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Full Length Article

Comprehensive evaluation of sustainable Self-Compacting concrete (SCC) with High-Density Polyvinyl Chloride (HDPVC) recycled pipes as partial coarse aggregate replacement

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ABSTRACT

This study explored the potential of recycled High-Density Polyvinyl Chloride (HDPVC) from scrap pipes as an environmentally friendly substitute for natural coarse aggregate in self-compacting concrete (SCC). incorporating fly ash as a supplementary cementitious material. The influence of varying HDPVC replacement levels (5 %, 10 %, 15 %, 20 %, and 25 %) by volume of natural coarse aggregate on the fresh, hardened, and durability characteristics of SCC was examined. The experimental results indicated satisfactory in passing ability, flowability, and segregation resistance for mixtures containing up to 25 % HDPVC. Optimal strength enhancement was observed at 10 % HDPVC replacement, resulting in a 20 %, 16 %, and 17 % improvement in compressive, splitting tensile, and flexural strength, respectively, at 28 days of curing relative to the reference mixture. Conversely, a subsequent decline in strength at higher levels occurred until it nearly equaled that of the control mixture. Furthermore, strong correlations of 0.9704 and 0.9117 were noted in comparison with the compressive strength with Schmidt rebound number and ultrasonic pulse velocity (UPV), respectively. SCC with HDPVC particles demonstrated superior resistance to sulfuric acid attack while maintaining adequate resistance to salt attack compared to reference mixture. However, significant weight and compressive strength losses were recorded at elevated temperature (450 °C), limiting the material's application in such conditions. Based on the comprehensive evaluation of fresh, hardened, and durability properties, the SCC mixture with 10 % HDPVC replacement is advisable for general construction applications where enhanced mechanical performance and improved acid resistance are beneficial, excluding high-temperature environments due to observed material degradation.

1. Introduction

Self-compacting concrete (SCC) constitutes a major branch within the broader classification of High-Performance Concrete (HPC), which is generally used with cast-in-place large structures in ginormous projects with highly dense reinforcement [1,2]. The SCC has offered some significant advantages over conventional concrete, primarily due to its faster placement and improved reliability during construction [3,4]. In general, the widespread use of reinforced concrete (RC) in bridges, buildings, highways, dams, and other constructions has resulted in a significant demand for concrete ingredients like water, cement, fly ash (in SCC), and aggregate [5]. Furthermore, aggregate consumption in concrete production is significantly higher than that of cement and water, almost 7 times higher than the other concrete ingredients [6,7]. This high demand for aggregate poses a significant threat to natural resources [8]. This high material consumption raises concerns about environmental sustainability in addition to CO_2 emissions [9–11]. Therefore, the incorporation of recycled industrial waste has the potential to revolutionize civil engineering by promoting sustainable construction practices [12–14]. This approach reduces reliance on natural resources and contributes to the development of building materials that offer improved efficiency [15–17]. Recent studies have explored using recycled solid waste to replace aggregate such as plastic [18], glass [19], electronic waste [20], ceramic waste [21], and rubber [22].

Globally, Polyvinyl Chloride (PVC) utilization places it among the most commonly employed plastics. PVC exhibits superior stiffness

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compared to its thermoplastic counterparts, coupled with excellent chemical resistance and adhesive bonding properties. Its dimensional stability and ease of processing further enhance its versatility [23–25]. While generally considered safe for most consumer products under normal conditions [26], it is important to be aware of the potential hazards of PVC, especially when burned. Burning PVC releases harmful chemicals, so proper disposal is crucial [27]. One potential solution for reducing PVC waste is using it as a recycled aggregate in concrete [28–30]. Researchers examined experimentally the incorporation of PVC as an alternative for aggregate (i.e., fine or coarse) in conventional concrete mixtures [31–43]. The success of concrete structures incorporating PVC hinges relies heavily on the interplay between the hardened and freshly mixed concrete properties. Fresh concrete characteristics, including workability, viscosity, consistency, and yield stress, significantly influence the hardened concrete's mechanical performance and durability. Moreover, controlling factors like air content, segregation, and bleeding within the fresh mixture is crucial for maximizing the benefits of using concrete [44]. Consequently, evaluating the workability of fresh SCC incorporating novel materials like PVC is essential. This evaluation ensures that the concrete flows easily, fills complex forms without obstruction (passing ability), and maintains its homogeneity by preventing the separation of its constituents (segregation).

Based on the authors' current knowledge, only a few studies addressed the workability and the strength of SCC mixtures containing PVC [45,46]. In the study of Yang et al. [45], investigations were conducted using Plastic Particles (PP) as a sand substitution, with replacement percentages of 10 %, 15 %, 20 %, and 30 % by volume. The results demonstrated a positive impact on the fresh aspects and the hardened concrete strength of the SCC. Notably, a 15 % fine aggregate replacement with PP yielded the optimal improvement for both fresh and hardened concrete characteristics. Abdulqadir and Mohammed [46] examined the influence of substituting fine aggregate with PVC in increments of 2.5 %, from 2.5 % to 10 %, on the fresh characteristics of SCC. The experimental outcomes revealed that all concrete samples containing HDPVC fell within the EFNARC classification of VS2/PA2. This indicates good rheological properties, as evidenced by no blockages observed in the V-funnel and L-box tests. Because of the limitations in research in this area, further experimental work is required to assess the large-scale viability of this approach.

1.1. Research significance

Based on the above summary, the authors know of no comprehensive prior research on the fresh, hardened, non-destructive, and durability aspects of SCC with partial HDPVC substitution of coarse aggregate. Therefore, the aim of this current investigation is to comprehensively analyze the overall behavior of sustainable SCC made with recycled High-Density Polyvinyl Chloride (HDPVC) from scrapped pipes as a partial substitution of natural coarse aggregate using fly ash as a filling and binder material to produce SCC. HDPVC was used as a partial replacement of coarse aggregate at ratios of 5 %, 10 %, 15 %, 20 %, and 25 % by volume. Additionally, a constant 30 % by volume of Fly Ash (FA) is incorporated as an additive to cement to produce SCC.

Different examinations were applied on both fresh and hardened characteristics of concrete to obtain the suitability of using HDPVC. Furthermore, most of the important tests were examined on fresh concrete (i.e., wet density, slump flow diameter and time T500, L-box, and V-funnel flow time). Moreover, the hardened state of concrete was also examined through several tests including dry density, compressive strength, splitting tensile strength, and flexural strength. The effect of adding HDPVC on the SCC durability is evaluated by performing the following tests: Schmidt rebound hammer, Ultrasonic pulse velocity (UPV), resistance to acid attack and salt media (H_2SO_4, $MgSO_4$), chloride permeability, water absorption, unit weight, and elevated temperature.

2. Experimental program

The flowchart of the experimental program of the current study is shown in Fig. 1.

2.1. Materials

2.1.1. Binders

Ordinary Portland Cement (OPC) (grade 42.5) Type I was utilized in all design mixtures with the chemical compositions (Table 1) and physical properties (Table 2) are provided. Fly Ash (FA) class F was employed in this study to produce SCC mixture with chemical and physical properties, as summarized in Table 3.

2.1.2. Aggregate and High-Density Polyvinyl Chloride HDPVC

For the aggregate combination, river sand with a maximum size of 5 mm was utilized as the fine aggregate, while crushed dolomite with a maximum size of 25 mm was provided as the coarse aggregate. High-density polyvinyl chloride HDPVC waste was collected from a local dump place of scrap pipes in the Shuaiba area of Basrah, as illustrated in Fig. 2a. The waste pipes were then crushed into small particles by a crusher machine shown in Fig. 2b. The crushed HDPVC waste was graded by using sieve analysis to get similar gradings to the coarse aggregate, as depicted in Fig. 2c. Particles distribution of the fine aggregate, coarse aggregate, and HDPVC are depicted in Fig. 3 and their results are within the requirements of ASTM C33-18 [49]. Table 4 summarized the physical properties of the aggregate and HDPVC.

The tensile strength of the HDPVC is 50 MPa. The compressive strength is 67.5 MPa. The elastic modulus of the HDPVC is 1400 MPa.

2.1.3. Superplasticizer

To enhance the flowability of concrete and to increase its workability, Master Glenium 54, which is a high-performance super plasticizing admixture was implemented in the current study. This superplasticizer contains a unique carboxylic ether polymer featuring long lateral chains that helps cement particles spread out better. This effect has several advantages for concrete that needs to be poured easily, such as less need for vibration equipment, reduced labor costs, and a smoother final surface.

2.2. Mixing proportions and procedure

Six concrete batches were prepared to evaluate the impact of adding HDPVC on the strength, performance, and durability of the SCC. All mixtures had the same binder content of 582 kg/m^3 with water-to-binder ratio of 0.28, which included cement and an additional 30 % fly ash (FA) added by volume to cement content. A reference mixture (SCCPVC0) was created without HDPVC with a target strength of 45 MPa, following guidelines from EFNARC [50] and ACI 237R-07 [51]. The SCC mixtures were designed with all parameters held constant, excluding the coarse aggregate content. Coarse aggregate was partially interchanged with HDPVC in varying amounts of 5 %, 10 %, 15 %, 20 %, and 25 % (by volume of coarse aggregate). The mixtures were named SCCPVC5, SCCPVC10, SCCPVC15, SCCPVC20, and SCCPVC25, respectively. Table 5 shows the details of each mixture for one cubic meter volume of SCC.

Achieving a successful SCC mixture relies heavily on a precise mixing process. Therefore, this study combined established EFNARC guidelines [50] with the efficient direct technique introduced by Kheder et al. [52]. For reference mixture SCCPVC0, the mixing began with half of the total aggregates in addition to small portion of water being loaded into the mixer and then rotated for a minute. After that, a portion of the binder (cement and FA), along with some fine aggregate was added, followed by another minute of mixing for proper blending. To ensure consistent material distribution, the superplasticizer was incorporated into half of the water before other ingredients were added. before gradual addition

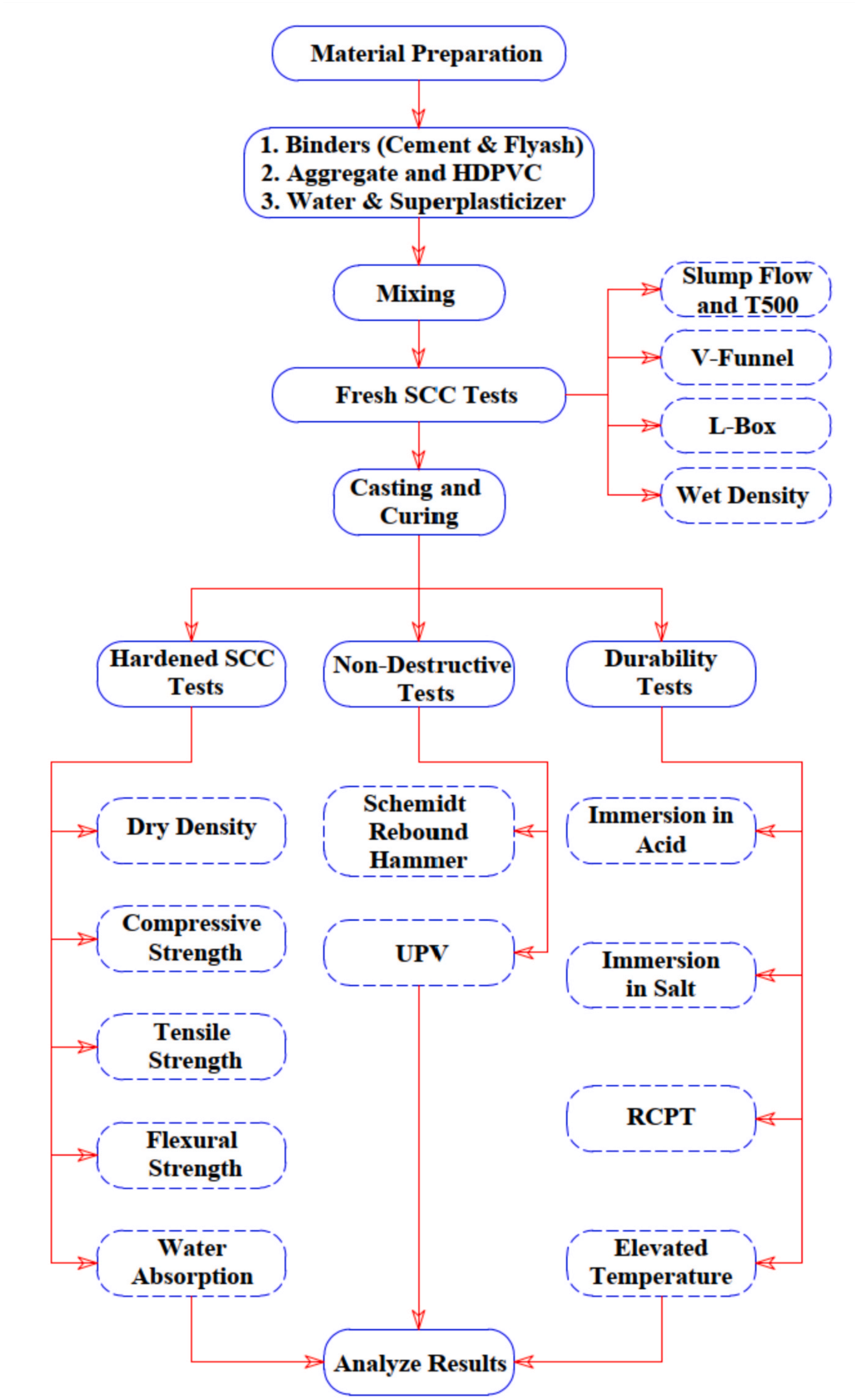


Fig. 1. The flowchart of the experimental program.

to the mixture for over two minutes. This extended mixing period allowed for a consistent and homogeneous SCC mixture. Finally, all remaining ingredients were added to the mixer, including the rest of the total aggregates, and the remaining of superplasticizer and water. This final mix was mixed for an additional three to five minutes to ensure complete homogeneity before ending the mixing process. For mixtures containing HDPVC, a modification was made where the required amount of HDPVC replaced a portion of the coarse aggregate before the first mixing stage. The remaining steps were the same. Following the completion of mixing, the workability and flowability of the fresh SCC mixture were assessed using different tests include slump flow, T500, V-funnel, and L-box tests.

2.3. *Casting and curing of specimens*

To assess the hardened mechanical behavior of the SCC mixtures, several samples were cast. Nine cubes with side dimensions of 150 mm were prepared to assess the compressive strength at different curing periods (7, 28, and 56) days. Additionally, the splitting strength was investigated using nine (100 mm diameter x 200 mm height) concrete

Table 1
Chemical composition of cement.

Components	Contents (%)	Limits of ASTM C150-09 [40,47]
CaO	62.21	–
SiO_2	20.8	–
Al_2O_3	5.18	–
Fe_2O_3	3.69	–
MgO	2.78	6.0 (max)
SO_3	2.31	–
Loss on Ignition (L.O.I)	1.96	3.0 (max)
Na_2O	0.36	–
K_2O	0.84	–
Insoluble residue	0.53	0.75 (max)
C_3S	52.2	–
C_2S	16.9	–
C_3A	2.45	3.0 (max)
C_4AF	13.8	25.0 (max)

Table 2
Physical properties of cement.

Physical properties	Test result	Limits of ASTM C150-09 [40,47]
Specific surface area (Blaine method) (m^2/kg)	315	Not less than 280
Setting time (Vicat method) (min)		
Initial setting time	130	More than 45
Final setting time	285	Less than 375
Compressive strength (MPa)		
3 days	15.4	More than 12
7 days	22.8	More than 19
Specific gravity (g/cm^3)	3.15	–
Color	Light grey	–

Table 3
Chemical and physical properties of fly ash type F.

Item	Description	Limits of ASTM C618-15 [41,48]
Chemical		
CaO	4.14 %	18.0 (max)
SiO_2	56.3 %	–
Al_2O_3	20.4 %	–
Fe_2O_3	6.7 %	$SiO_2 + Al_2O_3 + Fe_2O_3 > 50$
MgO	1.89 %	–
SO_3	0.51 %	5.0 (max)
Loss on Ignition (L.O.I)	1.78 %	6.0 (max)
Na_2O	0.52 %	–
K_2O	1.83 %	–
Physical		
Density (specific gravity)	2.18	–
Fineness- amount retained on #325 Sieve, 45 μm (#325) sieve, %	25.8	34 max
Specific Surface Area m^2/kg	287	–
SAI, 7 days, % of control	86	75 min

cylinders tested at different ages (7, 28, and 56) days. Finally, the flexural strength of the SCC was examined at 28 days involving the casting of three prisms with a cross-section of 100 mm x 100 mm and length of 350 mm. All samples were cured following the ASTM C192 standard [53], which involved covering them with plastic sheets and wet burlaps for a day and then submerging them in water at 20 ± 3 °C until examination day.

2.4. Testing Procedures

2.4.1. Fresh SCC tests

Different examinations were performed in the current study on the fresh characteristics of SCC mixtures, included slump flow diameter and time T500 to assess flowability and filling ability (Fig. 4a), V-funnel test to measure flow speed and viscosity (Fig. 4b), L-box test to examine filling ability and segregation resistance (Fig. 4c). Finally, wet density determines the fresh SCC weight per unit volume, which can influence handling and pumping. The above-mentioned series of comprehensive tests followed EFNARC guidelines [50]. These comprehensive testing approaches provide valuable insights into how the addition of HDPVC affects the SCC mixture's workability, allowing for adjustments or identification of potential compatibility issues before large-scale use.

2.4.2. Hardened SCC tests

Hardened SCC tests focused on the evaluation of the mechanical characteristics of the SCC mixture. The compressive strength evaluation was performed as stated by BS EN 12390–3:2009 [54] at different curing ages (7, 28, and 56 days) (Fig. 5a). ASTM C496-11 [55] was followed for splitting tensile strength testing at the same curing ages as in compressive strength (Fig. 5b), and Three-Point Loading flexural strength test was done based on the guide of ASTM C 293–02 specification [56] at 28 days (Fig. 5c) in addition to measuring the dry density at day 28 of casting. Following ASTM C642-13 [57], water absorption testing was conducted on 100 mm concrete cubes cured for 28 days in tap water.

Non-destructive and durability tests were also evaluated on the hardened SCC and reported in the current study. The Rebound Hammer examination was performed (Fig. 6a) as reported by ASTM C805 [58], prior to compression strength testing on cubic concrete samples. Ultrasonic Pulse Velocity (UPV) test was evaluated using a PUNDIT device [59] in line with ASTM C 597–09 [60] to examine concrete quality (Fig. 6b). The impact of acid and sulfate attack on the durability of hardened concrete was investigated following ASTM C267-97 [61]. After the 28-day curing period, 100 mm cubic specimens were weighed before submersion in either a sulfuric acid (H_2SO_4) or a magnesium sulfate ($MgSO_4$) salt solution with a 5 % concentration. Submersion was followed by re-weighing of the specimens. At 56 days, the modifications in compressive strength, tensile strength, and weight were recorded and subsequently compared to those of non-acid attack specimens.

Besides the aforementioned tests, the chloride permeability test followed ASTM C1202-19 [62] (Fig. 7) was performed. Electrical current through a concrete core or cylinder is monitored in this test method for 6 h with current measured at 30-minute intervals. A 60-volt DC potential difference is applied across a 50 mm thick sample, with one end submerged in a 0.3 M sodium hydroxide (NaOH) solution and the other in a 3 % sodium chloride (NaCl) solution. By measuring the total electrical charge (in coulombs) that flows through the sample, the impermeability of concrete to chloride ion penetration is able to be indirectly assessed. Furthermore, to evaluate the influence of elevated temperature on compressive strength, 100 mm cubes were weighed and then exposed to (150, 300, and 450) °C respectively for one hour by an electric furnace, as illustrated in Fig. 8. After cooling, cubes were examined for compressive strength then compared with the reference cubes. This method of exposing concrete to elevated temperatures was adopted from the study by Kelechi et al. [63].

It should be noted that in each test, an average of three samples were taken.

3. Results and discussions

3.1. Fresh characteristics results of SCC with HDPVC

The experimental evaluation of SCC workability with different HDPVC content is depicted in Fig. 9. The subsequent sections provide an in-depth examination of the findings from each test.

3.1.1. Slump flow

The reference mixture, SCCPVC0, as well as SCCPVC5 exhibited a slump flow diameter consistent with the SF3 class (most fluid SCC) [64]. However, incorporating a larger amount of HDPVC (i.e., greater than 5

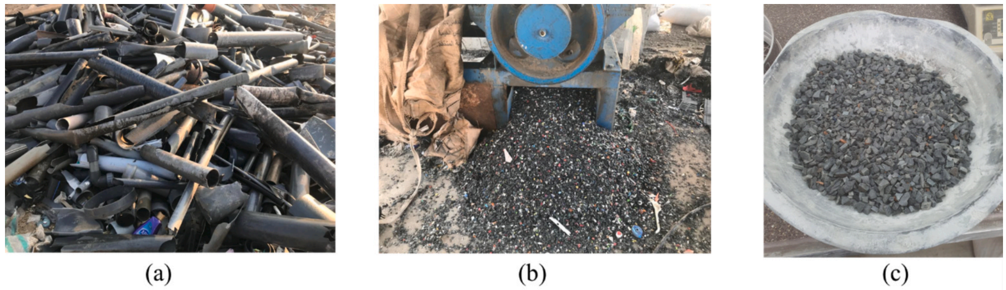


Fig. 2. HDPVC Assembly and preparation process: a) scrap pipes in the local dump area, b) the crushed pipes and crusher machine, and c) the sample after sieve analysis.

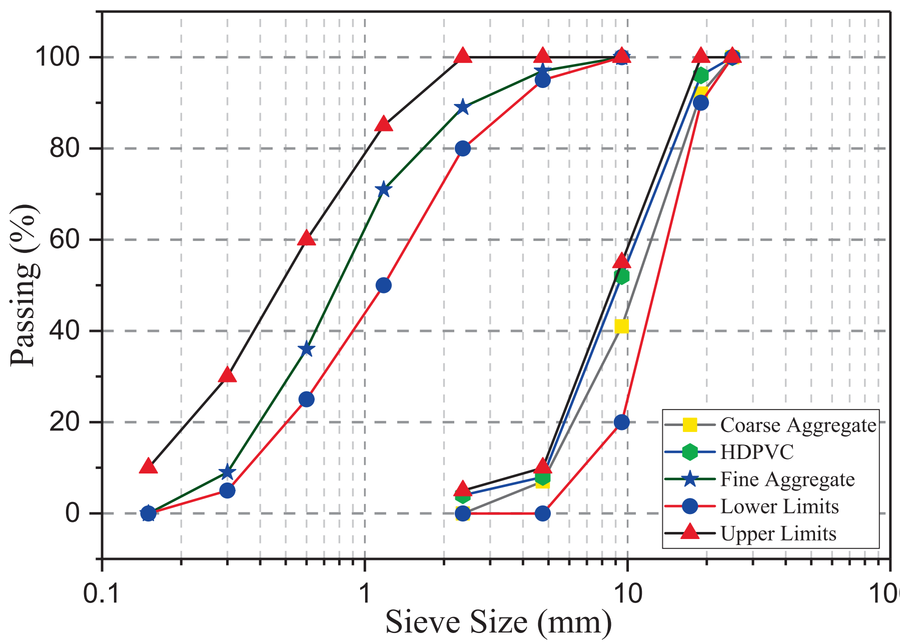


Fig. 3. Sieve analysis diagram for fine aggregate, coarse aggregate and HDPVC particles.

Table 4
The physical properties of fine aggregate, coarse aggregate, and HDPVC.

Physical properties	Fine Aggregate	Coarse Aggregate	HDPVC
Specific gravity	2.56	2.67	1.46
Bulk density (kg/m^3)	1681	1520	830.9
Sulfate content (SO_3) %	0.30	0.068	–
Absorption %	1.04	0.71	0
Fineness modulus	2.98	–	–

%) as partially substituted for coarse aggregate reduced the slump flow, as shown in Fig. 9a. This reduction is likely originated from the size, surface texture, and shape of the HDPVC particles. Although the decline in slump flow could be significant (up to 10.4 % for the mixture with the highest replacement level of HDPVC (i.e., 25 %), the mixtures (SCCPVC10, SCCPVC15, SCCPVC20, and SCCPVC25) achieved a slump flow diameter within the SF2 class (660–750) mm. This SF2 class represents moderately fluid SCC, offering a good balance between flowability and stability, resulting in its suitability for diverse applications such as wall, beams, slabs and precast elements.

The T500 flow slump time which measures the viscosity of the SCC mixture, increased with a higher replacement level of HDPVC, as illustrated in Fig. 9b. According to [50], a T500 value between 3–7 s is considered adequate for civil engineering purposes. Therefore, the SCC mixtures with 5 % and 10 % HDPVC content (SCCPVC5 and SCCPVC10) exhibited good flowability compared to the reference mixture (SCCPVC0) and could be suitable for field use. However, mixtures with T500 exceeding 7 s were negatively impacted by a further increase in

Table 5
SCC mixtures proportions.

Mixture ID	Cement	Fly ash	Water	Coarse aggregate	Fine aggregate	HDPVC	Super plasticizer
SCCPVC0	420	162	180	780	845	0	6.5
SCCPVC5	420	162	180	741	845	20	6.5
SCCPVC10	420	162	180	702	845	40	6.5
SCCPVC15	420	162	180	663	845	60	7
SCCPVC20	420	162	180	624	845	80	7
SCCPVC25	420	162	180	585	845	99	7

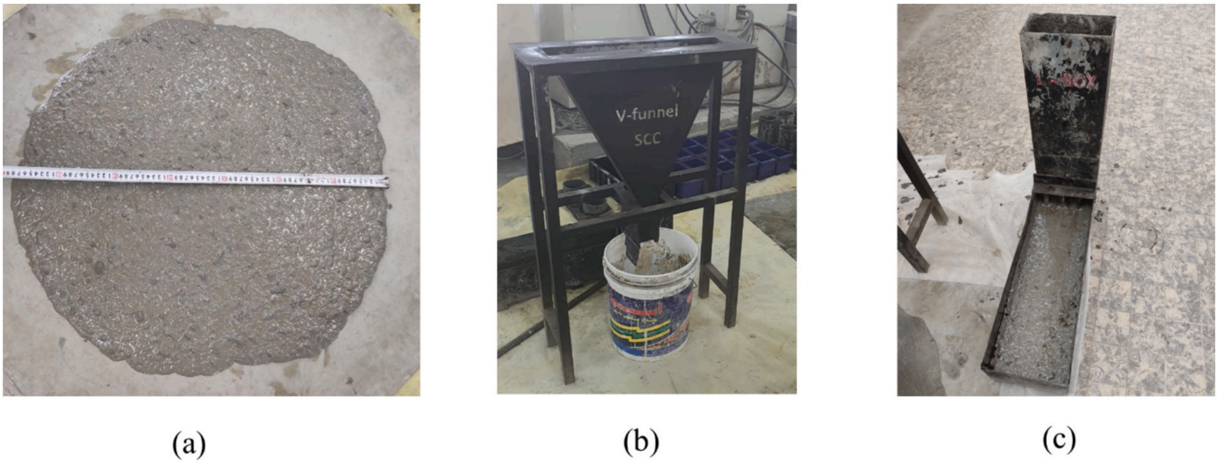


Fig. 4. Fresh SCC tests: a) slump flow, b) V-funnel, and c) L-box.

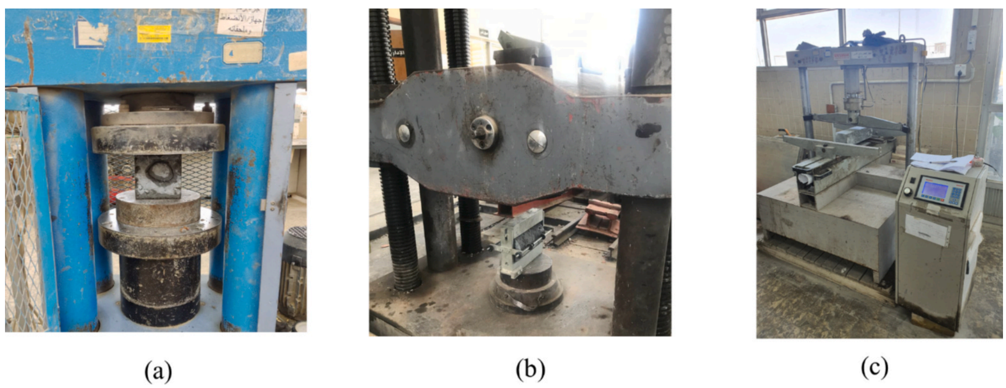


Fig. 5. Hardened SCC tests: a) compressive strength, b) splitting strength, and c) flexural strength.

Fig. 6. Non-destructive tests: a) Schmidt rebound hammer, and b) ultrasonic pulse velocity (UPV).

HDPVC replacement. This suggests that a higher HDPVC content can significantly reduce flowability.

3.1.2. Flow speed and viscosity

The V-funnel test offers another approach to measure SCC viscosity. This test evaluates both the flow time and the resistance to segregation of the SCC mixture as it flows through a funnel. Fig. 9c illustrates the impact of HDPVC addition on V-funnel flow time. As reported in the EFNARC guidelines [50], shorter flow times indicate better flowability. Following these guidelines, a flow time of 8 s is suitable for SCC mixtures. Based on this criterion, most mixtures containing HDPVC fit the viscosity class requirements of FS2/VF2 as defined by EFNARC [50] except for control and SCCPVC5 mixtures which met the FS1/VF3 requirement with the highest filling, the ability of passing through the obstacles and resistance to segregation. This indicated that despite the HDPVC addition, all mixtures maintain good flowability and resistance to segregation.

Fig. 7. Chloride permeability test.

Fig. 8. Electric furnace.

3.1.3. L-box test

The passing ability and segregation resistance of SCC mixtures containing HDPVC particles were evaluated through this test. Fig. 9d shows the height ratio of the L-box (H2/H1) for different HDPVC replacement levels. According to EFNARC guidelines [50], an H2/H1 value of at least 0.8 indicates acceptable passing ability for SCC. The results revealed a decreasing H2/H1 ratio with increasing HDPVC content. Similar to the slump flow evaluation, this decrease is likely because of the irregular shape of HDPVC particles, making the concrete mix "harsher" and increasing internal friction. However, all mixtures achieved an H2/H1 ratio exceeding the minimum requirement (0.82 for SCCPVC25). This indicates that despite the HDPVC addition, all mixtures maintained adequate passing ability and resistance to segregation.

3.1.4. Wet density result

Fig. 9e illustrates the impact of incorporating HDPVC as a replacement to the coarse aggregate on the wet density of SCC mixtures. As detailed in *Section 2.1*, the weight per unit volume (specific gravity) of the SCC ingredients (gravel, sand, and cement) significantly impacts the overall wet density of the mixture. HDPVC, with a specific gravity of 1.46, is nearly half that of natural coarse aggregate. Consequently, all mixtures containing HDPVC exhibited a reduction in wet density, with the SCCPVC25 mixture (25 % HDPVC) showing the most significant decrease (up to 10.7 %). This reduction in wet density suggests that SCC mixtures containing HDPVC can be categorized as Lightweight SCC. This translates to a potential benefit of reduced weight for the overall structure.

3.2. Hardened characteristics results of SCC with HDPVC

Fig. 10 illustrates the experimental results for SCC hardened properties with varying HDPVC content. Subsequent sections provide a detailed analysis of these findings through individual test examinations.

3.2.1. Dry density

The experimental assessment of the dry density for SCC mixtures at 28 days are depicted in Fig. 10a. As the proportion of HDPVC increased within the mixtures, the dry density proportionally decreased. This reduction was up to 13.1 % for the mixture with 25 % replacement in the HDPVC content (i.e., SCCPVC25) in comparison with the control mixture. As explained in Section 2.1, the weight per unit volume (specific gravity) of the concrete ingredients (gravel, sand, and cement) heavily influences the overall dry density of the final mixture. HDPVC has a much lower specific gravity (1.46) compared to coarse aggregate (2.67). This significant difference essentially leads to a lower overall dry density.

3.2.2. Compressive strength

The compressive strength experimental findings, averaged from three cubes tested at different periods of curing (i.e., 7, 28 and 56) days, are depicted in Fig. 10b. As HDPVC aggregate content increased, compressive strength increased to 21 %, 20 %, and 19 % for mixture with 10 % replacement of coarse aggregate (i.e., SCCPVC10) at different curing days (7, 28 and 56), respectively. Subsequently, compressive strength gradually dropped until it nearly equaled that of control mixture for SCCPVC25. The improvement of the strength was also observed from other studies with normal and high strength concrete [27,34,58]. Several factors likely contributed to the enhanced compressive strength witnessed in this study. The incorporation of HDPVC elements can act as internal reinforcements in the concrete matrix, enhancing load-bearing capacity. Additionally, HDPVC may reduce the overall water demand of the mixture, leading to a less water-to-binder ratio. This, in turn, can contribute to denser concrete with improved hydration and reduced porosity, further enhancing strength. Furthermore, the size and distribution of HDPVC particles significantly influence their interaction within the concrete matrix. The bond quality between HDPVC and the surrounding cement matrix plays a crucial role in effective load transfer and strength enhancement. Finally, the utilization of HDPVC has the potential to alter the microstructure of concrete, potentially leading to more homogeneous and denser matrices, which further contributing to improved mechanical properties [66,67]. Conversely, the reduction in strength after 10 % HDPVC incorporation might be assigned to two primary factors: (1) the higher availability of free water due to HDPVC's lower water absorption capacity, and (2) the formation of a pseudomorphic layer around cement particles, resulting from the accumulation of more HDPVC particles, which could slightly impede cement hydration.

The inclusion of HDPVC altered the behavior of the specimens in compression. The control specimens exhibited brittle, explosive failure with extensive cracking under maximum load. In contrast, HDPVC-incorporated samples demonstrated significantly reduced cracking, characterized by fewer hair cracks. This enhanced crack resistance is attributed to HDPVC acting as internal reinforcement improving ductility and enhancing interfacial bonding within the concrete matrix [68]. Visual representations of these contrasting failure modes are depicted in Fig. 11.

3.2.3. Splitting tensile strength

The influence of incorporating HDPVC on the splitting tensile

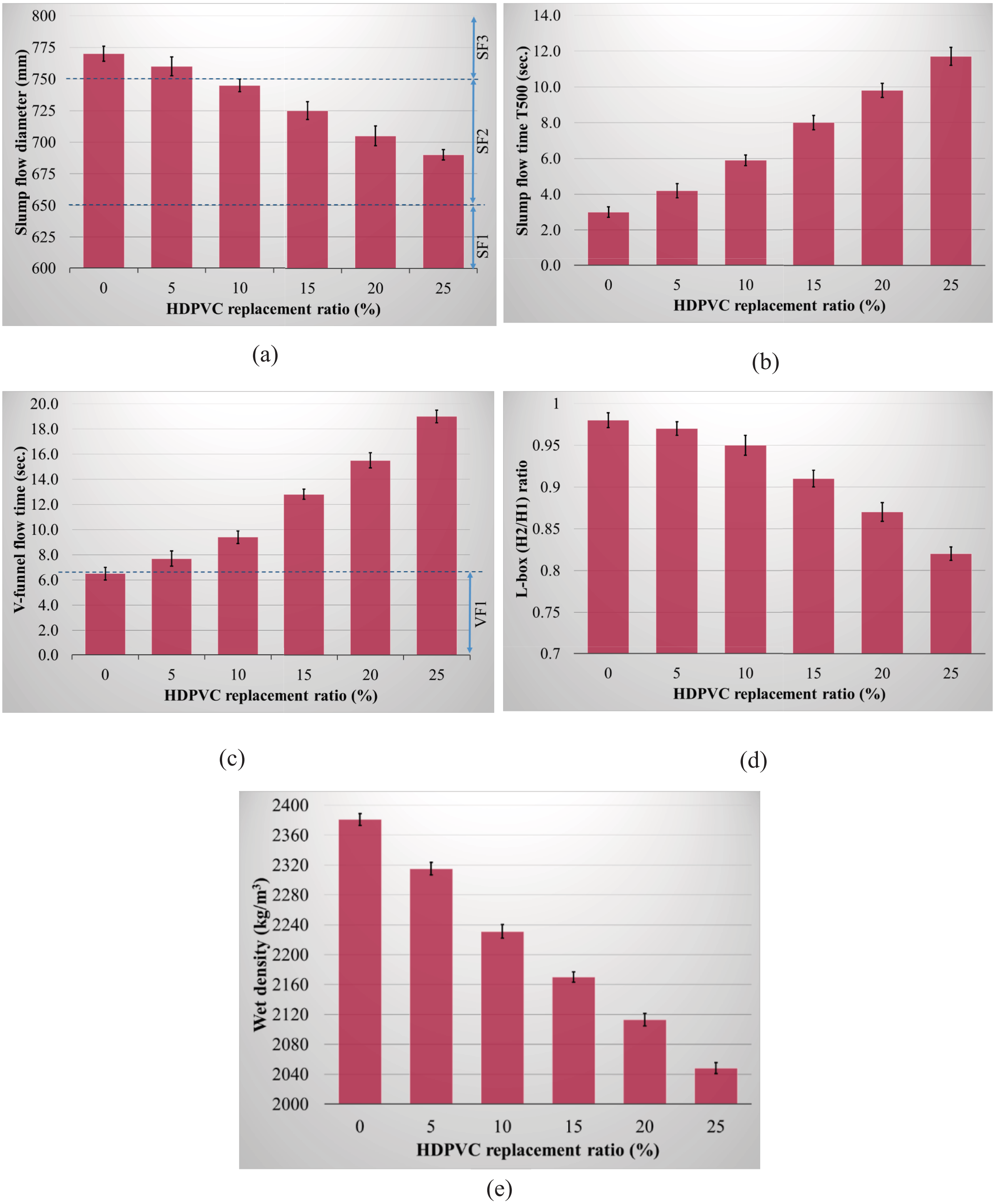


Fig. 9. The influence of HDPVC on: a) the slump flow diameter, b) T500, c) V-funnel flow time, d) the L-box (H2/H1) ratio, and e) wet density.

strength of the SCC mixtures is visually presented in Fig. 10c. Mixtures exhibited enhanced splitting tensile strength relative to SCCPVC0 mixture, with increases of 26 %, 16 %, and 15 % at different curing periods (i.e., 7, 28, and 56). This enhancement is attributed to the longer crack propagation path around the irregularly shaped HDPVC particles, as illustrated in Fig. 12b. However, for the SCCPVC25 mixture, splitting strength declined lower than SCCPVC0 mixture values by 7 %, 14 %, and 15 % at different days (7, 28, and 56), respectively. Consequently, these outcomes indicate that a maximum of 20 % coarse aggregate replacement with HDPVC can maintain the splitting strength as in the control mixture, while 10 % replacement is optimal.

3.2.4. *Flexural strength*

The flexural strength at 28-day was evaluated as illustrated in

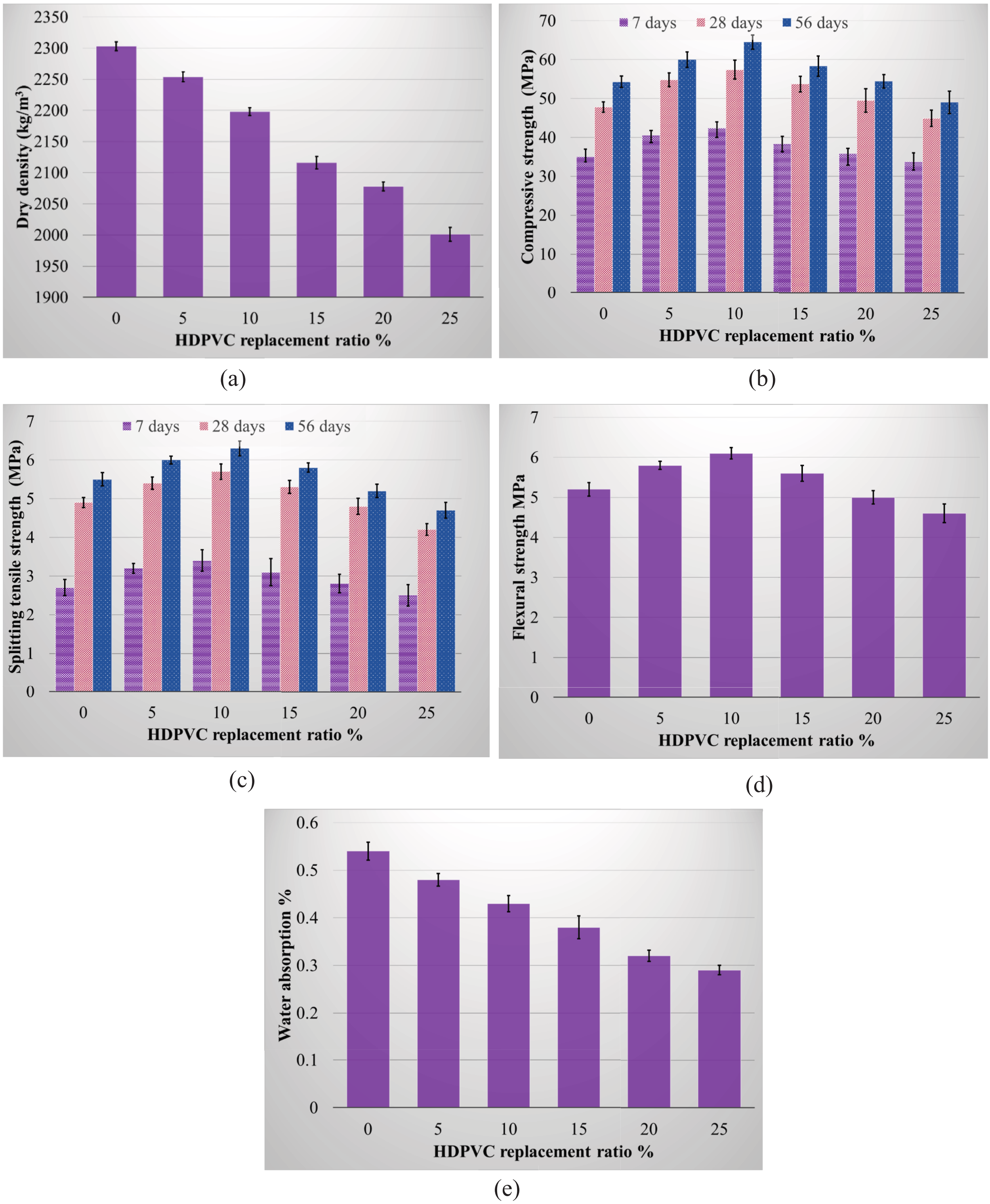


Fig. 10. The influence of HDPVC on: a) dry density, b) compressive strength, c) splitting tensile strength, d) flexural strength, and e) water absorption.

Fig. 10d. The influence of utilizing HDPVC on flexural strength has a large impact as the strength increased by up to 17 % for SCCPVC10 relative to SCCPVC0 mixture as the content of HDPVC increased to 10 %. Subsequently, a degradation in strength was recorded compared to the SCCPVC10 mixture until it reached a value lower than the control mixture for SCCPVC25 with 12 % reduction. Similar results were reported in previous studies [34] and [65]. Therefore, up to 20 % of replacement the coarse aggregate with HDPVC is also recommended based on the experimental results while 10 % of replacement is the optimal.

3.2.5. Water absorption

The examination of water absorption was conducted on an average of three 100 mm cubes at 28 days, and the experimental outcomes are illustrated in Fig. 10e. All the mixtures containing HDPVC aggregates exhibited significantly lower water absorption relative to relative to

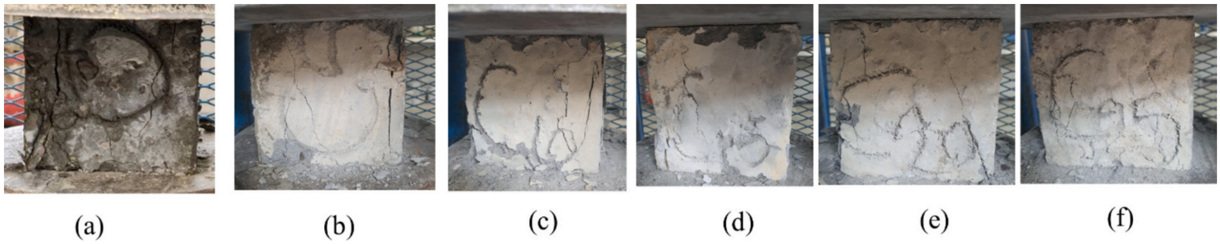


Fig. 11. Failure mode of concrete cubes for a) control mixture, b) SCCPVC5, c) SCCPVC10, d) SCCPVC15, e) SCCPVC20, f) SCCPVC25.

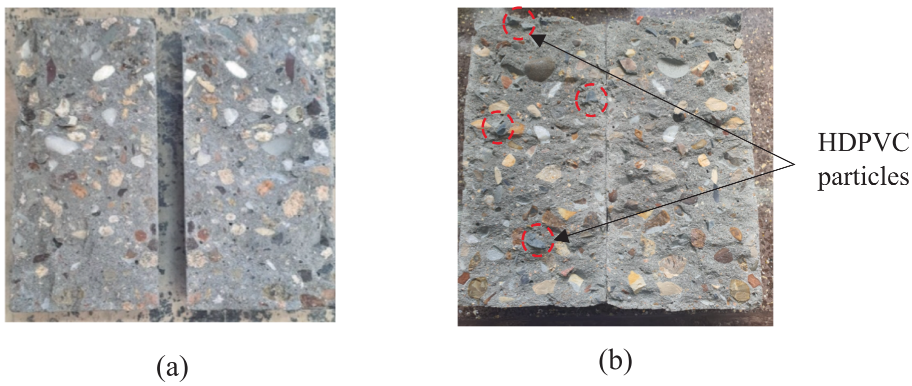


Fig. 12. Splitting tensile strength specimen failure surface for a) control mixture, and b) SCCPVC10.

reference mixture. The mixtures demonstrated absorption reductions of approximately 11 %, 20 %, 30 %, 41 %, and 46 % for SCCPVC5, SCCPVC10, SCCPVC15, SCCPVC20, and SCCPVC25, respectively. This reduction is assigned to the non-absorbed nature of the HDPVC material as reported in Table 4 *Section 2.1.2*. The same behavior was observed in mixtures with normal concrete [35].

3.3. Non-Destructive test results of SCC with HDPVC

Non-destructive tests included Schmidt hammer number N and Ultrasonic Pulse Velocity UPV performed after 28 days of curing on all mixtures to examine the impact of substituting coarse aggregate with HDPVC on SCC strength. The rebound number correlates with concrete hardness, with higher values indicating greater hardness. This principle, based on the elastic rebound of a mass impacting the concrete surface, informs the Schmidt hammer test. Conversely, UPV is the quality of concrete measuring test, with higher values generally associated with denser concrete.

The experimental outcomes are listed in Table 6 and depicted in Figs. 13 and 14. The rebound number demonstrated a trend comparable to that of compressive strength, as reported in *Section 3.2.2*. The percentage change in the rebound number was 11 %, 18 %, 14 %, 5 %, and −7% for SCCPVC5, SCCPVC10, SCCPVC15, SCCPVC20, and SCCPVC25, respectively, relative to SCCPVC0. Furthermore, the increase in Schmidt hammer rebound values can be explained by the enhanced bonding between HDPVC particles and the concrete matrix.

Despite variations between compressive strength and Schmidt rebound number results, a strong correlation ($R^2 = 0.9704$) was observed, as depicted in Fig. 13b. An empirical equation (Equation (1) was derived to estimate one value from the other.

$$f'_c = 1.1357N - 2.0286 \quad (1)$$

Fig. 14a presents the UPV results at 28 days for all mixtures. The UPV values demonstrated minimal variation relative to the control mixtures, as detailed in Table 6. SCCPVC10 exhibited the highest UPV, with a 5 % increase compared to the control. Subsequently, UPV values decreased for higher HDPVC contents, approaching the control level for SCCPVC25. As reported in [69], aggregate type significantly influences UPV values. The incorporation of low-density aggregates, as used in this study, aligns with previous research in demonstrating increased UPV compared to traditional concrete mixtures. In contrast, the observed reduction in UPV with increasing HDPVC content for mixtures SCCPVC15, SCCPVC20, and SCCPVC25 can be attributed to decreased interaction between particles and cement paste which is caused by the shape irregularity and increased in porosity of the mixture. Even though the mixture with low densities experiences lower UPV, adding HDPVC with no porous on its surface with homogeneity mixtures has no negative influence on UPV speed.

In addition, an excellent correlation ($R^2 = 0.9117$) was recorded between UPV and compressive strength for SCC with HDPVC (Fig. 14b), indicating a direct relationship between these properties as proposed in Equation (2).

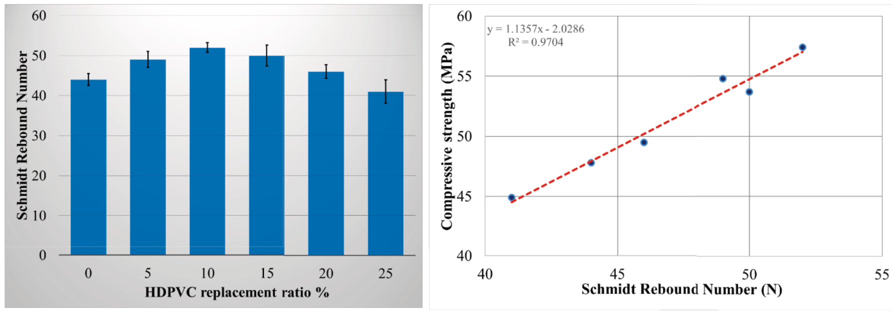
$$f'_c = 44.532UPV - 173.69 \quad (2)$$

Table 6
Non-destructive tests results of SCC with HDPVC.

Mixture ID	Schmidt Rebound Number (N)	% change	Ultrasonic Pulse Velocity UPV (km/sec.)	% change
SCCPVC0	44	–	4.95	–
SCCPVC5	49	11	5.08	3
SCCPVC10	52	18	5.19	5
SCCPVC15	50	14	5.13	4
SCCPVC20	46	5	5.04	2
SCCPVC25	41	−7	4.93	0

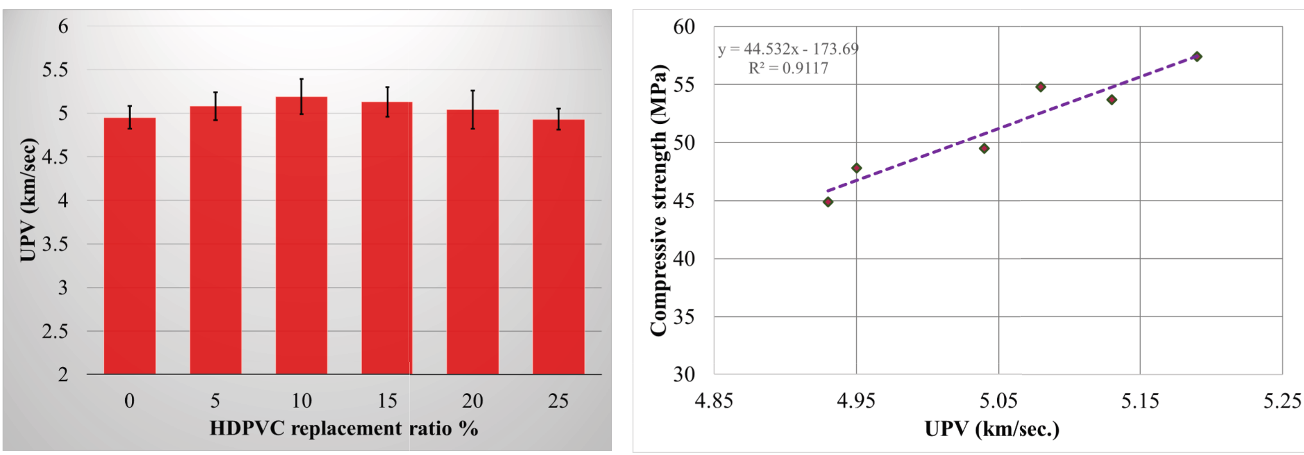
3.4. Durability test results of SCC with HDPVC

The experimental durability results for SCC mixtures with varying HDPVC aggregate content are presented in this section. These findings are analyzed in detail in the following sub-sections.



(a) (b)

Fig. 13. A) The influence of HDPVC on Schmidt rebound number, and b) the correlation relation between Schmidt number and compressive strength at 28 days.



(a) (b)

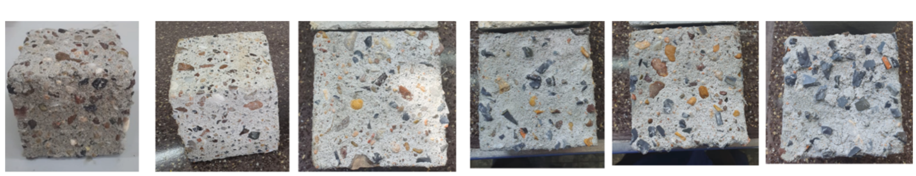
Fig. 14. A) The influence of HDPVC on UPV, and b) the correlation relation between compressive strength and UPV at 28 days.

3.4.1. Immersion in acid media

Concrete cubes were exposed to a 28-day moist curing time followed by immersion in a 5 % sulfuric acid H_2SO_4 solution for 28 days. Initial weights were determined according to ASTM C267 [61]. After acid exposure, cubes were surface cleaned with water, dried for 24 h, then reweighed and the ultimate appearance of the cubes for all mixtures are shown in Fig. 15. Compressive strength tests were conducted, and the weight and strength losses are summarized in Table 7 and Fig. 16. The SCCPVC0 mixture experienced a higher decrease in both weight and strength with11.4 % and 44.2 %, respectively. On the other hand, SCCPVC25 mixture had the least decrease in weight relative to SCCPVC0 with 7.0 % while the reduction in compressive strength is 22.6 % compared to non-acid attacked cubes for the same mixture. These results highlight the superior resistance of SCC with HDPVC particles to acid attack relative to control mixture. The enhanced acid resistance of SCC incorporating HDPVC is attributed to several factors: the inertness of HDPVC to acids, improved microstructure with reduced porosity [23–25], potential decrease in calcium hydroxide (Ca $(OH)_2$) content, and the production of a protective layer around cement paste particles [70–72].

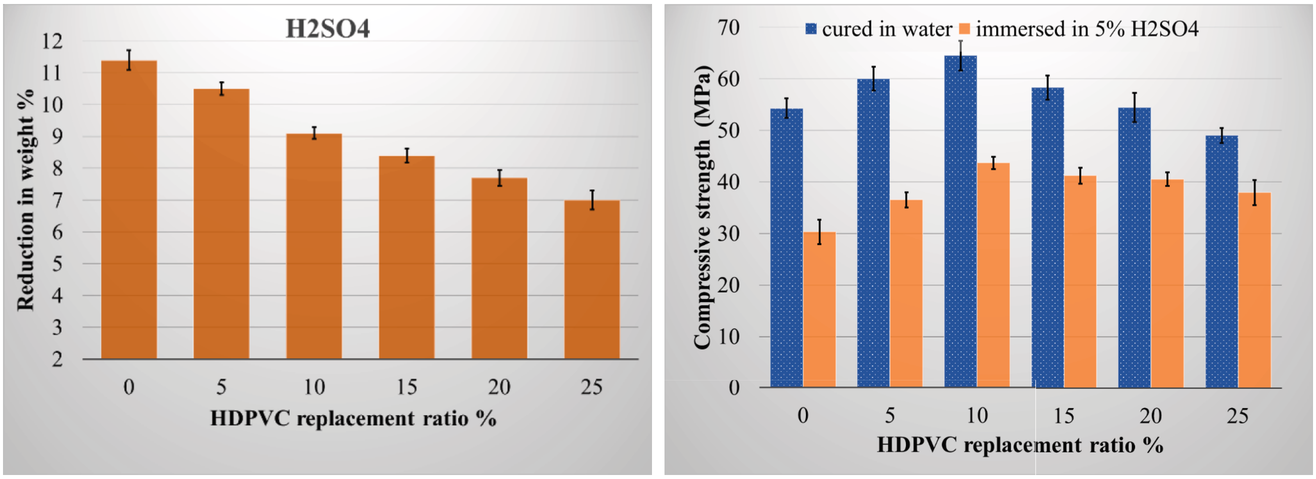
Table 7
Acid and salt resistance results of SCC with HDPVC.

Mixture ID	5 % Sulfuric acid (H_2SO_4) Percentage reduction in		5 % Magnesium sulfate ($MgSO_4$) Percentage reduction in	
	Weight	Strength	Weight	Strength
SCCPVC0	11.4	44.2	1.9	3.1
SCCPVC5	10.5	39.2	1.8	3.0
SCCPVC10	9.1	32.2	1.7	2.5
SCCPVC15	8.4	29.3	1.5	2.1
SCCPVC20	7.7	25.4	1.4	1.6
SCCPVC25	7.0	22.6	1.3	1.5



(a) (b) (c) (d) (e) (f)

Fig. 15. Cubes after 28 days of submersion in a 5 % H_2SO_4 solution for a) control mixture, b) SCCPVC5, c) SCCPVC10, d) SCCPVC15, e) SCCPVC20, and f) SCCPVC25.



(a) (b)

Fig. 16. The effect of a 5% sulfuric acid (H_2SO_4) solution on mixtures a) weight, and b) compressive strength.

3.4.2. Immersion in salt media

The impact of salt attack represented by $MgSO_4$ solution on SCC mixtures, with and without HDPVC aggregates, was evaluated through immersion in a 5 % $MgSO_4$. Results, tabulated in Table 7 and illustrated in Fig. 17, indicate weight and strength reductions for all mixtures. The SCCPVC0 mixture experienced the most severe deterioration, 1.9 % weight loss, and 3.1 % strength loss, while the SCCPVC25 exhibited the least 1.3 % and 1.5 %, respectively. Furthermore, these results are significantly lower than those observed in the acid attack test, indicating a greater ability to withstand the concrete to sulfate attack relative to acid attack. The improved resistance to salt attack is likely due to a reduced calcium hydroxide content, which typically reacts with magnesium sulfate to form expansive gypsum, and the creation of a protective layer around cement paste particles [73,75,73,74]

3.4.3. Rapid Chloride permeability (RCPT) test

The RCPT test was carried out after 28 days of curing, with results for three specimens averaged and presented in Fig. 18. As per ASTM C1202-19 [62], all samples exhibited very low permeability, as described in Table 8. Moreover, the impact of adding HDPVC as a substitution of coarse aggregate is clearly visible in Fig. 17. The percentage reductions in the charge passed through the specimen are 11 %, 21 %, 28 %, 33 %,

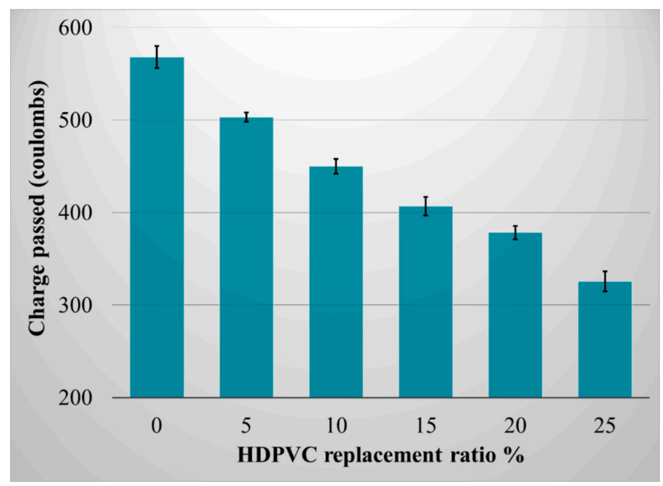
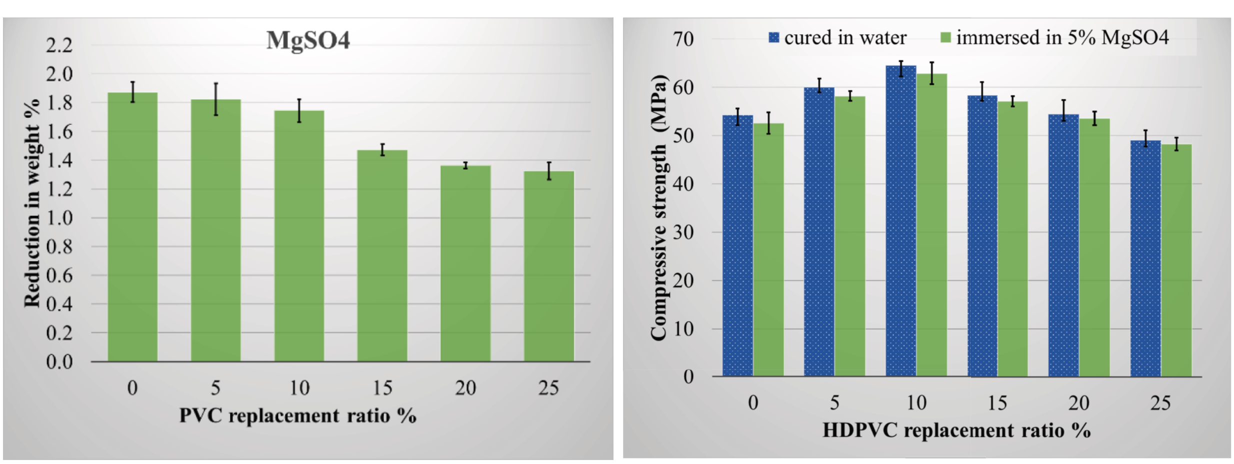


Fig. 18. The effect adding HDPVC on Rapid Chloride penetration of SCC.



(a) (b)

Fig. 17. The effect of a 5% Magnesium sulfate ($MgSO_4$) solution on mixtures a) weight, and b) compressive strength.

Table 8
Chloride Ion Penetrability based on ASTM C1202-19 [55].

Charged passed (coulombs)	Chloride ion permeability
> 4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very low
< 100	Negligible

and 43 % for SCCPVC5, SCCPVC10, SCCPVC15, SCCPVC20, and SCCPVC25, respectively, relative to SCCPVC0 mixture. The utilization of HDPVC significantly enhanced the concrete's resistance to chloride ion penetration. This enhancement is attributed to the material's ability to refine the concrete microstructure, reducing pathways for chloride ion diffusion. These findings align with previous research [32,34].

3.4.4. Elevated temperature

The elevated temperature impact on the SCC mixtures with HDPVC on the specimens' weight and strength are depicted in Fig. 19 and listed in Table 9. In addition, specimens' appearance after subjected to heat are illustrated in Fig. 20. The decrease in weight and compressive strength were insignificant for all specimens under 150°C with reduction of 0.8 %, 0.8 %, 0.9 %, 1.1 %, 1.1 %, 1.1 % and 1.1 %, 0.7 %, 0.5 %, 0.9 %, 1.3 %, 2.1 % for control, SCCPVC5, SCCPVC10, SCCPVC15, SCCPVC20, and SCCPVC25, respectively. The primary cause of weight and compressive strength loss in this stage was the evaporation of physically adsorbed and capillary water, which constitutes a significant portion of the cement paste [75]. At 300°C, the specimens for mixture with 5 % of coarse aggregate replacement with HDPVC had slight damage (Fig. 20b) with slight reduction in weight and strength 4.1 %, and 4.7 %, respectively, which is comparable with the control mixtures. Whereas all the other specimens for other mixtures with higher portion of HDPVC (i.e., SCCPVC10, SCCPVC15, SCCPVC20, and SCCPVC25) had noticeable damage (Fig. 20c-e) and degradation in weight and strength at 300°C and 450°C up to 14 %, 36.3 % and 19.6 %, 49.9 % respectively, for SCCPVC25 mixture. As observed visually, the samples exhibited progressive surface deterioration characterized by explosive spalling and crack formation as temperature increased. The HDPVC particles near the concrete surface expanded from the excessive heat bushing the concrete away causing damage to the specimen. This damage was attributed to combined effects of thermal expansion of HDPVC, water evaporation, and drying shrinkage, leading to increase in internal stresses. However, the core of the specimen remained undamaged after completing the compressive strength test as depicted in Fig. 21. It is undesirable to use HDPVC under high temperature, however coating the concrete surface with suitable material could prevent heat damage to the outer surface.

4. Conclusions

This study experimentally evaluated the fresh, hardened, non-destructive, and durability properties of self-compact concrete SCC involving 5 %, 10 %, 15 %, 20 %, and 25 % High-Density Polyvinyl Chloride (HDPVC) particles as a replacement to the coarse aggregate by volume. The following are the key findings of this study:

1. Coarse aggregate was substituted partially with HDPVC resulting in a decrease in slump flow, influenced by HDPVC particle size, shape, and texture. Nevertheless, the resulting mixtures maintained SF2 classification, ensuring a suitable balance of flowability and stability for diverse applications. SCC mixtures containing up to 25 % HDPVC exhibited satisfactory passing ability, flowability, and resistance to segregation.
2. All HDPVC containing mixtures demonstrated reduced wet and dry densities, with the SCCPVC25 mixture exhibiting the most significant decrease (10.7 % and 13.1 %, respectively). This reduction qualifies these mixtures as Lightweight SCC, offering potential structural weight savings.
3. Maximum strength enhancement was achieved with 10 % HDPVC replacement, resulting in improvements of 20 %, 16 %, and 17 % in compressive, splitting tensile, and flexural strengths at 28 days, respectively, for mixture SCCPVC10. Strength subsequently declined, approaching control mixture values at higher replacement levels. Based on these results, a maximum of 20 % HDPVC replacement is feasible, with 10 % replacement ratio recommended.
4. Rebound number and ultrasonic pulse velocity (UPV) which represent the non-destructive testing methods, exhibited trends consistent with compressive strength, with strong correlations of 0.9704 and 0.9117 observed between compressive strength and rebound number and UPV, respectively.
5. SCC with HDPVC particles exhibited excellent resistance to sulfuric acid attack relative to the control mixture. Both HDPVC and control mixtures demonstrated satisfactory resistance to salt attack. Furthermore, HDPVC inclusion enhanced chloride ion resistance.
6. One significant limitation of the current study is the observed weight and compressive strength reductions at elevated temperatures, particularly at 450°C.

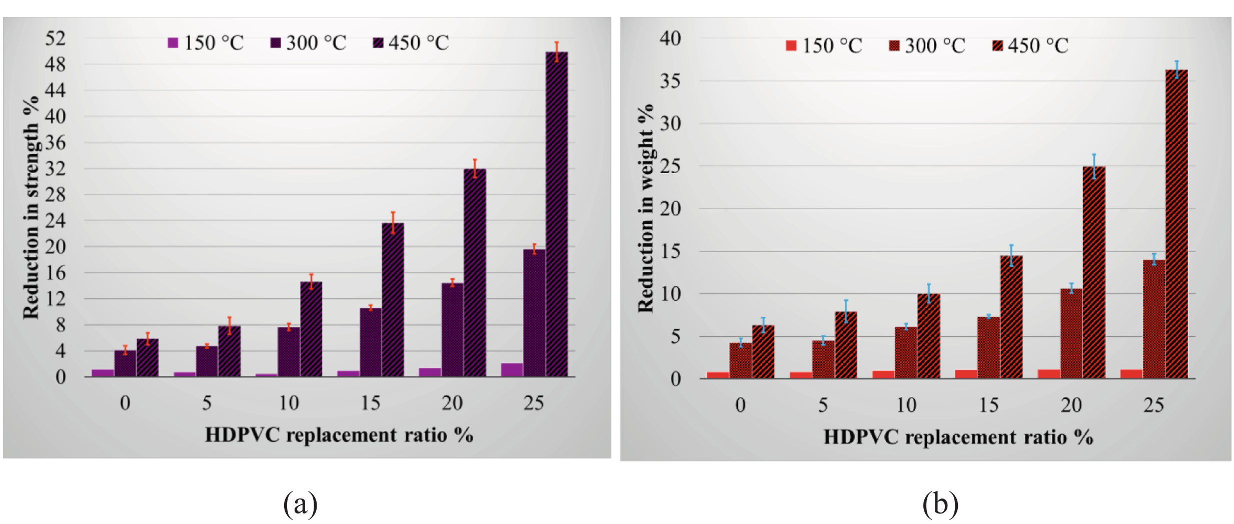


Fig. 19. The influence of elevated temperature on a) compressive strength, and b) weight of SCC mixtures containing HDPVC particles.

Table 9
Percentage of reduction in strength and weight of specimens after exposed to heat.

Mixture ID	% Reduction in strength under 150 °C	% Reduction in weight under 150 °C	% Reduction in strength under 300 °C	% Reduction in weight under 300 °C	% Reduction in strength under 450 °C	% Reduction in weight under 450 °C
SCCPVC0	1.1	0.8	4.1	4.2	5.9	6.3
SCCPVC5	0.7	0.8	4.7	4.5	7.8	7.9
SCCPVC10	0.5	0.9	7.7	6.1	14.6	10.0
SCCPVC15	0.9	1.1	10.6	7.4	23.6	14.5
SCCPVC20	1.3	1.1	14.5	10.6	32.0	24.9
SCCPVC25	2.1	1.1	19.6	14.0	49.9	36.3

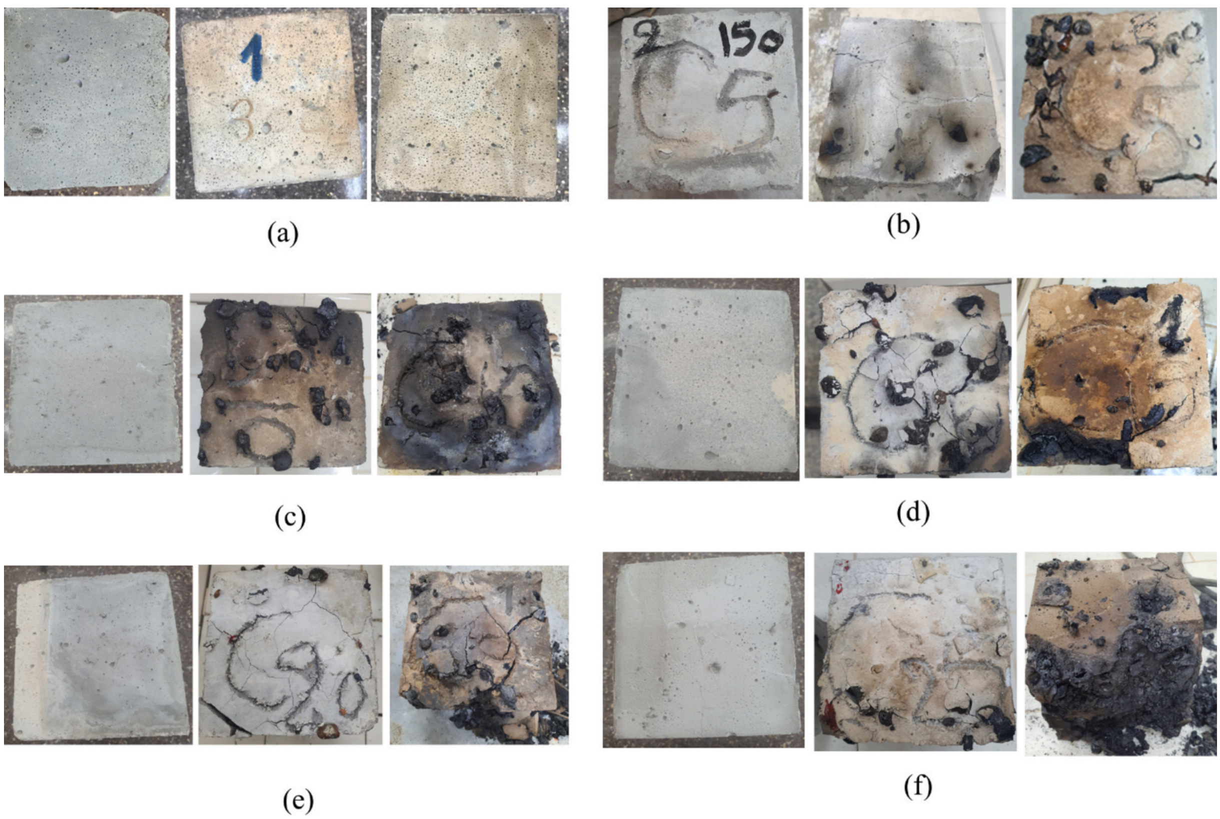


Fig. 20. Specimens appearance after subjected to elevated temperature: a) control mixture, b) SCCPVC5, c) SCCPVC10, d) SCCPVC15, e) SCCPVC20 and f) SCCPVC25.

Fig. 21. Compressive strength test for SCCPVC10 after subjected to 300°C.

7. Finally, this study demonstrates the potential of HDPVC particles as a sustainable and high-performance concrete component, paving the way for broader industry adoption.

Perspectives of the current study

The current study demonstrates the potential of recycling HDPVC from scrap pipes as a sustainable alternative to natural coarse aggregate in SCC, offering several promising perspectives:

Environmental Benefits

- **Waste Reduction:** The effective use of recycled HDPVC promotes resource conservation by diverting waste from landfills, minimizing environmental pollution, and supporting a circular economy
- **Resource Conservation:** Substituting natural aggregates with recycled materials conserves natural resources and reduces the environmental impact of quarrying.
- **Reduced Carbon Footprint:** Using recycled materials generally has a lower carbon footprint compared to the extraction and processing of virgin materials.

Future research directions

- **Deformation Behavior:** The deformation behavior of the SCC with HDPVC pipes in the elastic regime should be investigated.
- **Long-Term Performance:** Studies on long-term behavior are essential to assess the long-term durability and performance of HDPVC incorporated in SCC under various environmental conditions.
- **Cost-Effectiveness:** Further investigation is necessary to evaluate the cost-effectiveness of using recycled HDPVC compared to traditional concrete, considering factors such as material costs, processing costs, and potential performance benefits.

Overall, this study provides a valuable foundation for the implementation of sustainable and high-performance concrete materials using recycled waste streams.

CRediT authorship contribution statement

Meyyada Y. Alabdulhady: Writing – original draft, Supervision, Project administration, Methodology, Formal analysis. **Kadhim Z. Naser:** Writing – original draft, Formal analysis. **Muthana Sh. Mahdi:** Writing – original draft, Investigation, Formal analysis. **Ayman Moustafa:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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