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Use of Silica Fumes and Metakaolin with Polymer Modified Concrete in Retrofitting and Rehabilitation of Structure

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ABSTRACT

The retrofitting and rehabilitation of deteriorating structures pose significant challenges, requiring innovative materials and techniques to ensure longevity and enhanced performance. This dissertation explores the utilization of silica fumes and metakaolin in polymer-modified concrete mortar as a sustainable approach to address these challenges. The primary aim is to investigate the synergistic effects of these supplementary cementitious materials (SCMs) on the mechanical properties, durability, and microstructural characteristics of the modified mortar. The objectives of this study encompass evaluating the performance enhancement achieved through the incorporation of silica fumes and metakaolin, optimizing mix proportions to achieve desired properties, assessing microstructural changes, and conducting field performance evaluations to validate the effectiveness in real-world applications. Comparative studies with conventional methods provide insights into the economic and environmental benefits of the proposed approach. Through laboratory experiments and field trials, this research demonstrates that silica fumes and metakaolin can significantly improve the compressive strength, flexural strength, bond strength, and durability of polymer-modified mortar. Microstructural analyses reveal reduced porosity and enhanced hydration products, contributing to enhanced performance and long-term durability. The findings underscore the potential of SCMs in polymer-modified concrete mortar as a sustainable solution for retrofitting and rehabilitating structures, offering both technical advancements and environmental benefits.

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KEYWORDS: *silica fumes, metakaolin, polymer-modified mortar, retrofitting, rehabilitation*

1. INTRODUCTION

In recent years, the retrofitting and rehabilitation of structures have gained significant attention due to the increasing need to enhance the durability and structural integrity of aging infrastructure. Polymer-modified mortars have emerged as promising materials for these applications, offering improved properties such as enhanced adhesion, flexibility, and resistance to cracking compared to traditional cementitious materials. To further enhance their performance, additives like silica fumes and metakaolin are being increasingly utilized. Silica fumes, also known as micro silica, are ultrafine particles obtained as a byproduct in the production of silicon metal and ferrosilicon alloys. They are known for their pozzolanic properties, which contribute to improved compressive strength, reduced permeability, and enhanced durability of concrete and mortar matrices. Metakaolin, on the other hand, is a calcined form of kaolin clay that reacts with calcium hydroxide in cement to produce additional binder hydrates, leading to denser microstructures and improved mechanical properties. When incorporated into polymer-modified mortars, silica fumes and metakaolin act synergistically with the polymer to enhance their overall performance. This combination offers superior resistance to chemical attack, increased flexural strength, reduced shrinkage, and improved bond strength to existing substrates during retrofitting and rehabilitation projects. Moreover, these additives contribute to sustainable construction practices by optimizing material usage and extending the service life of structures. This paper explores the synergistic effects of incorporating silica fumes and metakaolin into polymer-modified mortars for retrofitting and rehabilitation applications. It reviews their influence on key properties such as mechanical strength, durability, and microstructure, providing insights into their potential benefits and practical considerations for engineers and practitioners involved in infrastructure maintenance and improvement. By leveraging the benefits of silica fumes and metakaolin in conjunction with polymer-modified mortars, engineers can effectively address the challenges associated with retrofitting and rehabilitating structures, ensuring long-term performance and sustainability in construction practices.

2. METHODOLOGY

Material Selection:

- Silica Fumes
- Metakaolin
- SBR Latex
- Polymer Modification
- Mix Design Optimization
- Testing And Evaluation

Silica Fumes:

Ultrafine particles derived from silicon metal or ferrosilicon alloy production, known for their pozzolanic properties. Silica fumes enhance the mechanical strength and durability of mortars by reducing permeability and increasing the density of the cementitious matrix.

Silica fume, also known as micro-silica, is a byproduct of producing silicon metal or ferrosilicon alloys. It consists of extremely fine particles, predominantly of amorphous silica, with a high surface area. Here are some key points for your dissertation: Composition: Silica fume is composed of silicon dioxide ($SiO2$) typically ranging from 85% to 98%. It also contains small amounts of other oxides such as aluminum, calcium, and iron oxides.

Metakaolin:

A calcined form of kaolin clay that reacts with calcium hydroxide to produce additional binder hydrates, leading to improved compressive strength, reduced shrinkage, and enhanced durability in mortars.

Metakaolin is a pozzolanic material that is produced by calcining kaolin clay at temperatures typically between 600-800°C. It undergoes a physical and chemical transformation during calcination, resulting in altered properties that make it highly beneficial in various applications.

SBR Latex:

Uses of SBR Latex Adhesive Applications: SBR latex is extensively used in adhesive formulations due to its ability to form strong bonds with various surfaces. It is commonly found in pressure-sensitive adhesives used in tapes, labels, and stickers. It is also used in construction adhesives for bonding carpets, tiles, and other building materials.

Polymer Modification:

Selection of appropriate polymer modifiers (e.g., acrylics, styrene-butadiene rubber) based on compatibility with silica fumes and metakaolin. Polymers enhance mortar flexibility, adhesion, and resistance to cracking, crucial for retrofitting applications.

Mix Design Optimization:

Conducting laboratory trials to optimize mix proportions of silica fumes, metakaolin, polymers, cement, and aggregates. Balancing factors such as water-cement ratio, superplasticizers, and admixtures to achieve desired workability, strength, and durability properties.

Testing and Evaluation:

Mechanical Properties: Perform tests including compressive strength, flexural strength, and bond strength to assess the influence of silica fumes and metakaolin on PMC/PMM performance.

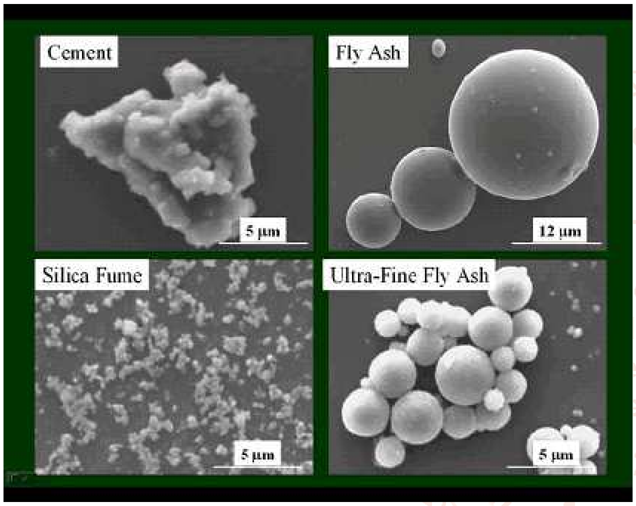
Durability Assessment: Evaluate resistance to freeze-thaw cycles, chemical attack, and carbonation to determine long-term durability and sustainability of PMC/PMMs in retrofitting applications.

Microstructural Analysis: Utilize techniques such as SEM (Scanning Electron Microscopy) and XRD (X-ray Diffraction) to analyze the microstructure and hydration products, validating the role of silica fumes and metakaolin in enhancing mortar properties.

Field Application and Case Studies: Implement optimized PMC/PMM formulations in real-world retrofitting and rehabilitation projects. Document performance in diverse environmental conditions and structural applications, including bridge decks, heritage structures, and industrial facilities. Conduct periodic inspections and performance monitoring to validate laboratory findings and ensure long-term effectiveness of PMC/PMMs with silica fumes and metakaolin.

Sustainability Considerations: Assess the environmental impact and sustainability benefits of using PMC/PMMs with silica fumes and metakaolin compared to conventional materials. Consider factors such as reduced material consumption, extended service life of structures, and minimized maintenance requirements.

Data Analysis and Reporting: Compile experimental data, field observations, and analysis results into comprehensive reports and technical papers. Discuss findings regarding the efficiency, practicality, and economic feasibility of PMC/PMMs with silica fumes and metakaolin in retrofitting and rehabilitation applications. By systematically integrating silica fumes and metakaolin with Polymer-Modified Concrete/Mortar using this methodology, engineers can effectively enhance the performance and sustainability of retrofitting and rehabilitation projects. This approach contributes to the advancement of durable, resilient infrastructure capable of meeting the challenges of modern urban environments.



Comparison of Micro structure under petrography

Methodology

The experimental investigation was conducted to determine the dosages of MK, SF and polymer latex in polymer-modified concrete. In order to achieve this objective, two compositions were formulated.

In the study of Composition-1, a mix design for M30 grade concrete was conducted, revealing a material ratio of 1:2.1:2.95 (cement: fine aggregate: coarse aggregate) with a water-cement ratio of 0.40. OPC Cement was substituted with MK by weight ranging from 0% to 20% at 5% intervals. The samples of Composition-1 underwent compressive strength tests and sorptivity tests to

identify the optimal percentage replacement of cement with MK in PMC/PMM. The composition exhibiting the highest compressive strength and lowest sorptivity was chosen for further analysis.

In the study of Composition-2, MK is replaced by SF with a mix design for M30 grade concrete. OPC Cement was substituted with SF by weight ranging from 0% to 20% at 5% intervals. The samples of Composition-2 underwent compressive strength tests and sorptivity tests to identify the optimal percentage replacement of cement with SF in PMC/PMM. The composition exhibiting the highest compressive strength and lowest sorptivity was chosen for further analysis.

In the study of Composition-3, both MK & SF partially replaced with PMM/PMC with a mix design for M30 grade concrete. OPC Cement was substituted with SF by weight ranging from 0% to 20% at 5% intervals. The samples of Composition-3 underwent compressive strength tests and sorptivity tests to identify the optimal percentage replacement of cement with SF in PMC/PMM. The composition exhibiting the highest compressive strength and lowest sorptivity was chosen for further analysis.

Several tests were conducted to analyze the physical and mechanical properties of the specimens. Additionally, Composition-3 was utilized in PMM for the restoration of columns in the existing RCC building. The post-restoration strength of the columns in the case study building was assessed using Non-destructive Tests such as Ultrasonic Pulse Velocity (UPV) and Rebound Hammer Test.

3. TEST RESULTS & DISCUSSION

The tests which are conducted are as follows: -

Ultrasonic Pulse Velocity:

Procedure

In this test method, the ultrasonic pulse is produced by the transducer which is held in contact with one surface of the concrete member under test. After traversing a known path length (L) in the concrete, the pulse of vibrations is converted into an electrical signal by the second transducer held in contact with the other surface of the concrete member an electronic timing circuit enables the transit time (T) of the pulse to be measured. The pulse velocity (V) is given by:

$$V=L/T$$

Once the ultrasonic pulse impinges on the surface of the material, the maximum energy is propagated at right angles to the face of the transmitting transducer and best results are, therefore, obtained when the receiving transducer is placed on the opposite face of the concrete member (direct transmission or cross probing). However, in many situations two opposite faces of the structural member may not be accessible for measurements. In such cases, the receiving transducer is also efficient as cross probing, because the signal produced at the receiving transducer has an amplitude of only 2 to 3 percent of that produced by cross probing and the test results are greatly influenced by the surface layers of concrete which may have different properties from that of concrete inside the structural member. The indirect velocity is invariably lower than the direct velocity on the same concrete element. This difference may vary from 5 to 20 percent depending largely on the quality of the concrete under test. For good quality concrete, a difference of about 0.5 km/sec may generally be encountered.

Transducers are held on corresponding points of observation on opposite faces of a structural element to measure the ultrasonic pulse velocity by direct transmission, i.e., cross probing. If one of the faces is not accessible, ultrasonic pulse velocity is measured on one face of the structural member by surface probing.

Rebound Hammer test on RC Members:

Procedure

For testing, smooth, clean and dry surface is to be selected. If loosely adhering scale is present, this should be rubbed off with a grinding wheel or stone. Rough surfaces resulting from incomplete compaction loss of grout, spalled or tooled surfaces do not give reliable results and should be avoided.

The point of impact should be at least 20mm away from any edge or shape discontinuity.

For taking a measurement, the rebound hammer should be held at right angles to the surface of the concrete member. The test can thus be conducted horizontally on vertical surfaces or vertically upwards or downwards on horizontal surfaces. If the situation demands, the rebound hammer can be held at intermediate angles also, but in each case, the rebound number will be different for the same concrete.

Rebound hammer test is conducted around all the points of observation on all accessible faces of the structural element. Concrete surfaces are thoroughly cleaned before taking any measurement. Around each point of observations, six readings of rebound indices are taken and average of these readings after deleting outliers as per IS: 8900: 1978 becomes the rebound index for the point of observation.

Cover meter Studies to Assess the Thickness of Cover to Reinforcement in RC Members:

Procedures

The cover meter is switched on and the meter adjusted so that the needle on the indicator dials (analogue devices) correspond to the appropriate calibration mark as indicated by the manufacturer ('zeroing' the instrument). In the case of digital indicating devices, the manufacturer's instructions on setting up the meter before the test should be followed.

In all cases this procedure should be carried out with the search head far removed from the reinforced concrete surface and in such a way that any other extraneous effects on the magnetic field are at a minimum. Rapid movement of the search head should be avoided as this can affect the 'zeroing'.

In any case, measurements should not be taken before the 'zero' reading is stable. During the period of operation, further frequent 'zero' checks should be made.

Ultrasonic Pulse Velocity Test

Rebound Hammer Test

Compressive strength:

The impact of MK or SF on the 28-day compressive strength at various replacement levels is shown in Figure. The development of MK and SF concretes' compressive strengths with curing age is depicted in Figure. Results make it abundantly evident that MK improved concrete strength at all ages to almost the same degree (about 5 to 55%) as did SF at the same replacement amount. MK strengthened effect improved with increasing replacement amount from 5 to 15%. Based on the data, it is evident that a replacement level of about 20% was ideal for providing the most long-term strength gain. The concrete mixtures MK5, MK10, and MK15 had compressive strengths that were roughly 28, 38, and 45% more than the control concrete after three days; at 28 days, they were 25, 28, and 53% higher; and at 65 days, they were approximately 4, 16, and 21% higher. This outcome differed in that MK's impact to concrete strength was limited to a period of 14 days. However, Fig. 3 did demonstrate that after 28 days, the 15% MK or 15% SF concrete's potential for strength improvements was very restricted; the 65-day compressive strengths of these two concretes only grew by roughly 6 to 8% when compared to the 28-day strength.

Results of variation of MK content in concrete:

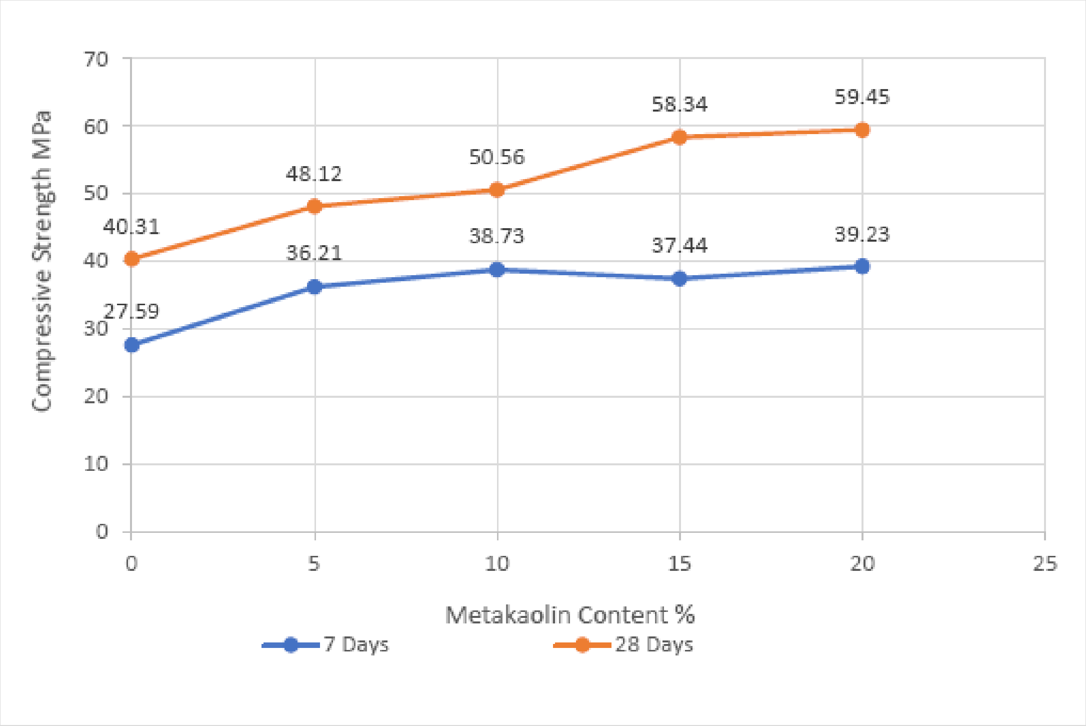
The progress of compressive strength over time and the Sorptivity index for all mixtures examined are displayed below. The graphs clearly indicate that the strength increases as the percentage of MK increases at a water binder ratio of 0.4. All mixes with MK reach their maximum strength within 7 days of curing. After 7 and 28 days of curing, the highest compressive strength was achieved in 20% of the MK admixed samples. This increase in strength can be attributed to the pozzolanic reaction and the filler effect of MK. MK reacts with calcium hydroxide and generates more C-S-H through a secondary cementitious reaction. As a result, the ultimate strength of 20% MK admixed concrete was approximately 49% higher than that of the control mix sample. Similarly, the ultimate strength of 10% MK admixed concrete was 26% higher than that of the control mix. In all mixtures, from MK5 to MK20, the sorptivity value was lower than that of the control mix. Among them, MK10 mixed with 10% MK exhibited the lowest sorptivity, with a 29% reduction in the sorptivity index. This decrease in the Sorptivity index in concrete can be attributed to the micro-filler effects of MK. These findings demonstrate that the durability of MK-based concrete improves due to the secondary pozzolanic reaction and micro-filler effects. Therefore, replacing 10% of the cement with MK proves to be effective in terms of both compressive strength and sorptivity index.

Experimental Observation:

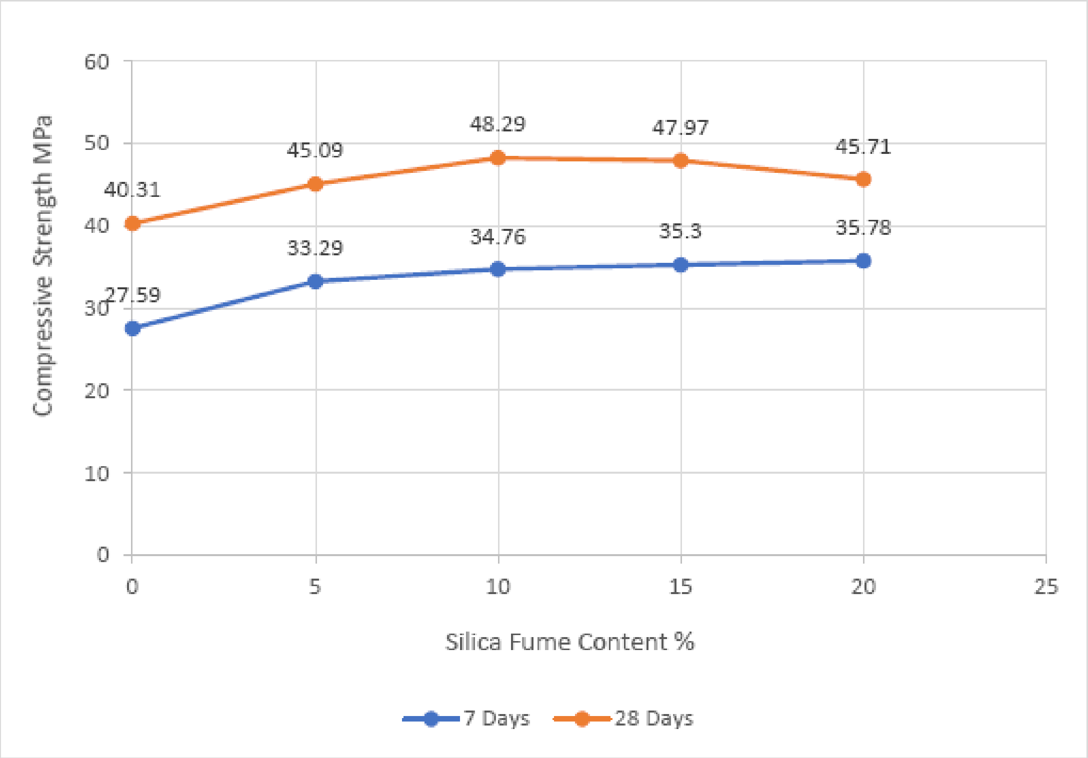
The case study results for the experimental investigation on the restoration of two distressed columns in an RCC building have been analyzed. The columns, beams each measuring 3.5m in height, were divided into two parts: A and B, with each part measuring 3m in height of column, 3m length of beam. NDT points were taken at 500mm c/c. The strength examination of polymer modified mortar, as specified, it was applied to the distressed columns. The compressive strength of the mixes was determined using the rebound hammer test and the calibration graph relating rebound number to compressive strength. The results showed that the P.5M mix had a 21% higher compressive strength compared to the FMP mix. This was attributed to the improved pore structure in the mortar due to the high reactivity of MK, resulting in early strength gain. The filler effect of MK contributed to denseness, while the polymer latex content enhanced adhesion by retaining water in the mortar for a longer period of time. The UPV value in the P.5M mix was 6% higher than the FMP mix. In the cost comparison between Polymer Modified Mortar (PMK) and MK admixed mortar in the restoration of columns at the RCC building, the PMK mix (10% MK) saved 43% of the cost but had 8% less strength than the FMP mix (5% Polymer latex). The PMK mix also exhibited lower water holding capacity compared to FMP. On the other hand, the P.5M mix saved 38% of its cost and had a 21% higher strength than FMP. The water-holding capacity of P.5M was higher than that of PMK. Lastly, the P1M mix saved 33% of its cost but had a strength that was 32% less than FMP

Replacement level (%)		Compressive Strength (MPa)	Compressive Strength (MPa)	Rebound Hammer	Ultrasonic Pulse Velocity (km/s)
Silica Fume	Metakaolin	7 Days	28 Days	28 Days	28 Days
0	0	27.59	40.31	45	4.38
0	5	36.21	48.12	53	4.41
5	0	33.29	45.09	50	4.42
0	10	38.73	50.56	54	4.48
10	0	34.76	48.29	52	4.40

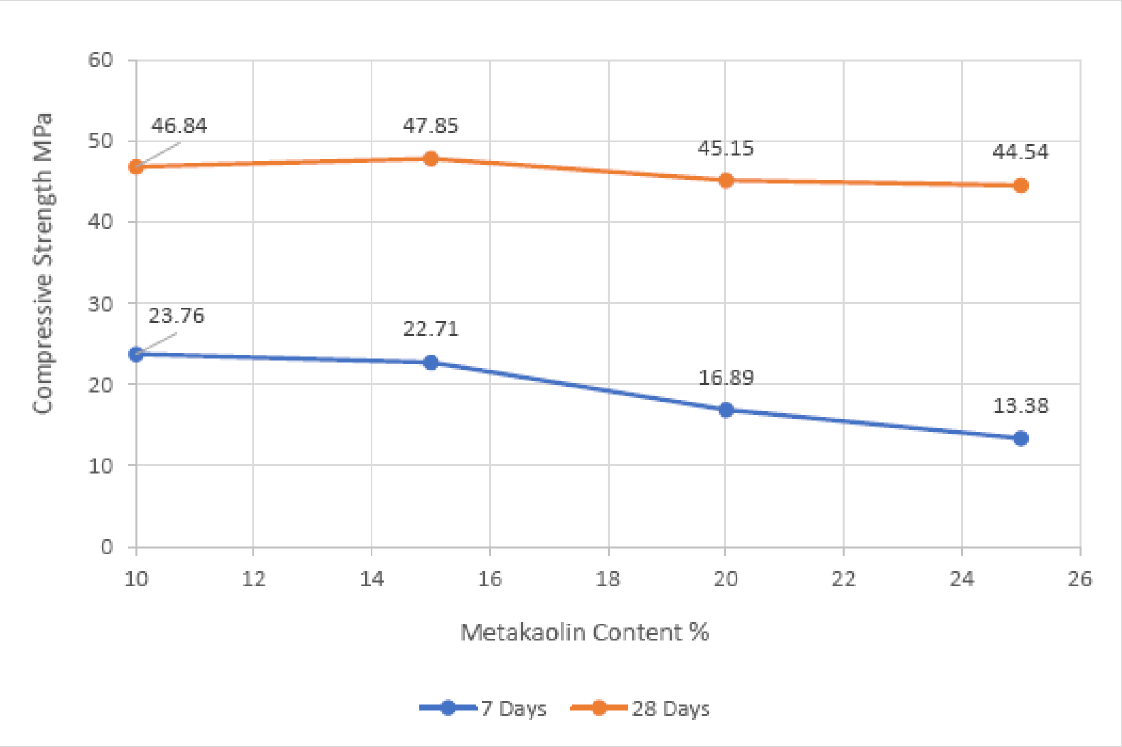
0	15	37.44	58.34	55	4.57
15	0	35.30	47.97	52	4.42
0	20	39.23	59.45	55	4.62
20	0	35.78	45.71	49	4.34
5	10	23.76	46.84	50	4.44
5	15	22.71	47.85	52	4.5
5	20	16.89	45.15	49	4.43
5	25	13.38	44.54	48	4.38
6	10	27.76	55.08	55	4.59
6	15	35.18	56.15	55	4.64
6	20	30.34	51.85	54	4.52
6	25	31.62	53.33	55	4.58
7	10	27.30	38.62	43	4.37
7	15	26.82	38.89	43	4.39
7	20	27.30	40.46	44	4.41
7	25	25.74	43.27	47	4.43
8	10	23.07	49.62	53	4.49
8	15	26.28	52.60	55	4.51
8	20	28.69	51.07	54	4.50
8	25	19.86	45.15	49	4.46



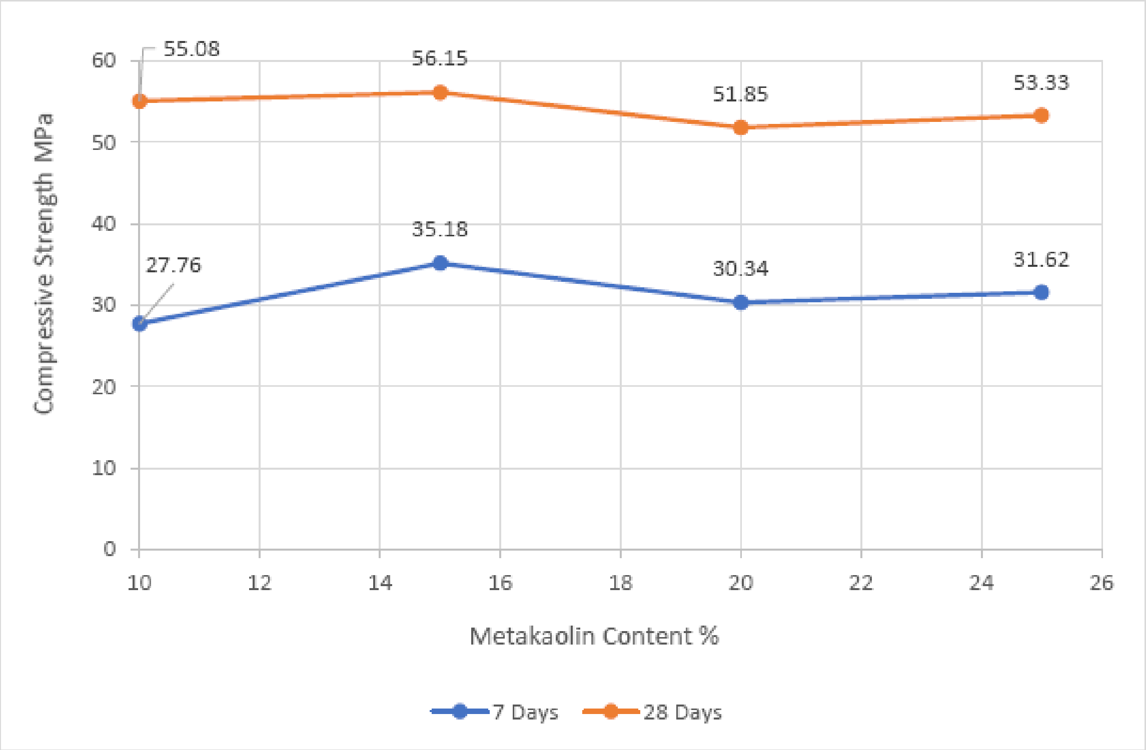
Variation of Compressive Strength with Metakaolin content



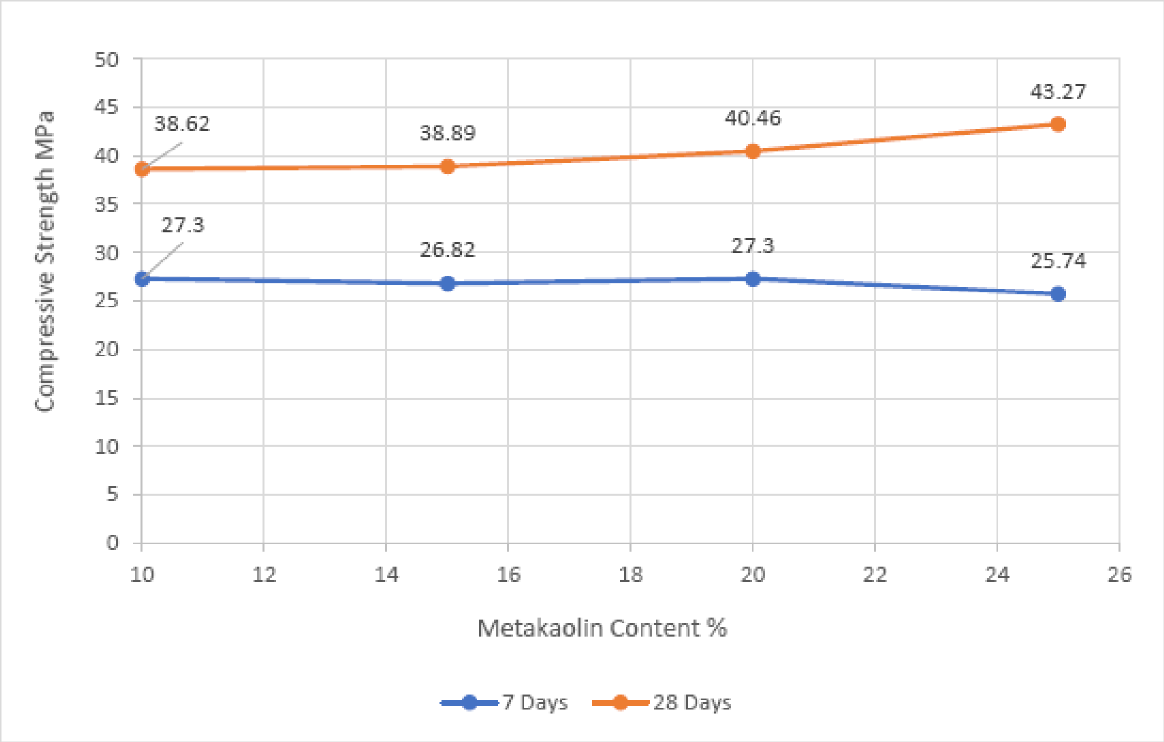
Variation of Compressive Strength with Silica Fume content



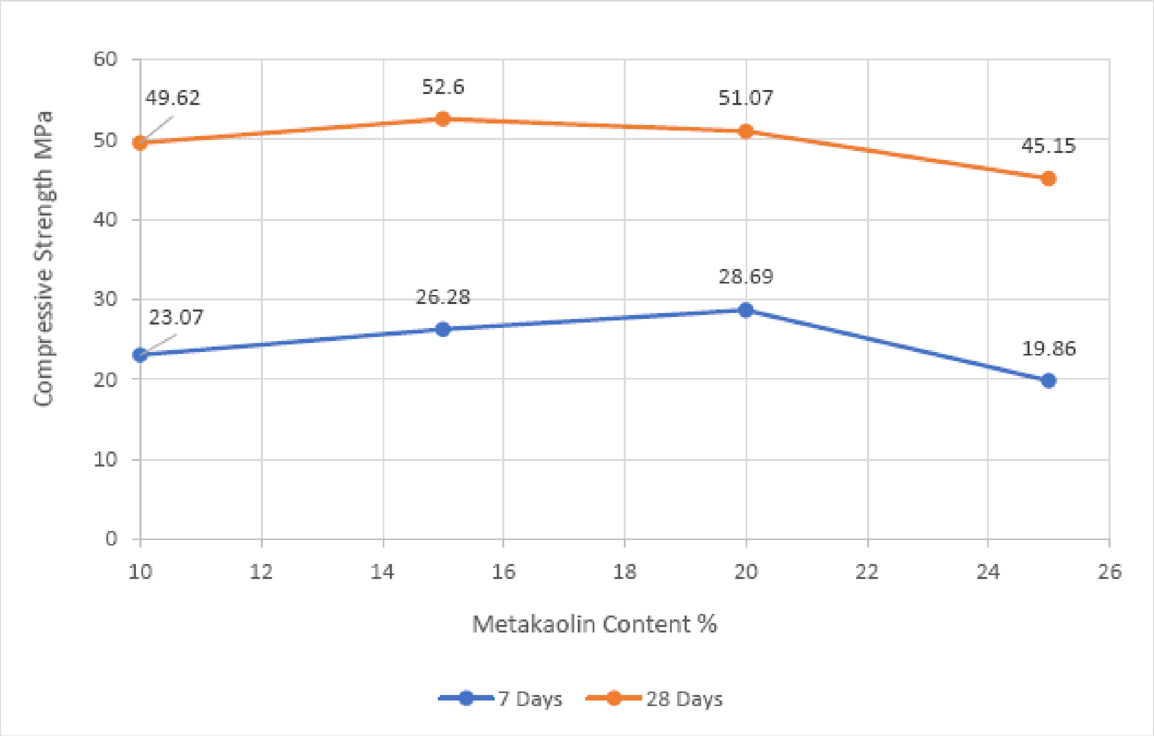
Variation of Compressive Strength with Metakaolin content at 5 % Silica Fume



Variation of Compressive Strength with Metakaolin content at 6 % Silica Fume



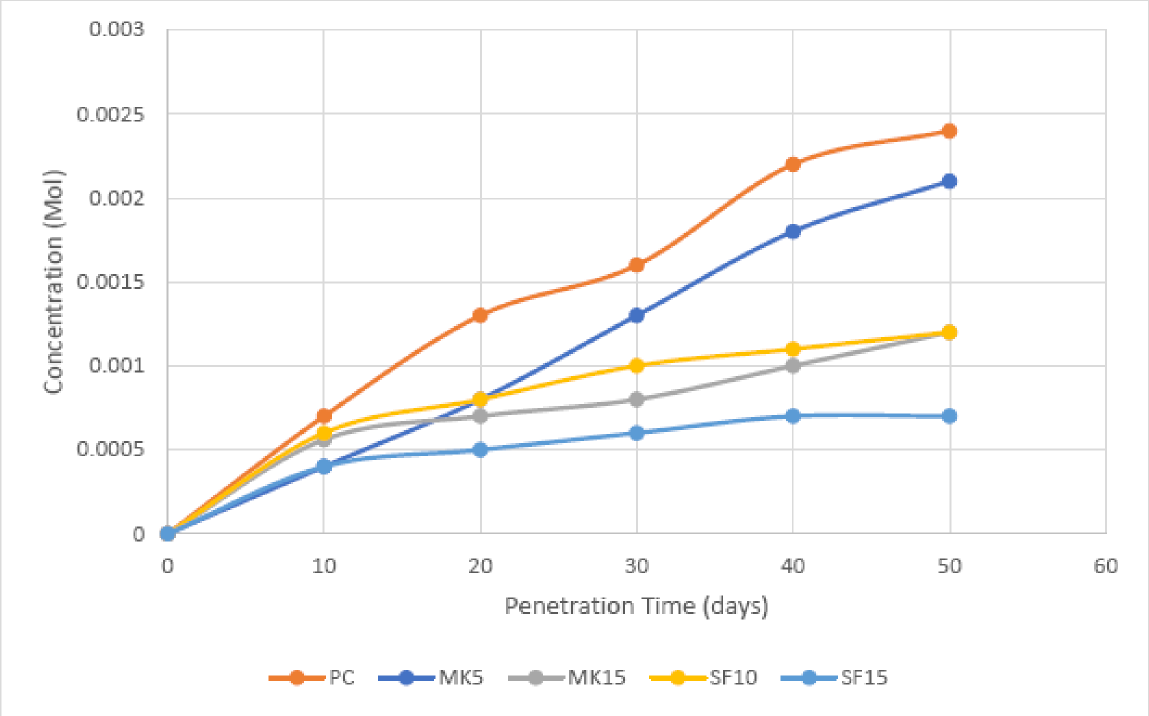
Variation of Compressive Strength with Metakaolin content at 7 % Silica Fume



Variation of Compressive Strength with Metakaolin content at 8 % Silica Fume

Chloride Diffusivity

The data presented in graph indicates a notable enhancement in chloride resistance with a 15% replacement of MK, while a 5% substitution also resulted in some improvement. Following a 43-day diffusion period, the 15% MK replacement led to a reduction of approximately 48% in chloride concentration within the Column. This finding aligns closely with our previous research, which illustrated a reduction of around 43% in diffusion coefficient with 8% MK and around 50% with 12% MK. Moreover, SF concrete exhibited a marginally superior chloride resistance performance compared to MK concrete. After three months of conventional curing, the impact of 10% SF was nearly as significant as that of 15% MK. When used at a replacement rate of 15%, SF decreased the chloride level by about 60% when compared to the control PC concrete after 43 days of curing, which was more pronounced than the impact of 15% MK.



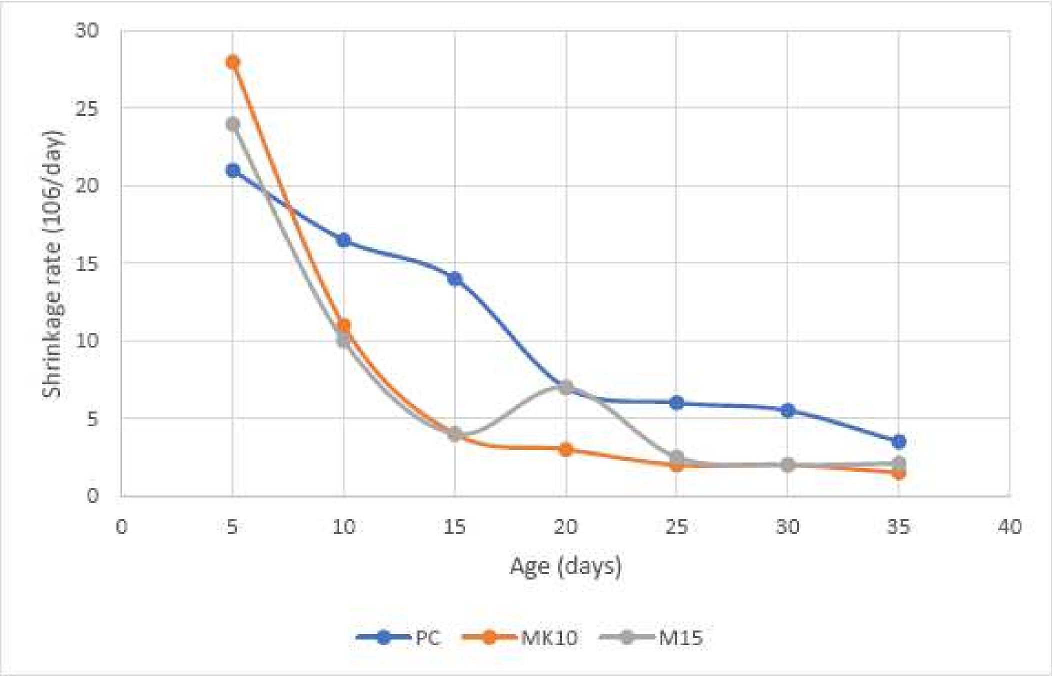
Variation of Chloride Diffusivity with variation in Metakaolin and Silica Fume

Free shrinkage

The graph illustrating the changes in stress over time for the free shrinkage samples is shown in graph. The specimens began to experience shrinkage at a rapid pace, reaching around 3 weeks before the rate started to slow down. The shrinkage rates for concrete mixes with either MK or SF levels increased with higher levels of replacement at day 28, but the shrinkage at that point started to decrease. Specifically, the shrinkage of concrete mixtures with MK5, MK10, MK15, SF5, SF10, and SF15 was estimated to be about 15, 25, 40, 15, 22, and 33% lower than that of the standard concrete mix at day 28, respectively.

Different conclusions have been drawn in the literature regarding the effects of incorporating SF on the shrinkage and creep of plain concrete. However, the researchers of this study have concluded that the inclusion of SF significantly or moderately reduces the shrinkage and creep of plain concrete. In fact, the incorporation of SF resulted in a one-month reduction in strain of 34.9% for shrinkage and 18.5% for creep. This reduction in strain ultimately led to a 20.8% decrease in the total deformation of the concrete. The researchers attribute this improvement to the smaller weight loss experienced during drying.

The shrinkage rates depicted in graph were calculated for the MK- and SF-modified concrete, respectively. The shrinkage rates of MK10 and MK15 concrete were initially higher than the control concrete before 4 and 5 days, respectively. Subsequently, the rates of the two MK concretes decreased and were lower than those of the control concrete. A higher MK content resulted in a lower peak shrinkage rate and a slower overall shrinkage rate of the concrete. When compared to SF concrete at the same replacement level, MK concrete exhibited a slightly faster shrinkage development before approximately one week, followed by a slower development thereafter. Review papers have also concluded that concrete with 10% MK displayed lower drying shrinkage compared to the control and SF concretes after 7 days of initial curing in lime water. Free shrinkage tests alone do not provide adequate information on concrete structure behavior due to various restraints present, such as reinforcement or structural boundary conditions. However, the strain from a free shrinkage test can be utilized as the eigenstrain for corresponding restrained shrinkage tests. The stress distribution resulting from shrinkage in the restrained specimen can be determined based on the eigenstrain value and the specific restrained conditions of the specimen.



Effect of metakaolin content on the rate of concrete shrinkage over time

CONCLUSION

The combination of polymer-modified concrete mortar (PMC/PMM) with silica fumes and metakaolin signifies a notable progress in the realm of retrofitting and rehabilitating structures. This amalgamation utilizes the distinct characteristics of each element to augment the longevity, robustness, and eco-friendliness of deteriorating infrastructure, effectively tackling crucial obstacles encountered in contemporary civil engineering methodologies.

The incorporation of silica fumes and metakaolin along with polymer-modified concrete mortar offers a potential strategy to improve the efficiency of retrofitting and rehabilitation endeavors in civil engineering. After conducting an extensive analysis of literature and experimental studies, numerous advantages have been recognized.

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