cement.

TABLE I. CEMENT CHEMICAL COMPOSITION AND MAIN COMPONENTS

| Oxide compositions | Weight (%) | Limits of [6] |
|---|---|---|
| Alumina ($Al_2O_3$) | 5.08 | ----- |
| Insoluble residue (IR) | 0.86 | ≤ 1.5 |
| Iron oxide ($Fe_2O_3$) | 4.16 | ----- |
| Lime (CaO) | 60.35 | ----- |
| Loss on Ignition (LOI) | 3.21 | ≤ 4 |
| Magnesia (MgO) | 3.86 | ≤ 5 |
| Silica ($SiO_2$) | 20.64 | ----- |
| Sulfate ($SO_3$) | 2.67 | $SO_3$≤ 2.8 if $C_3A$ > 3.5 $SO_3$≤ 2.5 if $C_3A$ ≤ 3.5 |
| **Main compounds of cement** | | |
| Dicalcium silicate ($C_2S$) | 27.83 | ---- |
| Tetra-calcium Aluminate –ferrite ($C_4AF$) | 12.64 | ---- |
| Tricalcium aluminate ($C_3A$) | 6.43 | ---- |
| Tri-calcium silicate ($C_3S$) | 41.07 | ---- |

TABLE II. PHYSICAL REQUIREMENTS OF THE CEMENT

| Physical properties | Weight (%) | Limits of [6] |
|---|---|---|
| Setting time: initial setting time (min) | 90 | ≥ 45 min |
| Setting time: final setting time | 4.42 hr | ≤ 10 hr |
| Soundness by autoclave approach (%) | 0.19 | ≤ 0.80 |
| Specific surface area (Blaine's approach) (m²/ kg) | 349.8 | ≥ 280 |
| **Compressive strength (MPa)** | | |
| Compressive strength 2-day | 21.75 | ≥ 20 |
| Compressive strength 28-day | 46.63 | ≥ 42.5 |

Sand (fine aggregate): The sand sieve grading and main characteristics complied with those in [7]. Table III presents the physical and chemical properties, while Table VI displays the sieve analysis results of the sand used.

TABLE III. CHEMICAL AND PHYSICAL PROPERTIES OF FINE AGGREGATES

| Property | Test result | Limits of [7] |
|---|---|---|
| Absorption, % | 0.72 | --- |
| Density (kg/m³) | 1580 | --- |
| Specific gravity | 2.6 | --- |
| Sulphate content,% (SO3) | 0.343 | 0.50% (max) |

TABLE IV. SIEVE ANALYSIS

| Sieve size (mm) | Passing % | Requirements of [7] |
|---|---|---|
| 10 mm | 100 | 100 |
| 4.75 mm | 95.6 | 90-100 |
| 2.36 mm | 80 | 75-100 |
| 1.18 mm | 78 | 55-90 |
| 600 µm | 54.4 | 35-59 |
| 300 µm | 26.3 | 8-30 |
| 150 µm | 4.7 | 0-10 |
| Finance modulus (F.M)=2.61 | | |

Coarse Aggregate (pumice): The pumice, which complied with the standards in [8]. Both its physical and chemical characteristics are presented in Table V.

TABLE V. PHYSICAL PROPERTIES OF PUMICE

| | |
|---|---|
| **Absorption %** | 28 |
| **Color** | white |
| **Density (kg/m³)** | 656 |
| **Hardness (MOHS)** | 6 |
| **Softening point** | 900 |

Silica Fume (SF): The SF strength activity index records 121% and conforms to [9]. Tables VI and VII provide the technical information for the SF.

TABLE VI. PHYSICAL TESTS OF SF

| Physical properties | Test results | Specification of [9] |
|---|---|---|
| Accelerated pozzolanic strength activity index with Portland cement at 7 days | 121 | ≥105 |
| Percent retained on 45-µm (no. 325) sieve | 7 | ≤10 |
| Specific surface $m^2/g$ | 10 | ≥15 |

TABLE VII. CHEMICAL ANALYSIS OF SF

| Oxide composition | Test results | Specifications of [9] |
|---|---|---|
| $Al_2O_3$ | 0.37 | -- |
| CaO | 1.9 | -- |
| $Fe_2O_3$ | 1.31 | -- |
| $K_2O$ | 0.09 | -- |
| Loss on ignition | 1.59 | ≤6.0 |
| MgO | 2.4 | -- |
| Moisture content (%) | 0.33 | ≤3.0 |
| $Na_2O$ | 0.1 | -- |
| $SiO_2$ | 92.84 | ≥85.0 |
| $SO_3$ | 0.65 | -- |

Water: Drinking water was used for mixing in this study, in accordance with the standards outlined in [10].

GFs: The present study used alkali-resistant GFs, each measuring 12 mm in length and 0.15 mm in diameter, with an aspect ratio of 80. Their detailed specifications and properties, which are provided by the supplier, are listed in Table VIII.

TABLE VIII. CHARACTERISTICS OF THE GF

| Properties | Details |
|---|---|
| Absorption | Nil |
| Appearance | Opaque |
| Elasticity modulus | 72 GPa |
| Fibre diameter | 0.15 mm |
| Fibre length | 12 mm |
| Chemical resistance | Very high |
| Soft-point | 860°C |
| Specific gravity | 2.68 g/cm³ |
| Tensile strength | 1,700 MPa |

A high-performance Superplasticizer (SP) was used in this study to improve the slump retention, workability, flexural and compressive strength, and to reduce the shrinkage and creep. It complies with the standards in [11] and is classified as Type A and G. The proposed dosage by the manufacturer ranges from 0.5% to 1.5% of the cementitious material by weight. Its technical specifications are depicted in Table IX.

TABLE IX. TECHNICAL PROPERTIES OF SP

| Color | Whitish liquid |
|---|---|
| Chloride content | Nill |
| Density | 1.06 to 1.08 |
| Ph | 3 to 4.5 |

Fiberglass Mesh (FGM): A type of reinforcement used in this experiment is FGM, which is available in the local market and IS used in construction fields. It was implemented in the mixes in one layer and three layers, as shown in Table X.

TABLE X. MECHANICAL PROPERTIES OF FGM

| | |
|---|---|
| **Diameter** | (0.5 mm) diameter |
| **Dimensions** | square opening size of (3 mm) |
| **Tensile Strength** | 1034 (MPa) |

The mixtures were designed according to [12] and were produced after multiple trial mixes until the final proportions met the LWC requirement. Table XI provides information on the mixtures used in this work. The mixing and sample preparations followed the procedures outlined in [13].

TABLE XI. MIX PROPORTIONS BY WEIGHT (KG/M$^3$)

| Mix | Cement | Sand | Pumice | SF | GF vol% | SP% | W/b% |
|---|---|---|---|---|---|---|---|
| MR | 450 | 775 | 490 | 50 | ---- | 1.25 | 0.37 |
| M1 | 450 | 775 | 490 | 50 | 1 | 1.25 | 0.37 |
| M FGM 1 Layer | 450 | 775 | 490 | 50 | ---- | 1.25 | 0.37 |
| M FGM 3 Layer | 450 | 775 | 490 | 50 | ---- | 1.25 | 0.37 |
| M hybrid | 450 | 775 | 490 | 50 | 1 | 1.25 | 0.37 |

SF percentage, *SP Super-plasticizer, *w/b: water to binder ratio

TABLE XII. RESULTS OF THE IMPACT TEST

| Mix | No. of blows to cause 1st crack at age (days) | | | Number of blows to cause failure at age (days) | | |
|---|---|---|---|---|---|---|
| | 28-day | 60-day | 90-day | 28-day | 60-day | 90-day |
| MR | 1 | 1 | 1 | 1 | 2 | 2 |
| M1%GF | 3 | 3 | 3 | 5 | 5 | 7 |
| M FGM 1 layer | 1 | 2 | 3 | 2 | 3 | 5 |
| M FGM 1 layer | 3 | 3 | 4 | 5 | 6 | 9 |
| M hybrid | 3 | 4 | 4 | 6 | 6 | 9 |

## III. RESULTS AND DISCUSSION

The impact test in this study was conducted to evaluate the concrete's ability to resist sudden, repeated loading. Specifically, it measured how well the material responded to the impacts from a 3.4 kg iron ball dropped from a height of 1.5 m. For each specimen, the number of blows needed to initiate the first visible crack and the number required to cause complete failure were recorded. Tests were performed on specimens measuring 50 cm × 50 cm × 5 cm at three curing ages: 28, 60, and 90 days. Five different pumice lightweight concrete mixtures were assessed: a reference mix without any fiber reinforcement, a mix containing 1% GF, a mix with a single layer of FGM, a mix with three layers of FGM, and a hybrid mix that combined 1% GF with three layers of mesh.

The results, presented in Table XII and Figures 1-3, provide insights into the effect of various fiber reinforcements on the impact resistance of lightweight pumice concrete. The results revealed that almost all mix types failed for the first crack at about 1-5 blows.

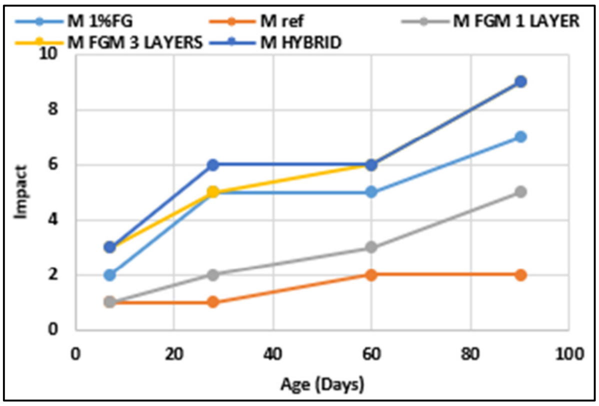


Fig. 1. Impact resistance with age.

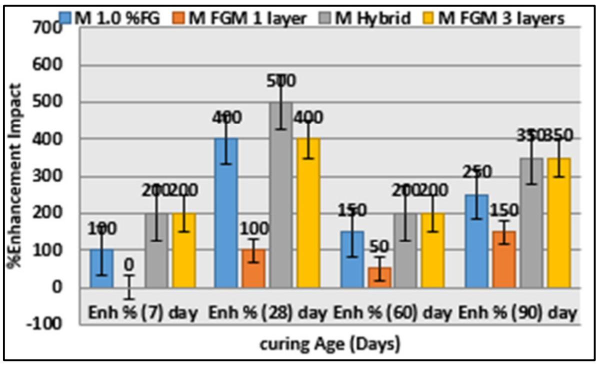


Fig. 2. Error bars for impact resistance % enhancement.

Fig. 3. The failure crack of one of the specimens.

Fig. 4. Examination method.

The best mix that resisted the continuous blows was the hybrid mix, due to the involvement of fibers within the mix in addition to the presence of FGM, which gives a superior arrest to the formation of the cracks and restricts theIR enlargement, enhancing the strength of the mix. The mixes with hybrid reinforcement exhibited a better behavior than the other mixes due to the combined effect of the fibers and meshes in enhancing the bending behavior of the mixes [14]. As shown in Figure 2, the error bars for the fiber-reinforced and hybrid mixes overlap, indicating a similar behavior in terms of the impact resistance. However, the degree of improvement varies depending on the type and percentage of the used fibers. These findings are consistent with the results in [15].

## IV. CONCLUSIONS

- Glass fibers (GFs) prevent the formation of microcracks and delay their development, as they connect the two sides of the crack and transfer some of the loads through them.
- The presence of the fibers increases the concrete's ability to absorb the energy resulting from the impacts and dynamic loads, delaying cracking and preventing collapse.
- The fibers improve the ductile toughness (post-cracking behavior), meaning that the concrete does not collapse immediately after cracking but continues to bear the load.
- The fibers help distribute the internal stresses more homogeneously, especially under repeated loads and sudden shocks.
- The results demonstrated that the hybrid mix (M hybrid) provided the highest shock resistance compared to the other mixes. It withstood nine impacts before failure at 90 days, compared to two impacts in the reference mix, which provided a 350% improvement.
- The combination of Fiberglass Mesh (FGM) and GFs in the hybrid mix significantly improves its ability to resist the crack formation and limit the crack growth, resulting in an enhanced overall strength.
- The results of this research may help in reducing the knowledge gap for the use of lightweight aggregate concrete made with sustainable pumice aggregate and reinforced with GFs. Such a type of concrete can be, thus, used in structures exposed to low velocity impact loading.

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## DATA AVAILABILITY

Data will be made available on request.

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