Review Article

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Durability and microstructure study on concrete made with sewage sludge ash: A review (Part II)

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Abstract: The quantity of carbon dioxide gas released during the manufacturing and acquisition of raw ingredients determines the sustainability of concrete. Industrial garbage dumping is a critical difficulty that humanity is experiencing because of globalization and the increasing population. Through the efficient use of industrial by products, efforts are being undertaken to lower carbon discharges in the concreting process. It has been recommended by sustainable development goals and standards to use byproducts that have lower embodied energy and carbon emissions. Ash from sewage sludge demonstrates its suitability for use in concrete. However, a compressive assessment is needed to determine the past, present, and future research aspects of using sewage sludge ash (SSA) as a construction material. Therefore, this research is carried out on using SSA as a construction material. All the essential properties such as the physical and chemical properties of SSA, its effect on durability properties, and morphology structure study are the main aspect of this review (Part II). The analysis also highlights the research gap for upcoming exploration which further improved its performance.

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1 Introduction

The manufacturing of mixed cement and concrete has long relied on the scavenger tactics of the cement and concrete industries, which collect waste from other industries [1–4]. This has resulted in situations where 20–70% of ordinary Portland cement (OPC) is replaceable with these silico-aluminate compounds, which have fulfilled the role of supplemental cementing ingredient. As proposed by Scrivener and Nonat [5], to obtain greater rates of cement replacement, it is required to create and employ new cementing materials that are also locally available. Various options are available such as fly ash [6], copper slag ash [7], marble waste [8], ceramic waste [9], paper pulp ash [10], wooden ash [11], rice husk ash [12], and wheat straw ash [13]. Additionally, ashes from sewage sludge ash (SSA) might be a good regional source for cementing materials. SSA results from the burning of sewage sludge, a waste management technique used by water treatment facilities to dispose of enormous quantities of sludge.

Alternatives to cement should be based on the availability of raw materials, fewer CO_2 discharges, less energy utilization, less noxious waste loads, and the potential usage of byproducts. Three viable strategies for the sustainable development of concrete manufacturing include clean manufacturing, the utilization of recyclable materials, and cement replacement [14–16]. SSA is one form of fly ash that has shown promise as a cementing material [17].

Several sludge treatment possibilities, involving energy improvement methods such as anaerobiotic incorporation, gasification, ignition, and pyrolysis, were implemented [18]. However, these technologies have several obstacles that must be addressed to enhance their logistical, ecological, and economic effectiveness.

Different chemical and physical properties of the sludge, for example, create a distinct technical difficulty that affects the energy recovery process and reactions [19]. In addition to addressing sludge buildup issues, substituting sludge for cement will help lower the negative effects of the cement industry. It is well known that cement is the primary ingredient in the creation of concrete, and the cement manufacturing process is expensive owing to its energy requirements. Furthermore, the production of cement generates enormous amounts of carbon dioxide (CO_2), the principal greenhouse gas, particle pollution, and depleted natural resources [20].

Annual production of waste sludge is substantial. In Europe, around 10 Mt of sewage sludge is generated annually. In contrast, burning may cut this quantity by 70% (by mass) and 90% (by volume). Due to its high phosphorus concentration, sewage sludge has been extensively utilized as a fertilizer. However, the trend in modern years has been to burn it. In the burning procedure, organic matter is burned to yield byproducts such as carbon, residue vapors, and water vapor, as shown in Figure 1.

Furthermore, the method of waste dumping is not concluded by incineration, since the SSA retains a significant percentage of unburned residue. The worldwide output of SSA is predicted to be roughly 1.7 million tons per year, mostly from the United States, the European Union, and Japan, and it is anticipated to expand [22]. Waste sludge comprises mostly silicon, calcium, aluminum, and iron oxides, which are all identical to other cement raw materials. Utilizing SSA as cement or sand replacements in cement-based products is one technique for removing such waste [23]. The most popular solution for sewage sludge removal is incineration and disposal in regulated landfills. Nevertheless, space constraints on traditional landfill sites and increasing environmental issues have motivated research into alternate waste disposal strategies [24]. Figure 2 depicts the advantages of employing silica fume in concrete.

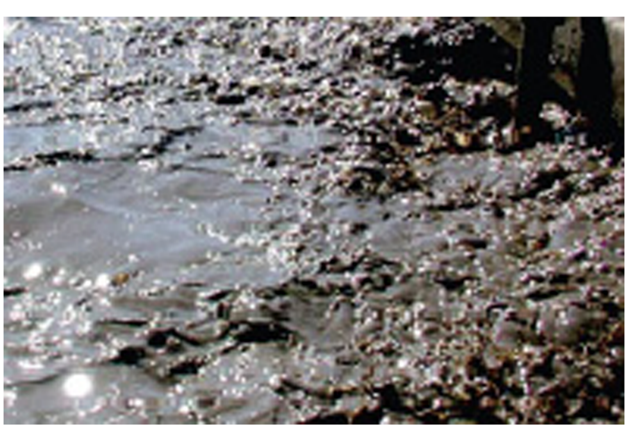

Figure 1: Waste sewage sludge [21].

The findings of the research suggest that SSA decreases the flow of mortars and increases the setting time. Most experiments demonstrated that sludge ash enhanced the quantity of gel concentrates and facilitated the absorption of water. The compressive capacity of the mortar was impacted by the weak strength characteristics of sludge ash in the mortar. In addition, the compressive capacity of the ash-cement mortar was diminished owing to the weak pozzolanic activity of sludge ash [23]. According to Lin et al., the quantity of water required to achieve a normal consistency increased as the nano-silica concentration increased. Additionally, reduced ash particle sizes led to a notable decrease in the setting time. As additional nano-silica was added to the ash-cement mortar, its strength capacity increased. The contact between sulfate and sludge ash promotes sulfate resistance by forming a denser composition of ettringite and aluminate hydrate that fills the paste's pores [25]. Donatello et al. revealed a correlation between the SSA particle size reduction and increased compressive capacity improvement in mortars containing SSA. Even though the particle sizes of the SSA were reduced because of milling, the surface area of the SSA did not increase in the same proportion. Consequently, it was determined that the SSAs had numerous open pores that trapped water, which affected the flow of the mortar and the hydration activity as a result of less accessible water in the system [26].

Although the literature shows that SSA shows the creditability to be utilized in concrete, a compressive review is essential to identify the past, current, and future research aspects of SSA as a building material. Therefore, this research is conducted on using SSA as a construction material. All the essential properties such as the physical and chemical properties of SSA and its effect on the durability properties of concrete are studied. The morphology structure of concrete with SSA is also reviewed. The assessment also highlights the research gap for upcoming research which further improved its performance.

2 Physical properties

The sludge is dehydrated, dried, and then burned at 850°C in a fluidized bed incinerator. The gray-colored SSA is entrained by the combustion gases and collected during the purification process (Figure 3).

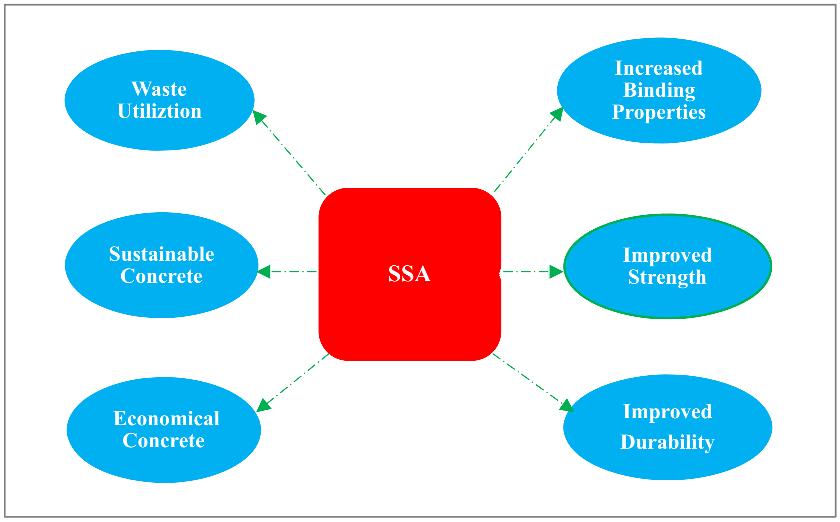

Figure 2: Benefits of SSA in concrete.

Figure 3: SSA [27].

The particle size of OPC ranges from 18 to 210 µm but the particle size of SSA ranges from 18 to 500 µm and cannot be classified as homogenous as presented in Figure 4. Taking cumulative dispersion into consideration, up to 50.4% of OPC particles are smaller than 18 µm in size. Only around 28.7% of SSA particles have a diameter lower than 18 µm. The fraction of SSA grains between 18 and 150 µm and between 150 and 500 µm is 59.2 and 12.1% of the total mass, respectively.

According to the results, the SSA has a rough surface structure as shown in Figure 5. This is a result of the pozzolanic interaction between SSA and $Ca(OH)_2$ in the mortar mixture. This structure has also filled the mortar's voids and pores [29]. The particle sizes seem to be more prominent than those of fly ash, as seen. Moreover, the particles of fly ash have a spherical form. Due to the ball-bearing effect, the spherical form of fly ash particles enhanced their fluidity. In addition, the SSA seems crystalline in appearance. It involves the random alignment of irregularly shaped and sized objects. The uneven form of sewage sludge particles increased internal friction, resulting in less flowable concrete. Due to interlocking, however, irregularly shaped particles of SSA enhanced the strength qualities [30,31]. Furthermore, Kumar et al. suggest that to get greater reactivity, SSA must be ground to a finer consistency [32].

Similarly, Chen and Poon [33] asserted that SSA particles had an uneven form and a large number of isolated, open holes. The uneven grains of SSA are transformed into smoother particles with fewer holes following grinding, as shown in Figure 6.

3 Chemical properties

The sludge has different physicochemical properties; thus, it is important to determine these features to pick the most appropriate strategies for its treatment. The chemical analysis of SSA revealed the presence of the principal oxides Fe_2O_3, SiO_4, CaO, and Al_2O_3 in various quantities, as reported in Table 1. These oxides constitute about 95% of cement clinker, which is accountable for the development of cement slurry hardening [34].

In addition, completing the combustion of dry sewage sludge at temperatures of 600°C to get SSA revealed a change in the oxide concentration. For example, the dry sewage sludge had 21.973% SiO_2 but the SSA contained 38.71% SiO_2, which is approximately twice the silicon level. The quantity of SiO_2 in the sludge ash increased as a consequence of the thermal destruction of the organic element of the sludge during the burning method, which

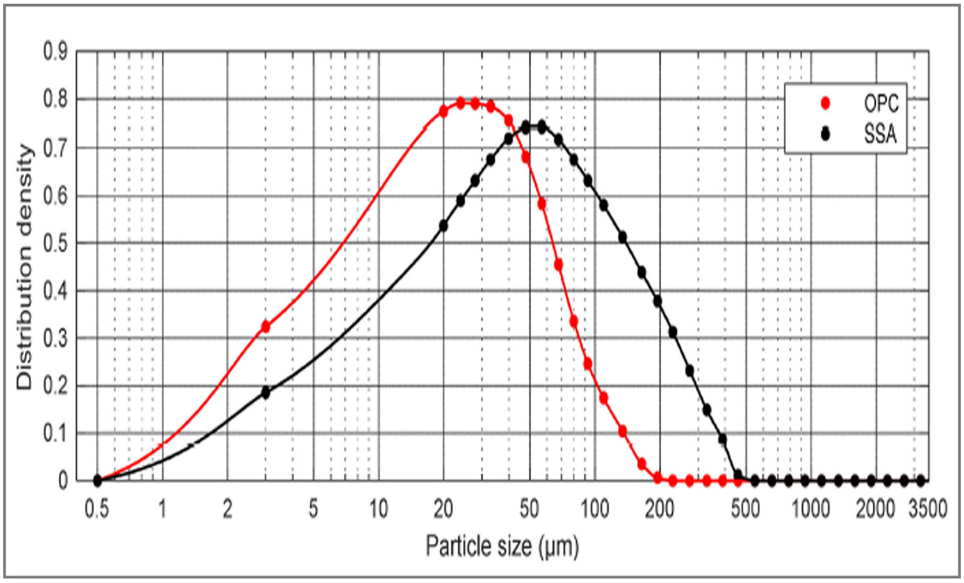

Figure 4: Gradation curve [28].

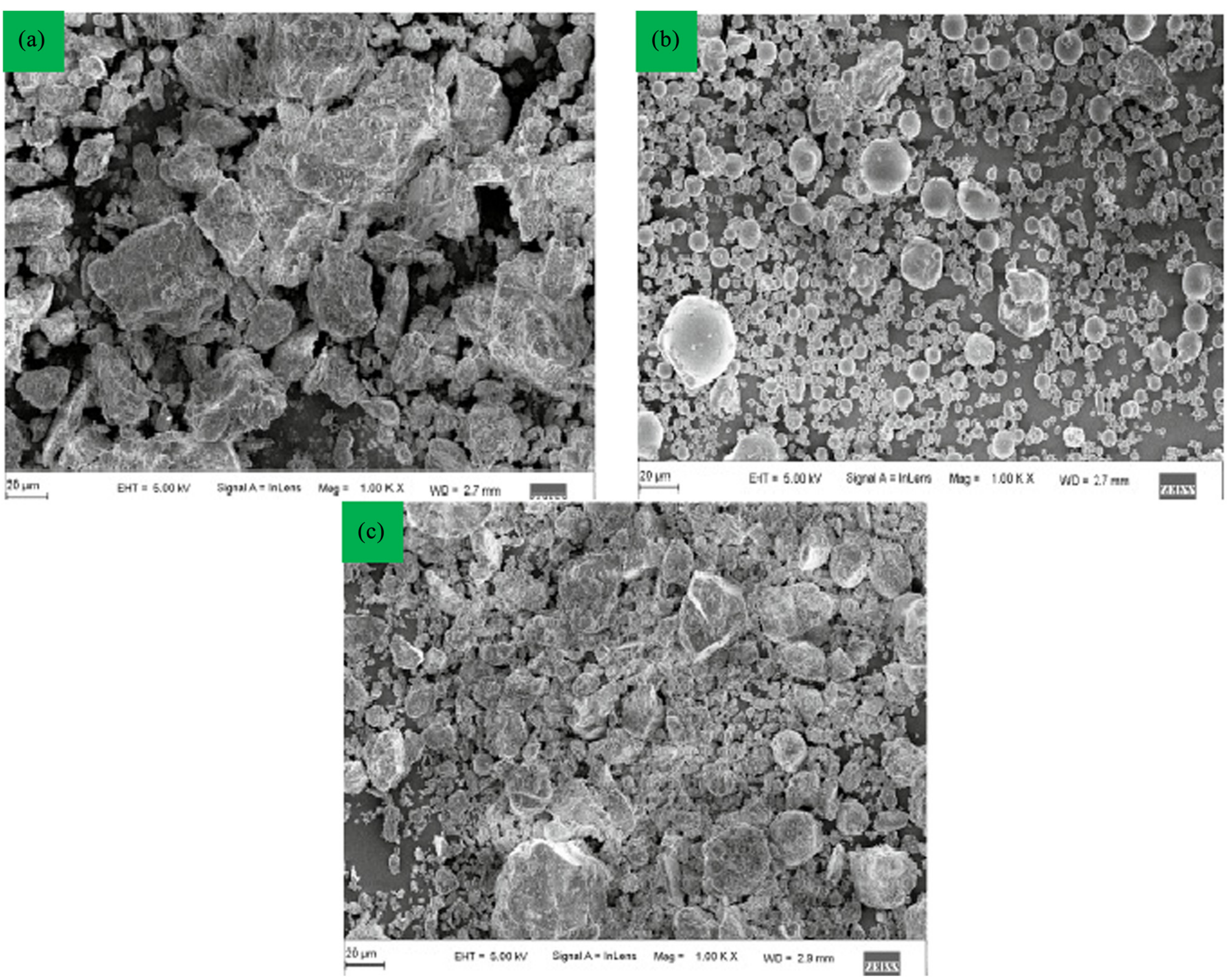

Figure 5: SEM of (a) SSA, (b) fly ash, and (c) cement [32].

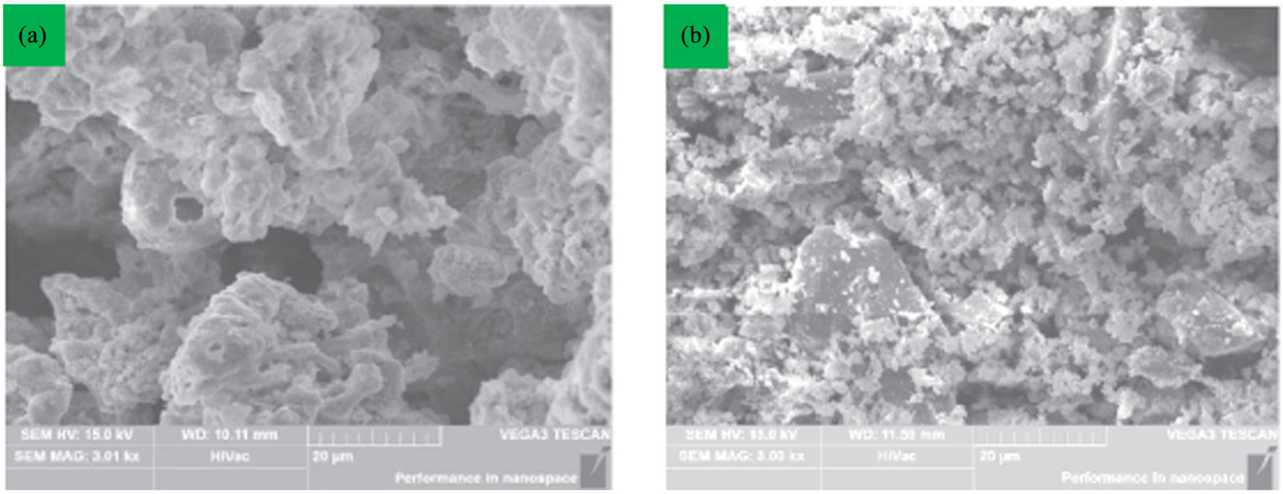

Figure 6: SEM of (a) coarse SSA and (b) fine SSA [33].

Table 1: Chemical composition of SSA

Reference	[24]	[35]	[27]	[29]
SiO_2	12.4	39.3	24.1	14.99
Al_2O_3	14.9	19.09	6.69	2.57
Fe_2O_3	7.4	12.48	12.6	11.14
MgO	2.6	1.89	3.90	0.34
CaO	31.3	10.12	22.2	5.36
Na_2O	—	1.26	—	—
K_2O	—	1.76	3.22	—

increased in its comparative proportion in the leftover matter of the burning method [36]. This demonstrates that the combustion of sewage sludge at temperatures up to 600°C increases the silicon (S) proportion of the SSA, which may be seen as an operating mineral addition to composites. XRD examination further validated the chemical contents of SSA, as shown in Figure 7. According to the XRD pattern, the major components of SSA were portlandite, calcite, and weddellite, with tiny quantities of quartz.

4 Durability

Concrete durability is the capacity of concrete constructions to withstand wear and tear and preserve their original characteristics throughout time. To maintain the durability of the construction and reduce maintenance costs, durability is an essential component of concrete performance. The following sections discuss different

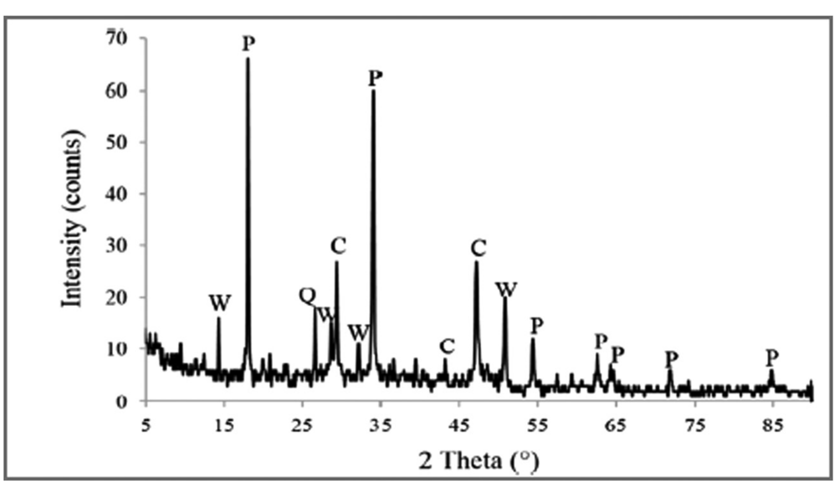

Figure 7: X-ray diffraction of SSA [18].

durability parameters of concrete with the inclusion of sewage sludge.

4.1 Porosity

Porosity often has a considerable influence on the physical characteristics of a substance. Mortar is a porous solid whose characteristics are determined by the chemical reactivity of its ingredients [37]. When cement and ash solution in water are permitted to hydrate, the reaction results produce a cohesive blend that encircles the leftovers of non-hydrated particles. Even after the predetermined hardening interval, the hydration process may continue for an extended time, and the matrix maintains a portion of its porosity throughout this time [38]. The partial substitution of cement with SSA increased the overall permeability of the reference mixture, according to the findings as presented in Figure 8. For instance, replacing 10 and 15% of OPC with SSA enhanced the overall porosity of the mixture by about 5.2 and 9.6%, respectively. SSA with 20% and 30% in cause to enhanced the porosity of the reference mixture by 18.0 and 22.4%, respectively [35]. Fine particles of wood ash generate a greater fraction of holes in the capillary range and a greater open porosity, according to the data [39]. The greater porosity of SSA may be attributed to its porous character. The results indicate that the greater the maximum size of recycled aggregate, the more likely it is that the recycled aggregate would improve the water absorption of the combination, even when extra water is added, as predicted. Increased water absorption by recycled concrete aggregate may lower the quantity of water/binder, hence promoting the formation of the pore structure and reducing porosity [40]. Ahmad et al. found that the permeability increases with the amount of fly ash substitute and decreases as its fineness increases. According to the authors, reducing the particle size of cementitious materials boosted their reactivity [41]. The packing of small particles and the reactivity of fly ash have a combined impact on the reduction in pore structures [42,43]. Several studies also conclude that the pozzolanic material gives more dense concrete due to the filling action [44–47].

4.2 Void index and water absorption

Figure 9 illustrates that the addition of SSA to concretes causes a small reduction in void ratio and water absorption. This characteristic is ascribed to the refinement of pore structure in these concretes as a result of the presence of a thin percentage (less than 150 µm) of waste grains [48]. The rate of capillary water absorption in combinations including both recycled aggregate and 20% rice husk ash decreased by an average of 55%, according to Cecconello et al. who examined mixes containing both recycled aggregate and rice husk ash to normal concrete. This result may be ascribed to a synergistic interaction between the pozzolanic reaction of rice husk ash and the decreased effective w/c ratio caused by the recycled aggregate's water absorption from the mix. These combined actions result in a change in the pore structure, with a decrease in size and an increase in deformability [40]. The water absorption of five various proportions of SSA concrete is investigated: 10, 15, and 20% of cement replacement by SSA had greater water absorption rates than the reference mix. The reference mixture whose water absorption rate is less than 10, 15, and 20% but

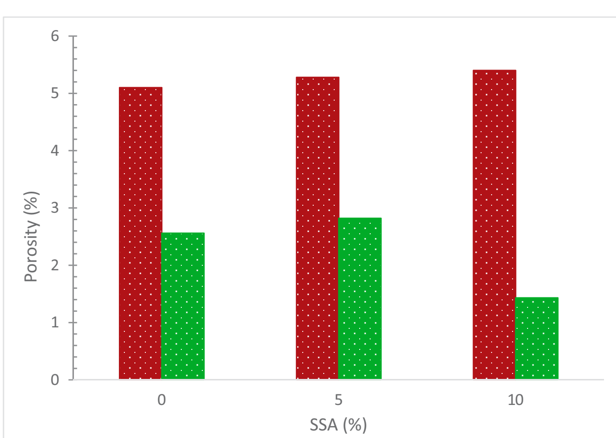

Figure 8: Porosity [35].

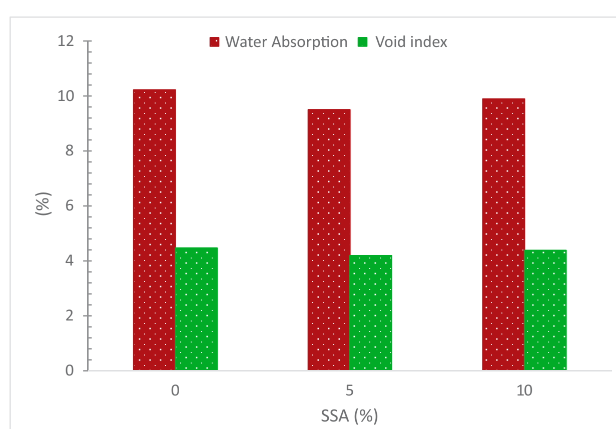

Figure 9: Water absorption and void index [48].

more than 5% cement replacement sample. It may be determined that 5% SSA concrete has more durability than the control sample; however, 10–20% SSA concrete has worse durability [49]. The hydration rate and product production were found to be highly dependent on the alkali concentration and water-to-binder ratio of combinations. Again, the wood ash concrete had a greater water need and a poorer mechanical strength. Nevertheless, a small increase in the hydration rates and a reduction in the setup time were noticed [50].

The results indicate that utilizing a sludge ash content of 5% or even 10% does not affect the capillary network of concrete. However, when 20% sludge ash is used, the capillarity water absorption coefficient almost doubles [51]. Udoeyo et al. examined the water absorption of concrete mixtures by adding varied amounts of waste wood ash as a substitute material. It was noticed that as the amount of wood ash substitution increased, so did water absorption. At a concentration of 5% wood ash, the water absorption rate was 0.4%; however, it increased to 1.05% at a concentration of 30% wood ash. However, these values are far lower than the maximum acceptable value of 10% for the majority of building materials [52].

4.3 Ultrasonic pulse velocity (UPV)

The UPV test is a prominent nondestructive method for evaluating homogeneity, quality, cracks, cavities, and flaws of the concrete. It may be used to estimate the interior structure of a material. With an increase in pulse velocity, it is possible to determine if the internal structure of a material is sound and dense. In the case of cement-based composites, it aids in evaluating the material's homogeneity. Over the first 28 days, the difference in the UPV rate is much larger than during the remainder of the testing period [53]. UPV traveling through a solid is impacted by its density, elasticity, and the presence of distinct phases within the material. A high UPV value indicates a greater compact mass [54], while a less UPV rate indicates a drop in the compaction of the cementitious blend as a consequence of an increase in the ash content. The UPV rate declined with SSA as shown in Figure 10. At 7 days, the reference blend UPV is 4.55 km/s and at 28 days it is 4.64 km/s. Meanwhile, the UPV values for SSA concrete were between 4.23 and 4.39 km/s at 5% SSA. The 5% SSA that was microwaved at a medium-high temperature in concrete had the greatest UPV rate, while the 15% SSA that was microwaved at a medium temperature had the lowest UPV rate. This demonstrated that microwave-heated concrete containing 5% SSA and cooked to a medium-high temperature exhibited a greater pozzolanic response than the control sample [55]. The UPV findings of mortars including 10% fly ash were comparable to the UPV results of mortars including 10% bagasse ash. The UPV readings decreased as the proportion of fly ash in the blends increased from 10 to 20%. The mortar with 20% fly ash had a lower UPV value than the mortars with 20% bagasse ash for 90 days, after which the mortar with

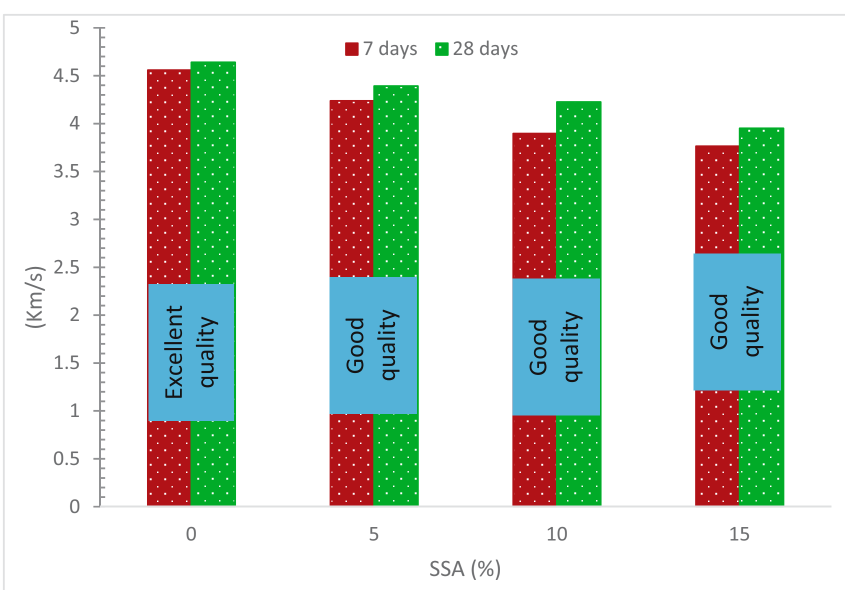

Figure 10: UPV [55].

20% fly ash had a greater UPV rate than the mortar with 20% bagasse ash. The pozzolanic reaction in the 5% SSA component that was cooked in a microwave to a medium-high temperature enhanced the concrete's density, homogeneity, and consistency. Consequently, the durability improved [55].

4.4 Shrinkage

Drying shrinkage refers to the volume loss of the concrete caused by the evaporation of water. If the concrete is not strong enough to withstand the tensile forces of this volume change during the curing period, it may fracture. As demonstrated in Figure 11, the drying shrinkage of the mortar enhanced in comparison to the control mortar with the addition of SSA. The increase in the amount of free water in the mortar may be the cause of the increased drying shrinkage [56]. In addition to the water in the past, the water absorbed by the holes of SSA elements produces free water. The free water in the holes of SSA fragments may evaporate during drying before being absorbed by cement hydration. Due to the higher surface area and smaller pore size of fine SSA, its detrimental influence on shrinkage was more than that of SSA. In addition, the increased quantity of mesopores in the fine SSA cement mortar results in a greater extent of shrinkage [33]. Also, according to Cecconello et al., when 20% rice husk ash is added to combinations including recycled concrete aggregate, shrinkage is reduced. This may be because increasing the quantity of the recycled concrete aggregate improves the contact between the pozzolan and the further elements of the combination, resulting in a decrease in the volume of pores and, consequently, a reduction in shrinkage when higher quantities are employed [40]. At 7 and 28 days, all concrete combinations demonstrated less free dry shrinkage than the reference mix, demonstrating that wood ash decreased the shrinkage. This was because the ash was essentially an aggregate filling, and the replacement of cement with ash decreased the paste proportion, hence minimizing dry shrinkage. There were no apparent connections between the proportion of wood ash substitute and the amount of shrinkage, showing that wood ash had a complex influence on shrinkage [50].

5 Microstructure properties

5.1 Pozzolanic activity

The pozzolanic reaction is the chemical interaction between reactive silica or alumina in the particles of secondary cementitious materials and calcium hydroxide generated by cement hydration in the presence of water at normal temperature Figure 12 shows the fixed lime concentration of silica fume and sewage sludge hydrothermally healed with lime at 100°C for 16 h. Both pozzolanic action and lime adsorption capability may contribute to the fixation of lime onto SSA. The fixed lime content changes with the sewage sludge burning temperature. Burning modifies the internal structure and reactive silica concentration of the sewage sludge. The fixed lime concentration reaches its greatest value at 800°C and then decreases significantly at 950°C. To retain the pozzolanic activity of the resulting ash, incineration of sewage sludge at 800°C may be desirable. From an economic perspective, it is advised that sewage sludge be burned at 800°C rather than at higher temperatures. The proportion of fixed lime in silica fume is

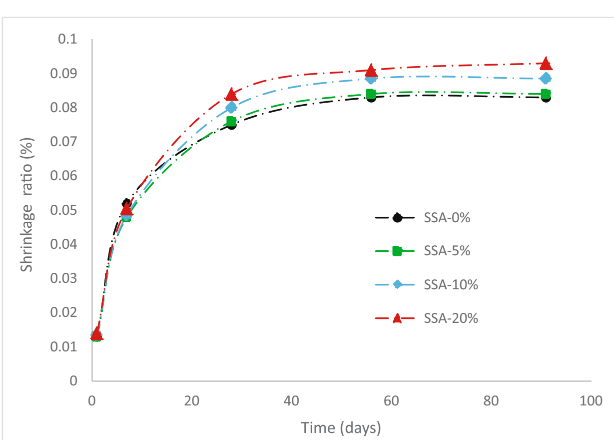

Figure 11: Shrinkage [33].

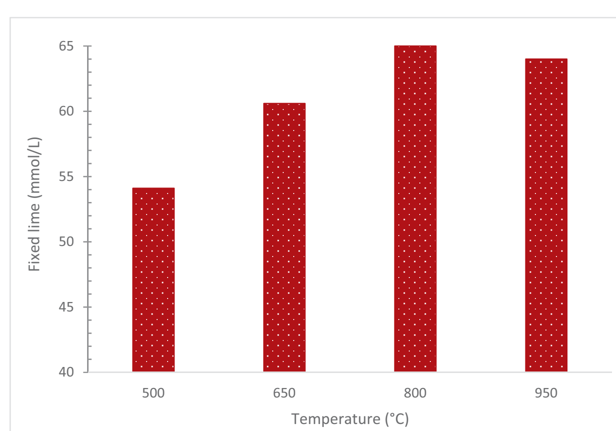

Figure 12: Fixed lime content at different temperatures [36].

much more than that of SSA. This is a result of the increased pozzolanic action of silica fume, which consists of amorphous micro silica particles with a relatively high surface area. Basumajumdar et al. found that fly ash combines with lime at room temperature in the presence of water to generate a compound having cementitious characteristics. The interaction between lime and fly ash creates calcium silicate hydrates, which contribute to the development of strength in bricks and blocks made from fly ash–lime. Lime combines with oxide components such as silica of ash to generate calcium silicate, etc., which are then hydrated in the presence of water to form a variety of hydrates [57]. These hydrates are accountable for the strength improvement in fly ash–lime compacts.

5.2 Heat of hydration

The heat of hydration in concrete containing pozzolanic materials as a partial substitute for cement is affected by several variables, including the ambient temperature in the curing environment, the quantity of cement, the quantity of ash, and the chemical composition and fineness of the cement and pozzolanic materials [58]. Figure 13 shows the findings of the rate of heat production for cement mortars containing SSA in proportions of 0, 2.5, 5, 7.5, 10, and 20% of the cement mass. The findings indicate that an increase in the quantity of ash reduces the maximum value of the initial peak of heat flow and delays its appearance when compared to a reduction in ash content. Figure 13 depicts the impact of the addition of SSA on the progression of the hydration process. The formation of a second peak may be attributed to the activity of the SSA in samples of cement mortar with a greater SSA concentration since the second peak has a higher temperature. In addition, when SSA is applied to heat curves, an expansion of the acceleration period and a transfer of the initial heat peak maximum to later dates are seen.

The SSA mortar requires longer heating than the control cement mortar to achieve the initial peak of heat generation rate. The hydration interaction between the cement and water generates heat, hence an increase in the cement content will increase the heat of hydration. As a result of a delayed hydration process, replacing cement with fly ash, according to research, often reduces heat release. The smaller average particle size in cement leads to a larger surface area, which in turn boosts hydration processes and facilitates the release of heat. Cement with a higher proportion of C_3A and C_3S will generate more heat since these compounds are engaged in the first phases of hydration [59]. The highest value of the first peak for mortar with 2.5% SSA is 4.65 J/g/h (at 15.28 h). Considering the second peak of heat flow, an increase in the quantity of ash causes an increase in the second peak: 4.98 J/g/h for cement mortar containing 2.5% SSA (at 31.25 h) and 6.88 J/g/h for cement mortar containing 20% SSA (at 34.52 h). The extent of disintegration of the tested material relative to the particle size may influence

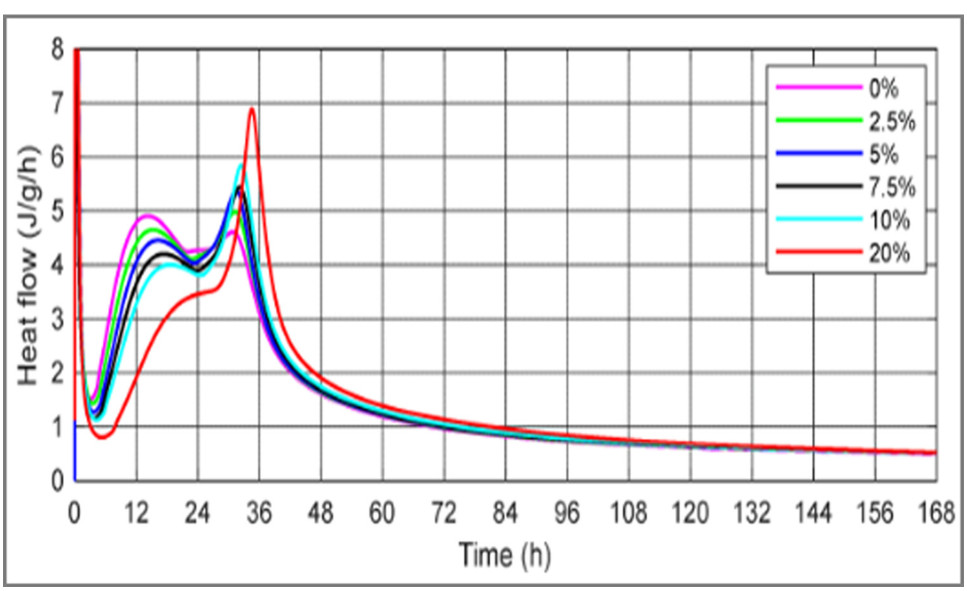

Figure 13: Heat flow [28].

the dissolving rate, involving the rate of production of chemical combinations in the composition of hydrating OPC, which may in turn influence the heat of hydration. Tests using isothermal calorimetry revealed that the addition of SSA might lengthen the induction time of cement hydration and affect the hydration frequency during the speeding-up period.

5.3 Scanning electron microscopy (SEM)

A different technique is used to study the internal property of materials such as SEM [60,61]. Chang et al. conducted a study on the morphological structure to determine the effects of SSA on the microstructures of mortar. Specimens taken from the center region of mortar samples were investigated using SEM with a focus on monosulfoaluminate crystals and CSH gel hydrates. Figure 14 displays SEM images of samples that were cured for 28 days and included varying levels of sludge ash. Sludge ash was utilized to substitute some of the OPC, which caused the CSH gel to become relatively thin and exhibit weak agglomeration. There were additional smaller monosulfoaluminate crystals to be noticed. This suggests that sludge ash interfered with hydration and crystallization development, decreasing the compressive strength of the mortar specimens [62]. They also found that an aggregate combination with a larger amount of sewage sludge had more open pores and a looser aggregate matrix. This is because sewage sludge has a high CaO and organic content but a low SiO_2 level [18]. According to Tantawy et al., silica fume is mostly made up of amorphous micro silica particles with a relatively high surface area when compared to ash made from sewage sludge. This might demonstrate that silica fume has more pozzolanic activity than SSA [36].

Figure 15 provides examples of SEM images without SSA. Crystals of ettringite have been found in cavities, including air voids. The holes weakened the strength and endurance of the concrete. According to a study, ettringite crystals may create fissures and the growth of already-existing ones due to the pressure that the reaction's positive volume differential places on the fracture walls [63].

Examples of SEM images with and without SSA are shown in Figure 16. In the planes that were seen, there were no indications of degradation, such as gaps surrounding the aggregates caused by cement paste expansion or fissures in the aggregate filled with a gelatinous

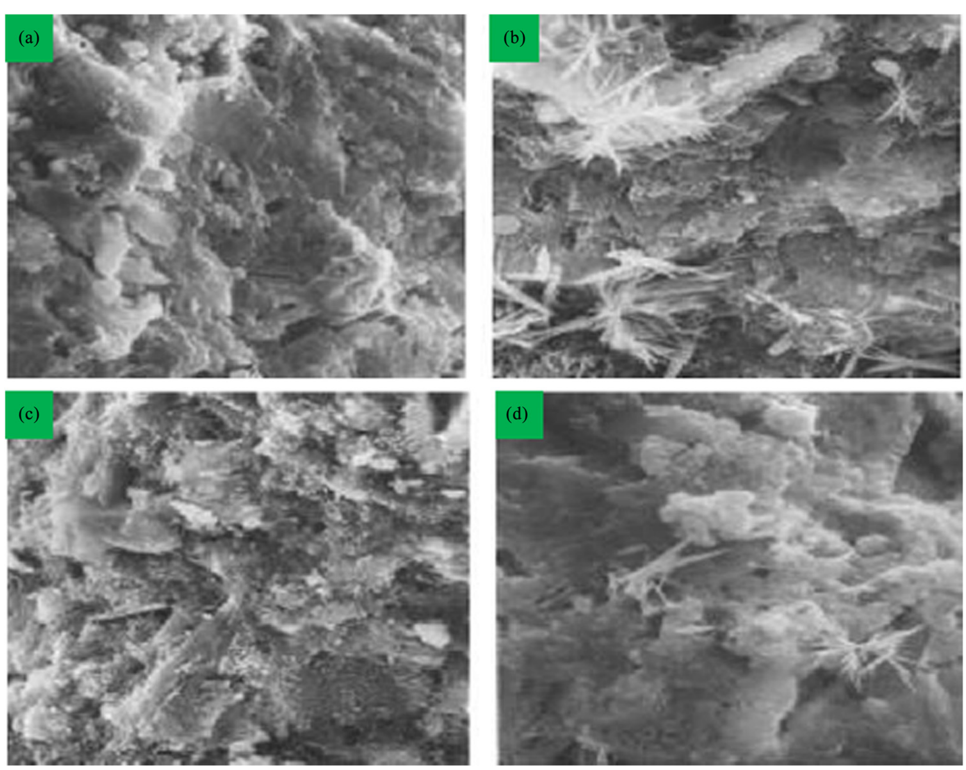

Figure 14: SEM: (a) 0%, (b) 10%, (c) 20%, and (d) 30% [62].

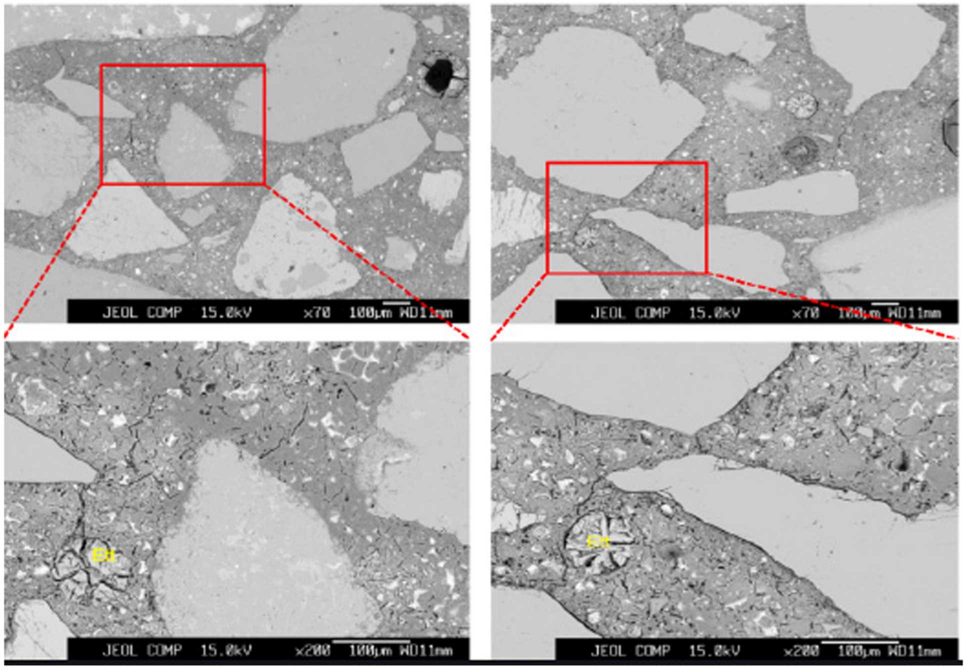

Figure 15: SEM without SSA [64].

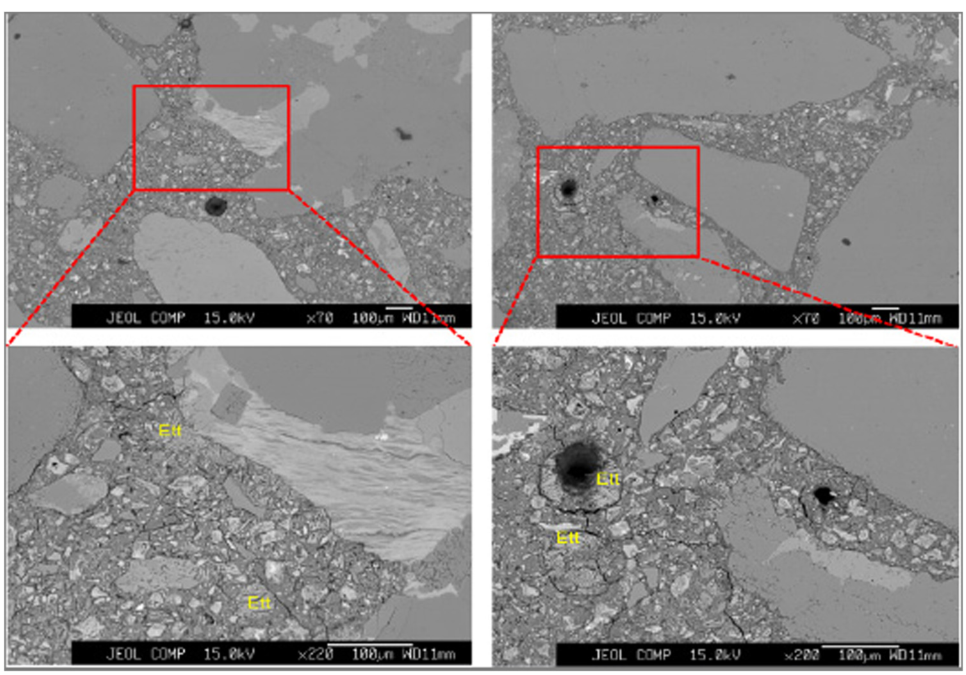

Figure 16: SEM image of concrete with SSA [64].

fluid. Denser microstructure results from the pozzolanic reaction of SSA. Additionally, the microstructure was enhanced by filling the gaps between the concrete with SSA. The filler effect of SSA and the coupled pozzolanic reaction result in a stronger microstructure, which ultimately improves strength and durability. Due to the high alumina content of SSA, the potential of delayed ettringite production was expected. In fact, several needle-like crystals could be seen in air spaces and other cavities. But further investigation revealed, which supported, the fact that the crystals were ettringite. Nevertheless, there were no indications that the crystals themselves were beginning to deteriorate. This demonstrates unequivocally that the danger of delayed concrete degradation due to ettringite production is not increased by the presence of SSA.

5.4 Thermogravimetric analysis (TGA)

By measuring the quantity of reacted lime and employing TGA and differential thermal analysis (DTA), pozzolanic activity may be identified immediately. Figure 17 displays the TGA and DTA patterns of sewage sludge. The best burning temperature was evaluated at three different temperatures (450, 550, and 650°C). The three temperatures were chosen to assess the potential emissions of components into the atmosphere during burning. The presence of a residual organic matter was confirmed at 450°C, and at burning temperatures of 550 and 650°C, about the same final composition of sludge mass was achieved. Due to the decreased energy usage, a temperature of 550°C was chosen to be employed in the calculations. During the process of combustion, none of the harmful components of the SSA were released into the atmosphere [35]. The research was also done on the raw sewage sludge using TGA and DTG. The weight loss in the temperature range of 50–130°C is because of the moisture and water absorption being expelled. Weight losses in the temperature ranges of 200–320 and 330–390°C are caused, respectively, by the combustion of complex nonvolatile organic matter and the release of volatile organic matter. This is because the sewage sludge is made up of a variety of hydrocarbon species with a broad range of boiling points [40]. The weight loss between 400 and 670°C is because of the combustion of fixed carbon collected by inorganic materials, the removal of structural water from the clay mineral, and the breakdown of carbonaceous matter found in the sewage sludge [36].

5.5 Fourier transform infrared spectroscopy (FTIR)

Figure 18 displays the spectra of silica fume and sewage sludge hydrothermally treated at 100°C for 16 h with lime. The spreading shaking of Si–O is attributed to the C–S–H absorption group at 970 cm^{-1} [65]. The absorption band caused by portlandite at 3,640 cm^{-1} falls to zero at 800°C and then increases at 950°C. This shows that the SSA processed at 800°C has more pozzolanic activity than at higher temperatures. Owing to its higher pozzolanic action with respect to SSA, portlandite's absorption group totally vanished when silica fume was hydrothermally treated with lime. The fractional carbonation of portlandite by ambient CO_2 may be attributed to the absorption group of carbonates at 1,463 cm^{-1}. This suggests that burning sewage sludge at temperatures over 800°C speeds up the manifestation of reactive silica, which may have a negative

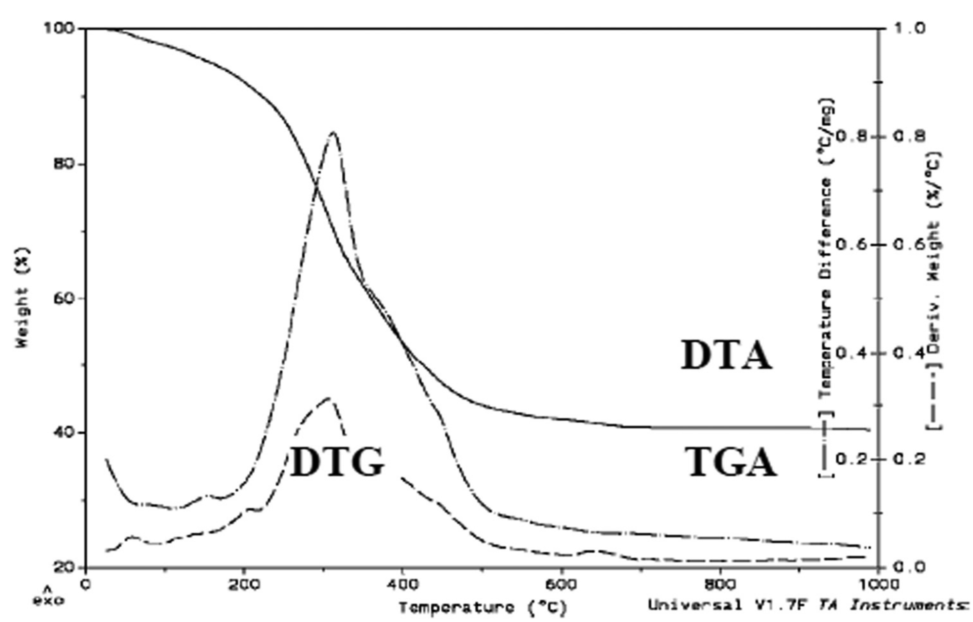

Figure 17: DTG and TGA curves [35].

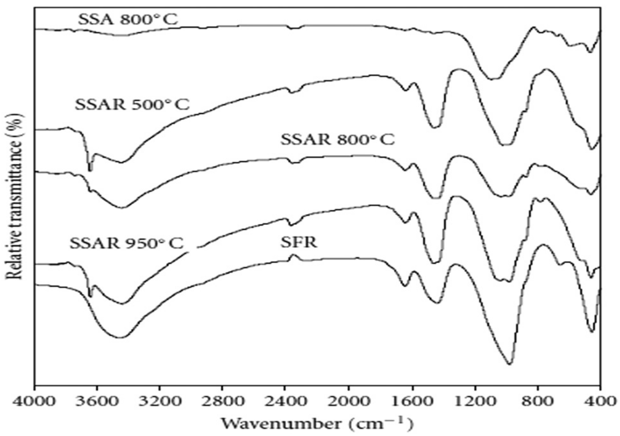

Figure 18: FTIR spectra [36].

impact on the pozzolanic action of the ash produced. High-intensity silica absorption groups are seen in silica fume [36]. The band area between 1,600 and 1,000 cm^{-1} shows increases in the Si–O–Si groups typical of quartz, while the band area between 800 and 500 cm^{-1} shows the equal spreading of the Si–O–Si and Al–O–Si groups that illustrate the formation of a reactive to semi-crystalline aluminum. The band area between 3,500 and 1,600 cm^{-1} shows the (OH^{-1}) bond extending and the (H_2O) sensations bending of attached water particles that they are trapped in (<500 cm^{-1}). It is noteworthy that over the band range region of 800–500 cm^{-1}, class F has a higher peak number than class C. This indicates that class F structural bonds (–Si–O–Al and –Si–O–Si) are more often formed than class C, as are CSH, CAH, and other compounds. Additionally, these outcomes are consistent with the chemical makeup of fly ash as found by the XRF study [66].

6 Conclusions

The use of byproducts with reduced embodied energy and carbon emissions has been suggested by sustainable development goals and guidelines. The suitability of ash from sewage sludge for use in concrete is a good option. In this study, we studied SSA as a building material. The key component of this review is the physical and chemical characteristics of SSA, its influence on durability qualities, and morphological structure analysis. The details conclusions are as follows:

- From the physical properties of SSA, it was confirmed that SSA has a porous and rough surface which affects concrete properties, particularly flowability.
- The chemical composition of SSA is similar to the OPC and hence SSA can be used as a cementing material.
- SSA enhanced the overall porosity and water absorption of the blend. The greater porosity and water absorption of SSA may be attributed to its porous character.
- The drying shrinkage of the mortar was enhanced in comparison to the reference mortar with the addition of SSA. The increase in the amount of water due to the porous nature of SSA in the mortar may be the cause of the increased drying shrinkage.
- The findings indicate that an increase in the quantity of SSA reduces the maximum value of the initial peak of heat flow. The decrease in the initial peak is due to the pozzolanic action which proceeds slowly.
- SEM results reveal that SSA improved the microstructure due to pozzolanic and filler actions.
- FITR and TGA results confirmed the pozzolanic action of SSA.

7 Recommendations

Although sewage sludge can be utilized in concrete due to microfilling and pozzolanic action which enhances concrete properties, the following area must be explored before the practical use of SSA in concrete.

- The SSA decreased the concrete flow properties due to its porous nature. The porous nature also adversely affects other properties such as hydration, shrinkage, etc. Therefore, the review recommends detailed studies to improve its flow properties. Decreasing the particle size overcomes its porous nature but detailed studies are required. Furthermore, decreasing the particle size improved its reactivity but detailed studies are required.
- No information is available on long-term durability with the substitution of SSA in concrete such as alkali–silica reaction, freezing/thawing action, and acid resistance. Therefore, the review also recommends detailed studies in these areas.

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