

Properties of High-Performance Concrete Containing High Reactivity Metakaolin

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Synopsis: High Reactivity Metakaolin (HRM) is an engineered pozzolanic mineral admixture, reacting aggressively with calcium hydroxide which results in significant performance of concrete. HRM has been introduced to be a beneficial alternative for silica fume, required in the formulation of high strength/performance concrete. In this study, different aspects of concrete mechanical behaviors have been studied including compressive, flexural and splitting tensile strengths. Also some characteristics of concrete durability were investigated including water absorption, water penetration and gas permeability. In mixture proportioning, 5%, 10% and 15% of cement content is replaced by HRM or silica fume for comparative study. It was observed that both concrete with HRM and silica fume would perform almost the same in improving the mechanical properties of the materials. However in the case of workability and durability, a better performance was obtained in concrete with HRM. It was concluded from the investigation that HRM could be an appropriate substitute for silica fume in producing high performance concrete.

Keywords: durability; gas permeability; high-performance concrete; Metakaolin; silica fume

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INTRODUCTION

Since the mid-1990s, High Reactivity Metakaolin (HRM) was introduced to engineers as a beneficial pozzolanic material for improving concrete properties. HRM is mostly manufactured by hydrocalcination of raw caolinite at the temperature range of 700 – 900 °C and contains high percentages of SiO₂ and Al₂O₃. HRM reacts rapidly and aggressively with Ca(OH)₂, via pozzolanic reaction to produce calcium silicate hydrates and calcium aluminosilicate hydrates. The presence of HRM accelerates the consumption of Ca(OH)₂, results to the subsequent modification of the microstructure of concrete, and improves strength and durability properties of the material¹⁻³. It has been reported that the replacement of cement by 5% to 15% HRM results in significant increase of compressive strength for producing high strength/performance concrete, specially in early ages^{4,5}. Also it has been observed that high durability of concrete would be achieved by using HRM, which results in decreasing the chloride penetration and sulfate attack, due to lower porosity of the material⁶⁻⁹.

In most studies on the effects of HRM on concrete behavior, w/b ratio of about 0.5 have been considered, though in few experiments, higher strengths were obtained with w/b ratio of about 0.3². The changes of ingredients in HRM depend on the chemical properties of the raw caolinite and the temperature of hydrocalcination. Most HRM products are white materials which affect the brightness of hardened concrete, as a way to reach attractive exposed concrete structures.

In this study, influence of two typical kinds of HRM and silica fume on the mechanical behavior of concrete was experimented including compressive, flexural, and tensile strengths. Also the durability characteristics of concrete were studied including water absorption, water penetration and gas permeability.

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EXPERIMENTAL PROGRAM

Materials

The materials used in this study were typical kinds of Portland cement type II, silica fume, HRM with chemical analysis presented in table (1). Also crushed aggregates with maximum size of 25mm and superplasticizer with polycarboxilate base have been used. Seven different mixture proportions were produced including a control mix and replacements of cement with silica fume or HRM in the ranges of 5%, 10%, and 15% by weight. The mixture proportions of experimental specimens are presented in table (2). For obtaining high strength concrete, w/b ratio of 0.26 was considered for all mixes and dosage of superplasticizer was altered from 1.2% to 1.8% of cement weight, in order to reach a consistent workability and slump of between 60 mm to 90 mm.

Sample Preparation

Different samples were prepared for a comprehensive study of HRM, including 150 mm cube specimens for compressive strength test, 100 × 100 × 400 mm prism specimens for flexure test, 300 × 150 mm cylindrical specimens for permeability and tensile strength tests, and 100 mm cube specimens for absorption test. Compressive strengths of concretes were measured after 3-days, 7-days and 28-days specimens while other tests were carried after 28 days of curing. Gas permeability test was experimented on disk specimens with the thickness of 50 mm and 150 mm in diameter cut from standard cylindrical specimens.

Test Procedure

Compressive, Flexural, and Tensile Strengths -- Compressive strength of all cube specimens was tested for the ages of 3, 7, and 28 days for observing the increase of strength in different mixture proportions in time (DIN-1048). Figure (1) shows the failure of a cube specimen under compression, indicating a high strength failure due to low w/b ratio and adding pozzolanic materials. Flexural test was carried out with three point loading method (TPL) for obtaining flexural strength of 28-days prism specimens (ASTM-C78). Tensile splitting strength was measured after 28 days of curing for cylindrical specimens in accordance with Brazilian Tensile test method (ASTM-C496).

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Gas and Water Permeability -- Gas permeability of concrete under a differential absolute pressure is a measure of the open porosity prevailing in the concrete. Gas flow depends not only on the pore structure of the solids, but also varies widely with the moisture content. As a material coefficient K_g (m^2), is determined for a steady-state laminar flow, taking into account the compressibility of the gas. Testing gas permeability is a rather rapid procedure; in general the time needed for one test is less than an hour. The instrument used in this study is shown in figures (2). Three disks with the thickness of 50 mm are cut from the top, middle and bottom of each 28-day cured cylindrical specimen. (RILEM-Report No. 12-Sec. 9.4)¹⁰

The water penetration of concrete was tested with the instrument shown in figure (3) on 28day cured cylindrical specimens. Water pressure was set to be 0.1 N/mm^2 for the first 48 hours, then 0.3 N/mm^2 for 24 hours, and 0.7 N/mm^2 for the last 24 hours (DIN-1048).

Water Absorption -- Water absorption of hardened concrete was tested on 28-days $100 \times 100 \times 100$ mm cube specimens. In the first step, cube specimens were kept in oven at the temperature of more than 100°C for more than 24 hours and then are weighed considering test method requirements. Then they were put in water with approximately 22°C for more than 48 hours and again were weighed considering standard requirements (ASTM-C642).

RESULTS AND DISCUSSION

Workability

It was observed that fresh concrete with HRM had a better workability, compared to control specimen and concrete containing silica fume. Also lower percentage of superplasticizer was used for obtaining the desired slump in the case of HRM.

Compressive, Flexural and Tensile Strengths

The results of compressive strength of all mixture proportions for 3-days, 7-days and 28-days are presented in table (3). Also the flexural and tensile strengths for 28-days are shown in table (4). For comparative study of strength improving in different ages, relative strengths are presented in table (5). As observed from the tables, it can be concluded that both HRM and silica fume have shown almost the same behavior in increasing the mechanical behavior. However, in the case of flexure, higher strength was obtained from concrete with HRM.

Gas and Water Permeability of Concrete

As presented in table (6), coefficients of concrete permeability, which have been derived from gas permeability test, show clearly the very low permeability of the material, especially for the specimens with pozzolans. Also in table (7), the results of water permeability test are shown. It can be concluded from the tables (6-7) that all mixes had very low permeability due to low w/b ratio and high cement content. However, HRM concrete showed a lower permeability of 50% that in control specimen, and 30% in the case of silica fume.

Water Absorption of Concrete

The results of water absorption of all mixes are shown in table (8). Based on the results, it can be concluded that all mixes had water absorption lower than 3% by weight, though, concrete with silica fume and HRM showed lower percentages of water absorption, less than 2%, which is highly desired for high performance concrete.

CONCLUSION

General improvements of mechanical behavior and durability characteristics of concrete with HRM and silica fume are shown in table (9). Following results have been concluded from the experiment:

1. All specimens including control, HRM, and silica fume concretes showed significant mechanical behaviors and durability properties, due to low w/b ratio and high cement content; however, the improvement of concrete properties was more considerable in the case of adding pozzolanic materials.
2. Both HRM and silica fume showed almost the same performance in improving concrete mechanical behaviors after 28 days, including compressive, flexural, and tensile strengths. Though better improvement was observed in durability characteristics from HRM concrete, including gas permeability, water penetration, and water absorption.
3. Better workability in fresh concrete and brighter color in hardened concrete were observed from HRM specimens which can be an alternative for decorative concrete.
4. It can be concluded that replacing the cement content with HRM by 10% to 15%, would significantly improve mechanical behaviors and durability properties of concrete required for producing high performance concrete.

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Table 1--Chemical Analyses of Cementitious Materials (%)

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	SO ₃	CaO	MgO	Na ₂ O	K ₂ O	P ₂ O ₅	MnO	L.O.I
Cement	20.9	6.19	3.86	0.4	-	65.9	0.2	0.17	0.6	0.05	0.06	1.53
Silica Fume	92.6	0.48	0.94	<0.01	-	0.4	0.63	0.28	1.24	0.02	0.23	2.54
HRM	53	43	1.2	<1.2	<0.1	0.1	0.1	0.05	0.3	-	-	1

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Table 2--Mixture Proportions for Concrete Specimens (Kg/m³).

Specimen code	cement	water	Super plasticizer	Coarse aggregate	Fine aggregate	HRM	Silica fume	Pozzolan (% b)	SP (% b)	w/b
C	450	110.5	5.4	904	904	0	0	0	1.2	0.26
M1	427.5	110.5	5.4	904	904	22.5	0	5	1.2	0.26
M2	405	110.5	6.3	904	904	45	0	10	1.4	0.26
M3	384.5	110.5	7.2	904	904	67.5	0	15	1.6	0.26
S1	427.5	110.5	5.4	904	904	0	22.5	5	1.2	0.26
S2	405	110.5	7.2	904	904	0	45	10	1.6	0.26
S3	384	110.5	8.1	904	904	0	67.5	15	1.8	0.26

Table 3--Rates of Compressive Strengths (MPa).

Specimen Code	3 days	7 days	28 days
C	48.4	59.0	73.7
M1	49.8	65.8	80.6
M2	48.5	69.3	83.7
M3	49.9	72.5	88.3
S1	50.1	55.9	72.5
S2	51.3	62.1	80.1
S3	50.8	69.3	88.4

Table 4--Flexural and Tensile Strength for 28 days (MPa).

Specimen Code	C	M1	M2	M3	S1	S2	S3
f_b	6.1	8.5	8.6	9.0	8.5	9.0	9.3
f_t	4.5	4.5	4.6	4.9	4.3	4.3	4.9

Table 5--Compressive Strength Increase.

Specimen Code	C	M1	M2	M3	S1	S2	S3
f_{c-7} / f_{c-3}	1.22	1.32	1.43	1.45	1.11	1.21	1.36
f_{c-28} / f_{c-3}	1.52	1.62	1.72	1.77	1.44	1.56	1.74

Table 6-- Gas Permeability coefficients (m²).

Specimen Code	C	M1	M2	M3	S1	S2	S3
Gas Permeability	2.1×10^{-19}	1.9×10^{-19}	0.88×10^{-19}	0.63×10^{-19}	1.9×10^{-19}	1.4×10^{-19}	1.2×10^{-19}

Table 7--Water Penetration for Concrete Specimens (mm).

Specimen Code	C	M1	M2	M3	S1	S2	S3
Water Penetration	6	3	1	0	4	1	0

Table 8--Water Absorption for Concrete Specimens.

Specimen Code	C	M1	M2	M3	S1	S2	S3
Water Absorption (%)	2.72	2.55	2.34	2.17	2.94	2.51	2.07

Table 9--Comparison of Mechanical and Durability Properties of Concrete Specimens.

	f_{c-3}	f_{c-7}	f_{c-28}	f_b	f_t	Water Absorption	Gas Permeability	Water Penetration
$\frac{M1}{C}$	1.03	1.11	1.09	1.40	1.06	0.92	0.9	0.5
$\frac{M2}{C}$	1.00	1.17	1.14	1.42	1.03	0.84	0.42	0.17
$\frac{M3}{C}$	1.03	1.23	1.20	1.48	1.05	0.78	0.3	0
$\frac{S1}{C}$	1.04	0.95	0.98	1.41	1.02	1.06	0.9	0.67
$\frac{S2}{C}$	1.06	1.05	1.09	1.50	1.09	0.91	0.67	0.16
$\frac{S3}{C}$	1.05	1.17	1.20	1.54	1.19	0.75	0.57	0



Figure 1--Concrete specimen after failure under compression.

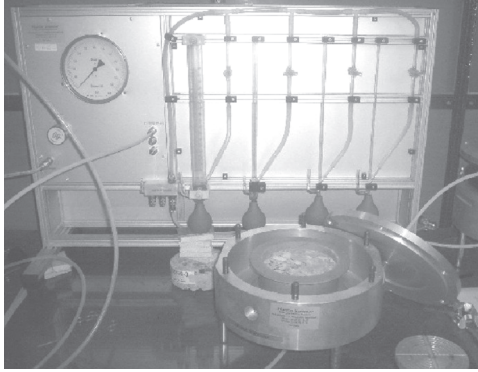


Figure 2—Gas permeability test instrument.

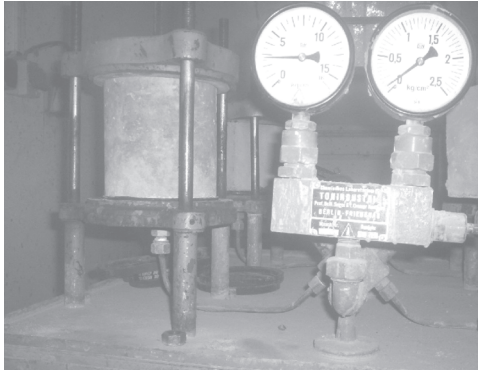


Figure 3—Water penetration test instrument.

