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Simplex-lattice strength and permeability optimization of concrete incorporating silica fume and natural pozzolan

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HIGHLIGHTS

- HPC with NP has improved sustainability and durability and satisfactory strength.
- The simplex-lattice design showed good capability to predict the strength of HPC.
- ANOVA confirmed the rationality of the quadratic simplex-lattice strength model.
- The solver tool of MS office provides a single optimum dosages of PC, SF and NP.
- The ternary plots exhibits two candidate superior strength regions of the HPC.

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ABSTRACT

In this paper, 24 high performance concrete (HPC) mixtures with 0.25 and 0.40 water-to-binder ratios (*w/b*) were designed and cast with binary and ternary blends of Portland cement (PC), silica fume (SF) and natural pozzolan (NP). The effect of using NP and SF on the strength and the chloride permeability of the concrete was investigated. The experimental results and simplex-lattice theory were used to develop the quadratic and third order analytical models for predicting the strength and the permeability of HPC. ANOVA confirms the accuracy of the quadratic model and therefore its efficiency requires relatively less experimental data. Two different numerical methods have been used to optimize the cementitious components of HPC using the quadratic model and lower and upper bounds of the experimental test results. Firstly, the "solver" tool of MS office provides unique optimum components of PC, SF and NP. The corresponding optimum percentages (by weight) of PC, SF and NP for HPC with 0.25 and 0.40 *w/b* are 86.04%, 8.16% and 5.80% and 88.78%, 5.85% and 5.37%, respectively. Secondly, the ternary plots produced by MATLAB establishes a single area for manufacturing HPC with *w/b* of 0.40 (the optimized PC-SP-NP component ranges are 0.875–0.925, 0.10–0.15 and 0.000–0.075, respectively) and two candidate superior strength zones for developing HPC with *w/b* of 0.25 (the optimum PC-SP-NP components are 0.875–0.950, 0.050–0.075, and 0.00–0.08 or 0.875–0.900, 0.08–0.15, and 0.12–0.22, respectively). For better sustainable, cost-effect and eco-friendly designs, it is suggested to use the topography of the targeted response surface for optimization purposes.

1. Introduction

The concrete products are graduated to new level of mechanical and durability performance because of the synergistic interactions among different combinations of binding materials. Most importantly, this advancement is also attributed to the technological advancement in testing and modeling methodologies of concrete. The interactive synergy at low water-to-binder ratio (*w*/*b*) of Portland cement (PC), fine mineral materials such as silica fume (SF) and natural pozzolan (NP), and chemical admixtures lead to the production of the high performance concretes (HPC). The use of these fine materials enhances the sustainability, reduces the production cost and emission of carbon dioxide. In addition, a HPC can be developed by decreasing the *w*/*b*, filling the gaps of the grain particle distribution, and utilizing advance techniques for mixing, placing, and curing. It is worth noting that HPC refers to an advanced kind of cement-based materials that exhibits superior strength and durability properties. The compressive strengths of more than 60–80 MPa are commonly described for HPC [1,2]. So far, no single definition for HPC has been suggested [3]. A HPC is essential to fulfil at least one of the following properties: high workability, superior strength and strength development rapidity,

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longer durability, and low shrinkage [4–6]. For this reason, Aïtcin [7] and [8] have suggested the *w/b* ratio for HPC to be 0.2–0.4. Due to the pozzolanic reaction, it is well established that the key source for the strength enhancement is due to increase in the pozzolana. During the hydration process of PC, a free lime releases that originates from its silicate phases. This lime reacts with the silica of the pozzolanic material and produces calcium-silicate-hydrate gel that contributes to the strength of the hardened product [9]. Moreover, the use of pozzolan in cement-based materials plays a vital role in enhancing the durability as it notably enhances the microstructure because of the gaps-filling capacity to the different phases of the material.

Due to its potential use, the scientific research community has been motivated to explore the influence of using NP (from several locations in the world) on the properties of cement-based materials. There is a general agreement between researchers that the use of NP in concrete notably reduces its workability, hence increases its demand to super-plasticizers (SP) more than SF and FA [10–14]. However, there are inconsistencies on the impact of using NP in concrete on its strength, yet most studies have indicated that the pozzolanic activity of NP is more than FA but less than SF and the optimum dosage of NP is about 10–20% [15–19]. In addition, various researchers have consistent findings regarding the favorable influence of using NP in concrete on its durability properties that has been attributed to its fineness, pozzolanic activity and synergistic interactions with other supplementary cementitious materials [20–23]. With regard to the Saudi Arabian NP, Khan and Alhozaimy [24] have demonstrated the potential use of various kinds of local NP to produce eco-friendly concrete. These researchers revealed that the chemical and physical properties of the abundant Saudi Arabian NP (irrespective to its origin) fits the specifications of ASTM C 618 and categorized as "Class N". It is worth noting that the effect of using NP on the properties of concrete at very low *w/b* (0.3 or less) is scarce. Additionally, the reports pertaining the impact of using NP that is locally available in the Edge of Arabian Shield (in Saudi Arabia) are scant.

As regard of material optimization, the dilemma of developing rational empirical models for optimizing the properties of blended concrete has forced merely the use of experimental techniques. The simplex-lattice modeling can have the potential use to establish predication models of the properties of concrete incorporating multi-component cementitious materials. The simplex-lattice can be described as an ordered system consisting of uniformly spaced distribution (array) of points on a lattice. This system is usually considered associated with a particular regression model. With respect to conventional regression modeling, the main feature of the simplex-lattice regression is that it has particular specifications of the test points in the desired simplex zone. Simplex-lattice regression model with *m*-order and *q*-component of the mixture is referred to [*q*, *m*] simplex-lattice. The contribution of all factors and their interaction are revealed by the coefficients of the regression model. The response of every point having the typical testing situation could be evaluated and the optimum ingredient proportions by using this polynomial model. Historically, the concept and approach of simplex-lattice design have been developed by the statistical research community since the fifties of the last century [25]. The first research article presents on simplex-design of three-component mixture was introduced by Claringbold [26]. Few years later, Scheffé [27] presents the concept of simplex-lattice design and the related regression modeling. For the civil engineering applications, Chen et al. [28] developed and validated regression models by using of simplex-lattice design for predicting the compressive strength of the blended concrete. These researchers have evaluated the optimized mixture content targeting the maximum compressive strength by solving the developed regression models with upper and lower constraints. It was concluded that the use of simplex-lattice design modeling together with the optimization philosophy establishes a useful methodology for the design of blended concrete mixtures. However, the study of Chen et al. [28] was limited to the first- and third-order models for the strength of the concrete containing SF and FA with *w/b* of 0.3. In this paper, the objectives are to investigate the effects of using binary and ternary blends of SF and local NP in concrete on its strength and durability properties. Additionally, to develop rational nonlinear models for predicting the strength and permeability of HPC with various w/b containing SF and local NP. Eventually, to optimize the properties and the cementitious components of HPC containing SF and local NP using the developed analytical models and various numerical methods.

2. Experimental materials and methods

2.1. Materials

In this investigation, Type I PC conforming the specifications of ASTM C150 was utilized. Table 1 shows the physical and chemical properties of PC, SF and NP. SF conforming to the requirements of ASTM C 1240 was used. Moreover, the exploited aggregates were

Table 1
Physical and properties composition of OPC, SF, and NP.

	PC-type I	SF	NP
Physical properties			
Bulk density (kg/m^3)	1362	1350–1410	2600–2700
Specific gravity (g/m^3)	3.14	2.0	–
Fineness (m^2/kg)	371	15–20	<1000
Average particle size (μm)	–	0.15	10–15
Compressive strength (MPa), 50 mm cubes			
03-days	19.4	–	–
07-days	24.9	–	–
28-days	35.7	–	–
Chemical composition (%)			
SiO_2	20.9	90.0	42.09
Al_2O_3	5.2	1.0	16.43
Fe_2O_3	2.3	1.0	14.97
MgO	2.8	0.6	3.47
CaO	64.4	0.3	9.51
SO_3	2.9	0.3	0.19
LOI	1.0	–	2.70
Insoluble residue	0.2	–	–