International Journal of Emerging Research in Engineering, Science, and Management
Vol. 3, Issue 4, pp.38-47, Oct-Dec 2024.
www.ijeresm.com eISSN – 2583-4894

Evaluation of the Performance of Plain Cement Concrete with Partial Replacement of Cement by Natural Pumice Powder and Polypropylene

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Abstract: Concrete is a fundamental construction material that is continually evolving to enhance its performance and sustainability. This research explores the potential of incorporating natural pumice powder and polypropylene as partial substitutes for cement in M20-grade concrete. The aim is to assess how these alternative materials influence concrete properties and sustainability. Through a comprehensive evaluation, the study provides valuable insights into improving the characteristics and environmental impact of concrete structures. This experimental study examines properties such as split tensile strength, compressive strength, and flexural strength of concrete specimens after curing periods of 7, 14, and 28 days. Concrete mixes with varying proportions of pumice powder (5%, 10%) and polypropylene (5%, 10%), as well as their combinations, are meticulously prepared and tested. The results indicate that adding pumice powder and polypropylene positively affects the strength properties of concrete, with some mixtures performing better than conventional concrete. The analysis reveals the underlying mechanisms contributing to enhanced strength, emphasizing the potential of these materials to boost the durability and long-term sustainability of concrete structures. These findings contribute to ongoing efforts to develop eco-friendly and highly durable concrete, promoting advancements in construction engineering.

Keywords: Compressive Strength, Flexural Strength, Natural Pumice Powder, Polypropylene, Tensile Strength.

1 INTRODUCTION

This study aims to evaluate the strength properties of concrete using zeolite pumice powder and polypropylene as partial cement replacements in M20-grade concrete. The research focuses on assessing the compressive, split tensile, and flexural strengths of concrete by substituting cement with pumice powder at varying levels ranging from 0% to 20%. Unlike previous studies, this research introduces zeolite and glass as supplementary materials at higher replacement percentages for M20 and M30-grade pumice-based concrete. Strength characteristics are analyzed after 7, 14, and 28 days, and the results are compared with a standard concrete mix.

Pumice powder, derived from the natural volcanic rock pumice, is a fine material with versatile applications. It is produced through the grinding and milling of pumice stones, resulting in a lightweight and abrasive powder. Due to its unique properties, pumice powder is widely utilized across various industries, including abrasive cleaning, horticulture, and dental care. Fig. 1 illustrates the pumice material.

Fig.1 Pumice material

https://doi.org/10.58482/ijeresm.v3i4.6

Polypropylene is a versatile polymer produced through the polymerization of propylene monomers. As a member of the polyolefin group, which also includes polyethylene, it has a linear structure and is renowned for its strength and durability. Its cost-effectiveness and favorable mechanical properties make it an ideal choice for various industrial applications, providing a good balance between performance and affordability. Fig. 2 illustrates pumice polypropylene.

Fig. 2 Polypropylene

The objectives of the current research are given below.

a. Evaluate Mechanical Properties: Analyze how partially replacing cement with natural pumice powder and polypropylene affects the compressive, tensile, and flexural strength of the concrete mix. Understand the influence of these additives on the overall mechanical performance.
b. Assess Workability: Study the workability of the concrete mix when pumice powder and polypropylene are incorporated. Optimize the mix to ensure it's easy to handle and finish while maintaining the necessary performance standards.
c. Investigate Durability: Explore the durability aspects of the concrete, such as its resistance to freeze-thaw cycles, chloride ion penetration, and sulfate attack. Determine how pumice powder and polypropylene impact long-term durability.
d. Analyze Porosity and Permeability: Examine changes in porosity and permeability due to the addition of pumice powder and polypropylene. Assess if these additives improve resistance to water absorption and chemical infiltration.
e. Evaluate Thermal Properties: Investigate the thermal characteristics of the concrete, including its heat resistance and thermal conductivity. Determine how these additives influence the concrete's performance under varying temperatures.

2 LITERATURE SURVEY

Concrete's performance can be enhanced by incorporating various supplementary cementitious materials (SCMs) such as fly ash, pumice powder, and silica fume. Kabay et al. [1] studied the partial replacement of cement with pumice powder (PP) and fly ash (FA) and found that although early-stage strength was lower, the long-term mechanical properties, including resistance to sulfate attack, improved significantly. Another study by Farooq et al. [2] demonstrated the potential of combining PP with hybrid fibers to increase compressive, tensile, and flexural strengths, revealing 15% PP as the optimal mix for strength and durability.

Abraham and Mohan [3] examined the strength properties of concrete by partially replacing cement with PP, showing that mechanical properties such as compressive and tensile strengths improved significantly after 28 days of curing. Zeyad et al. [4] also confirmed the role of fly ash in enhancing concrete's durability and mechanical properties in harsh environments, further supporting the idea that SCMs can mitigate the negative effects of aggressive chemicals on concrete structures.

Incorporating other materials such as silica fume also leads to improved mechanical and durability properties. Mousa et al. [5] investigated the effects of nano-silica and silica fume in high-performance concrete, finding that both materials contribute significantly to strength and resistance against water permeability. Similarly, Yang et al. [6] explored the combined use of silica fume and metakaolin in ultra-high-performance concrete (UHPC), highlighting their role in increasing the material's compressive strength and lowering its porosity. The study by Liu et al. [7] reinforced these findings, showing that adding silica fume enhances the concrete's microstructure and thus improves its durability, particularly in high-performance applications.

The integration of hybrid materials, such as fibers, into concrete has also been widely studied. Farooq et al. [8] tested a range of hybrid fiber-reinforced concrete (HyFRC) mixes and found that incorporating steel and polypropylene fibers significantly improved the flexural and tensile strength of concrete. Their research aligned with the findings of Sadrmomtazi et al. [9], who demonstrated that fiber-reinforced concrete mixes exhibit enhanced energy dissipation, particularly in high-stress environments. Furthermore, Toutanji et al. [10] focused on the effects of adding rubber particles to concrete, suggesting that this modification increases the toughness and durability of the material, which is particularly useful in dynamic loading scenarios.

In terms of environmental sustainability, concrete mixes that incorporate industrial by-products, such as waste glass powder or recycled aggregates, also show promising results. Studies by Raval et al. [11] and Aliabdo et al. [12] demonstrated that replacing part of the cement content with these waste materials leads to comparable mechanical performance while contributing to waste reduction. Additionally, research by Ling et al. [13] on the use of recycled aggregates in concrete emphasized its potential to maintain sufficient strength and durability while reducing the overall environmental impact of construction. Together, these studies highlight the ongoing innovation in concrete technology, driven by a desire for both enhanced performance and environmental sustainability [14]-[17].

3 MATERIALS USED

3.1 Cement

Cement is the fundamental binding component in concrete, providing strength and cohesion to the mixture. In this study, Ordinary Portland Cement (OPC) 53 grade from UltraTech Cement Company is used, meeting the criteria specified in IS 12269-1987. The physical characteristics of the cement are presented in Table 1.

Table 1. Properties of the Cement

S. No.	Particulars	Results
1	Specific Gravity	3.10
2	Initial setting time	36 min
3	Final setting time	320 min
4	Fineness (%)	6

3.2 Fine Aggregate

Fine aggregate plays a crucial role in concrete by filling voids within the coarse aggregate, thereby enhancing the compactness and strength of the concrete matrix. The physical characteristics of the fine aggregate are presented in Table 2.

Table 2. Properties of the Fine Aggregate

S. No.	Particulars	Results
1	Type	Normal sand
2	Specific gravity	2.68
3	Grading size	4.75mm – 0.075mm
4	Water absorption	0.6%
5	Fineness modulus	2.70
6	Bulk density	Loose state 1378.82 kg/m3 Compacted state 1544.67 kg/m3

3.3 Coarse Aggregate

The larger particle size of coarse aggregate is essential for imparting bulk and stability to concrete blends. In this research, crushed granite aggregate with a particle size of 20 mm is used as the coarse aggregate. The physical characteristics of the coarse aggregate are presented in Table 3.

Table 3. Properties of the Coarse Aggregate

S. No.	Particulars	Results
1	Type	Crushed stone
2	Specific gravity	2.66
3	Maximum size	20mm
4	Water absorption	0.8%
5	Fineness modulus	3.9
6	Bulk density	1688 kg/m3

3.4 Pumice Powder

Pumice powder enhances the concrete's resistance to high temperatures and sulfate attacks, contributing to improved durability. It can be used as a cementitious material to enhance mechanical and durability properties compared to ordinary concrete. The chemical properties of pumice powder are given in Table 4. The physical characteristics of the pumice powder are presented in Table 5.

Table 4. Chemical Properties of the Pumice Powder

S. No.	Particulars	Results
1	Silicon dioxide, $SiO2$	76%
2	Aluminum oxide, $Al2O3$	14 %
3	Sodium Oxide, Na2o	2%
4	Potassium Oxide	2%

Table 5. Physical Properties of the Pumice Powder

S. No.	Particulars	Results
1	Hardness	6
2	pH	7.2
3	Softening point	900 degrees C
4	Color	White color
5	Specific gravity	2.2

3.5 Polypropylene

Polypropylene, a thermoplastic polymer primarily composed of propylene monomer units, is one of the most cost-effective plastics available and has a low density.

Table 6. Physical Properties of the Polypropylene

S. No.	Particulars	Results
1	Friction coefficient	0.1-0.3
2	Poisson ratio	0.4
4	Yield stress	32MPA
4	Color	White color

4 EXPERIMENTAL RESULTS

This research utilized seven distinct concrete mixes, referred to as S1 through S7. Each mix varied in composition, specifically with differing percentages of pumice powder and polypropylene. Mix S1 represents the conventional concrete without any additives, while the subsequent mixes incorporate varying proportions of pumice powder and polypropylene. Table 7 below summarizes the concrete mixes and their respective compositions.

Table 7. Concrete Mix Compositions

Mix Code	Description	Pumice Powder (%)	Polypropylene (%)
S1	Conventional concrete	0	0
S2	5% Polypropylene	0	5
S3	10% Polypropylene	0	10
S4	5% Pumice Powder	5	0
S5	10% Pumice Powder	10	0
S6	5% Pumice Powder + 5% Polypropylene	5	5
S7	10% Pumice Powder + 10% Polypropylene	10	10

4.1 Slump Test

The slump test results indicate varying workability across the concrete mixes. The conventional concrete (S1) had a slump of 90 mm, while the mix with 5% polypropylene (S2) increased to 95 mm. As polypropylene content increased, particularly in combinations like S6 (5% PP + 5% pumice) and S7 (10% PP + 10% pumice), slump values decreased to 86 mm and 84 mm, respectively. These results, summarized in Table 8, suggest that higher polypropylene proportions reduce workability, reflecting the influence of natural pumice powder and polypropylene on concrete's consistency and applicability.

Table 8. Slump Test Results

Mix Code	Slump in mm
S1	90
S2	95
S3	90
S4	89
S5	88
S6	86
S7	84

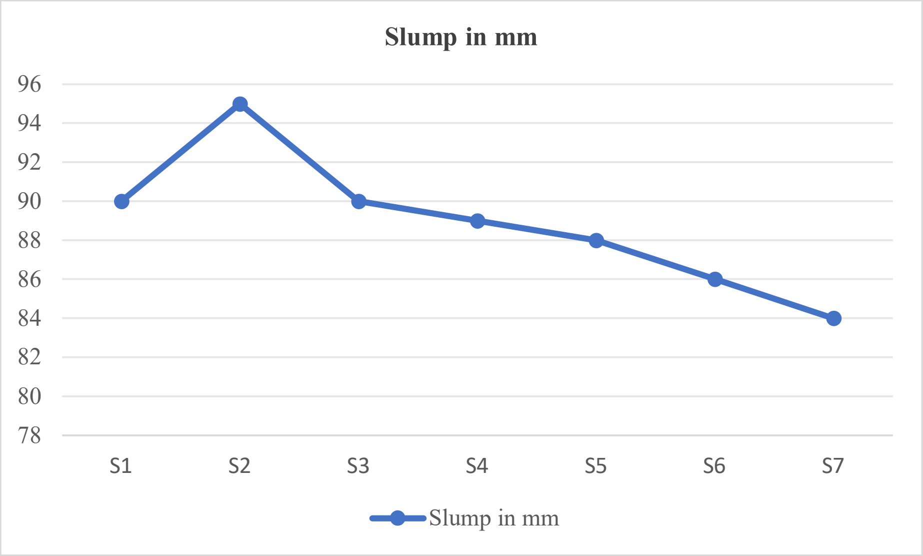

Fig. 3 Slump Test Results

The slump values for each mix are illustrated in Fig. 3. The graph shows a decrease in workability as the percentage of polypropylene increases, peaking at 95 mm for the 5% polypropylene mix.

4.2 Compressive Strength

Compressive strength tests were conducted on 7, 14, and 28 days. Conventional concrete (S1) achieved strengths of 13.3 N/mm², 18.4 N/mm², and 20.3 N/mm². Mixes with pumice powder, particularly S6 (5% PP + 5% pumice), showed the highest strengths at 16.7 N/mm², 19.5 N/mm², and 23.5 N/mm². The data in Table 9 and the corresponding graph in Fig. 4 reveal the effects of pumice powder and polypropylene on the compressive strength of concrete over time.

Table 9. Compressive Strength Test Results

Mix Code	7 days (N/mm^2)	14 days (N/mm^2)	28 days (N/mm^2)
S1	13.3	18.4	20.3
S2	13.4	18.6	20.5
S3	13.7	16.8	20.7
S4	14.5	18.3	21.5
S5	15.6	18.6	22.4
S6	16.7	19.5	23.5
S7	14.6	17.4	21.3

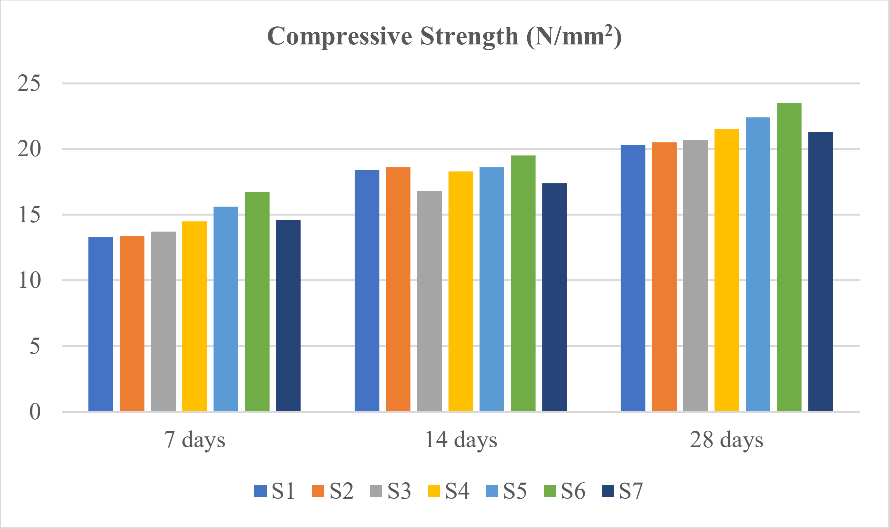

Fig. 4 Compressive Strength Test Results

Compressive strength increased with the addition of pumice powder and polypropylene, peaking at 23.5 N/mm² for the mix with 5% polypropylene and 5% pumice at 28 days.

4.3 Split Tensile Strength

The split tensile strength results, presented in Table 10, show an improvement with the addition of pumice powder and polypropylene. Mix S5 (0% PP + 10% pumice) achieved the highest split tensile strength, reaching 23.5 N/mm² at 28 days. This trend is illustrated in Fig. 5, demonstrating enhanced durability and strength for mixes with pumice powder.

Table 10. Split Tensile Strength Test Results

Mix Code	7 days (N/mm^2)	14 days (N/mm^2)	28 days (N/mm^2)
S1	1.50	1.58	2.50
S2	1.56	1.60	2.52
S3	1.61	1.68	2.69
S4	1.65	1.78	3.20
S5	1.69	1.92	3.90
S6	1.75	2.15	4.15
S7	1.64	2.0	3.10

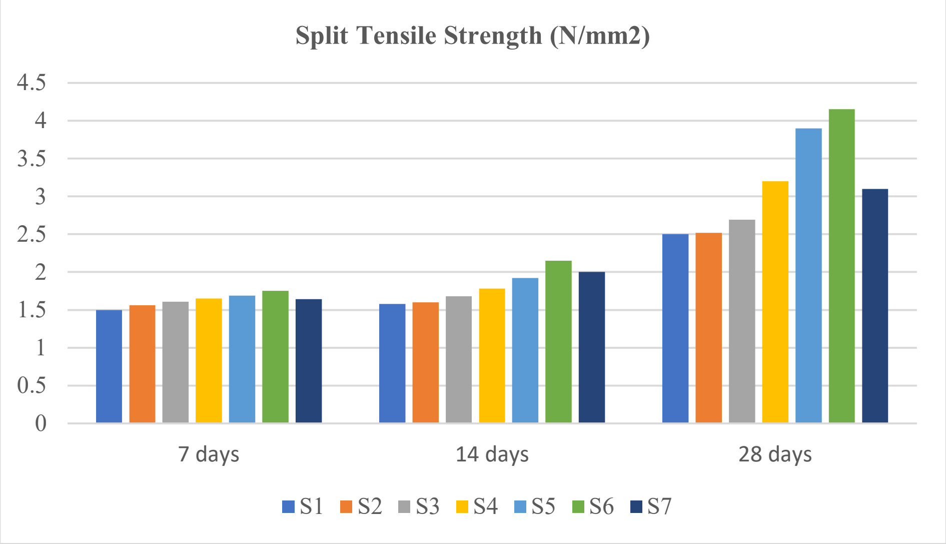

Fig. 5 Split Tensile Strength Test Results

4.4 Flexural Strength

Flexural strength test results in Table 11 indicate improvements with pumice powder and polypropylene additions, reaching a peak of 23.4 N/mm² at 28 days for mix S5. Fig. 6 illustrates the flexural strength performance across the concrete mixes, showcasing the impact of pumice powder and polypropylene on flexural strength.

Table 11. Flexural Strength Test Results

Mix Code	7 days (N/mm^2)	14 days (N/mm^2)	28 days (N/mm^2)
S1	3.45	4.15	4.25
S2	3.48	4.36	4.28
S3	3.50	4.33	4.40
S4	3.92	4.34	4.42
S5	3.94	4.34	4.44
S6	4.15	4.35	4.85
S7	4.13	4.32	4.42

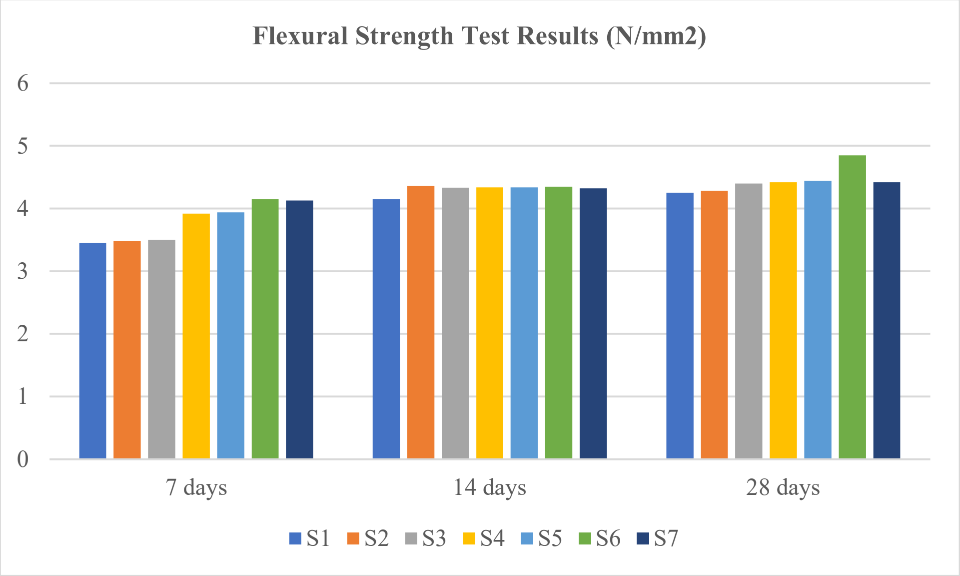

Fig. 6 Flexural Strength Test Results

4.5 Water Permeability Test

Water permeability decreased with the addition of pumice powder and polypropylene, indicating enhanced durability. Table 12 and Fig. 7 illustrate the penetration values, showing a significant reduction for the S7 mix (10% PP + 10% pumice), which achieved the lowest penetration at 1.3 mm.

Table 12. Water Permeability Test Results

Mix Code	Penetration (mm)
S1	2.0
S2	1.8
S3	2.0
S4	1.7
S5	1.6
S6	1.4
S7	1.3

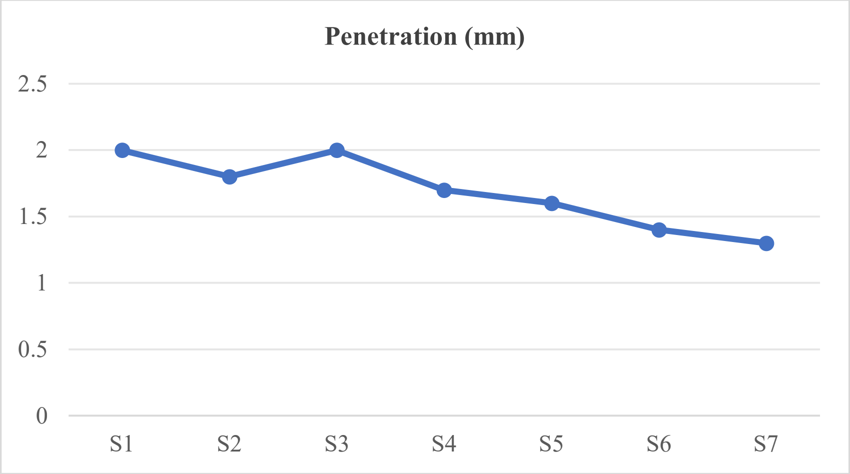

Fig. 7 Water Permeability Test Results (28 days)

4.6 Acid Curing Test Results

Under acid curing, mixes with pumice powder and polypropylene demonstrated improved compressive strength, with S6 reaching 24.5 N/mm². These results, shown in Table 13 and Fig. 8, highlight the performance benefits of these additives in acidic environments.

Table 13. Acid Curing Test Results

Concrete Mix	Compressive Strength (N/mm^2)
S1	20.5
S2	22.4
S3	22.8
S4	23.0
S5	23.5
S6	24.5
S7	20.8

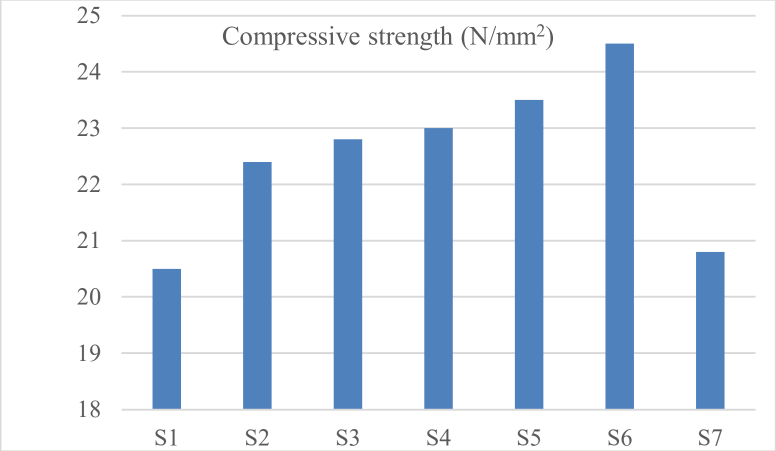

Fig. 8. Compressive Strength under Acid Curing Test Results

4.7 Water Absorption Test Results

The water absorption test results, summarized in Table 14, reveal an increase in absorption rates with the inclusion of pumice powder and polypropylene. Mix S3 (10% PP) recorded the highest absorption at 5.5%. Fig. 9 displays the absorption rates, emphasizing the effect of these additives on concrete's permeability.

Table 14. Water Absorption Test Results

Concrete Mix	Water Absorption %
S1	4.2
S2	4.5
S3	5.5
S4	5.3
S5	5.2
S6	5.3
S7	5.1

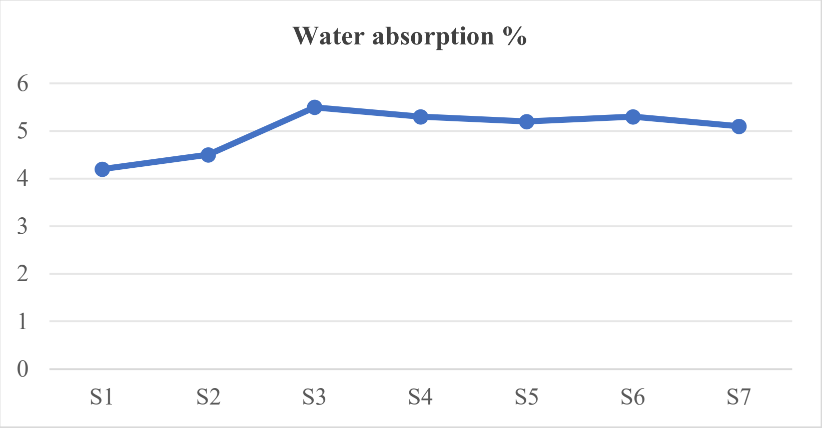

Fig. 9 Water Absorption Test Results

5 CONCLUSIONS

The experimental study demonstrates that incorporating natural pumice powder and polypropylene as partial substitutes for cement in concrete significantly enhances various performance metrics. Compressive strength reached a peak of 24.5 N/mm² with the 5% polypropylene and 5% pumice mix, indicating improved durability and structural integrity. Similarly, flexural strength showed notable improvements, with the 10% pumice mix achieving a maximum of 23.4 N/mm². Water permeability tests revealed a reduction in permeability, with the conventional concrete showing 4.2% absorption compared to higher values in modified mixes, indicating a potential trade-off in impermeability. Under acid curing conditions, the mixes continued to perform well, maintaining competitive strengths even in challenging environments. The findings highlight the potential of using pumice powder and polypropylene to produce concrete with superior mechanical properties, offering a sustainable approach to enhance the performance and durability of concrete structures. However, careful consideration of water absorption characteristics is essential for ensuring long-term durability.

ACKNOWLEDGEMENT

The authors would like to sincerely thank the Department of Civil Engineering, Bonam Venkata Chalamayya Engineering College (Autonomous), Odalarevu, for providing invaluable support throughout this research for the access to the necessary hardware and equipment, which greatly contributed to the successful completion of this research.

FUNDING INFORMATION

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ETHICS STATEMENT

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

STATEMENT OF CONFLICT OF INTERESTS

The authors declare no conflicts of interest related to this study.

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