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A comparative study of self-consolidating concretes incorporating high-volume natural pozzolan or high-volume fly ash

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HIGHLIGHTS

- HVNP and HVFAF concretes can be used to produce environment-friendly SCC.
- HVNP and HVFAF concretes can effectively be used to produce low-cost SCC.
- HVNP and HVFAF concretes showed comparable strength to the reference concretes.
- HVNP and HVFAF concretes showed comparable durability to the reference concretes.
- In binary mixes, NP and FAF increase the flowability of concrete mixes.

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ABSTRACT

The purpose of this study is to compare the effects of Portland cement replacement on the strength and durability of self-consolidating concretes (SSC). The two replacement materials used are high-volume natural pozzolan (HVNP), a Saudi Arabian aluminum–silica rich basaltic glass and high-volume Class-F fly ash (HVFAF), from Jim Bridger Power Plant, Wyoming, US. As an extension of the study, limestone filler (LF) is also used to replace Portland cement, alongside HVNP or HVFAF, forming ternary blends. Along with compressive strength tests, non-steady state chloride migration and gas permeability tests were performed, as durability indicators, on SCC specimens. The results were compared to two reference concretes; 100% ordinary Portland cement (OPC) and 85% OPC – 15% LF by mass. The HVNP and HVFAF concrete mixes showed strength and durability results comparable to those of the reference concretes; identifying that both can effectively be used to produce low-cost and environmental friendly SCC.

1. Introduction

As of 2012, more than 25 billion tonnes of Portland cement concrete is produced annually making it the world's most widely used manufactured material [35]. Even though the reasons for concrete's dominance are diverse [25], the massive production and consumption cycle of concrete have significant environmental impacts, making the concrete industry unsustainable [22]. Currently, Portland cement concrete production accounts for around 7% of anthropogenic carbon dioxide (CO_2) emissions annually [22]. Most of the emissions are attributable to the production of Portland cement clinker; the active ingredient in Portland cement [15]. Using an increased proportion of supplementary cementing materials (such as natural pozzolan (NP) and fly ash) provides a sustainable solution, while yielding concrete mixtures with high workability, high durability, and comparable ultimate strength. The term of high-volume fly ash concrete was defined by Malhotra and Mehta [20], as concrete with at least 50% replacement of the Portland cement (OPC) by mass. As a low-cost alternative, HVFAF concretes have been used successfully in many projects providing both technical and environmental advantages to conventional Portland cement concrete [20]. With growing field experience of fly ash and increasing demand for environment-friendly structural materials, fly ash consumption through the concrete sector is expected to rise [23,20]. However, the global availability of fly ash is around 800 million tonnes annually [24], and not all of it is suitable for use in blended cements or concrete mixtures. As a result, there is a need for other alternative materials, natural pozzolan and ground limestone, being two possibilities [18,9,10,12,34]. Studies of Portland cement-based ternary and quaternary blends containing combinations of fly ash Class F (FAF), silica fume, blast furnace slag, ground limestone and natural pozzolans show that blended cements can be optimized to minimize the shortcomings of each component, resulting in synergistic properties of the cementing material [11,26,29].

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With the ongoing technological advances, the design and placement techniques of concrete are also changing. The ultimate target is the freedom in design while considering improved productivity, profitability, and sustainability. SCCs are highly engineered concrete mixtures obtained by optimizing normal concrete ingredients with a superplasticizer and a viscosity modifying agent (VMA). This study is based on the authors' previous work on SCCs [9,10], performed to analyze and compare the effect of NP/FAF as OPC replacement at 30 mass% and 50 mass% in SCC production without utilizing VMAs. The interaction of NP/FAF with LF is also studied in 30 mass%, 40 mass%, 50 mass% NP/FAF and 15 mass% LF in the ternary blended cements. The results are compared in terms of compressive strength development and durability performance with reference concrete mixes that have either no mineral admixture or 15 mass% LF.

2. Materials and methods

2.1. Materials

Khan and Alhozaimy [18] reported that NP used in the present work complies with the requirements of ASTM C618 for Class N; there are several studies describing its pozzolanic properties [17,27]. The mean particle sizes of the powder materials used in this study were determined by laser light scattering as 10.4 μm, 17.4 μm, 22.3 μm, and 48.1 μm for OPC (ASTM Type I/II), NP from Saudi Arabia, FAF from Jim Bridger Power Plant, Wyoming, US, and LF respectively. The chemical composition of the powder materials used was determined by X-ray fluorescence (XRF) and it is given in Table 1. Aggregates used include quartzitic sand with fineness modulus of 3.1, pea gravel with maximum size of 12.7 mm and basalt with maximum size of 19.0 mm. Two types of high-efficiency polycarboxylate-based superplasticizers (ADVA-140M/ADVA-405) with specific gravity of 1.04 and water content of 0.68 were used as <1.5 mass% cement (Table 2).

2.2. Concrete mixture proportions

Concrete mixture proportions are given in Table 2. The water to cementitious material ratio (W/CM), being the water to total binder ratio, was held constant at 0.35 for all mixes and the amount of superplasticizer (SP) was added to provide a slump flow diameter between 635 and 690 mm, and a diameter of 50 mm flow time, T_{50}, between 3 and 5 s. The actual W/CM ratio was 0.36 as the water contribution for the SP increased the overall water content. In order to reduce cement content compared to typical SCCs, the total aggregate to fines ratio was fixed at 4:1, and the cement replacement (CR) ratio ranging from 30 mass% to 65 mass%. For the ternary blends, the LF content was set as 15 mass%, and the ratio of NP/FAF was varied between 30 mass% and 50 mass%. The mix designs are entitled 55 OPC-30 NP/FAF-15 LF, for instance, for the 55 mass% OPC, 30 mass% NP or FAF, and 15 mass% LF mix. The ratio between coarse aggregates (CA) and fine aggregates (FA) was kept at 1:1. The CA consists of 30 mass% pea gravel and 70 mass% basalt.

Table 1
Chemical composition of powder materials (oxides, % by mass).

	OPC	NP	FAF	LF
SiO_2	20.44	46.48	62.0	0.70
Al_2O_3	3.97	14.74	18.90	0.50
Fe_2O_3	4.07	12.16	4.90	0.12
CaO	62.90	8.78	5.98	47.40
MgO	2.42	8.73	1.99	6.80
Na_2O	0.37	3.39	2.41	–
K_2O	0.43	1.27	1.14	–
P_2O_5	0.16	0.629	0.26	–
TiO_2	0.23	2.31	1.09	–
MnO	0.32	0.19	0.04	–
L.O.I.	4.69	1.324	1.30	44.48

2.3. Sample preparation

For the each mixture, a total volume of 22L of concrete was prepared in a pan planetary-type mixer. The mixing procedure was as follows; CA and a small amount of water were mixed for 30 s. OPC, NP/FAF and more water were added and mixed for one minute. LF and the rest of the water were added and mixed for a further minute before the superplasticizer was added and again mixed for one minute. Fine aggregate was then added and mixed for three minutes. During that time, the mixer was stopped and the bottom scraped to remove fine particles. Then, the slump flow test was performed. If the concrete was satisfactory, it was then returned to the mixer and mixed for an additional minute before casting. If the slump flow was too low or flow time too high, the concrete was returned to the mixer, mixed for an additional minute and the water reducer added until the desired workability was reached. The slump flow test was again performed. If the concrete was then satisfactory, it was remixed for an additional minute before casting. Otherwise, it was discarded and the mix attempted again with more or less water reducer.

The material was cast into eighteen 75×150 mm cylinders and three 100×200 mm cylinders in two lifts without mechanical vibration. Light shaking was allowed as the only method of consolidation for the SCC specimens. Cylinders were immediately covered with plastic wrap and remained undisturbed for 24 h in lab conditions. After 24 h, cylinders were demolded and placed in an environmental chamber (100% relative humidity at room temperature) to cure until testing in accordance with ASTM C192 [3].

2.4. Experimental procedures

Each mixture was evaluated based on slump flow, compressive strength, chloride penetration coefficient, and gas permeability testing. These were selected as indicators of consistency, mechanical strength and durability properties.

2.4.1. Slump flow test

Freshly mixed samples were subjected to the slump flow of SCC test (ASTM C1611) [4]; performed to determine fresh state properties of each mix. The flow diameter and T_{50} was recorded. To test for SCC criteria, flow diameter and T_{50} are checked to be between 635 mm and 690 mm, and 3–5 s, respectively. In addition, the stability of SCC was observed visually by examining the concrete mass in terms of segregation, bleeding and the mortar halo near the slump flow perimeter.

2.4.2. Compressive strength test

Compressive strength tests were performed after seven, 28, and 91 days of hydration. In accordance with ASTM C1231 and ASTM C617 [7,6], rubber pads capped the seven-day-old samples; all others were capped with sulfur capping compound. The cylinders were compressed at a stress rate of 0.25 ± 0.05 MPa/s, until significant softening was observed in accordance with ASTM C39 [5]. The peak load value was taken as the compressive strength. In order to identify and remove outliers from data set, the coefficient of variation (ratio of standard deviation to mean) was kept less than 10% for each mix-curing period combination. The cylinder size was chosen for convenience and economy. The use of small specimens with aggregate of 19.0 mm maximum size of aggregate in compressive strength tests may result in lower strengths when compared with standard-size specimens due to the "wall effect" [16,33]. Therefore, the correction factor of 102.94% was applied.

Table 2
Concrete mix proportions.

	OPC-NP/FAF-LF (mass%)	OPC	NP/ FAF	LF	FA	CA	W/ CM	SP (NP/FAF) (mass%)	CM (with NP/FAF) (kg/m^3)	OPC (with NP/FAF) (kg/m^3)	CR (with NP/FAF) (kg/m^3)
Control mixes	100-0-0	1.00	–	–	2	2	0.35	1.43[a]	461	461	0
	85-0-15	0.85	–	0.15	2	2	0.35	1.43[a]	458	389	69
Binary HVNP/FAF blends	70-30-0	0.70	0.30	–	2	2	0.35	1.08/1.39[a]	456/453	319/317	137/136
	50-50-0	0.50	0.50	–	2	2	0.35	1.03/1.14[a]	454/449	227/224	227/224
Ternary HVNP/FAF-LF blends	55-30-15	0.55	0.30	0.15	2	2	0.35	1.22/1.14[a]	454/451	250/248	204/203
	45-40-15	0.45	0.40	0.15	2	2	0.35	1.22/1.03[a]	452/449	204/202	249/247
	35-50-15	0.35	0.50	0.15	2	2	0.35	1.12/1.00[a]	451/446	158/156	293/290

[a] With high-efficiency polycarboxylate-based superplasticizer (ADVA 140M).