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Experimental Analysis of Concrete with Partial Replacement of Metakaolin and Steel Fibers

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***Abstract*—The increasing environmental concerns caused by global warming and the rising costs of cement production due to quarrying have created a pressing need to explore alternative materials. To address this challenge, extensive research has been carried out to identify suitable replacements for cement. This research work is aimed to investigate the strength of concrete with partial replacement of cement with Metakaolin and compare it with conventional concrete. The grade of concrete is M30. Incorporating Metakoalin can potentially reduce the overall consumption of cement in the country while promoting sustainable construction practices. The primary objective of this research is to evaluate the influence of Metakoalin as a partial replacement for cement on the compressive, split tensile, and flexural strength of concrete. In this investigation, Metakoalin was used to replace cement in varying proportions of 10%, 20% and 30%. Based on the experimental results, the mix containing 20% Metakoalin exhibited optimal strength characteristics. The findings of this study highlight the potential of Metakoalin as an eco-friendly and cost-effective alternative material for sustainable construction.**

I. INTRODUCTION

Global warming has emerged as one of the most critical environmental challenges of the 21st century. Among the major contributors to anthropogenic greenhouse gas emissions is the cement industry, which is responsible for approximately 8% of global carbon dioxide (CO_2) emissions. In response to growing environmental concerns and the global push toward sustainable development, there is an increasing focus on identifying and incorporating alternative materials that can partially or wholly replace conventional cement in construction. Sustainable construction practices are guided by three primary pillars: environmental sustainability, economic feasibility, and social responsibility. Within this context, the present study investigates the partial replacement of cement with *Metakaolin,* a biomass-derived waste material, and the incorporation of *steel fiber as a reinforcing agent* in concrete. Metakoalin, often considered an clay, offers potential for value-added utilization when processed into ash, thus contributing to waste management and sustainability goals.

The objective of this research is to evaluate the mechanical performance and environmental benefits of concrete modified with *Metakaolin* and steel fiber, with the aim of promoting innovative and sustainable practices in civil engineering materials.

II. LITERATURE REVIEW

1) STUDY ON THE EFFECT OF METAKOLIN AS A PARTIAL REPLACEMENT OF CEMENT ON THE FRESH AND HARDENED PROPERTIES OF CONCRETE Prabeen Kumar Sahu*1, Niharika Patel*2 M.TECH Scholar, Department Of Civil Engineering, GIET University, Gunupur,India",. Concrete, in construction, a structural material consisting of binding material, fine aggregate, coarse aggregate and water. Today construction cost is very high with using conventional material, due to unavailability of materials. This problem can be solved by replacement of concrete with different material which is not convenient in terms of required properties. Due to this limitation of unavailability of material which plays the vital role of concrete, we have only choice of partial replacement of concrete ingredients by different waste material and pozzolanic material.use, the research team. has launched a startup to explore commercial applications of the materials

2) Combined effect of steel fiber and metakaolin incorporation on mechanical properties of concrete" Erhan Güneyisia,⇑, Mehmet Gesog˘lua, Arass Omer Mawlod Akoia, Kasım Mermerdas. This study reports the results of an experimental study on mechanical properties of plain and metakaolin(MK) concretes with and without steel fiber. To develop the metakaolin included steel fiber reinforced concrete mixtures, Portland cement was partially replaced with MK as 10% by weight of the total binder content. Two types of hook ended steel fibers with length/aspect ratios of 60/80 and 30/40 were utilized to produce fiber reinforced concretes. Two series of concrete groups were designed with water to binder ratios (w/b) of 0.35 and 0.50. The effectiveness of MK and different types of steel reinforcement on the compressive, flexural, splitting, and bonding strength of the concretes were investigated. All tests were conducted at the end of 28 days of curing period.
3) Jatinder Singh Kharb1, Sanjay Kumar Sharma2, During cement production, work has been conducted to examine the effect of metakaolin (MK) substitution with cement strength due to associated environmental pollution and to preserve virgin raw materials for future generations, and yet at the same time, utilizing the approachability of additional cementing materials such as metakaolin-an engineered material. In this study, the strength characteristics of Metakaolin concrete with and without crimped steel fiber have been tested. Reinforced concrete with short random fibers has been identified by monitoring the origin length/dia. propagation of fractures to enhance the strength of cementitious matrices. Steel fibers have contributed to mechanical qualities by minimizing the crack development inside concrete blocks and so improving concrete strength at all testing ages. Results show that the flexural strength of M60 concrete increases with 1.5 percentages of fiber content and strength-effectiveness at aspect ratio 60 is observed to be maximum.
4) Experimental Study on High Performance Steel Fibre Reinforced Concrete using Metakaolin" V. V. Sawant1, Dr. C. P. Pise2, Prof. G. D. Lakade3 1PG Student, Civil Engineering, SKNSCOE, Korti, Pandharpur, Maharashtra, India 2Head of Department, Civil Engineering. SKNSCOE, Korti, Pandharpur, Maharashtra, India 3Assistant Professor, Civil Engineering, SKNCOE, Korti, Pandharpur, Maharashtra, India.Abstract- The current paper presents the result and discussion of an experimental study on HSFRC using Metakaolin (MK). The effects of these fiber and Metakaolin on workability, density, and on various strengths of M60 grade concrete are studied. Fiber content varies from 2.5% to 10 % by weight of cement and Metakaolin content varies from 5% to 20% by weight of cement. The various strengths considered for investigation are compressive strength, flexural strength, split tensile strength, and shear strength. Cubes of 150mm for compressive strength, cylinders of size 150mm diameter x 300mm length for split tensile strength, beams of 100 x100 x 500 mm for flexural strength, push-off specimens of size 150 x 150 x 450 mm for shear strength were cast. The prepared specimens were water cured and tested for variety of properties up to certain period of the time.
5) C. Marthong, et.al (2012): The paper investigates how the partial replacement of Ordinary Portland Cement (OPC) with fly ash affects the mechanical and durability properties of concrete. Fly ash, a by-product from thermal power plants, possesses pozzolanic properties due to its silica and alumina content, which react with calcium hydroxide from cement hydration to form additional cementitious compounds. The study used three grades of OPC—33, 43, and 53—and replaced cement with fly ash in proportions of 10%, 20%, 30%, and 40% by weight. Tests were conducted on mortar cubes, concrete cubes, and beams to evaluate compressive strength, shrinkage, and durability under sulphate attack. The results revealed that adding fly ash significantly improves the workability of concrete due to its fine and spherical particles, which act as a lubricant and enhance flowability. However, early-age strength decreases with increasing fly ash content, especially at higher replacement levels (above 30%). This is because the pozzolanic reaction of fly ash is slower compared to cement hydration. Despite this, long-term strength (at 90 days) improved notably, especially for mixes with 20%

fly ash, where the strength approached that of conventional concrete.

III. STARCRETE AND CONVENTIONAL MIXES

Metakaolin is a by-product formed during theproduction and refining of clay, typically in ElectricArc Furnaces (EAF) and Argon OxygenDecarburization (AOD) units. During this process,impurities in the steel (such as sulfur, silicon,phosphorus) are oxidized and combine with fluxes like lime (CaO) and dolomite ($CaMg(CO_3)_2$) to formslag.Stainless steel slag (SSS), a byproduct of clayproduction, shows significant potential for sustainableuse in construction. It can be effectively utilized as apartial replacement for coarse aggregates in concrete,enhancing strength and durability while reducingreliance on natural resources.Steel Fiber Reinforced (SFR) bars are compositereinforcement materials made by combining Steelfibers with a polymer resin matrix. These bars serve asan alternative to traditional steel reinforcement inconcrete structures and are particularly valued for theirhigh strength-to-weight ratio, corrosion resistance, and durability in aggressive environments.
A conventional beam is a fundamental structural element used extensively in construction and engineering to support loads and resist bending.
Typically horizontal, conventional beams transferapplied loads primarily through bending moments and shear forces to supporting structures such as columns or walls. These beams are designed using classical beam theory, which assumes that the material behaves elastically under loading conditions. They are designedbased on our requirement such as size, shape etc.Common materials used in conventional beams includereinforced concrete, steel, and wood, depending on theapplication and load requirements. They are classifiedbased on their support conditions (simply supported,cantilever, fixed, continuous), cross sectionalshapes (rectangular, I-beam, T-beam), and materials.

IV. DIMENSIONS

For the experimental investigation, concrete specimens were cast in the form of cubes, cylinders, and prisms with standard dimensions. The cube specimens were prepared with a size of 150 × 150 × 150 mm for compressive strength evaluation. Cylindrical specimens of 150 mm diameter and 300 mm height were cast to assess the tensile strength characteristics. In addition, prism specimens measuring 150 × 150 × 700 mm were prepared to study the flexural behavior of the concrete. The use of these standard specimen sizes ensures consistency in testing and allows reliable comparison of the mechanical properties obtained from the experimental program.

V.EXPERIMENTAL INVESTIGATION

The experimental investigation comprised the collection of materials required for the preparation of both conventional concrete and metakoalin mixes. Material characterization tests were conducted for conventional and metakaolin constituents to evaluate their fundamental properties, and the obtained results were systematically compared. In addition, standard tests were performed on fine and coarse aggregates to assess their physical and mechanical characteristics, ensuring their suitability for concrete production. The outcomes of these material tests formed the basis for understanding the performance differences between conventional concrete and metakaolin in the subsequent experimental program. An M30 grade concrete mix was designed and adopted as the control mix for conventional concrete. The same mix proportions were maintained for all mixes to ensure consistency, and cement was partially replaced with Metakoalin at levels of 10%, 20%, and 30% by weight of cement. Based on these mix designs, concrete specimens were cast in the form of cubes, cylinders, and prisms for evaluating the mechanical performance of both conventional and metakoalin-modified concrete. This methodology enabled a systematic assessment of the influence of varying metakolin replacement levels on the strength characteristics of concrete.

VI. RESULTS

The results section presents the outcomes of strength tests conducted on the cast specimens, including cubes, cylinders, and prisms. Compressive strength tests were performed on cube specimens, split tensile strength tests on cylindrical specimens, and flexural strength tests on prism specimens to evaluate the mechanical behavior of the concrete. The measured strength values obtained for conventional concrete and metakaolin-modified concrete at different replacement levels are reported and compared. These results provide a clear understanding of the influence of steel fibers incorporation on the strength performance of concrete.

AB 1: RESULTS OF CONVENTIONAL BEAM(B1)

Load (kN)	Deflection at l/2 (mm)	Deflection at l/3 (mm)	Remarks
0	0	0	
15	0.5	0.2	
28	2.7	0.7	First crack
35	3.3	1.15	
44	4.6	1.4	
50	7	2.3	Ultimate Load

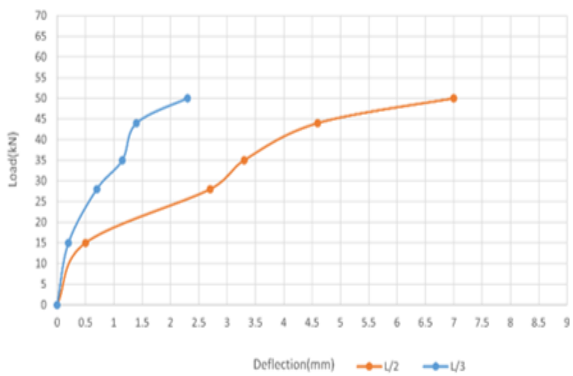

FIG 1: GRAPH RESULTS OF CC BEAM (B1)

The above graph represents the load–deflection behavior of the conventional concrete beam under two-point loading .

TAB 2: RESULTS OF 20% METAKOALIN BEAM (B2)

Load (kN)	Deflection at l/2 (mm)	Deflection at l/3 (mm)	Remarks
0	0	0	
12.7	0.6	0.2	
27.7	2.1	0.9	
31.7	2.6	1.2	First crack
43.6	4.1	1.9	
50.2	5	2.4	Ultimate Load

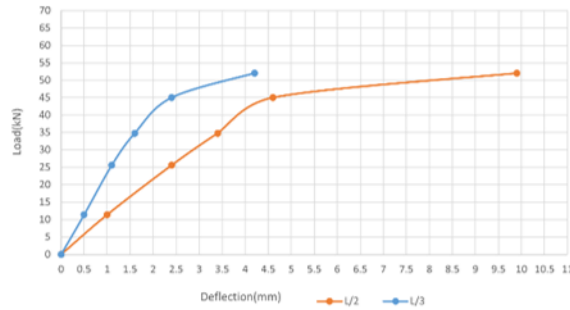

FIG 2: GRAPH RESULTS OF 20% METAKOALIN BEAM (B2)

The above graph represents the load–deflection behavior of the 20% starcrete beam under two-point loading conditions.

TAB 3: RESULTS OF 1% STEEL FIBER BEAM (B3)

Load (kN)	Deflection at l/2 (mm)	Deflection at l/3 (mm)	Remarks
0	0	0	
11.4	1	0.5	
25.6	2.4	1.1	
34.8	3.4	1.6	First crack
45	4.6	2.4	
52	9.9	4.2	Ultimate Load

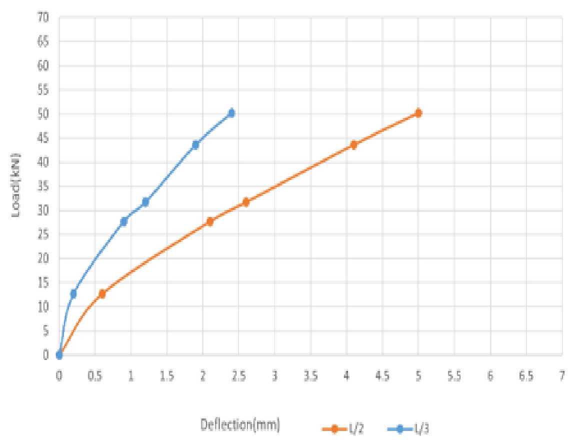

FIG 3: GRAPH RESULTS OF 1%STEEL FIBER BEAM (B3)

The above graph represents the load–deflection behavior of the 1% Steel fiber beam under two-point loading .

TAB 4: RESULTS OF 20% METAKOALIN AND 1% STEEL FIBERS BEAM

Load (kN)	Deflection at l/2 (mm)	Deflection at l/3 (mm)	Remarks
0	0	0	
17.1	1.1	0.6	
34.7	2.6	1	
45.9	3.5	1.5	
63.9	5.8	2.2	
73.8	10.9	3.1	
82.7	13.6	6.1	Ultimate Load

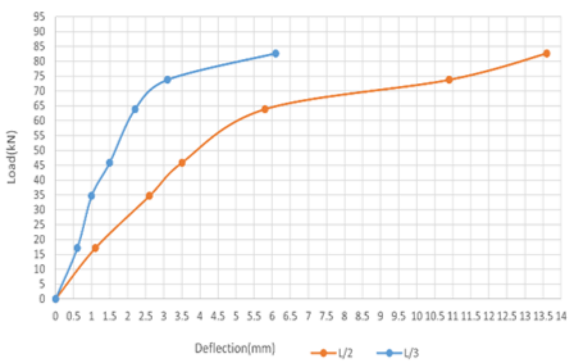

FIG 5: GRAPH RESULTS OF 20% METAKOALIN AND 1% STEEL FIBERS BEAM

CRACK PATTERN AND FAILURE MODE

Crack pattern refers to the distribution, direction, shape, and location of cracks that develop in a structural member when it is subjected to loading. It helps in identifying the type of stresses acting on the structure, such as flexural, shear, or torsional stresses.

FIG 5: FAILURE OF BEAM

VII.CONCLUSION

This project effectively demonstrates the potential of incorporating Metakaolin and steel fibers into concrete to enhance both environmental sustainability and structural performance.With an average compressive strength gain of about 1.8-3%, split tensile strength gain of about 1.4-12% and flexural strength gain of about 0.32% when compared to the control, metakaolin replacement levels of about 10% .With an average compressive strength gain of about 4-8%, split tensile strength gain of about 4.3-12% and flexural strength gain of about 5-6% when compared to the control, metakaolin replacement levels of about 20% in this study demonstrated the best performance. A 20% replacement provides the ideal ratio of Metakaolin to portlandite (the free calcium hydroxide byproduct) to maximize the pozzolanic reaction. This process converts the weak and permeable calcium hydroxide into a strong, cementitious C-S-H gel.With 20% metakoalin, the fine particles fill a significant number of voids in the cement paste, creating a denser and less permeable microstructure. This denser packing not only increases strength but also enhances the concrete's resistance to sulfate attacks, chloride penetration, and other environmental degradation, improving its long-term durability

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