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Experimental analysis of strength and durability properties of quaternary cement binder and mortar

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HIGHLIGHTS

- Quaternary cement binder strength and durability.
- Quaternary cement mortar strength and durability.
- Supplementary cementitious materials like silica flume, GGBS, metakaolin, fly ash.
- Rapid chloride permeability test (RCPT).
- Development of new quaternary binder.

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ABSTRACT

The aim of this research work is to produce quaternary cement binders and mortars with combination of ordinary Portland cement (OPC) and supplementary cementitious materials (SCMs), such as, fly ash (FA), silica flume (SF), ground granulated blast furnace slag (GGBS), metakaolin (MK) and lime powder (LP) at 30% and 50% replacement levels. Water-binder ratio was kept constant (0.5) for binders and mortars. Normal consistency, setting time, density, water absorption and compressive strength (at ages of 3, 7, 28, 56 and 90 days) tests was carried out on quaternary binders. Compressive strength (at ages of 3, 7, 28, 56 and 90 days) and rapid chloride permeability (RCPT) (at 28 and 90 days), tests were carried out on quaternary cement mortars mixes of 1:3, 1:4, 1:5 and 1:6. The purpose of this investigation was to develop a new quaternary binder which can reduce our dependency on cement. The related combinations of quaternary binders showed better development in compressive strength than control binder. Quaternary mortars with the combinations of GGBS and MK showed better development in compressive strength and permeability than quaternary mortar with combination of lime powder. The overall performance of quaternary binders and mortars are adequate for industrial application.

1. Introduction

Concrete is one of the major construction materials throughout the world [1] owing to its design versatility, availability and cost efficiency. Ordinary Portland cement (OPC), which is a major constituent of concrete, is produced enormously. The blending of cement with SCMs has always resulted in many advantages such as savings in cement, recycling of waste products, and increase in physical properties along with increased durability of concrete and reducing impact on the environment by reducing green house gases produced. According to Isaia's [2] studies, when a less reactive pozzolan is employed in ternary mixtures together with another one more reactive such as silica fume or rice husk ash, there is a synergy between these pozzolans, thus the obtained result is higher than those verified in the respective binary mixtures; this result is called synergic effect. Cement production is responsible for about 5% of the global man made CO_2 emission. For each tone of cement being produced, an average of 0.87 tons of CO_2 is being emitted [3,4]. It is to be noted that for every ton of cement produced, approximately a ton of CO_2 is emitted seriously impacting the environment. Hence, increasing the use of supplementary cementitious materials (SCMs) in concrete is an obvious and necessary step to reduce carbon footprint in the

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production of cement. The use of SCMs can significantly reduce the embodied energy of precast concrete produced by substituting waste materials for relatively high energy hydraulic cement. SCMs, such as, fly ash (FA), silica flume (SF), ground granulated blast furnace slag (GGBS), metakaolin (MK) and lime powder (LP) are often available as waste materials from various industrial processes. Their judicious use in concrete production is desirable both for environmental and energy conservation as well as for the technical benefits. SCMs are added to concrete as part of the total cementitious binder system, either as an addition or partial replacement of Portland cement. Studies carried out on the durability of the quaternary binder and mortars indicates [5–7] their suitability for various applications in construction.

Several researchers [8–10] have used SCMs in the past to evaluate the effect of pozzolanic materials on the properties of fresh and hardened cement mortars. The natural pozzolana has been widely used as a substituent of the Portland cement in the concretes. In addition to its environmental and economic benefits, this also includes the decrease the permeability [11–15]. Studies of binary and ternary blends of SCMs have shown improvements in economy, early and later strength, durability and decrease in the heat of hydration as compared to unitary and binary concrete blends [16]. Probable and well investigated cement substitutions are silica rich materials like GGBS, FA and MK [17–27]. Several studies have reported utilization of FA, GGBFS and SF as supplementary cementitious materials in binary, ternary and quaternary binder blends.

These studies observed that the use of FA and SF in ternary blended cements provide better compressive strength than the binary blends. A critique of the literature indicates that synergy of binary blends of (OPC + silica fume, OPC + fly ash or OPC + BFS) and ternary blends (OPC + BFS + SF) and (OPC + FA + SF) has been thoroughly researched.

The aim of this study is to investigate the behavior of quaternary composite cements (OPC + FA + SF + BFS, OPC + FA + SF + MK and OPC + FA + SF + LP) as binders and mortars prepared and checked physical, mechanical and durability properties of binders and mortars.

2. Materials and methods

The materials used in this research work are: ordinary Portland cement (OPC-53 grade) confirming to IS: 8112-1989. Fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), metakaolin (MK) and lime powder (LP). The chemical and mineralogical compositions of different compounds are represented in Table 1. The mortars were prepared from these binders had a water/binder ratio of 0.5.

River sand confirming to IS: 383, grading zone – II was used as fine aggregate. The physical properties of sand are presented in Table 2.

Five series of cement binders were prepared: series-C (OPC), i.e., control binder, series-F (OPC + FA), series-G (OPC + FA + SF + GGBS), series-L (OPC + FA + SF + LP), series-M (OPC + FA + SF + MK). The mix proportions of the various binders and their physical characteristics are provided in Table 3.

Table 2
Physical properties of sand.

PROPERTIES	Test result
Specific gravity	2.64
Bulk density kg/m^3	1587
Fineness modulus	2.61
Porosity (%)	42.3
Absorption (%)	5.3

Cement binder and mortar cubes were cast in 70.6 mm × 70.6 mm × 70.6 mm moulds. The mixing of binders and mortars was carried out at room temperature (27 ± 2 °C). The mortar cubes were cast for 1:3, 1:4, 1:5 and 1:6 proportions at a water cement ratio of 0.5 and the mixtures were stirred for 3–5 min. After 24 h curing at 95% humidity, the samples were demolded and immersed in tap water and cured up to 28 days. Compressive strength tests were conducted as per IS 516-1959 in a Compression Testing Machine (CTM). All the strength values reported are an average of three specimens. The flow of mortar was kept constant at a value of 115 by utilizing super-plasticizer.

Rapid chloride permeability test (RCPT) performed according to AASHTO T 277 or ASTM C 1202 by monitoring the amount of electrical current that passes through a sample 50 mm thick by 100 mm in diameter in 6 h. The test results are obtained at 28 and 90 day of curing. A voltage of 60 V DC is maintained across the ends of the sample throughout the test. One lead is immersed in a 3.0% salt (NaCl) solution and the other in a 0.3 M sodium hydroxide (NaOH) solution.

3. Results and discussion

3.1. Consistency characteristics

Uses of supplementary cementitious materials increase the consistency of the fresh binder pastes because an additional volume of fines is added to the mixtures. The consistency values of different binder mixes in % are given in Table 3. Results indicate that fly ash and slag do not demand much water, but increase in their replacement levels increases the consistency of fly ash and slag mixes. Fineness of metakaolin was about 2.5 times that of fly ash and slag. Therefore, the consistency of MK mixes was relatively high for the same replacement level. The consistency of the binders with 15% MK was 20% higher than the control binder. However, for all other binder combinations the consistency increased by only 4.5% over the control value.

3.2. Setting characteristics

The setting time (initial and final) of the quaternary paste containing different replacement materials is provided in Table 3. From the results, it can be noted that in binary replacement (OPC and FA only) there is an increase in initial and final setting times. Similarly, in the quaternary replacement cases, there is an increase in the setting times (5–15%). In general, the increase in the setting times may be due to the reduction in the rate of pozzolanic reaction with

Table 1
Chemical and mineralogical compositions of compounds.

Description	Water	OPC	FA	GGBS	SF	MK	LP
Physical characteristics							
Specific gravity	1.00	3.12	2.26	2.86	2.23	2.51	2.21
Blaine's fineness, cm^2/gm	–	2285	3720	3250	16,018	8735	4387
Chemical characteristics							
Calcium oxide, Cao, %	–	66.72	1.31	35.90	1.45	1.47	56.53
Silicon dioxide, SiO_2, %	–	17.53	61.21	40.65	87.28	50.62	0.04
Aluminum oxide, Al_2O_3, %	–	9.82	24.98	17.07	0.9	46.91	0.06
Ferric oxide, Fe_2O_3, %	–	2.19	3.3	0.68	1.52	0.38	0.05
Manganese oxide, MnO, %	–	0.02	0.02	0.03	0.00	0.00	0.00
Magnesium oxide, MgO, %	–	1.24	2.60	3.75	0.13	0.09	0.10
Potassium oxide, K_2O, %	–	0.48	0.98	0.56	2.01	0.18	0.04
Sodium oxide, Na_2O, %	–	0.22	0.05	0.19	0.39	0.08	0.04
Loss of ignition, %	–	0.9	3.30	1.08	2	0.56	5.62