Original Article

Durability and strength characteristics of high-strength concrete incorporated with volcanic pumice powder and polypropylene fibers

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A B S T R A C T

In this paper, the partial replacement of volcanic pumice powder (VPP) was investigated for use as a supplementary cementitious material. High-strength concrete (HSC) was prepared using two sets of VPP (10% and 20%) incorporated with three sets of polypropylene fiber (PF) (0.20%, 0.35%, and 0.50%) to produce different concrete mixtures. Several tests, including slump, compressive strength, indirect tensile strength, flexural strength, water absorption, initial surface absorption, and sorptivity, were conducted to evaluate HSC performance. Results showed the prepared specimens with 10% cement replacement with VPP and 0.20% PF content indicated a slight increase in compressive strength compared with the control concrete at later ages. Indirect tensile and flexural strengths were optimized at 10% VPP replacement with 0.50% PF content. Furthermore, adding PFs to mixes increased indirect tensile and flexural strength but decreased slump. The sorptivity test indicated low water soaking due to VPP content in the mixes compared with the control mix (HSC); it declined as the replacement of VPP increased. The different standard tests on mixes depicted favorable results and good prospects for the inclusion of VPP in HSC structures.

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1. Introduction

Global demand and urbanization have contributed to the consumption of large quantities of concrete. Nowadays, the demand for high-strength concrete (HSC) has increased due to its high resistance to compressive loads and minimum thickness requirement for individual sections, reducing the weight of the structure. In addition, reduction in space can economically benefit an owner. HSC demand has also increased in the construction of heavy structures, such as bridges, tunnels, shear walls, foundations, and skyscrapers. HSC production typically uses high Portland cement content with low water–cement ratio, water-reducing admixtures, superplasti-
cizer (SP), and furnace slag or silica fume [1].

Recent research has shown that Portland cement production has high environmental effects and greenhouse gas emissions [2,3]. In 2015, the amount of cement consumed globally amounted to 4.5 billion metric tons [4]. However, researchers have developed alternate replacements for Portland cement to reduce cement consumption [5–9,10]. In addition, the partial replacement of Portland cement with other materials not only reduces CO₂ emission and energy consumption but also improves the properties of concrete and the sustainability of construction [11]. Hence, volcanic pumice (VP) can be a supplementary cementitious material (SCM) to replace Portland cement [12]. Furthermore, SCMs have been adopted widely due to their environmental and economic benefits. The effects of SCM on the hydration behavior of fresh and hardened cement paste and concrete mixtures were compared, and results indicated the greater suitability of pumice for precast application compared with ready mix concrete [13].

Pozzolanic materials are limited and cannot replace more than 60% of cement mass because using these materials in concrete involves several problems, such as decrease in workability, and requires the addition of large amounts of water or SPs [14–16]. Maximum strength is achieved by an optimum pozzolana/cement ratio, which results in maximum productivity and efficiency [17–19]. SCMs have been widely investigated as a replacement for Portland cement in industrial waste materials, such as palm oil clincker [19], pyrite cinders [20], rice husk ash [21], waste glass [22,23], zeolite [24,25], and fly ash [26]. The properties of these materials may also decline in addition to a decrease in strength [16,27].

Using natural pozzolanic (NP) materials resulting from volcanic activity in concrete applications is remarkable, especially for HSC, which consumes large amounts of cement (at least 500 kg/m³). Furthermore, cement consumption savings of up to 50% was achieved on a 28-day compressive strength, indicating a substantial reduction in cost, energy, and raw material consumption [28]. Previous studies on the hydration and strength of mortar and concrete containing volcanic ash (VA) based on global standards are limited [7,12,17]. However, NP materials cannot be used in any region; their use depends on the data sources of VA and volcanic tuff (VT). Factors such as origin region, mineralogical components, particle size distribution, and manner of formation may change the properties of cement [29,30]. Volcanic wastes that are classified as NP materials, such as VA, VT, and VP, are abundant in the southwest Arabian Peninsula. Research has suggested that locally available pozzolanic material has potential for the production of durable and sustainable concrete [31,32].

This paper investigates the performance of HSC mixtures produced by partially replacing cementitious material from locally available VP. Proposed mixes produced in the experimental program were tested for compressive, indirect tensile and flexural strength, slump, and water absorption.

2. Material investigation

2.1. Volcanic pumice powder

Volcanic pumice powder (VPP) was collected from the Jabal Al Akwa Al Shamiya volcanic region (area: 5.89 km²) in the north, located in Sabya (Jazan Province) in the southwest corner of Saudi Arabia [33], as shown in Fig. 1. The VPP sample was collected from the quarry site, sieved (600 μm sieve), and ground to powder in the laboratory using a ball mill (Fig. 2). The fineness after grinding was 4298 cm²/g. The mineral composition and score factor of VPP are provided in Table 1, and the physical and chemical properties are provided in Table 2. The physical properties of the VPP were measured through an air permeability test (Blaine) and complied with ASTM C204 [34] for surface area, gas pycnometer complied with ASTM C604 [35] for specific gravity, and pozzolana reactivity complied with ASTM C311 [36]. In addition, the sum of major oxides (SiO₂ + Al₂O₃ + Fe₂O₃) for VPP exceeded 76%, which met the ASTM requirements for classification as pozzolanic materials. X-ray fluorescence (XRF) analysis was adopted to measure the chemical composition percentage of VPP.

2.2. Cement

Ordinary Portland cement (OPC) used in all mixes meet the required specifications of ASTM C150 [37]. The physical properties of OPC were measured through an air permeability test (Blaine) and complied with ASTM C204 [34] for surface area. The gas pycnometer complied with ASTM C604 [35] for specific gravity. XRF analysis was performed to measure the chemical composition percentage of OPC.
Table 1 – Main phase names and scores of VPP.

<table>
<thead>
<tr>
<th>Ref. code</th>
<th>Score</th>
<th>Mineral name</th>
<th>Scale factor</th>
<th>Chemical formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>98-010-6045</td>
<td>20</td>
<td>Silicon oxide–Quartz-type (Amorphous)</td>
<td>0.481</td>
<td>SiO₂</td>
</tr>
<tr>
<td>98-010-9496</td>
<td>14</td>
<td>Magnesioferrite</td>
<td>0.475</td>
<td>MgFe₂O₄</td>
</tr>
<tr>
<td>98-004-6457</td>
<td>22</td>
<td>Anorthite</td>
<td>0.791</td>
<td>CaAl₂Si₂O₈</td>
</tr>
<tr>
<td>98-003-4993</td>
<td>13</td>
<td>Monticellite</td>
<td>0.334</td>
<td>Ca(Mg₈.88Fe₅.12)SiO₄</td>
</tr>
<tr>
<td>98-010-9102</td>
<td>21</td>
<td>Clinopyroxene</td>
<td>0.290</td>
<td>Ca₉₀Al₂⁹Mg₃⁶Si₈₁₅₆O₇</td>
</tr>
</tbody>
</table>

Table 2 – Comparative study of VPP and OPC.

<table>
<thead>
<tr>
<th>Major compounds</th>
<th>OPC (%) by mass</th>
<th>VPP (%) by mass</th>
<th>Physical properties</th>
<th>OPC (%) by mass</th>
<th>VPP (%) by mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>19.01</td>
<td>47.40</td>
<td>Specific gravity (g/cm³)</td>
<td>2610</td>
<td>3100</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.68</td>
<td>18.57</td>
<td>Specific surface area (cm²/g) Blaine</td>
<td>4298</td>
<td>3410</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>3.20</td>
<td>10.04</td>
<td>Pozzolan activity index (%) at 28 d</td>
<td>–</td>
<td>87.5</td>
</tr>
<tr>
<td>CaO</td>
<td>66.89</td>
<td>7.90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>0.81</td>
<td>6.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.90</td>
<td>2.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.22</td>
<td>1.62</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td>1.17</td>
<td>1.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.08</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO₃</td>
<td>3.66</td>
<td>0.34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>0.19</td>
<td>0.133</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>–</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂ + Al₂O₃ + Fe₂O₃</td>
<td>–</td>
<td>76.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOI</td>
<td>2.48</td>
<td>2.21</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 – Configuration and physical properties of PF.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>910 kg/m³</td>
</tr>
<tr>
<td>Length</td>
<td>12 mm</td>
</tr>
<tr>
<td>Diameter</td>
<td>18 μm</td>
</tr>
<tr>
<td>Specific surface area</td>
<td>200 m²/kg</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>350 MPa</td>
</tr>
</tbody>
</table>

2.3. Aggregate

Coarse aggregate (CA) consisting of limestone crushed with a maximum size of 12.7 mm, specific gravity of 2.71, and water absorption of 0.46% was used. Fine aggregate (FA) consisting of desert sand with a specific gravity of 2.68 and water absorption of 0.62% was used. The CA and FA aggregate gradients conformed to ASTM specifications.

2.3.1. Superplasticizers

ViscoCrete 1050-type SP was used. SP quantity was determined based on the slump test, that is, 180 ± 20 mm. SP was constant for HSC and V HSC F, that is, 9.9 kg/m³.

2.4. Polypropylene fiber

Three combinations (0.20%, 0.35%, and 0.50% of concrete volume) of polypropylene fiber (PF) were used to prepare different mix combinations. The configuration and physical characteristics of PF are shown in Table 3.

3. Mineralogical and thermal analysis

The microstructural behavior of VPP was analyzed using different characterization techniques. X-ray diffraction (XRD) analysis of VPP was accomplished using a Bruker AXS D8
instrument. In addition, a scanning electron microscopy combined with energy dispersive X-ray spectroscopy (SEM/EDX) model Zeiss Supra 35 VPP was used. Thermogravimetric and differential thermal analyses (TGA/DTA) were applied to estimate the amount of Ca(OH)$_2$ and C–S–H as well as C–S–A–H in cement paste.

3.1. XRD analysis

The mineralogical analysis of VPP presented in the diffractogram demonstrates the peaks of the crystalline phases of VP. Table 1 shows quartz as a main mineral constituent and an aluminosilicate amorphous phase developed by SiO$_2$ and Al$_2$O$_3$.

3.2. SEM/EDX analysis

The morphology of VPP shows irregular micropores, and each grain has small closed forms, as shown in Fig. 4. The main chemical elements present in this pozzolan are Si, Al, K, Na, Ca, Fe, and Mg. The SEM micrograph in Fig. 4 shows fine porosity and angular particle sizes ranging from 1 μm to 15 μm.

3.3. TGA/DTA

Simultaneous DTA and TGA were performed on a (Instrument name-Mettler Toledo TGA/SDTA851) at a constant heating rate of 10 °C/min on a dry air flow until 1000 °C.

<table>
<thead>
<tr>
<th>Table 4 – Proportion of HSC mixtures.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix Code</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>0%VPP+0%PF</td>
</tr>
<tr>
<td>10%VPP+0%PF</td>
</tr>
<tr>
<td>10%VPP+0.20%PF</td>
</tr>
<tr>
<td>10%VPP+0.35%PF</td>
</tr>
<tr>
<td>10%VPP+0.50%PF</td>
</tr>
<tr>
<td>20%VPP+0%PF</td>
</tr>
<tr>
<td>20%VPP+0.20%PF</td>
</tr>
<tr>
<td>20%VPP+0.35%PF</td>
</tr>
<tr>
<td>20%VPP+0.50%PF</td>
</tr>
</tbody>
</table>

$^a$ VPP – Volcanic pumice powder.
$^b$ FA – Fine aggregate.
$^c$ CA – Coarse aggregate.
$^d$ SP – Superplasticizer.

preparation of HSC mixes, the VPP replacement levels of 10% and 20% of cement mass were adopted with PF content of 0.2%, 0.35%, and 0.50% of concrete volume. Table 4 shows the proportion of mix design.

4.2. Sample preparation, casting, and curing

Nine mixes of HSC samples were prepared for each test category and the average value of three samples was computed. For the compressive strength test, samples were tested on cubes (100 mm) at ages 7, 14, 28, 90, and 180 d. For the flexural and indirect tensile strength tests, prismatic (100 mm × 100 mm × 400 mm) and cylindrical (d = 100 mm and H = 200 mm) specimens were used. The specimen molds were filled with two layers for the compaction of concrete using a vibration table. The cast specimen was covered with wet cloth for 24 h as initial curing before demolding. The specimens were demolded carefully within 24 h, and their identities were marked. The specimens were immersed in a water tank under laboratory conditions (indoors) at 23 ± 2 °C until testing age.

4.3. Experimental testing

The slump test was performed in accordance with ASTM C143 [38] for fresh concrete, whereas those for compressive, indirect tensile and flexural strength, water absorption, and rate of water absorption were performed on hardened concrete samples. The compressive, indirect tensile and flexural strength, water absorption, and rate of water absorption tests of the mixtures were performed in accordance with ASTM at ages 7, 14, 28, 90, and 180 d. Fig. 5 shows the test samples.

Durability is extensively associated with the water absorption capacity of concrete. Water absorption was used to assess concrete durability. The specimens were dried in an oven at 105 ± 5 °C for 48 h until mass stability (not exceeding 0.1% of the initial mass for two successive weigh-ins) was achieved, and their mass was recorded. The samples were cooled at laboratory temperature for 3–4 h until the sample temperature decreased to 25 ± 2 °C. The samples were immersed completely in distilled water for 2 d. After 2 d, the samples were...
collected and cleaned using a cloth to remove excess water. The wet specimen’s mass was measured in air.

For the sorptivity test, the sample was dried in an oven at 105 ± 5 °C for 48 h. The weight of the oven-dried samples was recorded to the nearest 0.01 g. The specimen surface was immersed in a tray of water at 25 ± 2 °C with a maximum depth of 2 ± 1 mm and supported on rods to allow water movement. The water absorbed was measured through the increase in sample mass at intervals of 10, 30, and 60 min. Before the test, the sample surface was cleaned using a brush and cloth to remove any impurities. The sorptivity test was conducted in accordance with ASTM C1585 [39]. The average sorptivity of the three samples was calculated and plotted. The sorptivity at each time interval was calculated in accordance with the following equation:

\[ l = S \times \sqrt{t}, \]

where

\[ l \] cumulative amount of water absorbed per unit (g/mm²),
\[ S \] sorptivity coefficient, and
\[ t \] time measured in seconds (g/mm²/s^1/2).

5. Results and discussion

5.1. Mineralogical analysis

Fig. 3 shows the XRD pattern of the processed sample centered at 2θ = 25°. The main crystalline phases are quartz, anorthite, clinopyroxene, and a small fraction of monticellite. The major peaks are associated with quartz, indicating a main crystalline product. The results indicate the silica content exceeded 47%, 11% of which is amorphous (Fig. 3).

5.2. Microstructural analysis

5.2.1. Thermogravimetric analysis

DTA and TGA tests were used to identify the correlation between the binding phases of concrete, such as C–H, C–S–H, C–A–S–H, C–A–H, and C–A–F (C = CaO, S = SiO₂, A = Al₂O₃, F = Fe₂O₃, H = H₂O, or –OH) for three different cement–VPP matrices and their mass loss was evaluated under controlled heating. The thermal behaviors of the three samples (0%, 10%, and 20% VPP replacement) are plotted in Figs. 6–8, respectively. The three plots depict identical behavior and transformation in temperatures in the range of 150–450 °C, 450–550 °C, and 550–850 °C. Mass loss was observed for all plots until 200 °C due to C–S–H production [40,41]. Fig. 6 shows the DTA of the control cement without VPP content. The major thermal transformation (endothermic) was observed in the range of 450–550 °C. This peak shows Ca(OH)₂ or C–H decomposition on heating [42]. A minor second peak, which is attributed to the loss of H₂O from C–S–H gel and CaCO₃ decomposition, was observed between 550 °C and 850 °C [40,43].

A low Ca/Si ratio indicates more Al-absorbed content produces more C–A–S–H phases and that C–A–S–H gel crystallinity decreases with increasing Al content [40].

5.3. Evaluation of fresh concrete testing

Table 4 shows the slump results according to ASTM C 143 for all mix combinations. VPP replacement rates of 10% and 20% of cement mass were high for HSC, whereas the amount of SP was constant 9.25 kg/m³. For a constant water/binder ratio content, CA, and SP, the slump values of ¹⁰HSC₀₀ and ²⁰HSC₀₀ were increased by 20 and 30 mm, respectively, without considering PFs. The increase in slump results may be due to the reduction in cement content through the VPP replacement and the high fineness of VPP content. The fineness of the VPP contributed additional lubrication to the aggregates, which led to decreased frictional resistance. These factors increased the slump values in relation to the incorporation of VPP content and are consistent with those of Soliman and Tagnit-Hamou [44] in which the softness and shape of the substituting materials affect the operability of concrete. However, the addition of the PFs in concrete has a negative effect on workability leading to a decreased slump test value [45,46]. In the 10% and 20% VPP mixes with PF content of 0.20%, 0.35%, and 0.50% by concrete volume, the slump values decreased by 30, 50, and 75 mm and 30, 40, and 60 mm, respectively. Fig. 9 shows the relationship between the percentage of PF and slump test results. The results show the addition of PFs to concrete leads to a decline in workability and that a high PF content is accompanied by a high reduction in workability. The results support the findings of previous researchers when adding different
Fig. 4 – SEM and EDX analyses of studied VPP samples at points A and B.

Fig. 5 – Tests of hardened concrete.

a. Compressive strength test  b. Flexural strength test

a. Water absorption test  b. Indirect tensile strength test
percentages of the PFs for HSC [9,47]. In this case, the addition of VPP contributed to the reduction of the effect of PFs on concrete workability.

5.4. **Evaluation of hardened concrete testing**

5.4.1. **Compressive strength**

Compressive strength ($f_c$), which is one of the most important properties of hardened concrete, is used generally as a characteristic material value for concrete classification. The concrete properties are affected by VPP and fiber content.

Fig. 10 shows the logarithmic trend of the compressive strength results of the HSC, $^{10}$HSC$_{0.20}$, $^{10}$HSC$_{0.35}$, and $^{10}$HSC$_{0.50}$ at 7, 14, 28, and 90 d. The graphical representation of compressive strength shows similar patterns for all specimen cases. The 10% VPP replacement at early age (7 and 14 d) exhibited lower compressive strength as compared to HSC. This lower compressive strength may be attributed to...
the low cement content and may be associated with low level of compounds responsible for early strength. Moreover, the pozzolanic materials in VPP required a long period to interact with Ca(OH)₂. The use of 0.20% of PFs yielded a slight increase in compressive strength at 28 and 90 d [47]. The incorporation of 0.20% of PF enhanced the compressive strength by 5% at an early age (7 d) unlike other added ratios of the PF caused a decline in the compressive strength as compared to HSC. The experimental results showed that 10HSC₀ and 10HSC₀.20 mixes gained higher compressive strength compared with the HSC at the late strength ages (28 and 90 d). The compressive strength values of 10HSC₀ and 10HSC₀.20 increased by 2.79%, 4.33%, and 2.13%, 2.8% at 28 and 90 d, respectively, compared with HSC. The combination of VPP with PF is favorable in gaining strength at certain proportions and ages. Therefore, the use of VPP in HSC production is feasible and advantageous.

The rate of strength development from the observed results is associated with the chemical and physical effects of VPP and PFs. Behnoood and Ghandehari [48] observed the chemical effects of PF in the range of 300–600 °C and reported that the relative compressive strength of PF concrete is higher than that without PF concrete. In this study, the compressive strength results for 10HSC₀.20 showed almost higher values in all mixes at 7, 14, 28, and 90 d. All plotted trends showed a high compressive strength for HSC production can be achieved when the mixes are cured for a longer period.

The 10HSC₀ strength curve shows that compressive strength improved at 28 and 90 d compared with the test at 7 d, which may be attributed to accelerated pozzolanic reactions at a long period. Turanli et al. [29] reported that using different SCMs indicates improvement in compressive strength and durability under long curing time. Moreover, adding 0.20% PFs of concrete volume (10HSC₀.20) resulted in high compressive strength. The PFs decreased workability, resulting in incomplete compaction compared with concrete having a higher PF content. [49,50] concluded that the improvement in compressive strength is associated with a certain PF content, and strength starts declining once PF content exceeds 0.5%.

By contrast, the 20% VPP replacement rate reduced the compressive strength for all mixes as shown in Fig. 11. According to Samimi et al. [8], the use of pumice for up to 15% improves compressive strength [51]. However, this reduction in compressive strength is attributed to low cement content and free water hydration [52]. For the same VPP content (20%), the compressive strength grew at 90 d but did not even attain the 100% compressive strength of HSC.

Fig. 12 shows the compressive strength results of HSC and 10HSC₀ at 7, 14, 28, and 90 d. The partial VPP replacement was limited by 10% of the cement mass. A further improvement in compressive strength was observed at the optimum PF content (0.20%) of concrete volume.

5.4.2. Indirect tensile strength and flexural strength
Figs. 13 and 14 show the indirect tensile and flexural strength results of the HSC and 10HSC₀ at 7, 14, 28, and 90 d. These results were similar to those of compressive strength, except that PF incorporation improved its strength further because the addition of the PF reinforced the HSC mix, consequently increasing the indirect tensile and flexural strength for all mixes. In addition, the increases in indirect tensile and flexural strengths can be attributed to a greater extent through PF compared with VPP content for HSC mixes. The results show that indirect tensile and flexural strength increase with the increased in PF content.

At early age (7 d), the tensile strength for 10HSC₀.20, 10HSC₀.35, and 10HSC₀.50 increased by 3%, 5.5%, and 7%, respectively, compared with HSC. The tensile strength development for the same PF incorporation stalled at a later age (28 and 90 d). Flexural strength results followed the same pattern as tensile strength. The same trends were reported by Ananthi and Karthikeyan [53] and Matar and Assaad [54] in which split (indirect) tensile and flexural strength increase with the increase in PF.
Indirect tensile and flexural strength improved considerably when 10% VPP replacement of cement mass was used, and compressive strength was delayed at 28 and 90 d.

5.4.3. Water absorption
The water-absorption capacity of concrete was measured through standard specimen cubes measuring 100 mm. Fig. 15 shows the water absorption results of HSC and $V^\text{HSC}_F$ mixes at 7, 14, 28, and 90 d. The trend lines of different specimens showed mixed absorption rate behavior at different ages. Maximum absorption was observed for the HSC control specimen for all ages.

Fig. 15 shows the water absorption capacities at 3, 7, 28, and 90 d. The results show that the water absorption rates decreased when the VPP content increased. This reduction in water absorption may be due to the contribution of VPP in filling the pores of the specimen, reducing water movement through the free voids in the concrete specimen. By contrast, the addition of PFs led to increased water absorption rates for all mixes of the HSC and $V^\text{HSC}_F$ at all test ages. This result may be attributed to the effect of PFs on workability; the PFs led to decreased flowability and additional pores in the concrete mix [55].

5.4.4. Sorptivity
This test determines the sorptivity capacity of concrete by using cube specimens with a size of 100 mm. Figs. 16–18 show the results of the water absorption of the HSC and $V^\text{HSC}_F$ mixes at 10, 30, and 60 min, respectively. All tests were performed at 7, 14, 28, and 90 d.

All sorptivity test results (10, 30, and 60 min) exhibited similar patterns. Water absorption was initiated abruptly (i.e. 10 min) and decelerated at 30 and 60 min. The reduction in water absorption after a long time (30 and 60 min) can be
Fig. 14 – Flexural strength of HSC and $^{\gamma}$HSC$_F$.

Fig. 15 – Water absorption of HSC and $^{\gamma}$HSC$_F$.

Fig. 16 – Sorptivity test at 10 min.
attributed to the slow water flow in the capillary pores. The sorptivity test result indicated that water absorption was higher for the HSC control sample without VPP content for all test ages. Sample specimen HSC0.20 displayed the lowest water absorption results because of the closely packed pores by the VPP. These closely packed pores developed because of the high surface area of the VPP (4298 cm²/g) as compared with cement (3410 cm²/g). Thus, filling the pores contributed to impeding the movement of water and decelerating the absorption. The PFs led to decreased workability, which in turn led to additional pores on the concrete mix as compared with the mix without PFs [56].

6. Conclusions

In this paper, the role of VPP incorporation in HSC production was investigated. The following conclusions are drawn based on the results and discussion:

1. Maximum compressive strength and durability were observed at 10% VPP replacement rate combined with 0.20% PF content, but its reduction started as a percentage of PF increased above 0.20%.
2. Maximum durability was observed at 20% VPP replacement rate combined with 0.20% PF content, and it started to decline as the percentage of PF increased to above 0.20%.
3. The use of VPP improved fresh concrete properties because of the decreased cement content. For 10% and 20% VPP replacement rates without PFs, the slump results increased from 200 and 210, respectively.
4. The slump value decreased as the addition of PFs increased, indicating lower workability compared with concrete mixes without PFs.
5. Indirect tensile and flexural strength were optimized at 10% VPP replacement rate with 0.50% PF.
6. High VPP replacement rates with 20% cement mass decreased the properties of hardened concrete.
7. Adding PFs above 0.35% and 0.50% of concrete volume to HSCF led to reduced compressive strength. How-
ever, indirect tensile and flexural strength improved with increased PF content.

8. HSC produced by the replacement of VPP content exhibited higher durability compared with control HSC by depicting low water absorption and initial surface absorption results. These properties increased as the VPP replacement rates increased.

9. The combination of 10% VPP and 0.20% PF was most suitable among all combinations for HSC.

10. HSC production by (locally available) VPP replacement from cement also reduced the cost of construction.

The conclusions above demonstrate the feasibility of using VPP in concrete production with some constraints, such as VPP composition, VPP replacement rates, and PF incorporation rates. Moreover, using VPP in HSC production minimizes massive cement production and protects the environment from pollution.

Conflict of interest

The authors declare no conflict of interest.

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