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Influences of Pozzolanic Materials on the Rheological and Hardened Properties of High-Strength Concrete

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Abstract

Superior compressive strength and longer service life are two of the many benefits of high-strength concrete (HSC), a specialized type of concrete. HSC is made better with the help of pozzolanic ingredients, which also contribute to the concrete's longevity and sustainability. This abstract provides a review of the application of pozzolanic materials in HSC, including a discussion of the impacts of these materials on both the rheological and hardened properties of concrete. The abstract starts by introducing commonly used natural pozzolan volcanic pumice powder (VPP) as a substitute for cement. To do so, VPP was used as a supplemental cementitious material (SCM) in place of ordinary Portland cement (OPC) at 0%, 10%, 15%, and 20% volumes by weight to examine the resulting changes in rheological and hardened properties. The experimental results show that VPP considerably improves both compressive and splitting tensile strength. Taking into account rheological and hardened properties, the optimal option was found to be a 10% VPP substitution, in comparison to the control mix and overall results.

Keywords: *High-strength concrete; Volcanic pumice powder; Compressive strength; Rheological properties; Sustainable materials.*

1 Introduction

High-strength concrete (HSC) is in greater demand in recent years because of its superior resilience in the face of extreme conditions and loads that conventional concrete can't handle. In most cases, high-strength concrete can be identified by having a compressive strength that is greater than 55 MPa (ACI, 2010). High-strength concrete requires a lower water-cement ratio which enhances density and decreases porosity, water-reducing admixtures along with high-quality Portland cement content (Nawy, 1996). Portland cement is the primary component of concrete and its production accounts for more than 5% of the world's annual CO_2 emissions which is known as a greenhouse gas. In recent years many researchers have been working on developing alternatives that can replace cement and have settled on pozzolan as a material that can help reduce CO_2 emissions (Bentz & Ferraris, 2010; Letelier et al., 2020)

Cement substitutes like pozzolans, which are siliceous and aluminous substances, undergo a chemical reaction with calcium hydroxide ($Ca(OH)_2$) in the presence of water to form compounds having cementitious properties. However, fly ash (FA) (Yerramala & Ganesh Babu, 2011), blast furnace slag (BFS) (Higashiyama et al., 2014), rice husk ash (RHA) (Gill & Siddique, 2018), silica fume (SF) (Rossen et al., 2015), volcanic pumice (VP) (Kılıç & Sertabipoğlu, 2015), palm oil fuel ash (POFA) (Mohammadhosseini & Yatim, 2017), marble powder (Aditto et al., 2023) have all been the subject of several research into their potential use as cement replacement materials in concrete. Depending on factors including chemical composition, price efficiency, and accessibility, the proportion of alternative materials used to replace cement might vary widely from one mixture to the next. As per the report of Kadri et al. (2012), the compressive strength of concrete containing up to 20% silica fume was found to be greater than that of concrete containing the control mixture. Conversely, Zeyad et al. (2016) along with others (Megat Johari et al., 2011; Turanli et al., 2005) successfully substituted 60% palm oil fuel ash agro-waste for cement to get the same results in terms of strength and durability.

A natural pozzolan named volcanic pumice pozzolan (VPP) has recently been effectively implemented by researchers. Pumice is a rock formed when gases are released during the solidification of lava, making it a naturally occurring product of volcanoes. However, extensive literature reviews have been conducted on the fresh and mechanical properties of VPP-based HSC, with promising results. There have also been reports of success with using pumice powder to enhance the rheological qualities of concrete (Güneyisi et al., 2014). Similarly, researchers have also observed that a 0%–30% replacement level of VPP to concrete mixes fundamentally improved the material's mechanical qualities as well as its durability (Mehrinejad Khotbehsara et al., 2017; Ramasamy & Tikalsky, 2012; Zeyad et al., 2019). Therefore, the purpose of this study is to evaluate the effects of the rheological and hardened properties of HSC with varying VPP concentrations (0%, 10%, 15%, and 20%). To assess the rheological and hardened qualities of all mixtures slump, compressive, and splitting tensile strength tests were carried out.

2 Materials and methods for experimentation

2.1 Materials

All HSC mixtures used in this analysis conformed to the requirements of ASTM C150 (ASTM, 2020) and were formulated using Type I ordinary Portland cement (OPC). To make a fine powder, local volcanic pumice was sieved through a 30-number sieve after being ground up in a laboratory. Crushed natural stone up to a nominal size of 12 mm was utilized as coarse aggregate while fine aggregate was provided by natural river sand, both in accordance with ASTM C 127 (A. ASTM, 2015) and ASTM 128 (A. ASTM, 2015) standards. However, the grading curve for both fine and coarse aggregates is depicted in Figure 1. In addition, 17% silica fume was added as a mineral admixture, and 1% polycarboxylic ether was employed as a superplasticizer.

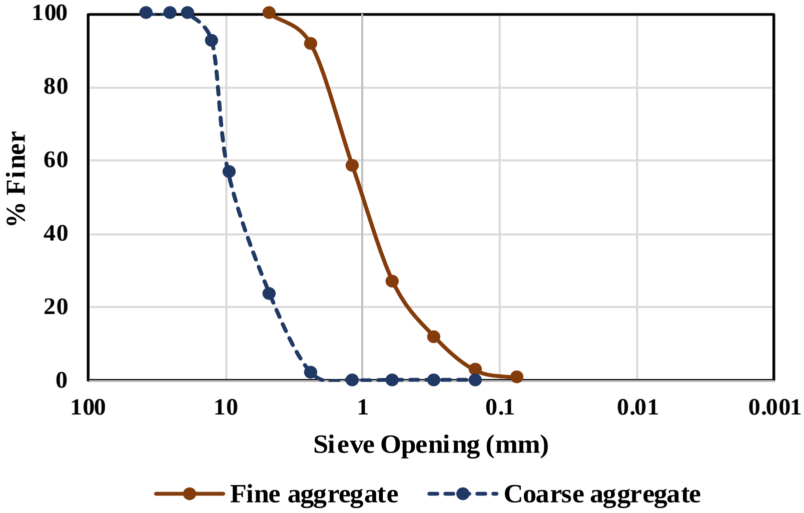

Figure 1. Fine and coarse aggregates on a gradation curve

2.2 Mix proportion

A total of four distinct mixes were formulated for this investigation, with the mix design having been done in accordance with ACI 211R (ACI, 1992) as shown in Table 1. In each batch, the water-cement ratio was maintained at 0.32, and the mix proportions were optimized for 0%, 10%, 15%, and 20% VPP. The mixes were cast into cylinders (100 mm x 200 mm) and allowed to cure for 7, 28, and 56 days in portable water before being put through further testing.

Table 1: The mix proportions of HSC mixtures in Kg/m^3

Materials	0% VPP	10% VPP	15% VPP	20% VPP
OPC	550	495	467.5	440
VPP	-	55	82.5	110

Fine aggregate	712	712	712	712
Coarse aggregate	1006	1006	1006	1006
Silica fume	93.5	93.5	93.5	93.3
Water	176	176	176	176
Superplasticizer (%)	1	1	1	1

2.3 Experimental methods

Newly mixed concrete was subjected to a slump test in accordance with ASTM C143 (ASTM, 2015) to establish the workability of VPP-based HSC with varying quantities of VPP. After the appropriate amount of time had passed for curing (7, 28, and 56 days), the compressive strength of cylindrical specimens was measured in accordance with ASTM C39 (ASTM, 2010). Similarly, the splitting tensile strength was evaluated in accordance with ASTM C496 (ASTM, 2017) for 7, 28, and 56 days.

3 Results and discussion

3.1 Workability

For the experiment conducted in its fresh form, the slump values of various mixtures were measured and analyzed to establish the workability, as shown in Figure 2. By contrasting the performance of the reference HSC with that of the VPP-based HSC, it can be seen that the workability improves when the VPP percentage is raised. Graphically, the slump value was attained at 150 mm with 0% VPP, however, it rose to 170 mm with 10% cement replacement. It continued to increase with 15% and 20% VPP replacement, reaching 185 mm and 195 mm respectively, which is indicative of concrete that is highly workable. The reason behind the increase in slump results may be possibly the decrease in cement content that occurred as a result of the use of VPP as a replacement and the high fineness of the VPP content. Several pieces of study are in agreement with this phenomenon and have demonstrated that the addition of pozzolanic materials or supplementary cementitious materials results in an increase in slump value (Soliman & Tagnit-Hamou, 2017; Zeyad et al., 2019).

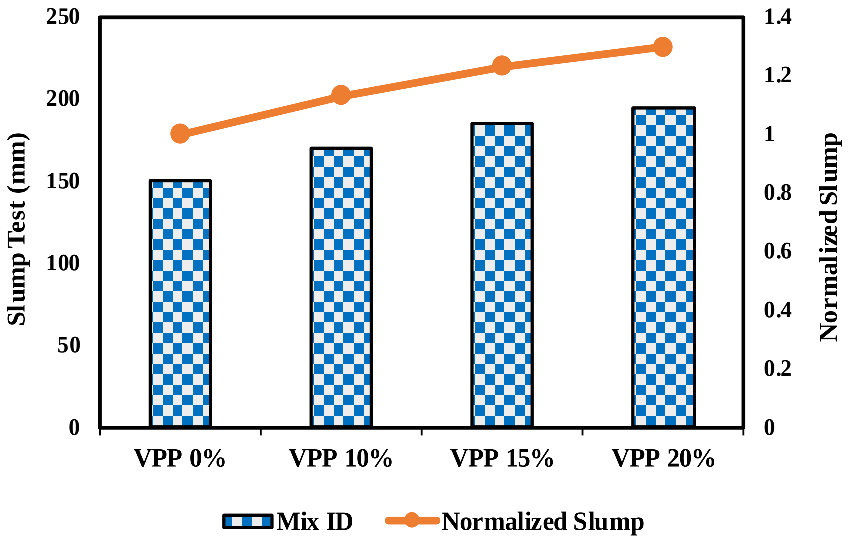

Figure 2. Slump value of all HSC mixtures

3.2 Compressive strength

Figure 3 is an illustration of the slight decrease in compressive strength with an increasing percentage of VPP after a curing time of 7 days. After seven days, the control specimen had achieved a compressive strength of 33.20 MPa, which was a minor drop above 2%, 4%, and 14% when treated with 10%, 15%, and 20% VPP respectively. Conversely, after 28 and 56 days, a 10% or 15% rise in VPP causes a rapid increase in compressive strength, but the scenario stayed the same for 20% VPP as it was at 7 days. Increases of 14%, 4%, and 9%, 1% were seen for 10% and 15% VPP at 28 and 56 days, respectively. Upon closer inspection of the data, it becomes clear that VPP substitution at early ages (7 days) demonstrates a reduced compressive strength in comparison to the control mix. One possible explanation for the decline is the prolonged period of time needed for calcium hydroxide ($Ca(OH)_2$) and VPP to interact (Zeyad et al., 2019).

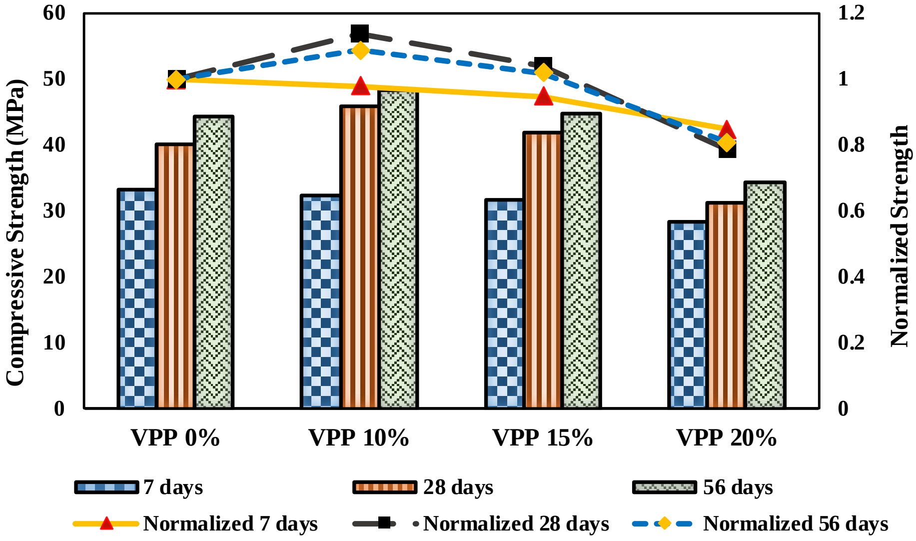

Figure 3. Compressive strength of all HSC mixtures at 7, 28, and 56 days

3.3 Splitting tensile strength

Along the same lines as the compressive strength, the rising percentages of VPP content also reflect a substantial decline in the splitting tensile strength after 7 days, as seen in Figure 4. After 7 days, the strength had grown by more than 5% for 10% VPP that had been replaced. It grew even more by more than 7% when it reached 56 days for the 10% VPP. At both 28 and 56 days, there was a small increase in strength associated with 15% VPP replacement. In contrast, the 20% VPP showed a steadily declining strength that reached more than 34% after 56 days. Both Zeyad et al. (2019) and Ananthi and Karthikeyan (2017) noted a similar tendency in their studies.

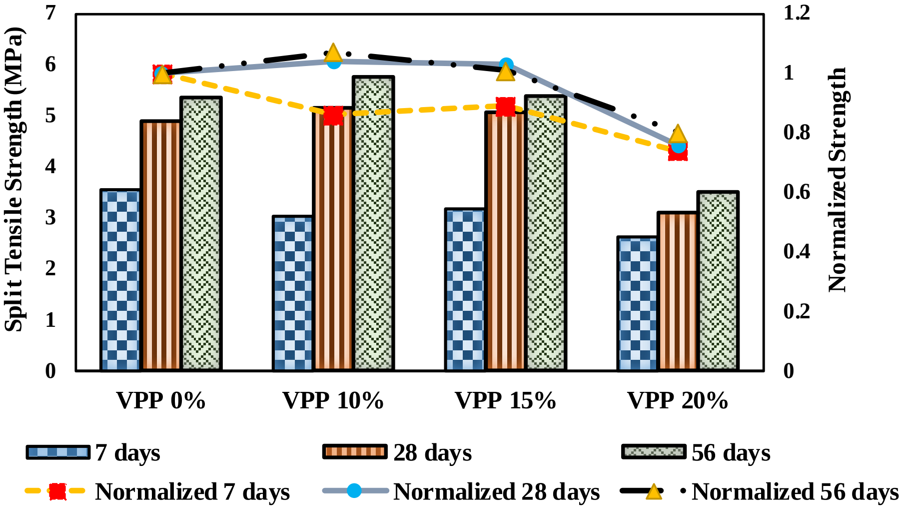

Figure 4. Splitting tensile strength of all HSC mixtures at 7, 28, and 56 days

3.4 Relationship between compressive and splitting tensile strength

Analytical calculations employing a number of industry-standard codes are displayed in Figure 5 for the correlations between the splitting tensile strength and compressive strength test results at 7, 28, and 56 days. It is demonstrated that an increase in compressive strength results in a corresponding increase in tensile strength in HSC mixtures and that this trend persists throughout the investigation.

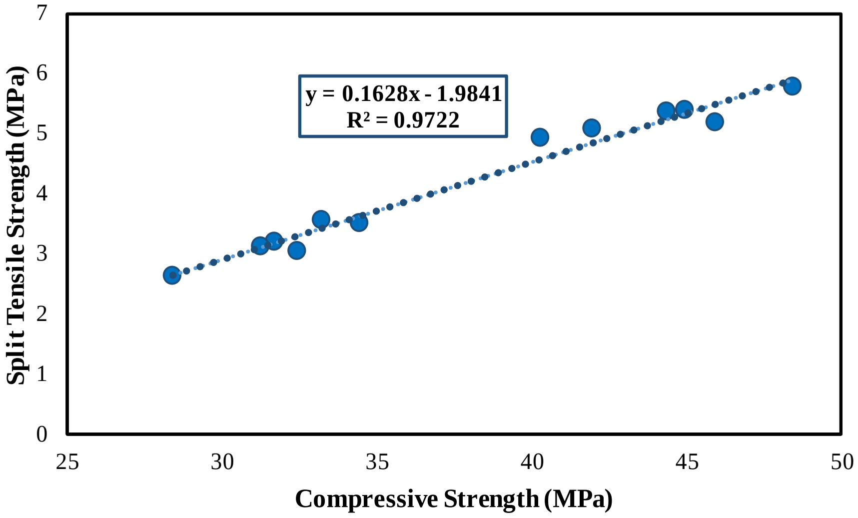

Figure 5. Correlation between compressive and splitting tensile strength

4 Conclusion

According to the results of the experiments conducted in this research, it is reasonable to assert that the addition of VPP improves both the workability and the mechanical behavior of concrete. Both an increase in compressive and splitting strength can be shown with a replacement of 10% or 15% VPP; however, the performance of the 10% VPP replacement is superior. At 28 days, both the compressive and splitting tensile strengths improve to levels greater than 14% and 5%, respectively, for 10% VPP. Therefore, as a conclusion, it is possible to recommend that 10% of the VPP be replaced with cement as one of the most appropriate alternatives for the rheological and toughened qualities of high-strength concrete.

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