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Evaluation Of Durability Performance Of Metakaolin Modified Cement Mortar

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Abstract-Durability is one of the most important properties of cement-based materials, as it determines the long-term performance and service life of structures. Conventional cement mortar is often affected by environmental factors such as acid attack, carbonation, and chloride penetration, which can lead to deterioration over time. In this study, metakaolin was used as a supplementary cementitious material to improve the durability performance of cement mortar. Metakaolin was incorporated as a partial replacement for cement at different percentages of 0%, 5%, 10%, and 15%. The durability performance of the mortar was evaluated using acid attack tests, carbonation tests, and chloride penetration tests. The results indicated that the addition of metakaolin significantly improved the durability characteristics of cement mortar. Among all the mixes, the 10% replacement level showed the best overall performance. The improvement in durability is mainly due to the pozzolanic reaction of metakaolin, which reduces calcium hydroxide content and refines the pore structure. This leads to reduced permeability and enhanced resistance to aggressive environmental conditions. The study concludes that metakaolin is an effective material for improving durability and sustainability in cement-based construction

Keywords-Metakaolin, Durability performance, Modified cement mortar, Compressive strength, Water absorption, Permeability, Sustainability, Supplementary cementitious material (SCM), Long-term performance.

1. INTRODUCTION

Cement mortar is one of the most essential and widely used materials in the construction industry, primarily serving as a binding agent for masonry units such as bricks, stones, and concrete blocks. Its role is not only limited to providing adhesion between structural elements but also extends to contributing to the overall strength, durability, and serviceability of structures. Due to its ease of preparation, availability of raw materials, and cost-effectiveness, cement mortar has been extensively used in both traditional and modern construction practices. However, despite its widespread application, conventional cement mortar is often susceptible to durability-related problems when exposed to aggressive environmental conditions. Factors such as carbonation, chloride ion penetration, and acid attack significantly affect the long-term performance of cement-based materials. Carbonation leads to a reduction in alkalinity, which can initiate corrosion in reinforced structures. Chloride penetration is a major concern in marine and coastal environments, as it accelerates corrosion of steel reinforcement. Similarly, exposure to acidic environments, commonly found in industrial and sewage conditions, can result in chemical deterioration of the cement matrix.

The durability of cement mortar is closely related to its microstructure, particularly the pore structure and permeability. A highly porous and permeable matrix allows the easy ingress of harmful substances such as carbon dioxide, chloride ions, and sulphates. Therefore, improving the microstructure of mortar is essential for enhancing its resistance to environmental degradation and extending the service life of structures. In recent years, significant research has been directed towards the use of supplementary cementitious materials (SCMs) to improve the performance of cement-based systems. SCMs such as fly ash, silica fume, ground granulated blast furnace slag (GGBS), and metakaolin have been widely studied for their ability to enhance durability and sustainability. Among these materials, metakaolin has gained considerable attention due to its high pozzolanic reactivity and effectiveness in improving both mechanical and durability properties.

Metakaolin is produced by the calcination of kaolin clay at controlled temperatures, typically between 600°C and 800°C. It is a highly reactive aluminosilicate material that reacts with calcium hydroxide, a byproduct of cement hydration, in the presence of water. This pozzolanic reaction results in the formation of additional calcium silicate hydrate (C–S–H) gel, which is the primary compound responsible for strength in cementitious materials. The formation of additional C–S–H gel leads to a denser and more compact microstructure, thereby reducing porosity and permeability.

Metakaolin improves cement mortar by increasing compressive strength, reducing water absorption, and enhancing resistance to chloride penetration and chemical attacks such as sulphate and acid exposure. It also supports sustainable construction by lowering cement usage and associated carbon dioxide emissions.

Additionally, metakaolin refines the interfacial transition zone (ITZ), reducing porosity and microcracking while improving bonding between cement paste and aggregate, thereby enhancing overall durability.

The performance of metakaolin-modified mortar depends strongly on the replacement level. Low percentages may not fully utilize its benefits, while higher percentages can reduce workability and increase water demand. Therefore, identifying an optimum replacement level is essential to achieve a balance between strength and durability.

This study evaluates the durability of cement mortar with varying metakaolin content through tests such as acid attack, carbonation, and chloride penetration, simulating real environmental conditions. The objective is to determine the effectiveness of metakaolin and identify the optimum replacement level for producing durable and sustainable construction materials.

2. LITERATURE REVIEW

Metakaolin is a highly reactive supplementary cementitious material (SCM) derived from the calcination of kaolin clay, and it has gained significant attention in cement-based materials due to its ability to enhance durability and sustainability. Its fine particle size and high pozzolanic activity enable it to react efficiently with calcium hydroxide, leading to improved microstructural properties and long-term performance of cement mortar. In recent years, extensive research has been conducted to evaluate the effectiveness of metakaolin both as an individual additive and in combination with other supplementary materials in enhancing durability characteristics.

Studies on metakaolin-modified mortars have demonstrated notable improvements in resistance to various deterioration mechanisms. For instance, the incorporation of metakaolin in the range of 10% to 15% has been widely reported to significantly reduce chloride ion diffusion and improve microstructural densification. This enhancement is primarily attributed to the reduction of calcium hydroxide content and the formation of additional calcium silicate hydrate (C–S–H) gel, which blocks pore spaces and limits the ingress of aggressive ions. Similarly, metakaolin has been found to improve resistance to sulphate attack by reducing the formation of expansive compounds such as ettringite and gypsum, thereby minimizing cracking and expansion.

To further enhance performance, recent research has focused on optimizing metakaolin dosage and exploring synergistic effects with other materials. Studies indicate that while 15% replacement often yields optimal mechanical strength, higher replacement levels such as 20%–25% can significantly improve durability parameters like chloride penetration resistance and water permeability. Additionally, the combination of metakaolin with materials such as limestone or nano-silica has shown enhanced performance due to synergistic interactions, including the formation of carboaluminate phases and improved interfacial transition zone (ITZ) characteristics. These interactions contribute to reduced microcracking and a denser cement matrix.

Further advancements highlight the importance of curing conditions and mix design in maximizing the benefits of metakaolin. Accelerated curing regimes have been shown to enhance the pozzolanic reactivity of metakaolin, promoting rapid formation of secondary C–S–H and C–A–S–H gels. This results in improved early-age strength and durability, making metakaolin particularly suitable for fast-track construction projects. Moreover, metakaolin-modified mortars exhibit improved resistance to carbonation due to their refined pore structure and reduced calcium hydroxide content, which slows down the penetration of carbon dioxide.

Research has also emphasized the role of metakaolin in reducing permeability and enhancing long-term durability. Microstructural studies using advanced techniques have confirmed that metakaolin significantly refines pore size distribution and reduces pore connectivity, leading to lower water absorption and improved resistance to chloride ingress. These improvements are critical for extending the service life of structures exposed to aggressive environmental conditions.

Despite these advantages, certain challenges such as increased water demand and potential reduction in workability at higher replacement levels need to be carefully managed through proper mix design. However, the overall trend in research clearly indicates that metakaolin is an effective and sustainable material for improving the durability of cement mortar. This study builds upon previous findings by evaluating the durability performance of metakaolin-modified cement mortar and identifying the optimum replacement level, aiming to enhance resistance against chloride ingress, sulphate attack, acid exposure, and carbonation for long-lasting infrastructure applications.

3. MATERIALS USED

3.1 Ordinary Portland Cement (OPC)

- **Type:** 53 Grade OPC
- **Source:** Local cement supplier
- **Properties:**
- Fineness: ~320 m²/kg
- Setting Time: Initial 30 min, Final 600 min
- Specific Gravity: 3.15
- **Purpose:** Acts as the primary binder in the mortar, providing strength and durability.

3.2 Metakaolin

- **Type:** Pozzolanic material obtained by calcining kaolin clay at 650–800°C.
- **Source:** Commercially available
- **Properties:**
- Specific Gravity: 2.53
- Colour: Off-white
- Particle Size: Very fine (similar to cement)
- **Purpose:** Partial replacement of cement to improve strength, reduce permeability, enhance durability, and reduce alkali-silica reaction.

3.3 Fine Aggregate (Sand)

- **Type:** Natural river sand, clean and well-graded
- **Properties:**
- Fineness Modulus: 2.5–3.0
- Specific Gravity: 2.65
- Maximum Particle Size: 1.18 mm
- **Purpose:** Provides volume, improves workability, and ensures proper packing of the mortar matrix.

3.4 Water

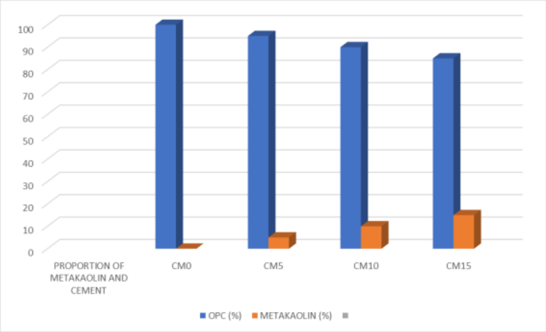
- **Type:** Potable water free from impurities
- **Properties:** pH ~7, free of suspended solids or organic matter
- **Purpose:** Hydrates the cement, initiates pozzolanic reactions of metakaolin, and improves workability.

4. METHODOLOGY

4.1 Mix Proportions

Four different mortar mixes were prepared to investigate the effect of metakaolin on durability:

- **CM0** – 0% metakaolin (control mix)
- **CM5** – 5% metakaolin replacement of cement
- **CM10** – 10% metakaolin replacement of cement
- **CM15** – 15% metakaolin replacement of cement



The replacement percentages were chosen based on previous studies suggesting that 5–15% metakaolin provides a balance between mechanical performance and durability, while minimizing negative effects on workability. The control mix (CM0) served as a baseline to compare the effects of metakaolin incorporation.

4.2 Casting of Specimens

Mortar was prepared by thoroughly mixing cement, sand, metakaolin, and water in a standardized sequence to ensure uniformity. First, dry components—cement, sand, and metakaolin—were blended to achieve a homogeneous powder mixture. Water was then added gradually while continuously mixing to obtain a consistent and workable mortar.

The fresh mortar was poured into cylindrical moulds of specified dimensions. Proper compaction was carried out using a tamping rod to remove air voids and ensure dense packing. The surface was levelled, and care was taken to avoid segregation of the mix components.

4.3 Curing

After 24 hours, the specimens were carefully demoulded. To promote complete hydration and development of microstructure, the demoulded specimens were submerged in clean water for curing. Curing was continued under controlled conditions until testing, as proper hydration is critical for achieving the desired strength, pore refinement, and durability characteristics of the metakaolin-modified mortar.

4.4 Durability Tests

The durability performance of the metakaolin-modified mortar was assessed through a series of tests designed to simulate real-world environmental conditions:

- **Acid Attack Test** – This test evaluated the resistance of the mortar to acidic environments by exposing specimens to acidic solutions over a specific period. The loss in mass and changes in compressive strength was measured to quantify the degree of deterioration.
- **Carbonation Test** – Specimens were exposed to a controlled carbon dioxide environment to determine the depth of carbonation. The test assessed the ability of metakaolin to reduce calcium hydroxide content and densify the pore structure, thereby delaying carbonation-induced strength loss and corrosion of reinforcement.
- **Chloride Penetration Test** – This test measured the ability of the mortar to resist the ingress of chloride ions, which are critical in preventing corrosion of steel reinforcement in concrete structures. Specimens were subjected to chloride solutions, and the penetration depth and diffusion coefficients were recorded to evaluate performance.

Collectively, these tests provide a comprehensive understanding of the long-term durability of metakaolin-modified mortars under aggressive environmental conditions.

5. EXPERIMENTAL PROCEDURES

The durability performance of metakaolin-modified mortar was evaluated using three key tests: acid attack, carbonation, and chloride penetration. Each test was conducted under controlled laboratory conditions to simulate real-world aggressive environments.

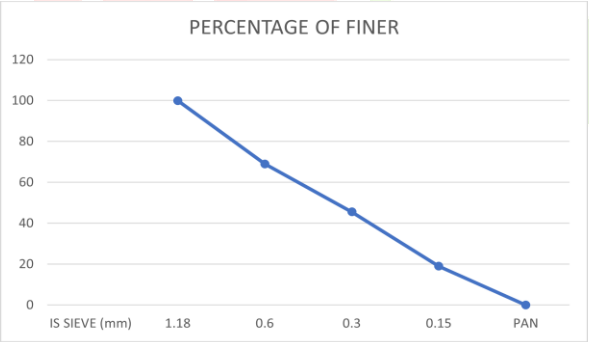
5.1 Sieve Analysis of Sand

➢ Sieve analysis was carried out to determine the particle size distribution of the fine aggregate. In this test, sand is passed through a series of standard sieves arranged in decreasing order of size.

➢ The amount of sand retained on each sieve is measured and the percentage retained is calculated. This helps determine the grading of sand. Proper grading ensures good workability and reduces segregation in mortar.

IS SIEVE	PARTICLE SIZE (mm)	MASS RETAINED	CORRECTED MEAN RETAINED	% RETAINED	CUMULATIVE % RETAINED	% FINER
1.18	1.18	50	50.316	6.32	0	100
600	0.6	195	196.23	24.68	31	69
300	0.3	185	186.17	23.41	54.417	45.583
150	0.15	210	211.32	26.58	80.997	19.003
PAN	-	150	150.94	18.98	99.977	0.023

- The grading of sand was determined from the percentage retained on each sieve.



5.2 Acid Attack Test

To assess resistance to acidic environments, the mortar specimens were immersed in a **sulfuric acid (H_2SO_4) solution** of predetermined concentration. The specimens were fully submerged to ensure uniform exposure of all surfaces.

- **Procedure:**
- Initial weights of all specimens were recorded before immersion.
- Specimens were then immersed in the acid solution for a period of four weeks, with weekly monitoring.
- Every week, specimens were removed, gently washed with distilled water, and weighed to determine the **percentage weight loss** due to acid attack.
- Any visible surface deterioration, such as scaling, pitting, or cracking, was also noted.

This test helped quantify the chemical resistance of metakaolin-modified mortars and provided insight into the role of metakaolin in reducing calcium hydroxide content, which is vulnerable to acid-induced degradation.

- The initial weights of concrete specimens (CM0, CM5, CM10, and CM15) were recorded prior to immersion in the acidic solution. The values are presented in Table 1.

	CM0	CM5	CM10	CM15
A	272	283	281.7	298.6
B	281.6	321.6	317.8	263
C	272	291	379.5	290.4
D	320.4	328.1	277	282.3
E	330.1	342.5	368.6	371.2
F	281.6	324	389.7	282.3
G	286.6	326	277.8	280.6
H	291.3	292	270	379.8

- After 1 week of immersion, a slight variation in weight was observed, indicating initial interaction between the acid and concrete matrix.

	CM0	CM5	CM10	CM15
A	280	290	285	280
B	290	330	320	290
C	280	300	385	280
D	330	335	280	330
E	340	350	370	340
F	290	335	395	290
G	295	340	280	295
H	300	300	275	300

- A noticeable reduction in weight was observed after prolonged exposure, indicating deterioration due to acid attack. Weight After 4 Weeks (g)

	CM0	CM5	CM10	CM15
A	252.9	278.6	283.4	292
B	262	295.3	319.9	255.3
C	269.1	272	378.5	292.7

D	277.9	314.9	278.1	285.6
E	294.4	326.2	367.2	370.5
F	260.8	306.2	392.7	309.4
G	260.7	267.5	278	280.2
H	256.1	301.5	271.7	376.4

- The degradation process continued with further weight loss observed across all mixes. Weight After 6 Weeks (g)

	CM0	CM5	CM10	CM15
A	243.1	268.7	276.4	282.4
B	252.6	285.1	312.7	246.1
C	257.4	262.9	371.6	284.9
D	267.8	305.6	271.5	275.8
E	281.9	316.8	359.4	360.7
F	249.1	294.2	382.9	299.8
G	248.5	255.8	268.4	272.3
H	244.2	289.7	265.3	366.1

- After 8 weeks, significant weight loss was recorded, indicating severe acid attack and material degradation.

	CM0	CM5	CM10	CM15
A	239.9	265.9	273.9	279.6
B	249.6	282.4	309.8	243.3
C	254.1	260.4	368.5	282.1
D	264.1	302.6	268.7	273
E	278.3	313.7	356.4	357.9
F	246.1	291.3	379.8	297.2
G	245.5	253.1	265.6	269.9
H	241	286.8	262.9	363.2

5.3 Carbonation Test

The carbonation test evaluated the ability of the mortar to resist **carbon dioxide (CO_2) ingress**, which can reduce alkalinity and lead to corrosion of embedded reinforcement in concrete.

- **Procedure:**
- After curing, the specimens were exposed to a controlled CO_2 environment for a set duration.
- The specimens were then split, and the freshly exposed surfaces were sprayed with **phenolphthalein indicator solution**.
- The **colour change** was observed:
  - **Pink areas** indicated non-carbonated zones (high alkalinity).
  - **Colourless areas** indicated carbonated zones (reduced pH).
- The **carbonation depth** was measured using a calliper at multiple points to obtain an average value.

This test provided an indication of the densification of the mortar microstructure due to metakaolin addition, as denser matrices reduce CO_2 diffusion and delay carbonation.

- Carbonation depth after 1 week (mm).

	CM0	CM5	CM10	CM15
A	9	6	3	4
B	8	6	3	5
C	7	5	4	5
D	7	5	4	4
E	6	4	3	5
F	8	6	4	4

- Carbonation depth after 4 weeks (mm).

	CM0	CM5	CM10	CM15
A	14	12	10	11
B	13	11	9	10
C	12	10	9	10
D	11	10	9	11
E	12	11	8	9
F	13	12	8	12

- Carbonation depth after 6 weeks (mm).

	CM0	CM5	CM10	CM15
A	16	14	12	13
B	15	13	11	12
C	14	12	11	12
D	13	12	11	13
E	14	13	10	11
F	15	14	11	14

- Carbonation depth after 8 weeks (mm).

	CM0	CM5	CM10	CM15
A	18	16	14	15
B	17	15	13	14
C	16	14	13	14
D	15	14	13	15
E	16	15	12	13
F	17	16	13	16

5.4 Chloride Penetration Test

The chloride penetration test assessed the ability of metakaolin-modified mortar to resist **chloride ion ingress**, which is critical for preventing steel reinforcement corrosion in concrete structures.

- **Procedure:**
- Mortar specimens were exposed to a **sodium chloride (NaCl) solution** for a specified duration.
- After exposure, the specimens were split, and the freshly fractured surfaces were sprayed with **silver nitrate ($AgNO_3$) solution**.
- The formation of a **white precipitate (AgCl)** indicated the presence of chlorides.
- The **depth of chloride penetration** was measured at multiple locations to obtain an average value.

This test provided insight into how metakaolin refines the pore structure, reduces permeability, and slows down chloride transport through the mortar matrix.

- Chloride depth after 1 week (mm).

	CM0	CM5	CM10	CM15
A	12	12	9.1	11.9
B	11	13	9	12
C	13	10	9.4	12.2
D	12	10	9.1	11.9
E	10	8	9.3	11.9
F	11	7	9.2	12.1

- Chloride depth after 4 weeks (mm).

	CM0	CM5	CM10	CM15
A	17	18	13	17
B	15	17	14	17
C	14	17	15	20
D	15	18	14	18
E	19	17	14	18
F	20	15	17	16

- Chloride depth after 6 weeks (mm).

	CM0	CM5	CM10	CM15
A	19	20	15	19
B	17	19	16	19
C	16	19	17	22
D	17	20	16	20
E	21	19	16	20
F	22	17	19	18

- Chloride depth after 8 weeks (mm).

	CM0	CM5	CM10	CM15
A	21	22	17	21
B	19	21	18	21
C	18	21	19	24
D	19	22	18	22
E	23	21	18	22
F	24	19	21	20

6. RESULT AND DISCUSSIONS

The durability performance of cement mortar with varying metakaolin content was evaluated through acid attack, carbonation, and chloride penetration tests. The results provide insights into how metakaolin influences the long-term behaviour of cementitious materials.

6.1 Acid Attack Results

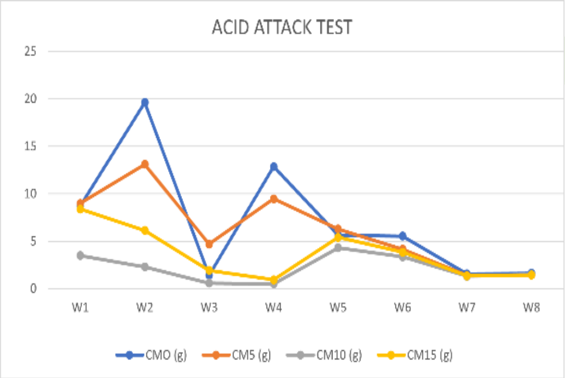
During the initial stages of immersion in sulfuric acid, specimens exhibited a slight **weight gain** due to the absorption of the acidic solution into the porous mortar matrix. However, with prolonged exposure, chemical reactions between the acid and calcium hydroxide in the cement paste led to the **dissolution of $Ca(OH)_2$ and formation of soluble salts**, causing **weight loss and surface degradation**.

- The **control mix (CM0)** showed the **highest deterioration**, with visible surface scaling and significant weight loss, indicating poor resistance to acid attack.

- The incorporation of metakaolin improved chemical resistance, with **CM5, CM10, and CM15** showing progressively lower weight loss.
- Among the tested mixes, **CM10 exhibited the least weight loss**, highlighting that a 10% replacement of cement with metakaolin optimally enhances resistance by reducing free calcium hydroxide and densifying the microstructure.

The improvement in acid resistance is attributed to the **pozzolanic reaction of metakaolin**, which consumes CH and generates additional C–S–H gel, leading to a more compact matrix that resists acid penetration.

WEEK	CMO (g)	CM5 (g)	CM10 (g)	CM15 (g)
W1	8.7	8.98	3.49	8.38
W2	19.63	13.1	2.29	6.14
W3	1.4	4.7	0.588	1.93
W4	12.86	9.46	0.51	0.93
W5	5.64	6.28	4.3	5.4
W6	5.53	4.15	3.36	3.85
W7	1.55	1.39	1.31	1.34
W8	1.63	1.43	1.5	1.44
TOTAL WEIGHT LOSSS	48.24	40.51	13.55	21.35



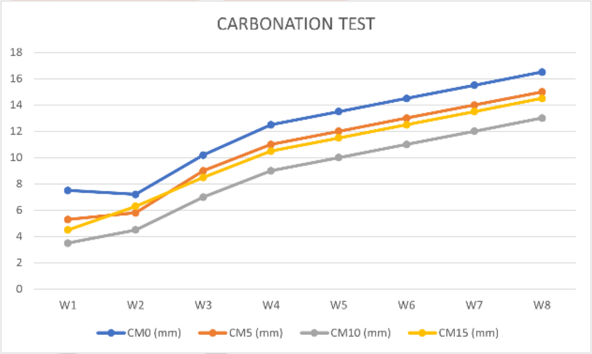
6.2 Carbonation Results

Carbonation depth increased for all mixes over time due to **diffusion of carbon dioxide** into the mortar matrix, which reacts with calcium hydroxide to form calcium carbonate, lowering the alkalinity.

- Metakaolin incorporation significantly **reduced carbonation depth** in all modified mixes compared to the control.
- **CM10 exhibited the lowest carbonation depth**, indicating superior resistance.
- The reduced depth is a result of the **densified pore structure** and **lower calcium hydroxide content** in metakaolin mixes, which slows down CO_2 diffusion and delays the carbonation process.

This demonstrates that metakaolin not only improves mechanical properties but also enhances the durability of cement mortar against environmental degradation processes like carbonation.

WEEK	CM0 (mm)	CM5 (mm)	CM10 (mm)	CM15 (mm)
W1	7.5	5.3	3.5	4.5
W2	7.2	5.8	4.5	6.3
W3	10.2	9	7	8.5
W4	12.5	11	9	10.5
W5	13.5	12	10	11.5
W6	14.5	13	11	12.5
W7	15.5	14	12	13.5
W8	16.5	15	13	14.5



6.3 Chloride Penetration Results

The **penetration of chloride ions** increased with exposure time for all specimens, simulating the risk of corrosion in reinforced structures.

- The addition of metakaolin significantly **reduced chloride penetration depth** in comparison to the control mix.
- The **CM10 mix showed the best performance**, with the shallowest chloride ingress.
- This improvement is attributed to **refined pore structure, reduced connectivity, and increased tortuosity**, which limit ion transport and enhance resistance to chloride-induced deterioration.

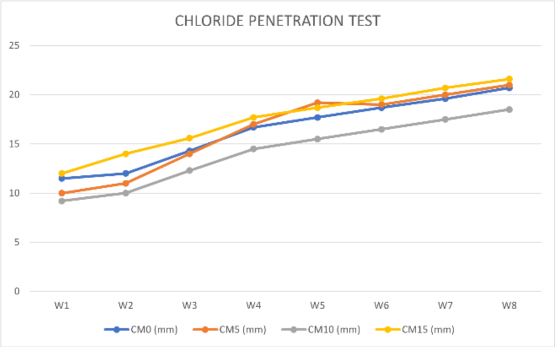
The results confirm that metakaolin effectively enhances the durability of cement mortar in chloride-rich environments by limiting permeability and strengthening the microstructure.

6.4 Overall Analysis

The overall findings clearly indicate that **metakaolin substantially improves the durability of cement mortar** by:

- Densifying the microstructure and refining pore distribution
- Reducing permeability and transport of aggressive ions
- Enhancing chemical resistance against acid and sulphate attacks
- Delaying carbonation and chloride penetration

WEEK	CM0 (g)	CM5 (g)	CM10 (g)	CM15 (g)
W1	11.5	10	9.2	12
W2	12	11	10	14
W3	14.3	14	12.3	15.6
W4	16.7	17	14.5	17.7
W5	17.7	19.2	15.5	18.7
W6	18.7	19	16.5	19.6
W7	19.6	20	17.5	20.7
W8	20.7	21	18.5	21.6



Among the tested replacement levels, 10% metakaolin (CM10) consistently provided the optimal balance between durability enhancement and workability. Higher replacement (CM15) showed slight improvements but may require adjustments in water content due to increased fineness. These results align with previous studies, confirming that metakaolin is a highly effective supplementary cementitious material for producing durable and sustainable cement-based systems. Its incorporation can significantly extend the service life of mortar and concrete structures exposed to harsh environmental conditions.

7 CONCLUSION

The present study demonstrates that incorporating metakaolin as a partial cement replacement significantly improves the durability performance of cement mortar. Experimental results from acid attack, carbonation, and chloride penetration tests confirm that metakaolin-modified mortars exhibit superior resistance to chemical deterioration and environmental degradation compared to conventional mixes.

Key conclusions include:

- **Enhanced Durability:** Metakaolin improves the overall durability of cement mortar by refining the pore structure, reducing permeability, and densifying the microstructure. This leads to reduced ingress of aggressive ions and gases, thereby enhancing resistance to **acid attack, carbonation, and chloride penetration**.

- **Optimal Replacement Level:** Among the replacement levels studied, **10% metakaolin** was identified as the optimal dosage. At this level, the mortar achieved the best balance between durability enhancement, workability, and mechanical performance. Lower replacement levels did not fully exploit the benefits of pozzolanic activity, while higher levels could increase water demand and reduce workability.

- **Microstructural Improvements:** The pozzolanic reaction of metakaolin with calcium hydroxide generates additional C–S–H gel, which densifies the cement matrix and strengthens the interfacial transition zone (ITZ). These microstructural improvements contribute directly to reduced microcracking, improved bonding, and better long-term performance of the mortar.

- **Sustainability Contribution:** Incorporating metakaolin reduces the amount of ordinary Portland cement required, thereby lowering CO_2 emissions associated with cement production. This highlights the dual benefit of metakaolin: improving durability while promoting sustainable construction practices.

Overall, the findings of this study confirm that **metakaolin is an effective supplementary cementitious material** for producing durable, long-lasting, and environmentally friendly mortar. Its proper incorporation in mix design can significantly extend the service life of structures and contribute to the development of resilient and sustainable infrastructure systems.

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