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Experimental Study of Compressive Strength And Flexural Strength of Standard Concrete by Using Metakaolin as Mineral Admixture

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Abstract

This experimental study investigates the influence of metakaolin as a mineral admixture on the compressive strength and flexural strength of standard concrete (M-25). Metakaolin, a highly reactive pozzolanic material, was introduced as a partial replacement for cement by weight. Metakaolin is a valuable addition to many concrete mixes. It can improve the strength, durability, and resistance of concrete, making it a more versatile and sustainable material. Here are some of the key properties of metakaolin:

- **High pozzolanic activity:** Metakaolin is a highly reactive pozzolan, which means that it reacts with calcium hydroxide to form a gel that binds the concrete particles together. This gel helps to improve the strength, durability, and resistance of concrete.
- **Fine particle size:** The particle size of metakaolin is smaller than the particle size of cement, which means that it can fill the voids in the concrete matrix and improve the density of the concrete.
- **High surface area:** The high surface area of metakaolin also contributes to its pozzolanic activity. The larger surface area provides more sites for the reaction between metakaolin and calcium hydroxide to take place.
- **Low water content:** Metakaolin has a low water content, which means that it does not contribute to the water-to-cement ratio of the concrete. This helps to improve the strength and durability of the concrete.
- **Chemical resistance:** Metakaolin is resistant to a variety of chemicals, including acids, alkalis, and salts. This makes it a good choice for use in concrete that will be exposed to harsh environments.
- **Heat resistance:** Metakaolin is also resistant to high temperatures. This makes it a good choice for use in refractory materials and other high-temperature applications.

The research aimed to assess the impact of metakaolin on the mechanical properties of concrete, with a focus on its ability to enhance compressive The research aimed to assess the impact of metakaolin on the mechanical properties of concrete, with a focus on its ability to enhance compressive strength and flexural strength. The study involved the preparation of M-25 grade of concrete mixes with PPC 33 grade cement, locally available sand and aggregate with varying metakaolin proportions, ranging 10%, 20% and 30% by weight of cement. Specimens were cast and cured under controlled laboratory conditions. Compressive strength tests were conducted on cubical specimens, and test after 7 and 28 days and flexural strength tests were conducted on beam specimens, and test after 28 days respectively. Results revealed that the inclusion of 10% and 20% of metakaolin led to improves the 28 days compressive strength and flexural strength by 3.33% and 5.34% as compared to normal concrete respectively. The increase in strength is attributed to the pozzolanic reaction between metakaolin and calcium hydroxide, resulting in improved microstructure and reduced pore size within the concrete matrix.

Keywords: Compressive strength, Flexural strength, PPC, Concrete, Metakaolin, Grade M25

1. Introduction

Concrete is one of the most widely used construction material worldwide due to its versatility, affordability and durability *(Ref 6)*. However, the production of conventional concrete contributes significantly to CO2 emissions, posing environmental concerns *(Ref 7)*. Additionally, the depletion of natural resources like sand and gravel necessitates the exploration of sustainable alternatives. Enhancing the mechanical properties of concrete, such as compressive strength and flexural strength, has been a focal point of research to meet the increasing demands of the construction industry *(Ref 9)*. One promising approach to improve these properties is the incorporation of mineral admixtures into the concrete mix.

Metakaolin, a highly reactive pozzolanic mineral obtained by calcining kaolin clay, is a popular choice as a mineral admixture in concrete. It exhibits several advantageous properties, including:

- **Improved strength:** Metakaolin reacts with calcium hydroxide in concrete to form additional C-S-H gel, leading to enhanced compressive and flexural strength.
- **Increased durability:** Metakaolin refines the concrete microstructure, densifying the matrix and enhancing resistance to water penetration, chloride ingress, and chemical attack.
- **Reduced CO2 emissions:** Replacing a portion of cement with metakaolin reduces the overall clinker content, thereby lowering the CO2 footprint of the concrete.
- **Sustainable alternative:** Metakaolin utilizes industrial waste (kaolin clay) and reduces reliance on natural resources like sand and gravel.

When used in appropriate proportions by weight of cement, metakaolin can significantly enhance the performance of standard concrete. This study aims to investigate the effects of metakaolin on the compressive strength and flexural strength of standard concrete mix. The addition of metakaolin as a mineral admixture introduces several potential benefits. Metakaolin is known to enhance the pozzolanic reaction in concrete, leading to increased density and reduced porosity *(Ref 12)*. This, in turn, can improve the mechanical properties, making the concrete more durable and resistant to cracking. Moreover, metakaolin can contribute to sustainability in construction by reducing the demand for cement, a material associated with significant carbon emissions *(Ref 14)*. In this experimental study, preparation of M-25 grade of concrete with varying percentages of metakaolin as a replacement for cement by weight. Compressive strength and flexural strength test will be conducted to assess the concrete's ability to withstand axial loads. These tests will be essential in understanding how metakaolin affects the mechanical performance of the concrete. The study's findings will contribute valuable knowledge towards the development of sustainable concrete with improved mechanical properties and reduced environmental impact. It will provide insights into the optimal replacement levels of cement with metakaolin for achieving desired performance characteristics, potentially paving the way for a more sustainable and eco-friendly construction industry.

Figure 1. Metakaolin Powder

2. Experimental Investigation

2.1 Materials

Cement – PPC 33 grade cement (ACC cement) is used in this investigation and having specific gravity of 2.94.

Fine Aggregates – Narmada River sand is used in this investigation which passing through 4.75 mm sieve and having specific gravity of 2.61. The passing percentages as per IS 2386 part 1 and gradation lying under zone II as per IS 383:1970.

Coarse Aggregates – Angular shape machine crushed stone was used as aggregates for two different fractions i.e. 20 mm and 10 mm whose specific gravity is 2.85 and 2.82 respectively.

Water – Potable tape water free from chemical substances and suspended particles was used for mixing of concrete and curing of concrete mix.

Metakaolin - Metakaolin is a pozzolanic material that is formed by the calcination of kaolin clay, typically at temperatures between 600 and 850 degrees Celsius. Specific gravity of metakaolin is 2.6.

2.2 Test data for materials

- **Cement**

Cement	PPC, Make – ACC cement				
S.No.	**Parameter**	**Test method**	**Results**	**Units of measurements**	**Norms as per IS:1489**
1.	Consistency	IS:4031 (Part-IV)1988	30.5	%	NA
2.	Initial setting time	IS:4031 (Part-V)1988	140	Minutes	>30 minutes
3.	Final setting time	IS:4031 (Part-V)1988	310	Minutes	<600 minutes

4.	Compressive strength after 72±1 hr	IS:4031 (Part-VI)1988	19.25	MPa	16 MPa minimum
5.	Compressive strength after 168±2 hr	IS:4031 (Part-VI)1988	20.40	MPa	22 MPa minimum
6.	Compressive strength after 672±4 hr	IS:4031 (Part-VI)1988	38.30	MPa	33 MPa minimum
7.	Specific gravity	IS:4031 (Part-XI)1988	2.94	-	-
8.	Fineness by Blain air	IS:4031 (Part-II)1988	314	m^2/kg	300 m^2/kg minimum
9.	Soundness by Le chatelier	IS:4031 (Part-III)1988	1.65	mm	10 mm maximum

Table 1 – Test Results for Cement

- **Coarse aggregate**

Sieve analysis – 20 mm

S.No.	**Parameters**	**Test value**	**Requirements as per IS:383-2016**	**Test method**
	Sieve analysis	**% passing**		
1.	40 mm	100.00	100	IS:2386 part-1
2.	20 mm	85.90	80-100	
3.	10 mm	0.80	0-20	
4.	4.75 mm	0.45	0-5	

Table 2 – Sieve Analysis of 20 mm Coarse

Sieve analysis – 10 mm

S.No.	**Parameters**	**Test value**	**Requirements as per IS:383-2016**	**Test method**
	Sieve analysis	**% passing**		
1.	12.50 mm	100.00	100	IS:2386 part-1
2.	10 mm	86.24	85-100	
3.	4.75 mm	1.33	0-20	
4.	2.36 mm	0.12	0-5	

Table 3 - Sieve Analysis of 10 mm Coarse aggregate

- **Grading of Mixed Coarse Aggregate**

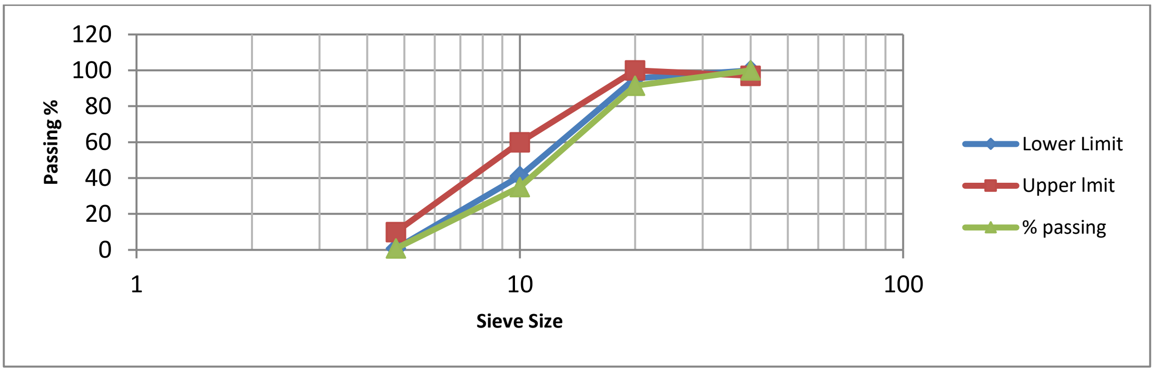
Fraction – I (20 mm) – 60%
Fraction – II (10mm) – 40%

S.No.	Parameters Sieve analysis	Test value % passing	Requirements as per IS:383-2016	Test method
1.	40 mm	100	100	IS:2386 part-1
2.	20 mm	91.54	90-100	
3.	10 mm	35.04	25-55	
4.	4.75 mm	0.80	0-10	

Table 4 – Grading of Mixed Coarse Aggregate

S.No.	Test Parameter	Units of measurement	Test result	Norms as per IS:383-2016	Test Method
1.	Specific Gravity (20mm)	-	2.85	-	IS:2386 P-3
2.	Specific Gravity (10mm)	-	2.82		IS:2386 P-3
3.	Water absorption (20mm)	%	0.65	2% max	IS:2386 P-3
4.	Water Absorption (10mm)	%	0.76	2% max	IS:2386 P-3
5.	Free Surface Moisture	%	Nil	-	IS:2386 P-3
6.	Aggregate Impact value	%	12.00	30% max	IS:2386 P-4
7.	Combined Flakiness and Elongation Index	%	31.00	40% max	IS:2386 P-1
8.	Aggregate Crushing Value	%	15.00	30% max	IS:2386 P-4
9.	Los Angeles Abrasion Value	%	19.00	30% max	IS:2386 P-4

Table 5 – Test Results for Mixed Coarse Aggregate



Graph 1. Grading of Coarse Aggregate

- **Fine Aggregate**

S.No.	Sieve size	Test Result Passing %	Norms % as per IS:383-2016	Test Method
1.	10 mm	100.00	100	IS:2386 P-1
2.	4.75 mm	99.20	90-100	
3.	2.36 mm	96.40	75-100	
4.	1.18 mm	87.50	55-90	
5.	600 micron	56.20	35-59	
6.	300 micron	17.25	8-30	
7.	150 micron	3.50	0-10	

Table 6 – Grading of Fine Aggregate

S.No.	Test Parameter	Units of measurement	Test result	Norms as per IS:383-2016	Test Method
1.	Fineness Modulus	-	2.40	2-3.5	IS:2386 P-1
2.	Specific Gravity	-	2.61	-	IS:2386 P-3
3.	Water Absorption	%	1.80	2% max	IS:2386 P-3
4.	Silt Content	%	2.70	3% max	IS:2386 P-2
5.	Free Surface Moisture	%	Nil	-	IS:2386 P-3

Table 7 - Test Results for Fine Aggregate

- **Mix Proportions**
  - **Target Mean Strength of Mix Proportion**
    Target Mean Strength, fck`=fck+1.65xSD Where, Standard deviation for M-25 is 4and fck is 25 N/mm2 for M-25 mix fck`=25+1.65x4 = 31.6 N/mm2
  - **Selection of water Content**
    Maximum Water Content for 20 mm Aggregate for 50 mm slump = 186 Liter
    Estimated water Content for 20 mm Aggregate for 100 mm Slump = 197 Liter
    As per Trial Basis Used water content = 178 Liter
  - **Selection of Water Cement Ratio**
    As per trial Basis we adopt
    Water Cement Ratio = 0.45<0.50 (Hence ok)
    Hence, Cementious Content = water Content/ Water Cement Ratio = 396 kg
  - **Proportion of Coarse aggregate and Fine Aggregate**
    Corrected Volume of CA/FA as per Zone 2 Aggregate and WC Ratio 0.45
    Ratio of Coarse aggregate by volume 0.600, Ratio of fine aggregate by volume 0.400
  - **Mix Calculation**

Volume of Concrete = 1 m^3
Volume of concrete for 1.0 % entrapped air = 0.99 m^3

Volume of Cement = Cement Content /(Specific Gravity of Cement x 1000) = 0.135m^3 Volume of water = Water Content /Specific gravity of water x 1000 = 0.178 m^3
Volume of Mineral Admixture = Mass of admixture/Specific Gravity X 1000 = 0.000 m^3
Volume of all in one Aggregate = Cl 1- Cl 2- Cl 3- Cl 4- Cl 5 = 0.677 m^3
Mass of 20 mm aggregate=Cl 6 x Ratio of blending proportion x ratio of Coarse aggregate x Specific Gravity x 1000 = 637.15 kg
Mass of 10 mm aggregate = Cl 6 x Ratio of blending proportion x ratio of Coarse aggregate x Specific Gravity x 1000 = 515.82 kg
Mass of Sand =Cl 6 x ratio of Fine aggregate x Specific Gravity x Blending x 1000 = 707.27 kg

- **Design Mix Proportion**
  - **Trial Mix 1(With 0% Mineral Admixture)**

S.No.	Ingredients	Quatity of Material per m^3 in SSD Condition in kg	Ratio	Material Required for mix per bag of cement in kg
1.	Cement	396	1.00	50.00
2.	Sand	707	1.79	89.27
3.	Coarse Aggregate Fraction I 20 mm & Down	637	1.61	80.43
4.	Coarse Aggregate Fraction II 10 mm & Down	515	1.30	65.03
5.	Water	178	0.45	22.47
6.	Mineral Admixture	0	0.00	0.00

  - **Concrete Characteristics**

S.No.	Parameter	Units	Results
1.	Slump initial	mm	75
2.	7 Days Compressive Strength	N/mm2	19.81
3.	28 Days Compressive Strength	N/mm2	28.67
4.	28 Days Average Flexural Strength	N/mm2	3.67
5.	**Remarks:- 1. Homogeneous and cohesive concrete mix. 2. Not Achieved specified strength in 07 & 28 days.**		

Trial Mix 2 (With 10% Mineral Admixture

S.No.	Ingredients	Quatity of Material per m^3 in SSD Condition in kg	Ratio	Material Required for mix per bag of cement in kg
1.	Cement	356	1.00	50.00

2.	Sand	697	1.96	97.89
3.	Coarse Aggregate Fraction I 20 mm & Down	692	1.94	97.19
4.	Coarse Aggregate Fraction II 10 mm & Down	581	1.63	81.60
5.	Water	178	0.45	22.50
6.	Mineral Admixture	40	0.11	5.56

- **Concrete Characteristics**

S.No.	Parameter	Units	Results
1.	Slump initial	mm	80
2.	7 Days Compressive Strength	N/mm2	22.38
3.	28 Days Compressive Strength	N/mm2	32.00
4.	28 Days Average Flexural Strength	N/mm2	4.52
5.	**Remarks:-1. Homogeneous and cohesive concrete mix. 2. Achieved specified strength in 07 & 28 days.**		

- **Trial Mix 3 (With 20% Mineral Admixture)**

S.No.	Ingredients	Quatity of Material per m^3 in SSD Condition in kg	Ratio	Material Required for mix per bag of cement in kg
1.	Cement	316	0.89	44.38
2.	Sand	685	1.92	96.21
3.	Coarse Aggregate Fraction I 20 mm & Down	617	1.73	86.66
4.	Coarse Aggregate Fraction II 10 mm & Down	499	1.40	70.08
5.	Water	178	0.45	22.50
6.	Mineral Admixture	80	0.22	11.24

- **Concrete Characteristics**

S.No.	Parameter	Units	Results
1.	Slump initial	mm	65
2.	7 Days Compressive Strength	N/mm2	22.58

3.	28 Days Compressive Strength	N/mm2	34.01
4.	28 Days Average Flexural Strength	N/mm2	4.69
5.	**Remarks:- 1. Homogeneous and cohesive concrete mix. 2. Achieved specified strength in 07 & 28 days.**		

- **Trial Mix 4 (With 30% Mineral Admixture)**

S.No.	**Ingredients**	**Quatity of Material per m^3 in SSD Condition in kg**	**Ratio**	**Material Required for mix per bag of cement in kg**
1.	Cement	277	1.00	50.00
2.	Sand	669	2.42	120.76
3.	Coarse Aggregate Fraction I 20 mm & Down	603	2.18	108.84
4.	Coarse Aggregate Fraction II 10 mm & Down	488	1.76	88.09
5.	Water	178	0.45	22.50
6.	Mineral Admixture	119	0.43	21.48

- **Concrete Characteristics**

S.No.	**Parameter**	**Units**	**Results**
1.	Slump initial	mm	60
2.	7 Days Compressive Strength	N/mm2	22.03
3.	28 Days Compressive Strength	N/mm2	38.60
4.	28 Days Average Flexural Strength	N/mm2	4.10
5.	**Remarks:-1. Homogeneous and cohesive concrete mix. 2. Not Achieved specified strength in 07 & 28 Days**		

Mix proportions for different mixes are given below :

1. The mix proportion for M-25 concrete mix without any replacement is 1:1.78:2.91
2. The mix proportion for M-25 concrete mix with 10% replacement of PPC by metakaolin is 1:1.94:3.16
3. The mix proportion for M-25 concrete mix with 20% replacement of PPC by metakaolin is 1:2.16:3.52
4. The mix proportion for M-25 concrete mix with 30% replacement of PPC by metakaolin is 1:2.42:3.93

3. Specimen Preparation

Cube molds of size 150mmx150mmx150mm and beam molds size 150mmx150mmx700mm are prepared for casting. Molds fill with concrete mix with metakaolin in varying proportion and compact it thoroughly by using a vibrating table to remove air voids. Placed the cube and beam molds in the curing chamber for 24 hours to cure the specimens and followed the curing procedures. After 7 and 28 days curing duration demolded cube molds carefully and test under compressive testing machine and after 28 days curing duration demolded beam molds carefully and test under flexural testing machine with center point loading method.


Figure 2. Slump Cone Test


Figure 3. Cube Casting


Figure 4. Cube Specimen


Figure 5. Compressive Strength Test


Figure 6. Beam Casting


Figure 7. Beam Specimen

Figure 8. Flexural Strength Testing

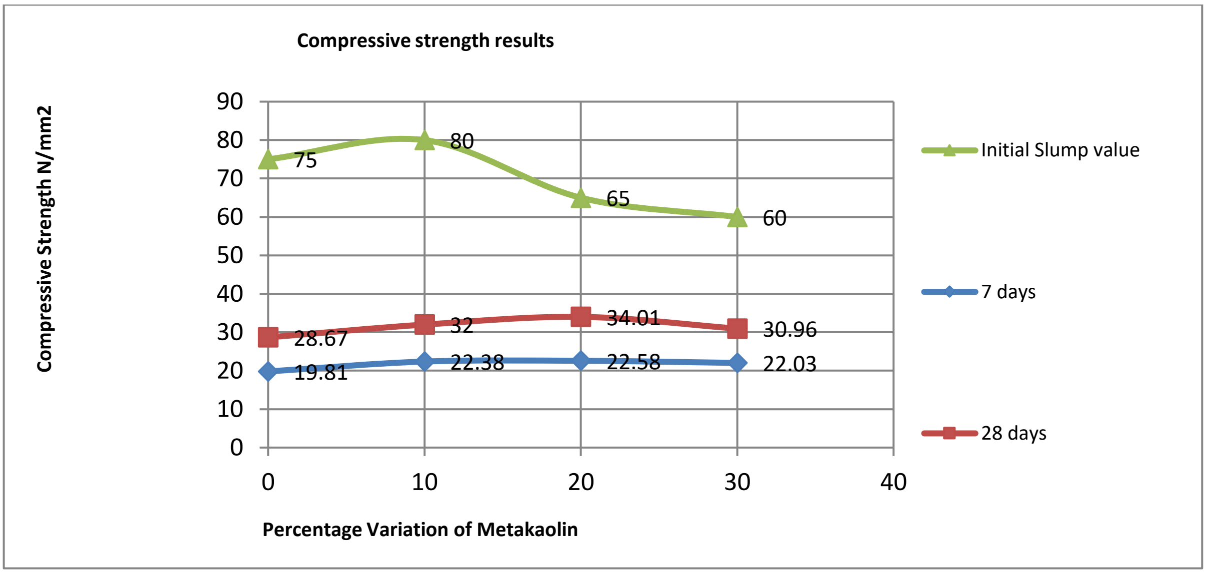
4. Result and Discussions

The test results obtained are given below:

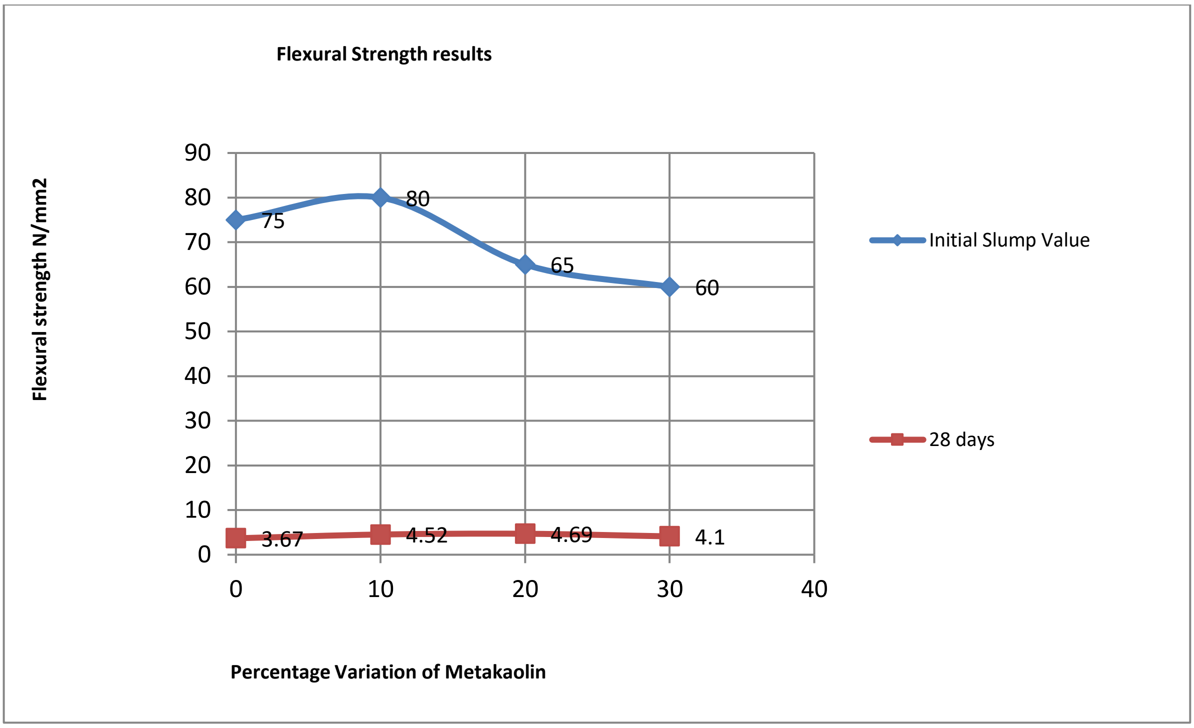
S.No	MK%	Slump (mm)	7 days compressive strength (Mpa)	28 days compressive strength (Mpa)	28 days flexural strength (Mpa)
1.	0	75	19.81	28.67	3.67
2.	10	80	22.38	32.00	4.52
3.	20	65	22.58	34.01	4.69
4.	30	60	22.03	38.60	4.10

Table 8. Compressive Strength and Flexural Strength test results

From the above result it is observed that the metakaolin with 20% is mixed with concrete gives high strength after 28 days as compared to normal concrete



Graph 2 . Average Compressive Strength of different % of Metakaolin of M-25 Grade of concrete



Graph 3 . Average Flexural Strength of different % of Metakaolin of M-25 Grade of concrete

5. Conclussions

The experimental study investigated the compressive strength and flexural strength properties of M-25 grade of concrete by using metakaolin as a mineral admixture by weight of PPC 33 grade cement. The study was conducted by casting specimens with 0%, 10%, 20% and 30% replacement levels of metakaolin. The methodology involved the collection of materials, casting of specimens, and testing and analysis of the properties of the concrete as per IS 10262:2019. Based on above study the outcomes are as follows:

- The 7 and 28 days compressive strength of various mixes is shown in Graph 2, and the results are indicated in Table 8, that the compressive strength of metakaolin with 20% in concrete mix is high as compared to other percentages.
- The 28 days flexural strength of various mixes is shown in Graph 3, and the results are indicated in Table 8, that the flexural strength of metakaolin with 20% in concrete mix is high as compared to other percentages.
- The study concluded that the use of 20% of metakaolin as a partial replacement of PPC in concrete can increase its compressive strength by 5.34% and flexural strength by 1.02% as compared to conventional concrete.
- Graph 4 and Graph 5 shows the 28 days compressive strength and flexural strength of different percentages of metakaolin with corresponding three values of every percent of metakaolin.

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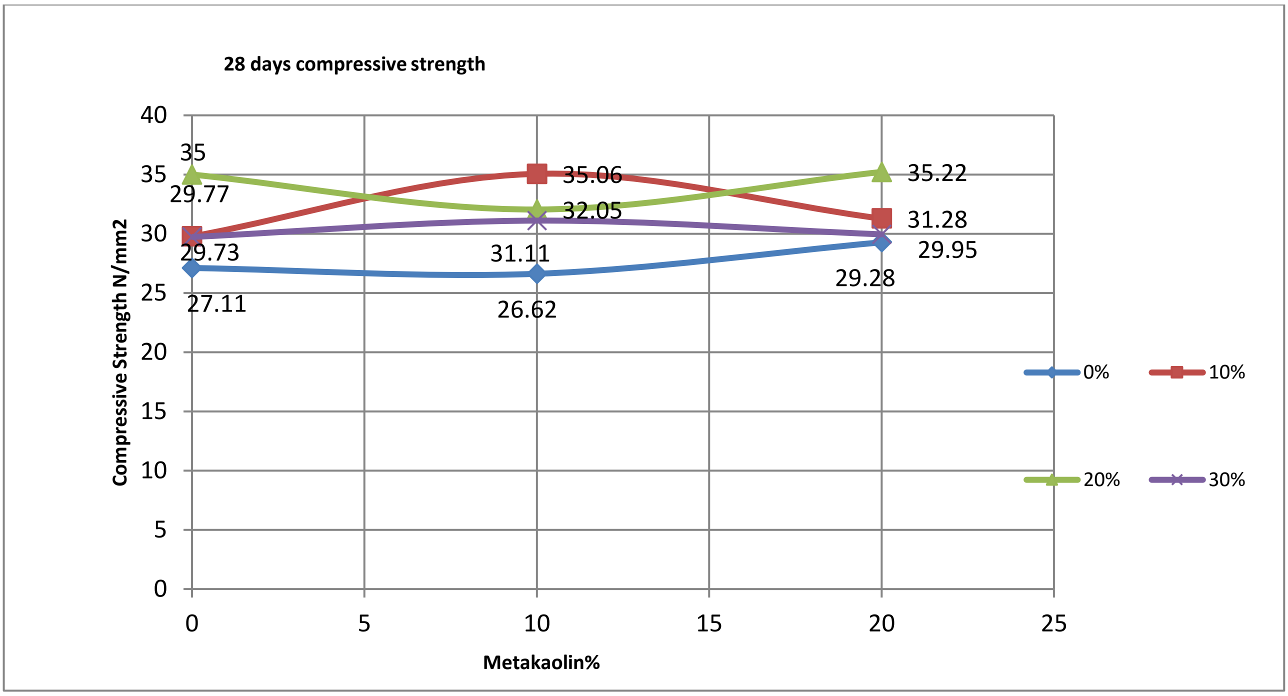
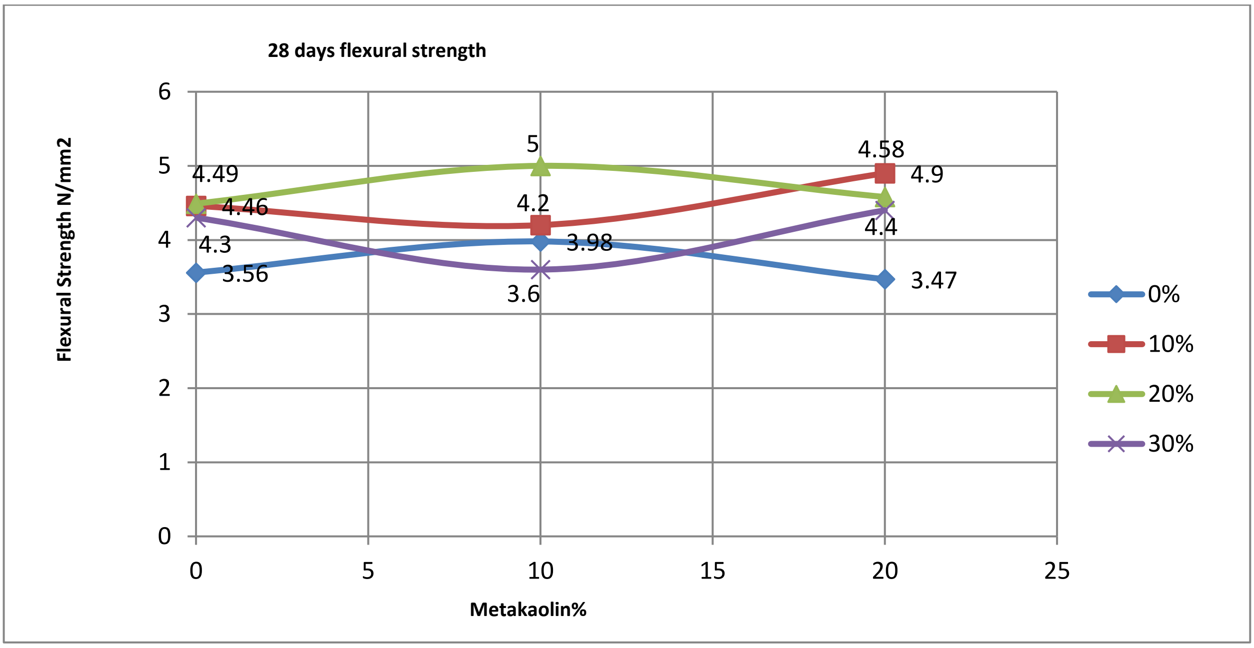


Graph 4. 28 Days Compressive Strength Analysis



Graph 5. 28 Days Flexural Strength Analysis

In summary, the experimental study showed that the use of metakaolin as a mineral admixture in M-25 grade of concrete can improve its compressive strength, flexural strength and durability. The study also highlighted the importance of testing and analyzing the properties of concrete to determine the effects of mineral admixtures on its strength properties.

6. Research Gap

While the given research topic investigates the influence of metakaolin on the mechanical properties of concrete, there are potential research gaps that could be explored further:

- **Life Cycle Assessment (LCA):** Conduct an LCA to compare the environmental footprint of metakaolin concrete with conventional concrete, considering factors like embodied energy, greenhouse gas emissions, and resource consumption.
- **Waste utilization:** Explore the potential of using industrial waste products like rice husk ash or ground granulated blast furnace slag as partial replacements for metakaolin, promoting sustainable construction practices.
- **Additional Points:**
  The study could benefit from a more detailed literature review to identify existing research gaps and avoid redundancy.
  - Consider incorporating numerical modeling techniques like finite element analysis (FEA) to validate the experimental findings and predict the behavior of metakaolin concrete under different loading conditions.
  - Emphasize the practical implications of the research findings and provide recommendations for the potential implementation of metakaolin concrete in construction projects.

By addressing these research gaps, the study can contribute valuable insights into the effectiveness of metakaolin as a mineral admixture and promote its wider adoption in the construction industry for sustainable and high-performance concrete applications.

7. Acknowledgement

The satisfaction and euphoria of the successful completion of any task would be incomplete without the mention of the people who made it possible whose constant guidance and encouragement crowned our effort with success. It gives me enormous pleasure to express my most profound sense of gratitude and sincere thanks to my highly respected guide, PROF. ANUBHAV RAI, Head, Department of Civil Engineering, Gyan Ganga Institute of Technology and Science for their valuable guidance, supervision, and encouragement throughout my work, which made this task pleasant.

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