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Optimization of lightweight concrete using vermiculite, silica fume and naphthalene-based superplasticizer

[1]Rahul Darvesh, [2]Sujeet Patil
[1]Student, [2]Professor,
[1] Department of Civil Engineering.
[1]P.D.A College of Engineering, Kalaburagi, India

Abstract: Concrete remains the most extensively used construction material worldwide due to its versatility, strength, and durability. However, increasing demand for natural sand has led to severe environmental concerns due to excessive sand mining. To solve this problem, using lightweight concrete with alternative fine materials can help both the structure and the environment. Adding vermiculite to concrete improves its ability to resist shrinking and cracking, makes it more fire-resistant, lowers its environmental impact, and can also reduce costs. In this study, an effort was made to examine the mechanical properties of M30 grade concrete when different percentages of vermiculite, ranging from 10%, 20%, and 30%, are used to replace fine aggregate, based on the total weight of the fine aggregate. Cement is also partially replaced by adding 10% silica fume based on the weight of the cement, which helps increase its reactivity. A naphthalene-based superplasticizer is added to make the concrete easier to work with without needing more water. The water-cement ratio is set at 0.48 and remains the same for all mixes. The concrete was extensively tested to check its fresh properties, like slump, and its hardened properties, such as compressive and split tensile strength, after 7 and 28 days of curing. The results show that using vermiculite lowers the density, making the concrete lighter, while silica fume greatly improves its strength and durability. The best mix was found by balancing strength, workability, and weight reduction, making this type of concrete good for both sustainable and structural uses.

***Index Terms* - Exfoliated vermiculite, silica fume, CERA PLAST300, Compressive Strength, Split Tensile Strength**

I. INTRODUCTION

The building and construction on industry has grown tremendously in the recent past. Thus, the production on and use of concrete has increased significantly. This, in turn, places a heavy burden on scarce natural resources and exacerbates environmental problems. Population on growth, increased industrial activity, and ongoing infrastructural development all have a hand in further straining these resources [1].

Engineering advances in construction rely on materials that can reduce structural self-weight without compromising performance. Lightweight concrete uses aggregates like pumice, expanded clay and vermiculite to decrease the structure's dead load. With vermiculite's bulk density being 60–130 kg/m3, the concrete density is significantly lower than 1800 kg/m3. However, the efficiency of this property relies on an optimal water–cement ratio [2].

High-strength concrete (HSC) is generally recognized as a very strong, durable, and versatile material. It is more powerful than standard concrete mixes and is often so dense that it may not be suitable for certain applications. However, the density of concrete can be reduced using additives without compromising its strength. For instance, using fibers and mineral additives like silica fume can greatly improve the performance of concrete, resulting in development of high-strength, lightweight concrete (HSLWC). This type of concrete has the potential to be a breakthrough in fields where both weight reduction and high strength are required [3].

Lightweight Engineered Cementitious Composites (LWECC), with densities below 1500 kg/m³, reduce structural dead weight while maintaining strength and durability. Replacing fine aggregates entirely with exfoliated vermiculite improves insulation, cohesion, and crack resistance, enhancing both performance and sustainability of structural components [4]

lightweight concrete is a relatively new construction on material that enhances the effectiveness and green credentials of a construction on project. With the inclusion of certain low-density aggregates or additives, concrete achieves an overall lower weight compared to conventional mixes, although the concrete's key structural characteristics are still preserved. To achieve the desired result, fine aggregates are omitted or reduced, increasing porosity and improving insulation properties. This results in handling and thermal and acoustic insulation, in addition to a greater range of architectural and non-structural application versatility. The concrete also aids in increasing resource savings and aids in the development of energy-efficient structures by lowering the self-weight of structural elements, an increasingly popular construction practice [5].

Lightweight concrete has enhanced thermal resistance and reduced weight, which lowers the load demands on the structure. Expanded vermiculite, which has low density and good heat insulation qualities, is ideal for use in the nonstructural parts of a building and for plastering walls. Nonetheless, the application of hemp fiber in concrete is still limited and further research is necessary to improve its strength and thermal resistance for energy-efficient and fire-proof materials [6].

The proposal aims to make buildings more energy-efficient and to People should use materials that are easier to find and more durable. More people are looking for different materials to use with concrete. Light and insulating materials, like vermiculite, are being tested and used to make concrete better at keeping heat in or out while making it lighter. This means concrete can be used in new ways, such as being more insulating or easier to carry. Vermiculite works well as a substitute for fine sand because it is easy to find, has good insulation, and doesn't let heat pass through easily. When used in concrete, vermiculite improves insulation, fire safety, and how well materials are used, without making the concrete weaker. This helps make concrete more eco-friendly, longer-lasting, and better suited for modern building needs [7].

Modern maintenance techniques promote the training of mechanics, operators, and supervisors, enhancing the technical skills of the workforce and creating diverse opportunities, from simple buildings to large structures. Concrete, a crucial construction material, is composed of special mixtures that offer unique qualities compared to stone, such as greater resistance to weather, lower maintenance requirements, and longer durability. Certain types of concrete, like lightweight aggregate concrete, use materials that reduce weight, improve earthquake safety, and increase fire resistance. These benefits can result in buildings with longer spans, thinner walls, and reduced construction costs. Vermiculite is a light material that works well for insulation and can handle heat, and it is commonly used as a replacement for regular building materials like sand or gravel. The study examines how incorporating vermiculite affects the strength and thermal properties of concrete, aiming to develop more efficient and environmentally friendly building materials [8].

The purpose of this research is to develop an optimized lightweight concrete mix by partially replacing fine aggregates with vermiculite and cement with silica fume, along with the addition of a naphthalene-based superplasticizer. Vermiculite is a light material that also helps with insulation, so it can help make concrete more eco-friendly by making it lighter and better at keeping heat. The main focus of this study is to check how different amounts of vermiculite, specifically 10%, 20%, and 30%, influence the compressive strength and split tensile strength of concrete. Silica fume is also included in the mix. improve the concrete stronger and more durable, while the superplasticizer makes the mix easier to work with. The overall aim is to find the best mix that offers good strength, long life, and less weight for use in environmentally friendly construction projects.

II Literature Review

Krishnaraj Loganathan, Kattankulathur (2023)

This study looked at using vermiculite as a partial substitute for sand, replacing between 40% to 60% of it in concrete bricks. It found that the bricks had compressive strengths between 3.2 and 5.9 N/mm², and their densities ranged from 1,780 to 2,142 kg/m³. The researchers used advanced statistical methods such as regression analysis and heatmaps to model and predict the material's properties. These findings are very useful because they that vermiculite can improve thermal and acoustic insulation without reducing the strength of the bricks. They also help in figuring out the best mix ratios for new design tools. Overall, the study shows that adding vermiculite to concrete supports sustainable building by lowering environmental impact and helping to achieve a good balance between strength, density, and performance.

P. Ashveen Kumar (2022)

The results show that the best lightweight concrete is made when 5% to 10% of the fine aggregate is replaced with vermiculite. Using more than that makes the concrete weaker because vermiculite has many tiny holes. GGBS is better than dolomite at keeping the strength of the concrete. For this project, the findings suggest that adding silica fume can help improve the strength that is lost because of vermiculite. This means we can make lightweight concrete that is strong and lasts a long time. This also means that mixing vermiculite with silica fume is a good way to make lightweight concrete that has better insulation, strength, and durability. The best results happen when about 10% to 20% of the fine aggregate is replaced with vermiculite, and the right amount of silica fume is added, creating a well-balanced mix that works well for building structures and sustainable use.

Savitha Somasundaram, Krishnaraja Ammapalayam Ramasamy (2020)

The study showed that Lightweight Engineered Cementitious Composite (LWECC) has a density between 1400 and 1500 kg per cubic meter. This makes the material much lighter than normal concrete, which helps reduce the total weight of a structure. The material absorbed water at a rate of 5 to 6 percent, which is considered acceptable. It was also found that mixes with less fine vermiculite had better strength and lower water absorption. These results show how the size of vermiculite particles and the type of fiber used affect the strength and durability of the material. This is important for choosing the best mix and predicting how well the material will perform if natural sand is replaced with vermiculite. In general, mixing vermiculite with PVA or PP fibers creates a lightweight, flexible, and strong material with a good strength-to-weight ratio. The best results came from using smaller vermiculite particles, which reduced the overall weight without lowering the strength.

K. Naveen Kumar, D.S. Vijayan, R. Divahar, R. Abirami (2019)

The study tested three different mix ratios—1:1:2, 1:1.5:1.5, and 1:2:1—and discovered that the 1:1.5:1.5 mix performed best. It achieved a 28-day compressive strength of 5.33 N/mm² and a split tensile strength of 3.35 N/mm². The dry weight of the blocks was between 1800 and 2010 kg/m³, which, based on IS standards, qualifies them as solid load-bearing units. For this project, this is very important because it shows that vermiculite-based lightweight concrete can meet both strength and density requirements. the aim of creating sustainable and efficient building materials. In conclusion, using the 1:1.5:1.5 mix classifies vermiculite lightweight concrete blocks as Type: Solid Load Bearing, Grade: C (5.0) under IS 2185–1 (2005). This meets the necessary criteria for density and strength, proving that these blocks are suitable for use in structural projects.

Kim Hung Moa, Hong Jie Leea, Michael Yong Jing Liu (2018)
The study found that using expanded vermiculite made the mix flow better and more consistent. This is because there were fewer fine particles and the mix needed less water, which helped the flow spread wider by about 11%. The weight of the mixes also went down a lot—by 12% in the V30 mix and 27% in the V60 mix compared to the regular mix. This shows that vermiculite is a good option for making lightweight materials. However, as more vermiculite was used, the strength of the mix went down. At 28 days, the strength was 16.6 MPa for V30 and 12.1 MPa for V60, which is lower than the regular mix. This is because vermiculite has more pores and is weaker. Even though the strength was lower, the mixes made with vermiculite still gained strength faster between 7 and 28 days. these results are useful because they show how vermiculite can reduce weight and improve resistance to heat, but also show that strength is a bit lower. Overall, expanded vermiculite is a good lightweight material that helps reduce the weight of cement mortar and improves fire resistance and temperature stability. While there is some loss in strength, the benefits of lighter weight and better thermal performance, along with acceptable strength, make it a good choice for projects where light weight and fire resistance are important.

III Objectives

1. To study the compressive and split tensile strength properties at 7 and 28 days curing for concrete with varying percentages of sand replaced by vermiculite.
2. optimize lightweight concrete by partially replacing fine aggregate with vermiculite and cement with silica fume, along with the use of a naphthalene-based superplasticizer.
3. The purpose is to study how concrete behaves when some of the fine aggregate is replaced with vermiculite. The replacement percentages being tested are 10%, 20%, and 30%.
4. To identify the optimal combination of materials to develop lightweight concrete.

IV Methodology

4.1 Materials Used

4.1.1 Cement

OPC 53 grade was used for casting cubes and cylinders for all concrete mixes. The cement had a uniform colour, which was grey with a slight greenish tint, and there were no hard lumps in it. Different tests were performed on the cement, including initial and final setting time, specific gravity, fineness, and compressive strength.

4.1.2 Sand

Fine aggregate is made from sand that comes from the land or the sea. It usually includes natural sand or crushed stone, and most of the particles are small enough to pass through a sieve with a 9.5mm opening. conforming to zone II of IS:383-2016 served as reference fine aggregate

4.1.3 Coarse aggregate

Hard granite broken stones were used as the coarse aggregate. The coarse aggregate was passed through a 20mm sieve, and the portion that went through the sieve was used, which followed the standards given in IS:383-2016.

4.1.4 water

Portable water was used for mixing and curing of concrete specimens.

4.1.4 Silica fume

silica fume used as supplementary cementitious material, partially replacing cement to improve strength and reduce permeability.

Table1: properties of silica fume

Properties	Values
Appearance	Grey
Form	Amorphous (non-crystalline) powder
Bulk density	200 – 300 kg/m³
Specific value	2.3
Average Particle Size	0.1 – 0.3 µm

4.1.5 Exploited vermiculite

The Exfoliated vermiculite was used as a lightweight fine aggregate replacement at 10%, 20%and 30% level by weight of sand. The specific gravity of vermiculite is 2.06**.**

Table 2: Physical properties of vermiculite.

Examination	Value
Specific gravity test of vermiculite	1.785
Water absorption test of vermiculite	72%
Sieve analysis of vermiculite	Fineness modulus=4.75mm

Fig 1: Exploited vermiculite

4.1.6 Superplasticizer

A naphthalene based high range water reducing admixture was add at a fixed dosage to improve workability without increasing water content.

Table 3: properties of naphthalene-based superplasticizer

Properties	Values
Appearance	Brown liquid
pH	5-7
Dosage	1% by weight of cement
Specific Gravity	1.2 $\pm$ 0.03

4.2 Mix design

- The mix proportions were made for M30 grade concrete following the standards IS:10262-2019 and IS:456-2000
- A control mix was made without using vermiculite or silica fume for comparison purposes.
- For the experimental mixes, sand was partially replaced with vermiculite in amounts of 10%, 20%, and 30%
- Silica fume was added as a replacement for cement in fixed proportion of 10% by weight of cement.
- A consistent dosage of 1% of naphthalene-based superplasticizer was used to keep the workability of the mixes the same.
- The mix proportion for 1m3 of vermiculite.

Table 4: mix proportion

%	cement	Fine aggregate	vermiculite	Coarse aggregate	Silica fume	water	Chemical admixture
10%	350	606.42	52.02	1161.90	38.9	179.12	3.89
20%	350	539	103.89	1161.90	38.9	178.82	3.89
30%	350	471.58	155.73	1161.90	38.9	178.52	3.89

4.3 Preparation of specimen

4.3.1 Batching and mixing:

The correct amounts of cement, sand, vermiculite, silica fume, and coarse aggregates were mixed together while they were dry until everything was evenly mixed. Then, water that was already mixed with the superplasticizer was slowly poured into the dry mixture, and the concrete was mixed thoroughly until it became a smooth, uniform mix that was easy to work with and had no lumps.

4.3.2 Casting:

The cube molds, which were dry, were covered with oil on the sides and got ready to be filled with the concrete mix. The concrete was added in three layers, and each layer was pressed 25 times using a standard tamping rod. The top of the molds was made smooth with a trowel. After the cubes were cured, they were labeled with details like the date they were made and the percentage of silica fume used to help identify them. They were left to dry for 2 to 3 hours at room temperature. The cylindrical samples were made using the same method and the same molds.

Fig 2:Casting

4.3.3 Curing Process

Curing is a process that helps concrete become as strong as it can be. It lets the concrete keep hydrating, which makes it stronger over time. Hydration happens when the concrete has enough moisture and the right temperature for a long time. After 24 hours, the specimens were taken out of their molds and put into a tank with clean water. They were cured for 7 days and 28 days before being tested.

Fig 3: Curing

V Test of specimen

5.1 Fresh properties

The slump test was done using a standard cone mold that is 300 mm tall, with a base diameter of 200 mm and a top diameter of 100 mm. This cone was placed on a flat, non-absorbent surface. Freshly mixed concrete was poured into the cone in four equal layers, and each layer was compacted using 25 strokes of a tamping rod. After making the top surface level, the cone was slowly lifted straight up in about 5 to 10 seconds without any sudden movements. This allowed the concrete to settle on its own. The slump value was measured by comparing the original height of the cone (300 mm) with the highest point of the settled concrete. This measurement shows how workable the concrete mix and the results are shown in table 5.

Fig 4: Collapsed Slump

5.2 Test on Hardened Properties

5.2.1 Compressive strength test:

The compressive strength of the concrete was tested according to the standards specified in IS: 516–1959. Standard cube samples measuring 150 × 150 × 150 mm were used, and they were tested after being cured for 7 days and 28 days. Before the test, the cubes were dried on the surface and placed right in the middle between the plates of the Compression Testing Machine to make sure the pressure was spread evenly. Pressure was added at steady load was applied slowly of every minute until the cube broke. The maximum pressure measured when the cube broke was used to determine the compressive strength with a particular formula.

$$f_c = P/A$$

Where:

- f_c = Compressive strength (MPa)
- P = Maximum load applied (N)
- A = Cross-sectional area of cube specimen (mm^2)

Fig 5: compressive strength test

5.2.2 Split tensile strength:

The split tensile strength of concrete was tested according to IS: 5816–1999. Cylindrical samples with a diameter of 150 mm and height of 300 mm were used. After curing for 7 and 28 days, the cylinders were dried on the surface and placed horizontally between the plates of a Compression Testing Machine. A steady load was applied along the length of the sample at a steady speed until it cracked apart. The highest load before failure was noted, and the split tensile strength was calculated using the formula.

$$f_{st} = 2P/\pi DL$$

Where:

- f_{st} = Split tensile strength of concrete (MPa)
- P = Maximum load applied before failure (N)
- L = Length of the specimen (mm)
- D = Diameter of the specimen (mm)

Fig 7: Split Tensile Strength

VI RESULTS AND DISCUSSION

6.1 Fresh behavior

The characteristics of lightweight aggregates influence the workability of lightweight concrete. The slump test for the concrete flowability. It is found that the addition of vermiculite decreases the workability of concrete. As the vermiculite content decreases the slump gets greater. Vermiculite was dispersed irregularly throughout the matrix and impeded the flow of concrete.

Table 6: Slump Result

Percentage of vermiculite	Slump values
10%	95
20%	80
30%	75

6.2 Compression Test

Compressive strength was tested in compressive testing machine. Cube specimens of size 150mmx 150mm x 150mm were adopted for the test. Compressive strength was tested after 7 and 28 days of curing. The results of the tests are tabulated below.

Table 7: Compressive strength of vermiculite concrete

Type of Mix (Cube specimen)		Age of curing	Average strength (MPa)
10% of vermiculite	90%of fine aggregates	7	25.43
		28	38.52
20% of vermiculite	80%of fine aggregates	7	20.12
		28	33.22
30% of vermiculite	70%of fine aggregates	7	19.28
		28	30.22

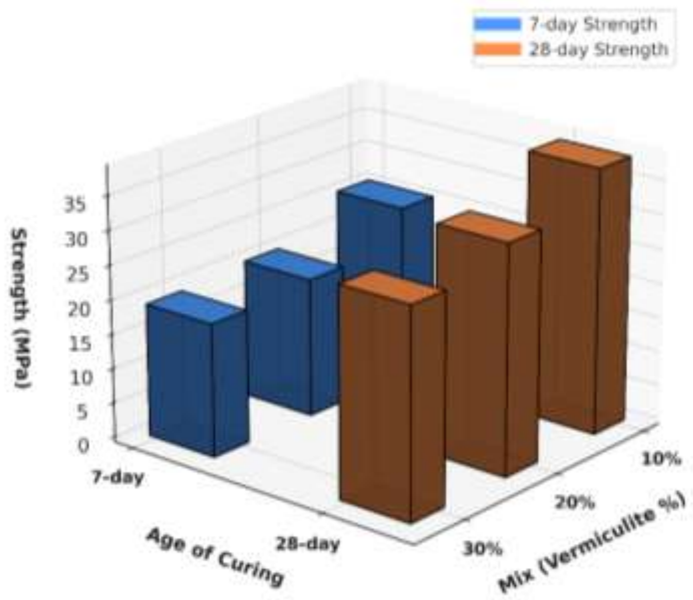

Fig 6: Compressive Strength

6.3 Split Tensile Strength

The test was conducted in compression testing machine. Cylindrical specimens were 150 mm diameter and 300 mm height. The results of the tests conducted are tabulated below.

Table 9: Split tensile strength of vermiculite concrete

Type of Mix (Cylinder specimen)		Age of curing	Average strength (MPa)
10% of vermiculite	90%of fine aggregates	7	2.31
		28	3.45
20% of vermiculite	80%of fine aggregates	7	2.56
		28	3.10
30% of vermiculite	70%of fine aggregates	7	2.21
		28	2.90

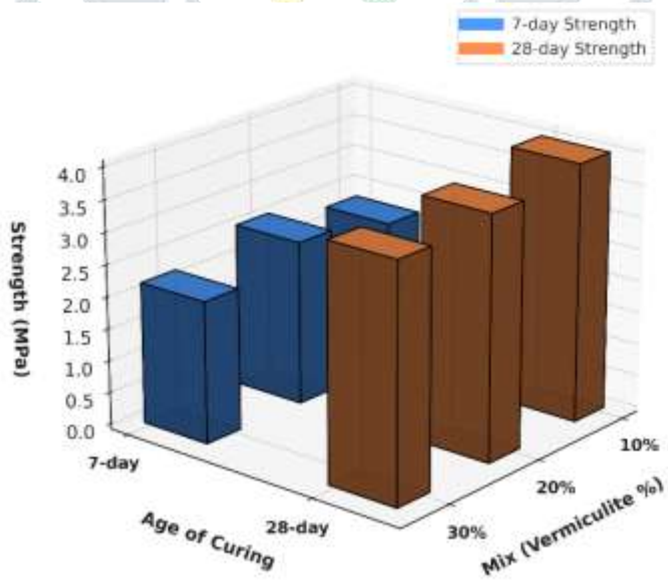

Fig 8: Split Tensile Strength

6.4 Outcomes and Observations

- As the amount of vermiculite increased, the slump and compaction factor values went down. This happened because vermiculite is light, flaky, and has many air pockets.
- Adding a naphthalene-based superplasticizer helped improve the flow of the mix, making sure the workability stayed within good limits.

- At 10% vermiculite replacement, the compressive strength was almost the same as the control mix. When the replacement was increased to 20%, there was a small decrease in strength, but it was still good enough for use in structures.
- At 30% replacement, the compressive strength dropped a There was a lot of porosity because there was more space between the materials. However, adding silica fume helped by making the pores smaller and improving how the materials stuck together, which increased the strength.
- The maximum split tensile strength was achieved at 10% vermiculite replacement, while 20% replacement showed only a moderate reduction, remaining within acceptable limits.
- At 30% replacement, split tensile strength reduced considerably, following the same trend observed in compressive strength.

VII Conclusion

- Using more vermiculite (20% and 30%) reduces strength but also makes the concrete lighter.
- Workability decreases as vermiculite content increases due to its porous nature.
- The highest compressive strength (38.52 MPa at 28 days) is seen when 10% of the material is replaced with vermiculite.
- Split tensile strength is also the highest at 10% replacement (4.02 MPa at 28 days).
- The best mix that balances strength, durability, and lighter weight is when 10% vermiculite, 10% silica fume, and a naphthalene-based superplasticizer.

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