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Impact of Additional Cementitious Materials on Pervious Concrete's Compressive Strength: An Experimental Study

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Abstract:

Pervious concrete is a sustainable construction material that facilitates stormwater infiltration and groundwater recharge through its interconnected void structure. Its comparatively poor compressive strength, however, restricts its extensive use. The impact of mineral admixtures, specifically metakaolin (MK) and silica fume (SF), on the compressive strength of pervious concrete is examined in this study. Ordinary Portland Cement (OPC), coarse aggregates, and water were used to create concrete examples. SF and MK were added to the cement at replacement levels of 10% and 20%. After 7 and 28 days of curing, cube specimens measuring 150 mm by 150 mm by 150 mm were cast and their compressive strength was evaluated.The findings demonstrated that adding silica fume to pervious concrete increased its compressive strength from 19.86 MPa for the control mix to 21.34 MPa and 22.56 MPa at replacement levels of 10% and 20%, respectively. Compared to the control mix strength of 20.18 MPa, metakaolin replacement produced lower compressive strengths of 19.50 MPa and 18.32 MPa at 10% and 20% replacement levels, respectively. 20% silica fume substitution yielded the maximum compressive strength and optimal performance. According to the study, silica fume is a useful additional cementitious element that can improve pervious concrete's mechanical performance and increase its appropriateness for environmentally friendly pavement applications.

Objective:

This study's main goal is to increase the compressive strength of pervious concrete by substituting extra cementitious ingredients like metakaolin and silica fume for some of the Ordinary Portland Cement (OPC). Despite the fact that pervious concrete is well known for its superior permeability and stormwater management qualities, its use is sometimes restricted due to its comparatively poor compressive strength, which is caused by many linked voids.

The particular goals of this research are:

1. To look at how metakaolin and silica fume affect pervious concrete's compressive strength.
2. To analyse the influence of different replacement levels of silica fume and metakaolin on the mechanical performance of pervious concrete.
3. To ascertain the ideal cement replacement % that maximizes compressive strength while preserving the fundamental properties of pervious concrete.
4. To assess how modified pervious concrete mixes perform in terms of compressive strength in comparison to traditional pervious concrete.
5. To evaluate the suitability of metakaolin and silica fume as additional cementitious materials to improve pervious concrete's performance in environmentally friendly pavement applications.

Literature Review

A network of interconnected spaces in pervious concrete allows water to seep through the pavement top and replenish groundwater, making it a unique kind of concrete. Cement, water, and single-sized coarse aggregates with little to no fine aggregate make up a typical pervious concrete composition. The 28-day compressive strength typically varies between 5 and 20 MPa according on mixture composition, aggregate size, and void content, while the water–cement ratio typically ranges from 0.27 to 0.43. Permeability ratings of pervious concrete commonly fall between 0.025 and 0.600 cm/s when the vacancy ratio is between 14% and 31%.

- Lian et al. (2010) investigated how superplasticizers and silica fume affected the characteristics of pervious concrete. According to their research, the addition of silica fume increased permeability and compressive strength by improving paste quality and aggregate particle bonding. The researchers found that silica fume made the cement matrix denser and decreased microstructural flaws.
- Jain et al. (2021)- The impact of aggregate size and water-to-cement ratio on the permeability properties of pervious concrete was investigated by Jain et al. (2021). The findings showed that while smaller aggregate sizes decreased permeability but enhanced strength, larger aggregate sizes increased permeability due to more linked voids. One of the biggest issues with pervious concrete, according to their research, is the inverse relationship between permeability and compressive strength.
- Cameyisi et al. (2022)- The combined impact of metakaolin and steel fibers on the mechanical properties of concrete was examined by Cameyisi et al. (2022). According to the study, using metakaolin in place of some Portland cement improved the microstructure of concrete through pozzolanic reactions, increasing its durability and compressive strength. Additionally, the addition of metakaolin improved interfacial bonding and decreased pore connectivity.
- In 2024, Chandrappa, A.K., and Biligiri, K.P. conducted research on the "Effect of Metakaolin on the Properties of Pervious Concrete." The study found that while higher aggregate sizes increased permeability but decreased strength, 15% metakaolin replacement produced the best mechanical performance. The authors concluded that metakaolin strengthens the cement matrix and improves pervious concrete's overall performance.

Keywords: Cement, coarse aggregate, silica fume, metakaolin, Pervious concrete

Materials Usedand Methodology:

Cement: We have utilized grade 53 Ordinary Portland Cement (OPC). To fulfil consumer's requirements for high-strength concrete, it should be a high-strength cement. The minimum of 28 days' compressive strength of 53 Grade OPC should be at least 53 MPa, as per the guidelines of BIS. The usage of 53-grade OPC has proven to be highly helpful for some specialised operations, such as prestressed concrete and some types of precast concrete that require consistently high-strength concrete. Higher-grade concrete with a very low cement percentage is produced by 53-grade OPC. The use of 53 Grade OPC will help save 8-10% cement content in the mix design of M20 grade concrete and above grades of concrete.

Fig 1. Ordinary Portland cement

Coarse Aggregates: There are no fine aggregates in Pervious concrete. Fine aggregates from regular concrete are removed to create this concrete. The only ingredients are water, cement and coarse aggregate.A thin layer of cement paste envelops the coarse aggregate particles. A 20mm aggregate size increases the workability even though it permits voids space. Aggregate use may reduce workability and settling.

Fig 2. 20mm Coarse aggregates

Water: Any drinking water can be used for mixing, but W/C ratio will range from 0.270 to 0.300 with ratios as maximum as 0.400. An extremely weak binder can be produced by a mix design with little water. This will result in an extremely dry mixture that is prone to crumbling and spalling. An almost impenetrable concrete surface might result from a design of mix that contains more water, which collapses the void or null space.

Fig 3. Pervious Concrete with enough water

Supplementary Cementitious Materials (SCMS):

- **Silica fume**

Silica Fume is produced during the production process of silicone. This material comprises extremely fine round particles, which improve the toughness and hardness of the concrete significantly. The material helps in producing concrete with more than 140 MPa compressive strength. It is generally used for constructing high-rise buildings. Ten to fifteen percent ofcement can be replaced with silica fume.

Fig 4. Silica Fume

- **Metakaolin**

Metakaolin improves the mechanical qualities of a pervious concrete by fortifying its matrix. For aggregate mixes with sizes of 12.5mm and 20mm, the ideal amount of metakaolin to substitute cement is found to be 15%.

Fig 5. Metakaolin

MIX DESIGN DETAILS:

S.No	Materials	Proportions (Kg/m^3)
1	Cement (OPC or blended)	270 to 415
2	Aggregate	1480-1500
3	Water: Cement ratio (by mass)	0.27 to 0.34
4	Fine: Coarse aggregate ratio (by mass)	0 to 1:1
5	Void ratio	<15%
6	Unit weight of Density	1600-2000 Kg/m^3
7	water	120 Kg/m^3
8	Silica Fume	10%
9	Metakaolin	10%
10	Wastage Allowance	15%

Table 1: M20 grade (1:1.5:3)

Concrete commonly uses ordinary Portland cement (OPC) as the main binder. Pozzolanic materials such as fly ash, blast furnace slag, and silica fume may also be added, but they can change the concrete's setting time, strength, porosity, and permeability. Fine aggregates help decrease porosity and improve concrete strength.

- Uniform coarse aggregates, typically measuring 6.25–12.5 mm, are utilized to enhance aesthetics and minimize surface roughness.
- Typical additives consist of water reducers, retarders, viscosity modifiers, hydration stabilizers, and internal curing agents.
- The suggested water–cement ratio falls between 0.27 and 0.34, with the option to utilize both ordinary Portland cement and blended cements.
- In comparison to regular concrete, pervious concrete necessitates extended mixing durations, exhibits reduced workability due to its dry consistency, and requires precise water management.
- Surplus water can lead to segregation more readily than in traditional concrete.

Experimental works and Results:

Preparation of Cube Samples:

- Cube Samples of 150mm*150mm*150mm were manufactured.
- The concrete was mixed thoroughly and placed in molds in layers, followed by compaction using a tamping rod. To ensure that there are no cavities, the concrete is moderately tempered after being poured into the mold.
- These molds are taken out after one day, and test samples are submerged in water for curing. These samples should have a good, plain top surface. This is achieved by evenly coating the entire sample with cement paste.

Fig 6. Cube Samples preparation

- After being cured for 7 or 28 days, the samples are subjected to tests on a compression test machine. The force is applied at a rate of 140 kg/cm² per min until samples fail.

Fig 7. Pervious concrete Cubes

S.No	Parameter	Standard Values	Typical values
1.	Specific Gravity	2.65	2.50-2.80
2.	Fineness modulus	6.8	6.0-7.5
3.	Water absorption	1.2%	0.5-2.0%
4.	Aggregate crushing value (ACV)	18.5%	15-25%

Table 2: Basic parameters with the standard values and resulted values

Mixing:

Preparing of the concrete can be done either by manually or by laboratory batch mixer.

Fig 8. Mixing of materials

All these values are adopted from IS 456 & IS 12727 and for pervious concrete tests performed according to ACI 522R & ACI 211.1.

Curing:

After keeping the specimens in moisture for 24 hours, they are identified, removed from the moulds, and placed in fresh water until the time for testing. The specimens are then taken out of water after the required curing period and surface water is wiped fromtheir Surface prior to testing.

Fig 9. Curing

- The sample measurements are measured to the closest
- Cleaned the UTM's bearing surface.
- 3 samples are tested as per each of 7,28,90 days each respectively per mix.
- Total of 9 samples for each 0,10,20% replacement mix respectively.
- The specimen was positioned in the compression testing machine so that the loading was done through the opposite faces of the cube.
- The specimen was carefully centered on the base plate of the machine.
- The moving part of the machine was turned by hand carefully till it contacted the top surface of the specimen.
- Loading was done steadily without any shock at the rate of 140 kg/cm² per minute until failure occurred.
- Noticing any peculiarities in the failure type and recorded the maximum load.
- For every chosen age, at least three samples were examined, all these samples gave the strength of compressive of concrete.

Table 3: Adding silica fume to Pervious concrete and analyzing compressive strength

S.No	Nominal Concrete +SF	7DaysKN/M^2	28Days KN/M^2	56Days KN/M^2	90Days KN/M^2
1	Nominal concrete+0%SF	6.57	19.86	20.12	22.05 (11% gain)
2	Nominal concrete+10%SF	10.56	21.34	22.06	22.83 (7% gain)
3	Nominalconcrete+20%SF	11.26	22.56	23.21	23.91 (6% gain)
4	Nominal concrete+30%SF	12.57	22.97	23.94	24.46(5.76% gain)
5	Nominal concrete+40%SF	13.54	23.37	24.22	25.06 (5.02% gain)
6	Nominal concrete+50%SF	14.05	23.97	24.84	25.73 (4% gain)

Table 4: Compressive strength of pervious concrete with Metakaolin

S.No	Nominal Concrete +SF	7DaysKN/M^2	28Days KN/M^2	56Days KN/M^2	90Days KN/M^2
1	Nominal concrete+0%SF	11.07	20.18	21.35	22.4 (11% gain from 28-90 days)
2	Nominal concrete+10%SF	12.58	19.50	21.57	22.62 (16% gain)
3	Nominalconcrete+20%SF	13.5	18.32	20.85	21.80 (19% gain)
4	Nominal concrete+30%SF	11.80	17.2	18.6	19.4 (12% gain)
5	Nominal concrete+40%SF	8.9	13.1	14.3	15.0 (11% gain)
6	Nominal concrete+50%SF	6.2	9.4	10.2	10.9 (10% gain)

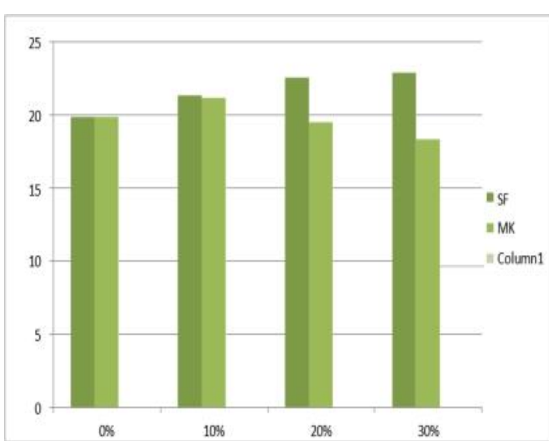
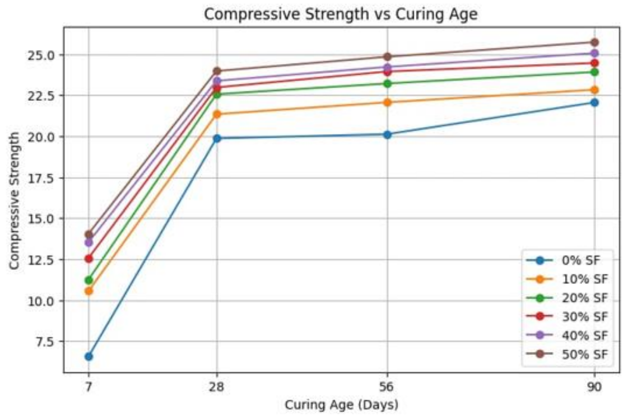
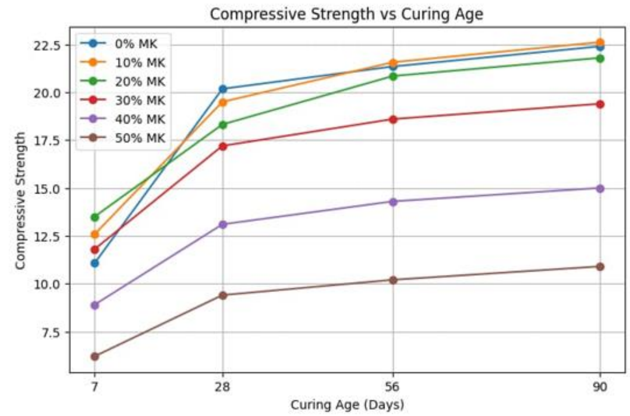


Fig 10. Strengthcharacteristicsof Silica Fume&Metakaolin



Strength characteristics of Silica Fume vs curing age



Strength characteristics of Metakaolin vs curing age

Fig 11. Compressive Strength vs Curing Age Characteristics

Conclusion:

- The compressive strength of pervious concrete depends on parameters such as coarse aggregate size, water-cement ratio, and aggregate-cement ratio.
- Void ratio and unit weight are regarded as two major considerations in pervious concrete mixture design.
- There is a reverse relation between the compressive strength (CS) and coefficient of permeability (K) of pervious concrete up to an addition of 8% particles.
- Silica Fume Enhancement: The study successfully demonstrates that the incorporation of Silica Fume significantly improves the compressive strength of pervious concrete.This represents an approximate 13.6% strength improvement over the control mix, making it highly viable for sustainable pavement applications.
- Metakaolin Retardation: Conversely, the incorporation of Metakaolin reduced the 28,56,90-day compressive strength of the pervious concrete mixes to 22.62 MPa and 21.80 MPa at 10% and 20% replacement levels, respectively, down from a control baseline.
- Replacing 20% cement with metakaolin delivers the highest strength, boosting it by up to 35%. Fast and Steady Growth. It speeds up early strength at 7 days and keeps strengthening concrete up to 90 days. High-Dose Failure: Replacing 20% and above cement weakens the paste, causing the pervious concrete to crumble. So preferable metakaolin replacement percentage 20% as per experimental values shown in **Table 4**.
- Long-term Gain Trends: Environmental curing highlights that while metakaolin mixes underperform at 28 days compared to the control mix, they show notable late-stage strength gains between 28 and 90 days (ranging from 16% to 19% improvement), indicating delayed pozzolanic activity.

Scope:

- Earlier, pervious concrete was extensively employed owing to the scarcity of cement.
- With time, the significance of pervious concrete diminished owing to the mass production and abundant availability of cement.
- However, because of its many benefits, pervious concrete has become more popular.
- The regions have turned into concrete jungles across the earth. Under current circumstances, stormwater discharge is a particularly challenging issue.
- We can replenish the groundwater table and dispose of stormwater by using pervious concrete.

- Pervious concrete is therefore one practical way to address the mentionedissues in the future and shield the people from flooded areas.

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