Research Article

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Mechanical and Durability Performance of Concrete using Dolomite Powder and Pond Ash as Cement Replacements

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ABSTRACT

The construction sector, reliance on substantial quantities of raw materials has historically imposed a significant environmental burden due to its reliance on cement in concrete production. Cement manufacturing, being energy-intensive, has been a major contributor to CO_2 emission, emphasizing the urgent need for sustainable alternatives. This study explored the substitution of cement with industrial by-products such as pond ash (PA) and dolomite powder (DP) to address these challenges. PA was incorporated at an optimal level of 10% by cement mass, while DP was added in varying combination of 5%, 10%, 15%, 20%, 25%, and 30%. Eight mix proportions were formulated for M20-grade concrete, designed with a w/b ratio of 0.5 in adherence to IS:10262-2019. The experimental program assessed the mechanical properties of the mixes, including compressive strength, split tensile strength, and flexural strength, alongside durability characteristics such as Rapid Chloride Permeability Test (RCPT), weathering resistance, and permeability tests. Results demonstrated that the combination of 10% PA and 15% DP (M4 mix) exhibited the most favorable performance at 7, 28, and 90 days, with significant improvements in strength compared to the control mix. The M4 mix displayed enhanced resistance to chloride penetration, superior weathering resilience, and reduced permeability, affirming its effectiveness as a sustainable concrete solution at 7, 28, and 90 days. Overall, the integration of PA and DP in concrete improved strength and reduce the environmental impact of construction materials, offering a promising pathway for eco-friendly and cost-effective building practices.

Keyword: Pond ash; Dolomite powder; Mechanical performance; Durability performance; Environment benefits.

1. INTRODUCTION

Concrete, an essential construction material, derives its primary binding capacity from cement, which serves as the key precursor in formulating structural elements like beams, columns, and slabs, thereby ensuring the requisite strength and stability for buildings and infrastructure (Padavala *et al*. 2023). Cement, the most commonly used type, is produced by calcinating limestone and other materials at high temperatures, typically exceeding 1,400°C. During this process, calcium carbonate decomposes into calcium oxide, releasing carbon dioxide (CO_2) as a byproduct. This chemical reaction, combined with the significant energy demand for heating, is a major contributor to cement's carbon footprint (Charan *et al*. 2023). Cement production is one of the most carbon-intensive industrial activities, responsible for approximately 7–8% of global CO_2 emissions (Carbone *et al*. 2022). Given the vast global demand for concrete, reducing the environmental impact of cement production has become a critical challenge in mitigating greenhouse gas emissions within the construction sector (Ahmed *et al*. 2021). Efforts to lower CO_2 emissions in concrete manufacturing have increasingly focused on adopting sustainable practices.

These include the use of alternative binders and the incorporation of by products such as fly ash (Qian *et al*. 2001), metakaolin (Siddique and Klaus 2009) and rice husk ash (Ajiwe *et al*. 2000). Furthermore, advances in blended cement, where a portion of clinker (the primary component of OPC) is replaced with materials that have a lower carbon footprint, have demonstrated significant potential in reducing emissions per unit of cement produced. Such measures are essential for steering the concrete industry toward greater environmental sustainability while maintaining the performance standards required for construction applications (Li *et al*. 2013).

Dolomite powder (DP), sourced from the natural mineral dolomite (Ajiwe *et al*. 2000) $CaMg(CO_3)_2$, is gaining prominence in the construction industry as a valuable material for concrete production. Due to its wide availability and beneficial properties, it has been used as a byproduct's material or filler in recent decades. In concrete, DP primarily acts as a filler, enhancing the density by reducing voids and improving overall strength and durability (Agrawal *et al*. 2021) . DP displays pozzolanic properties by reacting with calcium hydroxide during cement hydration, forming additional C-S-H gel that enhances concrete strength and durability

(Abdalqader *et al*. 2022). When finely ground, it can also participate in hydration reactions, forming carbonate-AFm phases that contribute to the strength aspect (Wang *et al*. 2018). The incorporation of DP in concrete has been shown to improve compressive strength, particularly in the later stages of curing. This is due to the continued reaction between the DP and the cementitious materials in the mixture, which tends to the make additional binding phases that improve the structural integrity of the concrete (Xu *et al*. 2021). Magnesium in dolomite contributes to forming stable cementitious phases, improving concrete durability over time (Zhang *et al*. 2015). The incorporation of DP with pozzolanic materials such as fly ash (Barbhuiya, 2011), metakaolin (Ye *et al*. 2020), or slag (Thakur and Bawa, 2024), exhibits synergistic effects. These combinations refine the pore structure of concrete, reduce its permeability, and increase its compressive strength, making it suitable for high-performance and sustainable construction applications. The advantage of DP is its lower energy demand during grinding compared to other materials like limestone, making it an energy-efficient option for concrete production (Gupta and Kumar, 2024). From a sustainability perspective, DP contributes to reducing the carbon footprint of concrete by partially replacing cement, which is a major source of CO_2 emissions in construction. Its use in blended cement and geopolymer systems aligns with global efforts to develop eco-friendly construction materials (Gu *et al*. 2014). The use of DP as a partial cement substitute can affect the concrete's workability and it's time to set (John *et al*. 2018).

Pond ash (PA), a by-product of coal combustion, primarily contains silica and alumina phase. It has gained attention as a potential substitute for cement, it makes environmental benefits, cost-effectiveness, and ability to improve concrete properties (Cheriaf *et al*. 1999). PA has a large size of particle, from coarse to fine particles. The finer particles have a higher surface area, which enhances their pozzolanic reactivity, leading to better strength and durability when used in concrete (Yuvaraj and Ramesh, 2019). The substitution of cement with PA influences the strength aspects in concrete, with results depending on the various conditions. The interaction between cement and PA involves a pozzolanic reaction, where PA combines with $Ca(OH)_2$ from cement hydration to produce additional C-S-H gel, enhancing concrete strength. This reaction progresses more slowly than cement hydration, resulting in reduced early strength but improving the strength over time (Yuvaraj and Ramesh, 2022). Consequently, concrete containing PA may show lower compressive strength at early ages (e.g., 7 days) but perform better at later ages (28 days and beyond) as the pozzolanic reaction continues. Studies suggest that the optimal percentage of PA for cement replacement typically ranges from 10% to 30%, where it can enhance strength without compromising the concrete's structural integrity. However, beyond 30%, the strength reduction becomes more significant, as the binder content may no longer be sufficient to ensure adequate performance (Yuvaraj and Ramesh, 2021). As a pozzolanic material, PA helps create a denser microstructure, reducing the concrete's permeability. This lower permeability makes the concrete more resistant to environmental stresses like water infiltration, sulfate attack, and chloride-induced corrosion of reinforcement (Jaturapitakkul and Cheerarot, 2003). It also enhances resistance to freezing and thawing cycles, which is especially useful for concrete exposed to harsh weather conditions. The pozzolanic reaction decreases the free $Ca(OH)_2$ content in the hardened stage, enhancing strength at 90 days and minimizing the risk of alkali-silica reaction (ASR) (Kurama and Kaya, 2008). Finally, concrete incorporating PA and DP individually has demonstrated enhanced mechanical properties and reduced porosity when used in optimal proportions. However, there is lack of research on the effects of PA and DP as alternative pozzolanic materials. This research aims to fill the existing knowledge gap by examining the influence of PA and DP on concrete, with a comparison to conventional M20-grade control mix (CM). By exploring these alternative binders, the research aims to offer valuable insights into creating more sustainable concrete solutions, promoting environmentally friendly construction practices on a global scale.

Table 1. Physical and Chemical proportions of PA and DP

Chemical compound	Cement (%)	PA (%)	DP (%)
CaO	63.5	0.92	31.5
SiO_2	22.4	52.4	1.9
Al_2O_3	5.23	30.5	0.35
Fe_2O_3	4.53	7.16	0.22
MgO	1.25	0.87	20.5
SO_3	1.15	4.28	0.09
Specific gravity	3.15	2.17	2.84
Surface Area	3020 cm^2/g	3980 cm^2/g	5500 cm^2/g

Table 2. Strength properties as per IS and ASTM

Strength Properties	Tests	Size of Specimens
Mechanical properties	Compressive strength	150 x 150 x 150 mm
	Split tensile strength	150 × 300 mm
	Flexural strength	100 × 100 × 500 mm
Durability properties	RCPT	Diameter of 90 mm and Thickness of 50 mm
	Weathering resistance	150 x 150 x 150 mm
	Permeability test	150 x 150 x 150 mm

2. MATERIALS AND METHODS

This study evaluates the concrete strength using a combination of materials including 53-grade cement, M-Sand, coarse aggregates, PA, DP, and potable water. Prior to use, the cement was tested in the laboratory to ensure compliance with the specifications outlined in IS 8112:1987. In place of river sand, M-Sand was fully replaced in this investigation, and 20 mm coarse aggregates were employed. The physical and chemical proportions of PA and DP, as detailed in the accompanying Table 1. M-Sand with specific gravity of 2.71 and coarse aggregates with specific gravity of 2.69, were used in the mix. To evaluate the mechanical and durability properties, concrete specimens were cast as per IS and ASTM standards as shown Table 2. The mix combinations were designed following IS 10262:2019 standards and were presented in Table 3.

Table 3. Mix proportions of concrete

Mix ID	W/B Ratio	Cement kg/m^3	PA kg/m^3	DP kg/m^3	M-sand kg/m^3	Coarse Aggregate kg/m^3	Water kg/m^3
CM	0.5	360	0	0	839	1064	180
M1	0.5	324	36	0	839	1064	180
M2	0.5	306	36	18	839	1064	180
M3	0.5	288	36	36	839	1064	180
M4	0.5	270	36	54	839	1064	180
M5	0.5	252	36	72	839	1064	180
M6	0.5	234	36	90	839	1064	180
M7	0.5	216	36	108	839	1064	180

2.1. Preparation and Casting of Specimens

In this study, a pan mixer was utilized for the preparation of the CM, concrete incorporating both PA and DP. The mixing protocol adhered to the guidelines outlined in BIS 456:2019. Initially, the dry materials, including cement, PA, DP, coarse aggregate, and M-sand, were homogeneously blended in the pan mixer for 2 minutes. Subsequently, water was introduced, and the mixture was further blended for an additional 2 minutes to ensure uniform material distribution. The prepared concrete was then placed into molds in accordance with BIS 516:1959 standards, with a vibrating table employed to achieve optimal compaction. The specimens were cured at ambient climate condition until the designated testing age.

3. RESULT AND DISCUSSION

3.1 Compressive Strength of Concrete

Fig. 1 highlights the substantial enhancement in compressive strength achieved through the combined use of varying proportions of pond ash (PA) and dolomite powder (DP), evaluated at curing intervals of 7, 28, and 90 days for all mix combinations. Over the 7 days, the compressive strength for mix M1 increased by 12.9% than control mix CM. For mix M2, the strength improved by 21.29%, while M3 showed a 24.5% increase. Mix M4 exhibited the highest gain of 33.54%, followed by M5 with a 27.7% increase. M6 demonstrated a 20.64% improvement, and M7 had a 13% higher compressive strength than CM. Over 28 days, the improvements were more pronounced, with respective gains of 3.66%, 19.74%, 24.7%, 28.54%, 26.47%, 20.1%, and 16.80% over CM. By 90 days, the compressive strength reached its peak, with M1 to M7 showing respective increases of 19.8%, 22.79%, 28.3%, 30.5%, 28.3%, 24.26%, and 21.69% than CM. Among all combinations, the M4 mix exhibited the highest compressive strength values, measuring 20.7 MPa, 30.6 MPa, and 35.5 MPa at 7, 28, and 90 days, respectively. The observed improvement in strength leads to make larger quantity of C-S-H gel across all curing ages. While the early-age strength showed moderate increases due to the slower reactivity of PA and DP than cement, significant improvements were observed at later stages. These gains were driven by the pozzolanic reaction between PA and DP, which resulted additional C-S-H gel that effectively utilized the portlandite generated during cement hydration, thereby enhancing the overall concrete strength.

3.2 Split Tensile Strength of Concrete

Fig. 2 illustrates the significant enhancement in split tensile strength attained through the synergistic incorporation of varying proportions of pond ash (PA) and dolomite powder (DP), evaluated at curing intervals of 7, 28, and 90 days across all mix variants. At 7 days, the split tensile strength for mixes increased by 4.96% for M1, 9.16% for M2, 11.45% for M3, 15.27% for M4, 12.60% for M5, 9.54% for M6, and 6.11% for M7 than CM. By 28 days, the improvements were more significant, with corresponding gains of 9.72%, 11.60%, 13.48%, 15.05%, 14.11%, 11.29%, and 10.03% over CM. At 90 days, the split tensile strength reached its maximum, with M1 to M7 showing respective increases of 10.40%, 11.56%, 13.01%, 14.45%, 13.29%, 11.56%, and 10.40% than CM. Among all mixes, M4 exhibited the highest split tensile strength values, achieving 3.02 MPa, 3.67 MPa, and 3.96 MPa at 7, 28, and 90 days, respectively. The results indicate that strength improvements with PA and DP at early stage are less pronounced than the enhancements observed at 28 and 90 days. This may be attributed to the slower reactivity of DP during the early stages under water curing. However, prolonged curing significantly enhanced the split tensile strength of the M4 mix, likely due to the combined effects of hydration reactivity and additional pozzolanic reactions.

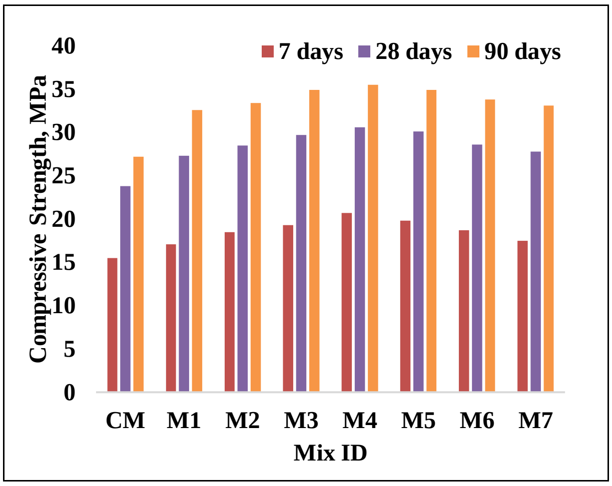

Fig. 1: Compressive strength result of combined effects of PA and DP in concrete

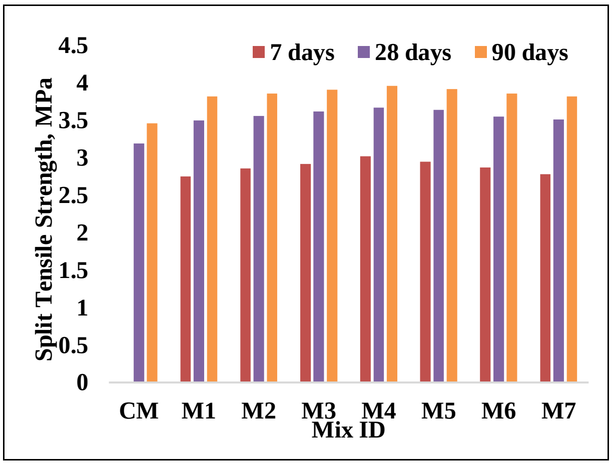

Fig. 2: Split tensile strength result of combined effects of PA and DP in concrete

3.3 Flexural Strength of Concrete

Fig. 3 highlights the substantial improvement in flexural strength achieved through the combined incorporation of varying proportions of pond ash (PA) and dolomite powder (DP), evaluated across all mix combinations at curing intervals of 7, 28, and 90 days. At 7 days, the flexural strength of mixes showed respective increases of 1.54% for M1, 5.23% for M2, 9.85% for M3, 11.69% for M4, 10.46% for M5, 6.46% for M6, and 3.08% for M7 than CM. At 28 days, more pronounced enhancements were observed, with gains of 1.59%, 3.96%, 6.59%, 7.91%, 7.03%, 5.27%, and 2.42% over CM. By 90 days, flexural strength reached its maximum of M1 to M7 mixes, with respective increases of 1.33%, 3.80%, 5.12%, 7.40%, 5.69%, 4.55%, and 2.28% compared to CM. Among all mixes, M4 exhibited the highest flexural strength values of 3.63 MPa, 4.91 MPa, and 5.66 MPa at 7, 28, and 90 days, respectively. This enhancement in flexural strength is predominantly leads to additional enhanced C-S-H gel matrix, promoted by the supplementary hydration facilitated by the synergistic effects of PA and DP.

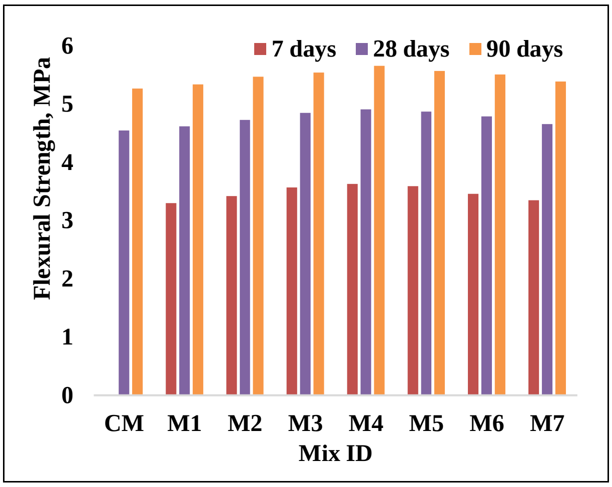

Fig. 3: Flexural strength result of combined effects of PA and DP in concrete

3.4 RCPT

Following the evaluation of mechanical properties, the RCPT of the CM and M4 mixes were assessed. The Table 4 illustrates that both the CM and the M4 mix exhibited a reduction in chloride ion permeability with extended curing durations. Notably, the M4 mix demonstrated a significant decrease in chloride ion penetration compared to the CM, particularly with prolonged curing. The total charge passed for the CM was observed to be higher at 28 and 90 days, attributed to the abundance of hydroxide ions (OH–) present in the pore solution. Conversely, incorporating PA and DP into the concrete mix resulted in a marked reduction in chloride ion permeability. This outcome causes an increased surface area, the additional generation of C-S-H gel.

Table 4. RCPT results of combined effects of PA and DP in concrete

Mix Code	Charge passed (Coulombs)		
	7 days	28 days	90 days
CC	2327	2075	1856
M4	2116	1820	1380

3.5 Weathering Resistance Test

The weather resistance of the CM and M4 mixes was evaluated at 7, 28, and 90 days, as illustrated in Table 5. The observations revealed a consistent reduction in specimen weight for both CM and M4 mixes across all curing durations. Specifically, the weight loss of the CM mix was recorded at 5.7%, 5.1%, and 4.7%, while the M4 mix exhibited lower reductions of 4.6%, 3.7%, and 3.0% after undergoing wetting and drying cycles at 7, 28, and 90 days, respectively. These findings suggest that the CM and M4 mixes demonstrate enhanced resistance to wetting and drying cycles, attributed to the formation of primary and secondary C-S-H gels, which contribute to improved weathering resistance.

Table 5. Weathering resistance results of combined effects of PA and DP in concrete

Mix Code	Residual Weight (%)					
	CC	M4	CC	M4	CC	M4
	7 days		28 days		90 days	
0	100	100	100	100	100	100
5	99.2	99.6	99.4	99.7	99.5	99.8
10	98.6	99.3	98.7	99.5	98.9	99.6
15	97.5	98.2	97.9	98.6	98.3	98.9
20	96.4	97.5	96.7	97.8	97.2	98.3
25	95.7	96.5	96.1	96.9	96.6	97.4
30	94.3	95.4	94.9	96.3	95.3	97.0

3.6 Permeability Test

The permeability test outcomes for CM and M4 mixes were depicted in Table 6. For the CM, the permeability depths were recorded as 40 mm and 38 mm, while the M4 mix exhibited reduced depths of 37 mm and 36 mm. At 90 days, the CM showed permeability values of 35 mm and 31 mm. Notably, all mixes demonstrated consistently lower permeability compared to the CM. This decrease in permeability in the CM and M4 mixes is attributed to the finer particle size of PA and DP relative to cement. These finer particles play a critical role in effectively filling residual voids, thereby enhancing the material's impermeability as the proportions of PA and DP increase.

Table 6. Permeability results of combined effects of PA and DP in concrete

Mix Code	Permeability (mm)		
	7 days	28 days	90 days
CC	40	37	35
M4	38	36	31

4. CONCLUSION

This research investigated the synergistic influence of PA and DP on concrete performance across curing durations of 7, 28, and 90 days. The findings culminate in the following key conclusions.

- The compressive strength of mixes M1 to M7 demonstrated significant improvements over the CM across curing periods. At 7 days, increases ranged from 12.9% to 33.54%, with the highest gain observed in M4. By 28 days, strength enhancements became more pronounced, peaking at 28.54% for M4. At 90 days, compressive strength reached its maximum, with M4 achieving the highest increase of 30.5%, showcasing its superior performance across all curing ages.

- The split tensile strength of mixes M1 to M7 showed steady improvements than CM across curing periods. At 7 days, increases ranged from 4.96% to 15.27%, with M4 showing the highest gain. By 28 days, enhancements became more pronounced, peaking at 15.05% for M4. At 90 days, maximum strength was observed, with M4 achieving the highest increase of 14.45%, demonstrating its superior performance.

- The flexural strength of mixes M1 to M7 improved progressively than the control CM over 7, 28, and 90 days. At 7 days, increases ranged from 1.54% to 11.69%, with M4 achieving the highest gain. By 28 days, M4 continued to outperform with a 7.91% increase. At 90 days, M4 maintained the maximum enhancement of 7.40%, demonstrating consistent performance across curing periods.

- The findings indicate that both CM and M4 mixes exhibit reduced chloride permeability. However, the M4 mix demonstrated notably superior resistance to chloride penetration at all curing than CM. Additionally, the M4 mix, incorporating PA and DP binders, exhibited enhanced weathering resistance and lower permeability than the CM. This may be tending to the improved pore structure of the concrete resulting from the inclusion of PA and DP.

- Therefore, the concrete mix with 10% PA and 15% DP substitution not only enhances strength and durability but also offers environmental benefits by reducing cement consumption and promoting the use of industrial by-products.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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