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Partial Replacement of Cement with Metakaolin in High Performance Concrete

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ABSTRACT: According to ACI “High Performance Concrete is defined as concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using conventional materials and normal mixing, placing and curing practices”. Characteristics of high performance concrete include low permeability, stronger and denser transition zone between aggregate and cement paste in the concrete, as a result increases the abrasion resistance of concrete. Metakaolin is not a by-product of an industrial process; it is manufactured for a specific purpose under carefully controlled conditions. It is a highly reactive, amorphous material with pozzolanic and latent hydraulic reactivity, suitable for use in cementing applications. This study is intended to prepare a HPC mix for M70 grade and to find the optimum partial replacement of cement with metakaolin from selected dosages. The strength was found to increase by 6% when 10% by weight of cement was replaced with metakaolin.

I. INTRODUCTION

Cement concrete is the most extensively used construction material. Maintenance and repair of reinforced concrete structures is a growing problem involving significant expenditure. As a result, it has been made possible to process the material, to satisfy more stringent performance requirements, particularly long-term durability. High performance is generally linked with high strength, which is not true in every case. Deterioration of structures due to environmental effects indicates strength is not the only criteria to assure durability of the structure. Characteristics of high performance concrete include low permeability, stronger and denser transition zone between aggregate and cement paste which results in increased abrasion resistance of concrete.

Recent studies found that with the use of super plasticizer to reduce the water/cement (W/C) or water/binder (W/B) ratios, strength and other characteristics, such as fluidity, elastic modulus, flexural strength permeability, abrasion resistance, and durability had drastic improvement. This led to the development of HPC. The use of HPC has become popular these days and is being used in many projects such as Nuclear power projects, flyovers, multi-storied buildings etc. According to ACI “High Performance Concrete is defined as concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using conventional materials and normal mixing, placing and curing practices”. There is dramatic increase in the use of mineral admixture, considering factors such as cost saving, energy saving, environmental protection and conservation of resources. However, environmental concerns caused by the extraction of raw materials and carbon dioxide emission during cement manufacture have brought pressures to reduce cement consumption by the use of supplementary materials. Commonly used mineral admixtures are fly ash, rice husk ash, metakaolin, silica fume etc. They help in obtaining both higher performance and economy. Metakaolin's Contribution in HPC:

- Improved Strength: Metakaolin's reaction rate is rapid, significantly increasing compressive strength^{[1][4]}, even at early ages, which can allow for earlier release of formwork.

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- Improved Durability: Densification of the microstructure resulting from the pozzolanic and hydraulic reactions of metakaolin leads to greater impermeability. Significant improvements in service life can be achieved through metakaolin utilization in chloride environments, since in concrete mixes with metakaolin at 8 to 12% of the total cementitious materials, 50-60% decreases in chloride diffusion coefficient occurs^[2]. In addition, metakaolin has been shown to be highly effective in mitigating expansion due to alkali-silica reaction (ASR) and sulphate attack^[4].

- Improved Early Age Behavior: The relative fineness of metakaolin can result in decreased slump, but the use of water reducing admixtures or use in combination with fly ash in ternary mixes can compensate for this. Slumps of 125mm to 180mm have been achieved with metakaolin at water to cementitious materials ratio (W/C) of 0.36 to 0.38, using 25-35% less high-range water reducing admixture than comparable mixes. Metakaolin concrete tends to exhibit a creamy texture, resulting in better finishes^[7] compared to other finely divided standard concrete mixes. This quality also improves pumpability and can be used to impart detailed surface textures to cast surfaces^[6].

In this study an attempt is made to design a M70 grade HPC mix with metakaolin. The work was divided into two stages. First stage of the experimental work is the development of a M70 grade High Performance Concrete without any admixture. The second stage of the work is to study the strength parameters of optimum mix of HPC containing Metakaolin partially replacing Cement.

II. METHODOLOGY

The study intended to prepare a M70 HPC mix with super plasticizers for workability and no admixtures added to the concrete according to the procedure mentioned by Aitcin. The control mix is fixed from the 28th day compressive test results showing better strength and workability among different trial mixes prepared.

The cement from the control mix obtained is then partially replaced with metakaolin in different percentage by mass of cement (2.5, 5, 7.5, 10, 12.5, 15, 17.5 & 20%). Cubes of side 150 mm is prepared for each mix and are tested for 28th day compressive strength.

A. PROCUREMENT OF MATERIALS

Different materials collected are:

- Portland Pozzalanano Cement (Ultra Tech cements)
- Coarse aggregate - Natural aggregate of nominal size 12mm
- Fine aggregate - Manufactured Sand
- Metakaolin - (English India clays)
- Super plasticizer – (Cera-Chem Pvt.Ltd)

B. TESTING OF MATERIALS

(a) Tests on Cement: The tests performed are Fineness and Consistency as per IS 4031(Part 4) 1988, Initial and final setting time as per IS 4031 (Part 5) 1988 and Specific Gravity as per IS 4031 (Part 11) 1988.

(b) Tests on Coarse Aggregate: The tests performed on coarse aggregate are Sieve analysis as per IS 383-1970, Specific gravity as per IS 2386 (Part III) 1963, Bulk density, Fineness modulus and Water absorption.

(c) Tests on Fine Aggregate: The tests performed on fine aggregate are Sieve analysis as per IS 383-1970, Specific gravity as per IS 2386 (Part III) 1963, Bulk density, Fineness modulus and Water absorption.

C. FRESH AND HARDENED PROPERTIES

The HPC for 9 cubes for each mix is prepared and slump tests were carried out for the same to determine the fresh concrete properties. The cubes are then cured in water. The compressive strength are tested for 7th, 14th and 28th day of curing (3 cubes each). Control mix is selected from the trial mixes.

With the control mix selected, 9 cubes each with Metakaolin in variable percentage by weight of cement are cast and fresh concrete properties are found out. The cubes are cured in water, the compressive strength tested for 7th, 14th and 28th day of curing (3 cubes each). The optimum replacement from the percentages is found out.

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III. EXPERIMENTAL PROGRAMME

Experimental investigation was carried out to study properties of HPC and HPC incorporated with metakaolin. The aim is to prepare a M70 HPC mix with optimum metakaolin as partial replacement of cement among the selected percentages.

A. MATERIAL STUDY: CEMENT

Cement used for the study was Portland pozzolanic Cement (Ultratech cements). The fine aggregate used was Manufactured-sand and natural coarse aggregate of nominal size 12mm. Cerahyperplast XR-W40 was used as high range water reducing admixture to achieve self compatibility and flowability. Metakaolin was used as the replacement material for cement. Physical properties and chemical composition of metakaolin given by manufacturer are shown in Tables 1 and Table 2 respectively.

Table 1: Physical properties of metakaolin

Sl No.	Specification	Values
1	Physical form	Off white powder
2	Surface area	19-20
3	pH	4.5-5.5
4	Specific gravity	2.6
5	Bulk density	0.4-0.5
6	Moisture	0.5-1
7	Metakaolin content	97

Table 2: Chemical composition of metakaolin

SINo.	Compound	Percentage by weight
1	SiO ₂	52
2	Al ₂ O ₃	46
3	Fe ₂ O ₃	0.60
4	TiO ₂	0.65
5	CaO	0.09
6	MgO	0.03
7	K ₂ O	0.03
8	Na ₂ O	0.1
9	LOI	1.00

IV. MIX DESIGN OF HPC

Mix designing was made according to the procedure proposed by Aitcin. Mix design involves selecting of five mix characteristics or material proportions.

- W/B ratio
- Water content
- Super plasticizer dosage
- Coarse Aggregate Content
- Entrapped air content

First the water content is fixed from the graph proposed by Aitcin for the required 28th day strength as shown in Fig2. The amount of cement can be found out from the water binder ratio.

The combination of water and super plasticizer can be found by finding the saturation point of sp and carry out a factorial design experiment, this method not being practical always. A simplified approach is given below as an alternative for doing the factorial experiments, if the saturation point is known.

As the saturation point not known, 1% by weight of cement is assumed first then trial and error method is used.

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Quantity of coarse aggregates is assumed suitably with the shape of aggregate.

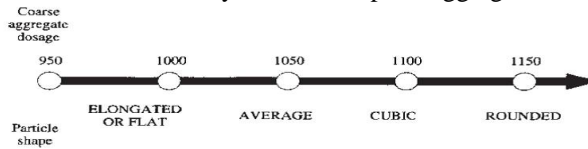


Fig 1: Coarse aggregate content^[9]

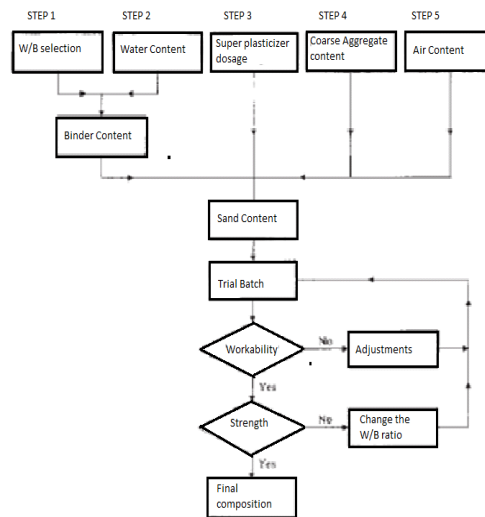


Fig 2: Flow chart of proposed mix design method^[9]

The air content is assumed to be 1.5%, the limits are between 1% and 3%. The water correction due to water absorption in coarse aggregate and fine aggregate is done as per the procedure proposed^[9].

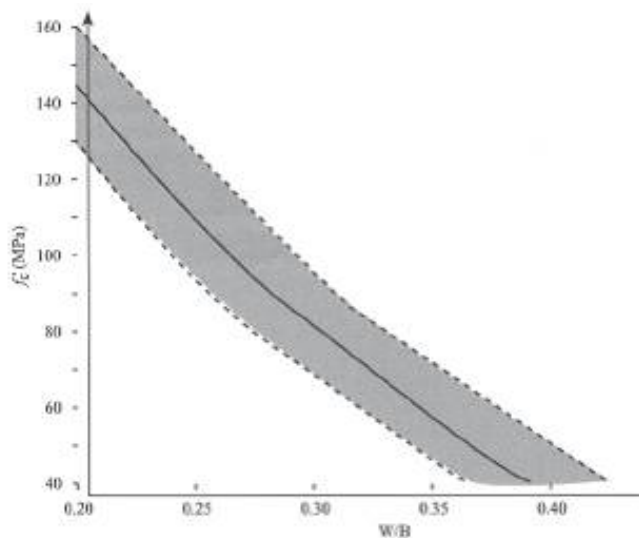


Fig 3: Proposed W/B vs Compressive strength relationship^[9]

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A. TRIAL MIX PREPARATION AND CUBE COMPRESSION TEST

Four trial mixes were prepared to obtain M70 mix with varying parameters as W/B ratio and dosage of super plasticizer. The quantity of materials used in each mix is tabulated in Table 3.

Nine cubes of side 150mm were cast for each mix and were cured in water. The 7th, 14th and 28th day cube compressive strength is measured. The control mix is chosen as the mix with required target strength at the 28th day test

Table 3: Mix proportion for Trial Mixes

Material	Trial mix composition			
	TM1	TM2	TM3	TM4
Cement (kg/m ³)	470	500	465	535
Coarse aggregate (kg/m ³)	1075	1075	1075	1075
Fine aggregate (kg/m ³)	635	581	619	517
W/B	0.3	0.3	0.32	0.3
Water (L/m ³)	107	118	117	130
Super plasticizer (L/m ³)	3.6 (1%)	4.5 (1.2%)	4.2 (1.2%)	5.6 (1.4%)

Mixes were prepared by partially replacing the cement content by weight with metakaolin on to the control mix obtained in varying proportions. Nine cubes for each mix were prepared and cured in water. The 7th, 14th and 28th day compressive strength is noted and the optimum replacement is fixed

V. RESULTS AND DISCUSSIONS

A M70 grade HPC mix with no added admixture is found out. From the control mix an optimum partial replacement of cement with metakaolin among the dosage selected is found out. The cube compressive strengths and the fresh concrete properties are recorded.

A. FRESH PROPERTIES AND COMPRESSIVE STRENGTH

For the trial mixes prepared the slump was found using slump cone test and was observed that the slump value increased as the dosage of super plasticizer increased. The compressive strength of mixes at 7th, 14th and 28th day of curing is obtained as tabulated in Table 4.



Fig 4: Setup of compressive test for trial mix 4

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Table 4: Strength of Trial Mixes

Trial Mix	Compressive Strength (N/mm ²)		
	7 th day	14 th day	28 th day
HPC TM 1	9.77	18.22	23.77
HPC TM 2	49.11	48.66	65.11
HPC TM 3	42	59.11	66.67
HPC TM 4	54	64.67	78.65

Material	Trial Mixes				
	M HPC2.5	M HPC 5	M HPC 7.5	M HPC 10	M HPC 12.5
Cement (kg/m ³)	5 21.6	5 08.2	4 94.8	4 81.5	4 68.1
Metakaolin (kg/m ³)	1 3.37	2 6.75	4 0.12	5 3.5	6 6.87
Coarse aggregate(kg/m ³)	1 075	1 075	1 075	1 075	1 075
Fine aggregate (kg/m ³)	5 17	5 17	5 17	5 17	5 17
W/B	0 .3	0 .3	0 .3	0 .3	0 .3
Water (L/m ³)	1 30	1 30	1 30	1 30	1 30
Super plasticizer(L/m ³)	5 .6	5 .6	5 .6	5 .6	5 .6

Table 5: Mix proportion for Trial Mixes

From the trial mix results TM4 was found to get M70 mix with a slump value of 200mm. In this mix the cement was partially replaced with metakaolin in percentage by weight of cement (2.5, 5, 7.5, 10 & 12.5%). The compressive tests was carried out at 7th, 14th and 28th day of curing and the results are tabulated in Table 6.

Table 6: Strength of Trial Mixes with Metakaolin

Trial Mix	Compressive Strength (N/mm ²)		
	7 th day	14 th day	28 th day
MHPC2.5	62	70.66	72
MHPC5	66	76	78.66
MHPC7.5	67	76.22	79
MHPC10	70	79.11	84
MHPC12.5	60	73.33	77.7

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Fig 4: Slump for trial mix 4

The optimum partial replacement of cement with metakaolin among the dosage percentage taken is found out to be MHPC 10 with 10% partial replacement of cement with metakaolin.

VI. CONCLUSIONS

The control mix was selected as the mix with maximum strength and considerable workability. TM4 showed satisfactory results with a 28th day compressive strength of 78.65 MPa and slump value of 200mm.

- High performance concrete for M70 mix was developed with 28th day strength of 78.65 N/mm².
- The strength of the specimens prepared with partial replacement of cement with metakaolin had improved.
- In 10% replacement the strength of specimens increased by 6% compared to control mix. With further increase in replacement dosage the strength was found to be decreasing.
- It can be concluded that the strength increase is due to the presence of silicon and aluminates that increases the cementing capacity. The workability was reduced while adding metakaolin which was rectified with the use of super plasticizer.

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