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Comparative Analysis of Mechanical Properties and Concrete Quality with Partial Replacement of Cement by Silica Fume and Metakaolin Using M-Sand as Fine Aggregate

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ABSTRACT: The review explores alternative construction strategies to stretch existing budgets and increase road capacity. It presents three options: replacing cement with Metakaolin, GGBS, and Silica Fumes, which can reduce cement dependency in concrete and enhance its strength and durability. High-strength concrete, with a characteristic cube strength above 40 MPa, is used in bridges, aqueducts, high-rise buildings, and dams. The study found that substituting cement with metakaolin, GGBS, or a combination of these materials improved compressive strength, workability, and durability. Additionally, the study examined the strength properties of M-80 grade concrete with Glenium B233, revealing that the strength of concrete increases with the addition of metakaolin, and the workability of concrete with GGBS is also improved.

KEYWORDS: Silica fume (SF); Manufactured sand; Metakaolin, replacement of coarse aggregate, Ordinary Portland cement.

I. INTRODUCTION

Concrete is widely used in civil engineering due to its brittleness combined with high compressive strength and low tensile strain capacity. Cracks develop when loads exceed the tensile strength of the material. Adding concrete to the matrix improves energy absorption and crack resistance. Recent studies show that concrete made with ground granulated blast furnace slag (GGBS) effectively prevents steel reinforcement from corroding, thereby increasing the structure's durability. GGBS concrete reduces corrosion and enhances durability by replacing a portion of the cement with industrial waste, without significantly increasing costs. This innovative method is gaining popularity globally.

The current study investigates the effectiveness of metakaolin as a mineral admixture and its impact on concrete properties. Metakaolin was mixed with cement in various ratios to study its effect on concrete strength. Concrete mixtures were prepared using ordinary Portland cement as the control and with 10%, 20%, and 30% metakaolin as a replacement for cement. The physicochemical properties and compressive strength of the concrete were then evaluated.

II. LITERATURE REVIEW

Compared to river sand, manufactured sand (M-sand) particles are more angular and have a rougher surface. M-sand also contains significant amounts of rock micro fines, which are particles smaller than 75 micrometers. Studies have shown that increasing the amount of limestone micro fines in M-sand from 4.3% to 20% by weight enhances the compressive and flexural strength of cement blocks and improves the abrasion resistance of Plain Cement Concrete (PCC). An increase in surface roughness, a decrease in crushing, and a lower Los Angeles abrasion value of the sand all contribute to better abrasion resistance in PCC.

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Natural river sand is the cheapest source of sand material, but excessive riverbed mining to meet the rising demand for construction sand has caused ecological imbalance. Today's riverbed sand is coarse with a high percentage of silt and clay, which weakens concrete blocks and retains moisture in the sand particles.

While there are a few alternatives, manufactured sand (M-sand) is considered the best replacement for river sand. M-sand has gained attention from both environmentalists and the construction industry due to its high quality and low environmental impact. Using M-sand can significantly reduce costs as it is free of contaminants, produces minimal waste, and is manufactured with advanced technology. As M-sand becomes more popular in the construction sector, the demand for river sand and illegal sand mining would decrease. The particles of M-sand are more spherical and granular, which helps to mitigate common concrete defects such as honeycombing, segregation, voids, and capillaries.

III. MATERIALS

Metakaolin:

Metakaolin (POZZOFILZ) is a supplementary cementitious material (SCM) that meets ASTM C618 and Class N pozzolan standards. POZZOFILZ HRM is produced from a naturally occurring mineral and is manufactured under strictly controlled conditions to improve its color, remove inert impurities, and optimize particle size for a much higher degree of purity. Additionally, achieving pozzolanic reactivity enhances various concrete properties while reducing cement consumption.

Figure 1. Metakaolin

Metakaolin is produced by heating the natural clay mineral kaolin to temperatures between 650°C and 800°C. Beyond this temperature range, metakaolin becomes inert and non-reactive. The transformation from kaolin to metakaolin is known as hydroxylation. The process involves the removal of water and the formation of metakaolin as an aluminosilicate with alumina (40–45%) and silica (50–55%). Typically, metakaolin appears as a white powder with particles smaller than 2 micrometres, finer than Portland cement. When metakaolin reacts with available calcium hydroxide or portlandite, it forms secondary calcium silicate hydrate (C-S-H) along with other hydrates (C4AH13, C3AH6, and C2ASH8), which can enhance concrete performance. The characteristics of concrete, such as its resistance to chloride, are influenced by its microstructure and hydration states.

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Table 1. Test Results for Workability & Compressive Strength of MK

MK (%)	SLUMP (mm)	SP (%)	COMPRESSIVE STRENGTH (N/mm^2)	
			7-days	28-days
0	45	0.32	56	72
5	50	034	58	74
10	50	034	64	84
15	50	0.34	76	90
20	50	0.34	62	80

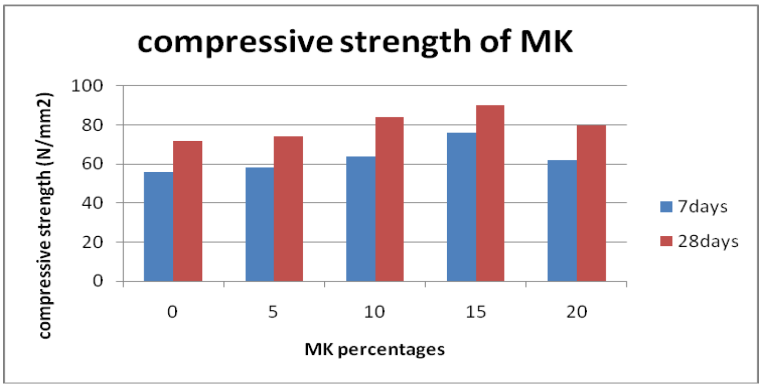

Figure 2. Test Results for Compressive Strength of MK

Manufacture Sand:

The relationship between the characteristic compressive strength of concrete mixes and the use of manufactured sand as an admixture over 7, 14, and 28 days shows that concrete strength increases steadily up to a certain point but then starts to decrease with higher amounts of manufactured sand. Experimental results indicate that incorporating manufactured sand as a filler up to 40% by weight enhances the initial compressive strength of concrete blocks. While the initial and final compressive strengths decrease with a 30% increase in manufactured sand in the mix, they rise by 10% to 20% after 7 days and by 10% to 15% after 28 days when lower amounts of manufactured sand are used.

S.No.	MANUFACTURED SAND (%)	Average Strengthat 7 Days (N/mm^2)	Average Strengthat 14 Days (N/mm^2)	Average Strengthat 28 Days (N/mm^2)
1	0	18.44	22	25.3
2	10	28.59	36.87	47.78
3	20	31.22	40.2	49.0
4	30	32.55	41.52	50.53
5	40	32.73	40.2	47.1

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Silica Fume:

Also known as micro silica, silica fume is an amorphous (non-crystalline) form of the mineral silica. It is an ultrafine powder collected as a byproduct during the production of silicon and ferrosilicon alloys. Silica fume consists of spherical particles with diameters less than 1 micrometer and an average diameter of about 0.15 micrometers, making it roughly 100 times smaller than typical cement particles. Its bulk density varies between 130 and 600 kg/m³, depending on the degree of densification in the silo. Ahmad et al., in their study of concrete incorporating waste paper sludge ash as a partial cement replacement, found that using 5% less cement and more waste paper sludge ash led to a 10% increase in compressive strength after seven days and a 15% increase after 28 days. Consequently, there has been increased effort to find suitable local resources for producing pozzolanic cement. To reduce greenhouse gas emissions, much of the rising demand for cement could be met through the use of supplementary cementing materials (Bentur, 2002).

IV. PROBLEM STATEMENT

Based on the literature review, the following conclusions can be drawn:

This study aims to evaluate the compressive strengths of concrete incorporating GGBS and metakaolin (MK) as alternatives to concrete made with Ordinary Portland Cement (OPC). The specific objectives include:

Exploring substitute materials such as fly ash, copper slag, and silica fume as alternatives to GGBS and MK.

Investigating the potential of metakaolin, a cost-effective alternative to the more commonly used super pozzolans, in enhancing concrete performance.

V. CONCLUSION

The following conclusions can be drawn from the results presented in the previous chapter:

1. Concrete cubes without chemical admixtures were tested for compressive strength, and their mechanical behavior was analyzed. Curing times of 7, 14, and 28 days showed a notable increase in the strength of the concrete.
2. Replacing 10% of the cement with manufactured sand under moderate conditions resulted in improved compressive strength at 28 days, while substituting up to 40% of the cement with manufactured sand in milder conditions led to variations in compressive strength.
3. Adding manufactured sand as an additive can be highly effective in enhancing the cohesion between mortar and concrete.
4. The study suggests that manufactured sand can serve as a substitute filler material, with up to 40% replacement yielding excellent results in terms of both strength and quality.
5. Increasing the amount of manufactured sand up to 40% will also enhance the durability and workability of concrete.
6. A concrete mix with a 20% replacement of manufactured sand for fine aggregate is the most cost-effective and provides high compressive strength compared to a standard mix.

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