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Effect of Agricultural Phragmites, Rice Straw, Rice Husk, and Sugarcane Bagasse Ashes on the Properties and Microstructure of High-Strength Self-Compacted Self-Curing Concrete

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Abstract: Each year, billions of tons of agricultural waste are generated globally. Egypt, being an agriculturally centered nation, faces significant challenges in disposing of this waste and coping with self-germinating plants that negatively impact agriculture. The common practice among farmers is to burn the waste, which exacerbates environmental concerns. With the global shift towards eco-friendly concrete, this study explores the utilization of agricultural waste ashes, particularly those abundant in Egypt and numerous other countries worldwide. Among the researched waste ashes are Phragmites ash (PGA), sugarcane bagasse ash (SBA), rice husk ash (RHA), and rice straw ash (RSA). This investigation examines the impact of partially substituting cement with varying ash percentages from these wastes on the characteristics and properties of fresh and hardened high-strength self-compacting self-curing concrete (HSSCSCC). The findings indicate the potential applicability of these ashes in producing HSSCSCC, specifically highlighting the promising outcome of PG ash, which exhibited favorable results as a new type of natural ash suitable for the concrete industry.

Keywords: sugarcane bagasse ash; rice husk ash; rice strew ash; phragmites ash; self-compacted concrete; self-curing concrete

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1. Introduction

Currently, air pollution is regarded as a pressing issue, with open air waste burning accounting for approximately 6% of air pollutant sources in Egypt. The Egyptian Agricultural Waste Recycling Unit estimates that the country produces 30–35 million tons of agricultural waste annually, which equates to 33.4% of the total waste generated. Of this, merely 11 million tons are utilized as animal fodder and organic fertilizer, while the remaining waste is burned. This practice contributes to 42% of Egypt's overall air pollution [1,2].

Phragmites (PG) is a plant species that poses significant challenges worldwide. As depicted in Figure 1, the rapid spread of PG is a global issue. Phragmites quickly proliferates across various regions, regardless of whether it has been intentionally introduced [3]. Prior to 1910, only a few areas in northeastern United States harbored phragmites; however, by 1960, samples revealed their presence from coast to coast. Invasive PG rapidly overruns wetland and marshland ecosystems, hindering water access for recreational activities such as swimming and fishing. Furthermore, it negatively impacts coastal views, displaces native vegetation, infringes upon habitat space for fish and wildlife, obstructs waterways, and creates fire hazards. Land areas engulfed by PG often provide shelters for detrimental insects, snakes, scorpions, and other hazardous creatures—consequently leading to their disposal via burning in countries like Egypt [4–7].

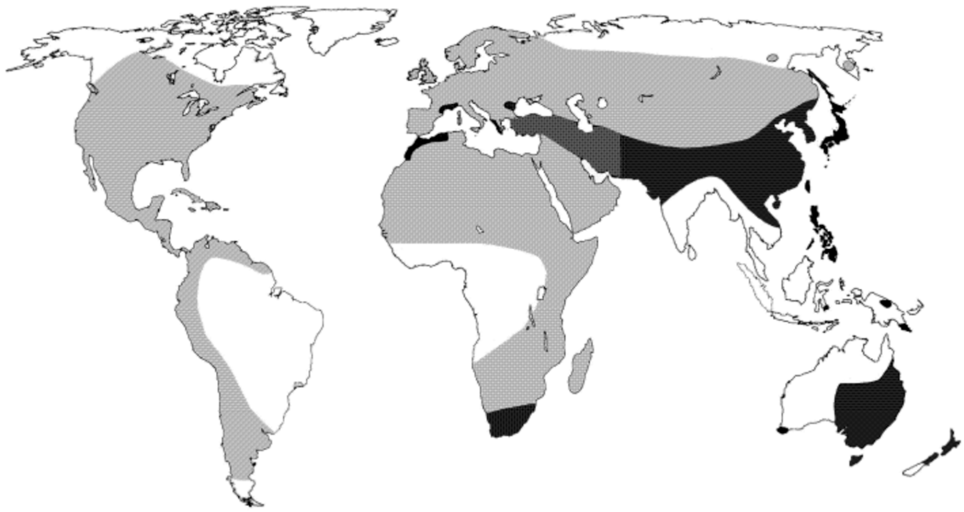


Figure 1. Map of Phragmites distribution worldwide (The shaded areasindicates the areas where PG is located) [8].

The concrete industry's environmental footprint stems from its substantial cement consumption. Cement production accounts for 51% of total industrial emissions in Egypt, making it one of the primary sources of carbon dioxide release [9,10]. Researchers have explored utilizing agricultural waste ashes as a partial cement substitute in concrete mixtures to create more environmentally friendly and sustainable solutions.

Numerous studies have suggested that incorporating agricultural waste ashes enhances concrete durability and resistance to chlorides and acids while diminishing permeability. The high content of amorphous silica present in these ashes, formed during the burning process, increases Calcium–Silicate–Hydrate (C-S-H) levels, thus improving concrete strength. Several types of agricultural waste ash have been proposed for use in concrete production, including rice straw ash (RSA), rice husk ash (RHA), palm oil ash, coconut ash, and sugar cane bagasse (BA) [11–16].

Rice ranks as the world's second-largest cereal crop, following wheat, and generates significant amounts of crop residue. Consequently, researchers have explored using rice waste, specifically rice straw and rice husk, to create ash for the concrete industry. Rice straw refers to the dried stalks of rice plants after grain and chaff removal, while rice husk is a natural sheath encompassing rice grains that lacks commercial value when removed during refinement [2,3,17–28].

Similarly, sugarcane bagasse is the residue remaining after extracting juice from sugarcane stalks. As a by-product of the ethanol industry, sugarcane contains 25–30% bagasse. Utilizing bagasse can not only decrease global CO_2 emissions but also enhance the market value of waste materials. Recent studies have primarily focused on incorporating sugarcane bagasse in building materials, revealing its potential as a pozzolanic material suitable for use in mortar or concrete [29–38].

Despite the challenges posed by PG in the concrete industry, research in this field remains limited. Studies have dealt with PG in concrete production, particularly in light concrete [39] and fibrous concrete [40]. This paper examines the utilization of PG as a partial substitute for cement in concrete.

The rapid expansion of the concrete industry has led to innovations in terms of increased resistance and cost effectiveness. As such, self-compacting concrete (SCC) has emerged as a promising solution. SCC flows under its own weight, ensuring homogeneity and minimal voids while providing superior finish and durability compared to traditional vibrated concrete [13,41,42].

Historically, preserving conditions to prevent water evaporation from the concrete surface has been crucial during the curing process. Curing typically commences externally and progresses internally. Conversely, internal curing, also known as self-curing, initiates from within and proceeds externally. Inner reservoirs for concrete curing, such as saturated lightweight fine aggregates, superabsorbent polymers, and saturated wood fibers, are employed [43,44].

Moreover, self-curing concrete has been developed for use in large-scale constructions and complex areas where traditional curing methods prove difficult. Self-curing is pivotal for enhancing durable microstructures and overall performance without relying on conventional techniques that often require chemical additives. According to ACI-308, internal curing refers to cement hydration resulting from additional internal water not accounted for in the mixing process [45–48].

The aim of this research is to investigate the influence of incorporating natural ashes (specially Phragmites ash (PGA)) as a partial replacement for cement in high-strength self-compacted self-curing concrete (HSSCSCC) with regard to fresh concrete characteristics (flowability and passingability) and mechanical properties, specifically compressive strength. Compressive strength test results were evaluated at various ages up to 365 days. This study also introduces the impact of different replacement ratios of the used natural ashes as a partial replacement for cement on high-strength self-compacted self-curing concrete (HSSCSCC) on the concrete's durability and microstructure.

2. Materials and Methods

2.1. Materials and Mix Proportions

Cement: The cement used was ordinary Portland cement (OPC) CEM I 52.5N, and its chemical and physical properties met the requirements set by the Egyptian Standard of Specifications (E.S.S. 4756-1/2013) [49].

Silica fume: The silica fume employed in this study was obtained from the Egyptian Ferro Alloys Corporation (EFACO) and followed the ASTM C 1240 standard [50]. The utilized silica fume had a fineness of 23.52 m^2/gm and a density of 2210 kg/m^3.

Super plasticizer: Master Glenium RMC 315, a polycarboxylate-based superplasticizer from BASF Egypt for the Construction Chemicals Company, was utilized in this application. This third-generation superplasticizer for concrete and mortar is chloride-free, low in alkali, and compliant with ASTM-C-494 types G and F [51]. Appropriate for all cement varieties, the superplasticizer has a specific gravity value ranging from 1.060 at 25 °C, and a sulphate content below 1 gm/lit.

Fine aggregate (F.A.): Sand with a specific gravity of 2.59 was utilized in this study. This particular sand complies with the Egyptian Code of Practice (ECP 203/2018) [52] and (ESS 1109/2008) [53], and satisfies the standards set by ASTM C33 [54]. The grain size distribution curve of the used fine aggregate (sand) can be observed in Figure 2.

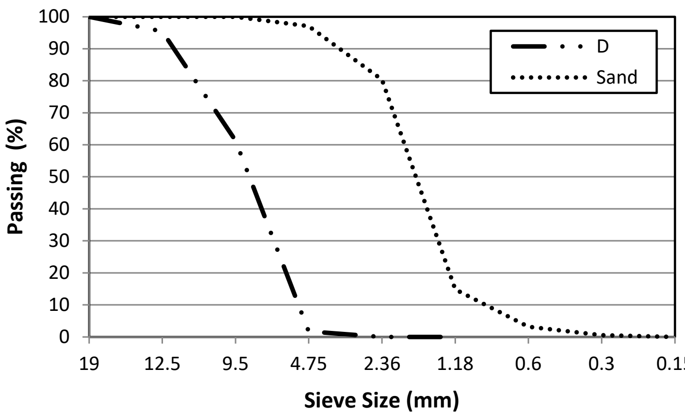


Figure 2. Grain size distribution curves for the used aggregates.

Coarse aggregate (C.A.): In this study, the coarse aggregate used was a crushed dolomite (D) with a specific gravity of 2.61. The coarse aggregate satisfies the same requirement that was satisfied by the fine aggregates [52–54]. The maximum nominal size was 12.5 mm. The grain size distribution curve for the used coarse aggregates is shown in Figure 2.

Polyethelene glycol (PEG): Polyethylene glycol (PEG) with a molecular weight of 600 appears as a clear to slightly hazy colorless liquid that exhibits mild hygroscopic properties and possess a faint distinct odor. PEG 600 is specifically utilized as a self-curing agent in concrete. The particular type and quantity of PEG used in this study were determined based on the research conducted by Arab et al. [45]. The PEG was acquired from El-Gomhouria Company for Trading Chemicals and Medical Appliances, located in Egypt.

Natural Ashes: Four distinct varieties of natural agricultural waste were utilized, sourced from Egypt's local agricultural landscape. These wastes included sugarcane bagasse ash (SBA), rice husk ash (RHA), rice straw ash (RSA), and phragmites ash (PGA), as depicted in Figure 3. The processing and treatment procedure was carried out in three main stages. Firstly, agricultural waste was collected from Beni-Suef Governorate, Egypt. Secondly, the gathered waste was washed with clean water, cut into smaller pieces, and left to dry under the July sun (between 39 °C and 44 °C) for varying periods based on individual waste types until reaching a semi-dry state. Finally, the semi-dry chopped waste was incinerated in a furnace at 500 °C for six continuous hours, with an approximate heating and cooling rate of 10 °C per minute. The final product was sieved using a 170 μm mesh. Table 1 details the chemical compositions of the cement, silica fume, and natural ashes employed in this study.

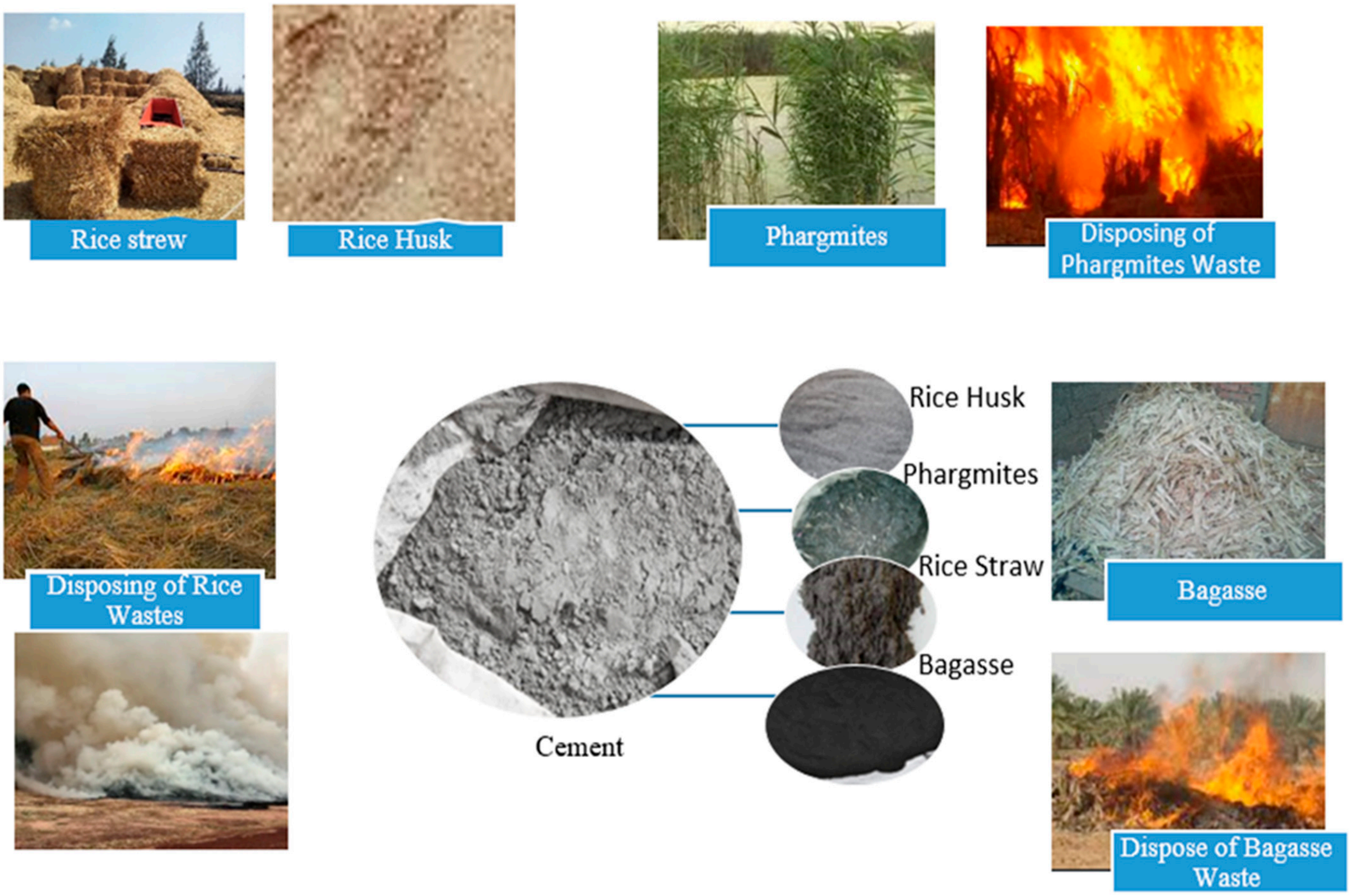


Figure 3. The used ashes types.

Table 1. XRF chemical analysis for OPC, SF, and the natural ashes.

Elements	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	SO_3	Cl
OPC	18.52	5.26	3.41	63.14	0.450	0.160	1.58	2.58	0.06
SF	96.0	0.19	0.17	0.11	0.62	0.48	0.47	0.15	0.02
PGA	67.60	5.17	2.23	6.405	1.923	6.89	1.70	1.58	0.365
RSA	73.30	2.93	1.74	3.09	3.480	9.480	1.57	1.14	0.52
BGA	45.26	5.98	5.83	7.088	5.716	5.716	4.13	3.474	0.78
RHA	71.38	3.61	0.84	2.62	0.529	5.206	2.00	2.26	0.771

Table 1 displays the chemical compositions of the locally sourced natural ashes utilized in this study, comparing them to ordinary Portland cement (OPC) and silica fume (SF). The primary constituents of cement are lime, silica, alumina, and iron oxide. The relative proportions of these oxide compositions significantly influence various cement properties and are typically represented as CaO, SiO_2, Al_2O_3, and Fe_2O_3. To measure the elemental composition of the materials, an X-ray fluorescence (XRF) analytical technique was employed. The results indicated varying silica content among the different ash types. RSA had the highest silica content, followed by RHA, PGA, and BA, respectively. According to ASTM C618 (1994) [55], a minimum combined content of 50% for the three major oxides (SiO_2 + Al_2O_3 + Fe_2O_3) is required.

The XRD analysis results aligned with those obtained through the XRF chemical analysis. Table 2 shows the XRD analysis outcome for various ashes samples and also includes scanning electron microscope (SEM) micrographs for each ash type.

SEM micrographs at three different scales (30 µm-10 µm-1 µm) are featured in Table 3. The first column (30 µm) demonstrates particle sizes for each ash type; the second column (10 µm) presents particle shapes; and the third column (1 µm) provides surface images for ash particles.

The RHA images reveal that its particles possess a flaky texture with rugged surfaces, while RSA particles exhibit an elongated shape and slightly less surface roughness compared to RHA particles. BA particles are characterized by irregular cube-shaped forms with very rough surfaces. In contrast, PGA presents equant-shaped particles that display the lowest surface roughness among all analyzed ash types.

Mix proportions: The selection of mix proportions for high-strength self-compacting and self-curing concrete (HSSCSCC) was made using guidelines, findings of previous researches, and specifications, as well as laboratory trials [45,52,56]. Table 3 displays the chosen mix proportions for the control mixes with and without self-curing agent. Natural ash types were partially utilized to replace cement by 1%, 3%, 5%, 10%, and 15% of the overall cement content.

2.2. Testing Procedures and Equipment

Fresh concrete tests: Tests on fresh concrete are essential for assessing the impact of the added ash types on the fresh properties of self-compacting concrete. Slump flow and J-Ring tests were conducted to evaluate flowability and passingability attributes, respectively, as per British standard [56] and Egyptian code [52]. The workability of the mixture was determined through slump flow tests, while passing ability was assessed by the J-ring test. An acceptable (T50) value for slump flow tests is between 2 and 5 s, measured by how long it takes concrete to flow to a diameter of 500 mm. The average slump flow diameter (Dav) should be between 600 and 800 mm. For J-ring tests, (T50) values are considered acceptable if they do not exceed 5.5 s. The average diameter (Dav) is also measured and compared to that of the slump flow, ensuring that the difference between both diameters does not exceed 25 mm.

Table 2. SEM and XRD analysis for the used natural ashes.

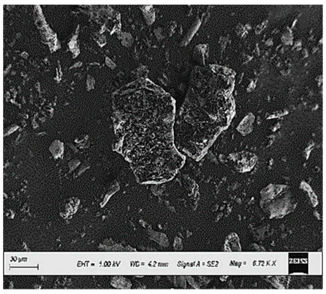
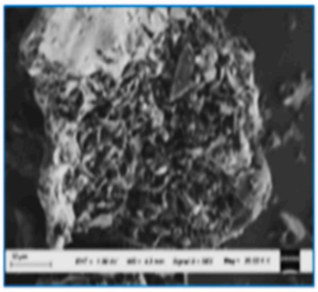
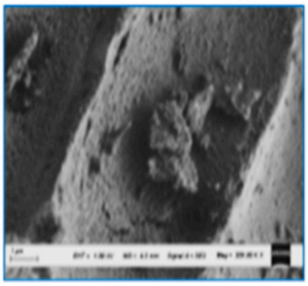
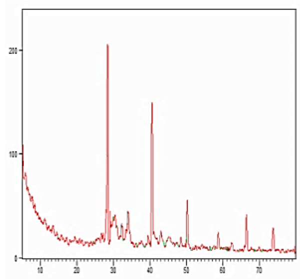
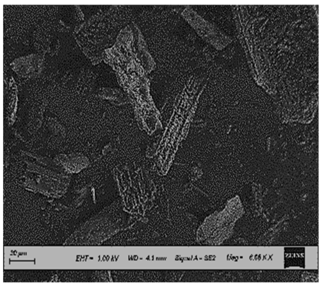
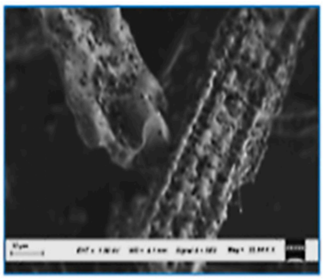
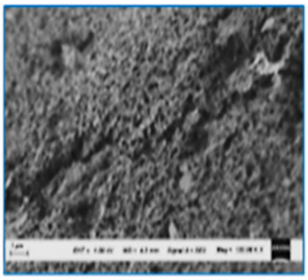
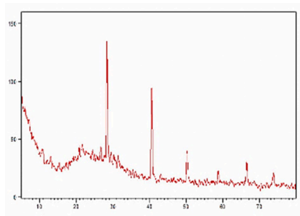
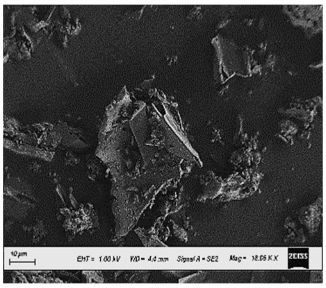
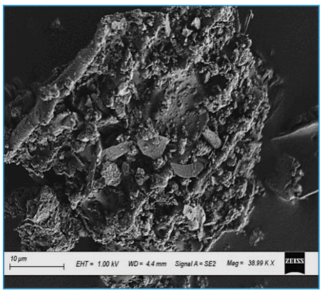
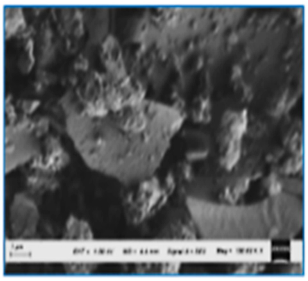
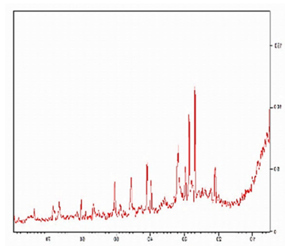
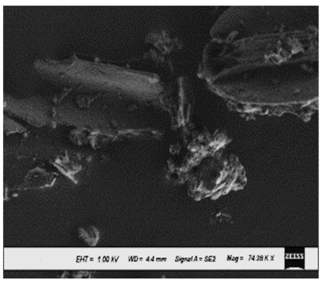
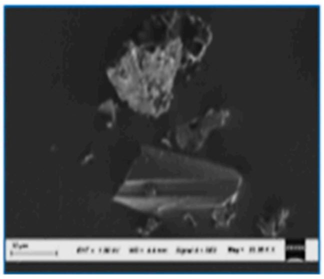
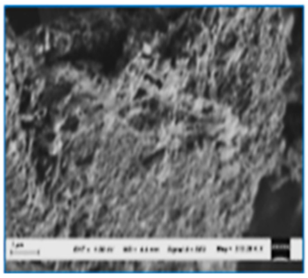
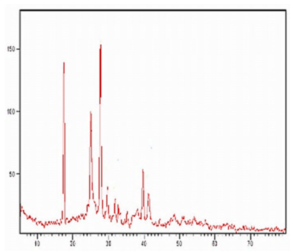
	Scale 30 µm	Scale 10 µm	Scale 1 µm	SEM
RH ASH				
RS ASH				
BA ASH				
PG ASH				

Table 3. Mix proportions for tested concrete mixes in kg/m^3.

	Control WA	Control CA
Cement	500	500
Silica fume	25	25
Coarse aggregate	820	820
Fine aggregate	820	820
Water	160	160
Super-plasticizer	10	10
Polyethylene glycol (PEG 600)	-	2.5

Hardened concrete tests: The concrete compressive strength is the main mechanical property that must be taken into consideration in the design of reinforced concrete structures. In this study, the compressive strength of the tested mixes was examined. Test samples were cast, cured in water until testing, and then assessed according to the Egyptian code of practice [52]. Tests involved conducting compression tests to find the compressive strength of 100 × 100 × 100 mm concrete cubes. Specimens were tested at 7, 28, 90, 180, and 365 days, with three cubes for each mix tested on a specific age. The average value of the three specimens is reported as the strength for that particular age.

Concrete durability test: A sorptivity test was performed as an indicator for the concrete durability. This test measures the capillary suction of concrete when exposed to water and followed the ASTM C 1585 [57] procedure using 150 mm cube specimens. After a 28-day water curing period, the specimens were oven-dried to a constant weight, exposed to water on one surface, and sealed on all other surfaces. Mass gain due to sorption was measured after two hours, and the average value was used for comparison among various mix types.

Microstructure: A scanning electron microscope (SEM) analysis was conducted on the concrete samples. The samples were dried, placed on an SEM stub, and coated with a thin, conductive layer. A narrow electron beam was used to scan the sample, which could be focused on a specific area to emit X-ray photons that interact with a silicon detector, generating electrical pulses. These pulses were then collected with a multi-channel analyzer for elemental analysis. The observation was made using a Philips XL 30 SEM model with an attached EDX unit, at an accelerating voltage of 30 KV, magnifications ranging from 10× to 230,000×, and a resolution of W (3.5 nm).

2.3. Specimens' Nomenclature

The tested mixes' nomenclatures are shown in Figure 4. The first part refers to the existence of the curing agent, where (WC) indicates that no curing agent is used and (CA) indicates samples contain curing agent. The second part indicates the type of the used natural ashes ((PG) for Phragmites ash, (RS) for Rice Straw ash, (RH) for Rice Husk ash, and (BG) for Sugarcane Bagasse ash). The third part indicates the replacement ratio of the OPC with the natural ash (01 for (1%), 03 for (3%), 05 for (5%), 10 for (10%), and 15 for (15%)).

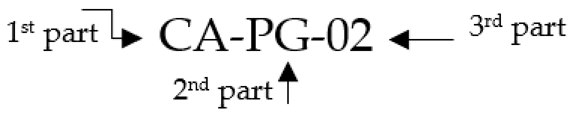


Figure 4. Nomenclature for tested mixes.

3. Results and Discussions

The effects of self-curing agent on the properties of high-strength self-compacted concrete samples' containing the chosen types of natural ashes were investigated through examining test results for both fresh and hardened concrete. The effect of the replacement ratio of the OPC with the natural ash was also investigated.

3.1. Fresh Concrete Tests Results

Slump flow and J-Ring tests were conducted on fresh concrete to investigate the flowability and passingability of concrete mixes containing natural ashes. The average diameter (D_{av}) results and the 500 mm diameter's time (T_{50}) are displayed in Table 4. It was observed that the higher percentages of replacing OPC with natural ash led to reduced workability, as confirmed by the slump flow and J-Ring test results regarding flowability and passability. By comparing the different types of natural ash used in the study at the same replacement ratios, it could be noticed that, at the same replacement ratio, the phragmites ash (PGA) showed the best results among the used types in the slump flow test, followed by rice straw ash (RSA), rice husk ash (RHA), and sugarcane bagasse ash (SBA).

The J-Ring test results showed a great convergence between samples containing phragmites ash (PGA) and rice straw ash (RSA) at the same OPC replacement ratio, followed by rice husk ash (RHA) and sugarcane bagasse ash (BGA).

Table 4. Slump flow and J-Ring tests results for tested concrete mixes.

Ash Type	Code	Slump Flow Test			J-Ring Test		
		D_{av} (mm)	T_{50} (sec)		D_{av} (mm)	T_{50} (sec)	
-	ControlCA	700	2.3	A	689	2.7	A
PG	CAPG01	697	2.4	A	688	2.8	A
	CAPG03	694	2.5	A	683	2.8	A
	CAPG05	688	2.6	A	679	2.9	A
	CAPG10	682	3	A	667	3.4	A
	CAPG15	656	3.6	A	639	3.9	A
RS	CARS01	696	2.5	A	687	2.8	A
	CARS03	694	2.5	A	683	3	A
	CARS05	687	2.8	A	675	3.5	A
	CARS10	682	3.3	A	664	3.8	A
	CARS15	652	3.8	A	640	4.2	A
RH	CARH01	696	2.5	A	684	3	A
	CARH03	690	2.7	A	675	3.3	A
	CARH05	685	3.1	A	674	3.4	A
	CARH10	677	3.5	A	666	4	A
	CARH15	640	4	A	628	4.4	A
BG	CABG01	691	2.6	A	680	3.2	A
	CABG03	689	2.8	A	675	3.3	A
	CABG05	683	3	A	673	3.5	A
	CABG10	670	3.6	A	657	3.9	A
	CABG15	640	4.3	A	626	4.7	A

A: Refers to accepted mixes as a self-compacted concrete.

3.2. Compressive Strength Test Results

The investigation of hardened properties of the evaluated concrete mixes focused on compressive strength as the main mechanical property of concrete. The rest of the mechanical properties follow the same behavior as concrete in compressive strength, so most design codes depend mainly on compressive strength. By studying compressive strength, we can cover a majority of the crucial mechanical properties of concrete. Testing was carried out from 7 to 365 days with curing agent and without any curing agent for up to 28 days to check the efficiency of the curing agent while using the natural ash. Table 4 displays the compressive strength test results for high-strength self-compacted self-curing concrete mixtures. The effects of utilizing different ash types on compressive strength at 7, 28, 90, 180, and 365 days were also examined.

The incorporation of the used natural ashes types had a good impact on the compressive strength compared with the positive environmental effect due to decreasing the cement content. Upon examining the impact of various natural ash types in the research, it became evident that implementing a curing agent alongside the utilized natural ash positively influenced the compressive strength of concrete containing different replacing percentages of natural ash. This is demonstrated by comparing the compressive strength results at 7 and 28 days for concrete with and without a curing agent. The replacement of cement by the used natural ash types and percentages in general, did not affect the compressive strength badly while using the PEG 600 as a curing agent in the HSSCSCC casting.

With regard to the effects of using the distinct natural ash types shown in Table 5 and Figure 5, it is apparent that incorporating PG ash at replacement ratios of 1, 3, 5, 10, and 15% resulted in a change in compressive strength in 28 days of 0.8, −2.6, −1.1, 1.0, and −4.0% as a percentage of the control CA mix compressive strength at 28 days, respectively. As for RS ash, replacing OPC with 1, 3, 5, 10, and 15% RS ash caused a change in compressive strength in 28 days by about 4.3, 2.5, −0.8, −7.0, and −11.50%, respectively.

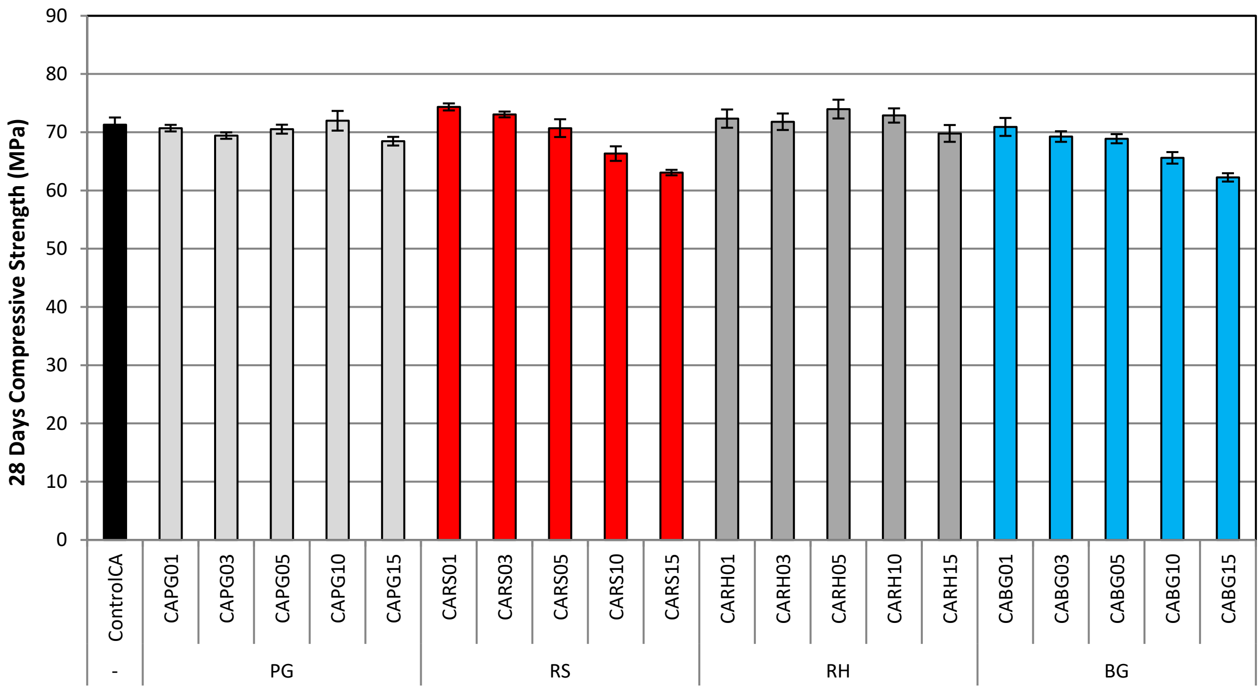


Figure 5. 28 Days Compressive Strength for HSCSCSC Mixes.

For RH ashes, there was a change of approximately 1.5, 0.7, 3.7, 2.2, and −2.1% in the 28 days compressive strength for samples containing 1, 3, 5, 10, and 15% of RH ash as a replacement of OPC than that of the control CA mix. Lastly, there was a decrease in the 28 days compressive strength compared to that of the control CA mix when using BG ash by about 0.6, 2.9, 3.4, 8.0, and 12.7 for 1, 3, 5, 10, and 15% of BG ash as a replacement of OPC, respectively. Consequently, it can be concluded that using RH ash followed by PG ash proved most effective as a replacement of OPC in the range from 1 to 15% when compared to RS and BG ash. Additionally, by tracking the compressive strength results at subsequent ages until the age of 365 days that shown in Table 5 and comparing Figure 5 with Figure 6, it could be found that the improvement of the compressive strength over age for RH, PG, and RS ash was better than that in the case of using BG sh.

The optimal replacement percentage of the used natural ash types to be used in HSSCSCC ranged from 1 to 15% for PG and RH ash types. In the case of RS and BG ash types, it is recommended to limit the replacement percentage of these types to with the range of 1–10%.

Table 5. Compressive strength test results for the tested concrete mixes.

Asht Type	Code	%	Compressive Strength (MPa)		Asht Type	Code	%	Compressive Strength (MPa)					
			7 Days	28 Days				7 Days	28 Days	56 Days	90 Days	180 Days	365 Days
-	ControlWC	0	59.52	68.85	-	ControlCA	0	59.85	71.31	76.1	78.06	79.34	81.89
PG	WCPG01	1	57.98	67.73	PG	CAPG01	1	61.13	70.71	74.43	78.01	78.83	81.2
	WCPG03	3	59.58	67.61		CAPG03	3	58.28	69.44	73.96	75.79	76.88	79.35
	WCPG05	5	58.67	69.9		CAPG05	5	62.16	70.53	73.73	76.83	77.35	80.51
	WCPG10	10	61.33	71.69		CAPG10	10	61.02	71.98	75.47	76.73	77.76	83.31
	WCPG15	15	59.44	67.45		CAPG15	15	60.33	68.46	71.56	74.94	76.41	79.16
RS	WCRS01	1	63.43	71.97	RS	CARS01	1	64.27	74.35	77.8	82.41	83.4	84.79
	WCRS03	3	64.14	72.78		CARS03	3	64.39	73.07	76.23	80.76	81.33	82.83
	WCRS05	5	58.65	69.19		CARS05	5	61.13	70.71	73.62	75.75	77.88	80.32
	WCRS10	10	56.5	64.11		CARS10	10	57.92	66.35	69.22	72.77	74.56	76.12
	WCRS15	15	52.84	61.72		CARS15	15	55.59	63.08	65.69	69.11	70.52	72.51
RH	WCRH01	1	62.2	70.58	RH	CARH01	1	63.76	72.35	76.76	79.5	80.54	83.25
	WCRH03	3	60.26	69.04		CARH03	3	62.67	71.8	75.88	78.52	80.26	82.7
	WCRH05	5	63.73	72.32		CARH05	5	62.71	73.98	77.57	80.71	82.95	86.04
	WCRH10	10	61.29	71.6		CARH10	10	63.01	72.89	76.2	80.25	81.93	84.12
	WCRH15	15	60.26	69.04		CARH15	15	59.76	69.8	73.28	78.22	79.68	80.79
BG	WCBG01	1	59.64	69.66	BG	CABG01	1	60.71	70.91	75.01	76.34	77.36	82.31
	WCBG03	3	58.8	67.9		CABG03	3	58.13	69.26	72.69	76.55	75.49	78.59
	WCBG05	5	58.46	66.34		CABG05	5	57.82	68.89	71.74	73.58	74.42	78.27
	WCBG10	10	55.51	64.84		CABG10	10	57.83	65.62	68.32	71.06	72.09	75.06
	WCBG15	15	52.87	61.16		CABG15	15	53.3	62.26	64.89	69.01	69.98	72.41

3.3. Sorptivity Test Results

Concrete durability was assessed using the sorptivity test for HSSCSCC mixes containing various used types of natural ashes. The test served as an indicator of durability and highlighted how different types of ashes influenced HSCSCSC mixtures' sorptivity. The reduction in sorptivity is proof of the improvements in specimen permeability which leads to durability improvement. Figure 7 shows the sorptivity test results for HSSCSCC mixes. Generally, using RS ash gave the best sorptivity results compared with the control CA mix, followed by mixes containing PG, RH, and BG ash.

3.4. Microstructure Analysis

The microstructure of concrete was analyzed through electron microscope scanning and Energy Dispersive X-ray Spectroscopy (EDS) to compare HSSCSCC samples with and without the used natural ash types. Furthermore, SEM-EDS analysis provided insight into the microstructure of the optimum mixtures by analyzing paste samples. With a focus on the development and enhancement of cementitious pastes' microstructure, EDS analysis was used to determine the Ca/Si ratio for all mixtures. Previous studies have explored the effect of the Ca/Si ratio on the C-S-H phase [58–61].

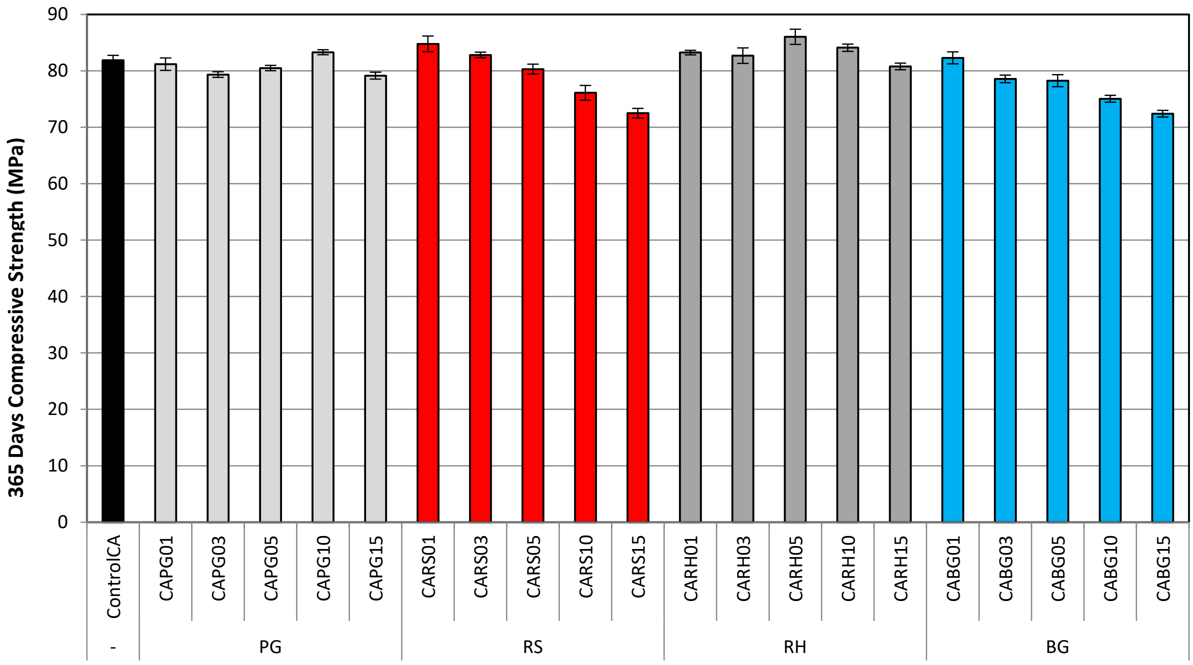


Figure 6. 365 Days Compressive Strength for HSCSCSC Mixes.

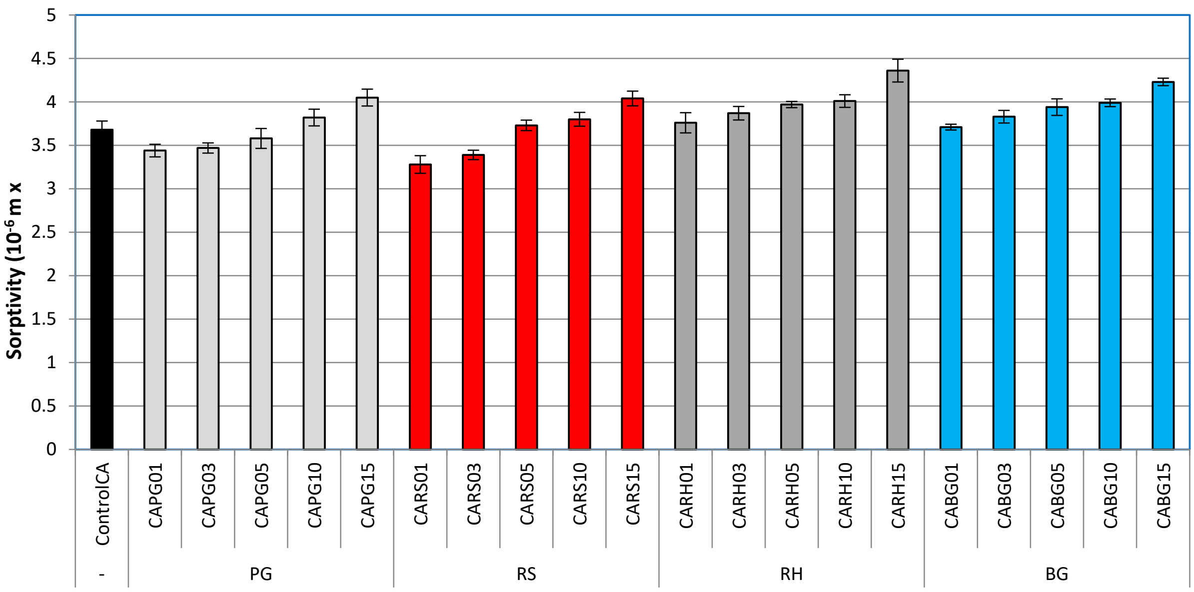


Figure 7. Sorptivity test results for HSCSCSC mixes.

The outcomes of the SEM-EDS analysis reveal that mixes containing RS and RH ash types have a larger Ca/Si ratio compared to the other combinations containing BG, PG, and even the control mix. This can be linked to the enhanced pozzolanic attributes and greater fineness of both RS and RH, leading to a denser paste matrix due to high-density C-S-H and C-H phase formation. Traditional high-density C-S-H and C-H phase formation lead to densifications and microstructure refinement, ultimately enhancing performance in practical engineering applications.

Figure 8 presents the SEM and EDX for the control CA mix and samples contain 10% of the used natural ash (CAPG10, CARS10, CARH10, and CABG10). Figure 8 demonstrates that substituting cement with various natural ashes (BG, RH, RS, and PG) in concrete may result in a decrease in pore volume. This change could be linked to an increase in bond action, which contributes to strength development. The microstructure is obviously improved and the structure becomes more compacted after the addition of RH, PG, and RS which was likely due to the high levels of SiO_2 compared to other samples tested, and this lead to compressive strength growth.

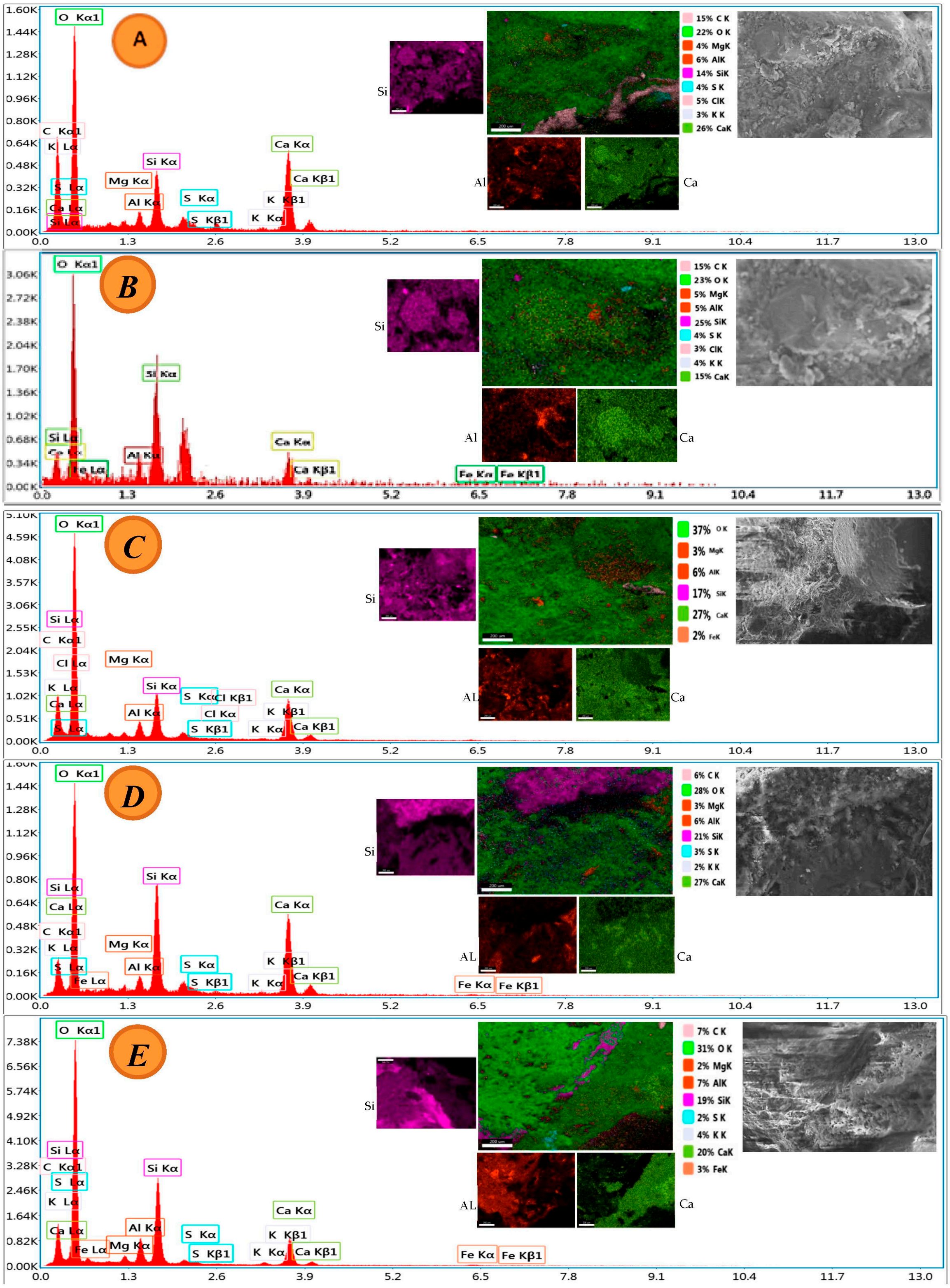


Figure 8. EDX and SEM analysis for HSSCSCC mixes (**A**) Control CA (**B**) CAPG10 (**C**) CARS10 (**D**) CARH10 (**E**) CABG10.

SEM micrographs of concrete specimens containing RH, PG, and RS ashes, demonstrating improvements in their characteristics due to the physical and chemical properties of these types of natural ash. The chemical effect stems from pozzolanic reactions between calcium hydroxide (C-H) created during cement hydration and amorphous silica from natural ash, especially RH and PG ash, forming calcium–silicate–hydrates (C-S-H). Consequently, CARH10 and CAPG10 decrease the amount of continuous pores, turning them discontinuous and reducing the number of large pores, resulting in a denser, more homogeneous microstructure.

4. Conclusions

The current research presents an investigation on the effect of various proportions of the types of natural ash used as partial cement replacements. It was conducted on the fresh properties, compressive strength up to 365 days, durability, and microstructure of HSSCSCC. Key findings from this research include the following:

- Through experimental work, replacing OPC with Phragmites ash (PGA) and Rice husk ash (RHA) types with replacement percentages ranged between 1 to 15% have a noticeable impact on the compressive strength of HSSCSCC mix;
- Adding Polyethelene glycol (PEG) with a molecular weight of 600 has an observable effect as a self-curing admixture on the studied concrete mix properties;
- The use of PEG alongside natural ashes proved effective in producing self-curing concrete for the tested mixtures;
- The optimal dosages as a percentage of total binder content (Cement + ash) were determined: 3% for Sugarcane bagasse ash (SBA), 10% for Rice husk ash (RHA), 5% for Rice straw ash (RSA), and 10% for Phragmites ash (PGA) for high-strength concrete mixes;
- The strength of high-strength concrete mixes is affected positively by the addition of the optimal content for each natural ash type;
- The compressive strength trend indicates a growth over time of up to 365 days for concrete mixes containing the optimal natural ash content for high-strength self-compacted self-curing concrete mixes.
- Using RS ash gave the best sorptivity results compared with the control CA mix followed by mixes containing PG, RH, and BG ash as an indicator for concrete durability.
- SEM micrographs of concrete specimens containing the used types of natural ash, especially RH and PG S ashes, demonstrated observable improvements in their characteristics compared with the control mix, showing a decrease in the amount of continuous pores, turning them discontinuous and reducing the number of large pores, resulting in a denser, more homogeneous microstructure.

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