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Influence of Metakaolin on the Engineering Properties of Self-Compacting Concrete.

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Abstract

This research studied the effects of Metakaolin pozzolan on the engineering properties of self-compacting concrete (SCC) in which Complast sp40 was used as a superplasticizer. Laboratory tests were conducted on the Metakaolin and the aggregates to determine their properties. Different fine aggregate / coarse aggregate (FA/CA) mix proportions for SCC with a target strength of 35 N/mm² were used to produce concrete cube specimens of sizes 150mm x 150mm x 150mm by mixing the aggregates, water, complast sp40 and partially replacing cement with 0%, 5%, 10%, and 15% metakaolin. The fresh concrete for each batch was tested for workability using slump test. The concrete cubes prepared were cured in water for 28, 60 and 90 days, after which the density and the compressive strength of the hardened concrete were determined. The slump test results showed a decrease in the workability of fresh concrete as the percentage Metakaolin increases. The results showed a reduction in the density of concrete as Metakaolin content in concrete increases. It was observed from the results that the compressive strength of the concrete increases as the curing age increased from 28 to 90 days. Aggregate proportioning significantly impacted strength, with optimal fine aggregate to coarse aggregate (FA/CA) ratios of 0.45/0.55 yielding the highest strength for all curing ages. 10% Metakaolin replacement level exhibited the highest strength compared to 5% and 15% replacement levels.

Keywords: Compressive strength; Self-compacting concrete; Metakaolin; Pozzolan; Aggregates.

1. Introduction

Concrete is probably the most widely used material in the construction of infrastructures in the world (Anya et.al., 2024). Also, modern Civil Engineering construction tends to progress towards more economic, design and construction of structures through gradually improved methods of design and the use of higher strength materials (Gana and Okoye, 2015). One constituent of concrete that determines its strength is coarse aggregate, which takes about 50 and 60 percent of the concrete volume depending on the mix proportion adopted (Onyechere et.al., 2021). Several studies and research have been done and are still in progress on the effect of aggregate shape, type and size on the strength properties of concrete (Eme and Nwaobakata 2019). Structures constructed with normal-strength concrete mostly fail in compression by separation of the aggregates when excessive load is exerted on them, but in high-strength concrete structures, there is higher bonding force between the aggregates and the binding agent so that under the action of very high compressive loads, the structure does not fail.

Self-compacting concrete (SCC) being a high-performance concrete has the ability to flow under the influence its self-weight to fill the form without segregating even in a concrete section with congested reinforcements and compacts itself without the help of a mechanical vibrator. Concrete of such a model enhances its placement and compaction, thus reducing the labour cost for placement, compaction, reducing the environmental pollution caused during concreting and producing hardened concrete with better finishes. SCC is recommended for mass concreting and while casting concrete in sections with some restrictions and insufficient work area for compaction hence, enabling the engineer to

sufficiently satisfy the specifications of a given project. The main features of SCC include; ability of the fresh concrete to flow easily under its own weight in sections with highly congested reinforcements without requiring vibration and being able to maintain the uninformed homogenous nature of the concrete without segregation. To successfully produce a self-compacting concrete, water reducers are employed to lower the yield stress to a level to accommodate the free-flowing features of the concrete, thereby striking a balance between yield stress and the flowability of the concrete paste (Shetty, 2005). Aggregate gradation is a very important part of concrete production hence the need to combine coarse aggregate with fine aggregate in its simplest form. An improperly graded aggregate structure can have undesirable effects on the properties of concrete as it can produce weak, stiff or porous concrete (Ukala, 2019). The techniques employed in the batching of self-compacting concrete include using less portions of coarse aggregates and using larger portions of fillers or employing concrete admixtures to modify the viscosity of the concrete produced so as to easily fill the formworks without segregation and sufficiently compact itself without requiring any mechanical compactor (Promsawat et.al. 2020). Among the several important factors that influence the proportions of the constituents of a concrete mixture is the grading of the aggregate. It is well known that aggregate grading directly influences concrete mix proportions and that satisfactory concrete can be produced with aggregates whose grading does not fall entirely within normal specifications or conform to typical grading curves. In developing countries, such aggregates are often the only ones locally available or within economic distance, and the concrete manufacturer has no choice

but to select the most suitable mix proportions. Since more than one-third of concrete volume is occupied by coarse aggregate, variations in the proportioning of coarse aggregates will affect the strength and shear properties of the concrete (Rozalija and Darwin 1997).

According to Dinakar, Pradosh and Sriram (2013), From the previous studies, it can be noted that concrete strength depends upon the water-cement ratio and the materials used that are used other than the conventional materials such as cement, fine aggregate, coarse aggregate, and water (Li et.al., 2020). Most studies are basically on aggregate gradation effect on workability with little focus on the extensive influence of alternating the fine and coarse aggregate proportion.

Furthermore, the manufacturing of high-strength and performance concrete is somewhat different from conventional concrete preparation by utilizing additional materials such as mineral and chemical admixtures and use of techniques like re-vibration and seeding (Samimi et.al., (2017). Supplementary materials such as mineral admixtures or burnt ash or calcined kaolin etc. are added. For maintaining such quality in the HPC and HSC, many pieces of research are carrying out throughout the world (Priya, and Raja, 2021).

On the other hand, Among the components of concrete, the aggregate accounts for approximately 60–70% of the total volume of concrete; thus, it has a significant impact on concrete properties. In general, concrete aggregate can be classified as fine aggregate (FA) or coarse aggregate (CA). The workability and mechanical properties of concrete vary depending on the physical properties and mix proportions of the different aggregates. In some regions, three or more types of aggregates are used because of the quality characteristics of the aggregates produced in those regions. As the number of aggregates used in a concrete-mix increases, the influences of each aggregate on the properties of the concrete become increasingly complicated. Therefore, to optimize the basic properties of concrete, including workability and strength, significant attention needs to be paid to the proportions of aggregates used in the concrete mix (Lee, et.al, 2021).

In general, the properties of an aggregate that affect the strength of concrete include the strength, shape, surface texture, maximum size, and particle size of the aggregate (Alexander and Mindess, 2005). It is notable that the compressive strength of concrete depends on the water-to-cement ratio, degree of compaction, ratio of cement to aggregate, bond between mortar and aggregate, and grading, shape, strength and size of the aggregate (Rocco and Elices, 2009). Concrete can be visualized as a multi-phase

composite material made up of three phases; namely the mortar, mortar/aggregate interface, and the coarse aggregate phase. The coarse aggregate in normal concrete are mainly from rock fragments characterized by high strength. The aggregate interface is not a limiting factor governing the strength requirement (Beshr, Almusallam, and Maslehuddin 2003). The onset of failure is manifested by crack growth in the concrete. For normal concrete the crack growth is mainly around the cement paste or at the aggregate/cement paste interfacial zone. The strength of concrete at the interfacial zone essentially depends on the integrity of the cement paste and the proportioning of the aggregate.

The main constituents of SCC include; coarse aggregates (mainly within size range of 10 – 20mm, though sometimes, bigger sizes could be used if the reinforcements in the sections are not congested), fine aggregates (containing more of fines), Ordinary Portland Cement (grade 43 – 53), Potable water, chemical

admixtures (superplasticizers are used to contribute the required workability and viscosity of the fresh concrete without segregation) and mineral admixtures which enhances the quality of the concrete and makes the concrete more durable (Shetty, 2005).

Therefore, this research studied the effects of Metakaolin pozzolan on the engineering properties of self-compacting concrete produced using a chemical admixture (Complast sp40) as a superplasticizer. The Kaolin was obtained from a natural deposit and then converted to Metakaolin by calcining the kaolin within a temperature range of 4000C to 8000C under a controlled supply of oxygen.

2. Materials and Methods

The Kaolin was obtained from a natural deposit and first raised to a temperature of about 4000C, thereafter, it was grinded and was heated further continuously to a temperature of 8000C using logs of piled up woods in a furnace for about nine to ten hours. The fine calcinated kaolin was placed inside a stainless-steel basin and the top was covered with another second stainless-steel basin. An infrared thermometer was used to monitor the temperature of the heated calcinated kaolin, the colour of the calcinated kaolin was observed to change from white to a cementitious colour at 800 degrees Celsius. Heating was stopped and the calcinated kaolin was allowed to gradually cool to room temperature.

Sieve analysis was carried out on both the fine and coarse aggregates used, in accordance with the recommendations of BS 812: Part103.1:1985 to determine their grain size distribution. Specific Gravity and Bulk Density tests were conducted on the aggregates following the recommendations of ASTM C127-07, 2007.

The physical properties of the Metakaolin were determined using the procedures prescribed by ASTM C618-15, (2015). X-ray diffraction method was used for the chemical analysis of the Metakaolin to determine its chemical compositions.

Concrete mixes were prepared for concrete grade 35 using the various combinations of different proportions of coarse aggregate (CA) and fine aggregate (FA) shown in Table 1. Where; “C” designates control samples at 0% Metakaolin, “N1” designates samples at 5% replacement of cement with Metakaolin, “N2” designates samples at 10% replacement of cement with Metakaolin, and “N3” designates samples at 15% replacement of cement with Metakaolin.

Table 1: Mix Combination at Different aggregate volume ratios

MN	W/C	C	Aggregate volume ratio			FA ratio	CA ratio
			Total VA	CA	FA		
C ₁₁	0.65	1	0.704	0.4020	0.3020	0.65	0.55
C ₁₂	0.65	1	0.704	0.4020	0.3020	0.60	0.40
C ₁₃	0.65	1	0.704	0.4020	0.3020	0.55	0.45
C ₁₄	0.65	1	0.704	0.4020	0.3020	0.50	0.50
C ₁₅	0.65	1	0.704	0.4020	0.3020	0.45	0.55
N ₁₁	0.64	1	0.716	0.4654	0.2506	0.65	0.55
N ₁₂	0.64	1	0.716	0.4654	0.2506	0.60	0.40
N ₁₃	0.64	1	0.716	0.4654	0.2506	0.55	0.45
N ₁₄	0.64	1	0.716	0.4654	0.2506	0.50	0.50
N ₁₅	0.64	1	0.716	0.4654	0.2506	0.45	0.55
N ₂₁	0.63	1	0.719	0.4674	0.2517	0.65	0.55
N ₂₂	0.63	1	0.719	0.4674	0.2517	0.60	0.40
N ₂₃	0.63	1	0.719	0.4674	0.2517	0.55	0.45

N ₂₄	0.63	1	0.719	0.4674	0.2517	0.50	0.50
N ₂₅	0.63	1	0.719	0.4674	0.2517	0.45	0.55
N ₃₁	0.61	1	0.725	0.4713	0.2538	0.65	0.55
N ₃₂	0.61	1	0.725	0.4713	0.2538	0.60	0.40
N ₃₃	0.61	1	0.725	0.4713	0.2538	0.55	0.45
N ₃₄	0.61	1	0.725	0.4713	0.2538	0.50	0.50
N ₃₅	0.61	1	0.725	0.4713	0.2538	0.45	0.55

Legend: MN = Mix number; W/C = Water/Cement ratio; VA = Volume of Aggregate; CA = Coarse Aggregate; FA = Fine Aggregate; C = Cement.

For each fresh concrete mix, slump test was conducted according to the procedures outlined in BS 1881: Part 102: (1983), to determine the workability of the concrete. Also for each concrete mix, concrete cubes of size 150x 150 x 150 mm³ were prepared for compressive strength test in accordance to the guidelines enshrined in BS 1881: Part 108: (1983). After 24 hours of casting, the cubes were demoulded and cured by immersion in water for a period of 28 days, 60 days and 90 days. After curing, the cubes were brought out of water, and air-dried. Thereafter, the density of the concrete were determined in accordance to the recommendations of BS 1881: Part 114: (1983). The density is thus given by the expression;

$$\rho = \frac{Mass(kg)}{Volume(M^3)} \quad (1)$$

The cubes thereafter were tested for compressive strength using a 2000KN Universal Testing Machine adopting the procedures enshrined in BS 1881: Part 115, (1983). The compressive strength (CS) is given as;

$$CS = \frac{Crushing\ Load(N)}{Cross - sectional\ Area(mm^2)} \quad (2)$$

3.0 Result and Discussion

The results for the research work are presented in this section for both material characterization and the engineering properties of concrete.

Table 2: Summary of Physical Characteristics of Sample Material

Description/ Material	Fine Agg.	Coarse Agg.	Metakaolin (MK)	Cement (OPC)
Bulk Density (g/cm ³)	0.299		0.547	1.116
Specific Gravity	2.650	2.705	2.064	3.150
Fineness Modulus (%)	2.90	-	3.60	2.00
Aggregate Impact Value (%)	-	8.0	-	-

A critical study of the physical properties of the concrete materials (aggregates, cement and Metakaolin) shown in Table 2 reveals that both the bulk densities and specific gravities of the Metakaolin used are less than those of OPC, this implies that the concrete produced with Metakaolin will be of lighter weight, this will thus, reduce the self-weight of a superstructure produced with this concrete and hence, requiring less cost for construction of foundations to carry

the superstructure. The specific gravity of the fine aggregate used agreed with the typical value 2.65 for natural sand (Shetty, 2005).

Table 3: Results of the Sieve Analysis of Fine Aggregate

Sieve size (mm)	Retained mass (gm)	%Retained (%)	Cumulative percentage retained (%)	Passed percentage (%)
4.750	6.50	1.30	1.30	98.70
2.360	13.80	2.76	4.06	95.94
1.180	44.30	8.86	12.96	87.08
0.600	92.20	18.44	31.36	68.64
0.425	100.00	20.00	51.36	48.64
0.150	221.40	44.28	95.64	4.36
0.075	17.10	3.42	99.06	0.94
PAN	4.70	0.94	100.00	0.00

Table 4: Results of the Sieve Analysis of Coarse Aggregate

Sieve size (mm)	Retained mass (g)	Mass Retained (%)	Cumulative percentage retained (%)	Percentage Passing (%)
25.00	836.3	55.75	55.75	44.25
19.00	531.4	35.43	91.18	8.82
9.50	112.5	8.17	99.34	0.66
4.75	9.8	0.66	100.00	0.00
Pan	0.0	0.00	0.00	0.00

From the Tables, it is observed that the grading results for both the fine and coarse aggregates complies with to the recommendations of BS 882 for heavy duty concrete.

Table 5: Chemical composition of the Metakaolin

S/N	Chemical Component	Mass %
1	SiO ₂	59.11
2	Al ₂ O ₃	16.18
3	Fe ₂ O ₃	6.82
4	CaO	1.44
5	MgO	1.43
6	K ₂ O	1.53

The results of the Metakaolin with respect to chemical composition in Table 5 shows the sum of the percentage composition of the major oxides [Silica (SiO₂), Aluminum Oxide (Al₂O₃), Iron (III) oxide (Fe₂O₃) and Potassium Oxide (K₂O)] for Metakaolin to be 84.26% which is above the stipulated minimum index of 70% as reported by Ettu et al. (2016), to be minimum percentage for a perfect pozzolan. Also, the combined sum of the percentages of the Silica (SiO₂), Aluminum Oxide (Al₂O₃) and Iron oxide

(Fe₂O₃) is 82.11%, this value is far above the minimum value of 70% prescribed for pozzolan by ASTM C618-06. This higher pozzolan index can be attributed to the suitability of the mineral deposit as well as quality of calcining and milling to fine powder process. Thus, the calcined kaolin used in this research is a satisfactory pozzolan.

Table 6: Slump Test Result

% Metakaolin replaced	Slump of concrete (mm)
0%MK	89
5% MK	70
10% MK	68
15% MK	60

A critical study of Table 6 reveals that as the Metakaolin content in concrete increases, the workability of concrete reduces. Thus, Metakaolin is recommended in concrete mixes that requires less workability. Also, when Metakaolin – cement blended concrete are to be used in concrete sections with congested reinforcements, superplasticizers are required to enhance the workability of the concrete produced.

Table 7: Density of Concrete After 90 Days Curing (Kg/m³)

FA/CA	Density of Concrete after Curing in Water (Kg/m ³)				
	0.65/0.35	0.60/0.40	0.55/0.45	0.50/0.50	0.45/0.55
% MK					
0	2320.97	2364.44	2350.05	2313.74	2302.4
5	2305.84	2363.93	2348.72	2223.10	2291.0
10	2304.52	2352.99	2344.97	2222.92	2278.6
15	2289.66	2348.64	2323.81	2219.75	2272.9

From Table 7, it is evident that density of concrete reduces as the Metakaolin content in the concrete increases. This is further supported by the fact that Metakaolin has lower bulk density and lower specific gravity than cement.

Table 8: Compressive Strength of Concrete at 28 Days Curing Period.

FA/CA	Compressive Strength at 28 days (N/mm ²)				
	0.65/0.35	0.60/0.40	0.55/0.45	0.50/0.50	0.45/0.55
% MK					
0	38.67	38.67	40.34	40.96	42.30
5	38.12	38.67	40.74	41.56	42.00
10	39.30	39.85	42.30	42.00	42.59
15	38.81	39.19	35.41	40.89	41.26

Table 9: Compressive Strength of Concrete at at 60 Days Curing Period.

FA/CA	Compressive Strength at 60 days (N/mm ²)				
	0.65/0.35	0.60/0.40	0.55/0.45	0.50/0.50	0.45/0.55
% MK					
0	38.89	38.89	40.74	41.33	42.59
5	38.37	38.96	41.26	42.15	42.44

10	39.93	40.58	43.04	42.22	43.26
15	38.96	39.48	40.13	41.33	41.63

Table 10: Compressive Strength of Concrete at 90 Days Curing Period.

FA/CA	Compressive Strength at 60 days (N/mm ²)				
	0.65/0.35	0.60/0.40	0.55/0.45	0.50/0.50	0.45/0.55
% MK					
0	39.85	39.85	41.93	41.56	43.11
5	39.26	39.70	41.69	42.52	43.01
10	40.52	42.31	43.33	43.41	44.89
15	39.26	39.70	40.37	41.33	42.00

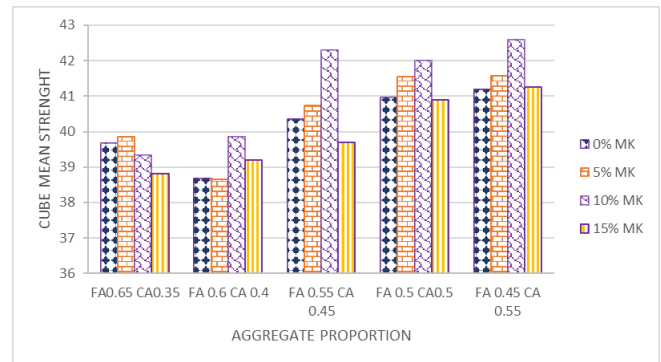


Figure 1: Compressive Strength of Concrete after 28 days of curing for all percentages of cement replacement.

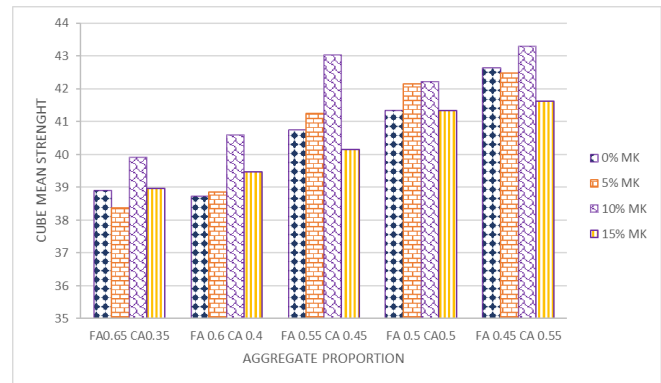


Figure 2: Compressive Strength of Concrete after 60 days of curing for all percentages of cement replacement.

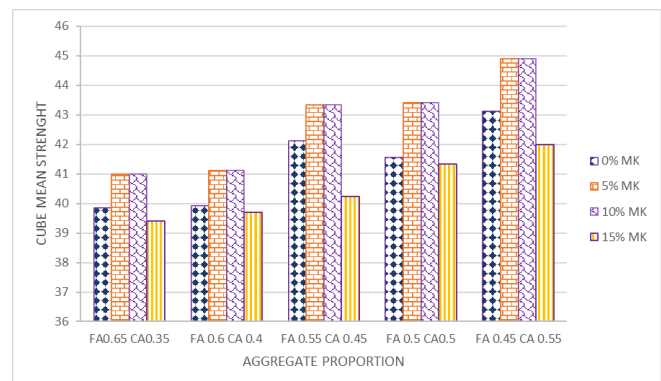


Figure 3: Compressive Strength of Concrete after 90 days of curing for all percentages of cement replacement.

From the results presented in Tables 8 – 10 and Figures 1 - 3, it is observed that the compressive strength of the samples with 100% Ordinary Portland Cement and super plasticizer with 0% Metakaolin pozzolan meets and exceeded the stipulated designed cube mean of 35 N/mm² thus validating the mix design used in this research. It is observed that for all the curing ages and for all the percentage replacement of OPC with Metakaolin, the Fine aggregate / Coarse aggregate (FA / CA) proportioning of 0.45 / 0.55 produced concrete with the highest compressive strengths. This shows that increase in the proportion of coarse aggregate in a concrete mix increases the compressive strength of the concrete produced. Furthermore, as OPC was replaced with the Metakaolin pozzolan up to 5%, the compressive strength reduces minimally but increases rapidly beyond 5% with a maximum strength recorded at 10% replacement of OPC with Metakaolin pozzolan, as more cement was replaced with the pozzolan up to 15%, the strength improvement for all proportion of FA to CA ceased progressing. Thus, for all the curing ages and FA/CA proportioning considered, concrete produced with 10% Metakaolin replacement with OPC yielded the highest compressive strength even greater than the compressive strength of the control mix (concrete made with 100% OPC). This shows that from this research, 10% replacement is the optimum percentage for replacement of OPC with Metakaolin. Also, as the curing age increases, the compressive strength of the concrete produced increases. For all the curing ages and FA/CA proportioning considered, 90 days curing age produced the highest compressive strength.

Conclusion.

From the results of the laboratory analysis carried out in this research, it was observed that metakaolin has a high pozzolanic index. Also increase in metakaolin content in concrete leads to increase in the workability and decrease in the density of the concrete produced, this is because, metakaolin has a lower bulk density and specific gravity than cement.

For all the curing ages and all the percentage replacement of OPC with Metakaolin, the Fine aggregate / Coarse aggregate (FA / CA) ratio of 0.45 / 0.55 produced concrete with the highest compressive strength. It was observed from the study that metakaolin can replace Ordinary Portland Cement in Concrete up to 10% for optimum results.

From the results of the various laboratory analysis conducted in this research, the following conclusions can be drawn. Results of chemical analysis of Metakaolin show that Metakaolin has a high pozzolanic index. Increase in Metakaolin content in concrete leads to decrease in the workability of the concrete produced. As the Metakaolin content in concrete increases, the density of the concrete produced reduces. This is so because, Metakaolin has a lower bulk density and specific gravity than cement.

For all the curing ages and all the percentage replacement of OPC with Metakaolin, the Fine aggregate / Coarse aggregate (FA / CA) ratio of 0.45 / 0.55 produced concrete with the highest compressive strengths.

Metakaolin can be used to substitute Ordinary Portland Cement up to 10% for optimum results.

Declaration Statement.

The authors hereby declare that this work is original and that they all agree to publish this work in SEET Engineering and Technology Journal.

Conflict of Interest.

There is no conflict of interest.

Authors Contributions.

(1) J. C. Ezeh; Conceptualized the study and supervised the work. (2) O.M Ibearugbulem; Developed the methodology and supervised the work. (3) I. C. Onyechere; Analyzed the data, discussed the results and wrote the original draft of the manuscript. (4) C. D. Okolie; Conducted the laboratory experiment and collected the data. (5) A. U. Igbojiaku; Edited the work and interpreted the results.

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