OPTIMIZATION OF MIX DESIGN FOR HIGH-STRENGTH LIGHT WEIGHT CONCRETE USING NATURAL PERLITE AGGREGATE

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Abstract:
Recent advancements in concrete technology have shifted focus towards concrete performance rather than constituent materials, notably seen in Lightweight Concrete (LWC). This study investigates the utilization of natural perlite aggregates in LWC to address concerns about depleting natural resources. The research explores different M20 grade concrete mixes, complying with IS 10262 (2009), where varying percentages of natural perlite aggregates replace coarse aggregates. The investigation delves into fresh and hardened properties, structural behaviour, bond strength, and durability aspects of LWC.
Mechanical properties (compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity) were assessed at different ages, including a 365-day compressive strength study. Durability assessments encompassed rapid chloride penetration, water absorption, permeability, acid resistance, sulphate resistance, and marine environment resistance, establishing correlations with compressive strength. The study also examined bond strength and explored structural applications through reinforced cement concrete beams. Findings indicate the potential of natural perlite aggregates as partial replacements in LWC for structural use, addressing environmental concerns associated with natural resource depletion and solid waste management.

Keywords: Lightweight Concrete, Natural Perlite Aggregates, Partial Replacement, M20 grade concrete.

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1. Introduction:

The evolution of concrete technology has undergone significant transformation, shifting from conventional material-centered approaches to a performance-based paradigm. This transition is particularly evident in the development of Lightweight Concrete (LWC), where emphasis is placed on achieving superior performance characteristics rather than focusing solely on constituent materials. One of the key challenges facing the construction industry is the dwindling availability of natural aggregates, prompting a re-evaluation of material resources and an exploration of alternatives to conventional aggregates.

Amidst this scenario, the utilization of natural perlite aggregates in concrete has emerged as a promising avenue to address concerns related to depleting natural resources. Perlite, a naturally occurring volcanic glass, possesses advantageous properties that make it an attractive candidate for incorporation into concrete mixtures. Its lightweight nature, coupled with favourable mechanical and thermal properties, presents opportunities for enhancing the performance of concrete while reducing its environmental impact.

2. Objectives:

Here are three objectives for the research on the utilization of natural perlite aggregates in Lightweight Concrete (LWC):

i. **Objective 1: Production of High-strength Light weight concrete using IS code 10262-2009.**

- Producing a lightweight concrete by fully replacing the conventionally used coarse aggregates with perlite aggregates.

ii. **Objective 2: Comprehensive Evaluation of Mechanical Properties**

- Conduct a comprehensive assessment of the mechanical properties of Lightweight Concrete containing natural perlite aggregates. This objective involves evaluating parameters such as compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity at different curing ages to understand the concrete's structural performance and durability over time.

iii. **Objective 3: Investigation of Durability and Structural Behaviour**

- Investigate the durability aspects and structural behaviour of Lightweight Concrete incorporating natural perlite aggregates. This objective aims to assess the concrete's resistance to chloride penetration, water absorption, acid and sulphate attacks, as well as its performance in marine environments. Additionally, analyze the bond strength, crack patterns, and load-bearing capacity of reinforced concrete structures made with these innovative concrete mixes.

3. Method & Methodology

3.1 Materials:

1. Cement: The investigation utilized Ordinary Portland Cement (OPC) of standard brand, specifically OPC 53 grade, adhering to IS 12269 – 1987 standards. This cement, procured from the local market, was carefully stored in airtight containers within a humidity-controlled environment to prevent moisture exposure. Prior to usage, the cement underwent thorough testing for compliance with IS 4031 standards to ensure its various properties. Table 1 presents the physical properties of the cement.

S. No.	Physical Properties	Test Results of Ultra Tech - OPC (53 Grade)	Requirements as per IS 12269-1987
1	Standard consistency (%)	30	-
2	Setting Time a. Initial Time (min) b. Final (min)	 120 320	 30 (min) 600 (max)
3	Compressive Strength (MPa) a. 3 Days b. 7 Days c. 28 Days	 32 44 54	 27 (min) 37 (min) 53 (min)
4	Fineness a. By sieving with IS sieve No. 9 (%) b. Blain's permeability method (m2/kg)	 2 320	 10 225 (min)
5	Specific Gravity	3.1	-

Table 1 Physical Properties of 53 Grade Ordinary Portland Cement

2. Natural Perlite Aggregate: The laboratory utilized perlite aggregate provided by local vendor, comprising five commercial sizes: perlite sand in sizes ranging from 0-2 mm, 0-3 mm, and 0-4 mm, along with coarse perlite aggregate available in sizes of 4-8 mm and 8-12 mm. For the creation of

high-performance lightweight concrete, a composite gradation was employed. This composite gradation encompasses aggregates of 0-4 mm, 4-8 mm, and 8-12 mm sizes, constituting 55%, 25%, and 20% by mass, respectively. This particular gradation scheme aligns with the specified boundaries outlined for combined lightweight aggregates as per ASTM C330 standards.

Aggregate Size (mm)	0-2	0-3	0-4	4-8	8-12
Dry-Loose Unit Weight (kg/m^3)	1286	1288	1322	1025	1002
Oven Dry Specific Gravity	2.09	2.06	1.99	1.89	1.93
Saturated-Surface Dry Specific Gravity	2.21	2.18	2.15	2.00	2.04
Water Absorption Capacity (%) - 72 hr.	5.45	5.64	7.79	6.14	5.59
No.200 Sieve - % Passing	10.44	11.64	8.75	-	-
Los Angeles Abrasion (%)	-	-	-	49.7	

Table 2 Physical Properties of Natural Perlite Aggregate

3. Coarse Aggregate:
Machine-crushed angular granite metal with a size of 20 mm sourced locally served as the coarse aggregate in this study. The knowledge of the density, specific gravity, and water absorption of aggregates is crucial for determining concrete mix proportions. Tests were conducted following the guidelines outlined in IS 2386 (Part 3) – 1963 to ascertain these properties. The outcomes of the tests, including sieve analysis, are presented in Table 3, offering insights into the characteristics of the coarse aggregate used in the investigation.

Sl. No.	Property	Value
1.	Specific Gravity	2.70
2.	Bulk Density i) Loose ii) Compacted	 1368 kg/m^3 1527 kg/m^3
3.	Water absorption	0.42%
4.	Impact Value	12.40%
5.	Crushing Value	6.30%
6.	Abrasion Value	1.90%

Table 3 Physical Properties of Natural Coarse Aggregates

4. Fine Aggregate: The present investigation utilized locally available river sand as the fine aggregate, ensuring its freedom from clayey matter, salt, and organic impurities. Comprehensive testing was conducted in adherence to IS 2386 (Part 3) – 1963 standards, covering properties such as specific gravity, fineness modulus, and bulk density. The fine aggregate, passing through a 4.75 mm IS sieve and conforming to grading zone II of IS 383 – 1970, exhibited specific gravity and fineness modulus values of 2.56 and 2.60, respectively. These test results are documented in Table 4, presenting a clear overview of the fine aggregate's properties obtained through sieve analysis.

Sl. No.	Property	Value
1.	Specific Gravity	2.56
2.	Bulk Density	1693 kg/m^3
3.	Fineness Modulus	2.60

Table 4 Properties of Fine Aggregates

5. Water: Potable tap water adhering to IS 456 – 2000 standards was utilized in this study for both mixing and curing of the concrete.

Mix Proportions (Kg/m^3)		
Concrete Type	HSLWC	HSNWC
Cement	315	315
Water	100	140
Aggregate	Perlite	Conventional
0-4 mm	875	1135
4-8 mm	392	450
8-12 mm	312	391
Superplasticizer	1.26	1.23
w/c ratio	0.32	0.45
Theoretical Fresh Density	1996	2425
Setting Time		
Initial Set (hr:mm)	5:30	4:30
Final Set (hr:mm)	9:30	7:30

Table 5 Mix Proportion design

3.2Mix Proportion:
The concrete mix was designed targeting a 28-day compressive strength of 20 N/mm², as per IS 10262 – 2009 standards. The optimized quantity of cement was established at 315 kg/m³ to achieve this specified strength value. Notably, studies suggest that for structural lightweight concrete, the cement content typically ranges between 285 and 510 kg/m³ (Mannan and Ganapathy, 2001a, 2004), indicating the variability in compositions. The mix proportions for this OPC concrete are detailed in the table 5 above. Workability assessments were conducted using the slump cone test, performed

approximately 10 minutes after water addition to the mix constituents. These workability tests were conducted in adherence to the procedures outlined in IS 1199 – 1959.

3.3Casting and Curing:

The concrete mixtures were manually prepared on a water-tight, non-absorbent platform, following the guidelines specified in IS 516 – 1959. The procedure involved meticulous mixing of cement and fine aggregate until a uniformly colored and thoroughly blended mixture was achieved. Subsequently, the Perlite Aggregates (PA) in saturated surface-dry (SSD) condition was added and thoroughly mixed into the batch until homogeneity was attained, ensuring uniform distribution of the coarse aggregate. Water was then added gradually while continuing the mixing process until the concrete appeared homogenous. The casting and preparation of these diverse specimens were conducted in adherence to standardized procedures for accurate testing and evaluation of various concrete properties.

S.No.	Type of Test	Shape	Dimension mm	Number of Specimens	Age in Days
1	Compressive Strength	Cube	150 * 150 * 150	90	7 , 14 , 28, 56 , 90 and 365
2	Splitting Tensile Strength	Cylinder	150 Diameter * 300 Height	15	28
3	Flexural Strength	Prism - Beam	100 * 100 * 150	15	28
4	Modulus of Elasticity	Cylinder	150Diameter* 300 Height	15	28

Table 6 Details of specimens cast for determining Mechanical Properties

3.4Properties of Evaluate:

i. Compressive Strength
ii. Flexural Strength
iii. Modulus of Elasticity
iv. Splitting Tensile Strength
v. Rapid Chlorine Penetration Test
vi. Water Permeability Test
vii. Water Absorption Test
viii. Acid Resistance – H_2SO_4
ix. Sulphate Resistance - Na_2SO_4

4. Result & Discussion

a. Compressive Strength

As stated previously, the mix proportions are determined such that 28th day specific strengths of both designed concrete types would be comparable. Since the concrete in structural applications is generally air-dry in service condition, specific strength calculations are based on air-dry density of the specimens. The provided data presents a comparative analysis between High-Strength Lightweight Concrete (HSLWC) and High-Strength Normal Weight Concrete (HSNWC) across various parameters. In terms of compressive strength (in MPa), both concrete types show a consistent upward trend in strength over time. At 7 days, HSLWC demonstrates a compressive strength of 39.5 MPa, while HSNWC records a slightly higher strength of 49.7 MPa. However, this trend persists over the test period of 270 days, with HSLWC eventually surpassing HSNWC at 58.2 MPa compared to 63.2 MPa, respectively. Considering density (in kg/m³) under different moisture conditions (SSD, AD, OD), HSLWC consistently exhibits lower densities across all conditions compared to HSNWC.

Compressive Strength (MPa)		
Age	**HSLWC**	**HSNWC**
7 Days	39.5	49.7
28 Days	43.7	54.9
56 Days	47.2	57.3
90 Days	47.8	57.7
120 Days	49.1	58.2
180 Days	52.7	59.9
270 Days	58.2	63.2
Density (kg/m³)		
Moisture Condition	**HSLWC**	**HSNWC**
SSD	1939	2416
AD	1881	2376
OD	1849	2327
Specific Strength (MPa)		
Moisture Condition	**HSLWC**	**HSNWC**
AD	23.2	23.1

Table 7 Compressive Strength, Density & Specific Strength

For instance, under the AD condition, HSLWC records a density of 1881 kg/m³, whereas HSNWC presents a higher density of 2376 kg/m³. When examining specific strength (in MPa tons/m³) at the AD moisture condition, HSLWC and HSNWC demonstrate similar specific strength values, with HSLWC at 23.2 MPa tons/m³ and HSNWC at 23.1 MPa tons/m³. This data suggests that while HSNWC exhibits higher early-age compressive strength, HSLWC achieves comparable specific strength with notably lower densities, emphasizing its potential as a viable lightweight alternative for structural applications. In Table 7, compressive strength, specific strength, unit weight of the designed concretes in saturated surface dry (SSD), air-dry (AD) and oven-dry (OD) condition have been provided.

b. Splitting Tensile Strength

The splitting and flexural tensile strength of the designed concretes at 28 and 90 days of age are presented in Table 8. The results indicate that HSLWC exhibit splitting tensile strength and flexural tensile strength values that are approximately 1-2 MPa lower than those of HSNWC. Furthermore, the data suggests that there is no significant increase in tensile strength between 28 and 90 days, except for the splitting tensile strength of HSNWC and the flexural tensile strength of HSLWC.

Table 8 Splitting and flexural tensile strength

Splitting Tensile Strength (MPa)			
Age	HSLWC		HSNWC
28 Days	3.5		4.3
90 Days	3.7		5.2
Flexural Tensile Strength (MPa)			
Age	HSLWC		HSNWC
28 Days	5.1		7.9
90 Days	5.9		8.1

c. Elastic Modulus

Table 9 provides the elastic modulus values of the designed concretes at 28th and 90th days. It can be observed that there is negligible change in the elastic modulus between these two time periods. The elastic modulus of HSLWC is approximately 50% of that of HSNWC. This decrease in elastic modulus for lightweight concretes can be attributed to the lower stiffness of the natural perlite aggregates used.

Table 9 Modulus of elasticity, compressive strength & density

Elastic Modulus (GPa)			
Age	HSLWC		HSNWC
28 Days	22.2		44.9
90 Days	22.2		42.5
Compressive Strength (MPa)			
Age	HSLWC		HSNWC
28 Days	43.7		54.9
90 Days	47.7		57.6
Density (kg/m^3)			
Moisture Condition	HSLWC		HSNWC
AD	1881		2376

d. Rapid Chloride Ion Permeability

The results of rapid chloride ion penetrability tests have been tabulated in Table 10. At the age of 28 days, HSLWC has low penetrability, on the other hand HSNWC has moderate penetrability. Although HSLWC and HSNWC has similar binder content, HSLWC has a lower penetrability because of several reasons such as lower w/c ratio, disconnected porous nature of perlite aggregate and pozzolanic activity in contact zone.

Table 10 Chloride ion penetrability of concrete specimens

Charges Passed(coulombs) - Chloride Ion Penetrability				
Age(days)	HSLWC		HSNWC	
28	1486	Low	3696	Moderate
90	767	Very Low	3054	Moderate

e. Magnesium Sulphate Solution

The change in the compressive strength of the specimens stored in 0.352 M MgSO4 solution is as shown in the figures from 1 and 2, separately for each type of the concrete. The line representing the control group and the line representing the specimens in the magnesium sulphate solution almost coincides in both graphs. This means that HSLWC and HSNWC are equally resistant to sulphate attack when the change in compressive strength is considered.

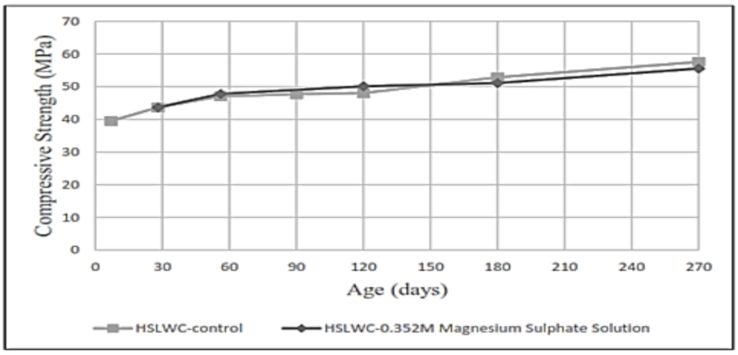

Figure 1. Change in compressive strength of HSLWC specimens stored in Magnesium Sulphate solution

In Figures 3 and 4, surface deterioration of the specimens stored in magnesium sulfate solution have been illustrated. It can be concluded that surface deterioration of HSLWC is relatively higher than HSNWC.

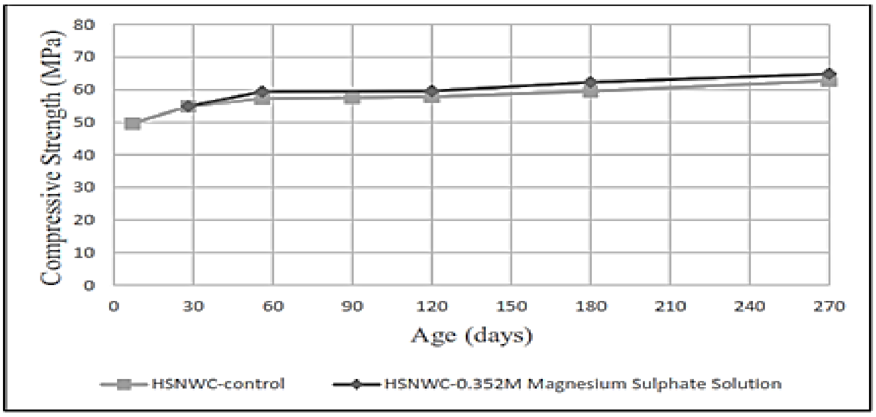

Figure 2. Change in compressive strength of HSNWC specimens stored in Magnesium Sulphate solution

Figure 3. Surface Deterioration of HSLWC specimens stored in magnesium sulphate sol.

Figure 4. Surface Deterioration of HSNWC specimens stored in magnesium sulphate sol.

f. Sulphuric Acid Solution

The change in the compressive strength of the specimens stored in 1% H2SO4 solution (pH=1) is given in figures 5 and 6, separately for each type of the concrete. As it can be seen from the graphs, the line representing the control group and the line representing the specimens in the sulphuric acid solution almost coincides for the first three months of exposure. After that point specimens started to show loss in compressive strength. At the age of 9 months, percentage loss in the compressive strengths compared to control specimens were 12, 0.4 percent, respectively for HSLWC and HSNWC. It can be concluded that HSNWC is more durable to sulphuric acid than HSLWC. Nevertheless, when it is independently evaluated, HSLWC can also be considered durable since their compressive strengths under such aggressive conditions are still higher than the 28day compressive strengths, namely the compressive strengths at the start of the exposure.

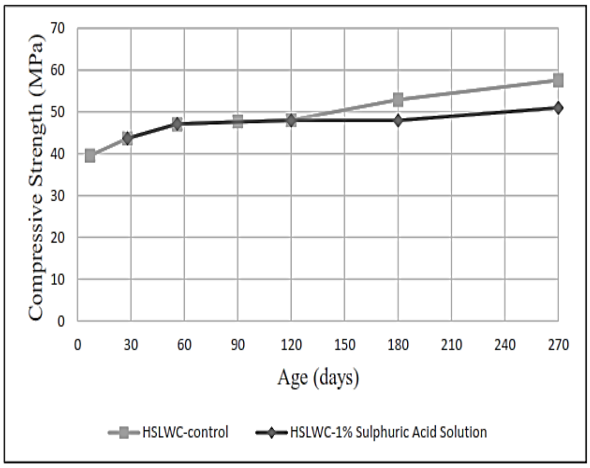

Figure 5. Change in compressive strength of HSLWC specimens stored in H_2SO_4 Acid sol.

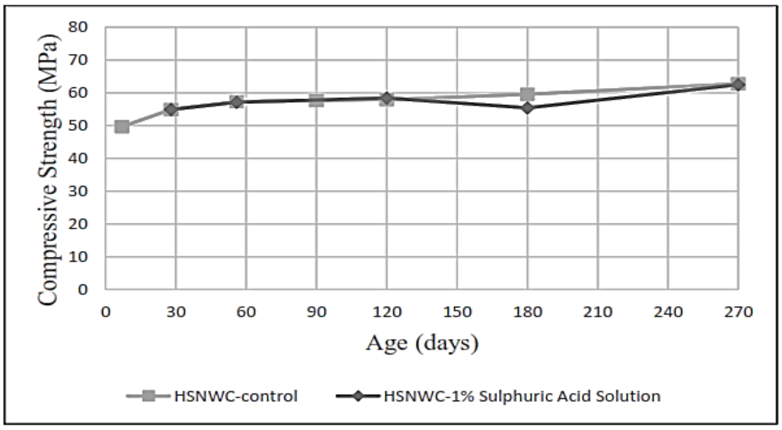

Figure 6. Change in compressive strength of HSNWC specimens stored in H_2SO_4 sol.

Figure 7. Surface Deterioration of HSLWC specimens stored in Sulphuric Acid sol.

Figure 8. Surface Deterioration of HSNWC specimens stored in Sulphuric Acid sol.

In Figures 7 and 8, surface deterioration of the specimens stored in sulphuric acid solution have been illustrated. It can be seen that the surface of both concretes have been deteriorated. In addition, for HSLWC, a weak cover formation was observed. The thickness of this deteriorated cover had been reached to 4 mm at the end of 8 months of exposure. This corresponds to 15% reduction in load bearing area, which is parallel to strength reduction (12-14%) observed in these specimens.

Conclusion

The findings derived from this comprehensive experimental study can be summarized as follows:

1. Natural perlite aggregate exhibits significant potential in creating high-performance lightweight concretes, achieving impressive 28-day compressive strengths of up to 50 MPa.
2. To achieve a comparable specific strength to that of high-strength normal weight concrete, high-performance lightweight concrete employing natural perlite aggregate requires similar cement contents, approximately around 300 kg/m³.
3. High-performance lightweight concretes with natural perlite aggregate demonstrate a noteworthy advantage, being approximately 20% lighter than high-strength normal weight concrete at similar specific strengths.
4. At similar specific strengths, the elastic modulus of high-performance lightweight concretes with natural perlite aggregate is approximately 50-60% of high-strength normal

weight concrete, attributed to the reduced stiffness of lightweight aggregates. Moreover, it was established that the ACI 318 formula for estimating elastic modulus is applicable to structural lightweight concretes utilizing natural perlite aggregates.

5. The expansion characteristics of perlite aggregates were primarily influenced by their chemical structure rather than their inherent porosity.
6. Self-compacting high-strength lightweight concrete incorporating natural perlite aggregate and perlite powder exhibits significantly lower chloride permeability compared to high-strength normal weight concrete with similar specific strengths. This improved performance is attributed to factors such as lower water-to-binder ratios, internal curing, and enhanced pozzolanic activity, leading to a more efficient contact zone.
7. When considering durability against magnesium sulfate attack, high-performance lightweight concretes with natural perlite aggregate and high-strength normal weight concrete demonstrated similar resilience concerning changes in compressive strength. However, the lightweight concretes exhibited higher surface deterioration when exposed to magnesium sulfate solution compared to limestone-based high-strength normal weight concrete.
8. Exposure to sulfuric acid revealed that perlite-containing high-performance lightweight concretes exhibited considerably greater surface deterioration than their limestone-containing counterparts. This deterioration formed a weakened cover on the concrete surface, resulting in approximately a 15% reduction in cross-sectional area and a parallel reduction of 12-14% in compressive strength.

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