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Durability and mechanical performance of eco-friendly portland cement mortars containing sewage sludge ash as a cement substitute

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Abstract:
This study explores the potential use of sewage sludge ash (SSA) as a sustainable supplementary material for the partial replacement of Portland cement in mortar production. The objective is to evaluate the influence of SSA on the mechanical and durability properties of cement-based mortars while promoting the valorisation of wastewater treatment residues. In this work, dried sewage sludge obtained from a wastewater treatment plant was calcined at 550°C and 700°C to produce two types of ash, namely SSA550 and SSA700. Prior to their use in mortar formulations, the ashes were characterised through physicochemical and mineralogical analyses. SSA was then incorporated as a partial replacement of cement at substitution levels of 0%, 5%, 10%, 15%, and 20% by mass. The prepared mortars were evaluated in terms of mechanical strength, apparent porosity, sulfate resistance, and chloride ion permeability in order to assess both their structural and durability performance. The results showed that the calcination temperature significantly affects the behavior of mortars containing SSA. Among the tested formulations, the mortar containing 5% SSA550 exhibited the most balanced performance, combining satisfactory mechanical strength with improved resistance to sulfate attack while maintaining chloride permeability comparable to that of the reference mixture. In contrast, the mortar containing 10% SSA700, although showing relatively higher initial strength, presented increased porosity and reduced chemical resistance. Overall, the results indicate that SSA calcined at 550°C can be effectively used as a partial cement replacement. The incorporation of 5% SSA550 appears particularly promising, offering a viable approach to reducing clinker consumption while contributing to the sustainable reuse of sewage sludge in construction materials.

Keywords:
sludge ash; calcination; mortars; durability; sustainability

1. Introduction

The increasing volume of sludge generated by wastewater treatment plants worldwide represents a major environmental challenge, particularly with the continuous growth of urban populations [1,2]. In Algeria, the National Sanitation Office reports that approximately 60% of this sludge is disposed of in landfills, 15% is stored, and only 25% is reused in agriculture [3]. Such management practices raise concerns about leachate infiltration into groundwater, potentially introducing heavy metals and pathogens into the food chain and posing environmental and public health risks [4,5].

In recent years, sewage sludge ash (SSA) has attracted increasing attention as a supplementary material in cementitious systems. Several studies have highlighted the favourable chemical and mineralogical composition of SSA, suggesting its use as a partial substitute for Portland cement clinker [6]. During calcination, organic matter in sludge is removed, and the resulting ash may develop pozzolanic properties after thermal treatment [7]. Previous studies indicate that calcination temperatures between 700°C and 800°C [8] enhance the pozzolanic reactivity of SSA, allowing the production of cementitious materials with mechanical strengths comparable to conventional mortars [9,10]. Djafari et al. [11] also reported that calcination at 550°C can produce satisfactory compressive strength results. Furthermore, Benoudjit et al. [12] identified 750°C as a suitable calcination temperature that promotes the immobilisation of heavy metals within the cement matrix, enabling the incorporation of up to 15% SSA without adversely affecting mortar properties. Other studies have reported improved compressive strength when approximately 5% of cement is replaced with SSA calcined within the range of 700–800°C [13].

Despite these promising results, some studies indicate that higher calcination temperatures may increase porosity and drying shrinkage in mortars containing SSA [14]. Conversely, calcination at lower temperatures, such as 550°C, may increase the specific surface area of the ash and influence its reactivity. However, excessive replacement levels may reduce compressive strength once the optimal substitution rate is exceeded [15].

In Algeria, the construction sector has experienced rapid growth due to population increase and infrastructure development, leading to a rise in cement demand. Wastewater treatment plants also generate increasing amounts of sludge [3,16]. The cement industry relies heavily on natural resources such as limestone and clay and contributes significantly to CO_2 emissions. Cement production is estimated to account for about 7–8% of global anthropogenic CO_2 emissions. This highlights the need to develop alternative materials to reduce the environmental footprint of cement-based construction [17].

Although previous studies have shown that mortars incorporating SSA can achieve acceptable mechanical performance, their durability under aggressive environmental conditions remains insufficiently investigated. Environmental concerns also persist regarding the potential long-term leaching of heavy metals contained in SSA. However, several studies suggest that these metals can be effectively immobilised within the cementitious matrix through chemical stabilisation and physical encapsulation mechanisms.

Therefore, this study investigates the mechanical performance of cement mortars incorporating sewage sludge ash (SSA) as a partial replacement for Portland cement. Particular attention is given to evaluating the influence of two calcination temperatures (550°C and 700°C) on the properties of SSA and on the behaviour of the resulting mortars. The durability of the mortars is examined through tests on chloride-ion penetration, sulfate attack, and the mechanical behaviour of mortars after exposure to elevated temperatures. The results provide insights into the interaction mechanisms between SSA and cement hydration products and highlight the potential use of SSA in sustainable cementitious materials.

2. Materials and methods

2.1. Materials

The cement used in this study was CEM I 42.5 R produced in Algeria, complying with the EN 197-1 standards. This Portland calcareous cement had a Blaine specific surface area of 3237 cm²/g. The sand used was certified CEN standardised sand in accordance with EN 196-1 and ISO 679. It was supplied in sealed plastic bags of 1350 ± 5 g, with a fineness modulus of 2.6 and an apparent density of 1700 kg/m³. The sewage sludge used in this study was collected from the Barraki wastewater treatment plant, which operates using the activated sludge process. The sludge had a dry matter content ranging from 28% to 30%. Prior to treatment, the sludge was dried at 105 °C in accordance with NF EN 12880, then ground using a VEB BHK Albert Funk disc mill and sieved through an 80 μm mesh. The dried sludge was subsequently calcined at two different temperatures, 550°C (SSA 550) and 700°C (SSA 700), for 4 hours in a Sintco muffle furnace. After calcination, the samples were allowed to cool naturally to room temperature before further use.

2.2. Formulation

In this study, eleven mortar formulations were prepared using calcined sewage sludge ash (SSA) as a partial replacement for cement, with substitution levels ranging from 0% to 20% by mass of cement. The mixture proportions are presented in Table 1. The water-to-binder ratio was kept constant for all mixtures. To achieve similar workability and fluidity in the mortars, a superplasticiser was used, particularly in mixtures containing SSA.

Table 1. Mixture proportions

Type of mixture	Sludge		Cement (g)	Sand (g)	Water (g)
	Sludge (%)	Sludge (g)			
Control	0	0	450	1350	225
SSA550	5	22.5	427.5	1350	225
	10	45	405	1350	225
	15	67.5	382.5	1350	225
	20	90	360	1350	225
SSA700	5	22.5	427.5	1350	225
	10	45	405	1350	225
	15	67.5	382.5	1350	225
	20	90	360	1350	225

2.3. Test procedure

The mechanical and durability properties of the mortars were evaluated according to standard procedures. Compressive and flexural strengths were measured at 2, 7, and 28 days in accordance with EN 196-1. The reported values correspond to the average of three specimens, and the measurement variability is expressed as standard deviation. The apparent porosity accessible to water of the mortars was determined at 28 days following NF EN 18459 by measuring the dry mass of specimens after drying at 50°C, then their saturated mass after immersion in water at 20°C for 24 h, followed by hydrostatic weighing. Mortars meeting the mechanical requirements of EN 197-1 and NF P 15-305 were selected for durability tests. Chloride penetration resistance was assessed using the Rapid Chloride Permeability Test (ASTM C1202, 2009). Disc specimens (110 × 50 mm) cut from cylinders (110 × 220 mm) were tested after 360 days of curing. The edges were sealed, and the samples were placed between two cells containing 3% NaCl and 0.3 N NaOH solutions. A 60 V voltage was applied for 6 h to determine the total charge passed. Sulfate resistance was evaluated by immersing specimens in a 5% Na_2SO_4 solution for 180 days, with periodic measurements of mass change, expansion, mechanical strengths, and ultrasonic velocity. Thermal resistance was assessed by exposing mortars to temperatures between 150°C and 600°C, followed by mechanical and physical evaluations.

3. Results and discussion

3.1. Physicochemical and mineralogical characterisation of raw materials

The chemical composition of cement and sewage sludge ash samples was determined using X-ray fluorescence (XRF), and the results are expressed as mass percentages (wt.%). The results indicate that the concentrations of the main oxides (SiO_2, Al_2O_3, Fe_2O_3, and CaO) increased with calcination temperature, which may promote the formation of C–S–H gel and consequently improve mortar performance. However, the CaO content in SSA (13.45–15.86%) remained significantly lower than that of Portland cement (57.75%), suggesting relatively low hydraulic reactivity. Although the concentrations of metallic trace elements in SSA were higher than those in CEM I 42.5 R cement, they remained below the limits specified by the NA 17671 standard, supporting the feasibility of incorporating SSA into cementitious materials.

Particle size analysis showed that SSA calcined at 700°C exhibited a coarser texture than cement, mainly due to particle sintering and partial fusion occurring at high temperatures (Table 2). This thermal densification decreases the specific surface area available for pozzolanic reactions and may affect the reactivity of the ash as well as the packing density of the mortar matrix.

The mineralogical composition of the samples was determined by X-ray diffraction (XRD). The diffraction patterns were analysed using HighScore Plus software (PANalytical), and phase identification was carried out by comparison with the ICSD (Inorganic Crystal Structure Database) reference database. The XRD patterns (Fig. 1) indicate that BS105, SSA550, and SSA700 are mainly composed of quartz (SiO_2), hematite (Fe_2O_3), and corundum (Al_2O_3), along with minor crystalline phases such as acmite ($NaFeSi_2O_6$) and hatrurite (C_3S). The presence of these phases indicates that certain silicate and ferrite minerals remained stable during calcination. Illite, a clay mineral with a layered silicate structure, was identified in SSA550 but disappeared in SSA700, likely due to dehydroxylation and structural collapse at higher temperatures. This transformation suggests that calcination at 700°C leads to the decomposition of clay minerals and promotes the formation of more stable crystalline phases, which may reduce the pozzolanic reactivity of the ash.

Table 2. Chemical composition of Portland cement and sewage sludge ash

Element	CEM I 42.5 (wt.%)	SSA105°C (wt.%)	SSA 550°C (wt.%)	SSA 700°C (wt.%)
SiO_2	16.23	21.78	28.57	32.47
Al_2O_3	3.81	9.13	11.81	13.30
Fe_2O_3	2.89	3.57	4.94	6.01
CaO	57.75	9.98	13.46	15.86
MgO	1.79	0.99	1.31	1.47
SO_3	3.45	2.16	2.29	2.60
K_2O	0.77	0.98	1.31	1.54
Na_2O	0.44	0.36	0.47	0.53
P_2O_5	0.18	1.75	2.30	2.67
TiO_2	0.19	0.37	0.51	0.61
MnO	0.06	0.03	0.04	0.05
Cl	0.02	0.08	0.10	0.12
CO_2	8.64	46.28	29.62	19.40
LOI	3.21	40.34	29.10	24.2

Table 3. Physicochemical properties of Portland cement and sewage sludge ash

Parameter	Unit	CEM I 42.5	SSA105°C	SSA 550°C	SSA 700°C
Apparent density	ρa (g/cm3)	1.11	0.65	0.48	0.49
Reel density	ρr (g/cm3)	2.95	1.95	2.19	2.11
10%; 50%, 90% of grains in diameter	D10 (µm)	7.92	-	1.581	2.514
	D50 (µm)	21.847	-	16.699	22.059
	D90 (µm)	52.72	-	67.629	79.99
Ph		9.94	6.34	6.70	8.08
$CaCO_3$ (%)		8.883	7.725	8.883	8.497

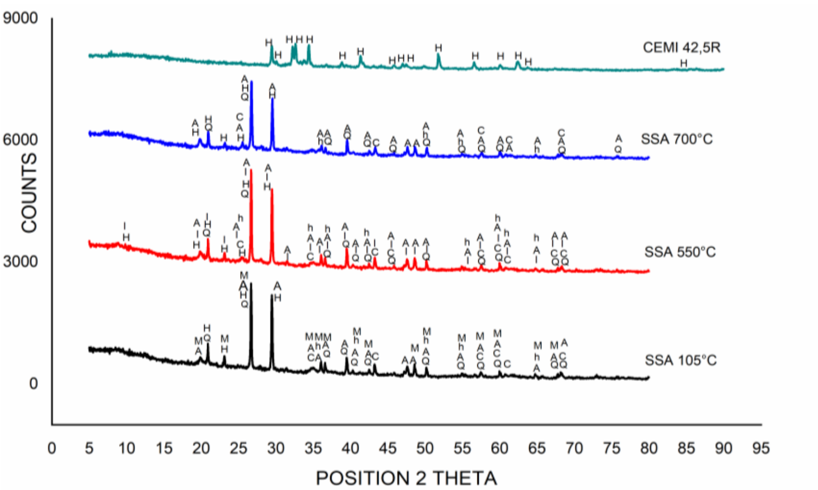


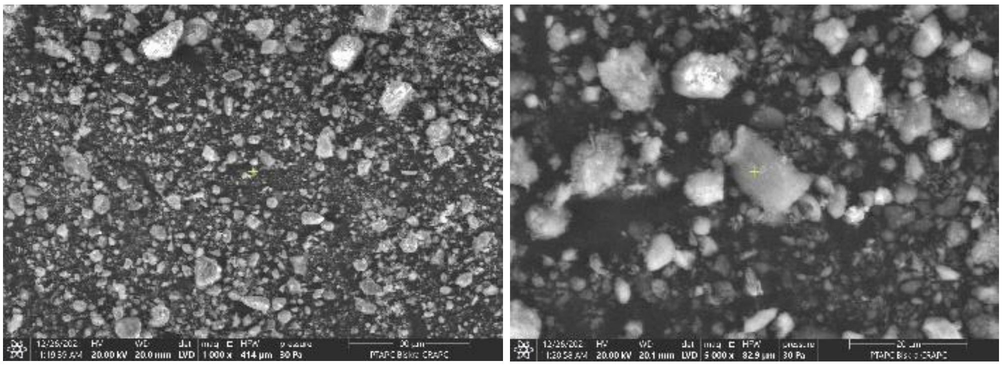
Fig. 1. XRD patterns of cement, SSA105, SSA550 and SSA700

Scanning electron microscopy (SEM) observations (Fig. 2, Fig. 3, Fig. 4) showed that both SSA550 and SSA700 consist of irregular and highly porous particles, a morphology typical of thermally treated ashes. Such porous structures can significantly influence water absorption, interfacial bonding with the cement paste, and the overall porosity of the mortar.

The concentrations of metallic trace elements (Cr, Ni, Cu, Zn, Ba, Pb) increase from SSA105°C to SSA 550°C and SSA 700°C, indicating that pyrolysis leads to the concentration of metals in the biochar. However, all measured values remain below the limits set by the NA 17671-2010, suggesting that these materials do not pose a significant risk of heavy-metal contamination.

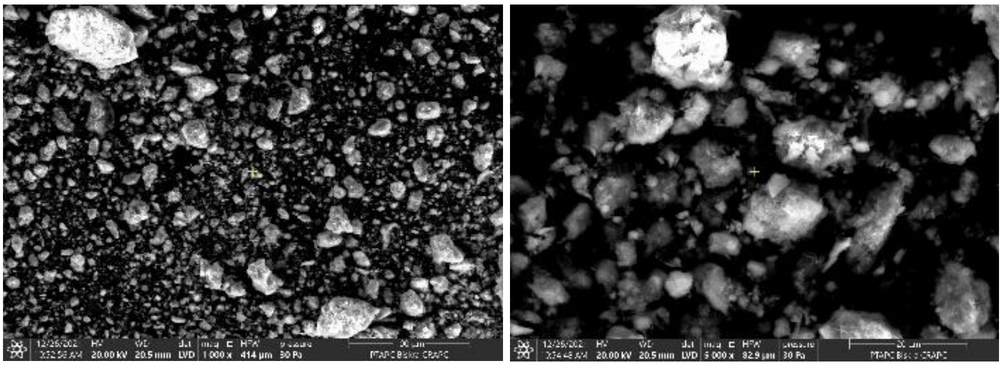
Table 4. Metallic trace elements of the SSA105, SSA550, SSA700 and cement

Metals	Cement (mg/kg)	SSA105°C (mg/kg)	SSA 550°C (mg/kg)	SSA 700°C (mg/kg)	NA 17671-2010 (mg/kg)
Cr	92.72	140.38	184.56	208.83	1750
Ni	22.00	31.43	58.93	64.43	400
Cu	28.75	142.98	194.91	247.63	1750
Zn	33.74	347.83	477.96	573.56	4000
Ba	–	316.15	375.26	574.08	–
Pb	–	86.33	106.75	128.11	1200



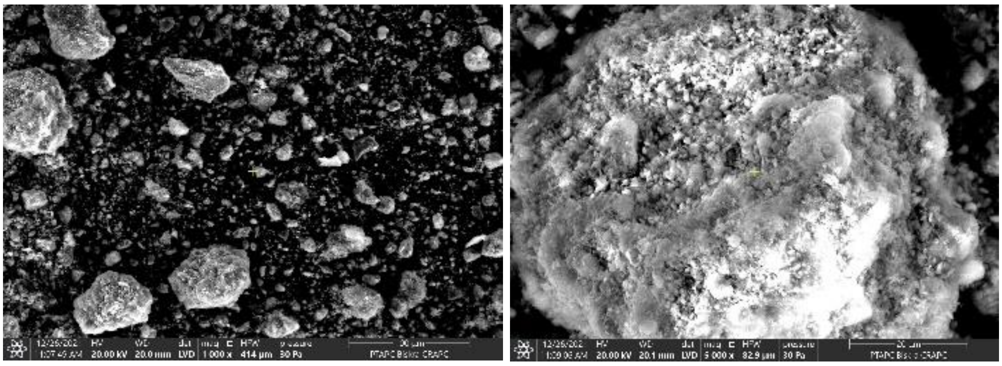
a) b)

Fig. 2. SEM observations of SSA105 at magnifications of ×1000 (a) and ×5000 (b)



a) b)

Fig. 3. SEM observations of SSA550 at magnifications of ×1000 (a) and ×5000 (b)



a) b)

Fig. 4. SEM observations of SSA700 at magnifications of ×1000 (a) and ×5000 (b)

3.2. Effect of sewage sludge ash on the porosity

The effect of sewage sludge ash (SSA) incorporation on the apparent porosity of mortars is presented in Fig 5. The results show that the addition of SSA generally leads to an increase in porosity compared with the control mortar, which exhibited an apparent porosity of 15.81%. For the SSA550 mixtures, the porosity increased progressively with the replacement level, reaching 17.18%, 19.29%, 19.71%, and 19.41% for substitution rates of 5%, 10%, 15%, and 20%, respectively. A similar tendency was observed for the SSA700 mixtures, where porosity values of 15.90%, 15.95%, 18.98%, and 20.83% were recorded for the same replacement levels.

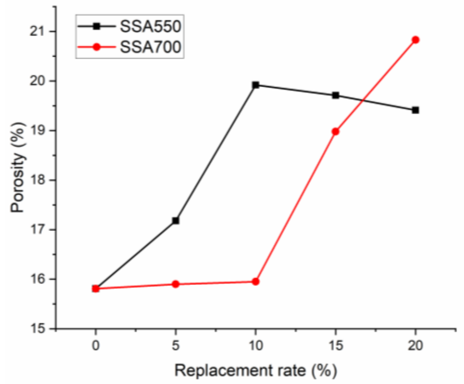


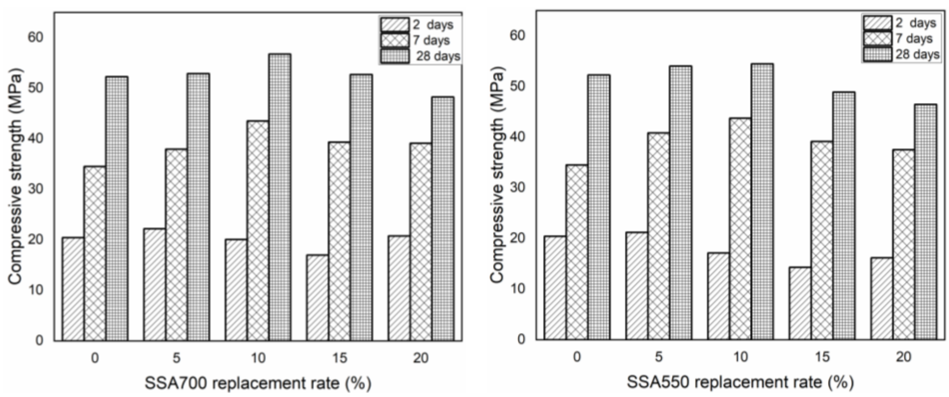
Fig. 5. Apparent porosity accessible to water of the mortar mixtures

This increase in porosity can be attributed to the relatively coarser particle size and irregular morphology of SSA compared with conventional cement particles [18]. These characteristics may lead to a less compact packing of the mortar matrix and the formation of additional voids. Consequently, higher SSA contents tend to increase the pore volume within the mortar structure, which may influence both the mechanical properties and the long-term durability of the material.

3.3. Effect of sewage sludge ash on the mechanical properties

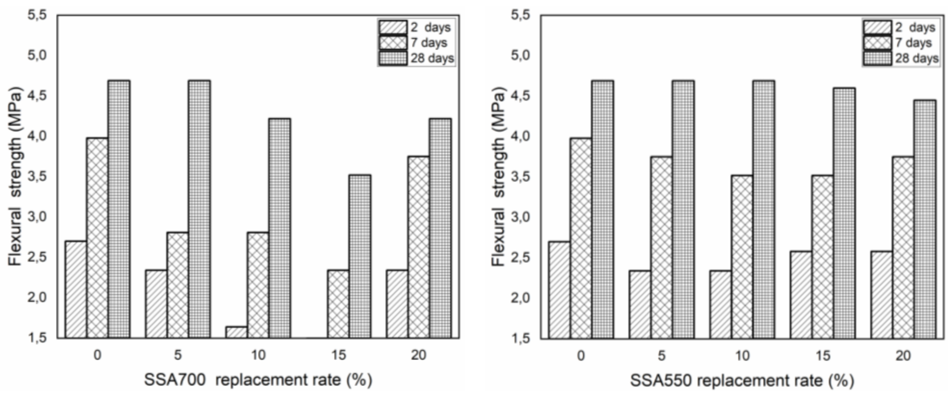
The compressive strength results at 28 days are presented in Fig. 6. The mortars incorporating SSA550 showed compressive strengths comparable to the control mixture for replacement levels up to 10%, with a slight increase of about 3% for 5%SSA550 and 10%SSA550. However, higher substitution levels (15% and 20%) resulted in decreases of approximately 6% and 11%, respectively. For mortars containing SSA700, the compressive strength increased slightly for 5%SSA700 and 10%SSA700, reaching an optimum at 10%SSA700 with an increase of about 8% compared to the control. Beyond this level, the strength decreased, with 20%SSA700 showing a reduction of approximately 7%. These variations can be attributed to the filler effect at low replacement levels and the increase in porosity at higher substitution ratios.

The flexural strength results are presented in Fig. 7. The control mortar and the mixtures containing 5%SSA550 and 10%SSA550 exhibited similar values (about 4.69 MPa), indicating that low SSA550 replacement levels did not significantly affect flexural strength. A slight decrease was observed for 15%SSA550, while 20%SSA550 showed a reduction of approximately 5% compared to the control. Mortars containing SSA700 showed a similar trend, with flexural strengths comparable to the control at low substitution levels and a slight decrease as the replacement ratio increased. These results suggest that moderate SSA incorporation does not significantly affect flexural performance, whereas higher replacement levels may slightly reduce mechanical strength due to increased porosity.



a) b)

Fig. 6. Compressive strength of mortars incorporating (a) SSA550 and (b) SSA700



a) b)

Fig. 7. Flexural strength of mortars incorporating (a) SSA550 and (b) SSA700

The increase in apparent porosity with increasing SSA substitution influences the mechanical behaviour of mortars. However, low replacement levels (5% SSA550 and 10% SSA700) maintain comparable or slightly improved strength due to the filler effect and improved particle packing. Moreover, SSA calcined at 550°C shows better durability performance than SSA calcined at 700°C, likely due to the preservation of reactive amorphous phases that enhance pozzolanic activity.

3.4. Effect of sewage sludge ash on the durability

3.4.1. Rapid chloride permeability test

Figure 8 shows the total charge passed during the rapid chloride permeability test for the control mortar and the mixtures containing 5%SSA550 and 10%SSA700. The incorporation of 5%SSA550 slightly reduced chloride ion penetration by 1.36% compared with the control mortar, whereas 10%SSA700 increased the charge passed by about 200%, indicating much higher chloride permeability. Although SSA increased the apparent porosity of the mortars, their permeability behaviour differed. The finer particle size of SSA550 (50% finer particles compared with 23% for cement) promotes a filler effect that refines the pore structure and limits chloride penetration. In contrast, the coarser texture of SSA700 results in a more open pore network and higher permeability. According to ASTM C1202 (2009), the control and 5SSA550 mortars fall within the moderate permeability category, while 10SSA700 is classified as high permeability [19].

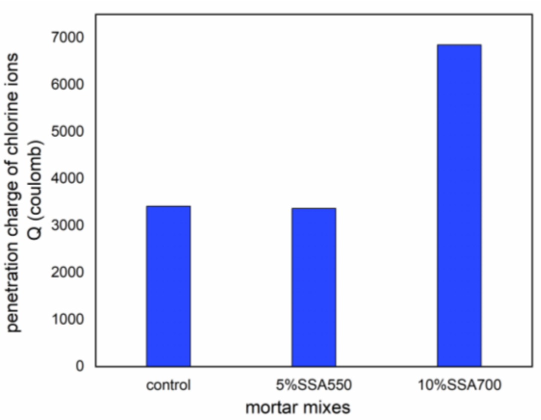


Fig. 8. Charge passed of mortar mixes during the rapid chloride permeability test

3.4.2. Sulfate attack

A. Mass and length variation

The results presented in Fig. 9 show that the mass variation of the mortars increases with immersion time in the sulfate solution. The mortars containing 5%SSA550 exhibit a mass change comparable to that of the control mortar, indicating similar resistance to sulfate attack. In contrast, the mortars incorporating 10%SSA700 show a higher mass variation, which may be attributed to the increased open porosity induced by the incorporation of sewage sludge ash. This higher porosity facilitates the penetration of sulfate ions into the mortar matrix.

The results of mortar expansion after sulfate exposure indicate that swelling increases with immersion time in the sulfate solution. After 180 days of immersion, mortars containing 5SSA550 and 10SSA700 exhibited expansions of 202% and 297%, respectively, compared with the control mortar. The control mixture showed better resistance to sulfate attack (Fig. 10), which can be attributed to the low C_3A content of the CEM I 42.5 R cement (4.89%). According to NF P 15-319, cements with a C_3A content lower than 5% are classified as sulfate-resistant. The significant expansion observed in mortars containing sewage sludge ash can be explained by two main factors: the increase in open porosity induced by the addition of SSA, which facilitates sulfate ion penetration, and the higher C_3A contents of the ashes, reaching 8.35% for SSA550 and 10.16% for SSA700.

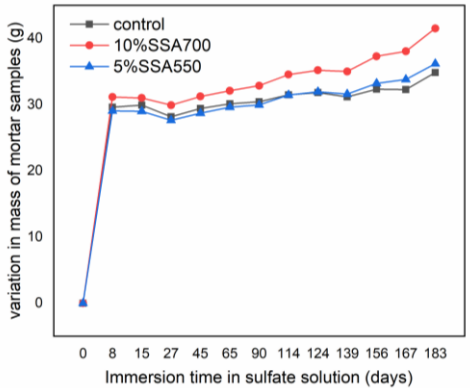


Fig. 9. Mass variation of mixes

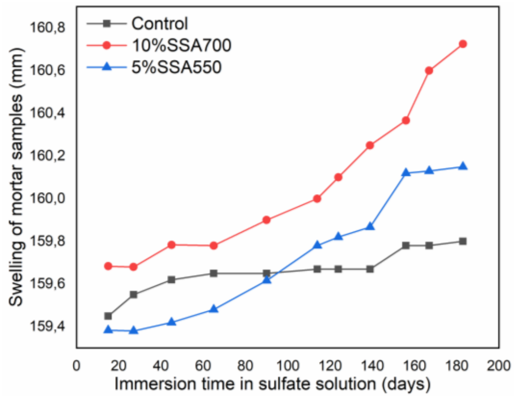
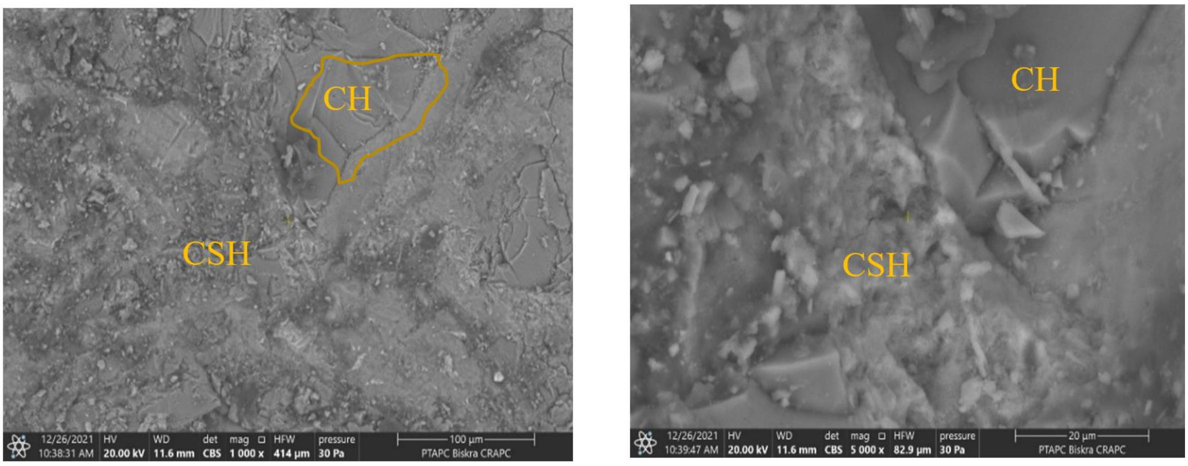


Fig. 10. Length variation of mixes

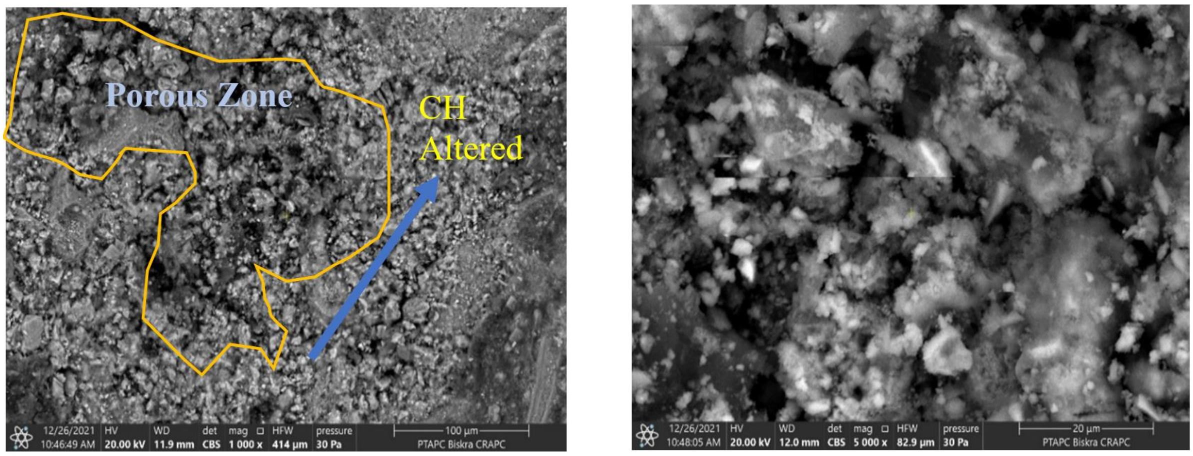
B. Morphology (MEB)

The scanning electron microscopy (SEM) observations provide qualitative information on the microstructural evolution of the mortars after sulfate exposure. The control specimens (Fig. 11a and 11b) exhibit a relatively compact and homogeneous microstructure, suggesting a stable cementitious matrix under sulfate attack. In contrast, the mortars containing 5%SSA550 and 10%SSA700 (Fig. 12a–b and Fig. 15a–b) show noticeable microstructural modifications. The SEM images reveal a more heterogeneous structure characterised by the presence of microcracks and a higher number of pores compared with the control mortar. These changes may be associated with the incorporation of sewage sludge ash, which can influence the pore structure of the cementitious matrix. The increase in microstructural heterogeneity and pore spaces may facilitate the penetration of aggressive ions during sulfate exposure, which could affect the long-term durability of the mortars. Similar trends have been reported in previous studies dealing with cementitious materials incorporating industrial by-products [20,21]. Overall, the SEM observations suggest that the incorporation of sewage sludge ash modifies the microstructure of the mortars, which may influence their durability behaviour under sulfate exposure.



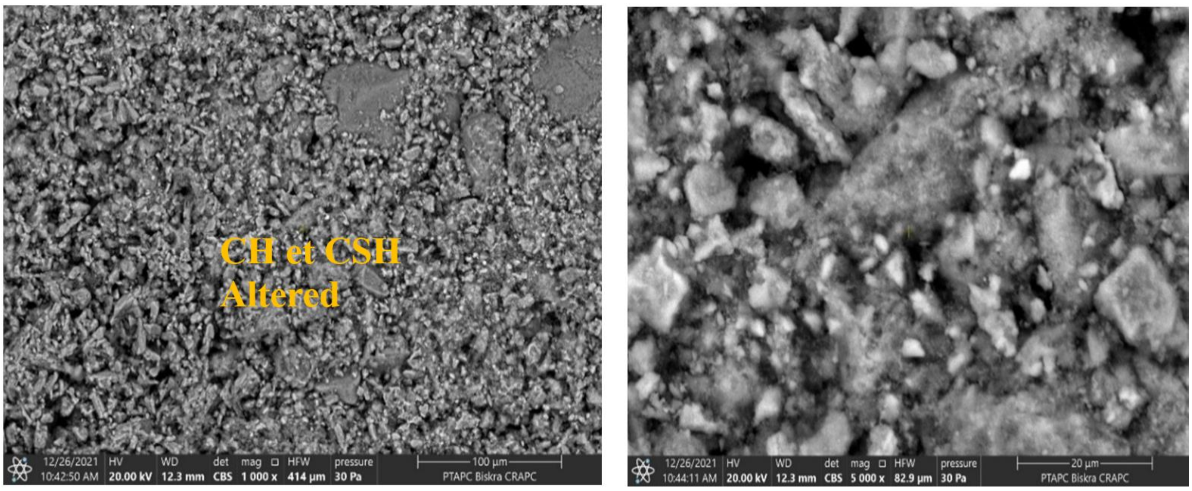
a) b)

Fig. 11. Control mortar after sulphate attack x1000 (a), x5000 (b)



a) b)

Fig. 12. Mortar with 5SSA550 after sulphate attack x1000 (a), x5000(b)



a) b)

Fig. 13. Mortar with 10 %SSA700 after sulphate attack x1000 (a), x5000 (b)

C. Mechanical strength and ultrasonic test

The results of compressive and tensile strength after external sulphate attack, presented in Fig. 14, show that the substitution of 5%SSA550 and 10%SSA700 in the mortar decreased the compressive and tensile strengths. Substitution of 5SSA550 in the mortar caused a loss in compressive strength of 14% and tensile strength of 63%, while substitution of 10SSA700 caused a decrease in compressive strength of 33% and tensile strength of 57%. The compressive and tensile strength results after sulphate attack are confirmed by the ultrasonic wave propagation results, presented in Fig. 15, where the reference mortars showed a propagation velocity of 4330 m/s while the substituted mortars of 5%SSA550 and 10%SSA700 had lower velocities of 4210 m/s and 3780 m/s, respectively. This confirms that the porosity created after the addition of the sludge ash accelerated the degradation process after external sulphate attack.

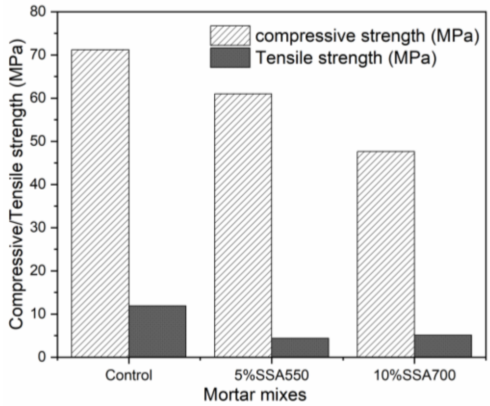


Fig. 14. Compressive and tensile strength of mortars after sulfate attack

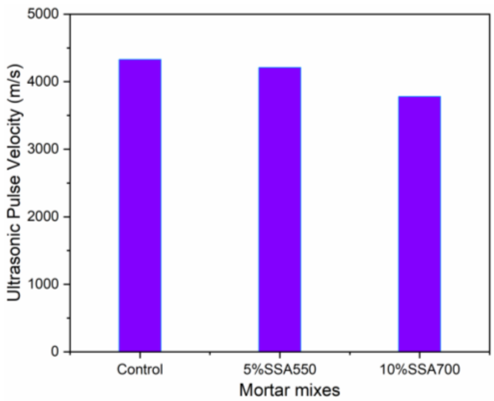


Fig. 15. Ultrasonic pulse velocity of mortars after sulfate attack

3.5. Effect of elevated temperature on mortars

A. Weight loss

Figure 16 presents the mass loss of the control mortar and mortars containing 5%SSA550 and 10% SSA700 after heat treatment at 150°C, 300°C, 450°C, and 600°C. The results show that the mass loss of all mortar specimens increases with increasing temperature. At 150°C, the control mortar exhibited a slightly higher mass loss (2.99%) compared with the mortars containing 5%SSA550 (2.95%) and 10%SSA700 (2.83%). This initial mass loss is mainly associated with the evaporation of physically bound water remaining in the hydrated cement matrix. Above 150°C, the mortars containing 5% SSA550 showed slightly higher mass losses than those containing 10% SSA700 and the control specimen. This behaviour may be related to the release of carbon dioxide from carbonate phases, which appears to be more pronounced in the mortars containing SSA550.

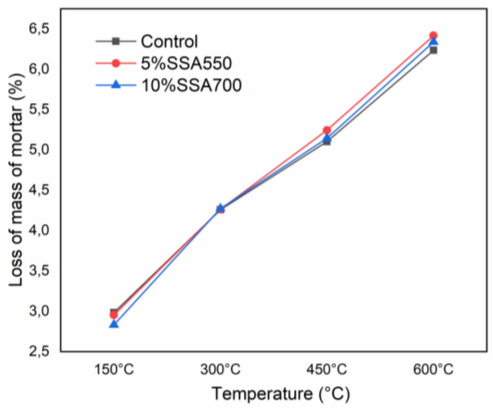


Fig. 16. Mass loss of mortars at elevated temperatures

B. Mechanical properties

The residual mechanical properties of the mortars after exposure to elevated temperatures are presented in Fig. 17 and Fig. 18. The variation in compressive strength is shown in Fig. 17. At 150°C, the control mortar and the mortars containing 5%SSA550 and 10%SSA700 exhibited comparable strengths. At 300°C, the control mortar showed the highest compressive strength, while the mortars containing SSA presented slightly lower values. The slight increase in strength observed for the control and 5%SSA550 mortars compared with the values at 150°C may be attributed to the rehydration of the cement paste and the migration of water into the pores [22]. After exposure to 450°C, a decrease in compressive strength was observed due to the decomposition of calcium hydroxide [23]. However, the mortars containing sewage sludge ash showed slightly higher residual strengths than the control, which may be related to the increase in connected porosity that reduces vapor pressure during heating. After exposure to 600°C, all mortars exhibited a significant reduction in compressive strength due to microstructural degradation and internal pressure build-up [24]. The tensile strength results are presented in Fig. 18. A similar trend was observed compared with compressive strength. At 150°C, the control mortar and the mortars containing 5%SSA550 and 10%SSA700 showed comparable values. At 300°C, the control mortar exhibited the highest tensile strength, whereas the mortars containing SSA showed slightly lower values. After exposure to 450°C, a decrease in tensile strength occurred mainly due to the decomposition of calcium hydroxide. At 600°C, the tensile strength of all mortars decreased due to cracking and portlandite decomposition, although 5%SSA550 showed slightly higher residual strength than the control, while 10%SSA700 showed a slight reduction.

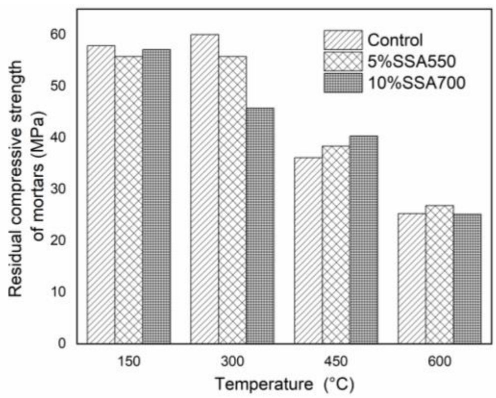


Fig. 17. Compressive strength of mortars at elevated temperatures

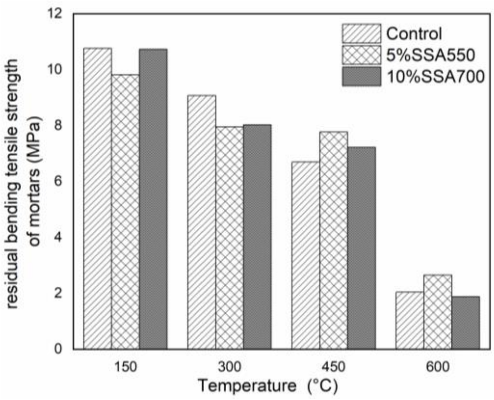


Fig. 18. Tensile strength of mortars at elevated temperatures at elevated temperatures

4. Conclusion

This study investigated the effects of partially replacing cement with sewage sludge ash (SSA) on the mechanical and durability properties of mortars. The results highlight the following main findings:

1. Calcination at 550°C significantly modifies the chemical composition of the sludge and increases the concentration of its main components, producing finer ashes that contribute to improved compactness within the cement matrix.
2. Replacing 5% and 10% of cement with SSA calcined at 550°C and 700°C, respectively, resulted in compressive and flexural strengths comparable to or slightly higher than those of the control mixtures.
3. The resistance of mortars to sulfate attack showed a slight decrease when 5% of cement was replaced with SSA calcined at 550°C, while mortars containing 10% SSA calcined at 700°C exhibited a more noticeable reduction in sulfate resistance.
4. Chloride ion penetration tests indicated that replacing 5% of cement with SSA calcined at 550°C resulted in permeability comparable to that of the control mortar.
5. Mortars containing SSA exhibited improved compressive and tensile strengths after exposure to temperatures above 450°C, indicating good thermal performance.

In conclusion, the partial replacement of Portland cement with up to 5% SSA is feasible, providing mechanical and durability performance comparable to reference mortars. The incorporation of SSA also contributes to waste valorisation and the development of more sustainable cementitious materials**.**

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