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Effects of Partial Replacement of Cement with Metakaolin on the Compressive Strength of Concrete Cured in Sodium Chloride Solution

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Abstract

The production of cement contributes significantly to carbon dioxide emissions, creating a need for sustainable alternatives such as metakaolin. This study investigated the effects of partial cement replacement with metakaolin and sodium chloride solution curing on the workability and compressive strength of concrete designed to achieve Grade 30 at 28 days. Cement was partially replaced with metakaolin at 0%, 5%, 10%, 15%, 20%, and 25% by mass. A mix ratio of 1:1.75:2.75, and a water-to-binder ratio of 0.45 were adopted. Workability was assessed using the slump test, while compressive strength was determined at 7, 28, and 56 days. Specimens were cured in normal water and a 3.5% sodium chloride solution. 39% reduction in slump were observed for the control mixture at 25% metakaolin replacement, indicating reduced workability at higher replacement levels. The 10% metakaolin blended concrete recorded the highest compressive strength of 35.2 MPa when cured in ordinary water and 35.8 MPa when cured in sodium chloride solution at 28 days and increases significantly to 56 days. These results exceeded the target strength of 30 MPa. The sodium chloride curing effect accelerate early strength. The findings revealed that 10% metakaolin replacement provides a suitable balance between workability and compressive strength under the investigated conditions. Thus, reduces the cement usage, environmental pollution from cement factory and production cost of cement.

1.0 INTRODUCTION

Concrete remains a fundamental material in civil engineering because of its high compressive strength, versatility, availability, and ability to be molded into different structural forms (1), (2). It is widely used in the construction of buildings, bridges, roads, dams, foundations, and other infrastructure. However, conventional concrete production depends heavily on ordinary Portland cement (OPC), whose manufacture requires substantial energy and releases significant quantities of carbon dioxide (2), (3), (4). The environmental consequences of cement production have encouraged researchers to investigate supplementary cementitious materials that can reduce cement consumption without compromising concrete performance (5). Metakaolin has attracted considerable attention because of its pozzolanic reactivity and potential to improve the mechanical and durability properties of concrete (6). Concrete performance depends on the quality and proportions of its constituent materials, the water-to-cement ratio, mixing procedures, compaction, and curing conditions. Among its mechanical properties, compressive strength is particularly important because it influences the load-bearing capacity and structural design of concrete members (7). Concrete strength develops through cement hydration, which produces binding compounds that connect aggregate particles and progressively strengthen the hardened matrix. Inadequate curing, excessive water content, unsuitable aggregates, and aggressive environmental exposure can interfere with this process (6), (7). Consequently, investigating alternative cementitious materials alongside different curing environments can provide useful information for improving concrete performance and developing appropriate construction practices. One promising approach to reducing cement consumption involves the incorporation of metakaolin as a partial replacement for cement. Metakaolin is a highly reactive aluminosilicate material produced by the controlled thermal treatment of kaolinite-rich clay (6), (7). Heating kaolin clay under suitable conditions

removes chemically bound water and transforms its crystalline structure into a more reactive, disordered form. When incorporated into concrete, metakaolin reacts with calcium hydroxide released during cement hydration to produce additional calcium silicate hydrate (C–S–H) and calcium aluminosilicate hydrate compounds. These products can contribute to matrix densification, reduce pore connectivity, and improve the bonding between cement paste and aggregates (6), (8). The effectiveness of metakaolin, however, depends on its chemical composition, fineness, replacement percentage, and the characteristics of the original cement and concrete mixture. Experimental investigations have demonstrated that metakaolin can improve concrete strength when used at an appropriate replacement level. Research on high-strength concrete has examined metakaolin as a partial alternative to cement, while broader reviews have assessed its influence on fresh properties, mechanical performance, microstructure, and durability (7), (9). Other studies have investigated metakaolin-based concrete under different exposure conditions, including elevated temperatures and chloride-rich environments (10), (11). These investigations indicate that metakaolin can enhance concrete performance, although the magnitude of improvement varies with the mixture composition and curing regime. The benefits of metakaolin do not necessarily increase with every additional percentage of cement replacement. At moderate replacement levels, its fine particles can improve particle packing, while its pozzolanic reaction contributes additional binding products. At excessive replacement levels, however, the reduction in available Portland cement may limit the production of primary hydration products. Metakaolin can also increase water demand because of its fine particle size and high surface area. These effects make it necessary to establish an appropriate replacement level through laboratory testing rather than assuming that higher metakaolin content will always produce stronger concrete. Recent research continues to examine its optimum dosage, strength development, and influence on concrete durability (12), (13). Curing is another critical factor in the development of concrete strength. It maintains the moisture and temperature conditions required for cement hydration and helps prevent premature moisture loss. Water curing is commonly adopted in laboratory investigations because it provides a controlled environment for strength development. Nevertheless, concrete structures may encounter water containing dissolved salts, particularly in coastal regions, marine environments, and locations affected by saline groundwater. Sodium chloride (NaCl), the principal salt in many saline solutions, can influence cement hydration and the behaviour of hardened concrete. Its effects depend on the concentration of the solution, duration of exposure, concrete composition, and whether the salt is present during mixing or introduced during curing.

Research on seawater and sodium chloride in cement-based materials has reported changes in hydration reactions and early-age strength development. Chloride ions can accelerate certain hydration processes under particular conditions and influence the formation of chloride-bearing hydration products. However, these effects do not establish that saline water will consistently improve the long-term performance of concrete (14). An experimental investigation of concrete containing sodium chloride also reported that increasing the salt content under sealed-curing conditions could reduce early-age compressive strength, demonstrating that the response depends on the curing environment and hydration mechanisms (15). The distinction between saline mixing water and saline curing water is

particularly important. When sodium chloride solution serves as mixing water, chloride ions are introduced throughout the fresh concrete and may influence cement hydration from the beginning. When concrete is initially produced with ordinary water and subsequently cured in sodium chloride solution, the salt enters primarily through exposure at the concrete surface and may progressively penetrate the hardened material. These two procedures represent different experimental conditions and should not be treated as equivalent. Studies investigating concrete mixed and cured with seawater have reported variations in workability, setting behaviour, and compressive strength, with the results depending on the combination of mixing and curing conditions (16). Research on seawater concrete has also examined its early-age mechanical response and deformation behaviour (17). Although sodium chloride can influence hydration and strength development, chloride exposure also raises durability concerns, especially for reinforced concrete. Chloride ions that penetrate concrete can reach embedded steel reinforcement, destabilise its protective passive layer, and initiate corrosion when the necessary environmental conditions are present. Corrosion products occupy a greater volume than the original steel, potentially causing cracking, delamination, and loss of reinforcement cross-section. Metakaolin may help reduce these risks by refining the pore structure and improving resistance to chloride transport. Research on metakaolin-modified concrete has reported improvements in chloride resistance and electrical resistivity, while investigations of nano-metakaolin have examined its potential to reduce chloride diffusion in cement-based materials (11), (18). The combined use of metakaolin and sodium chloride curing solution therefore presents an important research question. Metakaolin may improve the density and strength of the concrete matrix, while sodium chloride exposure may alter hydration behaviour and introduce chloride ions into the hardened concrete. The resulting compressive strength will depend on the interaction between these factors, alongside the water-to-cement ratio, metakaolin replacement percentage, curing duration, and age at testing. Studies on metakaolin concrete have examined strength and chloride penetration separately, but the performance of concrete containing different metakaolin replacement levels and subsequently cured in controlled sodium chloride solutions requires specific experimental evaluation (12), (19). The broader literature also identifies continuing research needs concerning the relationship between metakaolin content, microstructure, strength, and durability (20). This study therefore investigates the effects of partial cement replacement with metakaolin and sodium chloride solution as curing water on the compressive strength of concrete. It will examine the relevant physical and chemical properties of metakaolin, establish the influence of selected replacement levels, and compare the strength development of concrete specimens cured in sodium chloride solution with those cured in ordinary water. Compressive strength testing at specified curing ages will provide a basis for evaluating the effects of metakaolin content and saline exposure. The findings are expected to clarify whether metakaolin can improve strength under saline curing conditions and identify mixture combinations that offer satisfactory mechanical performance. The results may also provide useful experimental evidence for assessing concrete applications in environments where saline water exposure is a practical concern.

2.0 MATERIALS AND METHODS

The various materials, laboratory apparatuses and experiments used in this study are explained in this section.

2.1 Materials

The materials used in this study include metakaolin, sodium chloride (NaCl), Dangote 3X Ordinary Portland Cement (OPC) of strength class 42.5, fine aggregate, coarse aggregate, and clean potable water.

2.1.1 Metakaolin

Metakaolin shown in Fig. 1 is a reactive aluminosilicate material obtained by controlled calcination of kaolinite-rich clay. It is used as a supplementary cementitious material because its reaction with calcium hydroxide produced during cement hydration can generate additional cementitious compounds. These reactions can improve concrete strength, refine its pore structure, and enhance resistance to chloride penetration when an appropriate replacement level is used (21), (22). In this study, metakaolin with a particle size below 90 μm was used to replace cement at 0%, 5%, 10%, 15%, 20%, and 25% by mass. The 0% mixture served as the control. The reported chemical composition and physical properties of the metakaolin are presented in Tables 1 and 2, respectively.

Table 1
Chemical Composition of Metakaolin

Chemical composition	**Reported content (%)**
Silicon dioxide (SiO_2)	50–55
Aluminium oxide (Al_2O_3)	38–42
Calcium oxide (CaO)	1–3
Titanium dioxide (TiO_2)	0.8–1.2
Sodium oxide (Na_2O)	Less than 1
Iron(III) oxide (Fe_2O_3)	0.2–0.5
Potassium oxide (K_2O)	Less than 1
Manganese oxide (MnO)	Less than 0.5
Magnesium oxide (MgO)	Less than 0.1
Loss on ignition (LOI)	Maximum 1.5

Table 2
Physical Properties of Metakaolin

Property	Value
Particle size	Less than 90 μm
Bulk density (g/cm³)	0.5461 (packed condition)
Colour	White
Specific gravity	2.30

2.1.2 Sodium Chloride Solution (Saline Water)

Sodium chloride solution is prepared by dissolving sodium chloride (NaCl) in water. The salt dissociates into sodium ions (Na^+) and chloride ions (Cl^-), which can influence cement hydration and the properties of hardened cement-based materials. Experimental research has shown that sodium chloride and seawater can alter cement hydration, pore structure, and early-age strength development (23). In this study, a sodium chloride solution with a concentration of 3.5% was used as curing water to simulate saline exposure. The solution concentration was maintained throughout the experimental programme. Concrete specimens cured in the saline solution were compared with those cured in ordinary water to determine the influence of saline curing on compressive strength.

2.1.3 Cement

Cement is a hydraulic binding material that reacts with water to form compounds responsible for binding aggregates and developing concrete strength. Ordinary Portland cement (OPC) was used as the primary binder in this study. Dangote 3X cement of strength class 42.5 was used throughout the experimental programme. The cement served as the main binding material, while metakaolin replaced 0%, 5%, 10%, 15%, 20%, and 25% of the cement by mass. The cement type was kept constant across the mixtures to support a consistent comparison of the effects of metakaolin replacement and curing conditions. Cement classification and conformity requirements are covered by BS EN 197-1 (24).

2.1.4 Aggregates (Fine and Coarse)

Aggregates are granular materials that form the major portion of concrete. They contribute to strength, dimensional stability, and durability. Their grading, particle shape, surface texture, and cleanliness influence the workability and mechanical properties of concrete. The selection and quality assessment of aggregates for concrete are addressed by BS EN 12620 (25). The fine aggregate used in this study was sharp sand, while the coarse aggregate consisted of crushed granite with a nominal size of 12.5 mm (½ inch). Both aggregates were used in preparing the concrete mixtures. They were selected to provide the granular framework required for the production of concrete specimens.

2.1.5 Water

Clean potable water was used for mixing the concrete to minimize the risk of impurities interfering with cement hydration and the experimental results. The suitability of water for concrete mixing is addressed by BS EN 1008 (26).

2.2 Methods

The concrete mix was designed to achieve a target characteristic compressive strength of 30 MPa at 28 days (Grade 30). A mix ratio of 1:1.75:2.75 (cementitious binder: fine aggregate: coarse aggregate) and a water-to-binder ratio of 0.45 were adopted. Metakaolin replaced cement at 0%, 5%, 10%, 15%, 20%, and 25% by mass. The 28-day compressive strength test was conducted to determine whether the concrete achieved the target Grade 30 strength. For a 150 mm concrete cube, with a volume of 0.003375 m^3, the calculated quantities are presented in Table 3 below

Table 3
Material Quantities for One 150 mm Concrete Cube

Metakaolin replacement	Cement (kg)	Metakaolin (kg)	Sand (kg)	Granite (kg)	Water (litres)
0%	1.3500	0.0000	2.3625	3.7125	0.6075
5%	1.2825	0.0675	2.3625	3.7125	0.6075
10%	1.2150	0.1350	2.3625	3.7125	0.6075
15%	1.1475	0.2025	2.3625	3.7125	0.6075
20%	1.0800	0.2700	2.3625	3.7125	0.6075
25%	1.0125	0.3375	2.3625	3.7125	0.6075

2.2.1 Preparation and Curing of Concrete Specimens

The cement and metakaolin were blended to obtain a uniform binder. The fine and coarse aggregates were then added and mixed thoroughly before the measured mixing water was introduced. Mixing continued until a homogeneous concrete mixture was obtained. The fresh concrete was tested for workability in accordance with (27) as shown in Fig. 2. The concrete was subsequently placed into lubricated steel moulds measuring 150 × 150 × 150 mm and compacted uniformly to minimize entrapped air. After approximately 24 hours, the specimens were demolded and assigned to two curing conditions: ordinary water curing and sodium chloride solution curing. The water-cured specimens served as the reference group, while the saline-cured specimens were immersed in a 3.5% sodium chloride solution. The solution was prepared by dissolving 35 g of sodium chloride in water and making up the final volume to one liter. The solution concentration was maintained throughout the curing period to facilitate comparison of concrete strength under ordinary and saline curing conditions.

2.2.2 Compressive Strength Test

The compressive strength test was conducted in accordance with (28) at 7, 28, and 56 days. For each metakaolin replacement level, three replicate cubes were tested at each curing age under both curing conditions. The experimental programme comprised 108 concrete cubes, calculated from six metakaolin replacement levels, two curing conditions, three testing ages, and three replicates. The compressive strength results were used to evaluate strength development and determine whether the concrete achieved the target Grade 30 strength at 28 days.

3.0 RESULTS AND DISCUSSION

The various results obtained from this work are presented and discussed in this section.

3.1 Slump Test Results of Concrete Containing Metakaolin

The slump figure shown in Fig. 3 decreased progressively as the metakaolin replacement level increased. The control mix recorded a slump difference of 85 mm, whereas the 25% metakaolin mixture recorded 52 mm. This reduction is attributed to the fine particle size and relatively high surface area of metakaolin, which can increase water demand and reduce the water available for lubrication. The trend suggests that increasing metakaolin content will reduce the workability of fresh concrete at a constant water-to-binder ratio.

3.2 Compressive Strength under Ordinary Water Curing

The compressive strength increased with metakaolin replacement up to 10%, after which a gradual reduction was observed. At 28 days, the 10% mixture in Fig. 4 below recorded the highest strength of 35.2 MPa, compared with 31.5 MPa for the control, representing an increase of approximately 11.7%. This improvement is associated with the filler effect of metakaolin and its pozzolanic reaction, which will contribute to a denser cementitious matrix. At replacement levels above 10%, the reduction in cement content may have outweighed the benefits of metakaolin, resulting in lower strength.

Strength also increased between 28 and 56 days across all mixtures. This development reflects continued cement hydration and pozzolanic reactions. However, the 25% mixture recorded only 28.6 MPa at 28 days, below the 30 MPa target, indicating that a high replacement level will compromise the required strength.

3.3 Compressive Strength under 3.5% Sodium Chloride Solution Curing

The compressive strength under sodium chloride solution curing followed a similar pattern to that observed under ordinary water curing. The 10% metakaolin mixture achieved the highest 28-day strength of 35.8 MPa as shown in Table 4, while the control recorded 32.0 MPa. The strength of the 10% mixture increased further to 39.0 MPa at 56 days, suggesting continued strength development. The higher values

in the saline-cured group is associated with changes in early cement hydration in the presence of chloride ions. However, sodium chloride curing does not necessarily improve concrete strength or durability in every situation. Chloride exposure may also increase the risk of reinforcement corrosion in reinforced concrete.

Table 4
Compressive Strength of Concrete under NaCl Solution Curing

Metakaolin replacement (%)	7 days (MPa)	28 days (MPa)	56 days (MPa)
0	22.2	32.0	34.5
5	23.4	33.7	36.8
10	24.8	35.8	39.0
15	24.0	34.5	37.8
20	22.1	32.2	35.4
25	19.7	29.0	32.0

The 28-day results indicate that the control, 5%, 10%, 15%, and 20% mixtures exceeded the target compressive strength of 30 MPa under ordinary water curing. Under sodium chloride solution curing, the control and mixtures containing 5–20% metakaolin also exceeded 30 MPa. The 25% mixture recorded 28.6 MPa under water curing and 29.0 MPa under saline curing, both below the target. Overall, the results suggest that 10% metakaolin may be the optimum replacement level for compressive strength development among the mixtures considered.

4.0 CONCLUSION

This study evaluated the effects of partial cement replacement with metakaolin and sodium chloride solution curing on the compressive strength of concrete designed to achieve Grade 30 at 28 days. The slump results indicated a progressive reduction in workability as metakaolin content increased from 0% to 25%, with slump decreasing from 85 mm to 52 mm. This reduction may be attributed to the high surface area of metakaolin and its increased water demand. The compressive strength results indicated that 10% metakaolin replacement produced the highest strength under both normal water curing and 3.5% sodium chloride solution curing. At 28 days, the respective strengths were 35.2 MPa and 35.8 MPa, exceeding the target strength of 30 MPa. However, strength declined at replacement levels above 10%, suggesting that excessive cement replacement may reduce the benefits of metakaolin. Strength development continued up to 56 days across the mixtures. Overall, 10% metakaolin appears to be the most effective replacement level among those investigated. Nevertheless, the influence of saline curing and the suitability of the mixtures for structural applications should be confirmed using verified experimental results and appropriate durability assessments.

Declarations

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Declaration of Artificial Intelligence (AI) Assistance

The authors confirm that they have not used generative AI or AI-assisted technology in the preparation of this manuscript, either during writing or editing. The authors take full responsibility for the content's originality, interpretation and accuracy.

Research Ethics:

No human or animal subject is involved

Ethics Approval and Consent to Participate:

Informed consent was obtained from all individuals involved in the study. All human-related procedures were performed in accordance with institutional guidelines.

Consent for Publication:

Informed consent was obtained from all participants involved in the study.

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Author Contribution

O. A. Olaniyi: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. A.K. Oyelami: Supervision, Conceptualization, Writing – original draft, Writing – review & editing.A. P. Adewuyi: Writing – review & editing. J.O. Ogunmodede: Methodology, Writing – original draft.

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Data Availability:

All data generated or analysed during this study are included in this published article.

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Figures



Figure 1

Metakaolin



Figure 2

Workability test (Slump)

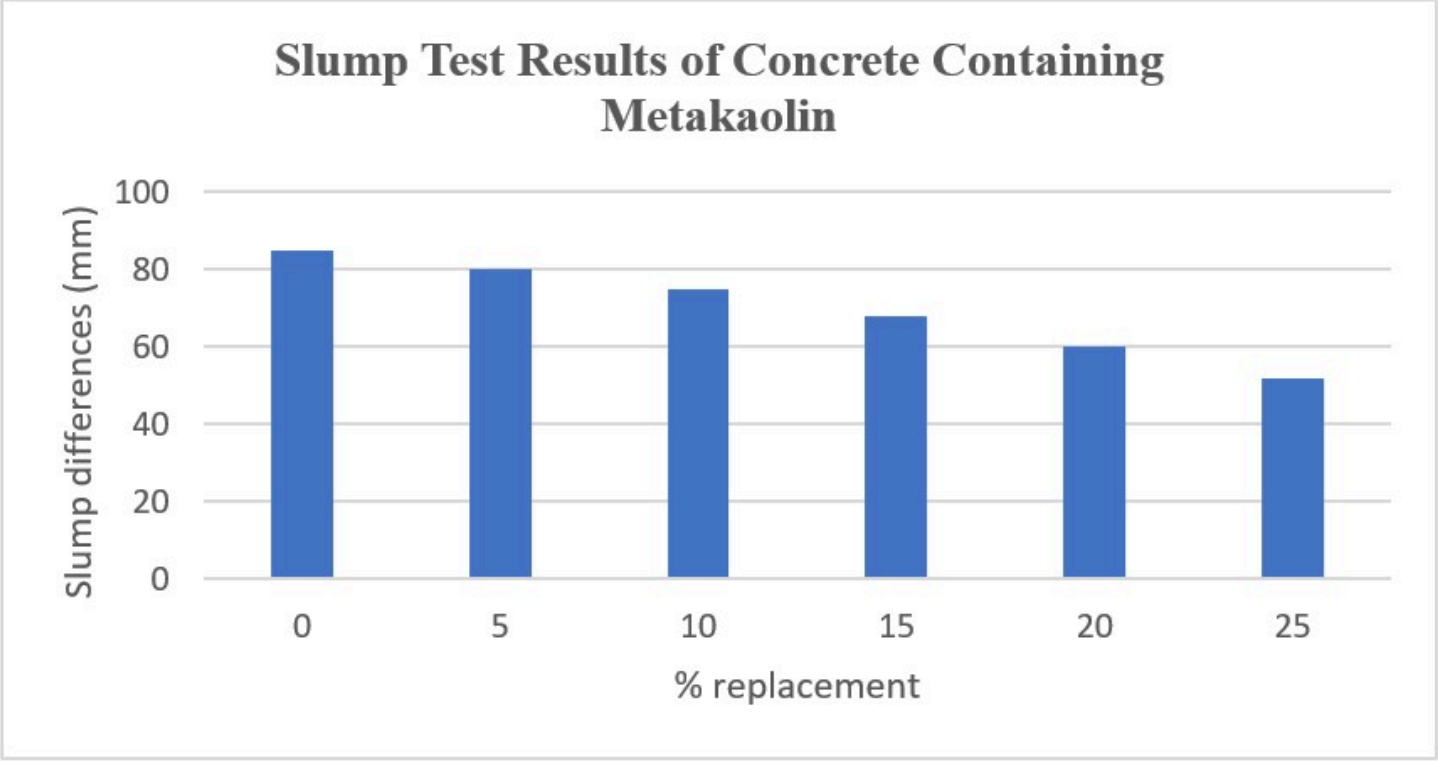

Figure 3

Slump Test Results of Concrete Containing Metakaolin

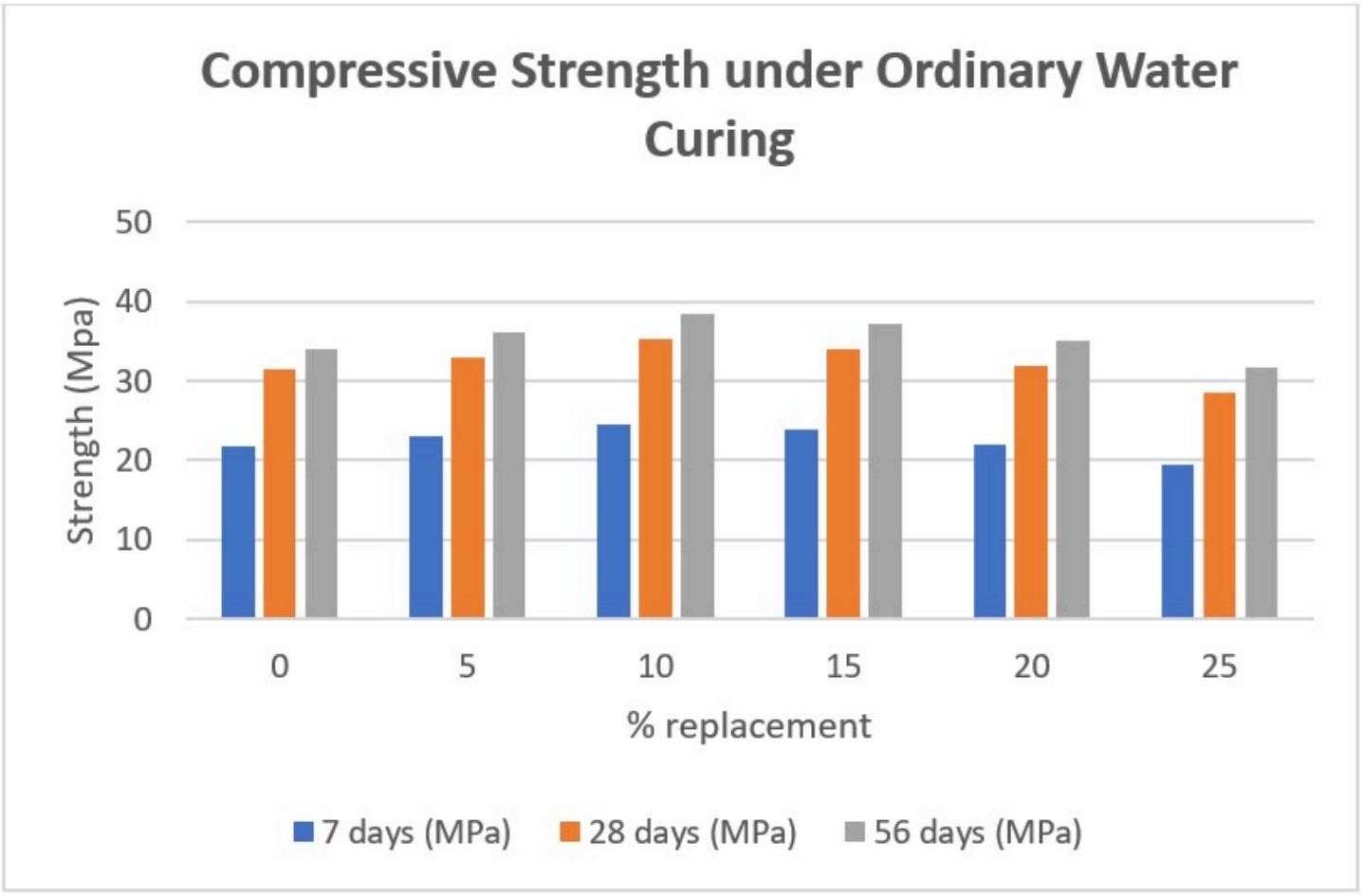

Figure 4

Compressive Strength under Ordinary Water Curing