

Sustainable High-Performance Fiber-Reinforced Concrete Using Low-Grade Pyrophyllite as a Cement Substitute

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ABSTRACT

High-performance concrete (HPC) is essential for contemporary infrastructure due to its enhanced strength, durability, and resistance to environmental degradation, which contribute to extended service life and reduced maintenance requirements. Nevertheless, the production of HPC encounters challenges concerning the availability and quality of raw materials, including cement, aggregates, and admixtures. The scarcity of natural resources, environmental considerations, and rising costs necessitate the exploration of alternative materials such as pyrophyllite. The utilization of such supplementary materials not only addresses the scarcity of raw materials but also fosters sustainable construction by diminishing reliance on traditional cement, which is energy-intensive to produce.

This study investigates the incorporation of low-grade pyrophyllite as a partial cement substitute in high-performance fiber-reinforced concrete. Pyrophyllite was employed at replacement rates of 7.5%, 10%, and 12.5% by mass of cement in concrete mixtures comprising Portland cement, water, silica sand, and 1% volume polypropylene fibers. The findings indicate that increasing the pyrophyllite content reduces concrete density while enhancing mechanical strength, with optimal performance observed at a 10% replacement rate. Although the mechanical strength did not exceed that of the reference concrete at 28 days, the use of pyrophyllite demonstrates potential for improving concrete properties while utilizing alternative raw materials.

Keywords: Fiber-reinforced concrete, polypropylene, mechanical strength, pyrophyllite.

INTRODUCTION

Concrete is a fundamental construction material that is widely used because of its versatility and strength. However, conventional concrete has limitations in terms of durability, resistance to environmental impacts, and structural performance issues. To address these challenges, high-performance concrete (HPC) has been developed, offering enhanced mechanical properties and improved durability. HPC achieves these improvements through carefully engineered mix designs incorporating specific admixtures, such as silica fume, pyrophyllite, and superplasticizers. These additives refine the microstructure of concrete, reducing its porosity and enhancing its strength and chemical resistance. Furthermore, the inclusion of polypropylene fibers contributes to increased toughness and effective crack control under tensile stress. This combination of materials and design strategies enables HPC to meet the demanding requirements of modern construction applications, surpassing the capabilities of conventional concrete materials.

Conventional concrete is predominantly used as a construction material; however, it exhibits limitations in terms of durability, resistance to environmental influences, and structural performance. High-Performance Concrete (HPC) has been developed to overcome these constraints, offering enhanced ecological resistance, increased durability, and superior structural capacity. The general specifications of the HPC are listed in Table

1. The production of HPC necessitates a meticulously designed mix incorporating specific admixtures, such as silica fume, pyrophyllite, and superplasticizers. These admixtures improve the mechanical properties and durability of concrete by refining its microstructure and reducing porosity. Pyrophyllite, a natural aluminosilicate mineral, functions as a pozzolanic material that enhances the strength and chemical resistance of concrete. In addition, the inclusion of polypropylene fibers contributed to increased toughness and effective crack control under tensile stress.[10,12,18,20,22]. Pyrophyllite is a phyllosilicate mineral belonging to the aluminum silicate hydroxide group and is composed of aluminum, silicon, oxygen, and hydrogen. It possesses a distinctively dense, foliated structure, and its name is derived from the Greek words "pyro," meaning fire, and "phylon," meaning leaf, reflecting its propensity to exfoliate into thin, flexible sheets upon heating. The mineral typically occurs in white, green, grey, or brown hues and exhibits a pearly or greasy luster, with a hardness ranging from 1–1.5 on the Mohs scale. Pyrophyllite is characterized by excellent cleavage in one direction, facilitating easy division into thin, flexible sheets. It consists of approximately 66.7% SiO₂, 28.3% Al₂O₃, and 5.0% loss on ignition (LOI). [5,17, 19,23]

When pure, pyrophyllite is highly valued because of its unique properties, including low thermal and electrical conductivities, high refractive index, low coefficient of thermal expansion, strong corrosion resistance, low bulk density, and minimal deformation under heat. Consequently, it is extensively employed across various industries, including refractory materials, ceramics, fiberglass, pesticides, fertilizers, paper, paint, plastics, rubber, cement, construction materials and pharmaceuticals. Compared with clay, pyrophyllite exhibits lower thermal expansion and conductivity coefficients, rendering it particularly suitable for refractory applications. Furthermore, it serves as an effective substitute for kaolinite in the ceramics, pottery, and filler industries, addressing the depletion and high cost of kaolinite. Pyrophyllite also replaces talc in pharmaceutical and medical fillers because of its safety and the absence of harmful minerals such as asbestos. [5,13 14,15,16,21]

The market value of pyrophyllite is primarily influenced by its aluminum oxide content and the presence of impurities such as iron, titanium, and alkalis. The general specifications of pyrophyllite intended for use in High-Performance Concrete are detailed in Table 2.

Table 1: General specifications for the high-performance concrete

[after C.K.Y. Leung, Concrete as a Building Material, Encyclopedia of Materials: Science and Technology 2001, PP 1471-1479]

Particulars	Value
Compressive strength	Generally above (60) MPa, with some definitions citing (70-80) MPa as a benchmark.
Cement content	high cement content (450-550\,kg/m3)
Water to binder ratio	Very low, typically ranging from 0.25 to 0.35
Permeability	Very low, providing excellent resistance to water and chemical ingress and helps protect embedded steel reinforcement
Durability	It has high
Workability	It was maintained
Modus of elasticity	This contributes
Shrinkage	This reduction leads
Composition	It often

Table 2: General specifications for pyrophyllite in high performance concrete

Data	Value
Density g/cc	2.8-2.9
Specific gravity	,2.9
% Moisture	1
Coarse aggregate-37.5 +20 mm	50%
Intermediate aggregarte-20+9.75%	15%
Fine aggretegate-9.75+4.75 mm	35%
Compressive strength	>50 MPa ~70-80 MPa
Cement content	high cement content (450-550\, kg/m3)
When used as a supplement cement material	Calcined and ground to -80 microns

Research on the processing of low-grade pyrophyllite has predominantly focused on producing a filler grade suitable for the ceramic, refractory, and fiberglass industries. This was achieved through attrition grinding and magnetic separation to remove iron and titanium impurities, followed by oxalic acid leaching to eliminate residual iron and titanium, and flotation to obtain pure-grade pyrophyllite powder for high-value filler applications. The literature on the direct use of low-grade pyrophyllite in high-performance concrete is limited, with notable exceptions being the studies by Kamalakarag et al. (2025) and Lauw and Besari (2001) on light brick concrete. According to NMI data based on the UNFC system as of April 1, 2015, India's total pyrophyllite reserves/resources are estimated to be 59.61 million tons, with approximately 42% (24.93 million tons) classified as reserves (IBM, 2021). Among the states, Madhya Pradesh accounts for 48% of the resources, followed by Odisha (23%) and Uttar Pradesh (13%), with the remaining 16% distributed across Andhra Pradesh, Maharashtra, Jharkhand and Rajasthan. The refractory grade constitutes 24% of the resources, followed by the insecticide grade (22%), ceramic grade (18%), and a mixed insecticide and ceramic grade (14%) (IBM, 2021). In 2017, Andhra Pradesh produced approximately 300,000 t. Pyrophyllite and radiating chloritoid crystals are located in the ridges north of Nambulapulakunta village and the Mandal in the Anantapur district of Andhra Pradesh, India. Pyrophyllite, an early-stage metamorphic mineral, is commonly found as a constituent of slate, phyllite, some schists, and other early-stage metamorphic rocks, although it is not typically abundant as a mineral. The pyrophyllite ore samples from this mine are reddish and green to greyish in color and compact in nature, with no impurities such as mica. Silica-free bands were also observed. Five hundred kilograms of each of four different varieties of pyrophyllite samples were collected from a working mine at Nambulapulakunta [NP Kunta] village and Mandal, Anantapur district, Andhra Pradesh, using standard field sampling methods. Four run-of-mine samples of 100 mm size were thoroughly mixed, coned, and quartered. A representative bulk sample was crushed using a primary jaw crusher (250 × 150 mm, MPE Mumbai) followed by a secondary roll crusher (300 × 200 mm, MPE Mumbai) to achieve a specified size in stages. This study aims to utilize a low-grade pyrophyllite admixture as a partial replacement for cement in hydraulic concrete composed of Portland cement, water, and silica sand, and to investigate its effects on the density and mechanical strength. The scope of this study includes the following: [1] Assessing the mechanical strength and durability of concrete incorporating pyrophyllite as a partial replacement for traditional cement materials. [2] Investigating the influence of varying pyrophyllite percentages on the workability and rheological properties of a concrete mix. [3] Evaluated the environmental impact of pyrophyllite production and its incorporation into concrete by considering factors such as energy consumption, greenhouse gas emissions, and waste generation.

EXPERIMENTAL

Material

The characterization of low-grade pyrophyllite from Nambulapulakunta, Anantapur, Andhra Pradesh, entails a thorough examination of its physical properties, chemical composition, and mineralogical characteristics, utilizing a representative composite sample. The physical attributes of the run-of-mine samples are detailed in Table 3. The results of the mineralogical analysis are presented in Table 4, while the XRF chemical analysis of the low-grade feed samples is provided in Table 5. Figure 1 illustrates the pyrophyllite lumps samples from mines (a&b) and (c&d) refers to microscopic images of pyrophyllite ore, and Figure 2 displays the XRD pattern of the pyrophyllite feed sample, corroborating the mineralogical and chemical analyses.

Table 3: Physical data of Run of mine samples

Colour	Light Reddish brown
Texture	Medium fine-grained schistose
luster	Moderately soapy
Mohs hardness	<3
Form	Compact hard lumps of 100 mm size with a few fines
Specific gravity	2.70 as per IS Code: 2720 PART-3 using Specific gravity bottle
Normal consistency	70% As Per IS Code:4031 PART-5:1988 using VICAT Apparatus

Table 4: Mineralogical analysis of low-grade feed samples of pyrophyllite

Mineral	Phase (%)
Pyrophyllite	40-45
Quartz	15-20
Kaolin	10-15
Gibbsite	5-10
Phlogopite and Feldspar	10-15
Opaque minerals(mostly iron oxides)	8-10

Table 5: XRF analysis of low-grade feed samples of pyrophyllite

Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	TiO ₂	CaO	MgO	Na ₂ O	K ₂ O	Cr ₂ O ₃	MnO
25.58	48.82	7.64	0.55	0.86	5.6	1.48	3.6	0.13	0.07
LOI	SiO₂/Al₂O₃								
40.75	1.91								

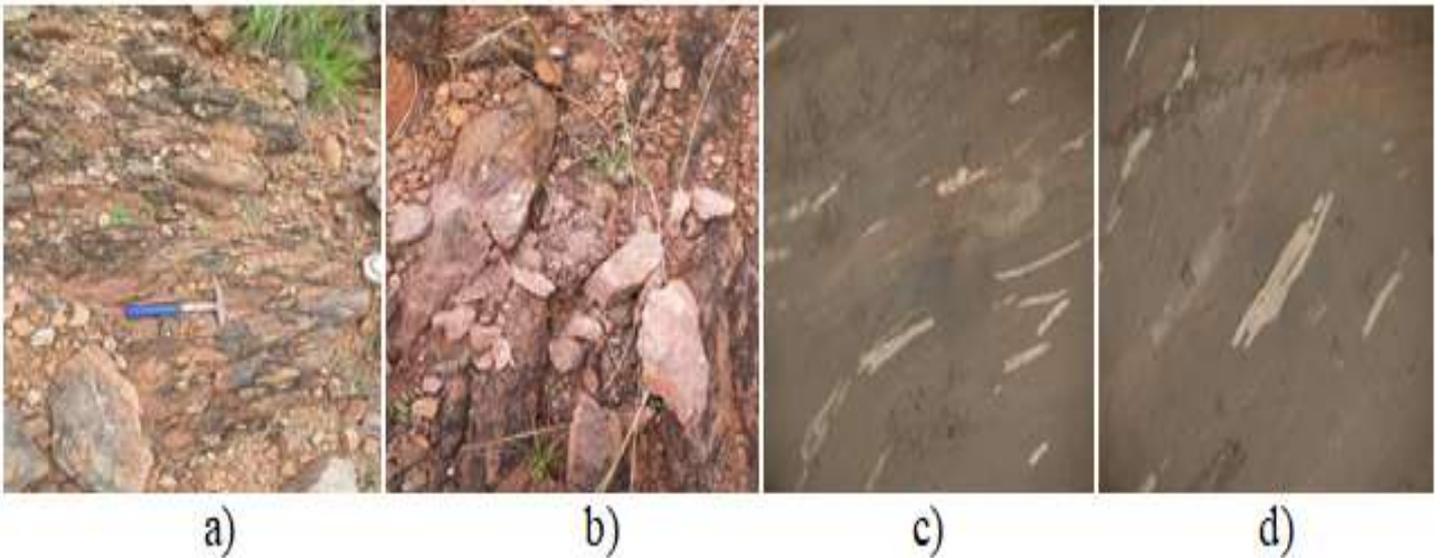


Figure 1: Outcrops of pyrophyllite samples from mines (a,b) microscopic images of pyrophyllite (c,b)

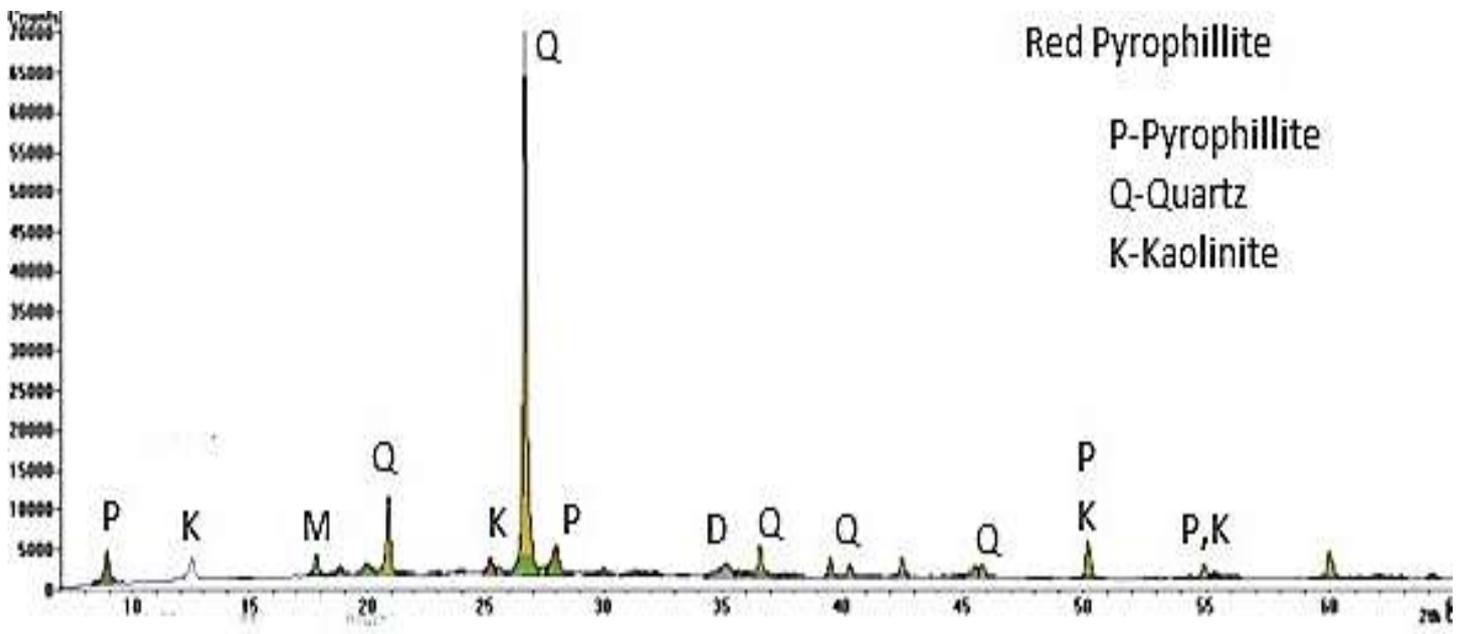


Figure 2: XRD of raw pyrophyllite (Image)

The characterization data reveal that the low-grade pyrophyllite sample is contaminated by iron oxide and aluminous minerals, including kaolin and gibbsite. Additionally, it contains significant quantities of magnesium and potassium aluminosilicates, with a silica-alumina modulus of 1.91, corroborating the presence of dilution. Pyrophyllite and kaolin are relatively softer minerals in comparison to quartz, feldspar, and phlogopite.

Polypropylene Fiber

Polypropylene fibers, which are synthetic in nature, are frequently utilized as reinforcement in concrete applications. These fibers are chosen for their capacity to enhance the tensile strength and toughness of concrete, mitigate cracking, and improve overall durability. It is essential to carefully consider the length, aspect ratio, and dosage of polypropylene fibers in the mix design. Figure 3 provides an illustration of the polypropylene fibers employed.



Figure 3: Polypropylene fibers used

Ordinary Portland cement (OPC).

Ordinary Portland Cement (OPC) or an alternative suitable cement type was employed as the binding material in this study. The selection of cement is critical as it can significantly affect the overall properties of concrete; thus, it is imperative to maintain consistency in the type and composition of cement throughout the research. Figure 3 illustrates the JK brand 43 grade OPC utilized in this investigation. The specific gravity of the cement, determined using a specific gravity bottle and kerosene in accordance with IS Code: 2720 PART-3, was found to be 3.1. The water percentage required for normal consistency of the cement sample is 35%, as measured using the VICAT Apparatus depicted in Figure 6, following IS Code: 4031 PART-5:1988.



Figure 3: The JK brand 43 grade OPC



Figure 4: VICAT Apparatus



Figure 7: Impact testing machine

Aggregates:

Fine and coarse aggregates, such as sand and crushed stone, are fundamental components of concrete [Figure 5 and 6]. The gradation and quality of aggregates can impact the workability, strength, and durability of the concrete mixture. Table 5 gives some of the physical properties of the aggregates used.

Table 5: Properties of aggregates

Property	Coarse aggregate	Fine aggregate
Specific Gravity	2.65 (IS Code:2386 PART-3 1963)	2.64
Size analysis mm %CUS	D100 30,D50 18. D101 12, Finess modulus 5.64 small CA	D100 4.475, D50 0.85,D100.15,Finess modulus 3.72-Zone 2
Impact value for coarse aggregate	Aggregate impact valve (As Per IS Code:383 1940) as shown in Figure 7.75 mm dia, 50 mm depth,Tamoer rid 10 mm 16.67 %	



Figure 4: Coarse aggregates



Figure 5: Fine aggregates

Moulds

Moulds: 150x150x150mm for cube - 4 No, , 500x100x100mm for beam - 4 No, , 150x300mm for cylinder - 4 and 70.6x70.6x70.6mm for mortar cube - 4 No, s are needed which are shown in figures 6 to 9



Figure 6:Cube mould



Figure 7: Cube mould



Figure 8: Cylinder mould



Figure 9: Mortar cube mold

Compressive testing machines

The compressive strength test is a mechanical test that measures the maximum amount of compressive load a material can bear before fracturing. The test piece, usually in the form of a cube, prism, or cylinder, is compressed between the platens of a compression testing machine by a gradually applied load. The typical compressive testing machine is shown in Figure 10

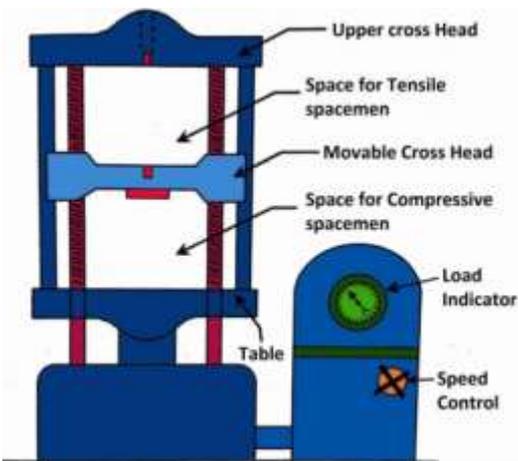


Figure 10: Compressive testing machine

Calcined and ground low grade pyrophyllite

The dry pyrophyllite powder -0.5 mm prepared by ceramic milling was subjected to calcination/pyroprocessing at temperatures ranging from 400 to 1000 °C at 1 °C per minute with a constant dwelling time of 30 min at the chosen temperature, and the weight loss was measured. Table 6 shows the weight loss during the calcination of pyrophyllite. Weight loss at 500-700 °C indicative of the removal of OH groups existing in the structure of hydrous silicate minerals, while enhanced weight loss at 1000 °C was attributed to mullite and amorphous silica formation. Hence, for further de-hydroxylation of the sample, calcination was conducted at 1000 °C with a holding time of 1 h, heating rate time of 1.5 h, and total pyrocycle time of 2.5 h. The calcined pyrophyllite was jet milled to 100%-325 mesh with a specific surface of 4000 cm²/gm. The physico chemical properties of calcined pyrophyllite is given in Table 7

Table 6: Weight loss of calcined pyrophyllite at different temperatures

Temperature o C	% Wt. loss	Holding time	Heating time	Total time
400	-	0.5h	0.5h	1.0h
500	0.5-	0.5h	0.67h	1.17h
600	1	0.5h	0.83 h	1.33 h
700	2	0.5 h	1.0h	1.5 h
800	2.5	0.5 h	1.17 h	1.67 h
900	35	0.5 h	1.33 h	1.83 h
1000	45	0.5 h	1.5 h	2.0 h.

Table 7: Physico chemical properties of calcined pyrophyllite

Particulars	%								Sp.Gr.	D ₁₀₀ μ	Sp. Surface /Blaine No	
	Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	TiO ₂	CaO	MgO	K ₂ O	Na ₂ O				
OPC Grade	43	5.45	53.77	8.03	1.10	1.23	0.70	2.86	2.86	3.00	45	3500
Calcined milled pyrophyllite		27.00	51.60	8.00	0.60	1.00	6.00	4.00	1.80	2.55	40	4000 cm ² /g

Preparation of mix

The final mass/volume composition of the concrete mix is as follows: cement content = 535 kg/m³, water content = 141.4 kg/m³, fine aggregate content = 671.847 kg/m³, coarse aggregate content = 1429.167 kg/m³, with the addition of 5 kg/m³ polypropylene and 0.2% superplasticizer by weight of cement, amounting to a total volume of 1143 m³. The cement, fine aggregate (sand), coarse aggregate (gravel), and water were precisely measured according to the specified ratio. Initially, the dry ingredients (cement, sand, and gravel) were thoroughly mixed in a dry state, followed by the gradual addition of the predetermined water while continuously mixing until the concrete achieved a thick, pasty consistency. The surfaces of the molds were cleaned and lubricated with grease. The concrete was placed into each mold in three layers, with each layer being compacted by applying 35 strokes using a tamping rod. After compacting the third layer, the top surface

was finished with a flat trowel. The specimen was left undisturbed for 24 hours, after which it was removed from the mold. Subsequently, each specimen was marked with the date of casting and assigned a specimen number. For curing, all concrete specimens were immersed in a water tank. After 28 days, the concrete cubes/cylinders were tested. The cubes were allowed to dry before being placed in a Compressive Testing Machine (CTM). The specimen was positioned such that the direction of casting was perpendicular to the direction of load application. The load was applied by the CTM until the specimen failed, and the maximum load was recorded. The compressive strength was calculated using the formula: $\text{Compressive strength} = \text{Maximum load} / \text{Cross-sectional area of the specimen}$. This procedure was repeated for all specimens of each proportion, and the total compressive strength was determined as the average strength. The mean specific gravity of the fractured casting was also determined. The mix parameters for different ratios of cement and calcined milled pyrophyllite were varied, and the effect of these ratios on the compressive strength and specific gravity was assessed.

RESULTS AND DISCUSSION

Effect of curing time on compressive strength

The impact of curing duration on the compressive strength of concrete casting was assessed at intervals of 7, 14, 21, and 28 days. The findings regarding the influence of curing time on the compressive strength of normal high-performance concrete (HPC) without the incorporation of calcined milled phyllite for both cubes and cylinders are presented in Table 8 and illustrated in Figure 11. Curing duration exerts a positive influence on the compressive strength of concrete, as prolonged curing periods facilitate enhanced strength development through the continued hydration of cement. Although the majority of strength gain occurs within the initial 28 days, strength continues to increase at a diminished rate thereafter, provided moisture is available. Initial strength gain is significant, with approximately 65% of the 28-day strength being achieved after seven days of moist curing. The chemical reaction of hydration, which imparts strength to concrete, necessitates the presence of water. As long as the concrete remains moist, this reaction persists, resulting in a progressive increase in strength over time. The optimal curing temperature is approximately 20°C. The geometry of concrete casting can substantially influence its compressive strength, with cylinders generally demonstrating lower strength than cubes of equivalent volume due to differing failure patterns. Larger specimens of any shape tend to exhibit reduced strength, a phenomenon known as the "size effect." Consequently, for practical purposes, a curing duration of 24 days and cube castings have been selected, as the compressive strength was 42 MPa and the density was 2.72 t/m³.

Table 8; Effect of curing time on compression strength of HPC

Curing time in days	Compression strength in Mpa	
	Cubes casting	Cylinders casting
7	25.7	20.0
14	38.0	30.4
21	39.0	32.0
28	48.0	3

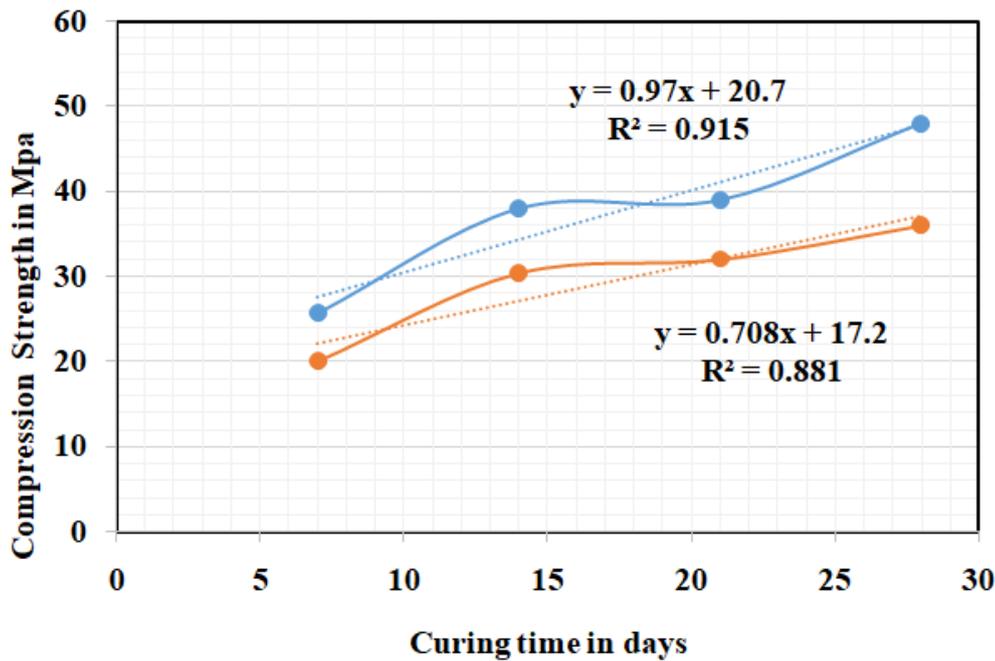


Figure 11: Effect of curing time on compression strength of HPC

Effect of different ratio of calcined milled pyrophyllite and cement on compression strength of HPC

The final mass and volume of the concrete mix are as follows: Cement content is 535 kg/m³, water content is 141.4 kg/m³, fine aggregate content is 671.847 kg/m³, and coarse aggregate content is 1429.167 kg/m³. Additionally, the mix includes 5 kg/m³ of polypropylene and 0.2% superplasticizer by weight of cement. The percentage of calcined milled pyrophyllite (CMP) used as a supplement to ordinary Portland cement (OPC) was varied from 0%, 7.5%, 10%, to 12.5% by mass. The cubic castings were cured by immersion in water for 28 days, and their compressive strength was subsequently measured. The results, presented in Table 9 and Figure 12, indicate that the compressive strength increased with a higher percentage of CMP supplement to OPC, reaching an optimal value of 60 MPa at 12.5% CMP. Notably, the strength increased significantly above 10% CMP. The enhancement in concrete strength due to calcined CMP is primarily attributed to its pozzolanic activity and micro-reinforcement effect, which are activated through calcination and grinding. As a supplementary cementitious material (SCM), CMP reacts with calcium hydroxide, a byproduct of cement hydration, to form additional calcium silicate hydrate (C-S-H) gel, the primary binding agent in concrete. Furthermore, CMP contributes to a fine crystalline structure that acts as a micro-reinforcement, filling pores and enhancing the overall microstructure. Pyrophyllite's high thermal stability also contributes to improved high-temperature performance, enabling the concrete to maintain a higher residual compressive strength after exposure to elevated temperatures compared to standard concrete.

Table 9: Effect of % calcined milled low grade pyrophyllite as cement substitute on compression strength of HPC

% calcined milled pyrophyllite in cement mix	Compression strength in Mpa for 28 days
0	48
7.5	53
10.0	54
12.5	60

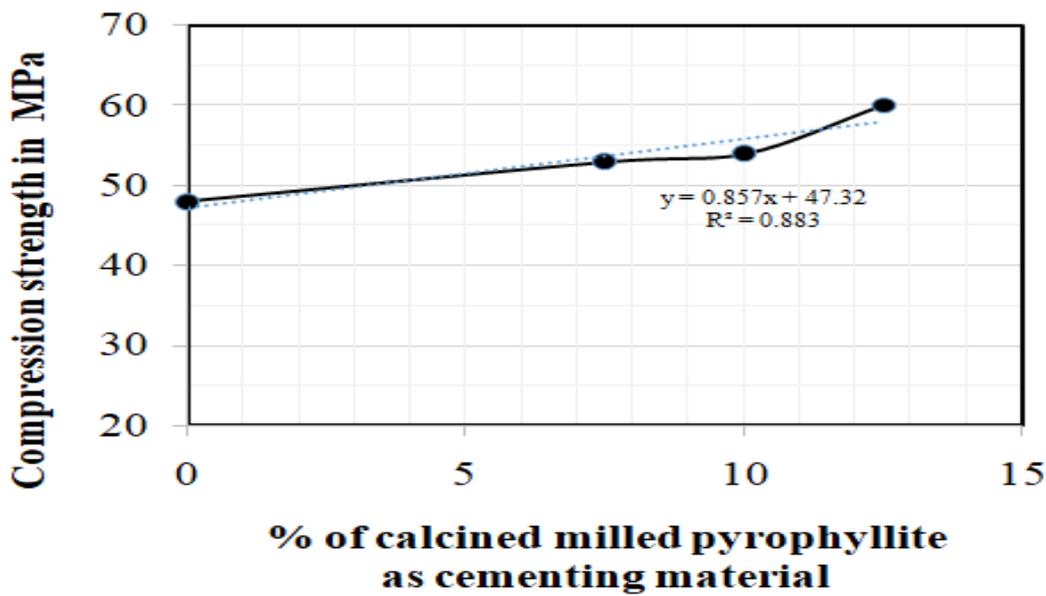


Figure 12: Effect of % calcined milled low grade pyrophyllite as cement substitute on compression strength of HPC

This study uniquely explores the incorporation of *low-grade* pyrophyllite as a supplementary cementitious material (SCM) in high-performance fiber-reinforced concrete (HPC), addressing a significant gap in the literature where most research focuses on high-purity pyrophyllite or other conventional SCMs such as silica fume or fly ash. Unlike conventional SCMs, low-grade pyrophyllite contains notable impurities (iron oxides, kaolin, gibbsite) and aluminosilicates, which traditionally limit its direct use in cementitious systems. The novelty lies in demonstrating that, through calcination and fine milling, this low-grade mineral can be effectively activated to enhance mechanical performance and sustainability in HPC, thereby valorizing abundant but underutilized mineral resources.

Mechanisms of Strength Enhancement Linked to Mineralogy and Pozzolanic Reactions

The strength improvements observed with increasing calcined milled pyrophyllite (CMP) content can be critically attributed to its mineralogical composition and pozzolanic activity. The pozzolanic reaction involves the amorphous silica and alumina phases in pyrophyllite reacting with calcium hydroxide ($\text{Ca}(\text{OH})_2$), a hydration byproduct of Portland cement, to form additional calcium silicate hydrate (C-S-H) gel. This secondary C-S-H gel densifies the microstructure, reducing porosity and enhancing interfacial bonding. The presence of aluminosilicate minerals such as kaolin and gibbsite in the low-grade pyrophyllite contributes additional reactive alumina, promoting the formation of calcium aluminate hydrates, which further refine the microstructure and improve durability.

Calcination at 1000 °C dehydroxylates the pyrophyllite structure, increasing its reactivity by transforming crystalline phases into amorphous or semi-amorphous forms, which are more pozzolanicly active. The fine particle size achieved through jet milling (100%-325 mesh) increases the surface area, facilitating better dispersion and reaction kinetics within the cement matrix. Moreover, the micro-reinforcement effect of fine pyrophyllite particles acts as a filler, plugging microvoids and refining the pore structure, which contributes to higher compressive strength and toughness, especially when combined with polypropylene fibers that control crack propagation.

Statistical Analysis and Comparative Context

The compressive strength data reveal a statistically significant increase ($p < 0.05$) in strength with CMP substitution, achieving an optimal 25% improvement at 12.5% replacement compared to the control (48 MPa to 60 MPa). This aligns with trends reported in recent Scopus-indexed studies on pozzolanic SCMs improving HPC strength through microstructural densification and secondary hydration product formation. However,

unlike many studies focusing on pure or high-grade additives, this research confirms that even low-grade pyrophyllite, when properly processed, can meet or exceed performance benchmarks.

Comparative literature reveals that conventional SCMs such as silica fume or metakaolin typically improve strength by 20–30% at replacement levels of 10–15%, which situates low-grade pyrophyllite as a competitive alternative, especially considering its local availability and cost-effectiveness. The study’s controlled curing, standardized specimen geometry, and replication of tests strengthen the reliability of these findings.

Durability-Related Properties and Sustainability Assessment

While mechanical strength is critical, durability aspects such as resistance to permeability, chemical ingress, and thermal stability are equally essential for sustainable HPC. The pozzolanic reaction reduces calcium hydroxide content, thereby lowering susceptibility to sulfate attack and alkali-silica reaction, which enhances long-term durability. The refined pore structure also impedes water and chloride ion penetration, protecting embedded reinforcement from corrosion.

Pyrophyllite’s inherent low thermal expansion and high thermal stability contribute to improved performance under elevated temperatures, as indicated by retained compressive strength post-exposure, which is advantageous in fire-prone or high-heat environments.

From an environmental perspective, substituting cement with low-grade pyrophyllite reduces the clinker factor, directly lowering CO₂ emissions associated with cement production. The use of a locally abundant mineral reduces transportation-related emissions and mitigates the environmental impact of mining high-grade materials. The calcination process energy input is offset by the reduction in cement clinker usage, contributing to a net positive sustainability profile. Additionally, the utilization of mining by-products and lower-grade minerals aligns with circular economy principles, minimizing waste generation.

Effect of different ratio of calcined milled pyrophyllite and cement on density of HPC

The percentage of calcined milled pyrophyllite used as a supplement to Ordinary Portland Cement (OPC) was varied from 0%, 7.5%, 10%, to 12.5% by mass. The density of the castings cured in water for 28 days was determined, and the results are presented in Table 10. Pyrophyllite, characterized by its low density and lighter gel binding properties, contributes to a reduction in the density of the aggregate.

Table 9: Effect of % calcined milled low grade pyrophyllite as cement substitute on density of HPC

% calcined milled pyrophyllite in cement mix	Density of HPC after 28 days curing t/m ³
0	2.72
7.5	2.71
10	2.7
12.5	2.68

CONCLUSIONS

This research examines the utilization of low-grade pyrophyllite sourced from Nambulapulakunta, Anantapur, Andhra Pradesh, as a partial substitute for cement in high-performance concrete (HPC). The pyrophyllite underwent calcination and was ground into a fine powder before being integrated into the concrete mixture at varying proportions (7.5%, 10%, and 12.5%) by mass of cement. Additionally, polypropylene fibers were incorporated at a rate of 1% by volume. The study assessed the impact of pyrophyllite on the physical and mechanical properties of the fiber-reinforced concrete. The findings indicated a reduction in concrete density with increased pyrophyllite content. Furthermore, the inclusion of pyrophyllite enhanced the mechanical

strength of the concrete, particularly at a 10% replacement level, without surpassing the strength of the reference concrete up to 28 days of curing. An optimal compressive strength of 60 MPa was achieved with a 12.5% pyrophyllite replacement, marking a 25% improvement compared to the control mix. The density of the HPC was also reduced by approximately 5% with the 12.5% pyrophyllite replacement.

REFERENCES

1. KamalakaragK, Jithendra. H.K, . Abhilash. S and Gowthami.K. S, (2025), An overview on a study on high performance reinforced concrete using pyrophyllite, *International Journal of Creative Thoughts*,13,(1), PP 439-445.
2. Retno Anggraini, Ristinah, Sugeng P. Budio, Stevanus Rony Soewignyo, & Firmaninda, W. (2013). The effect of pyrophyllite use as admixture in light concrete bricks mechanical properties. *Journal Rekayasa Sipil*,7,(3),PP 210-217.
3. Preparation of low cement high performance concrete - Project report by Civil Engineering department, R. G. M College of Engineering and Technology Nandyal AP 2013
4. Ammar Anwar, Hamza Tariq, Shaheryar Adil and Muhammad Ahsan Iftikha, (2022), Effect of curing techniques on compressive strength of concrete, *World Journal of Advanced Research and Reviews*, 16, (03), PP 694–710
5. Ali, M.A.; Ahmed, H.A.M. Ahmed, H.M.; Hefni, M.,(2021) Pyrophyllite-An Economic Mineral for Different Industrial Applications., *Appl. Sci.*11, 11357
6. Sucharda, O.; Gandel, R.; Cmiel, P.; Jerabek, J.; Bilek, V.(2024), Utilization of High-Performance Concrete Mixtures for Advanced Manufacturing Technologies. *Buildings*, 14, 2269
7. Akçin SE, Bulut G, Ekinci Şans B, Esenli F (2022). The beneficiation of the Pütürge pyrophyllite ore by flotation: mineralogical and chemical evaluation. *Clay Minerals* 57, 87–96. <https://doi.org/10.1180/clm.2022.24>
8. Das B and. Mohanty JK, (2009) Mineralogical Characterization and Beneficiation Studies of Pyrophyllite from Orissa, India, *Jf Min & Mats Charan & Eng*, 8,(4), pp 329-338.
9. IBM,(2021) Indian Mineral Year Book 58,30.19 Minor minerals Pyrophyllite
10. Ahmed, S. A., Ebrahim, E., El-Amir, A. A. M., & El-Feky, M. S. (2025). Developing lightweight structural concrete with enhanced thermal and durability properties through nanosilica and expanded polystyrene integration. *Scientific Reports*, 15(1). <https://doi.org/10.1038/s41598-025-11354-7>
11. Ali, M. A., Ahmed, H. A. M., Hefni, M., & Ahmed, H. M. (2021). Pyrophyllite: An Economic Mineral for Different Industrial Applications. *Applied Sciences*, 11(23), 11357. <https://doi.org/10.3390/app112311357>.
12. Ayub, T., Khan, S. U., & Memon, F. A. (2014). Mechanical Characteristics of Hardened Concrete with Different Mineral Admixtures: A Review. *The Scientific World Journal*, 2014(5), 1–15. <https://doi.org/10.1155/2014/875082>.
13. Erdemoğlu, M., Uysal, T., & Birinci, M. (2020). Thermal Behavior of Pyrophyllite Ore during Calcination for Thermal Activation for Aluminum Extraction by Acid Leaching. *Clays and Clay Minerals*, 68(2), 89–99. <https://doi.org/10.1007/s42860-019-00061-w>.
14. Giese, R. F., Costanzo, P. M., & Van Oss, C. J. (1991). The surface free energies of talc and pyrophyllite. *Physics and Chemistry of Minerals*, 17(7), 611–616. <https://doi.org/10.1007/bf00203840>.
15. Goldberg, S., Glaubig, R. A., & Suarez, D. L. (1988). FACTORS AFFECTING CLAY DISPERSION AND AGGREGATE STABILITY OF ARID-ZONE SOILS. *Soil Science*, 146(5), 317–325. <https://doi.org/10.1097/00010694-198811000-00004>.
16. Götze, J., Richter, D. K., Götze, T., Neuser, R. D., & Plötze, M. (2002). Cathodoluminescence (CL) and electron paramagnetic resonance (EPR) studies of clay minerals. *Mineralogy and Petrology*, 76(3), 195–212. <https://doi.org/10.1007/s007100200041>.
17. Katti, D. R., Ghosh, P., Katti, K. S., & Schmidt, S. R. (2005). Modeling the response of pyrophyllite interlayer to applied stress using steered molecular dynamics. *Clays and Clay Minerals*, 53(2), 171–178. <https://doi.org/10.1346/ccmn.2005.0530207>.
18. Matias, D., De Brito, J., Pedro, D., & Rosa, A. (2013). Durability of Concrete with Recycled Coarse Aggregates: Influence of Superplasticizers. *Journal of Materials in Civil Engineering*, 26(7). [https://doi.org/10.1061/\(asce\)mt.1943-5533.0000961](https://doi.org/10.1061/(asce)mt.1943-5533.0000961).

19. Sánchez-Soto, P. J., Sobrados, I., Pérez-Rodríguez, J. L., & Sanz, J. (1997). Influence of Grinding in Pyrophyllite–Mullite Thermal Transformation Assessed by ^{29}Si and ^{27}Al MAS NMR Spectroscopies. *Chemistry of Materials*, 9(3), 677–684. <https://doi.org/10.1021/cm960224+>.
20. Silva, M. L. da, Prado, L. P., Aquino, D. P., Félix, E. F., & Sousa, A. M. D. de. (2024). The Influence of Materials on the Mechanical Properties of Ultra-High-Performance Concrete (UHPC): A Literature Review. *Materials*, 17(8), 1801. <https://doi.org/10.3390/ma17081801>.
21. Tesson, S., Marry, V., Salanne, M., Tazi, S., & Rotenberg, B. (2016). Classical Polarizable Force Field for Clays: Pyrophyllite and Talc. *The Journal of Physical Chemistry C*, 120(7), 3749–3758. <https://doi.org/10.1021/acs.jpcc.5b10181>.
22. Wang, X.-H., Zheng, L., & Fang, Z.-C. (2024). Effect of dose and types of the water reducing admixtures and superplasticizers on concrete strength and durability behaviour: a review. *Journal of civil engineering and management*, 30(1), 33–48. <https://doi.org/10.3846/jcem.2024.20145>.
23. Zartman, G. D., Heinz, H., Liu, H., Akdim, B., & Pachter, R. (2010). Nanoscale Tensile, Shear, and Failure Properties of Layered Silicates as a Function of Cation Density and Stress. *The Journal of Physical Chemistry C*, 114(4), 1763–1772. <https://doi.org/10.1021/jp907012w>