Durability Test on Concrete with Partial Replacement of Cement with Metakaolin and Silica-Fume

P. Harini[1], Dr. S. Sundari[2], and Dr. G. Arunkumar[3]
[1]*Student, Government College of Engineering, Salem-636 011*
[2]*Assistant Professor, Government College of Engineering, Salem-636 011*
[3]*Head of the Department, Government College of Engineering, Thanjavur-613 402*

Abstract: The partial replacement of conventional Portland cement with supplementary cementitious materials (SCMs) such as metakaolin and silica fume has emerged as a promising strategy to address the sustainability and performance challenges in the construction industry. This research explores the effects of incorporating metakaolin and silica fume, individually and in combination, as partial replacements for cement in concrete mixtures. The results demonstrate that the addition of metakaolin and silica fume leads to improved compressive and flexural strengths, especially at early ages. These SCMs also enhance the durability of concrete by reducing permeability and enhancing resistance to aggressive chemical attacks. Achieving the ideal balance between enhanced characteristics and practical application requires workability considerations and mix optimisation. Additionally, silica fume and metakaolin used together have a synergistic impact that improves strength and durability even more than when used alone. This result highlights the potential for a more environmentally friendly and high-performing concrete by carefully mixing various SCMs. The research emphasises the environmental advantages of less cement consumption in the context of sustainability, helping to cut carbon emissions and support resource conservation. Overall, this study provides insightful information about the partial substitution of cement with metakaolin and silica fume, demonstrating their potential to improve the qualities of concrete while promoting sustainability goals. These findings have implications for the construction industry, encouraging the adoption of more sustainable and resilient concrete mixtures in future infrastructure projects.

Index Terms: cement replacement, Metakaolin, silica fume, durability test

I. INTRODUCTION

Concrete and mortar are two common building materials made with cement that are utilised in the construction industry. Although it is a crucial part of creating contemporary infrastructure, its manufacture has a number of negative environmental effects, such as: Carbon emissions: The process of making cement uses a lot of carbon. In order to create clinker, a crucial component of cement, high temperatures are used to heat limestone (calcium carbonate). This process contributes to greenhouse gas emissions and the global climate change by releasing carbon dioxide (CO2) into the atmosphere.

Consumption of energy: Making cement requires a lot of energy. Transporting raw materials, grinding clinker, and operating high-temperature kilns all demand a significant amount of energy, mostly from fossil fuels. Both resource depletion and greenhouse gas emissions are impacted by this energy use.

Resource Depletion: The removal of cement-making raw materials like limestone, clay, and shale may cause habitat disruption and landscape changes. The extraction of these resources may also harm the local biodiversity and ecosystems.

Air Pollution: During the process of making cement, a number of pollutants, including particulate matter, sulphur dioxide (SO2), nitrogen oxides (NOx), and volatile organic compounds (VOCs), can be released into the atmosphere. The air quality and public health may suffer as a result of these contaminants.

Consumption of Water: Cement plants need a lot of water for cooling and other activities. This may put a burden on nearby ecosystems and water resources in places with a shortage of water.

Waste Production: Waste from the manufacture of cement includes kiln dust, sludge, and dust. To reduce the negative effects on the environment, these waste items must be properly disposed of or recycled.

Land Use: Cement plants and quarries take up a lot of space, which can lead to habitat loss and fragmentation, which can have an impact on the surrounding flora and wildlife.

The use of metakaolin and silica fume as partial replacements for conventional cement in concrete offers several important advantages, making them valuable components in sustainable construction practices: Enhanced durability: Both metakaolin and silica fume improve the durability of concrete by reducing permeability and enhancing resistance to chemical attacks, such as sulfate attack, chloride penetration, and alkali-silica reaction. This results in longer-lasting and more resilient concrete structures, reducing maintenance and repair costs. Waste Utilization: Silica fume is a byproduct of industrial processes, while metakaolin can be produced from abundant clay sources. Utilizing these materials in concrete repurposes waste products and minimizes environmental burdens associated with their disposal. Innovation and Research: The ongoing research and development of metakaolin and silica fume in concrete offer opportunities for innovation and the advancement of construction materials technology. This contributes to the continuous improvement of concrete performance and sustainability.

II. LITERATURE REVIEW

A. (Ramezanianpour et al., 2010; Uysal and Yilmaz, 2007) Metakaolin, produced by calcining kaolin clay, has been extensively investigated for its impact on concrete properties. Researchers have consistently reported improvements in compressive strength, with some studies indicating that even modest additions of metakaolin can lead to significant strength gains, particularly at early ages.

B. (Penttala et al., 2002) Moreover, metakaolin has been found to enhance durability by reducing permeability, improving resistance to sulfate attack (Bentz et al., 1999), and mitigating alkali-silica reaction.

C. (Hossain et al., 2017) Its pozzolanic properties contribute to the formation of additional calcium silicate hydrate (C-S-H) gel, leading to denser and more impermeable concrete microstructures. While metakaolin offers clear advantages, researchers have also noted that the optimal replacement level varies with factors such as cement type, curing conditions, and mix design. Careful consideration is required to balance strength enhancement with workability and cost-effectiveness.

D. (Tang et al., 2007; Shannag and Al-Rousan, 2000) Silica fume, a byproduct of silicon and ferrosilicon alloy production, is another SCM commonly used in concrete. Numerous studies have highlighted its ability to significantly increase the compressive and flexural strengths of concrete This strength enhancement is attributed to the pozzolanic reaction and the formation of additional C-S-H gel.

E. (Thomas et al., 2003) silica fume has been found to enhance the durability of concrete by reducing chloride ion penetration (Mehta and Monteiro, 2014) and mitigating the risk of alkali-silica reaction. Its fine particle size and reactivity contribute to denser, less permeable concrete matrices.

F. (Zhang et al., 2016) However, silica fume can affect workability and may require the adjustment of mix proportions to maintain the desired properties.

G. (Li et al., 2015) Careful consideration of the particle size distribution and its impact on rheology is essential during concrete mix design.

Conclusion: The literature review underscores the significant potential of metakaolin and silica fume as partial replacements for cement in concrete. Both SCMs offer the opportunity to enhance strength, durability, and sustainability while posing challenges related to workability and mix design. The combined use of these materials has demonstrated synergistic benefits. Further research is needed to explore the optimal utilization of metakaolin and silica fume in various concrete applications, considering factors such as local materials and environmental considerations. Overall, these SCMs hold promise for advancing the field of high-performance and sustainable concrete technology.

III. MATERIALS

Cement: Cement serves as the binder in concrete, mixing with aggregates (such as sand, gravel, and crushed stone), water, and often supplementary cementitious materials (SCMs) to create a hardened, durable, and strong construction material. When mixed with water, cement undergoes a process known as hydration, where it chemically reacts to form calcium silicate hydrate (C-S-H) gel, responsible for the strength and stability of concrete.

Metakaolin: Metakaolin plays a significant role in enhancing the properties of concrete and is widely used as a supplementary cementitious material (SCM) in the construction industry. Its role in concrete is multifaceted and contributes to improving the performance, durability, and sustainability of concrete structures.

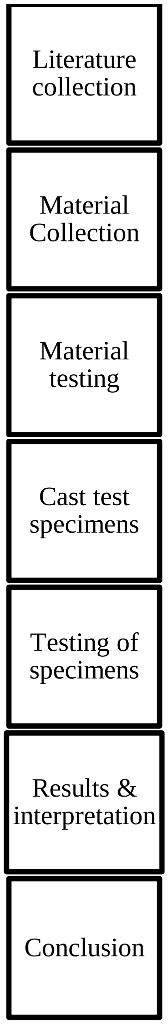
Silica Fume: Silica fume, also known as microsilica or condensed silica fume, plays a crucial role in improving the properties and performance of concrete. It is a highly reactive supplementary cementitious material (SCM) that is often used as an additive in concrete mixtures.

Fine Aggregate: Manufactured sand, often referred to as M-sand, plays a crucial role in the production of concrete. It is a fine aggregate made by crushing hard stones or rocks, typically granite or basalt, to obtain sand-sized particles. M-sand has become a popular alternative to natural river sand in the construction industry due to its consistent quality, availability, and environmental benefits. M-sand is a versatile and sustainable alternative to natural river sand in concrete production. Its consistent quality, cost-effectiveness, and reduced environmental impact make it an attractive choice for construction projects, contributing to the development of durable and environmentally friendly concrete structures.

Coarse Aggregate: This type of aggregate is commonly used in concrete mixtures for various construction applications. Coarse aggregates like 20mm size aggregate are a crucial component of concrete mixtures. They provide bulk and volume to the concrete, making it economical and practical for construction. These aggregates occupy the spaces between the cementitious paste and fine aggregates (sand) in the mix.

Water: water is a vital component in concrete, participating in the chemical reactions that lead to its hardening and strength development. Proper control of the water-cement ratio, along with considerations for workability, curing, temperature, and admixtures, is essential to produce high-quality concrete with the desired properties for specific construction applications.

IV. METHODOLOGY



V. DURABILITY TEST

A. *Water absorption:* The water absorption test results provide information about the concrete's permeability and its ability to resist water penetration. Lower water absorption values indicate improved resistance to moisture ingress and better durability. This test is useful for assessing the quality and durability of concrete mixes.

B. *Sorpitivity:* The sorptivity test provides a measurement of how quickly water is absorbed into the surface of concrete. The sorptivity value (S) is typically expressed in units of millimeters per minute (mm/min) and represents the rate of water absorption. Lower sorptivity values indicate lower permeability and better resistance to water penetration, which is desirable for concrete's durability and longevity.

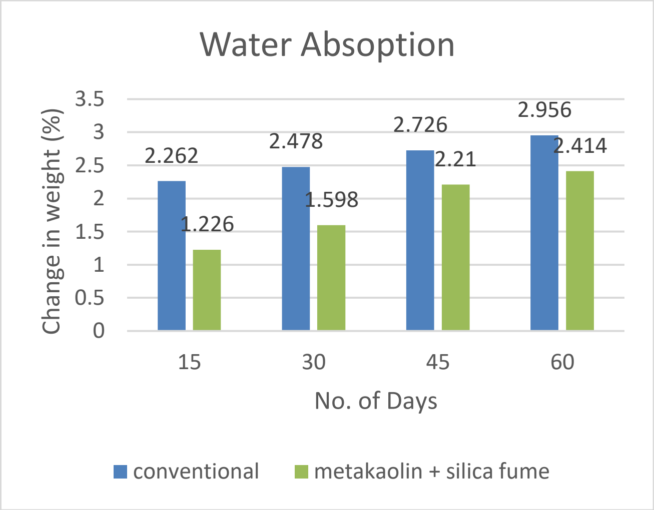
C. *Acid attack:* The results of the acid attack test provide information about the concrete's resistance to chemical deterioration by acids. Lower mass loss values and slower rates of deterioration indicate better acid resistance. The test helps assess the suitability of the concrete mix for specific environments.

D. *Sulphate attack:* The results of the sulfate attack test provide information about the concrete's resistance to sulfate-induced deterioration. Lower mass loss values and slower rates of deterioration indicate better sulfate resistance.

E. *SEM analysis:* SEM reveals the microstructure of concrete, including the arrangement of aggregates, cementitious phases, and porosity. It can help assess the quality of concrete

F. *Energy Dispersive X-ray Spectroscopy (EDS):* In addition to imaging, SEM can be equipped with an EDS detector. EDS allows for the analysis of the elemental composition of different phases within the concrete. It can identify and quantify the presence of specific elements and minerals, helping to understand the concrete's composition in detail.

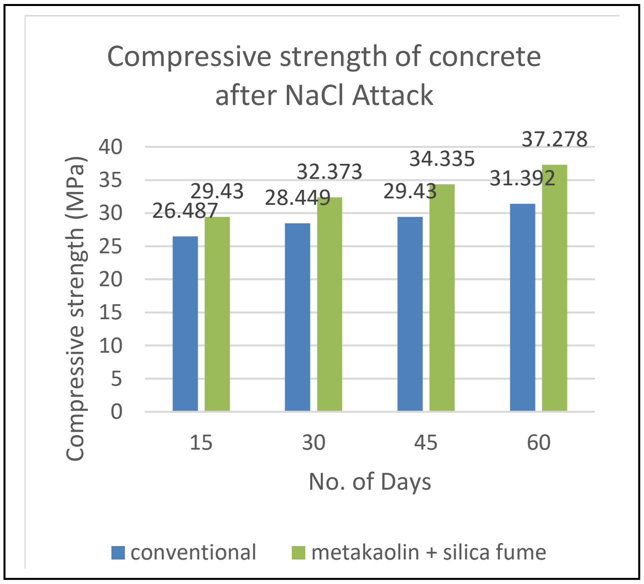
SPECIMEN	NO. OF DAYS	WEIGHT BEFORE ABSORPTION (kg)	WEIGHT AFTER ABSORPTION (kg)	CHANGE IN WEIGHT (%)
Water absorption				
Conventional	15	2.498	2.554505	2.262
	30	2.486	2.547603	2.478
	45	2.502	2.570205	2.726
	60	2.516	2.590373	2.956
Metakaolin + silica fume	15	2.396	2.425375	1.226
	30	2.254	2.290019	1.598
	45	2.412	2.465305	2.21
	60	2.288	2.343232	2.414

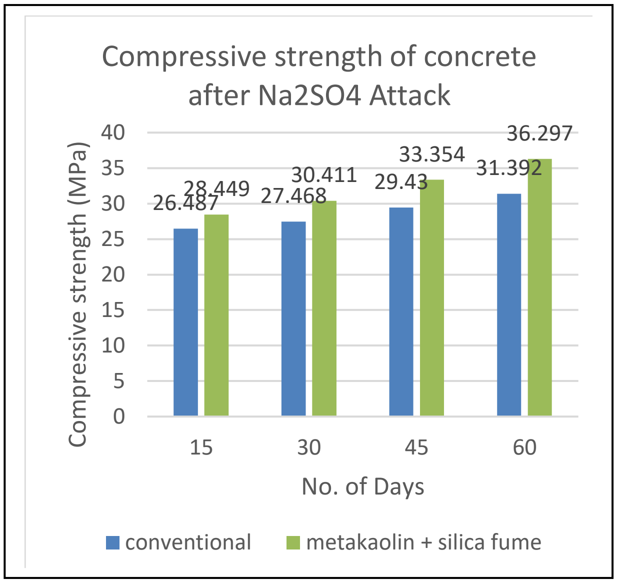


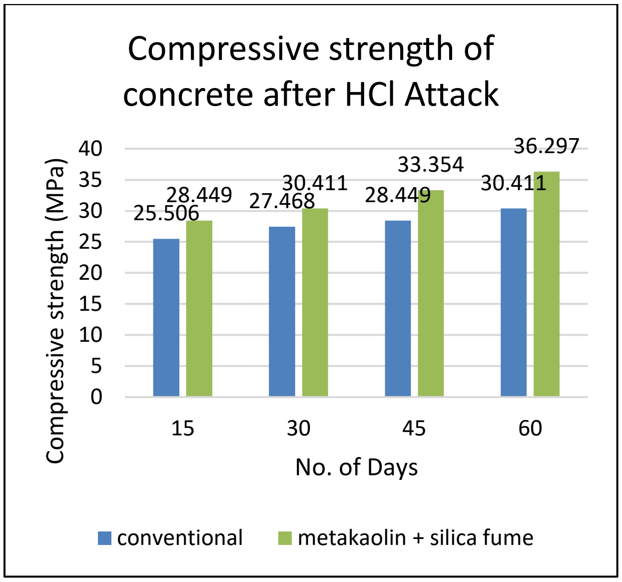
VI. RESULTS AND DISCUSSION

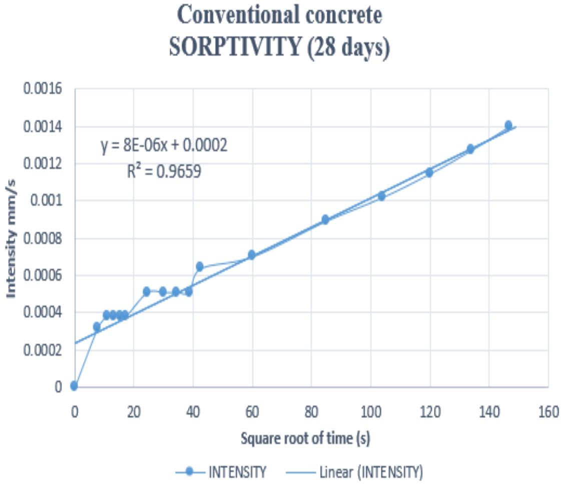
SPECIMEN	NO. OF DAYS	WEIGHT BEFORE ATTACK (kg)	WEIGHT AFTER ATTACK (kg)	% LOSS OF WEIGHT	COMPRESSIVE STRENGTH BEFORE ATTACK (kN/mm2)	COMPRESSIVE STRENGTH AFTER ATTACK (kN/mm2)	AVERAGE LOSS OF STRENGTH (%)
NaCl attack							
Conventional	15	2.502	2.575	2.942	27.468	26.487	3.571
	30	2.516	2.590	2.98	30.411	28.449	6.451
	45	2.496	2.574	3.142	32.373	29.43	9.090
	60	2.522	2.621	3.96	33.354	31.392	5.882
Metakaolin + silica fume	15	2.496	2.529	1.334	31.392	29.43	6.25
	30	2.49	2.527	1.492	34.335	32.373	5.714
	45	2.506	2.546	1.602	38.259	34.335	10.256
	60	2.516	2.559	1.726	41.202	37.278	9.524
Na2SO4 attack							
Conventional	15	2.504	2.577	2.928	27.468	25.506	7.142
	30	2.488	2.562	3.002	30.411	27.468	9.677
	45	2.512	2.590	3.126	32.373	28.449	12.121
	60	2.496	2.577	3.248	33.354	30.411	8.823
Metakaolin + silica fume	15	2.482	2.552	2.828	31.392	28.449	9.375
	30	2.478	2.549	2.896	34.335	30.411	11.428
	45	2.5	2.573	2.946	38.259	33.354	12.820

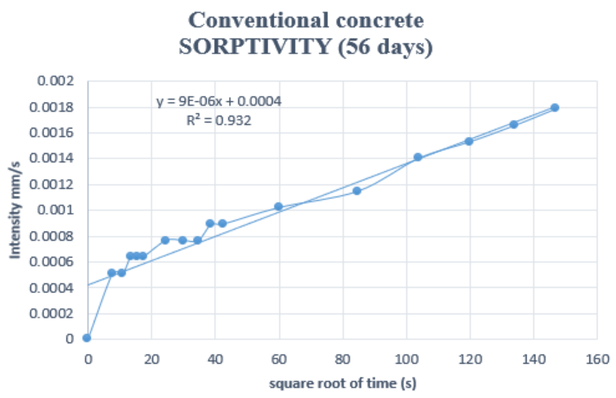
	60	2.152	2.219	3.114	41.202	36.297	11.904
HCl acid resistance							
Conventional	15	2.502	2.559	2.28	27.468	26.487	3.5714
	30	2.488	2.550	2.496	30.411	27.468	9.677
	45	2.512	2.581	2.748	32.373	29.43	9.091
	60	2.492	2.566	2.996	33.354	31.392	5.882
Metakaolin + silica fume	15	2.5	2.524	0.988	31.392	28.449	9.375
	30	2.486	2.512	1.04	34.335	30.411	11.428
	45	2.516	2.547	1.232	38.259	33.354	12.821
	60	2.523	2.562	1.564	41.202	36.297	11.904

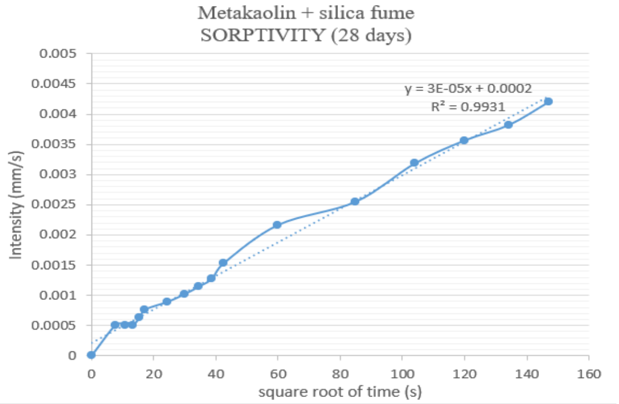


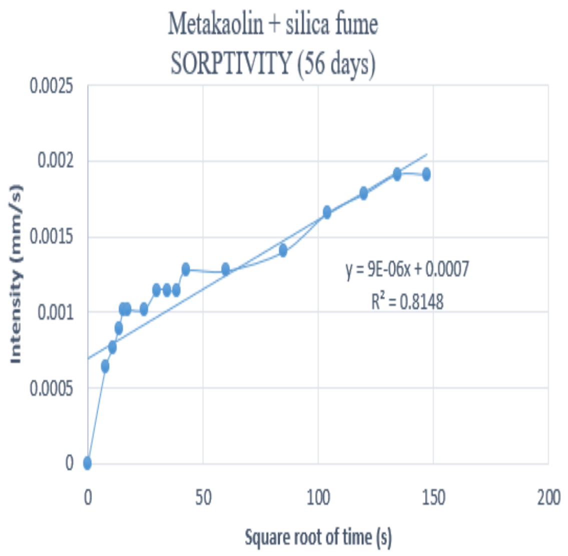












VII. CONCLUSION

From the investigation, rate of water absorption of conventional mix was found to be higher than the 5% Metakaolin + 10% silica fume replacement by weight of cement.

From the table, the average acid attack and chloride attack % loss in compressive strength of conventional mix was found to be more than 5% metakaolin + 10% silica fume replacement by weight of cement.

Sorptivity investigation was also done and it showed better results.

Thus, the optimum percentage of 5% metakaolin + 10% silica fume replacement by weight of cement was found to be effective in both mechanical and durability properties.

REFERENCES

[1] Bentz, D. P., et al. (1999). Influence of Metakaolin on the Performance of Mortars and Concrete. ACI Materials Journal, 96(6), 798-804.

[2] Ganesan, K., et al. (2008). Influence of Metakaolin and Silica Fume on the Mechanical Properties and Durability of High Performance Concrete. Construction and Building Materials, 22(9), 2105-2112.

[3] Hossain, K. M. A., et al. (2017). Effects of Metakaolin on Compressive Strength, Elastic Modulus, Permeability, and Durability of Concrete. Journal of Materials in Civil Engineering, 29(11), 04017112.

[4] Li, L., et al. (2015). Effects of Silica Fume and Water Reducer on the Rheological Behavior of Cement Paste. Materials and Structures, 48(6), 1899-1910.

[5] Mehta, P. K., & Monteiro, P. J. M. (2014). Concrete: Microstructure, Properties, and Materials. McGraw-Hill Education.

[6] Naceri, A., & Hamdani, H. (2006). Influence of Limestone Filler on Some Properties of Cement Paste, Mortar and Concrete. Construction and Building Materials, 20(9), 769-775.

[7] Ramezanianpour, A. A., et al. (2010). Influence of Metakaolin and Silica Fume on the Mechanical Properties and Durability of Low Portland Cement Concretes. Construction and Building Materials, 24(6), 1086-1095.

[8] Shannag, M. J., & Al-Rousan, R. Y. (2000). Silica Fume Effects on Concrete Properties. ACI Materials Journal, 97(3), 364-371.

[9] Tang, C., et al. (2007). Silica Fume and Fly Ash Effect on Compressive Strength and Pore Size Distribution of High-Performance Concrete. Cement and Concrete Research, 37(8), 1250-1259.

[10] Taha, B., et al. (2008). Effect of Silica Fume and Metakaolin on Concrete Properties. ACI Materials Journal, 105(6), 573-580.

[11] Thomas, M. D. A., et al. (2003). Role of Microstructure in the Development of Alkali–Silica Reaction Expansions in High-Performance Concrete. Cement and Concrete Research, 33(8), 1247-1253.

[12] Uysal, M., & Yilmaz, K. (2007). Effects of Metakaolin, Silica Fume, and Slag-Based Activator on the Strength and Microstructure of Alkali-Activated Fly Ash Binder. Materials Letters, 61(8-9), 1585-1590.

[13] Zhang, M. H., et al. (2016). Rheological Properties of Cement Paste with Microsilica and Viscosity Modifying Admixture. Cement and Concrete Research, 85, 53-64.