SUSTAINABLE CONCRETE DESIGN USING METAKAOLIN, POLYPROPYLENE FIBERS, AND ROBO SAND: AN EXPERIMENTAL STUDY

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ABSTRACT:
Concrete production contributes significantly to global carbon emissions due to high cement consumption and the depletion of natural river sand. In response to environmental and resource-related challenges, this study investigates a sustainable concrete mix incorporating metakaolin as a partial cement replacement, polypropylene fibers for enhanced tensile performance, and robo sand as a substitute for natural fine aggregate. The experimental program evaluates the mechanical properties, workability, and durability of modified concrete mixes through standard compressive, tensile, and flexural strength tests. Various proportions of metakaolin (5%, 10%, and 15% by weight of cement) and polypropylene fibers (0.5% and 1% by volume) are examined along with a 100% replacement of natural sand by robo sand. Results reveal that the optimized blend enhances both strength and durability while reducing the reliance on conventional materials. The study demonstrates the feasibility of this composite approach for producing environmentally friendly and performance-efficient concrete in modern construction applications.

I.INTRODUCTION

1.1 General

Concrete remains the most widely used construction material across the globe, primarily due to its versatility, strength, and ease of production. However, the extensive use of Portland cement and natural river sand in concrete production raises critical environmental concerns. Cement production accounts for approximately 8% of global CO_2 emissions, while the extraction of natural sand disrupts ecosystems and contributes to riverbed degradation. Therefore, sustainable alternatives are being actively explored to minimize the environmental footprint of concrete without compromising its performance.

Metakaolin, a highly reactive pozzolanic material derived from the calcination of kaolin clay, has emerged as an effective partial cement replacement. It enhances the durability and strength of concrete while reducing the amount of cement used. Similarly, polypropylene (PP) fibers, known for their high tensile strength and corrosion resistance, improve crack resistance, ductility, and impact strength. Additionally, robo sand, a manufactured fine aggregate produced from crushed rock, offers a viable substitute for natural river sand, promoting sustainable resource use.

This study aims to evaluate the mechanical and durability performance of concrete made with metakaolin, polypropylene fibers, and robo sand. By experimenting with different proportions, the research seeks to determine the optimal mix design that achieves high strength, enhanced durability, and improved crack resistance. The goal is to develop a sustainable concrete alternative suitable for modern construction while aligning with global sustainability and material efficiency goals.

1.2 Metakaolin

The use of cement in concrete has substantial greenhouse gas (GHG) consequences, with each tonne of cement generating about 0.9 tonnes of CO2 emissions during production. Partially replacing cement with additional cementing ingredients such as fly ash, GGBS, silica fume pulverized lime stone, and metakaolin may decrease the "GHG signature" of concrete.

Metakaolin is a dehydroxylated version of kaolinite, a clay mineral. China clay, often known as kaolin, is a kaolinite-rich stone that has historically been utilized in the production of porcelain. Metakaolin has a particle size that is lower than cement but not as fine as silica fume. It's also a pozzolanic substance. Calcination of kaolinitic clay at temperatures ranging from 700°C to 800°C produces it. Metakaolin is an useful additive for concrete/cement applications since it has twice the reactivity of most other pozzolans. When Portland cement is replaced with 8–20 percent (by weight) metakaolin, a concrete mix with advantageous technical characteristics emerges, including the filler effect, OPC hydration acceleration, and the pozzolanic reaction.

1.3 Robo Sand

Robo Sand, a byproduct of the stone crushing process that is readily accessible at cheap cost from rock quarries in many places, may be a cost-effective alternative to river sand. Robo Sand is described as the residual or tailing material left behind after rocks have been extracted and processed into tiny particles smaller than 4.75 mm. Robo Sand, which is often seen as a waste product, contributes to environmental pollution as a result of its disposal issues. Given that Robo Sand is a large waste product, using it in concrete seems to have a lower environmental effect. As a result, using robo Sand as a fine aggregate in concrete would decrease demand for real sand while also reducing environmental issues. Furthermore, using robo Sand as fine aggregate will reduce the cost of producing concrete, turning this waste material into a useful resource.

1.4 Scope of the work:

- The impact of Metakaolin on higher concrete grades should be studied.
- Several concrete mixtures were created. Compressive strength, split tensile strength, and flexural strength are the primary characteristics investigated.
- The mechanical characteristics of this concrete were compared to those of traditional concrete. Metakaolin replacement percentages of 0%, 5%, 10%, 15%, and 20% with robo sand replacement percentages of 10%, 20%, 30%, 40%, 50%, 75 percent, and 100% for fine aggregate.
- Concrete specimens were produced to evaluate mechanical characteristics.
- Cubes' compressive strengths differ from cylinders' tensile strengths and prisms' flexural strengths (Beams).
- After 7 and 28 days of curing, the outcomes of the specimens were discovered.

II.METHODOLOGY

2.1 General

In this experiment, the compressive strength, flexural strength, and split tensile strength of polypropylene fiber reinforced metakaolin based concrete are compared to the strength characteristics of conventional concrete. Initially, the tests were performed with the goal of partly replacing the cement with metakaolin content ranging from 5% to 20%, so that the monitoring of the optimal dose of metakaolin may be investigated in a wide way while keeping the strength criteria in mind. Polypropylene fibers are now added at various concentrations of 0.3 percent, 0.6 percent, and 0.9 percent to get the optimal proportion of metakaolin. The concrete mix was developed in accordance with IS 10262: 2009, taking into account all design factors such as the selection of the water-cement ratio, and the specimens were cast and tested to determine the outcomes. The tests were carried out in accordance with Indian norms, resulting in minimum errors in the depiction of the findings. At the ages of 7 and 28 days, cubes, cylinders, and beams were tested.

2.2 Collection of Materials

The materials utilized in the project work are listed below, with descriptions of each. The following are the details:

- Cement
- Aggregate (coarse and fine)
- Polypropylene fiber
- Metakaolin
- Robo sand

Table: 2.1: Sources of material

Materials	Source
Cement	Ultratech cement
Robo sand	Cmr cet
Polypropylene fiber	Cmr cet
Metakaolin	Cmr cet
Coarse aggregate	Cmr cet

2.2.1 Cement

Cement is a substance that holds things together. It's the substance that holds the fine and coarse aggregates together. The strength of the concrete increases as the water to cement ratio drops.

There are two kinds of cements in general:

Ordinary Portland Cement is a kind of cement that is often used in construction.

Cement Portland Pozzolana No. 2

The cement utilized in this project is standard 53-grade portland cement. The cement is brownish green in colour, and there are no lumps in it. While storing the cement bags, precautions were taken to ensure that they were not exposed to the outdoors and that moisture did not penetrate the bag.

Fig : 2.1.Cement bag

Table: 2.2: Physical properties of Cement

Properties	Test Result
Specific Gravity	2.9
Fineness Modulus	7.9%
Initial Setting Time	35min
final Setting Time	310min
Standard Consistency	30%

Table: 2.3. Composition limits of Portland cement

Ingredient	% Content
Lime (Cao)	60-67
Silica (Sio_2)	17-25
Alumina (Al_2O_3)	3-8
Iron Oxide (Fe_2O_3)	1-6
Magnesia (MgO)	0.1-4
Alkalies	1
Sulpher	1-3

2.2.2 Coarse aggregate

Coarse aggregate is defined as aggregate particles with a diameter larger than 4.75mm. In traditional concrete, aggregates make approximately 60 to 80 percent of the overall volume. As a result, the aggregate should be chosen in such a manner that it is durable, efficient, and produces consistent concrete strength and workability. An excellent aggregate should be angular, hard, and robust, as well as devoid of hazardous chemicals and other pollutants. Concrete gains strength when the particles are properly sorted. If the aggregates are properly graded, the amount of cement paste needed to fill the voids is reduced, which means less cement and water is used, resulting in increased strength, lower shrinkage, and better durability, as well as cheaper construction costs. The aggregates utilized in the project come from angular quarries with diameters of 10mm and 20mm. The aggregates with a diameter of 10 mm pass through a 10 mm sieve but remain in the 4.5 mm range. 20mm aggregate is passed through 20mm and kept on 16mm..

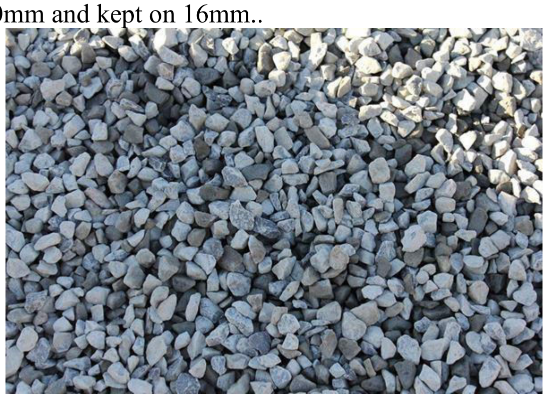


Fig: 2.2. Coarse aggregate

Table: 2.4: Physical Properties of Coarse aggregate

Coarse Aggregate	Results Test
Specific Gravity	2.85
Impact Value	19.22
Crushing Value	0.815
Density	1830kg/m^3

2.2.3 Metakaolin

The calcination of kaolin (clay material) at a high temperature produces metakaolin. It possesses pozzolanic characteristics that are very reactive. Metakaolin is an additive that is used in HSC as a partial substitute for cement (High Strength Concrete). It interacts with Ca(OH)2, a byproduct of the cement hydration process, to produce more C-S-H gel, resulting in enhanced strength.

Fig: 2.3.Metakaolin

Table: 2.5:Chemical properties of Metakaolin are as follows,

Silica (SiO2)	51-53%
Al2O3	42-44%
CaO	<20%
Fe2O3	<2.20%
SO4	<0.5%
K2O	<40%
Loss of Ignition	<0.50%

Table: 2.6: Physical properties of Metakaolin are as follows,

Physical Form	Powder
Color	Off white, Gray
Specific Gravity	2.40 to 2.60
Fineness	8000-15000M^2/Kg

2.2.4 Polypropylene fiber

A synthetic fiber made from a polypropylene melt is known as polypropylene fiber. It has a lesser resistance to wear. It has excellent heat insulation properties and is acid, alkali, and organic solvent resistant. Polypropylene is the lightest of all fibers, weighing less than a drop of water.

Fig:2.4. Polypropylene Fiber

Table: 2.7:Physical Properties of Polypropylene Fiber

Relative Density	0.91
Diameter(μm)	34
Length (mm)	12
Modulus of Elasticity	3750mpa
Geometry	Multifilament
Content	600-900g/m^3

2.2.5 Robo sand

Boulders are crushed to create crushed stone sand. Rock-on-rock or rock-on-metal Vertical Shaft Impact (VSI) is used to make manufactured sand, which closely resembles the process that created alluvial deposits. To achieve the required characteristics, particle size reduction and equidimensional form are essential. Many of the intrinsic characteristics of natural river sand are lost when rock is crushed under compression. Aggregates will become flaky and elongated if appropriate production techniques are not used. Before being used by the customer, sand may need to be improved by washing, grading, and mixing. In the case of manufactured sand, all of the aforementioned procedures may be completed within the production facility, and controls are considerably better in terms of creating high-quality fine aggregates.

Fig:2.5 Robo sand

2.2.6 Water

For mixing and curing, potable water is utilized. It must be devoid of harmful levels of oil, acids, alkalis, and other organic and inorganic contaminants. It should be devoid of iron, vegetable matter, and any other elements that may harm the concrete or reinforcement. It should be OK for drinking while being utilized in the concrete mixing process.

2.3 Equipment

The following is a list of the tools that were utilized in this project.

These items are purchased in accordance with their respective Indian Standard codes.

1.Tamping rod

2.Cubes, cylinders, and beams are examples of two-dimensional shapes.

3. Weighing scales

4. Testing machine for cubes.

2.4 Tests on Materials

The following are the many tests performed on the materials used in the project; various apparatus and equipment are used to test the quality and characteristics of the materials. These tests are carried out to determine the quality of the materials, and the findings aid in the mix design calculations. These fundamental tests must be carried out in order to get effective findings.

1. Gravity Specification
2. Relative Consistency
3. Analysis of Sieves
4. Cement Fineness
5. Absorption of water
6. Cement setting (first and final)

2.4.1 Specific Gravity

Specific gravity can be defined as the ratio of density of substance to the density of a reference substance.

Specific Gravity of Cement

Specific gravity is defined as the ratio of a material's density to that of a reference substance, or the ratio of a substance's mass to that of a reference substance for the same volume, using water as the reference substance. During the mix design calculation procedure, the material's specific gravity is utilized. For this test, a specific gravity bottle, a weight balance, kerosene, and cement were utilized as the equipment and supplies. Because kerosene does not react with cement, it is used instead of water.

The following procedures are used to determine the cement's specific gravity:

1.W1 gms is the weight of the empty specific gravity bottle.
2.A third of the capacity of a specific gravity container is filled with cement, and the weight of the bottle is recorded as W2 gms.
3. Fill the remaining 2/3 of the capacity of the specific gravity bottle with kerosene, and record the weight of the bottle as W3 gms.
4. Now carefully clean the specific gravity container and fill it solely with kerosene, noting the weight W4 gms.
5. Now solely use pure water to fill the specific gravity container, and record the weight W5 gms.

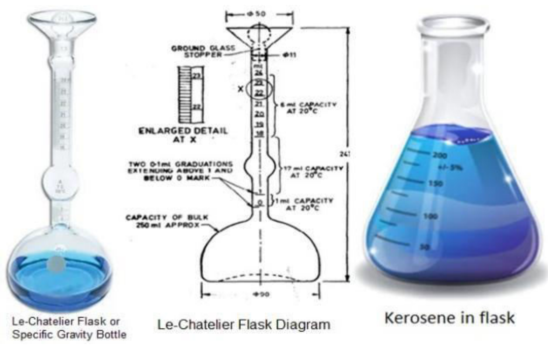


Fig :2.6. Le-Chatelier Flask

2.4.2 Test on Cement

Tests on cement are carried out to know the quality of cement. It gives idea about cement quality.

a) Normal Consistency

In this test, the Vicat plunger should penetrate 5 to 7 mm from the bottom of the Vicat mould. The quantity of water is given as a percentage [by weight] of dry cement. Normal consistency is another name for standard consistency.

A certain minimum amount of water must be mixed with cement in order to complete the chemical reaction between water and cement. If there is less water than this, the chemical reaction will not be completed, resulting in reaction strength. If there is more water, the water cement ratio will increase, reducing the strength. As a result, the proper w/c ratio is needed.

Aim:

To find out how much water is needed to make a standard consistency cement paste that may be utilized in other experiments.

Fig : 2.7.Vicat's Apparatus

The Results were showing in percentage.

2.5. Mix Design

Based on the quality of the materials used and their moisture content, concrete mix design recommends quantities of cement, fine aggregate, coarse aggregate, and water. The final mix proportions are recommended based on laboratory tests and mix design revisions. We can offer concrete with strength ranging from M10 to M100 and workability ranging from no slump to 150 mm slump value using mix design. Some admixtures are also needed to improve concrete characteristics such as setting time, workability, and so on. In order to make the most use of these admixtures, they must be taken into account during the mix design calculations. Because an excessive amount of them may alter the characteristics of concrete and compromise its strength.

2.5.1 Calculation of Mix Design

For M30 grade concrete, we need to determine the mix design. The mix design may be computed using the IS code (10262 – 2009) as follows.

Concrete Mix Proportioning

The following points give the general data of the concrete mix:

Grade designation: The concrete grade should be selected based on the function for which it will be utilized. As previously stated, the concrete grade is M30.

Type of cement: Ultratech OPC 53 grade cement was utilized in the construction of the project. This is the most often used cement in building.

Workability: Before proceeding with the mix design, the workability of the concrete should be anticipated in accordance with codal requirements. As a result, in this instance, the slump is considered to be 100mm.

Specific gravity: For calculating purposes, the specific gravity data should be utilized in the mix design. Which were acquired via the use of material testing.

Water absorption: Aggregates absorb a certain quantity of water, resulting in a reduction in water content. As a result, a proportion of water absorbed by the aggregates should be added to compensate.

Table : 2.8: Mix proportions

Materials	Weight
Cement	370 kg/m3
Water	167 kg/m3
Coarse aggregate	1259.84 kg/m3
Water-Cement ratio	0.45
Fine aggregate	681.775kg/m3

Mix details for concrete:

Table: 2.9.: Percentage of Metakaolin

Materials	0% MK	5% MK	10% MK	15% MK	20% MK
Cement(kg/ m3)	370	349.28	330.78	312.28	293.78
Metakaolin(kg/m3)	0	18.5	37	55.5	74
Fine aggregate(kg/m3)	681.775	681.775	681.775	681.775	681.775
Coarse aggregate(kg/m3)	1259.84	1259.84	1259.84	1259.4	1259.84
Water(liter)	167	167	167	167	167

Table:2.10 : Percentage of Polypropylene Fiber

Materials	0%PPF	0.3%PPF	0.6%PPF	0.9%PPF	1.2%PPF
Cement(kg/m3)	370	368.90	367.78	366.67	365.56
Polypropylene fiber(kg/m3)	0	1.11	2.22	3.3	4.4
Metakolin(kg/m3)	55.5	55.5	55.5	55.5	55.5
Fine aggregate(kg/m3)	681.775	681.775	681.775	681.775	681.775
Coarse aggregate(kg/m3)	1259.84	1259.84	1259.84	1259.84	1259.84
Water(liters)	167	167	167	167	167

III. RESULTS AND DISCUSSIONS

This chapter discusses the results of different strength tests of mechanical characteristics of concrete as well as the workability of concrete test. Compressive strength testing, split tensile strength testing, and flexural strength testing are all examples of strength tests. Also included in the workability test is the slump cone test.

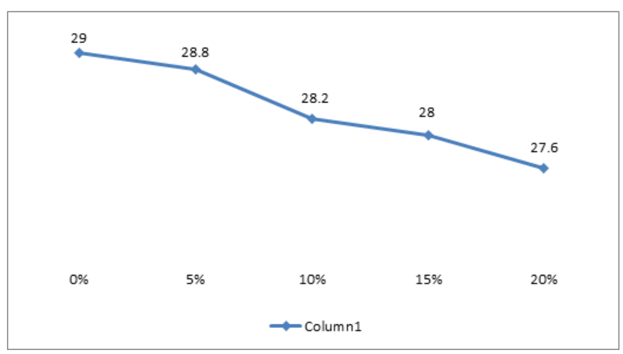
3.1 Workability Test Results

IS: 456-2000 is the Indian standard code. The slump value is determined by the placement circumstance (Type of structure). According to the findings, It is utilized in mass concrete, weakly reinforced sections in slabs, beams, columns, and floors with a slump of 25-75.

The findings of the slump cone tests for conventional and bottom ash concrete are described below.:

Table-3.1 Slump cone test results

S.No	w/c ratio	Percentage replacement of fine by Metakaolin	Type of slump	Slump value in (mm)
1.	0.45	0%	True Slump	29
2.	0.45	5%	True Slump	28.8
3.	0.45	10%	True Slump	28.2
4.	0.45	15%	True Slump	28
5.	0.45	20%	True Slump	27.6



Graph: 3.1: Slump cone test

3.2 Compressive Strength Test

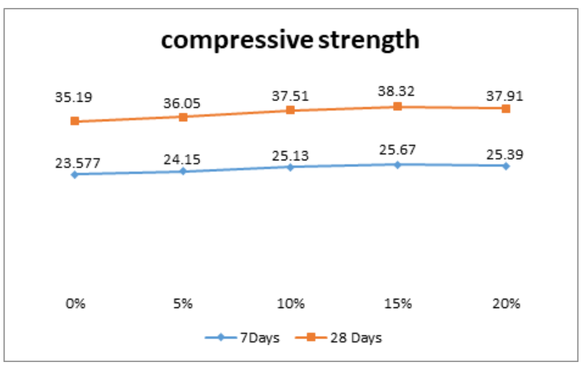
Concrete compression strength tests have been performed, and the results are tabulated and graphed below.

Table 3.2: Compressive strength of M30 concrete with varying % of metakaolin

% of Metakaolin	7 days	28 days
0%	23.577	35.19
5%	24.15	36.05
10%	25.13	37.51
15%	**25.67**	**38.32**
20%	25.39	37.91

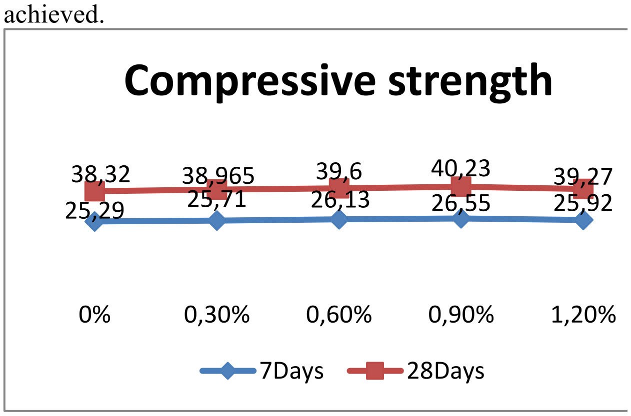
Table 3.3: Compressive strength of M30 concrete with optimum % of metakaolin and varying the % of polypropylene fiber

Optimum % of Metakaolin	% of polypropylene fiber	7 days	28 days
15%	0%	25.29	38.32
	0.3%	25.71	38.965
	0.6%	26.13	39.60
	0.9%	**26.55**	**40.23**
	1.2%	25.92	39.27



Graph: 3.2: Compressive strength of M30 concrete with varying % of Metakaolin

The compressive strength of concrete with various percentages of metakaolin is shown in the graph above. At 15% partial substitution of cement with metakaolin, the maximum compressive strength of concrete was achieved.



Graph: 3.3: Compressive strength of M30 concrete with optimum % of metakaolin and varying the % of polypropylene fiber

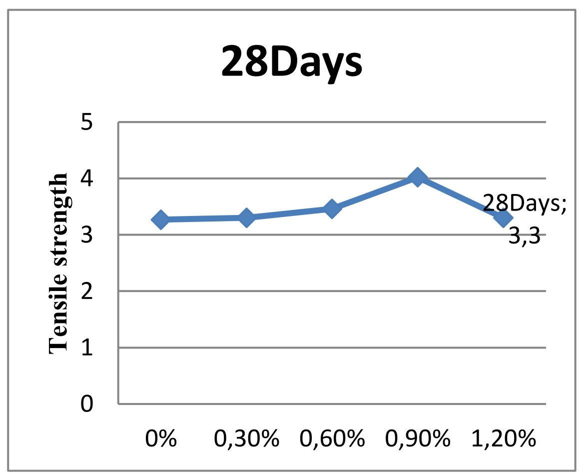
The graph above shows the compressive strength of concrete with the optimal amount of metakaolin (15%) and various percentages of Polypropylene fibers. Concrete's optimal compressive strength was achieved with 0.90 percent polypropylene Fibers.

3.2 Split tensile strength:

The results of split strength tests on concrete have been collated, and graphs have been produced below.

Table 3.4: Split tensile strength of M30 concrete with optimum % of metakaolin and varying the % of polypropylene fibers

Optimum % of Metakaolin	% of polypropylene fiber	28 days
15%	0%	3.27
	0.3%	3.3
	0.6%	3.46
	0.9%	**4.02**
	1.2%	3.3



Graph:3.4: Split tensile strength of M30 concrete with optimum % of metakaolin and varying the % of Polypropylene fiber

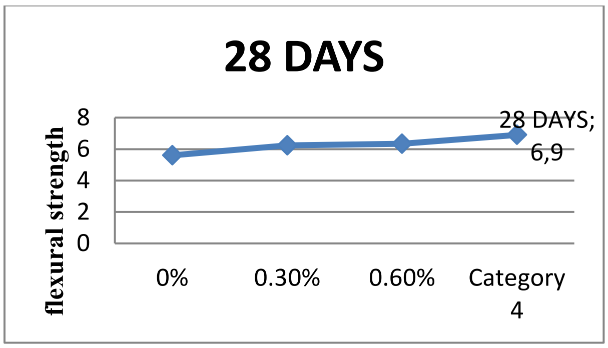
The split tensile strength of concrete with the optimal percentage (15%) metakaolin and changing the amount of Polypropylene fibers is shown in Figure 4.3. At 0.90 percent Polypropylene fibers, the optimal split tensile strength of concrete was achieved.

3.3 Flexural tensile strength:

The results of flexural strength tests on concrete have been collated, and graphs have been produced below.

Table 3.5: Flexural tensile strength of M30 concrete with optimum % of metakaolin and varying the % of polypropylene fibers

Optimum % of Metakaolin	% of polypropylene fiber	28 days
15%	0%	5.6
	0.3%	6.23
	0.6%	6.34
	0.9%	**6.9**
	1.2%	6.39



Graph:3.5: Flexural tensile strength of M30 concrete with optimum % of metakaolin and varying the % of Polypropylene fibers

IV.CONCLUSION

The experimental investigation demonstrates that the combined use of metakaolin, polypropylene fibers, and robo sand can effectively improve the sustainability and performance of concrete. Replacing cement with metakaolin enhances the pozzolanic reaction, leading to improved compressive and flexural strengths, while polypropylene fibers contribute to crack control and increased tensile strength. Meanwhile, replacing natural river sand with robo sand ensures resource conservation without negatively impacting workability or strength.

The concrete mix with 10% metakaolin, 0.5% polypropylene fibers, and 100% robo sand showed the most favorable balance between mechanical performance and environmental benefits. This mix achieved significant strength gains compared to the conventional concrete mix and demonstrated superior crack resistance and durability characteristics.

In conclusion, this research supports the practical implementation of sustainable concrete materials in the construction industry. The findings promote the use of industrial byproducts and synthetic fibers as eco-efficient alternatives, aligning with green construction practices and long-term environmental sustainability. Future studies may focus on long-term durability under aggressive environmental conditions and life cycle assessment of such sustainable mix designs.

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