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Optimizing Pelargonium Ash as a Partial Cement Replacement in High-Strength Self-Compacting Concrete: Mechanical and Durability Aspects

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Abstract - This study investigates the effects of Pelargonium Ash (PGA) as a partial cement replacement on the mechanical and durability properties of High Strength-Self Compacting Concrete (HSSCC). PGA was incorporated at 5%, 10%, 15%, and 20% replacement levels, and its influence on setting time, compressive strength, splitting tensile strength, and resistance to sulfate and chloride attacks was evaluated. The results indicate that a 5% PGA replacement is optimal, leading to slight improvements in compressive strength at early and late curing ages without compromising self-compacting properties. Higher replacement levels (10%, 15%, 20%) adversely affect mechanical performance and durability due to rapid hardening, increased water absorption, and dilution of cementitious components. The 5% PGA mix exhibited enhanced resistance to sulfate and chloride attacks, attributed to pore refinement and pozzolanic activity. However, excessive PGA content beyond 10% negatively impacts durability and mechanical properties. Adjustments in water and superplasticizer dosages are necessary at higher PGA levels to maintain workability. In conclusion, PGA can be effectively used as a sustainable partial cement replacement in HSSCC at an optimal level of 5-10%, balancing mechanical performance, durability, and environmental benefits.

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Introduction

The current global trend toward resource conservation is primarily focused on the development of new technologies and the enhancement of existing ones, particularly through the utilization of industrial by-products and recyclable materials [1–3]. This approach is especially significant in the construction sector, where such materials can be effectively incorporated into composite building materials and concrete production [4–6]. Consequently, the cement industry has become one of the major contributors to greenhouse gas emissions, ranking after the energy and transportation sectors, with emissions ranging between 5% and 8%, mainly due to the combustion of Portland cement clinker [7–9]. Recent statistics indicate that the annual global cement production exceeds 4 billion tons, which is associated with carbon emissions exceeding 4 billion tons per year [10–11]. Furthermore, cement manufacturing has significantly increased atmospheric carbon dioxide concentrations, reaching approximately 380 ppm, with projections estimating an increase to nearly 800 ppm by the year 2100 [12]. The rapid growth in infrastructure demand has further intensified cement consumption, leading to excessive waste disposal in limited landfill areas and, consequently, increased greenhouse gas emissions [13–14]. It has been estimated that the production of one ton of cement releases approximately 800 kg of CO_2 into the atmosphere.

SCC performance is considered satisfactory when specific workability and flowability parameters comply with established SCC guidelines. Typically, SCC contains a relatively high cement content, reduced coarse aggregate (CA) content, and superplasticizers (SP) to lower the water-to-binder ratio, with a common CA-to-fine aggregate (FA) ratio of 1:1. The water-to-binder (W/B) ratio and SP dosage are optimized through mortar and concrete flow tests, followed by trial mixes to finalize the concrete composition.

Compared to conventional concrete, SCC offers several advantages, including the elimination of vibration during placement, enhanced flowability, superior workability and pumpability, and improved bonding in areas with congested reinforcement. SCC is produced using conventional concrete ingredients; however, stricter control over mix proportions is required to ensure stable fresh properties. A typical SCC mixture demands a high powder content, reduced coarse aggregate proportion, high-range superplasticizers, and viscosity-modifying agents to maintain stability and prevent segregation [15-16].

Agricultural waste (AW) has emerged as a promising sustainable material for partial replacement of cement in concrete production, addressing both environmental and economic challenges associated with conventional cement use. Large quantities of biomass ashes are generated globally, especially in developing countries. These wastes, when properly processed and ground to suitable fineness, exhibit high silica content (often exceeding 60%), which imparts pozzolanic properties beneficial for cementitious applications [17]. Utilizing AW ashes in concrete not only reduces the environmental burden of waste disposal but also mitigates the substantial CO_2 emissions linked to cement manufacturing, which accounts for 5–8% of global greenhouse gases. Incorporation of these ashes refines the microstructure of concrete, enhancing mechanical strength and durability. Studies have shown that AW ashes improve resistance to sulfate and chloride attacks, freeze-thaw cycles, and reduce porosity, thereby extending the lifespan of concrete structures. However, the effectiveness of AW ashes depends on their chemical composition, fineness, and optimal replacement levels, as excessive substitution can lead to dilution of cementitious components, adversely affecting workability and mechanical performance [18].

High Strength Self-Compacting Concrete (HSSCC) combines the benefits of high-strength concrete with the unique flowability and self-compacting properties of self-compacting concrete (SCC), offering significant advantages in modern construction. HSSCC eliminates the need for mechanical vibration during placement, which reduces labor costs, noise pollution, and the risk of improper compaction, thereby ensuring uniform density and minimizing voids [19-20]. Its superior flowability allows it to fill complex and heavily reinforced formwork efficiently, improving the quality and homogeneity of the concrete matrix. The high powder content, low water-to-binder ratio, and use of superplasticizers in HSSCC contribute to enhanced early-age strength, accelerated curing, and improved bonding between cement paste and aggregates. These characteristics enable faster construction timelines and earlier demolding of structural elements, which is particularly beneficial in projects with tight schedules or complex geometries. Moreover, HSSCC exhibits improved durability properties, including resistance to segregation, bleeding, and permeability, which enhances its performance against chemical attacks such as sulfate and chloride ingress [21]. The dense microstructure of HSSCC reduces porosity and refines the pore network, leading to increased resistance to environmental degradation and longer service life. Additionally, the improved surface finish achievable with HSSCC reduces the need for secondary treatments, lowering maintenance requirements and lifecycle costs. Its adaptability to incorporate supplementary cementitious materials and industrial by-products further enhances sustainability by reducing cement consumption and associated CO_2 emissions [22]. Overall, HSSCC represents a technologically advanced concrete type that optimizes mechanical performance, durability, and constructability, making it highly suitable for demanding structural applications and sustainable construction practices [23].

SCC enables faster concrete placement and construction timelines, particularly in complex structural elements. Its high fluidity and resistance to segregation contribute to improved homogeneity, reduced void content, and uniform strength distribution, which collectively enhance surface finish and durability. Additionally, SCC is often designed with a low water–cement ratio, allowing for higher early-age strength, accelerated demolding, and earlier utilization of structural elements. The incorporation of fine alternative materials alters certain concrete properties due to their chemical reactivity, which is a key aspect investigated in this study. From both economic and environmental perspectives, reducing cement consumption through the use of fine pozzolanic materials is strongly recommended [24]. Consequently, significant attention has been directed toward replacing cement with supplementary cementitious materials that enhance microstructure and improve durability and corrosion resistance [25-26]. The inclusion of materials such as silica fume (SF), metakaolin (MK), and fly ash (FA) has been shown to improve mechanical performance and resistance to freeze–thaw cycles compared to conventional concrete [27–28.

On the other hand, substantial quantities of industrial and agricultural waste are generated worldwide, particularly in developing countries. Agricultural waste (AW) ashes represent a promising alternative to conventional cement when properly processed and utilized [29]. It has been reported that rice and palm oil industries alone generate approximately 156 and 184 million tons of rice husk and palm oil residues annually, respectively [30]. Agricultural wastes such as rice straw ash (RSA), rice husk ash (RHA), and sugarcane bagasse ash (SCBA) are commonly used as biomass fuels in power plants; however, the disposal of the resulting ash poses serious environmental challenges. Therefore, incorporating these ashes into concrete production provides an effective strategy for waste management while simultaneously reducing cement consumption [31].

The high silica content (exceeding 60%) present in ashes such as palm leaf ash (PLA), palm oil fuel ash (POFA), RHA, and SCBA facilitates their application as pozzolanic materials once ground to suitable fineness [32]. Numerous studies have demonstrated that the use of agricultural waste ashes enhances the mechanical and durability properties of concrete by refining the microstructure through pozzolanic reactions. Overall, the partial replacement of cement with agricultural waste materials not only improves concrete performance but also significantly mitigates environmental issues related to waste disposal and CO_2 emissions from cement production. The use of such materials aligns with the principles of green and sustainable concrete. While some agricultural waste materials have yielded promising results, others require further investigation to determine their optimal utilization [33].

In this study, (HSSC) was investigated to evaluate the effect of Pelargonium Ash (PGA) as a partial cement replacement. The research aims to assess the influence of PGA on both fresh and hardened properties of HSSC. Mechanical properties, including compressive strength, splitting tensile strength, and flexural strength, were examined. Additionally, the performance of concrete exposed to sulfate and chloride attack conditions. This study seeks to expand the understanding of agricultural waste utilization in concrete and to identify the potential of PGA as a sustainable pozzolanic material for high-performance concrete applications.

Experimental program

Raw materials

Ordinary Portland cement (OPC) of type CEM I 52.5 N, conforming to the requirements of BS EN 197-1:2011, was used as the primary binder in this experimental investigation. The cement exhibited a specific gravity of 3.14, a specific surface area of 3450 cm^2/g, and a grey color, with its detailed chemical composition presented in Table 1. Silica fume (SF), supplied by Sika Egypt Company, was incorporated as a mineral admixture based on the cement mass. The utilized SF possessed a high specific surface area of 16.8×10^3 m^2/kg and a specific gravity of 2.15, and complied with ASTM C1240, indicating its highly siliceous nature; its physical properties and chemical composition are listed in Table 2. Dolomite aggregate was used as coarse aggregate in a saturated surface-dry condition, with a maximum particle size of 12.5 mm, specific gravity of 2.65–2.70, and water absorption of approximately 0.6–1.0%. Natural sand was employed as fine aggregate, characterized by a maximum particle size of 2.36–4.75 mm, specific gravity of 2.6–2.81, and water absorption of about 0.65%, with grading and physical properties. To achieve the required workability of SCC, a polycarboxylate-based superplasticizer (Sika ViscoCrete-3425) was utilized in accordance with ASTM C494/C494M-17. This admixture, with a density of 1.08 kg/L and a pH value of 8.0 ± 1.0, is suitable for concrete mixtures requiring high flowability and early strength development and was dosed as a percentage of the total binder content. Pelargonium waste was collected from an agricultural farm in the Beni-Suef region, Egypt, and initially burned in open air as shown in **Fig. 1.** The resulting ash was carefully cleaned to remove impurities, then calcined in a furnace at 700 °C for 2 h, followed by cooling at room temperature for 1 h. The ash was subsequently ground, and particles passing through a 75 µm sieve were used in this study. The processed Pelargonium ash satisfied the requirements of BS 3892: Part 1–1997 and relevant ASTM standards. Visual inspection and SEM analysis revealed that the Pelargonium ash particles were irregular in shape, predominantly micro-sized, and exhibited a morphology suitable for pozzolanic applications

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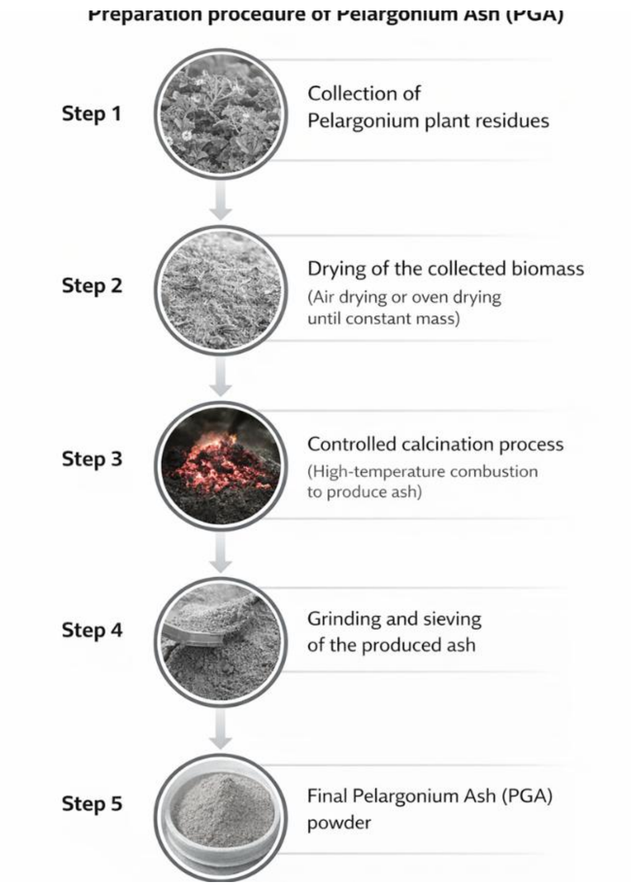

Fig. 1. Preparation steps

A. Concrete mix design

Mix proportions:

Make six (5) concrete mixes in total. In reference mix 1, the percentage of PGA was 0%. The remaining five mixes were created by partially substituting 5%,10%, 15%, and 20% of cement with PGA. **Tab. 1** represents mixing proportions

Tab. 1. Mixing proportions

Mix	PGA %	OPC Kg/m^3	PGA Kg/m^3	SF Kg/m^3	CA Kg/m^3	FA Kg/m^3	Water g/m^3	SP %	Water increasing	SP increasing %
HC0	0	550	-	27.5	762	762	184.8	1.25	-	-
HC5	5	550	27.5	27.5	762	762	184.8	1.25	-	-
HC10	10	550	55	27.5	762	762	184.8	1.25	0.33+0.03	-
HC15	15	550	82.5	27.5	762	762	184.8	1.25	0.33+0.04	0.1%
HC20	20	550	110	27.5	762	762	184.8	1.25	0.33+0.05	0.15%

B. Testing

The setting time of concrete was determined using the penetration resistance test in accordance with ASTM C403, which measures the initial and final setting times based on the penetration resistance of mortar sieved from fresh concrete with non-zero slump. Mechanical properties were evaluated through compressive, tensile, and elastic modulus tests. Compressive strength was measured on 100 × 100 × 100 mm cube specimens at curing ages of 7, 28, and 56 days following BS EN 12390-3, using a universal compression testing machine shown in **Fig. 2,** with the average value obtained from two specimens at each age. The modulus of elasticity in compression was determined in accordance with NS 3676, based on ISO 6784-1982, using 100 × 200 mm cylindrical specimens subjected to a controlled multi-cycle loading–unloading regime shown in **Fig. 3** with deformations recorded over a 120 mm gauge length using displacement transducers. Splitting tensile strength was assessed at 28 days on cylindrical specimens (100 mm diameter × 200 mm height) using the indirect tensile splitting method, where the tensile strength was calculated from the applied failure load. Additionally, uniaxial tensile strength was determined using Hansen's method, employing specially designed grips to ensure uniform stress transfer, with deformation measured over a 100 mm mid-gauge length to calculate the tensile modulus of elasticity. Durability performance was further investigated through chloride penetration resistance using the AASHTO T259 salt ponding test, in which concrete slabs were moist-cured, conditioned, and exposed to a 3% NaCl solution for 90 days to evaluate chloride ingress behavior.

Fig. 2. Compressive strength

Fig. 3 Split tensile strength

Results and discussion

a. Setting

A test was conducted to demonstrate the problems encountered during mixing and casting. The objective of the test was to determine the water absorption percentage of a mixture. The VICAT apparatus was used to measure the initial and final setting times of the mixture. Firstly, the standard water-to-cement ratio (w/c) for Ordinary Portland Cement (OPC) without (PGA) was determined. The w/c ratio was 0.33, which means 128ml of water was used for every 400gm of cement. The initial and final setting times of the control mixture were then determined. Next, additional specimens were prepared with 5%, 10%, 15%, and 20% replacement of cement with PGA. The results showed that the addition of PGA reduced the initial and final setting times. Compared to the control mix, the 5% replacement resulted in a 10.31% decrease in the initial setting time and a 9.1% decrease in the final setting time. However, the 10% replacement had a more significant impact, reducing the initial and final setting times by 64% and 59.1% respectively, compared to the control mix, as shown in **Fig. 4.**

During the mixing process, it was observed that the mixture exhibited characteristics of normal concrete instead of SCC, which was at 10% replacement. Additionally, the specimens with 15% and 20% replacement did not pass the test, as their setting times decreased significantly. The initial setting time reduced from 145 minutes to 15 minutes, and the final setting time reduced from 220 minutes to 55 minutes. This indicates that the samples experienced rapid hardening due to a lack of water, which affected the setting process [34]. The inconsistent results and failure to pass the setting test indicate that the high-water absorption rate is caused by PGA. Therefore, it is necessary to increase the amount of water and plasticizer to compensate for this effect. The figure illustrates that the time interval between the final and initial setting times is shorter compared to the standard mixture. This observation aligns with the difficulties encountered during the casting process.

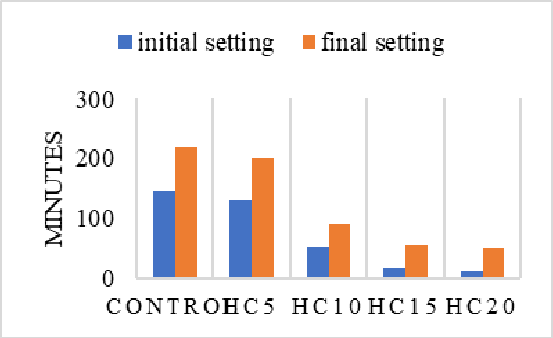

Fig.4: setting time of HSSCC

b. Compressive strength at 7 days

At the early curing age of 7 days shown in **Fig. 5** the compressive strength results clearly indicate that the incorporation of Pelargonium Ash (PGA) has a pronounced effect on the early hydration and strength development of HSSCC. The control mix (HC0) achieved a compressive strength of 49 MPa, which serves as the reference value. The addition of PGA at a low replacement level significantly enhanced early-age strength, as the HC5 mix recorded the highest compressive strength of 55.2 MPa, corresponding to an increase of approximately 12.7% compared to the control mix. This improvement can be attributed to the filler effect of fine PGA particles, which enhance particle packing density, reduce initial porosity, and promote early hydration. Similarly, the HC10 mix exhibited a compressive strength of 53.2 MPa, representing an improvement of about 8.6%, confirming that moderate PGA contents still contribute positively at early ages. However, further increases in PGA content resulted in diminished benefits, with HC15 and HC20 showing only slight increases of about 2.2% and 0.6%, respectively. This reduction in early-age performance at higher replacement levels is mainly associated with the dilution effect, where excessive replacement of cement reduces the amount of clinker phases responsible for early strength development, thereby limiting the hydration rate during the first curing period [35].

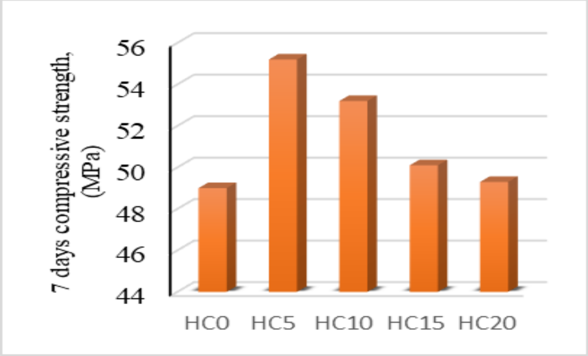

Fig. 5. 7 days compressive strength

C. *Compressive strength at 28 days*

At the standard curing age of 28 days shown in **Fig. 6** a more pronounced influence of PGA on compressive strength was observed, reflecting the contribution of pozzolanic reactions to the concrete matrix. The control mix (HC0) achieved a compressive strength of 50 MPa, while all PGA-modified mixes exhibited higher strength values. The HC5 mix again demonstrated superior performance, reaching 65 MPa, which corresponds to a substantial increase of approximately 30% compared to the control. This significant enhancement confirms the effectiveness of an optimized PGA content in improving the mechanical properties of concrete through secondary hydration reactions between the amorphous silica in PGA and calcium hydroxide released during cement hydration, leading to the formation of additional calcium silicate hydrate (C–S–H) gel [36-37]. The HC10 mix recorded a compressive strength of 56 MPa, showing an improvement of 12%, while HC15 and HC20 achieved values of 54 MPa and 52 MPa, corresponding to increases of 8% and 4%, respectively. Although these improvements are lower than those of HC5, they still indicate a positive contribution of PGA at moderate replacement levels. The gradual decrease in strength enhancement with increasing PGA content highlights the balance between beneficial pozzolanic activity and the adverse dilution effect associated with reduced cement content.

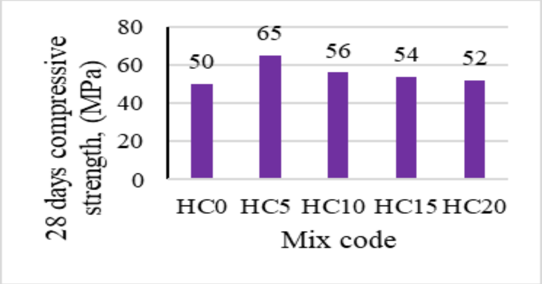

Fig. 6. 28 days' compressive strength

D. *Compressive strength at 56 days*

At the later curing age of 56 days shown in **Fig.7**, the compressive strength results reveal the long-term influence of PGA on strength development and durability-related performance. The control mix achieved a compressive strength of 66.5 MPa, indicating continuous hydration of cement over time. The HC5 mix maintained the highest compressive strength of 68 MPa, exceeding the control by approximately 2.3%, which confirms the sustained pozzolanic contribution of PGA at an optimal replacement level. In contrast, higher PGA contents resulted in noticeable reductions in compressive strength relative to the control mix, with HC10, HC15, and HC20 exhibiting decreases of approximately 9.8%, 12.8%, and 21.8%, respectively. Despite these reductions, it is important to note that the strength gain between 28 and 56 days for mixes containing higher PGA contents was relatively significant, indicating delayed pozzolanic activity and gradual microstructure densification at later ages. Nevertheless, the results clearly demonstrate that excessive replacement levels negatively affect long-term compressive strength due to insufficient cementitious material, despite ongoing pozzolanic reactions. Overall, the findings confirm that a PGA replacement level of 5% provides the most favorable balance between early-age strength enhancement and long-term performance, while higher replacement ratios lead to strength deterioration primarily due to cement dilution effects [38-39].

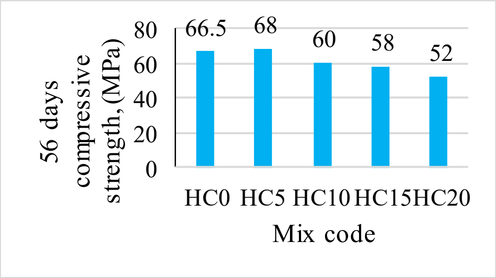

Fig. 7. 56 days compressive strength

E. Splitting tensile strength

Fig. 8 illustrates the effect of incorporating Pelargonium Ash (PGA) on the splitting tensile strength of HSSCC at the curing age of 28 days. The results clearly indicate that the addition of PGA has a noticeable influence on the tensile behavior of concrete, which is generally more sensitive to microstructural changes than compressive strength. The control mix (HC0) exhibited the highest splitting tensile strength, reaching approximately 3.52 MPa, reflecting the intact cementitious matrix and adequate bonding between the cement paste and aggregates. This value serves as a reference for evaluating the performance of PGA-modified mixtures.

The HC5 mixture recorded a splitting tensile strength of about 3.41 MPa, representing a slight reduction of approximately 3% compared to the control mix. This marginal decrease suggests that a low replacement level of PGA does not significantly impair the tensile performance of concrete. The slight reduction may be attributed to the partial replacement of cement with PGA, which initially reduces the availability of primary hydration products responsible for tensile resistance. However, at this replacement level, the filler effect and the gradual pozzolanic reaction of PGA may compensate for this reduction by refining the pore structure and improving the interfacial transition zone (ITZ) between the aggregates and the cement matrix [40].

In contrast, higher PGA replacement levels resulted in more pronounced reductions in splitting tensile strength. The HC10 mixture exhibited a tensile strength of approximately 3.00 MPa, corresponding to a reduction of about 13.5% compared to the control mix. Similarly, HC15 and HC20 showed further decreases to 2.80 MPa and 2.65 MPa, representing reductions of approximately 19.7% and 24.7%, respectively. This progressive decline in tensile strength with increasing PGA content can be primarily attributed to the dilution effect caused by excessive cement replacement, which reduces the formation of calcium silicate hydrate (C–S–H) gel, the main contributor to tensile resistance. Additionally, higher PGA contents may adversely affect workability and homogeneity, leading to increased entrapped air and microcracking, which are particularly detrimental to tensile performance [41].

Moreover, splitting tensile strength is highly influenced by the quality of the interfacial transition zone and the concrete's ability to resist crack initiation and propagation. The observed reductions at higher PGA levels suggest a weaker ITZ and less effective stress transfer across the matrix. Although PGA exhibits pozzolanic potential, its reaction rate is relatively slow, and at higher replacement ratios, the pozzolanic contribution at 28 days may not be sufficient to compensate for the reduced cement content. Overall, the results indicate that while a low PGA replacement level (5%) maintains acceptable tensile performance with only a negligible reduction, higher replacement ratios significantly compromise the splitting tensile strength of HSSCC. These findings highlight the importance of optimizing PGA content to achieve a balance between sustainability and mechanical performance.

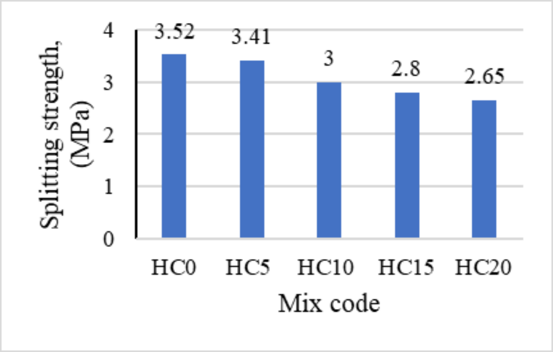

Fig.8: Splitting tensile strength of HSSCC

F. Sulfate attack

Sulfate attack was found to have a more severe impact on the compressive strength of HSSCC compared to chloride exposure, as shown in **Fig. 9** due to the aggressive nature of sulfate ions and their ability to form expansive products such as ettringite and gypsum. The control mix (HC0) exhibited a reduction in compressive strength from 50 MPa before exposure to 45.4 MPa after sulfate attack, corresponding to a loss of approximately 9.2%, accompanied by a mass loss of about 1.7%. This deterioration reflects the vulnerability of ordinary cementitious systems to sulfate-induced expansion and cracking, which progressively weakens the concrete matrix. The incorporation of PGA at a low replacement level significantly improved sulfate resistance, as evidenced by the performance of the HC5 mixture. This mix showed a reduction in compressive strength from 65 MPa to 62 MPa, corresponding to the lowest reduction rate of approximately 4.6%, along with a relatively low mass loss of 1.4%. The enhanced sulfate resistance of HC5 can be attributed to the pozzolanic reaction of PGA, which consumes calcium hydroxide and reduces the availability of reactive aluminates, thereby limiting the formation of expansive sulfate reaction products. In contrast, the HC10 mixture exhibited a strength reduction from 56 MPa to 50.5 MPa, corresponding to a decrease of about 9.8%, which is comparable to that of the control mix. This indicates that moderate PGA contents may not significantly improve sulfate resistance beyond a certain threshold. More severe deterioration was observed in mixes with higher PGA contents, as HC15 and HC20 showed substantial strength losses of 20.4% and 23.7%, respectively, with corresponding mass losses reaching up to 3.8% for HC20. These pronounced reductions suggest that excessive PGA replacement adversely affects sulfate resistance due to increased porosity and reduced cementitious content, which facilitates sulfate ion penetration and accelerates chemical degradation. Overall, the results confirm that sulfate attack is more detrimental than chloride attack for all mixtures; however, an optimal PGA replacement level of 5% markedly enhances sulfate resistance by improving microstructural densification and reducing the susceptibility of concrete to expansive chemical reactions, whereas higher replacement ratios lead to significant strength deterioration and reduced durability.

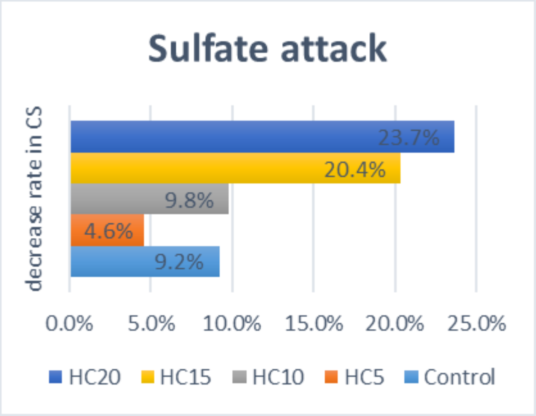

Fig. 9. Residual compressive strength of HSSCC after sulfate attack

G. Chloride attack

The influence of chloride attack on the compressive strength of HSSCC incorporating Pelargonium Ash (PGA) was evaluated by comparing the strength values before and after exposure to a chloride environment. The results shown in **Fig.10** indicate that chloride ingress caused a measurable reduction in compressive strength for all concrete mixtures; however, the extent of deterioration was strongly dependent on the PGA replacement level. The control mix (HC0) exhibited a reduction in compressive strength from 50 MPa before exposure to 47 MPa after chloride attack, corresponding to a strength loss of approximately 6.0%, with a relatively low mass loss of about 0.4%. This moderate reduction reflects the inherent susceptibility of conventional concrete to chloride penetration, which can disrupt the cementitious matrix and weaken the bond between hydration products. In contrast, the HC5 mixture, which contained 5% PGA, showed a compressive strength decrease from 65 MPa to 56.3 MPa, corresponding to a reduction of 13.4%. Although the percentage reduction appears higher than that of the control mix, HC5 maintained the highest residual compressive strength among all mixes after chloride exposure, indicating superior structural integrity. This behavior can be attributed to the pozzolanic activity of PGA at low replacement levels, which leads to pore refinement, reduced permeability, and a denser microstructure that restricts chloride ion penetration. The HC10 mixture exhibited a reduction in compressive strength from 56 MPa to 49 MPa, corresponding to a decrease of approximately 12.5%, while HC15 and HC20 experienced more pronounced strength losses of 16.7% and 15.4%, respectively. These higher reductions are associated with excessive replacement of cement, which results in a dilution effect and reduced formation of calcium silicate hydrate (C–S–H) gel, thereby weakening the resistance of the concrete matrix to chemical attack. Furthermore, the increased mass loss observed with higher PGA contents (up to 1.7% for HC20) suggests greater material degradation and microstructural damage. Overall, the results demonstrate that while chloride attack negatively affects compressive strength, the incorporation of PGA at an optimal replacement level of 5% enhances the residual strength and durability of HSSCC by limiting chloride ingress and preserving the integrity of the cementitious matrix [42]

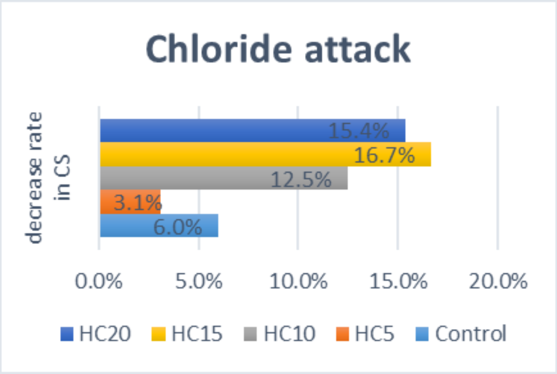

Fig. 10. Residual compressive strength of HSSCC after chloride attack

Conclusions

Partial replacement of cement with Pelargonium Ash (PGA) in High Strength- HSSCC reduces both initial and final setting times, with a significant reduction observed at 10% replacement. The optimum PGA replacement level for compressive strength is 5%, which showed slight improvements at early and late curing ages without compromising self-compacting properties. Higher PGA replacement levels (10%, 15%, 20%) lead to decreased compressive and split tensile strengths due to rapid hardening and increased water absorption, affecting workability and mechanical performance. Durability tests indicate that a 5% PGA replacement enhances resistance to sulfate and chloride attacks, attributed to pore refinement and pozzolanic activity improving the concrete microstructure. Excessive PGA content beyond 10% negatively impacts durability and mechanical properties, likely due to dilution of cementitious components and insufficient calcium hydroxide for secondary hydration. Adjustments in water and superplasticizer dosages are necessary at higher PGA levels to compensate for increased water absorption and maintain workability. Overall, PGA can be effectively used as a sustainable partial cement replacement in HSSCC at an optimal level around 5–10%, balancing mechanical performance, durability, and environmental benefits.

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