HIGH PERFORMANCE CONCRETE; METAKAOLIN

Investigating the Effect of Metakaolin on the Flow, Compressive Strength and Water Absorption of High Performance Concrete

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Abstract

High performance concrete (HPC) requires high binder contents, thereby increasing cost and CO_2 emissions. Metakaolin (MK) from locally available kaolin is a promising partial cement replacement, but its interaction with superplasticiser, water-cement ratio and aggregate-cement proportions in Portland-limestone cement HPC has not been fully investigated. This study examined the combined effect of five mix variables on the fresh, mechanical and durability properties of MK-HPC and identified mixes balancing flow, strength and impermeability. A five-factor, five-level central composite design (60 runs) varied MK (5-15% cement replacement), PCE superplasticiser (1.00-1.20%), water-cement ratio (0.31-0.35), coarse to fine aggregate ratio (0.60-1.00) and cement to fine aggregate ratio (1.10-1.50), using cement and metakaolin. Slump flow, 28-day compressive strength and water absorption of HPC were determined. The results revealed that slump flow ranged from 665 to 730 mm, placing every mix within EFNARC class SF2. Compressive strength ranged from 20.9 to 55.3 MPa, while water absorption value ranges from 0.09-1.17%. Concrete specimen that had 28 days compressive strength above 55 N/mm^2 was achieved by mixes containing (MK= 10-12.5%, SP = 1.1-1.15%, W/C = 0.32-0.33, CA = 0.9-1.0, CE = 1.3-1.4).

Keywords: central composite design; compressive strength; high-performance concrete; metakaolin; polycarboxylate superplasticizer

1 Introduction

1.1 Background to study

Concrete remains the principal material for buildings, bridges, pavements and drainage works because it can be produced from local materials and cast into varied forms (Tiza et al., 2024). Modern structures are expected to carry higher loads and last longer, which has increased demand for high-performance concrete (HPC), a concrete designed for improved strength, particle packing and controlled fresh behavior (Dushimimana et al., 2021). HPC typically combines a low water–cement ratio, good aggregates, sufficient binder and a high-range water-reducing admixture (Chahar and Pal, 2023). Raising cement content alone is costly and increases carbon dioxide emissions, so recent work has focused on supplementary cementitious materials (SCMs) that partly replace cement while maintaining or improving strength (Agboola et al., 2024; Akinpelu et al., 2024).

Metakaolin (MK) is produced by calcining kaolin clay, during which kaolinite dehydroxylates into a reactive amorphous aluminosilicate (Zunino and Scrivener, 2024). MK is commonly calcined between 600 and 900 °C, and its reactivity depends on the source of clay, calcination temperatures, time, and

conditions (Akinpelu et al., 2024). In concrete, MK consumes calcium hydroxide released by cement hydration and forms additional C–S–H and C–A–S–H gels that densify the matrix and strengthen the paste–aggregate interface (Sun et al., 2021; Abiodun et al., 2023). MK fineness provides a filler effect in concrete, although the fineness also increases water demand in HPC which can affect workability by reducing flow as MK replacement increases (Agboola et al., 2024). For the aforementioned reason, superplasticizers are usually added to HPC mix to improve flow dut to MK fineness, and low water-cement ratio. Polycarboxylate-ether (PCE) superplasticizers, a special tupe of superplasticizer has been used in various studies, and it is known to disperse particles randomly through electrostatic repulsion and steric hindrance, making it suitable for use in MK-modified HPC (Aïtcin and Flatt, 2015), since increase in MK substitution of cement increases superplasticizer demand due of MK's high surface area (Zaribaf et al., 2015).

The role of MK in HPC is random, as replacement levels varies with respect to the strength properties expected in various concrete mix. It is therefore insufficient to state that MK improves concrete; the optimum level and its interaction with water–cement ratio, admixture dosage and aggregate–cement proportions must be established. Many Nigerian and international studies have reported improved compressive, flexural and split-tensile strength with MK, but most address conventional concrete, mortar, sandcrete or geopolymers, often at a single water–cement ratio and using one-factor-at-a-time designs (Khatib and Clay, 2004; Shah et al., 2022; Abiodun et al., 2023; Agboola et al., 2024). Without information on the combined effect of MK content, PCE dosage, water–cement ratio and aggregate and cement proportions on low-water–cement HPC, mix selection falls back on trial-and-error batching that wastes material and gives inconsistent results. The research gap addressed here is the lack of a focused, and planned HPC study that combines MK, superplasticizer, low water–cement ratios, aggregate, and cement proportions in one CCD programme, in order to determine its flow, 28-day compressive strength and water absorption.

2 Materials and methods

2.1 Materials

The materials used in this work includes cement, water, fine aggregate, coarse aggregate, Metakaolin (MK), and superplasticizer.

Portland-limestone cement, grade 42.5N (Dangote 3X, CEM II/B-L), was the primary binder. Kaolin clay was calcined at 850 °C for 2 hours, it was then cooled, ground and sieved to a fine powder to produce metakaolin (MK). Also, the fine aggregate used was a clean natural sand, and coarse aggregate was crushed granite of maximum nominal size not exceeding 10 mm; both were washed and air-dried before batching. Clean potable water obtained from Baze University, Abuja was used for mixing and curing. The superplasticizer was Hydroplast 520GR, a PCE-based high-range water-reducing and slump-retaining admixture (density 1.10 ± 0.01 g/cm^3, pH 4 ± 1; recommended dosage 0.8–1.2% of cementitious material), which conforms to ASTM-C494 (2017) type F standard specification for chemical admixtures for concrete.

The constituent materials were tested before mixing (Table 1). Cement was tested for consistency, setting times, soundness and specific gravity; aggregates for specific gravity, bulk density and fineness modulus, with coarse aggregate additionally tested for aggregate crushing and impact values; and MK for specific gravity and specific surface.

2.2 Tests on materials

Table 1. Tests on cement, aggregates and metakaolin (MK).

Material	Tests	Standard
Cement	Consistency, initial/final setting time, soundness, specific gravity	BS-EN-196-3 (2016)
Fine and coarse aggregate	Specific gravity, bulk density	BS-812:2 (1995); BS-EN:12620 (2013)
Coarse aggregate	Aggregate crushing value, aggregate impact value	BS-812:2 (1995); BS-EN:12620 (2013); BS-812-110 (1990)
Metakaolin	Specific gravity, specific surface	BS-812:2 (1995); BS-EN:196-6 (2018)
Aggregates	Gradation of aggregates	ASTM-C33 (2018)

2.3 Design of experiment

Concrete mixes were designed in Design-Expert using a Central Composite Design (CCD), with five numeric factors, five levels each ($-\alpha$, -1, 0, $+1$, $+\alpha$; $\alpha = 2$) and a total of 60 runs. The factors were MK content (A), superplasticizer dosage (B), water–cement ratio (C), coarse aggregate to fine aggregate ratio (D) and cement to fine aggregate ratio (E) (Table 2).

Table 2. CCD factor levels.

Factor	Name (unit)	$-\alpha$	-1	0	$+1$	$+\alpha$
A	Metakaolin (% cement replacement)	5	7.5	10	12.5	15
B	Superplasticizer (% by mass of cement)	1.00	1.05	1.10	1.15	1.20
C	Water–cement ratio	0.31	0.32	0.33	0.34	0.35
D	Coarse aggregate – fine aggregate ratio	0.60	0.70	0.80	0.90	1.00
E	Cement- fine aggregate ratio	1.10	1.20	1.30	1.40	1.50

2.4 Tests on concrete

2.4.1 Slump flow test

This was done in accordance with BS-EN-12350-8 (2019). The slump of the concrete was measured by taking the average diameter of the spread in two perpendicular directions, with the aid of a measuring tape, and the mean value was obtained and compared to EFNARC (2005).

2.4.2 Compressive strength test

The compressive strength test of the hardened concrete cubes was determined after the required curing days of 28 days in accordance with BS-EN-12390-3 (2009).

2.4.3 Water absorption

Water absorption test was carried out to determine the level or rate at which concrete specimens absorbs/retains water in it. This test was done in accordance with BS-EN-206 (2013).

3 Results and discussion

3.1 Test results of materials

The results from Table 3 shows that the cement (consistency 29%, initial setting time 168 minutes, final setting time 245 minutes, soundness 0.5 mm, and specific gravity 3.14) all met British Standard (BS) code requirements. Also, the fine aggregate specific gravity (2.68), and bulk density (1480 kg/m^3) are within values recommended by BS-812:2 (1995). The coarse aggregate specific gravity, bulk density, aggregate crushing value, and aggregate impact values are 2.65, 1280 kg/m^3, 27.5%, and 26.88% respectively, and in-line with BS-812:2 (1995), and BS-812-110 (1990), making it suitable for concrete production. The MK has a specific surface of 23500, and specific gravity of 2.53, consistent with typical MK values of about 2.5-2.6 reported in literature (Siddique and Klaus, 2009; Rao and Raja, 2017; Harikaran et al., 2023).

Table 3. Physical and mechanical properties of the materials.

Description of Test	Results	Standard	Code
Cement			
Consistency (%)	29.0	26-33%	BS-EN-196-3 (2016)
Initial setting time (mins)	168	60	BS-EN-196-3 (2016)
Final setting time (mins)	245	600	BS-EN-196-3 (2016)
Soundness (mm)	0.5	10mm	BS-EN-196-3 (2016)
Specific gravity	3.14	3.1 – 3.16	BS-EN-196-3 (2016)
Fine Aggregates			
Specific Gravity	2.68	2.5 – 2.8	BS-812:2 (1995)
Bulk density	1480	<1520	BS-812:2 (1995)
Coarse Aggregate			
Specific gravity	2.65	2.5 – 2.8	BS-812:2 (1995)
Bulk density	1280	<1520	BS-812:2 (1995)
Fineness modulus	7.53	mm	BS-EN:12620 (2013)
Aggregate Crushing Value	27.5	25 – 30%	BS-812-110 (1990)
Aggregate Impact Value	26.88	25 – 30%	BS-812-110 (1990)
MK			
Specific Gravity	2.53		BS-812:2 (1995)
Specific surface (m^2/kg)	23500		BS-EN:196-6 (2018)

3.2 Gradation of fine and coarse aggregate

Figure 1 shows the particle size analysis of the fine and coarse aggregate. The fine aggregate grading complied with ASTM-C33 (2018). This shows that the fine aggregate is suitable for use in concrete production, and is in agreement with the studies of Mubaraki et al. (2019); Morales Fournier et al. (2020). Also, the coarse aggregate used in this study was uniformly graded from 6.3 - 10mm sized aggregate.

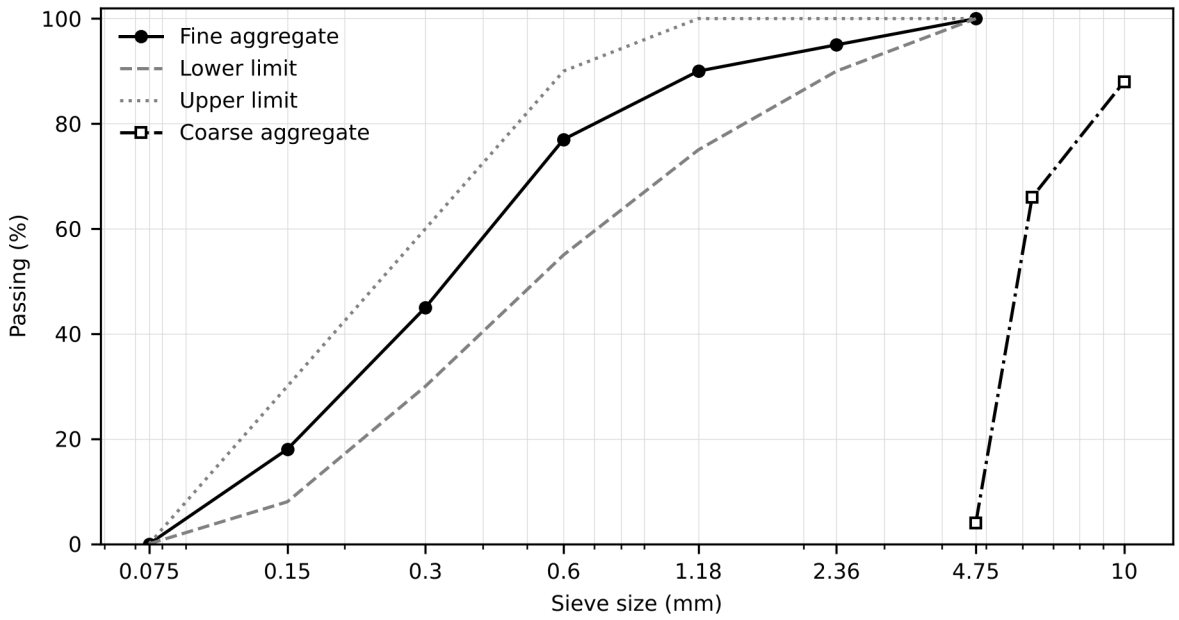


Figure 1. Gradation of the fine and coarse aggregate.

3.3 Properties of high performance concrete

There were 60 runs in the DoE, and the strength on the concrete varied from normal to intermediate, to high performance concrete. Hence, the analysis was done to split the strength into their various classes. For MK concrete compressive strength <40, between 40-50, and >50 N/mm^2, the data were split into 40.0, 50.0, and 10.0% respectively.

3.3.1 Normal strength concrete (< 40 N/mm²)

The slump flow results from Figure 2 shows that the slump values ranges from approximately 665 mm to 730 mm, and the highest slump flow values, approximately 725-730 mm, were obtained from mixes containing 10-12.5% metakaolin, 1.1-1.15% superplasticizer, and low water-cement ratios of 0.32-0.33, demonstrating that the superplasticizer dosage was sufficient to offset the increased water demand associated with metakaolin. On the other hand, the mix with 7.5% MK, 1.15% SP, W/C = 0.34, CA = 0.7, and CE = 1.4 showed the lowest slump flow value of about 665 mm. Because the application of superplasticizer preserved the intended flow characteristics despite the finer particle size and larger surface area of the mineral admixture, this demonstrates that the addition of metakaolin did not negatively impact workability. The rules of the European Federation of National Associations Representing for Concrete (EFNARC) classify self-compacting concrete into three slump-flow classes: SF1 (550-650 mm), SF2 (660-750 mm), and SF3 (760-850 mm). As a result, every observed slump flow measurement falls between 660 and 750 mm, which is the SF2 categorization, which is the recommended range for structural concrete involving normal reinforcement congestion (EFNARC, 2005).

Additionally, all of the concrete mix combinations showed extremely low absorption values, ranging about from 0.09% to 1.17%, according to the water absorption results from Figure 2, indicating a dense and impermeable concrete microstructure. Only two blends had greater water absorption rates of roughly 1.10% and 1.17%, whereas the majority of the mixes had values below 0.50%. The inclusion of metakaolin, a highly reactive pozzolanic substance that refines the pore structure by generating more calcium silicate hydrate (C-S-H) gel and decreasing pore connectivity, is responsible

for the generally poor absorption. Furthermore, the low water-cement ratios (0.31-0.34) and the use of superplasticizer enhanced particle packing and reduced capillary voids, thereby limiting water penetration.

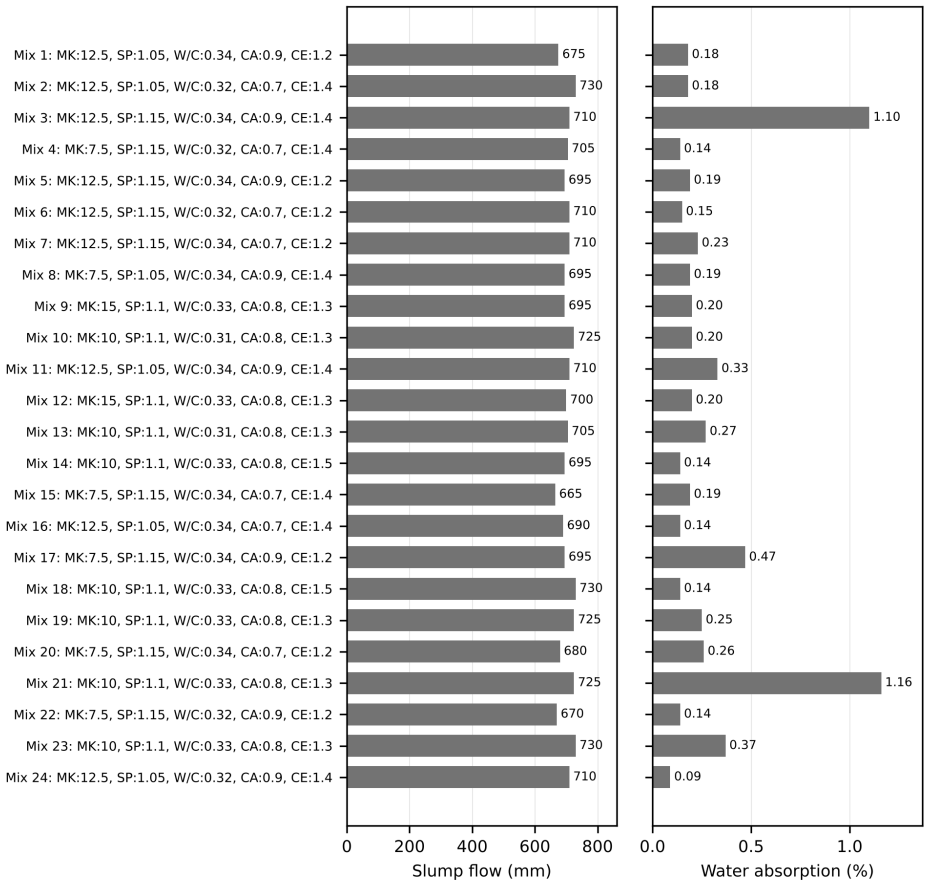


Figure 2. Slump flow and water absorption of MK concrete (< 40 N/mm^2).

According to Figure 3's results, compressive strength values range from roughly 20.9 to 39 N/mm^2. When MK concentrations rose to 12.5% and 15%, compressive strength typically reduced to values between 21 and 33 N/mm^2, suggesting that excessive replacement may have decreased the amount of available cementitious material needed for strength development. Similarly, because lower water content reduces capillary porosity and improves matrix densification, mixes with lower W/C ratios (0.31–0.33) often obtained better strengths than those with a W/C ratio of 0.34. While larger SP concentrations did not consistently improve performance, the SP dosage of 1.1% seemed to be the most beneficial since it offered adequate workability while retaining strength. Additionally, the ideal cement and aggregate ratios (CA = 0.8 and CE = 1.3) probably improved particle packing and decreased voids in the concrete matrix. The mix having 10% MK, 1.1% SP, W/C = 0.33, CA = 0.8, and CE = 1.3 produced the highest compressive strength of 39 N/mm^2, indicating that this combination offered the best compromise between binder reactivity, workability, and particle packing. The pozzolanic reaction of metakaolin, which consumes calcium hydroxide and generates more C-S-H gel, is responsible for the enhanced performance at 10% MK. This leads to a denser cement matrix and a stronger interfacial transition zone (Jing et al., 2023; Elsebaei et al., 2025).

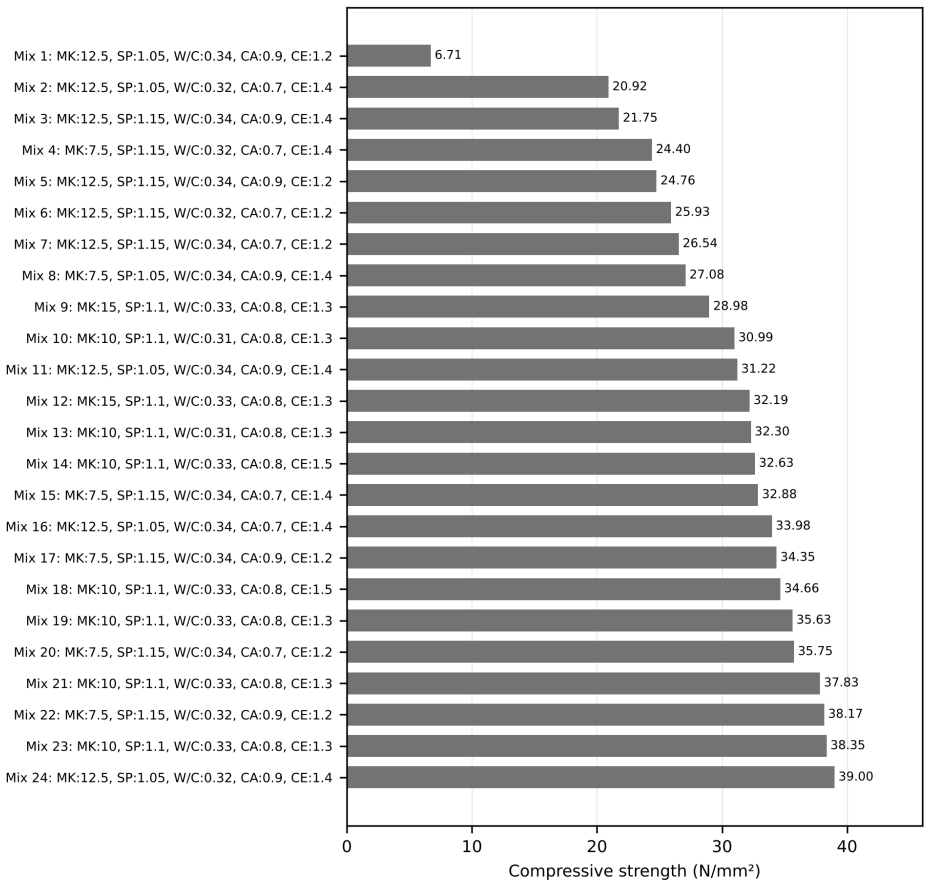


Figure 3. Compressive strength of MK concrete (< 40 N/mm^2).

3.3.2 Intermediate strength concrete (40–50 N/mm²)

The slump flow results from Figure 4 (expressed as ×1000 mm), ranged from approximately 0.665 to 0.730 m (665-730 mm), indicating consistently high workability across all HPC mixtures. The majority of the mixes recorded slump flows between 0.690 and 0.725 m, demonstrating that the incorporation of metakaolin and superplasticizer successfully maintained the self-compacting properties of the concrete despite the low water-cement ratios (0.31-0.35). All the tested mixtures therefore fall within the SF2 classification, which is recommended for most structural applications requiring good filling ability and passing ability through reinforcement (EFNARC, 2005).

Also from Figure 4, the water absorption ranges from approximately 0.09% to 1.17%, indicating the production of a dense and highly impermeable concrete matrix. Most of the mixtures exhibited water absorption values below 0.50%, while only a few mixes recorded values exceeding 1.0%. Since all the tested mixtures recorded absorption values are low (<3%), the results indicate excellent resistance to water ingress and suggest a high level of durability.

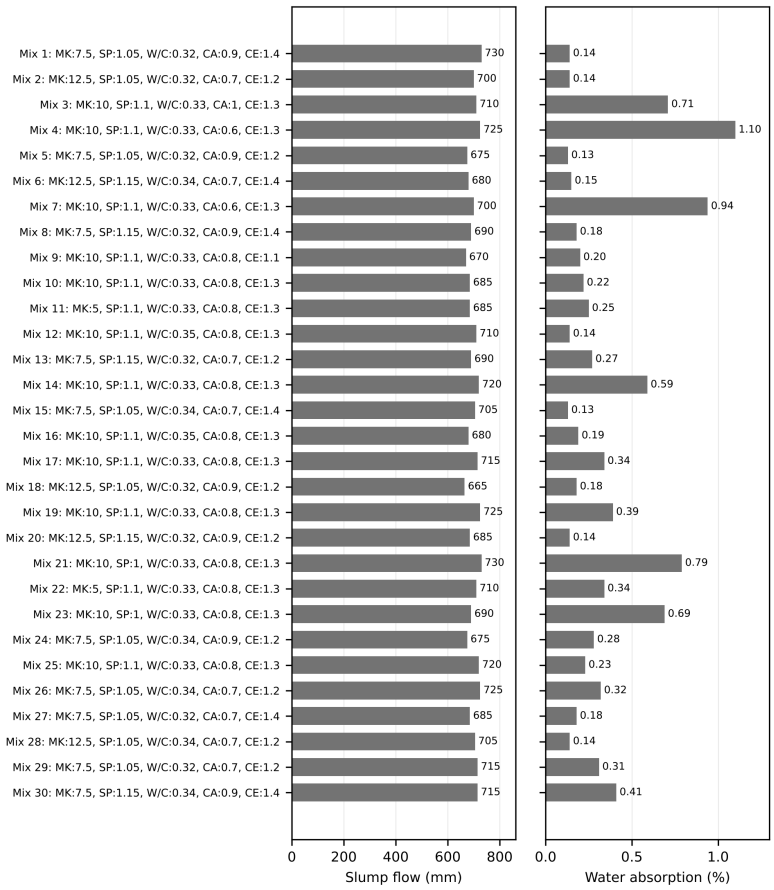


Figure 4. Slump flow and water absorption of MK concrete (40–50 N/mm^2).

The compressive strength results from Figure 5 shows that the highest compressive strengths approaching 49-50 N/mm^2 were obtained from mixes containing 7.5-10% MK, 1.05-1.10% SP, and a relatively low W/C ratio of 0.32-0.34, suggesting that these combinations promoted the formation of a dense and well-compacted cementitious matrix. Similarly, superplasticizer dosages between 1.05% and 1.10% likely improved particle dispersion and workability without increasing water demand, leading to better compaction and strength. Variations in coarse aggregate and cement ratios also influenced performance, with mixes containing coarse aggregate (CA) values between 0.7 and 0.8 and cement (CE) values between 1.2 and 1.4 generally achieving the highest strengths due to improved aggregate-paste balance and packing density.

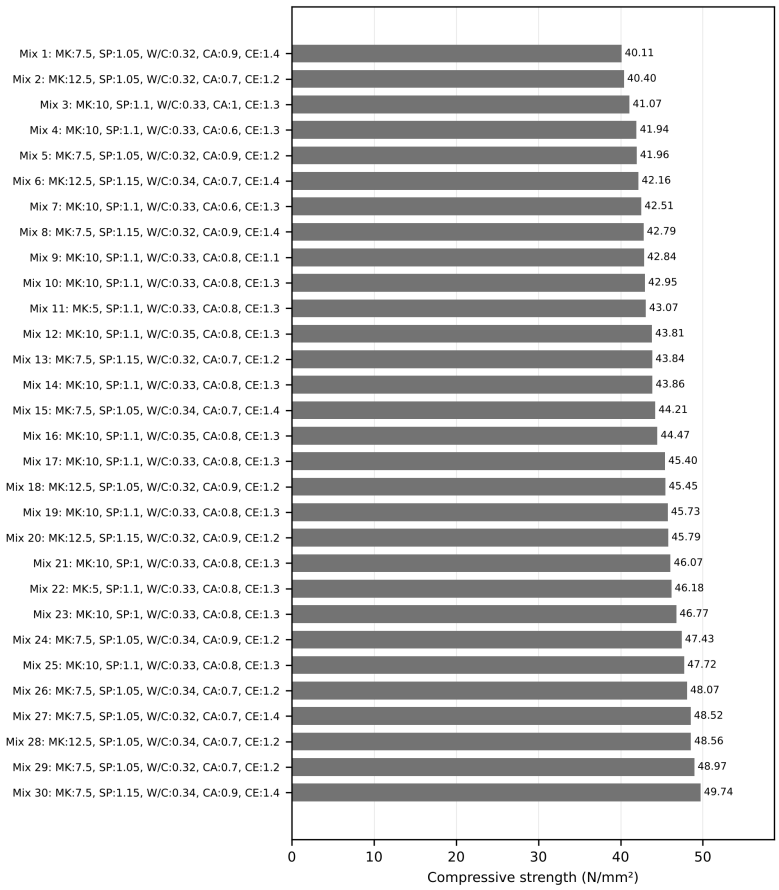


Figure 5. Compressive strength of MK concrete (40–50 N/mm^2).

3.3.3 High performance concrete (> 50 N/mm^2)

The slump flow results from Figure 6 ranged from 0.665 to 0.730 m (665-730 mm), indicating good flowability and self-compacting characteristics. The highest slump flow of 730 mm was recorded for the mix containing 10% MK, 1.1% SP, W/C = 0.33, CA = 0.8, and CE = 1.1, while the lowest value of 665 mm was obtained for the mix containing 10% MK, 1.2% SP, W/C = 0.33, CA = 0.8, and CE = 1.3. The EFNARC SF2 slump-flow class (660-750 mm) is the suggested range for the majority of reinforced structural concrete applications, and all of the mixes fell within this range despite these variances (EFNARC, 2005). The results showed that the use of MK (10-12.5%), SP (1.1-1.2%), and a low water-cement ratios (0.32-0.33) were adequate in improving workability of the mix. The outcome of these findings indicate that the superplasticizer improved the mix, despite the MK fineness (Table 3) that lead to water demand, thereby maintaining flow and maintaining the fresh properties of the HPC.

Also from Figure 6, the water absorption results ranged from 0.10% to 0.36%, which is an indication of low permeability as a result of highly dense concrete microstructure. At 10% MK, 1.2% SP, W/C = 0.33, CA = 0.8, and CE = 1.3 the water absorption was 0.10% which was the lowest, while at 10% MK, 1.1% SP, W/C = 0.33, CA = 1.0, and CE = 1.3 the highest water absorption obtained was 0.36%. These values are low compared to commonly accepted limit of 3- 5% threshold generally regarded as acceptable for durable structural concrete. The low absorption values can as a result of the the pozzolanic activity of metakaolin, which refines pore structure through the formation of C-S-H gel, and also as a result of low water-cement ratios that minimized capillary porosity (Arslan et al., 2020) in the HPC. The outcome of this study indicates that the HPC are dense and impermeable, making it

highly resistant to water ingress. Also, the excellent slump range (665-730mm) and low water absorption (0.10-0.36%) is indicative that the HPC exhibits adequate workability and excellent durability.

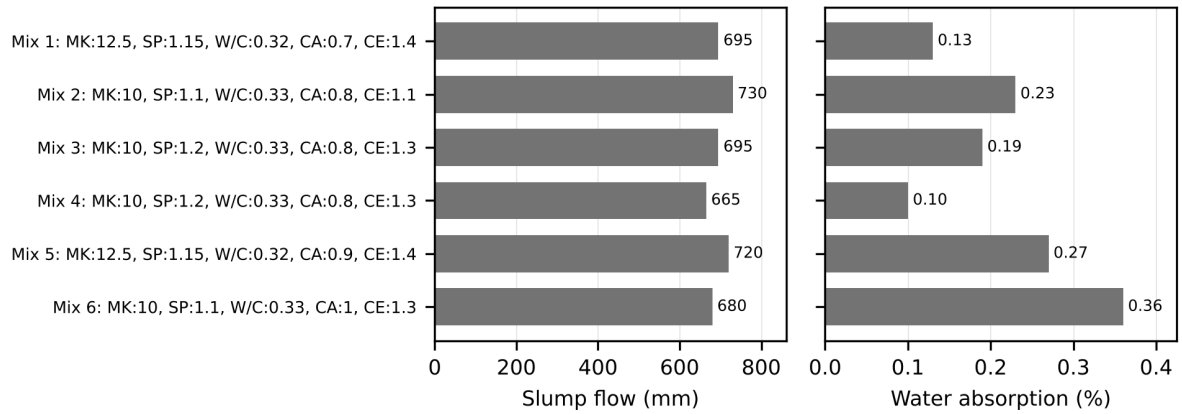


Figure 6. Slump flow and water absorption of MK concrete (> 50 N/mm^2).

The results from Figure 7 shows that all the HPC had compressive strengths from 50.1 and 55.3 N/mm^2, making it a medium-strength to high-strength concrete (>55 N/mm^2). The HPC strength of 50.1 N/mm^2 was achieved for the mix containing 12.5% MK, 1.15% SP, W/C = 0.32, CA = 0.7, and CE = 1.4, while the highest strength of approximately 55.3 N/mm^2 was achieved by mixes containing 12.5% MK, 1.15% SP, W/C = 0.32, CA = 0.9, CE = 1.4 and 10% MK, 1.1% SP, W/C = 0.33, CA = 1.0, CE = 1.3. The results suggest that metakaolin contents between 10 and 12.5% were effective in enhancing compressive strength at low water-cement ratios (i.e. 0.32-0.33). Furthermore, the use of superplasticizer dosages between 1.1 and 1.15% likely improved particle dispersion and workability, enabling adequate compaction without increasing water demand. The influence of aggregate proportion is also evident, as mixes with higher coarse aggregate ratios (CA = 0.9-1.0) generally produced greater strengths than those with CA = 0.7-0.8, suggesting improved load transfer and aggregate interlock.

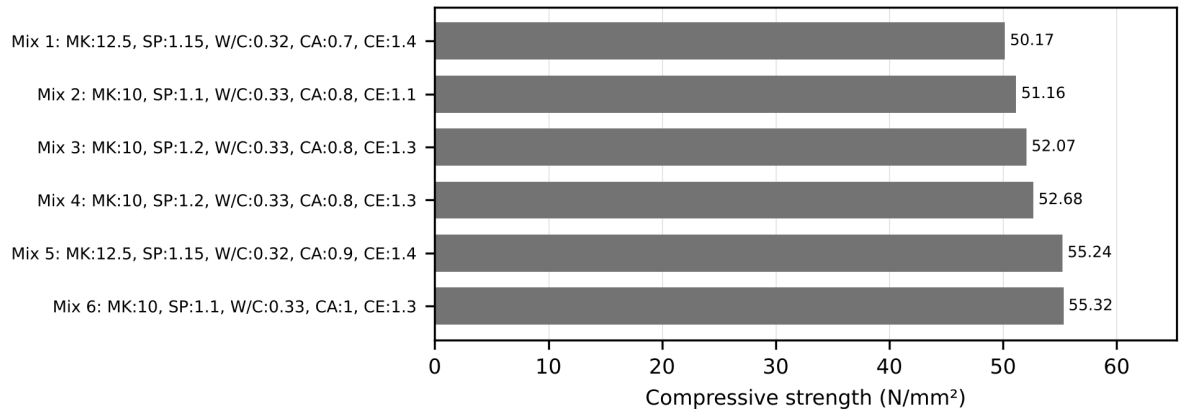


Figure 7. Compressive strength of MK concrete (> 50 N/mm^2).

4 Conclusions

Based on the outcome of findings from this study, it was concluded that the cement, aggregates and MK were suitable for high performance concrete production, and all the concrete mixes achieved

slump flow of 665-730 mm, which makes it suitable for use in concrete. Also, the 28-day strength ranged from 20.9 to 55.3 N/mm^2, and mixes that had 28 days strength above 55 N/mm^2 was achieved by mixes containing (MK= 10-12.5%, SP = 1.1-1.15%, W/C = 0.32-0.33, CA = 0.9-1.0, CE = 1.3-1.4). The results suggest that metakaolin contents between 10 and 12.5% were effective in enhancing compressive strength at low water-cement ratios (i.e. 0.32-0.33), coarse to fine aggregate ratio (0.9-1.0), and cement to fine aggregate ratio (1.3-1.4). Furthermore, the water absorption was 0.09-1.17% (0.10-0.36% above 50 N/mm^2), indicating a dense, durable matrix, whereas the slump and water absorption of mixes that had 28 days strength above 55 N/mm^2 ranges from 680-720mm, and 0.27-0.36% respectively.

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