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Mechanical and Flexural performance of Reinforced Concrete Beams with Calcined Kaolin as Partial Cement Replacement

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Abstract

Different researches have been carried out using calcined kaolin (CK) as a pozzolanic material to replace cement in concrete to reduce its effect on green gas emissions and raw materials consumption. However, in terms of mechanical properties of concrete and load carrying capacity of structural members, the results of the researches vary despite being very few to offer a specific conclusion. Keeping in mind that bending and shear behaviour are of concern to civil and structural engineers as bending could result in sudden and catastrophic failure. The main objective of this study is to investigate the mechanical and flexural performance behavior of reinforced concrete (RC) beams with kaolin calcined at 700˚C as partial cement replacement under four-point bending test. The physical properties and mechanical properties of control and concrete with CK in the proportion of 0% to 30% by weight of cement were determined. Six beams designed in accordance to Eurocode 2 with predetermined dimensions of 1800 mm × 150 mm × 200 mm, shape, number and size of steel bars and concrete grade of 30 MPa with a mix ratio of 1:1.55:2.75 and water-cement ratio of 0.54 were used. The optimum dosage of CK obtained from the compressive strength of the modified concrete to use in beams was found to be 20%. It was observed that initial crack load, failure load, deflections and crack patterns and failure modes of the beams were comparable to control beams which is a valuable insight for structural applications of CK.

Keywords: Calcined kaolin, Flexural performance behaviour, Flexural strength, Four-point bending, Reinforced Concrete beams.

1. Introduction

Calcined kaolin (CK) is a pozzolanic material with high SiO_2 content, highly efficient and can react rapidly with the excess calcium hydroxide $Ca(OH)_2$ resulting from ordinary Portland cement (OPC) hydration by a pozzolanic reaction, to produce calcium silicate hydrates (C-S-H) and calcium aluminate silicates (C-A-S) responsible for the durability and strength of cement and concrete [1, 2]. Moreover, the utilization of this material is also environmentally friendly due to the reduction of CO2 emission to the atmosphere by decreasing Portland cement consumption.

The chemical composition of CK varies with the location of raw kaolin (untreated), calcination temperature to remove impurities and improve its properties, and duration. Its reactivity depends on the high percentages of the oxides obtained after calcination mainly composed of oxides of silicon, aluminium and iron which affect the mechanical properties of concrete [3].

The feasibility of employing CK as a Supplementary Cementitious Materials (SCM) on mechanical properties of concrete has been the subject of numerous research studies [4, 5]. The findings of [6] on the effect of thermally treated metakaolin on the pozzolanic activity in cementitious materials found that 15% cement replacement was the optimum for the compressive strength of the metakaolin mixed with concrete and 10% replacement was the optimum for the flexural strength tested under three-point loading which was increased between 20 to 40%.

The study of [7] has shown that the replacement of metakaolin at 15% by cement weight increased the tensile strength by 28 % and the bond strength was increased by 38% at 28 days. In the study of [8], the effect of metakaolin replacement on high strength concrete using superplasticizer was explored and it was found that the optimum dosage of 15% had higher compressive, split tensile and flexural strengths compared to control in all mixes and encouraged the use of metakaolin in high strength concrete production. In contrast to the study of [9, 10, 11] which replaced different proportions of metakaolin from 0-15% directly in RC beams for high strength concrete and found that 10% metakaolin is the optimum performance. The study of [12] found that 2-4% metakaolin can be used as the optimum for cement replacement in RC beams.

As regards to shear strength behavior of beams, two beams of M-25 were studied with cement replaced by 10% of metakaolin and the study [13] found that metakaolin reinforced concrete beams have higher loads with lesser deflections than normal and fly ash concrete beams of the mis. At first crack metakaolin concrete beams deflected by an average of 20% less as compared to normal concrete beams and with steel fiber concrete beams deflected by 25% less than that of normal concrete beams with steel fibers. The study of [13] recommended to make a comparison of flexural behavior of reinforced metakaolin concrete with concrete for the grades M30, M40, M50 of reinforced normal concrete and other pozzolans.

It is clear that quite a number of researches were also conducted on concrete mixed with other SCM other than CK with major focus on flexural and shear failure behaviour. Very few researches have been done on flexural performance behaviour of concrete mixed CK under four-point bending test. It is very important for civil engineers to design durable structures which can withstand the designed load to prevent harmful cracks in modified concrete under service loads. [14] reported that a lot more needs to be done in examining of real causes of structural failures in developing countries particularly on concrete, steel reinforcing bars and reinforced concrete composite material. According to [15] steel reinforcing bars and concrete are essential components of any reinforced concrete construction, and the stability, safety and durability of the structures are closely correlated with their quality. To ensure that they experience tensile loads, reinforcing steel bars are properly placed in tensile zones. The primary component of reinforced concrete members is concrete which provides stiffness and resistance to compressive loads. In order to evaluate that the results are similar to working conditions as possible, the relevant engineering properties of these materials are examined in laboratories using carefully planned experimental tests.

In summary, the literature review clearly demonstrates that CK is a potential pozzolanic material to be used as cement replacement material. In some cases, the studies showed that the results of mechanical properties of concrete varied and were superior to that of normal concrete. It's difficult to reveal the optimum percentage of CK which can be used in casting of reinforced concrete beams incorporating CK. It's also clear that different researches directly chose any percentage of CK to replace cement without any optimum while others cast only beams with different percentages of CK to get the optimum dosages. Therefore, in this study, the physical and mechanical properties of CK were determined after the characterization of the materials, then RC beams containing the optimum dosage of CK were investigated experimentally under four-point bending test from which the load carrying capacity and shear behaviour together with crack patterns and mode of failures of RC beams with CK were evaluated after 28 days.

2. Materials and Methods

2.1. Materials

2.1.1. Cement

In this study, ordinary portland cement type I (CEM I) 42.5 N power plus manufactured by Bamburi cement in Kenya was used. This type of cement is highly recommended by [16] for structural casted elements. It has a minimum compressive strength of 42.5 MPa at 28 days of curing and manufactured to conform to East African Standard KS EAS 18-1 [17], which meets the requirements of European standard EN 197 [16]. Its chemical composition was tested by X-ray Fluorescence.

2. Fine aggregates

River sand conforming to [18] obtained locally from supplier (Warren Concrete Ltd, Nairobi) and with maximum size of 5 mm using BS 410 test sieve was used in this study.

3. Coarse aggregates

Coarse aggregates with two single sized aggregates, one of maximum size 20 mm and another of maximum size 14mm and retained on 5.0 mm BS test sieve conforming to [18] were procured from local supplier (Warren Concrete Ltd based in Nairobi) and used in this study. The aggregates were first washed to remove all the dust and dirtiness. After air drying to surface dry condition, the aggregates were proportioned to conform to the requirements of the referred British Standard.

4. Calcined kaolin

Raw kaolin clay samples were collected from Kajiado County, Kenya then ground. Thereafter, the ground samples were heated in a laboratory by Elsklo furnace having capacity of heating up to 1300 ˚C at the Department of Arts and Design at Kenyatta University with a controlled temperature of 700 ˚C for three hours as shown in Figure 1.

Fig. 1:Calcination of raw kaolin in furnace at the laboratory

The resultant CK samples were sieved and passed through 75µm sieve size and were used throughout this study. Then a sample of CK together with samples of raw kaolin and cement

were taken to the Ministry of Mining and Petroleum, Kenya for X-ray fluorescence test to determine their chemical composition.

5*. Reinforcement steel bars*

The high tensile steel bars were procured locally from Juja hardware shops. The rebars were first examined for their mechanical properties' compliance to ASTM-615-60 [19] using Universal Testing Machine (UTM) as in figure 3 (b). The average measured yield stresses for these rebars were 447Mpa,502MPa and 535Mpa. Corresponding to diameter 8 mm,10mm and 12 mm respectively.

6. Water

Potable water conforming to BS 8680:2020 obtained from general water supply system of Jomo Kenyatta University of Agriculture and Technology was used in this study for materials mixing and curing concrete samples.

2.2. Mix design and Preparation of concrete samples

The mix design was done with reference to British Research Establishment [20] using the method of the Department of Environment (DOE) for a target strength of 30 MPa. Steel mould of size 100 mm × 100 mm × 100 mm cubes and steel cylindrical mould of size 100 mm diameter and 200 mm depth were used in casting concrete specimens for testing of compressive strength and splitting tensile strength respectively. Plywood formworks of size 100 mm × 100 mm × 350 mm were fabricated and used for casting plain concrete beams for flexural strength test.

A total of 84 cubes, 84 cylinders and 63 prisms including 12 specimens each for cubes, cylinders and 9 prims as control specimens and 84 specimens for partial replacement of 5%-30% for each type of different mix proportions were casted, demolded after 24 hours and stored in curing tank at temperature of 22±1°C. After 28 days and 56 days, the specimens were removed and air dried. Then the specimens were tested using Universal Testing Machine to get their respective average strengths at age of 7, 14, 28 and 56 days in compliance to [21].

Finally, the optimum dosage of CK was determined from the average compressive strength. All tests were conducted at the Materials and Structural Engineering laboratory at Jomo Kenyatta University of Agriculture and Technology, Kenya.

Fig. 2: Cubical and cylindrical specimens casted for experiment

Fig. 3: (a) Prismatic specimens casted for experiment and (b) Steel rebars tensile testing

2.3. RC beam design

RC beam design was done taking into account three basic design stages of RC beam and design stress-strain block were mainly taken into account in the design as highlighted in [22] and considering rectangular section [22] in Figures 4 and 5 with respect to pre-determined dimensions of beam, shape, steel bar diameters and number, and capacity of the hydraulic loading jack of 26 tonnes following the design as per EN Eurocode 2 [22, 23] to satisfy the criteria of Ultimate Limit State (ULS) and check for the condition of Serviceability Limit State (SLS). The design information used in this study were presented in Table 1**.**

Design considered the equilibrium of the tensile and compressive forces on the section: $F_{st} = F_{cc} + F_{sc}$ and assuming initially that the steel stresses f_{st} and f_{sc} are the design yield values, hence $A_S = 0.567f_{ck}bs+0.87f_{yk}A'_s$. For simple beam, considering the jack load as live load and only acting on the beam after deducing the beam self-weight, the following parameters were computed and used in this study:

- The ultimate moment M= 25.22kNm
- Uniformly distributed load, ω=67.3kN/m
- Design total load, (ULS) F = ω × effective span = 67.3 × 1.5 = 100.95 kN
- Service load=75 kN
- Flexural strength (σ)= FL/BD^2 = (100.95 × 1.5)/ 0.15 × 0.2^2) =25.24 N/mm^2

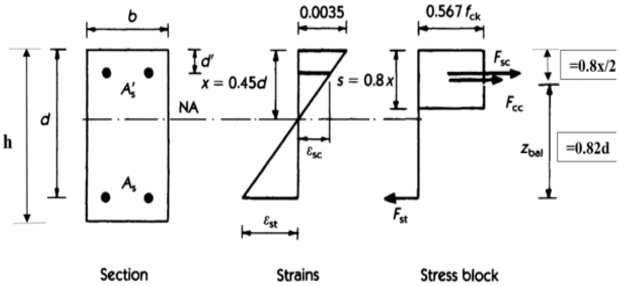


Fig. 4: Design of stress-strain block for RC beam

Table 1: Design information for the RC beam design

Design parameter	Value
High tensile yield strength (f_y)	500 N/mm^2
Steel rebars design strength (f_{yk})	435 N/mm^2
Characteristic cube strength (f_{cu})	30 N/mm^2
Characteristic cylinder strength (f_{ck})	25 N/mm^2
Concrete design strength (f_{ck})	14.2 N/mm^2
Tension steel (A_s)	226 N/mm^2
Compression steel (A’s)	157 N/mm^2
Span (L) =over length– supports	1500 mm
Width (b)	150 mm
Overall depth (h)	200 mm
Effective depth (d)	161 mm

Shear design was done in accordance to Eurocode [23, 24, 25] using Variable strut method [22]. Comparing the design shear stress to the concrete shear resistance is a common practice in Eurocode 2. The maximum shear force was 63.3 kN and the angle of inclination of the strut ϴ=22°. The shear reinforcements of 8 mm diameter were provided at support with spacing of 120 mm center to center (c/c) and at constant moment region, the minimum shear rebars of 8 mm diameter spaced at 170 mm c/c were provided. The maximum spacing was determined to fulfill the requirements of Eurocode 2 as presented in the sections of Figure 6 (a) and (b).

2.4. Testing set up, instrumentation and test procedure

After completion of beam design, timber formworks were fabricated to fit the predetermined sizes as shown in Figure 8. Steel cages in of each of the beams was prepared respecting the designed section and detailing shown in Figure 6.

Six electrical strain gauges were attached on the carefully selected internal positions on the bottom and top longitudinal steel bars, and at shear stirrups. All of the strain gauges were covered with protection layers to prevent them from being damaged due to moisture or while casting concrete beams as shown in Figure 8. Then steel cages were inserted into formworks and adjusted with concrete spacer blocks for concrete cover of 25 mm.

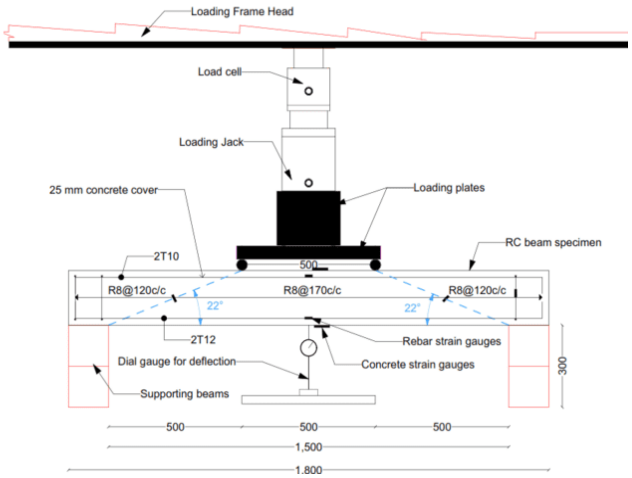
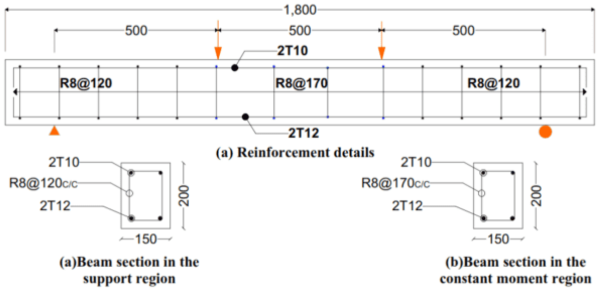


Fig. 5: Four-point bending design test set up model of RC beam



(a) Reinforcement details

(a)Beam section in the support region

(b)Beam section in the constant moment region

Fig. 6: Designed beam dimensions and reinforcement detailing

Finally casting of concrete beams was made with mix ratio of 1:1.55:2.75 with water-cement ratio of 0.54. The plastic slump was determined for each batch of casting. Each beam was casted in single mixing batch.

Then the procedures were repeated to the beams with CK by replacing cement with 20% of CK determined to be the optimum dosage obtained. Six (6) samples of reinforced concrete (RC) beams with dimensions of 1800 × 150 × 200 mm each with 2 steel longitudinal bars of 12 mm ø in tension and 2 of 10 mm ø in compression zones held together by 8 mm ø shear bars (stirrups) were prepared using concrete grade of 30 MPa.

The reinforced concrete beam specimens were cured till 28 days using covering blankets and daily curing. After 28 days, the blankets and any loose substances were removed as shown in Figure 10 The beams were allowed to dry off and the whole length was marked with dimensions before testing to know the exact points for loadings and external strain gauges [26]. Furthermore, the external rosette strain gauges were attached to side, top and bottom faces of the beams as can be seen in Figure 6.

The positions of the strain gauges were chosen so that they are able to capture the change in strut angle during the experimental testing. The deflections of the beams at midspan of the beams were monitored by linear variable differential transformers (LVDT). Before testing, load cell as pressure sensors, LVDT and strain gauges wires were all connected to data logger acquisition system which collected all test data in a computerized manner as shown in Figures 5,7-8.

The flexural test was conducted using four-point bending test with a system consisting of self-supported steel frames with beams that span the steel columns in both directions. This type of four-point arrangement was considered to be more effective than the three-point bending arrangement due to spacing between the applied loads. The addition of fourth bearing brings a much large portion of the beam to the maximum stress as opposed to only material specimen subjected to under central bearing. Each concrete beam was loaded vertically at its center by hydraulic jack of 400 kN capacity which transmitted the load to the specimen via a steel spreader laid on two bearings spaced at 500 mm on top of the specimen. It was done in such a way to generate a constant moment in that region.

A load cell of 26 tonnes capacity was used accurately to measure the applied load. The gradually increasing load was applied until the first crack was noticed. Then the corresponding load and deflections were recorded. The loading continued at regular load increment until the final failure of the beam to determine its ultimate load capacity. The parameters of interest i.e., initial crack load, ultimate load, deflections and crack pattern together with modes of failure were all recorded and marked respectively. The flexural strength corresponding to the failure load was calculated and recorded as the fractured strength (modulus of rupture). Since the fracture occurred in the tension zone where the loading span is middle third of the support span for four-point bending test with rectangular section, the flexural strength (MPa) was calculated using the formula [27].

$$f_b=\frac{PL}{BD^2}$$

where; f_b is the flexural strength or modulus of rupture (N/mm^2), P is the maximum load applied at fracture (N), L is the span length (mm), B is the width of the specimen (mm) and D is the depth of the specimen (mm).

Table 2: Reference concrete mix proportions with respect to weight of cement and CK

Material	Cement+CK	FA	CA	Water
Material composition (kg)	388.89	601.6	1069.51	210
Mix ratio	1.00	1.55	2.75	0.54

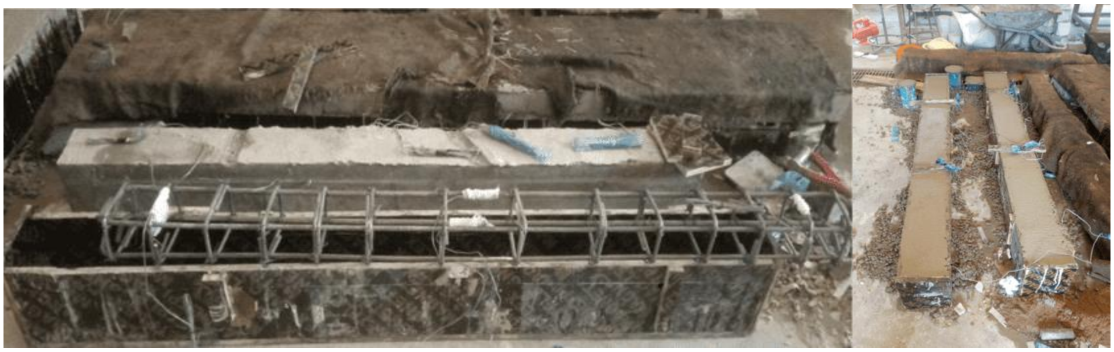


Fig. 7: (a) Steel cages and internal strain gauges fixing; (b) beams Casted and covered for curing

Fig. 8: Four-point bending experimental testing set up of RC beam

3. Results and Discussion

3.1. Chemical composition analysis

The results of the chemical analysis were presented in Table 5 which shows that the produced CK is a highly reactive alumino-silicate pozzolanic material rich in silica and alumina as required by [28]. It was found that the CK fulfills the chemical requirement of ASTM [28] which requires minimum percentage of 70% for a combination of silicon dioxide, iron oxide and aluminium oxide. In Table 5, the obtained chemical composition of the used CK is 93.45% which is far above the requirement [28].

The closeness of results for the percentage of the oxides of silicon, aluminium and iron were also noted for raw kaolin and CK. Compared to cement results, raw kaolin and CK have low calcium oxide with very high silicon dioxide which symbolizes lack of cementitious properties. Hence these materials are classified as class "N" as a naturally occurring and very good pozzolan in accordance to [28].

3.2 Characterization of fine and coarse aggregates

The results of the properties of fine aggregates (FA) and coarse aggregates (CA) were presented in Table 3 and Table 4 respectively whereas their corresponding particle size distribution curves in Figure 9 and10 falling within the limits of the ASTM C33 standards [29] were presented in Figure 1 and Figure 2.

Table 3: Characterization of aggregates

Property	FA	CA	Limits [29]
Specific gravity	2.3	2.5	2.4-2.9
Loose density (kg/m^3)	1071	1553	-
Bulk density (kg/m^3)	1639	1317	1200-1750
Water absorption (%)	0.50	2.73	< 4%
Moisture content (%)	3.41		0-4%
Silt content (%)	1.34	-	<5%
Fineness modulus	2.33	2.56	2.3-3.1

Aggregate Crushing value (%)	-	6.25	-
Aggregate Impact Value (%)	-	16.74	-

Table 4: Chemical composition of raw kaolin, CK and cement

Element name	Al_2O_3	SiO_2	Fe_2O_3	P_2O_5	K_2O	CaO	TiO_2	LOI
Raw kaolin (%)	12.955	72.118	7.020	0.000	4.851	0.579	0.43	
Calcined Kaolin (%)	14.684	73.296	6.647	0.025	4.459	0.655	0.48	0.71
Cement (%)	5.634	21.644	2.681	0.390	0.364	65.60	0.18	4.46

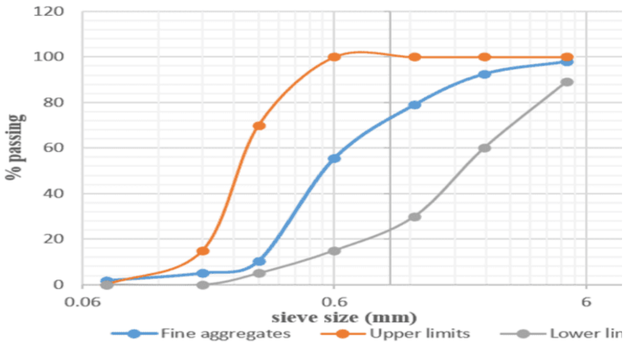


Fig. 9: Particle size distribution of fine aggregates

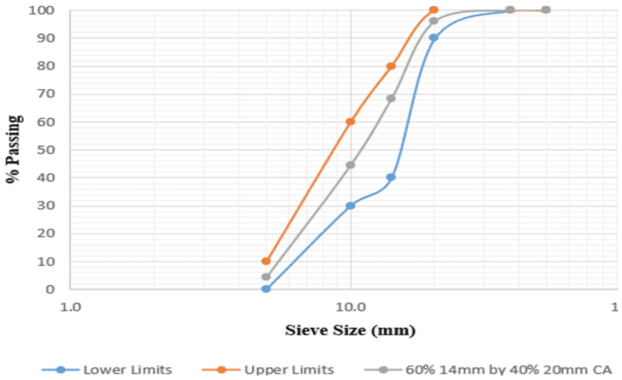


Fig. 10: Particle size distribution of coarse aggregates

Fine aggregates with 97.90%. have sizes ranging of 0.18 to 5 mm which resulted a properly closed-packing of mixing aggregate in concrete is the outcome of proper aggregate grading. The fineness modulus of 2.33 was found, falling between 2.3 and 3.1 range in the ASTMC C33.The grading of CA is shown in Figure 4, which shows that 94.22% of CA was found between 5 mm and 20 mm in aperture diameters. This shows that the majority of the aggregates are able to pass through the 20 mm sieve. The curve envelope consisted of the upper limit and lower limit curves, per BS882-1992 [18].

3.3 Compressive strength

The results of the compressive strength test at the age of 7, 14, 28 and 56 days with UTM for both control concrete and partially cement replacement by calcined kaolin in accordance with [21] are presented Figure 11.

It was found that the compressive strength of control concrete increased from 26.10 MPa after 7 days to 42.88 MPa. The compressive strength decreased with the CK replacement of as shown in Figure 9. At 5% and 10% of CK replacement, the compressive strength became higher compared to all other replacements of CK and the control concrete after 56 days by 0.26% and 0.63%. However, at 28 days with 20% CK replacement, the compressive strength was 31.40 MPa which is lower than the control (40.29 MPa) by 22.06% but it was greater than the minimum required strength for concrete grade 30 by 4.47%.

This increase can be attributed to the reactions between the oxides of silicon, aluminium, ferrous iron and calcium in the cement and pozzolanic CK, the two materials enhanced one another by adding significant amount of the aforementioned metal oxides to concrete. When mixed with OPC, the silica of the pozzolan combines with the free lime released during the hydration of cement as shown in Equation 1. This action is called pozzolanic reaction. The silica in the pozzolan reacts with the lime produced during hydration of Portland cement and contributes to the development of strength. Slowly and gradually, additional calcium silicate hydrate C-S-H is formed in Equation 2, which is a binder and fills up the space, thus giving impermeability, durability and increasing strength [30, 31].

$$C_3S + H_2O \rightarrow C\text{-}S\text{-}H + Ca(OH)_2 \qquad (1)$$

$$Ca(OH)_2 + SiO_2 \rightarrow C\text{-}S\text{-}H \qquad (2)$$

For other substitution of 25% and 30% of CK, the compressive strength fell below the minimum required at 28 days which lead to the conclusion that 20% CK was the optimum dosage to use in RC beams casting in this study.

This decrease in compressive strength was attributed to the ineffective interaction between silicon dioxide and calcium oxides which produced calcium silicate hydrate (C-S-H) gel, which is in charge of giving concrete its strength, improving its pore structure and preventing the formation of capillary pores [31].

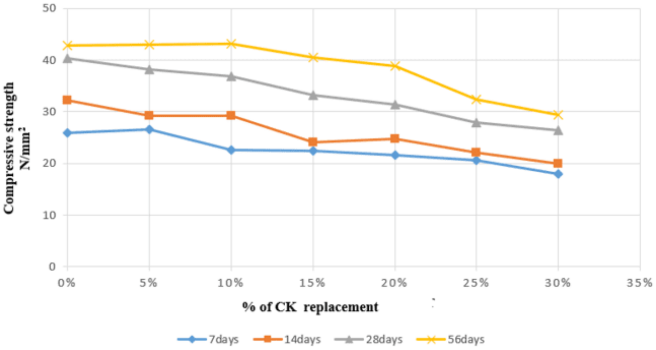


Fig. 11: Compressive strength of control concrete and concrete with% CK

3.4. Split tensile strength

The results of UTM machine at the age of 7, 14, 28 and 56 days for both control concrete and partially cement replacement by CK are presented in Figure 12. At 56 days, the replacement of 5%, 10%, 15% and 20% showed better performance in concrete whereby the tensile strength increased and was greater than the control by 6.76%, 5.01%, 2.44% and 2.76%, respectively. At 25% and 30%, the split tensile strength decreased by 2.76% and 8.26 %, respectively after 56 days.

At 28 days, the replacement of 5%, 10%, 15% and 20% showed also an increase in split tensile strength and was greater than the control by 8.25%, 8.03%, 3.24% and 4.80%, respectively, whereas at 25% and 30%, the split tensile strength decreased by 3.65% and 7.58%, respectively.

This increase of the split tensile strength was due to the strong intermolecular forces between Si-O- and -O-Si that emerged from the fundamental pozzolanic reaction involving the separation of Si- O-Si and Si-O-Al bond by hydroxyl ions [31, 30]. This reaction is represented schematically in Equation 3.

$$\text{Si-O-Si+2OH-} \rightarrow \text{Si-O-+-O-Si+H2O} \qquad (3)$$

The increased amount of silicon dioxide in CK also explains why the split tensile strength increased at all replacement proportions. The higher rate of SiO2, means the more silicon can contribute to the improvement of the concrete tension as shown in equation 3.

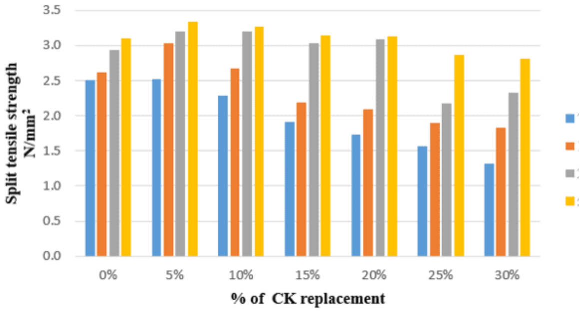


Fig. 12: Split tensile strength of control concrete and concrete with %CK

3.5. Flexural strength

The flexural strength experiment was carried out using 100 mm × 100 mm × 350 mm prisms in accordance with ASTMC78 [32]. The specimens were tested for flexural strength at 7, 14 and 28 days for both control and concrete containing 5%, 10%, 15%, 20%, 25% and 30% of CK by weight of cement and results of the UTM flexural tests were presented in Figure 13.

The results at 7, 14, 28 days of 5% and 10% replacement of CK were 1.90%, 5.01%, 5.10% greater than the control of 0.31%, 3.78%, 1.38%. Flexural strength lowered from 15% to 30% CK replacement. In general, the increase in replacement percentage of CK decreased the flexural strength compared to the control as seen in Figure 13. Equation 2 indicates that any increase in the flexural strength can be ascribed to the dispersion of CK as the rate of silicon dioxide increased.

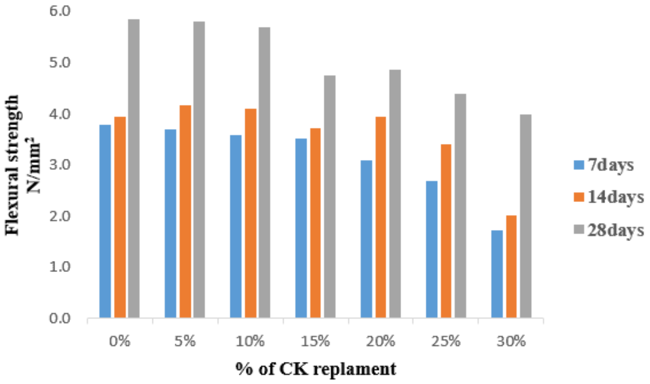


Fig. 13: Flexural strength of control concrete and concrete with % CK

3.5. Flexural Performance behaviour of RC beams

Flexural Strength (modulus of rupture) is essential to estimate the load carrying capacity of beams at which the structural concrete members may crack. The resistance of reinforced concrete beam to the applied load causes deflection, cracking and results in failure of the beam. To ensure that deflection of RC beams does not compromise the structural integrity and safety criteria, member's resistance to the applied load must be satisfied [22]. The ductility of the structure is also crucial because each part of the RC structure must be able to withstand deflection before at near maximum load carrying capacity before failing [33]. Cracks are not harmful unless they widen to the point where the reinforcement is exposed to corrosion, then the appearance and ductility decrease [22]. On the other hand, it is recommended by [34] that for structural concrete elements to meet serviceability criteria, the design crack width could not cause spoilage, steel corrosion or performance loss. The calculated width of the crack should not be more than 0.3 mm.

The results of the flexural strength characteristics of the reinforced concrete beams at 28 days for both control and CK inclusion were shown in Figure 14 and Figure 15. The higher strengths recorded for beam tests were results of the reinforcement introduced in the beams. At 28 days with 20% replacement as the optimum chosen dosage, the failure load and deflections for control beams were in the range of 93.89 kN to 110.63 kN corresponding to the flexural strength 23.47 N/mm^2 and 27.66 N/mm^2 and 15.55 mm to 37.75 mm, respectively. These results were slightly comparable to the failure load and deflections for beams containing optimal CK which were in range of 92.3 kN to 105.76 kN corresponding to flexural strength 23.08 N/mm^2 and 26.44 N/mm^2 and 17.53 mm to 38.74 mm, respectively. This led to a conclusion that, in comparison to the control beams, the RC beams containing the optimal 20% CK sustained somewhat larger loads and resisted much more deflections before collapsing, the higher deflections provide sufficient time for vacation before collapse.

3.6. Crack patterns and failure modes of RC beams

The presence of cracks in reinforced concrete members indicates damage. This is the main reason that crack in RC structures is one of the important parameters that should be checked during the design process. The concrete starts cracking when the tensile stress reaches or exceeds its tensile strength. The codes also provide crack limitation for aesthetical and protection reasons [23]. In this study, the observations for crack pattern and failure modes were made from the start of the first crack until the final failure and were based on the materials cracking behaviour since the concrete tensile properties were kept uniform as well as the amount and number of reinforcements.

The control beam experienced crack at a load of 78.86 kN which when the beam reached at 83.99% of its ultimate load carrying capacity and the deflection of 15.55 mm was recorded. The cracks were narrow and of flexure nature vertically located at the soffit of the beam at midspan. When load increased, the cracks depth increased from the soffit towards the upper part of the beam but the width did not change.

In the shear region, no cracks were noticed for both the beams containing CK and control beams whereas in the region of constant moment, the flexural cracks appeared from the soffit of the beams. As the load increased, the second crack appeared and only three cracks appeared having depths in the range of 150 mm to 170 mm from the soffit of the beams as shown in Figures 14 (a) and (b). The flexural cracks spacing were averaged at 170 mm center to cent which is almost the same spacing of the stirrups in middle of the beam between the two points loads.

For the beams containing the optimum CK of 20%, the first crack occurred at a load of 75.54 kN corresponding to the 81.76% ultimate load and deflection of 16.86 mm. The cracks were also of flexural nature at mid span. Their width and depth continued to develop until failure of the beam which decreased the deformability of the beam and led to a small collapse-load failure compared to the control beam. The cracks appeared in either side of the center of the middle of the beam. Three cracks also appeared having depths in the range of 150 mm to 170 mm from the soffit of the beams as shown in Figures 15 (a) and (b). The flexural cracks separation reduced to the average of 150 mm center to center compared to the control beams. The cracks appeared mainly directly below the point loads, after other cracks appeared in the constant moment region

Fig. 14 : Flexural cracks failure for control (a)beam 1 and (b)beam 2

Fig. 15: Flexural cracks failure for beam 1&beam 2 with opt %CK

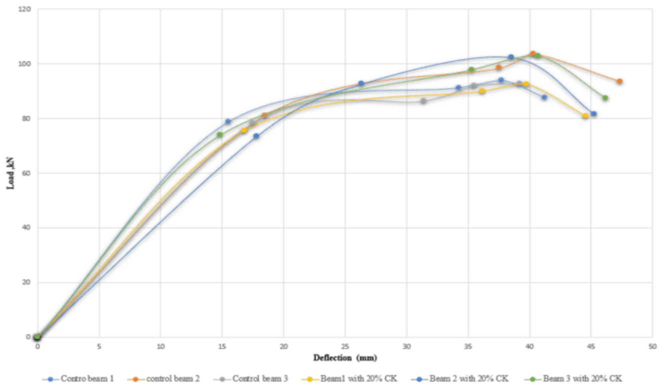


Fig. 16: Load vs deflection curve

Generally, as in Figure 16 of load-deflection curves, all the beams followed a similar pattern, a linear portion for the first part of the loading until the appearance and propagation of cracks, then a change of slope till the failure of the beam. There was no big difference between the stiffness of the control beams and beams with containing optimal CK.

4.Conclusion

The main objective of this study was to investigate experimental mechanical and flexural performance behavior of reinforced concrete (RC) beams with calcined kaolin (CK) as partial cement replacement under four-point bending test.

According to the physical and mechanical properties of concrete with CK as partial cement replacement determined, the compressive strength, and flexural strength tests demonstrated that the optimum dosage of 20% CK as partial replacement gave the improved results at 28 days and 56 days but remain below compared to the control concrete except for splitting tensile strength. In terms of workability, CK required more water consumption for workability of the modified concrete so there is need of admixtures or superplasticizers for it to become workable.

Based on the experimental investigation of the flexural and shear performance behavior of RC beams, the experimental results of first crack load and ultimate load for all beams are more than the theoretical designed values with respect to the design by Eurocode 2. The results revealed that with optimal CK replacement in concrete, there was no significant difference in terms of the ultimate load and first crack load compared to the control beams. The observed failures modes and crack patterns matched those predicted by Eurocode 2 for under-reinforced sections.

Based on abundance and importance of raw kaolin, further researches are required for other grades and for high strength concrete to fully provide the performance behaviour of modified concrete with CK with or without admixtures under four-point bending test.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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