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Combined Use of Sewage Sludge Ash and Silica Fume in Concrete

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Abstract

The lack of adequate space for sewage sludge disposal has become a significant challenge in many countries. Landfilling and using sewage sludge as fertilizer in agricultural lands are the main methods for disposal. However, these methods can result in soil and groundwater contamination as well as heavy metal and microbial pollution in soil. An alternative disposal method is using sewage sludge ash (SSA) in concrete production. If the sludge ash is reactive, it can replace a portion of cement in concrete; otherwise, it can be used as a filler. In the present study, X-ray fluorescence (XRF) experiments were conducted to determine the elemental composition of sewage sludge. Then, the sewage sludge was incinerated, and XRF and X-ray diffraction (XRD) tests were performed on the resulting sewage sludge ash. The ash was utilized in different proportions in the mortar and concrete specimens, and compressive strength tests were conducted on the resulting specimens. The results indicate that using 20% SSA instead of cement resulted in a 25% reduction in compressive strength in concrete specimens. However, the combination of 10% silica fume and 10% SSA was the optimal combination to compensate for the reduction in compressive strength caused using SSA.

Keywords Sewage sludge ash, Silica fum, Compressive strength, Cement replacement, Recycling

1 Introduction

Sewage sludge is a by-product of the wastewater treatment process. The disposal of sewage sludge produced during sewage treatment has always been one of the main issues in modern societies and metropolises. The large amounts of accumulating sewage sludge in wastewater treatment plants, on one hand, and the lack of enough space for disposal, on the other hand, have increased concerns about the environmental conditions of this city. Currently, landfilling is generally used to dispose of the sludge generated in wastewater treatment plants(Kelessidis & Stasinakis, 2012; Lin et al. 2016). However, both methods can cause many destructive problems. The first method needs enough landfill space, resulting in soil and groundwater contamination. In contrast, the second method can permeate heavy metals and microbial pollution into the soil and result in health problems for humans and animals (Cyr et al., et al. 2007). Therefore, it seems necessary that some alternative methods be considered to dispo of sewage sludge.

One of the most efficient and, simultaneously, the most straightforward methods for this purpose is sewage sludge incineration. This process not only reduces the volume of sludge by up to 95% (as reported by Cieślik et al. 2015) but also decreases the amount of heavy metals and organic materials in the sludge (as confirmed by Alvarez et al. 2021, Hanein et al. 2022, and Lundin et al. 2004). The resulting product, known as sewage sludge ash (SSA), can be used for various applications. One of SSA's most notable and widely recognized applications is to be used as a partial substitute for cement in concrete

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production, attracting significant attention from the global community.

Cement is a critical ingredient in concrete production, and its presence directly impacts its mechanical and thermal properties (Kioumarsi et al. 2020, 2023). Production of one ton of cement emits a significant amount of CO_2, so up to 7% of the total amount of CO_2 is produced globally (Azarhomayun et al. 2022; Benhelal et al. 2013; Herisson et al. 2017). These, all taken together, obviously illustrate how the partial replacement of cement with SSA can benefit the disposal of sewage sludge and decrease cement production and, subsequently, CO_2 emission (Farahzadi & Kioumarsi, 2023). The density of SSA-based concrete probably depends on the incineration temperature and causes a wax in density (Nakic et al. 2018; Salim et al. 2018). The massive sewage sludge production was about 5.3 million m^3 per year; it will be doubled in a few future years. It contains organic materials and toxic heavy metals, a global issue (Mariscal et al. 2004). However, with the evolution of industrial processes in pozzolanic activities, the incorporation of SSA and its components, such as SiO_2, AL_2O_3, Fe_2O_3, CaO, MgO, P_2O_5, which are produced through the combustion of sewage sludge as a means of reducing the CO_2 emissions (900 kg per ton of cement) and mitigating their environmental impacts (Istuque et al. 2019; Series, 2019).

An experimental investigation conducted in 1999 by Monzó et al. (Monzó et al. 1999) showed that 15% or 30% replacement of the cement with SSA does not significantly affect the compressive strength of cement mortar at 40 °C within curing periods of 3–28 days. Pan et al. (2003) determined that the workability of mortar mixtures incorporating SSA could be improved by regulating the fineness of the SSA particles. The study found that the compressive strength of the mortar was not influenced by the duration of grinding the SSA particles. In an experimental study in 2007, Cyr et al. (2007) showed that cement replacement with 25% and 50% SSA decreased the compressive strength of cement mortars but positively affected their compressive strength in the long term. Garcés et al. (2008) examined the compatibility of SSA with different cement types and concluded that the CEM II/B-M (V-LL) 42.5R cement is the best choice to use with SSA. In addition, the optimal percentage for enhancing compressive strength was found to be 10% replacement. However, it was noted that using superplasticizers could alleviate the detrimental impact of SSA on workability. Chang et al. (2010) investigated the chemical composition of SSA and used it in concrete. The results showed that using SSA caused a reduction in the compressive strength and workability of mortar. Lynn et al. (2015) found that SSA is suitable for concrete as fine or filler aggregates due to its irregular shape of particles which fall in fine sand size and silt in terms of the fraction.

Studies have shown that a rate of 8% SSA by weight had a negative effect on the ductility of ultra-high strength concrete (UHPC) while inhibiting the initial hydration of cement. Despite this, pozzolanic reactions improved in the later stages of curing. The addition of SSA was observed to impact the pore structure of UHPC, resulting in an increase in cumulative pore volume and a decrease in large pore volume. Economic and environmental evaluations conducted by Xia et al. (2023) indicated that incorporating SSA in UHPC concrete could significantly reduce costs and environmental impact. The use of SSA in the cement mixture also resulted in a slight reduction in the flowability and flexural strength of UHPC, as evidenced by the 7-day and 28-day compressive strength tests. These tests showed a slow increase in the compressive strength of UHPC containing 10% SSA. In addition, Gu et al. (2022) reported that SSA also increased autogenous and drying shrinkage values. In addition, the use of SSA in the mortar was found to increase its compressive strength and decrease its water absorption rate. It is observed that the best compressive strength and water absorption rate results were in mortars containing 10% and 5–10%, respectively (Nazierah et al. 2015). Chen et al. (2018a) observed that the long-term compressive strength of concrete blocks was increased due to the pozzolanic activity of SSA and reported that a more significant amount of SSA in the binder led to an increase in drying shrinkage in the blocks. In another study, Tutur et al. (2019) studied the effect of the replacement of cement with rice husk ash (RHA) and sewage sludge ash combination on compressive strength for various proportions (10%, 20%, 30%, 40%, and 50%). The results showed that 10% cement replacement with SSA and RHA had the best effect on compressive strength. The management of the growing production of SSA has prompted the consideration of various solutions, including landfilling and use in agriculture, in addition to its use as a concrete ingredient. However, high costs and environmental concerns cause significant challenges to these methods (Cyr et al. 2007). As an alternative, incorporating SSA as an ingredient in concrete has been identified as a potentially effective solution (Cong et al. 2020). Overall, the literature indicates that SSA enhances the performance of mortar and results in an increase in concrete setting time (Ahmed & A. El-Kourd, 1989; Pinarli, 2000). In addition, previous research has explored the use of SSA in combination with other materials, such as slag and fly ash. Guo et al. (2023) found that the addition of 30% SSA reduced the flowability and compressive strength of the mixture, but the inclusion of 10% slag and 10% fly ash improved overall performance. Meanwhile, Shi et al. (2021) discovered that the use of river sediment as a foaming agent in ultra-light concrete improved its thermal and mechanical properties compared to conventional methods. He et al. (2021) investigated the impact of using modified sludge as a partial cement replacement in concrete, resulting in decreased drying shrinkage and increasing the width of the interface transition zone.

Using waste materials such as SSA is essential in terms of environmental aspects, but, as a reported disadvantage, it can reduce the mechanical properties of concrete. However, appropriate additives can be used in the concrete mix design to overcome this problem. For the first time, this study investigates the application of silica fume together with SSA. The main objective of the current paper is to evaluate the potential impacts of the partial replacement of cement with SSA in both mortar and concrete and determine an optimum content for combining SSA with silica fume to compensate for the possible compressive strength reduction in concrete. For this purpose, sewage sludge was taken from an urban wastewater treatment plant in Tehran City, and its elements were examined. Dewatered sewage sludge was incinerated, and ground and different contents of the obtained SSA were partially used to replace cement in mortar and concrete. To investigate their properties, various tests were conducted on mortar and concrete specimens, including SSA. Elements and crystalline phases of the SSA were determined. Pozzolanic activity of the SSA was investigated in both mortar and concrete specimens. The workability, durability, tensile strength, and compressive strength of the specimens were investigated. Since severe strength reduction was observed in the concrete specimens, different contents of SSA were used together with silica fume. An optimum percentage for silica fume was achieved to completely compensate for the strength reduction in concrete specimens.

2 Materials and Experiment Procedure

Obtaining SSA involves collecting dry sewage sludge from a treatment plant, followed by drying it in a heater for 24 h to eliminate moisture. The dried sludge is then sieved through a number 50 sieve, resulting in a powder that is analyzed using X-ray fluorescence (XRF) to determine the presence of organic matter. Given the high levels of organic matter typical in urban sewage treatment plants, the sludge was heated in a furnace located in the foundry laboratory at 900 °C for 30 min to eliminate the organic matter and produce SSA.

To make SSA usable as a supplementary cement material in concrete, it must go through sieve No. 200. The resulting ash from the furnace had larger particle sizes, so a centrifuge was utilized to reduce it to a suitable size for concrete reaction. The ash was spun in the machine for 2 h at 100 rounds/minute (rpm) to pass through sieve No. 200.

2.1 Materials

This study used type II Ordinary Portland Cement (OPC) to make all the specimens. According to ASTM C114 (2009), the chemical analysis results of the cement used are shown in Table 1. In addition, bulk density tests were performed on fine and coarse aggregates following ASTM C 128-88 (ASTM 1989) and ASTM C 127–88 (ASTM C 127-88 2001). The physical properties of the aggregates can be seen in Tables 2 and 3. Moreover, corresponding gradation curves are provided in Fig. 1.

Sewage sludge was taken from an urban wastewater treatment plant west of Tehran, where dry sewage sludge

Table 2 The test of specific gravity and water absorption of fine aggregate

Relative weights in the dry state (gr/cm^3)	2.029
The relative weights in the dry saturated state (gr/cm^3)	3.39
Apparent specific gravity (gr/cm^3)	2.53
The water absorbed aggregate (%)	4.2
Plyometric weight with water up to line mark (gr)	656
Saturated specimen weight with dry air level (gr)	500
The weight of the meter with water and the specimen to the mark (gr)	942
Dry specimen weight in the oven (gr)	479.8

Table 1 The results of the Portland cement analysis

Element	Content (%)	Element	Content (%)	Element	Content (%)
SiO_2	22.7	Na_2O	0.27	SO_3	1.65
Al_2O_3	4.8	K_2O	0.81	IR	0.42
Fe_2O_3	3.8	Alkalinity equivalent	0.8	C_3A	6
CaO	64.2	CO_2	0.0	C_2S	30
MgO	1.8	C_3S	47	L.O.I	0.7
C_4AF	12				

Table 3 The test of specific gravity and water absorption of coarse aggregate

Relative weights in dry state(gr/cm^3)	2.18
The relative weights in the dry saturated state (gr/cm^3)	2.27
Apparent specific gravity (gr/cm^3)	2.38
The water absorbed aggregate (%)	3.8
Saturated specimen weight with dry air level (gr)	1000
Saturated specimens weight immersed in water (gr)	559
Dry specimen weight in the oven (gr)	192.6

is the outcome of the treatment process, as shown in Fig. 2.

The sand used was in accordance with the standard sand suggested in ASTM C33 (2003). As previously mentioned, some concrete mix designs included the addition of silica fume, the results of which are shown in Table 4. In addition, as discussed earlier, using SSA decreases the workability of concrete; thus, superplasticizers were added to some of the specimens to maintain a consistent slump.

2.2 Mixture Proportioning and Specimen Preparation

2.2.1 Mixture Proportioning of Mortar

The pozzolanic activity of SSA should be measured before using it as a partial replacement for cement. For this purpose, specimens with different contents of SSA can be compared with a free-sludge specimen (i.e., the specimen which contains only Portland cement as a binder); therefore, seven mix designs were considered to evaluate the compressive strength of 50 mm cubic mortar specimens according to the ASTM C109 (2008). Details of the mix designs are provided in Table 5.

As seen in this table, the ratio of standard sand to cement was considered different such that all the mortar specimens could reach the same consistency.

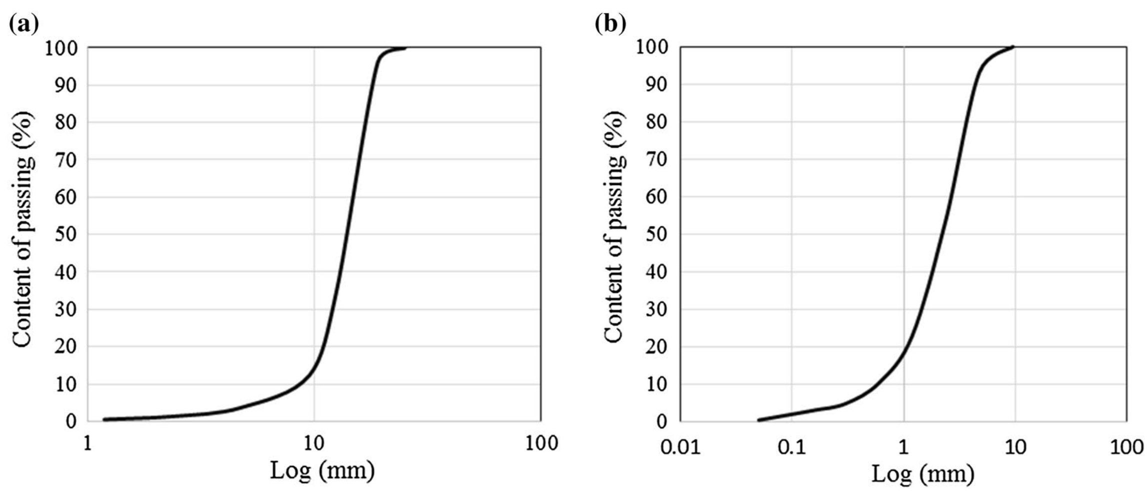

Fig. 1 Curve natural grain segments: **a** fine aggregate and **b** coarse aggregate

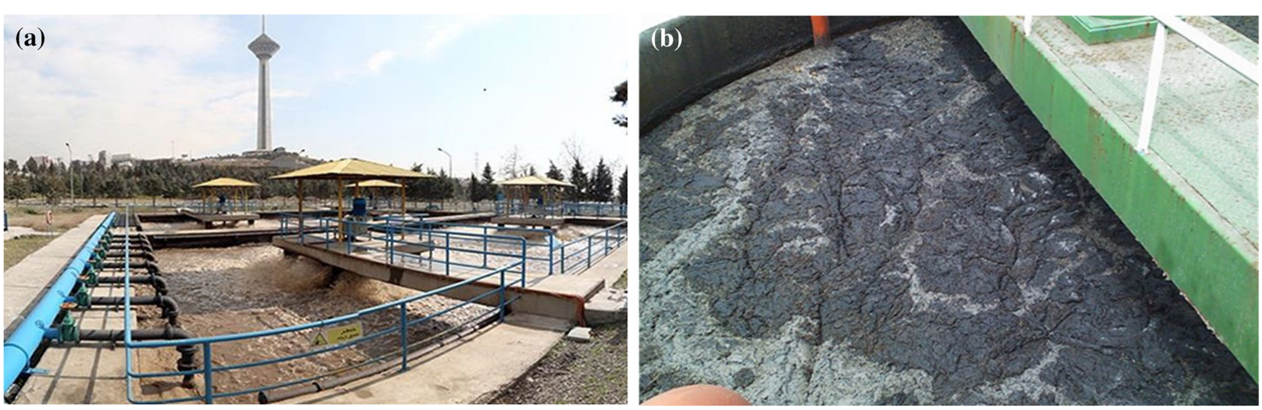

Fig. 2 Wastewater treatment plant: **a** activated sludge process, and **b** dry sewage sludge

Table 4 Chemical analysis results of silica fume

Element	Content (%)	Element	Content (%)
Na_2O (sodium oxide)	–	SiO_2 (silicon dioxide)	86.18
K_2O (potassium oxide)	–	Al_2O_3 (aluminum oxide)	1.44
TiO_2 (titanium dioxide)	–	Fe_2O_3 (ferric oxide)	0.2
P_2O_5 (phosphorus pentoxide)	–	CaO (calcium oxide)	3.06
ZnO (zinc oxide)	–	MgO (magnesium oxide)	1.32
Mn_2O_3 (manganic oxide)	–	SO_3 (sulfur trioxide)	0.337
Sulfide sulfur	–	Loss on ignition	1.15

Table 5 Mix design of mortar specimens

Mix design no	Water (gr)	Cement (gr)	SSA (gr)	Sand (gr)
1	242	500	0	1350
2	242	475	25	1350
3	242	450	50	1350
4	242	425	75	1350
5	265	400	100	1350
6	270	350	150	1350
7	280	250	250	1350

2.2.2 Mixture Proportioning of Concrete

The mix designs of concrete specimens, both with and without silica fume, are presented in Tables 6 and 7. These mix designs were provided following ASTM C192/C192M (2009). The ratio of w/c was 0.6 in all the specimens. 250 kg cement was used to make the concrete mix designs since it could exhibit possible reductions in the strength of concrete specimens. The volume of mix design, initial water, and the amount of aggregates is 60 kg/m^3, 9 kg/m^3, and 111 kg/m^3 in Table 6, respectively. These values are equal to 20 kg/m^3, 3 kg/m^3, and 37 kg/m^3 in Table 7. According to previous research (Ajileye, 2012; Hussain & Sastry, 2014; Suda & Srinivasa Rao, 2020), it has been found that the optimal percentage for incorporating SF in concrete is typically around 10%. Therefore, in this study, a 10% SF content is utilized.

2.2.3 Specimen Preparation

The dry materials were added to a mixer and allowed to mix uniformly. The amount of sludge powder was used as a replacement for cement and then poured into the mixer. After adding dry materials and mixing them for two minutes, the water and superplasticizer lubricant was added. Then the mixing of water with materials continued until the mixture was prepared.

Table 6 Concrete mix designs without silica fume

Mix design no	Cement (Kg/m^3)	Superplasticizers (Kg/m^3)	SSA (Kg/m^3)	Water (Kg/m^3)	Sand (Kg/m^3)	Gravel (Kg/m^3)
1	15	0	0	11.62	66.6	44.44
2	14.25	0	0.75	11.65	66.6	44.44
3	13.5	0	1.5	11.92	66.6	44.44
4	12.75	0.025	2.25	11.85	66.6	44.44
5	12	0.05	3	11.75	66.6	44.44
6	10	0.075	5	11.75	66.6	44.44

Table 7 Concrete mix designs with silica fume

Mix design no	Cement (Kg/m^3)	Superplasticizers (Kg/m^3)	SSA (Kg/m^3)	Water (Kg/m^3)	Sand (Kg/m^3)	Gravel (Kg/m^3)
7	4.5	0	0	3.96	22.2	14.8
8	4	0.03	0.5	3.96	22.2	14.8
9	3.5	0.045	1	3.96	22.2	14.8
10	3	0.06	1.5	3.96	22.2	14.8

2.3 Experiment Procedure

2.3.1 X-Ray Fluorescence (XRF)

The X-ray fluorescence (XRF) test is widely used for the elemental analysis of materials. The dewatered sewage sludge obtained from the treatment plant was placed into an oven for 24 h until the remaining moisture was taken. Then, the sludge was passed through sieve No. 50, and finally, the XRF test was performed on the specimens.

2.3.2 Sludge-Burning Incinerator

After conducting the XRF test, considerable amounts of organic materials were seen in the dewatered sludge, which was predictable since the sewage sludge had been taken from an urban treatment plant. Therefore, to reduce the amount of organic materials and the potential disadvantages of the dewatered sludge, it was incinerated in a sludge-burning incinerator for 30 min at 900 °C. Then SSA was obtained, as shown in Fig. 3. After incineration, another XRF was also performed on SSA to evaluate the possible changes in its elements.

2.3.3 Powdered X-Ray Diffraction (XRD)

Powdered X-ray diffraction (XRD) test was also conducted on the specimens to identify the crystalline phases of SSA. This method of testing utilizes X-rays, directing the beam toward the specimen and measuring the scattered intensity of the X-rays as a function of their outgoing direction. The data obtained are then analyzed. This test was carried out using an X′pert diffractometer (see Fig. 4) with generator tension and current of 40 kV and 40 mV, respectively. The angular range of $8–90^\circ$ 2θ in a step interval of 0.02° and a scan speed of 1.5°/min were adopted throughout the test in which θ is the angle between the radiation beam and its reflection.

Fig. 4 X′pert diffractometer conducting XRD test

2.3.4 Centrifuge

Using SSA in the mortar and concrete specimens results in lower pozzolanic activity and higher water demand which can be overcome by grinding (Pan et al. 2003). Therefore, SSA was passed through a No. 200 sieve, and then the particles were crushed into a centrifuge for 2 h with a speed of 100 rpm, as depicted in Fig. 5.

2.3.5 Workability

The workability of concrete was measured by slump test according to the ASTM C143 (2008), whereas the workability of mortar was determined by the flow table test based on the ASTM C230/C230M-20 (2020).

2.3.6 Water Permeability

The durability of concrete depends mainly on the difficulty of water penetrating the porous network of concrete. Therefore, the water permeability test was performed following BS EN 12390–8 Standard test method (BS EN 12390–8 2000) to evaluate the durability of

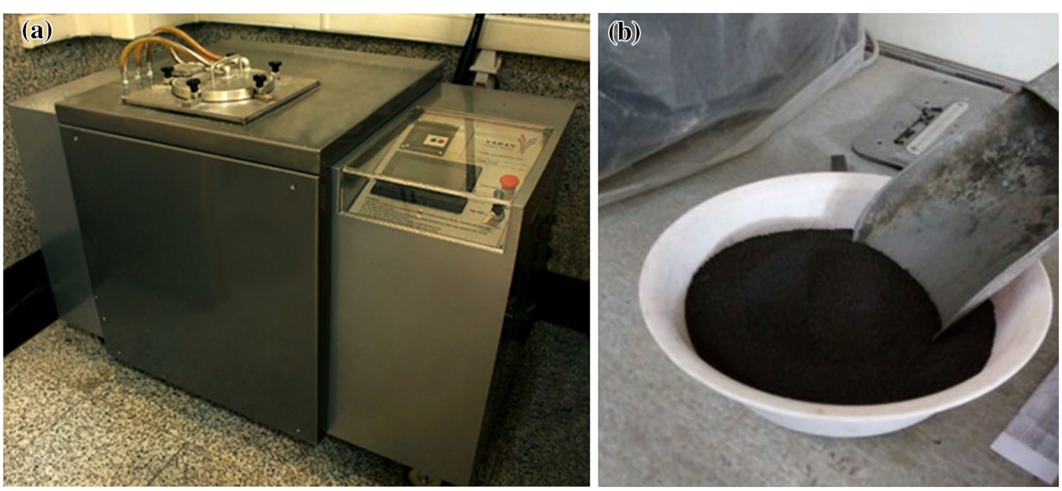

Fig. 3 Sludge burning process: **a** electric sludge burning incinerator and **b** obtained sewage sludge ash (SSA)

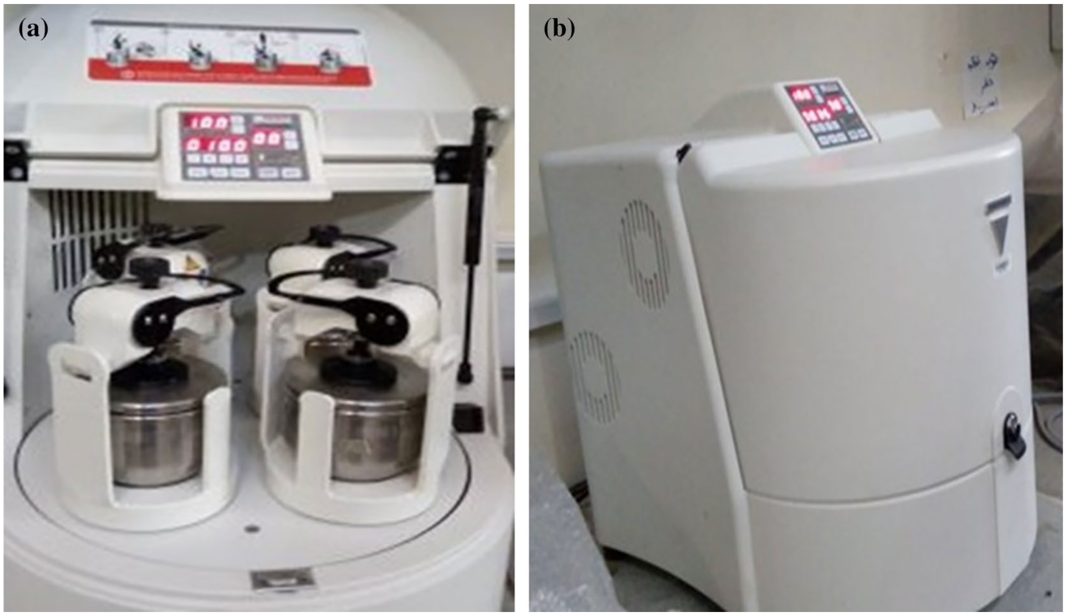

Fig. 5 **a** digital centrifuge and **b** rotating and crushing SSA

Fig. 6 Semi-cylindrical specimens in water permeability test

concrete. In this test, three semi-cylindrical specimens (see Fig. 6), including mix designs 1 to 6 (according to Table 7), were tested after 56 days. After taking the specimens out of the water tank, they were placed into an oven for 24 h to make them almost free of moisture. Then, the specimens were exposed to high water pressure for three days. Finally, the specimens were loaded to fail, and the penetration depth of water was measured.

2.3.7 Tensile Strength

The Brazilian tensile test was accomplished following ASTM C496 (2004) to examine the tensile strength of concrete specimens. For this purpose, two 30 × 15 cm cylindrical specimens of each mix design were tested at the ages of 7 days and 28 days.

3 Results and Discussion

3.1 Results of the Tests on SSA

3.1.1 XRF

As mentioned previously, two XRF tests were conducted in this research. The first XRF test was performed on the dewatered sewage sludge. The result of this test is presented in Table 8. As can be seen, the dewatered sludge contained relatively large amounts of organic materials before incineration.

The dewatered sludge was incinerated, and another XRF test was conducted to eliminate the organic materials and reduce the volume of the sludge. The result of this test is also presented in Table 9. As seen in this table, incineration appropriately reduced the amount of organic materials.

Suppose the main elements of the OPC in Table 1 are assumed Silicon dioxide (SiO_2), Calcium oxide (CaO), Aluminum oxide (Al_2O_3), and Iron oxide (Fe_2O_3), and they are compared with the elements of SSA in Table 9. In that case, it can be concluded that OPC and SSA cement contents are 95% and 65%, respectively.

Table 8 XRF test results on the dewatered sludge before incineration

Element	Content (%)	Element	Content (%)	Element	Content (%)
L.O.I	59.11	Na_2O	1.23	Zn	0.54
Al_2O_3	3.7	SiO_2	10.1	Zr	0.1
Fe_2O_3	2.12	SO_3	1.9	Cu	0.07
CaO	10.3	K_2O	0.81	Cl	0.21
MgO	1.86	P_2O_5	7.6	Sr	0.1
TiO_2	0.77	MnO	0.11		

Table 9 XRF test results on the SSA (the dewatered sludge after incineration)

Element	Content (%)	Element	Content (%)	Element	Content (%)
L.O.I	10.02	Na_2O	1.23	Zn	0.54
Al_2O_3	7.7	SiO_2	25.3	Zr	0.1
Fe_2O_3	6.12	SO_3	5.9	Cu	0.07
CaO	23.7	K_2O	1.81	Cl	0.21
MgO	2.86	P_2O_5	13.6	Sr	0.1
TiO_2	0.77	MnO	0.11		

Therefore, SSA could act as a moderate pozzolan in the mortar and concrete specimens.

3.1.2 XRD

XRD test was carried out to evaluate the crystalline phases of SSA. The results of the X-ray analysis are depicted in Fig. 7. The crystallinity percentage of the sample was determined from the X-ray analysis by calculating the ratio of the intensity of the crystalline peaks to the sum of the intensities of both the crystalline and amorphous phases. To determine the percentage, the area under the peaks corresponding to the crystalline sections was measured, and the total area under the spectrum was obtained by including both the crystalline and amorphous sections. The percentage of crystallinity was then calculated by dividing the area of the crystalline peaks by the total area and multiplying by 100. It should be noted that non-crystalline phases generally correspond to the increased activity of these materials. As can be seen, the dominant crystalline components of SSA were Magnesium cobalt oxide ($Mg_{0.19}Co_{0.81}O_4$), Calcium silicate oxide (Ca_2O_4Si), Iron oxide (Fe_2O_3), Sodium oxide (NaO_2), and Silicon oxide (SiO_2) with the percentage of 9, 24, 20, 7 and 3, respectively.

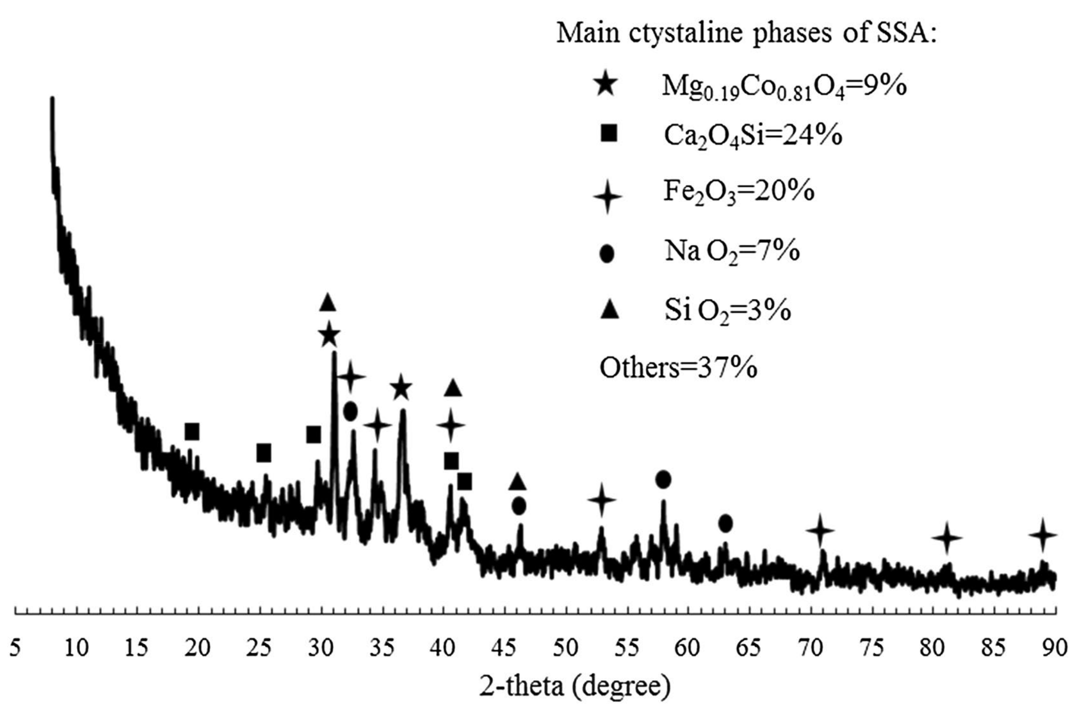

Fig. 7 Semi-quantitative analysis of SSA

Table 10 Results of the flow table test

Mix design no	SSA (%)	Excess water	Slump (cm)
1	0	0	21.08
2	5	0	20.5
3	10	0	20.95
4	15	0	19.25
5	20	23	21.74
6	30	28	21.26
7	50	38	19.57

3.2 Results of the Tests on Mortar

3.2.1 Flow Table

A flow table test was conducted to evaluate mortar workability. The results of this test can be seen in Table 10. In this table, the column of excess water indicates the amount of added water to the mortar mix designs to provide the same mortar consistency. According to previous research studies (Kwan & Wong, 2008; Nematzadeh & Naghipour, 2012), it has been found that adding additional water to achieve the same fluidity is necessary to compare the compressive strength of the specimens. As illustrated, in the contents of 5%, 10%, and 15% replacement of cement with SSA, the reduction in workability is relatively low. However, to achieve sufficient workability, the addition of water is required in the contents of 20%, 30%, and 50%. Comparing mix design no. 1 (i.e., control specimen in which no SSA has been used) with mix design no. 7, in which 50% of SSA was employed, it can be concluded that the workability of mix design no. 7 is reduced by 7% by adding 16% excess water. According to studies conducted by Chang et al. 2010 and Guo et al. 2023, it has been observed that the use of SSA in concrete can result in a reduction in workability.

3.2.2 Compressive Strength

A compressive strength test was carried out on the mortar specimens. This is important to note that initial water was adopted constant in all the specimens. However, to achieve the same mortar consistency, some excess water was added to mix designs no. 5, 6, and 7 (according to Table 10). The results of this test are shown in Fig. 8. In this figure, all the specimens in which cement content was replaced with SSA showed a reduction in compressive strength at 7 and 28 days. In comparison to other studies, Monzó et al. (1999) showed that the addition of 15–30% SSA has no significant effect on the compressive strength of mortar. On the other hand, Cyr et al. (2007) discovered that using 25–50% SSA could decrease the compressive strength of mortar.

This study focuses on the effect of pozzolan on concrete compressive strength during the early stages of curing, specifically within the time frame of 7–28 days. This period has been established in previous research as the time frame where the most remarkable changes in compressive strength occur (Boshoff & Combrinck, 2013; Cyr et al. 2007). Evaluating the effect of pozzolan on concrete compressive strength at 28 days provides a representative understanding of its impact on the strength of concrete

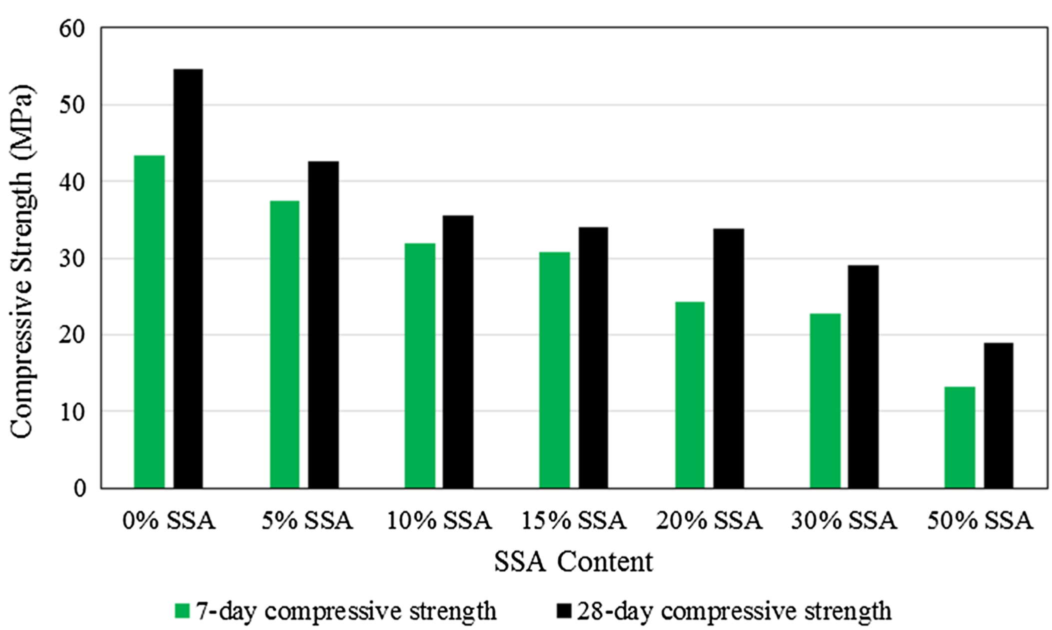

Fig. 8 Compressive strength of mortar specimens

after 90 days, as the effect at 56 and 91 days is relatively small compared to that at 28 days.

This reduction rate of compressive strength is relatively low, up to almost 15% of replacement. However, when higher amounts of SSA were used, a more significant reduction of compressive strength was observed, e.g., the 28-day compressive strength of the mortar specimens was reduced up to 65%, 47%, and 38% for the SSA contents of 50%, 30%, and 20%, respectively. Therefore, at ranges of more than 20%, replacing cement with SSA in mortar seems problematic.

3.2.3 Pozzolanic Activity of SSA

The ratio of 28-day to 7-day compressive strengths of mortar specimens was measured in different contents of SSA to evaluate the pozzolanic activity of SSA. As shown in Fig. 9, this ratio has increased in higher SSA contents. Hence, it can be concluded that the presence of the non-crystalline structures in SSA acts as a pozzolan in the long term and improve the strength of the mortar specimens.

3.3 Results of the Tests on Concrete

After obtaining favorable outcomes for cement replacement with SSA in concentrations ranging from 5 to 20%, the following step was to perform testing on concrete specimens. This involved conducting experiments on ten mix designs, including six without silica fume and four that utilized silica fume. The results of the tests on concrete specimens are described in this section.

3.3.1 Appearance Change

The first change in concrete after using SSA appeared in the appearance of the specimens. Fig. 10 shows six concrete specimens in which the content of sludge ash

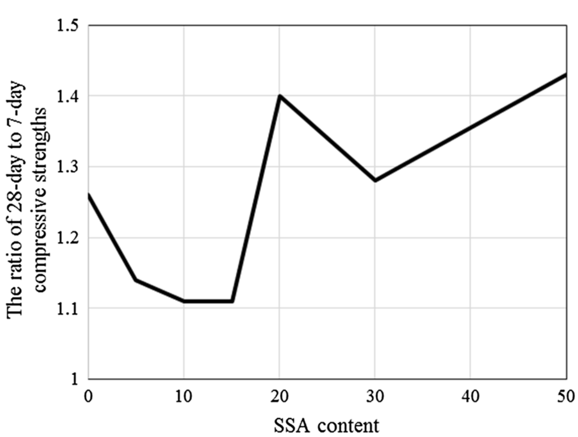

Fig. 9 28 to 7 days compressive strength ratios in different SSA contents

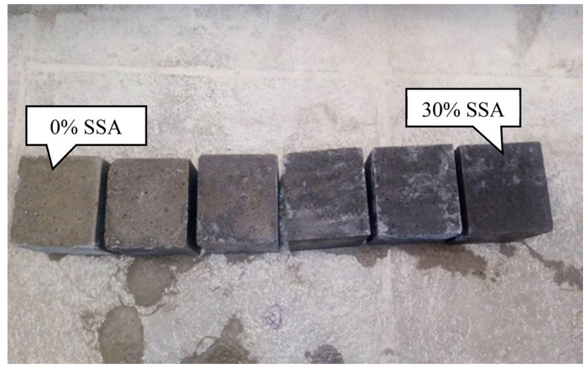

Fig. 10 Appearance change in specimens after adding SSA

was increased from left to right. In this figure, the control specimen, with no SSA, is shown on the left, while the specimen in which 30% of cement was replaced with SSA is shown on the right. As can be seen, the color of specimens has become darker as the content of SSA has increased, such that the specimen containing 30% SSA is entirely dark.

3.3.2 Slump

Table 11 shows the results of slump tests on the mix designs. All the mix designs were prepared to obtain the same slump value. As can be observed in the table, the value of the slump decreases when the amount of SSA increases. Therefore, the more SSA was utilized, the more superplasticizer was added. The main reason for this reduction in a slump can be attributed to the high water absorption of SSA. Adding SF, similar to SSA, decreased the workability of the concrete mix. However, when both SSA and SF are used together, adding more than 20% SSA increases the workability compared to the same mix without silica fume.

3.3.3 Permeability

The permeability test results are presented in Fig. 11. As demonstrated, concrete specimens containing SSA showed lower permeability than the free-sludge specimen (0% of SSA), so the mix design with the highest content of SSA (30%) had the lowest water penetration. This observation suggests that the particles of sewage sludge ash decrease its permeability when incorporated into the concrete. As shown in Fig. 11, the rate of permeability reduction in the 10, 20, and 30 percent substitutions is higher than the 5 and 15 percent. Using sludge ash in concrete reduced the permeability of the specimens, thereby increasing their resistance to water penetration. This characteristic is crucial in applications where concrete must exhibit water resistance. As seen in Fig. 11, adding up to 5% SSA has a minimal impact on the

Table 11 Slump values of all the mix designs

Mix design No	SSA and SF (%)	Superplasticizers (gr)	Ratio of plasticizers to cement %	Slump (cm)
1	0% SSA	0	0	11
2	5% SSA	0	0	10
3	10% SSA	0	0	10
4	15% SSA	0	0	9
5	20% SSA	50	0.33	9
6	30% SSA	75	0.5	7
7	0% SSA + 10% SF	0	0	9
8	10% SSA + 10% SF	30	0.6	10
9	20% SSA + 10% SF	45	0.9	11
10	30% SSA + 10% SF	60	1.2	10

SSA Sewage sludge ash, *SF* Silica fume

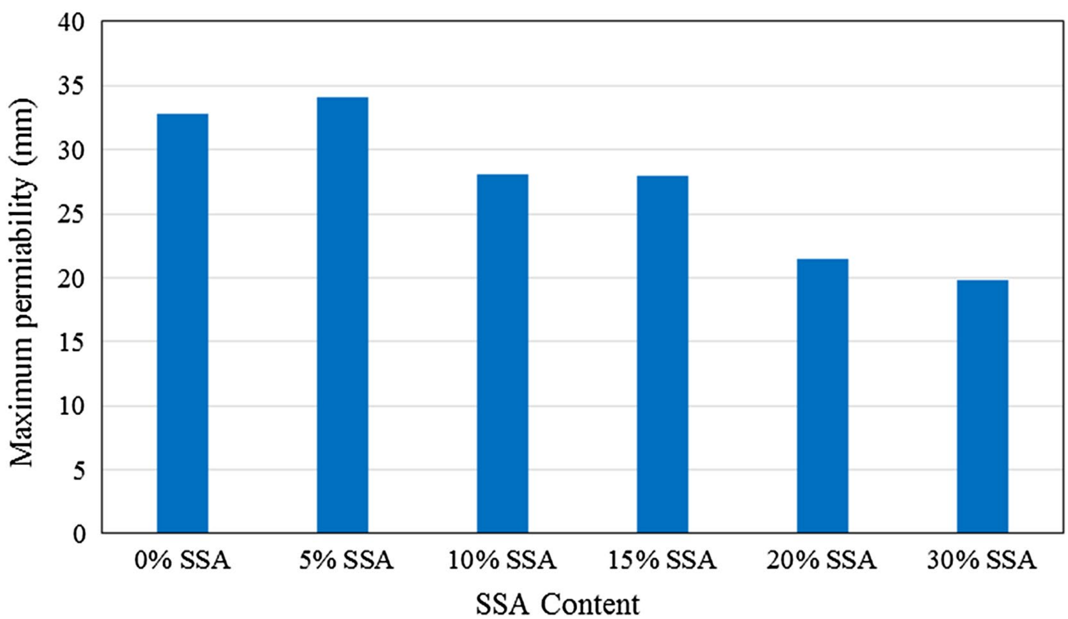

Fig. 11 Results of the water permeability test

permeability coefficient, which slightly increases. However, as the SSA content increases, the permeability coefficient decreases negatively, indicating that higher SSA content leads to lower water permeability. The formation of gels when adding more than 5% SSA can reduce capillary pores in concrete, leading to a decrease in the permeability coefficient.

3.3.4 Tensile Strength

Fig. 12 shows the tensile strength of concrete specimens in different contents of SSA. As seen in this figure, tensile strength is reduced by increasing the amount of SSA. However, the rate of this reduction is low such that the tensile strength reduction for specimens containing 5%, 10%, and 15% SSA is almost constant and equal to 12%.

Fig. 13 shows the impact of the pozzolanic activity of SSA on the tensile strength of concrete. This figure indicates that the highest ratio of 28-day tensile strength to 7-day tensile strength was for 10% and 30% replacement contents. This figure shows that SSA can improve the tensile strength of concrete in the long run.

3.3.5 Compressive Strength

3.3.5.1 Specimens Without Silica Fume Fig. 13 shows the compressive strength of mix designs no. 1 to no. 6, in which no silica fume was used. The compressive strength

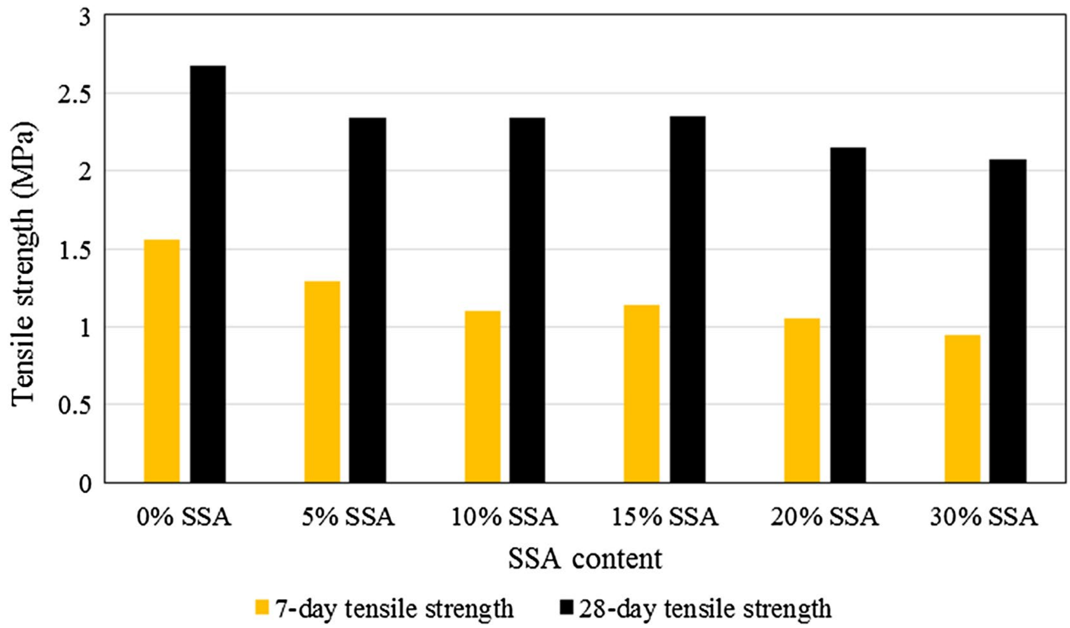

Fig. 12 Comparison of the tensile strength of concrete specimens containing SSA

of all the specimens containing SSA was reduced at ages 7 and 28 days. The reduction in compressive strength is 5%, 23%, 25%, 25.5%, and 30% for replacement contents of 5%, 10%, 15%, 20% and 30%, respectively. Fig. 14 depicts the ratio of 28-day to 7-day compressive strengths. As depicted, an increase in the percentage of SSA in the cement replacement led to an increase in the 28-day to 7-day compressive strengths ratio. Therefore, it can be concluded that some of the non-crystalline structures in SSA act as a moderate pozzolan in the long term and improve the strength of the concrete specimens. In a similar study, a decrease in the compressive strength of concrete was observed when 30% SSA was utilized (Guo et al. 2023).

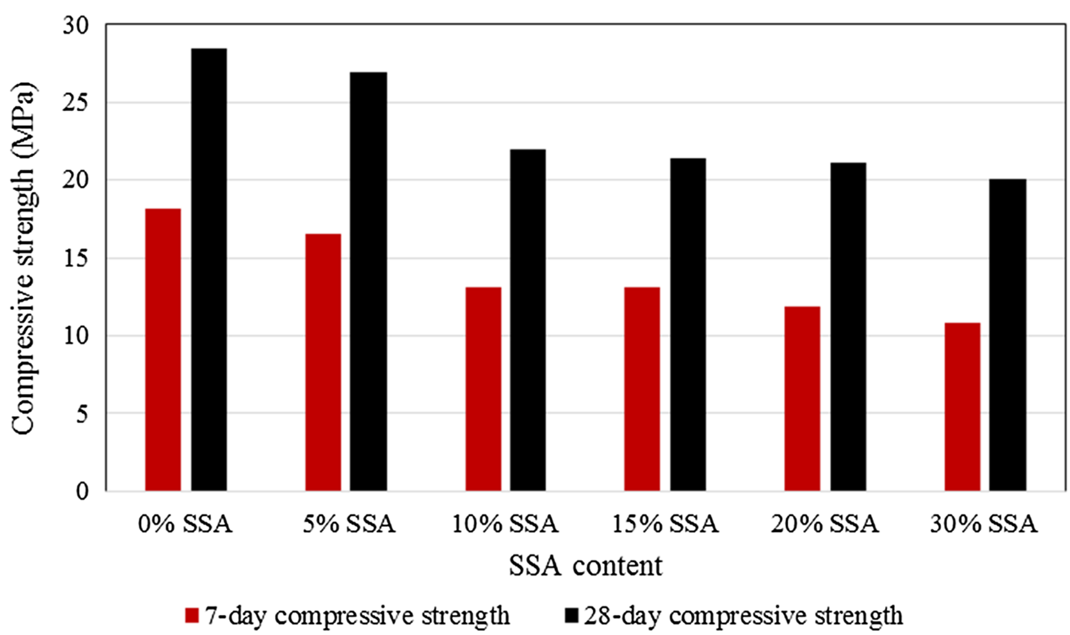

Fig. 13 Compressive strength of the concrete mix design without using silica fume

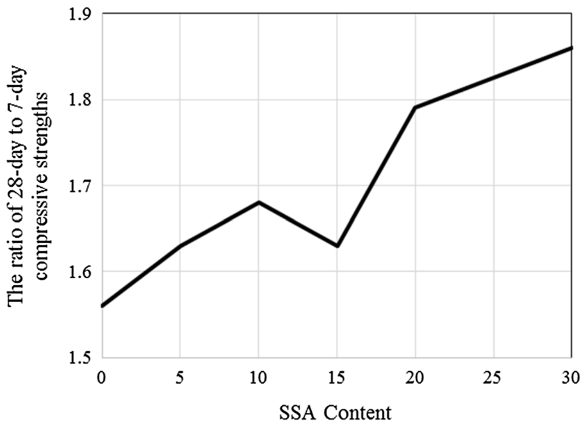

Fig. 14 Pozzolanic activity of SSA in concrete without using silica fume

3.3.5.2 Specimens with Silica Fume As observed in the previous section, the compressive strength of concrete dropped severely when the content of SSA increased. Hence, to compensate for the strength reduction, a constant content of 10% silica fume was used with SSA in mix designs no. 7 to no. 10. Fig. 15 illustrates the compressive strength of these mix designs from left to right, respectively.

This is important to note again that the amount of silica fume is constant and equal to 10%, and the content of SSA only varies between 0 and 30%. Therefore, a severe reduction in compressive strength can be observed in this figure by increasing the SSA percentage. The strength reduction equals 11%, 34%, and 45% left to right.

Comparing Fig. 13 with Fig. 15, it can be concluded that if 10% silica fume and 10% SSA are used together in concrete (the second column in Fig. 15), almost the same compressive strength with ordinary concrete in which no silica fume and SSA is used (the first column in Fig. 13), would be obtained.

In Fig. 16, the pozzolanic activity of SSA in the presence of silica fume is shown. As can be seen in this figure, in contrast to Figs. 14 and 17, in which the pozzolanic activity of SSA increased in higher contents of SSA, the maximum pozzolanic activity of SSA was achieved in 10% usage of SSA with silica fume. Also, SSA could not reach this value when used solely in mortar and concrete. Hence, the content of 10% is an optimum value for SSA, which can be used with silica fume in concrete to represent the same results with a free-sludge specimen.

In this study, we have collected data for 7 and 28 days. The focus is on the early-age effect of pozzolan on the compressive strength of concrete. Previous literature has indicated that the most significant changes in compressive strength occur between 7 and 28 days (Boshoff & Combrinck, 2013; Cyr et al. 2007). Moreover, these studies have shown that the influence of pozzolan on the compressive strength of concrete at 56 and 91 days is relatively minor compared to its effect at 28 days. Therefore,

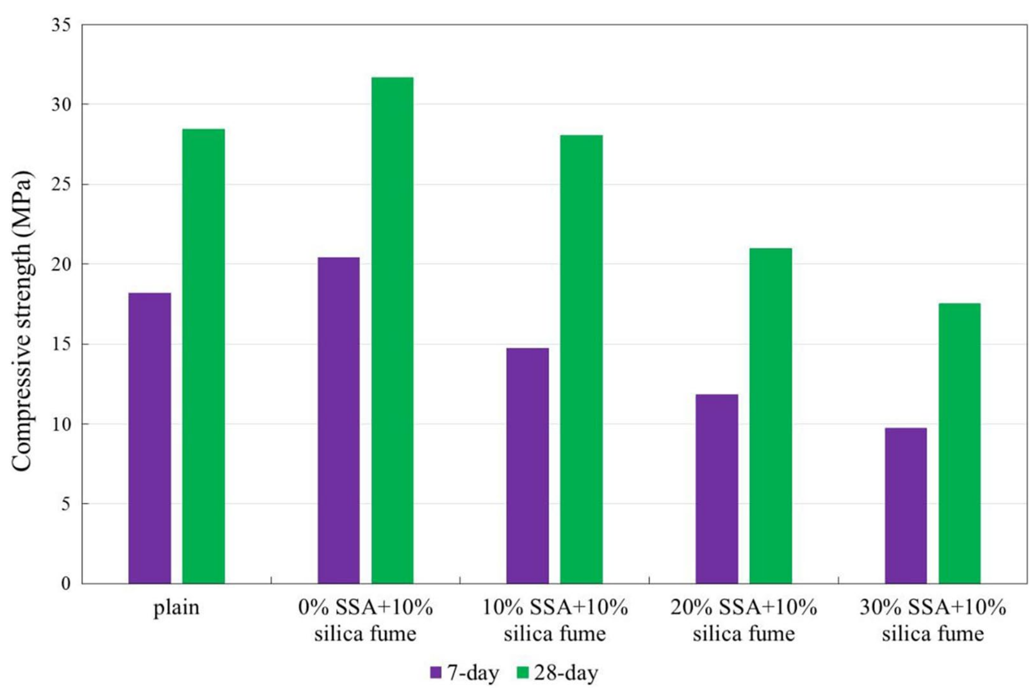

Fig. 15 Compressive strength of the concrete mix designs containing silica fume

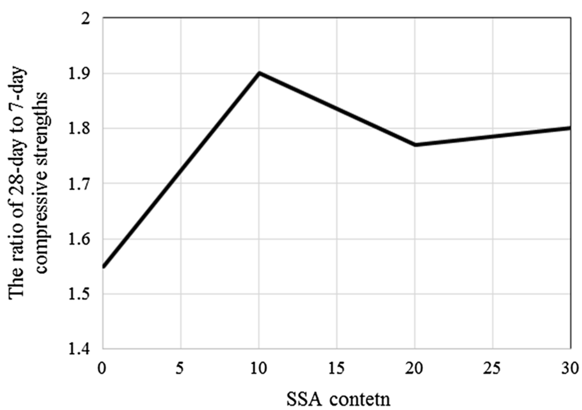

Fig. 16 Pozzolanic activity of SSA in concrete using silica fume

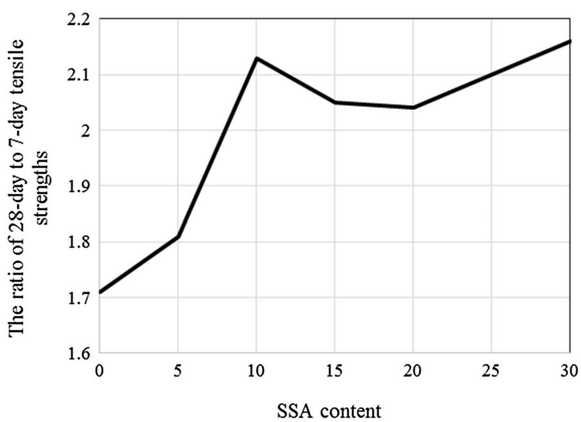

Fig. 17 28 to 7 days tensile strength ratios in different SSA contents

evaluating the effect of pozzolan on the compressive strength of concrete at 28 days is considered most appropriate, as it provides a representative understanding of its effect on the strength of concrete at 90 days.

4 Conclusion

This paper investigated the use of urban SSA as a partial replacement for cement in mortar and concrete specimens. First, the pozzolanic properties of SSA were analyzed using XRF and XRD tests. Then, different percentages of SSA were used to replace cement in the specimens, and some of the concrete specimens also included 10% SF to mitigate any potential adverse effects of using SSA. The results of various tests conducted on the specimens showed that:

- Adding SSA to the mortar specimens reduced the slump of the mixes.
- As the percentage of SSA replacement in cement increased, the color of the specimens became darker.
- Increasing the percentage of SSA replacement in cement resulted in a decrease in the permeability of the concrete. The rate of decline in permeability was more significant in the specimens with 10% SSA replacement compared to those with 5% replacement.
- The average reduction in the 28-day tensile strength of the concrete for every 5% increase in SSA was 4.83%. On the other hand, the 28-day to 7-day tensile strength ratio showed the highest values at 10% and 30% SSA replacement.
- Adding 10% SF to the control specimen increased compressive strength by 11.49%. However, higher amounts of SSA decreased compressive strength in both specimens with and without SF. Incorporating 10% SF mitigated the adverse impact of SSA on compressive strength by 4% compared to specimens without SF. The optimal balance in concrete compressive strength is likely achieved by combining 10% SF with 10% SSA.

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Author contributions
FA: experimentation, validation, software, formal analysis, investigation, writing original/final draft and writing review/editing. MH: formal analysis, investigation, review/editing and formal analysis. MK: supervision, project administration, conceptualization, validation, software, formal analysis, writing original/final draft and writing—review/editing. AK: conceptualization, supervision, project administration, review/editing and formal analysis. All authors read ad approved the final manuscript.

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Declarations

Competing interests
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