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Experimental Study on the Mechanical Properties of Concrete using Metakaolin and Waste Glass Powder for Sustainable Construction

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***Abstract*— As current demand for sustainable construction materials in the world today has made researchers pay attention to eco-friendly construction materials which do not negatively impact the environment, besides not influencing the strength of the material. The current study examines the mechanical properties of concrete using "Metakaolin (MK) and Waste Glass Powder (WGP) as some of the alternatives. Various concrete blends were made in varying amounts of metakaolin (3, 5, 6, 9 and 12) and waste glass powder (3, 5, 6, 9 and 12) as a weight percentage of cement. Cube and cylinders were to be cast, after which they were cured and tested at 7, 14 and 28 days to determine compressive and split tensile strength. The combination of 5 percent metakaolin and 12 percent waste glass powder presented the highest compressive strength that offered superior pozzolanic activity as well as superior microstructure.**

***Index Terms*— Metakaolin; Waste Glass Powder, Supplementary Cementitious Materials (SCMs), Mechanical Properties, Compressive Strength.**

I. INTRODUCTION

The foundation of the infrastructure development of the entire world is the concrete that is the subject of the biggest environmental problems, yet it is consumed in huge quantities, and its production is mainly associated with the fact that Portland cement production yields significant amounts of carbon. A thermally activated form of kaolinite clay (metakaolin) is generally known to be highly reactive and has a high potential for enhancing early and long term strength of the concretes.

Metakaolin as a waste-glass-powder mixture can be considered a sustainable solution that would have a potential of twofold benefit of the previous metakaolin improving the early-age performance and the previous waste glass powder improving the long-term performance. Despite these advantages, the optimal proportions, interactions and effects on mechanical propertie such as compression strength, split tensile strength, require further experimental studies.

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II. Review of Literature

Zhou, C., et al. (2025) Ground waste glass powder (WGP) functions as silica-rich supplementary cementitious material when ground to sufficient fineness (commonly <75 µm and often much finer), enabling pozzolanic reaction rather than deleterious aggregate ASR. Experimental syntheses show WGP typically performs best as a partial cement replacement in 10-20% range,with later age (56-90 days) strengths benefiting most because the glass pozzolanic reaction is comparatively slower than cement hydration.[1,2]
A growing international literature shows that combining Mk and WGP often yields synergistic effects superior to single -SCM mixes. Mechanistically , MK supplies alumina-rich reactive phases that accelerate early pozzolanic response and improve nucleration , while WGP supplies reactive silica that contributes strongly to later-age streth and further densification of the pore network [3] . Empirical studies and recent systematic reviews report optimized total binder replacements (typically 10-20% total) with split ratios (MK:WGP) commonly between 60:40 and 50:50, producing balanced early and later age strengths , improved flexural and split tensile performance , and enhanced durability indicators.[4]. The study investigated the use of crushed waste glass as sand replacement and metakolin as cement replacement in concrete. It showed that combination improve the density, compressive strength and frost resistance, while reducing the porosity [5]. The review explained that metakolin improves chloride resistance and durability by refining pore structure and increase chloride binding capacity.[6] This paper reviewd concrete containing waste glass powder, showing it can improve strength and sustainability when used in proper proportion.[7]. The review discussed waste glass as the partoal cement replacement, highlight its role in reducing cement usage and improving sustainability.[8]

III. Material Testing

A. Cementitious Binders

- Metakaolin (MK): A thermal activated dehydroxylated kaolinitic clay. It is highly reactive and acts as a pozzolan that refines the concrete microstructure by consuming portlandite to form additional C-S-H.
- Waste Glass Powder (WGP): Ground to a fineness of <75 µm to act as a silica-rich supplementary cementitious material (SCM). It contributes to long-term strength and pore refinement.
- Cement (OPC 53 Grade) used as the primary binders, conforming to IS 12269:1987. It is characterized by high early strength due to a high proportion of tricalcium silicate (C3S)

Physical properties of cement were determined as per relevant IS codes and are given below in Table I:

Table I: Physical Properties of Cement OPC 53 Grade

Sr. No.	Property	IS Code	Result
1	Standard Consistency	IS 4031 (Part 4)	As obtained in labortary
2	Initial Setting Time	IS 4031 (Part 5)	> 30 minute
3	Final Setting Time	IS 4031 (Part 5)	< 600 minute
4	Specific Gravity	IS 4031 (Part 11)	3.15

B. Fine Aggregates

Natural Sand

Natural river sand was clean, free from organic impurities, well graded as shown in Table II.

Table II: Physical Properties of Fine Aggregates

Material	Specific Gravity	Water Absorption (%)	Remarks
Natural Sand	2.60	1.0	Zone II grading

B. XRF on Materials

X -ray Fluorescence (XRF) analysis to determine the chemical and elemental composition of the supplementary materials used in the research. This testing is essential for identifying the oxide components as shown in Table III that contribute to strength of concrete and mortor mixes.

Table III: Chemical Composition

Oxide Compound	Metakaolin (%)	Ordinary Portland Cement (OPC) (%)	Glass Powder (%)
SiO_2 (Silicon Dioxide)	51.6	20.2	72.0
Al_2O_3 (Aluminium Oxide)	43.4	5.2	1.9
Fe_2O_3 (Ferric Oxide)	1.1	3.0	0.4

CaO (Calcium Oxide)	0.2	63.1	10.5
MgO (Magnesium Oxide)	0.1	2.4	1.2
Na_2O (Sodium Oxide)	0.1	0.2	13.7
K_2O (Potassium Oxide)	0.2	0.6	0.6
TiO_2 (Titanium Dioxide)	1.5	0.3	—
SO_3 (Sulphur Trioxide)	0.0	2.3	—
LOI (Loss on Ignition)	1.8	2.7	0.8

IV. METHODOLOGY

A. Materials Used

- Cement: The base binder , partially replaced by supplementary cementitious materials (SCMs).
- Metakaolin (MK): A thermally activated kaolinite clay used to improve early-age performance and refine the concrete microstructure.
- Waste Glass Powder (WGP): Ground glass (typically <75 µm) used to improve long-term performance through pozzolanic reactions.

B. Mix Proportioning

These study utilized water – cement ratio of 0.52 for all blends. Cement was replaced by WHA, and sand was replaced by QD in reverse proportions represented in Table IV.

TABLE IV: MIX PROPORTION

Name	Cement	Metakaolin	Glass Powder	Fine Aggregate	Coarse Aggregate
NC	100%	—	—	100%	100%
CM5G3	92%	5%	3%	100%	100%
CM5G6	89%	5%	6%	100%	100%
CM5G9	86%	5%	9%	100%	100%
CM5G12	83%	5%	12%	100%	100%
CM3G5	92%	3%	5%	100%	100%
CM6G5	89%	6%	5%	100%	100%
CM9G5	86%	9%	5%	100%	100%
CM12G5	83%	12%	5%	100%	100%

C. Cement Cubes Preparation and Casting

- Casting: Cement mix was poured into 150x150x150 mm diameter cube molds in three layers, each receiving 25 gentle strokes as shown in Fig.1.
- Curing: Demoulded after 24 hours.

Figure 1. Cubes Casting

D. Test on Specimen

- Compression Strength: Test performed on concrete cubes at 7, 14, and 28 days, revealed that Metakaolin accelerates early-age hydration due to its high pozzolanic reactivity, leading to rapid strength gains in the initial stages.

- Split Tensile Strength: Test conducted on cylindrical specimens, showed a linear increase in tensile capacity as these supplementary cementitious materials were added.

V. RESULT AND DISCUSSION

Compression strength with metakaolin and waste glass powder as showed in Table V.

TABLE V: COMPRESSION STRENGTH

Mix ID	7 Days (N/mm²)	14 Days (N/mm²)	28 Days (N/mm²)
NC	23.8	29.28	35.07
CM5G3	26.02	31.58	37.84
CM5G6	27.74	32.98	39.43
CM5G9	27.04	34.12	42.49
CM5G12	29.03	38.0	45.83
CM3G5	23.63	31.03	38.06
CM6G5	27.93	36.1	40.16
CM9G5	28.78	35.51	39.06
CM12G5	29.63	37.6	43.23

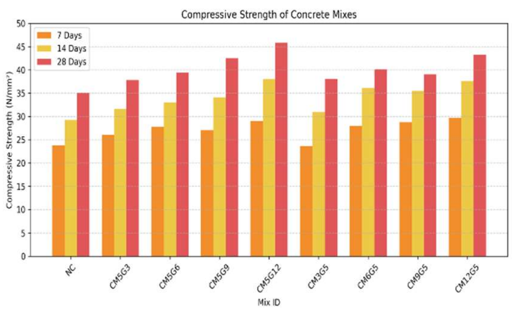

Figure 2. Compression Strength

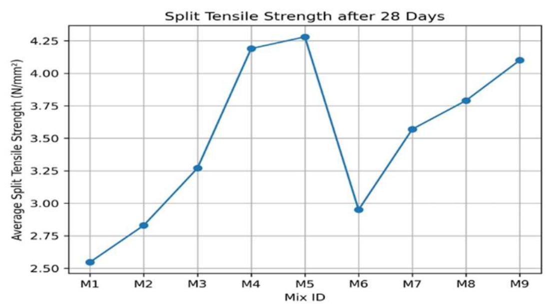

Figure 3. Split Tensile Strength

The experimental research focuses on enhancing the mechanical properties of concrete through synergistic use of agro-industrial waste as partial replacements traditional binders. In concrete study (M35 grade), the integration of Metakaolin (MK) and Waste Glass Powder (WGP) demonstrated that MK significantly improves early-age strength and microstructure through its high pozzolanic reactivity, while WGP contributes to long-term performance and further densification. The optimum mix was found to be 5% MK and 12% WGP, which achieved a compressive strength of 45.83 N/mm² and a split tensile strength of 4.28 N/mm² which we can see in Fig.2 and Fig.3, representing a substantial improvement over the control specimens as in Table V and Table VI:

TABLE VI: SPLIT TENSILE STRENGTH WITH METAKAOLIN AND GLASS POWDER (FOR 28 DAYS)

Mix ID	Description	28 Days (MPa)
M1	NC	2.547
M2	CM5G3	2.83
M3	CM5G6	3.27
M4	CM5G9	4.19
M5	CM5G12	4.28
M6	CM3G5	2.95
M7	CM6G5	3.57
M8	CM9G5	3.79
M9	CM12G5	4.1

VI. FINDINGS

A. Compressive Strength Improvement with Partial Replacement

Removal of metakaolin and waste glass powder in the concrete in different percentage proportions exhibited an increase in compression strength at an optimal rate as shown in Fig.3. In both materials, middle proportions have recorded significant increase in 28 days of compressive strength as compared to the control mix of M35 mix.[9]

B. Optimum Mix Performance

M5 as highest compressive strength of 45.83 N/mm2 at 28 days, respectively, which was higher than normal concrete strength of 35.07 N/mm2. It is shown that this replacement partially with metakaolin and waste glass powder influences the formation of strength positively.

C. Early Strength Development

The blends with metakaolin strengthened more rapidly at 7 days and 14 days of the blends compared with regular concrete. It implies that metakaolin can be applied in initial hydration reaction as it is pozzolanic activity.

D. Effect on Split Tensile Strength

Cylindrical specimens as well were found to have a linear increase in strength with addition metakaolin and waste glass powder. The mean tensile strength of 4.28 N/mm2 achieved with mix proportion M5 and 2.547 N/mm2 was achieved with control mix.

VII. CONCLUSION

The experimental study on M35-grade concrete concludes that the partial replacement of cement with Metakaolin (MK) and Waste Glass Powder (WGP) is a highly effective strategy for developing sustainable construction materials. The research demonstrates that these two supplementary cementitious materials (SCMs) work synergistically to improve both the mechanical strength. Metakaolin , a dehydroxylated kaolinite clay is highly reactive pozzolan which accelerates early-age hydration through nucleation effects. This result in the significant strength gains as early as 7,14 days compared to conventional. Portland cement concrete. Simultaneously, waste glass powder, ground to a fineness of less than 75 µm, provides a silica-rich source for secondary pozzolanic reactions. While glass powder typically reacts slower than cement , it contributes to long term strength .

Investigation identified that M5 mix, consisting 5% Metakaolin and 12% waste glass powder, is the optimal proportion for maximizing performance. Under this configuration the compressive strength reached 45.83 MPa at 28 days, which is substantial improvement over the 55.07 MPa observed in the control mix. The study also found a linear increase in tensile properties, with the split tensile strength of M5 mix peaks at 4.28 MPa, nearly doubling the 2.54 MPa recorded for standard concrete.

Beyond mechanical strength the physical filling effect of these finely graded material improve the overall particle size distribution, which increase packing density and reduce voids with the concrete. This definition result in a more durable materials with refined interfacial transition zone(ITZ). Ultimately, The research concludes that replacing cement with MK and WGP not only enhance the technical properties of the concrete but also provides an ecologically sound solution to the construction industry carbon footprint by reducing cement consumption and repurposing industrial waste.

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