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Influence of fineness of volcanic ash and its blends with quarry dust and slag on compressive strength of mortar under different curing temperatures

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HIGHLIGHTS

- Strength activity index values and compressive strength increased with increasing fineness of VA.
- The strength activity index for VUF was highest among all other mortars containing FA, QD, and EAFS.
- VUF blends with FA and EAFS (20%) demonstrated comparable 91 days strength to CM under standard curing.
- "Cross-over effect" was clear in FA, EAFS, and CM, while not so obvious in VA mortars.
- VUF30 demonstrated strength better than CM and FA mortars under moderate and high curing temperatures.

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ABSTRACT

In this study researchers investigated the influence of fineness of locally available basaltic volcanic ash (VA) and its blend with other potential supplementary cementitious materials (SCMs) on compressive strength of mortar. Local quarry sites and steel making industries in the eastern province of Saudi Arabia produces tons of wastes commonly known as quarry dust (QD) and electric arc furnace slag (EAFS), respectively. Including the CM, a total of 19 mortar mixtures were prepared by substituting cement with various SCMs (VA, FA, QD, EAFS), their different percentages in binary mixes, fineness of VA, and blends of ultra-fine VA with other SCMs (ternary and quaternary). After casting, specimens were subjected to different curing temperature (20, 40, and 60 °C) and moisture conditions (continuous and partially moist). Compressive strength was measured according to ASTM C 109 at ages 7, 28, and 91 days and an average value of three identical 50-mm^3 specimens was reported. The test results indicated that improved fineness of VA up to 30% mass replacement of cement demonstrated compressive strength comparable to control and reference FA mortars at all ages particularly under high curing temperatures. Moreover, a quaternary blend of ultra-fine VA (20%) with EAFS (10%) and QD (10%) produced strength higher than all other ternary and quaternary blends at all ages and comparable 91 days strength to control mortar.

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1. Introduction

Concrete is extensively used in building infrastructure around the world. It is the second most consumable commodity after water by the society on the earth. According to a rough estimate, the annual global consumption of concrete was about 30 billion tons in 2006 [1]. About 4.1 billion tons of Portland cement was produced in 2015 [2]. High strength and durability along with the local availability of raw materials has increased the concrete production in recent years in most parts of the world. Besides the important role which concrete is playing and will continue to play in the future, the cement which is the main ingredient of concrete produce approximately 5% of global man-made CO_2 emission [3]. This CO_2 emission is mainly due to calcination and grinding processes during the production of cement. Around 60% of the total CO_2 is produced by calcination of limestone in the kiln and the remaining 40% is linked to the usage of fossil fuel and electricity [4–7]. Currently, there is a persistent high demand of reducing CO_2 emission due to its negative impact on earth climate changes and global warming.

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In order to reduce the CO_2 emission in cement industry, various alternate cementing systems have been discussed such as changing the fuel source; capturing CO_2; changing clinker manufacturing processes; and high volume replacement of cement with supplementary cementitious materials (SCMs) [8,9]. Out of these four technologies, the most effective and economical approach is to substitute clinker by an alternative material with cementitious properties and it can be straightforwardly applied to the ready mix concrete field [10]. SCMs such as ground granulated blast furnace slag (GGBFS), fly ash (FA), silica fume (SF) and natural pozzolans can be used to partially substitute the clinker, therefore reducing the amount of clinker and the associated CO_2 emission [11].

Kingdom of Saudi Arabia (KSA) per capita consumption of cement is one of the highest in the world. According to a rough estimate, the annual production of cement in KSA was 55 million tons in 2014 and 2015 [1]. Currently, KSA is importing huge amounts of SCMs such as FA and SF to fulfill their local concrete industry requirements [12]. Recently, naturally occured volcanic pozzolan, spread over a large area in western KSA has identified to be a potential substitute for partial replacement of cement [13–15]. The use of locally available natural basaltic volcanic ash (VA) as a partial substitute to Portland cement can be a viable alternative for producing sustainable and durable cementitious materials.

Many researchers investigated the effect of different scoria sources, fineness and percentage replacement on strength and durability properties of concrete. Moufti et al. [16] showed that fine ground scoria (Natural Pozzolan) passing through 45 μm at 10% by mass showed a compressive strength result close to the control sample. Sabtan et al. [17] found that all the sample collected from central Harrat Rahat exhibited a pozzoalnic behavior and fulfill the requirements of Italian standards. Khan et al. [12] reported that finely ground natural pozzolana having a Blain Fineness of 1800, 3400 and 3750 cm^2/g from two different sources showed same pozzolanic behavior and strength at all ages. They demonstrated that 15% of replacement gave same strength and better durability at later-ages as compared to that of control samples. Ghassan et al. [18] concluded that the natural pozzolanas from KSA having a Blain fineness of 3590 cm^2/g can be satisfactorily substituted for FA when tested against ASTM C618. They found that the natural pozzolana was effective in reducing the expansion of mortar subjected to Alkali silica reaction and also produce 15% less heat of hydration than FA. Celik et al. [19] reported that a 30% mass replacement of OPC (ordinary Portland cement) by finely-ground VA of fineness equal to cement exhibited compressive strength similar to that of control (100% OPC) at all ages, while a 50% replacement fulfills the criteria of self-compacting concrete. Moreover, a 45% replacement in form of ternary mix (30% VA and 15% limestone powder) produced low cost, highly durable and environment friendly concrete. Patil et al. [20] found that VA substitution greater than 30% by mass with OPC resulted in increased porosity as well as vesicularity in the cementitious matrix system when compared to OPC control samples.

In this study, pozzolanic potential through strength activity index and the compressive strength of mortar containing different percentages of potential SCMs (VA, EAFS, and QD) in binary, ternary, and quaternary mixes was investigated incorporating different curing moisture and temperature conditions. Effects of different curing temperatures were not considered in the previous studies, which however, could affect the development of compressive strength of mortars due to its direct effects on hydration reaction both at early and later-ages. High temperature variations within mass of concrete can be occurred either due to seasonal changes or the rate of cement hydration in mass concretes. Therefore, the effect of different normal and high curing temperatures (20, 40 and 60 °C) was studied to incorporate the local normal and hot environmental temperature conditions of most eastern and western parts of Saudi Arabia. ASTM C618 was used to evaluate the pozzolanic potential through strength activity index, while, the compressive strength of mortar was determined according to ASTM C109 using the cube specimens of size 50 mm^3. Mortars containing FA (ASTM C618 Type-F) were also cast as a reference pozzolanic material to compare the results of this study. With respect to (w.r.t.) mix proportions, various experimental variables include different percentage replacements of cement with SCMs (VA (10%, 20% and 30%), QD (10% and 15%), EAFS (10%) and FA (10% and 20%)), different fineness of VA (100% passing 38-μm (VF) and 20-μm (VUF)), and the blends as ternary (VUF + FA (20%), VAF + S (20%), VUF + QD (30%), VUF + QD (35%), VUF + QD (45%)) and quaternary mixes (VUF + QD + EAFS (40 and 50%)). Finally, the characteristics of SCMs, their strength activity index and the compressive strength results were presented and compared to those of CM (100% cement) and the reference mortar containing FA.

2. Materials and experimental plan

2.1. Materials

In this study, a locally available ordinary Portland cement type-I manufactured by Saudi cement factory was used as main binder material. A commercially available standard sand meeting the requirement of EN 196-1 and ISO 679: 2009 was used as fine aggregate. Its grain size distribution was done and the results are shown in Table 1. The fineness modulus of sand was calculated equal to 2.54 according to ASTM C125. Physical and chemical properties of cement and its substitute SCMs used in this study (FA, VA, electric arc furnace slag (EAFS) and limestone quarry dust (QD)) are given in Table 2. In Fig. 1, all the binders (cement and SCMs) were presented in their final powdered form. A brief description of each SCM is also given below.

2.1.1. Basaltic volcanic ash

Volcanic activity occurred about 25 million years ago led to the formation of vast field of basaltic flows in the western part of KSA, referred to by the Arabic term "Harrat" [21]. There are 12 large Harrat and few smaller ones spread over an area of 90,000 km^2 in the western part of KSA as shown in Fig. 2a [22]. Several occurrences of pyroclastic scoria cones were explored in these Harrats. Harrat Rahat contains 644 scoria cones [21], Harrat Kishb consists of 163 scoria cones [23], while Harrat Khaybar, Ithnayn and Kura contains combined 327 scoria cones [24]. These cones are either composed entirely of scoria layers, or in few cases as alternating scoria layers and lava flows. Fig. 2b and c show studied VA quarry site and its crushing plant, respectively. The scoria materials are found to be light in weight, reddish or black in color and particle size ranges from fine to coarse vesicular particles with most in the range of 2 to 32 mm. Many investigators evaluated the pozzolanic reactivity of the scoria samples obtained from ground surface and drilled holes from different cones. They found that 99% of samples showed a pozzolanic activity and might be a viable substitute to cement in the concrete industry [25–29].

VA used in this study was supplied by Super Burkani Blocks Company, Jeddah, KSA. The parent source of this VA is located in Harrat Rahat, Jabal Kadaha quarry, Medina Province, KSA. To conduct this research, five different sizes (average 30 μm, 40 μm, 4.75 mm, 9.5 mm, 12.5 mm) of VA were received to investigate its effectiveness as coarse aggregate, fine aggregate and SCM. However, to start with authors have limited this study to investigate its role only as a SCM. Dry sieving was performed on fine ground sample of average particle size 30 μm using micro sieves #400 (38 μm) and #635 (20 μm). This was done to achieve a high fineness VA more than cement and close to commercially available FA. Finally, two different fineness levels of VA were attained (smaller than 38 and 20 μm) to investigate influence of its fineness on compressive strength of mortar. Sample of VA passed 100% through micro sieves #400 and #635 were named as VA fine (VF) and VA ultra-fine (VUF), respectively. A comparison of particle size distribution curves between cement, FA, VA as obtained (average particle size 30 μm (V30) and 40 μm (V40)), and reduced high-fineness VA (VF and VUF) is shown in Fig. 3. The comparison of curves clearly demonstrated a successful attainment of fine VA by dry sieving method. It shows that the both VA samples (VF and VUF) are finer than cement and their fineness is close to commercially available FA.

2.1.2. Electric arc furnace slag

Slag is a byproduct of iron and steel making industry. There are three different types of slag produced based on the furnace from which they are generated. Among them, EAFS is generated when steel scrap with some pig iron is used in the electric arc furnace for the production of steel [30]. Annual estimated production of slag in US was in the range of 16–22 million tons in 2015 [31]. Effective use of EAFS in con-

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