Review Article

Muhammad Alam, Hani Alanazi, Fadi Althoey, Ahmed Farouk Deifalla* and Jawad Ahmad*

Mechanical performance of concrete made with sewage sludge ash: A review (Part I)

https://doi.org/10.1515/secm-2022-0203
received January 29, 2023; accepted April 24, 2023

Abstract: Sewage sludge is frequently stable and safe when used as construction materials since it bypasses several of the costly and energy-intensive phases of usage. This is supported by numerous studies, particularly when the proportion of sewage sludge is at ideal levels. The primary goal of this article is to demonstrate the use of sewage sludge in building and construction materials. Novel properties such as slump flow and setting time as well as strength properties such as compressive strength, tensile strength, flexural strength, elastic modulus, impact energy, and absorbed energy are the main aspects studied in this review (Part I). Part II describes the physical and chemical properties, durability, and morphological structure of the sewage sludge ash. The findings in this review (Part I) indicate that the flow of concrete decreased with the addition of sewage sludge ash due to its porous nature, but the strength properties improved with sewage sludge ash due to micro-filling voids and pozzolanic activity, which improved the binding properties of cement paste. However, optimum substitution is critical as a greater proportion decreased the strength due to a deficiency of flowability, which boosted compaction energy leading to more cavities. Different studies recommend different optimum doses. However, the typical range for the optimum dose of sewage sludge ash is 5–10% (by wt) of cement.

*** Corresponding author: Ahmed Farouk Deifalla,** Structural Engineering Department, Future University in Egypt, New Cairo 11845, Egypt, e-mail: ahmed.deifalla@fue.edu.eg
*** Corresponding author: Jawad Ahmad,** Department of Civil Engineering, Swedish College of Engineering, Wah Cantt, 47040, Pakistan, e-mail: jawadcivil13@scetwah.edu.pk
Muhammad Alam: Department of Civil Engineering, University of Engineering & Technology Mardan, Mardan 23200, Pakistan
Hani Alanazi: Department of Civil and Environmental Engineering, College of Engineering, Majmaah University, Al-Majmaah 11952, Saudi Arabia
Fadi Althoey: Department of Civil Engineering, College of Engineering, Najran University, Najran, Saudi Arabia

Keywords: concrete, sewage sludge ash, compressive strength

1 Introduction

More energy and raw materials are used in current construction industry. Around the world, concrete is a widely utilized building material [1–3]. An energy-intensive method is used to synthesize cement, a key ingredient in concrete. Many greenhouse gas emissions from cement production cause climate change [4–6]. With a contribution of 5–7% to overall CO_2 emissions, cement manufacturers are the second-largest industrial CO_2 emitter [7,8]. To reduce CO_2, the use of different waste products as cement alternatives has been explored [9–11]. In modern societies, the use of waste as a secondary material in building engineering is a practical and sustainable way to get rid of waste [12–15]. The importance of sustainability in the building sector has increased, and much work has been carried out to reduce the ecological impact of the current building activities [16–18]. Growing energy supply costs, declining CO_2 discharges, and the supply of unrefined, low-quality materials are all harmful to the cement industry [19,20].

Concrete made from waste materials like plastic trash is one of the solutions to waste disposal, according to Faraj et al. [21]. Additionally, the majority of researchers in this century are focusing on creating sustainable concrete by adding different industrial wastes such as corn cob ash [22], sea sand [23], copper slag [24], etc. Sewage sludge ash is another excellent alternative to using diverse waste products as cementitious ingredients in concrete.

The possibility of integrating different waste materials into the manufacture of concrete has drawn greater attention due to the increasing focus on environmental preservation and sustainable growth in the building sector [25–31]. Due to its increasing production, excess sewage sludge in municipal or industrial wastewater treatment plants becomes a significant issue. This growth is due to the creation of new industrial units, the expansion of sewage infrastructure, and the advancement of treatment technology. Currently, treating sewage sludge as a substrate provides the foundation for the application and advancement of new technologies connected to its exploitation. Sewage sludge and other waste products may be utilized in the construction business. The finished product is often stable and safe since several of the costly and energy-intensive phases of consumption are eliminated when sewage sludge is utilized in building materials [32].

The management of sewage sludge is an issue not only in European nations but also in Asia. The output of sewage sludge in Japan increased by as much as 170% between 1990 and 2004. Currently, Japan produces more than 2.2 million tons of dry sediments [33]. The progressive reduction in landfill "capacity" and the EU-wide ban on sewage sludge storage have led to a propensity for people to reject traditional remedies. Additionally, there is a greater focus on the sewage sludge's quality and the compost made from it, which must be regulated in terms of, among other things, the amount of heavy metals and pathogens. Sewage sludge from several European nations does not fulfill the standards for its purity; thus, it cannot be utilized in agriculture or stored and can only be burned in sophisticated incineration facilities [34].

The construction sector, which plays an important role in developing nations, is one of the sectors that may provide the opportunity to utilize waste materials [35–39]. Waste materials from buildings and other sectors include ashes from biofuel incineration, blast furnace slag, sewage sludge, ashes after thermal usage, waste glass, and materials after building demolition. These factors include pro-ecological activity, sustainable building procedures, and increasing demand for cement [40]. By incorporating sewage sludge into mortars or building supplies, some of the costly and resource-intensive steps in its disposal are cut out. Additionally, the trash that is damaging the environment is changed into a reliable product.

This article provides a review of sewage sludge ash as a concrete ingredient. The important points covered in this study include novel characteristics like slump flow and setting time as well as strength properties such as compressive strength (CPS), tensile strength, flexural strength, elastic modulus, impact energy, and absorbed energy. The results show that the porous nature of sewage sludge ash caused a reduction in the concrete flow but increased the strength properties by micro-filling gaps and pozzolanic activity, which gives more dense mass and improved the cement paste's adhesion.

2 Novel properties

2.1 Setting time

Figure 1 shows the setting times for different replacement percentages of ash and sewage sludge contents. It should be noted that the setting time was increased using

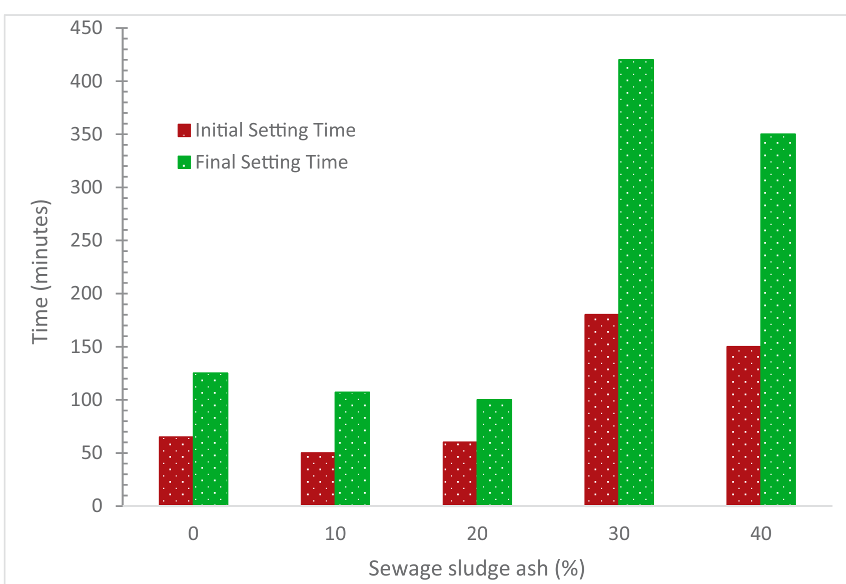

Figure 1: Setting time [41].

sewage sludge ash. Increased water needs are caused by the irregular morphology of sewage sludge's ash and porosity, which is seen from the lesser workability achieved and, in turn, the shorter setting time. The longer setting time is caused by the weaker pozzolanic activity of sewage sludge ash when compared to cement [41].

However, as demonstrated in Figure 1, increased setting time was observed at larger replacement ratios of sewage sludge ash. Because ash is less reactive than cement, cement takes longer to hydrate, which extends the setting time and increases the concentration of the pozzolanic material. The delay in setting time may sometimes be helpful for civil engineering purposes, such as casting deep wells and in certain repair concrete operations [42]. The final setting time is reduced from 345 to 300 min for mortars devoid of red mud and those that contain 20% waste. This influence on the mud may be explained by the presence of aluminum and sodium hydroxides, which are recognized as accelerators [43], as well as by the mud's high alkaline content. The fineness of waste particles might perhaps aid in water retention by outcompeting cement. The remaining free fraction, which may be mixed with cement particles, will be swiftly consumed since all formulations include the same quantity of water [44]. The gap between the setting has also reduced as the wooden ash content of the paste increased from 10 to 30% [45]. Due to a proportionally lower hydration heat of the combined cement as a result of the previously mentioned lowered hydration rate, ash-mixed cement paste was found to be suitable for use. Temperature fluctuations, such as those that occur during large concreting operations, might induce stress but they are mitigated by the needed low-heat development.

2.2 Slump flow

Figure 2 illustrates the slump flow replaced with varying amounts of sewage sludge ash. It should be mentioned that using sewage sludge ash increased the slump flow. The fluidity is significantly decreased by adding sewage sludge ash to the binder. Because the sewage sludge ash particles are porous and have an irregular form, they are more likely to absorb water on their surfaces [46]. The fluidity of mortar falls by 4.07% for every 5% increase in the average sewage sludge ash content. This is caused by porous characteristics and uneven shape of sewage sludge ash [47]. The uneven shape may rearrange the sewage sludge ash particles in a mortar and create a lot of gaps, and the porous microstructure promotes water absorption [48]. Additionally, the workability of mortar is significantly impacted by the sewage sludge ash particle size distribution. The smoother sewage sludge ash particle surface, less interlocking and friction between particles, and improved workability of mortar are all effects of grinding [49].

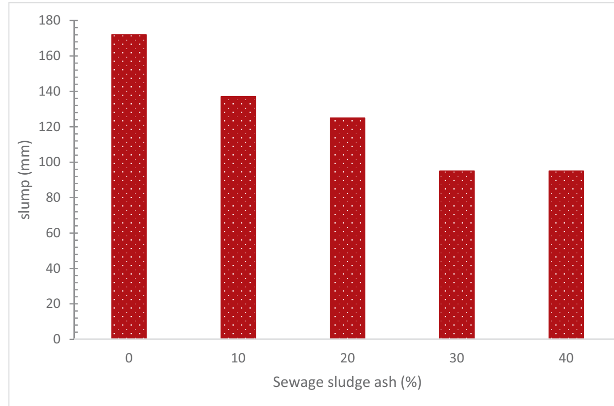

Figure 2: Slump flow [41].

The slump value for the concrete in both 75 and 150 µm particle size decreased as the amount of sewage sludge ash substitution increased [50]. Additionally, it should be noted that the increased surface area of sewage sludge ash particles causes flowability to be negatively impacted by lowering the sewage sludge ash particle size. As a result, more paste is needed to coat the particle, which means that there is less paste available for flowability. Kumar et al. observed that the 75 µm drop in slump outweighs the 150 µm decrease in the slump flow [50]. Unlike the majority of coal fly ash, the form of sewage sludge ash particles is not spherical. According to previous research, sewage exhibits an uneven grain shape and a noticeably rough surface, as shown in Figure 3.

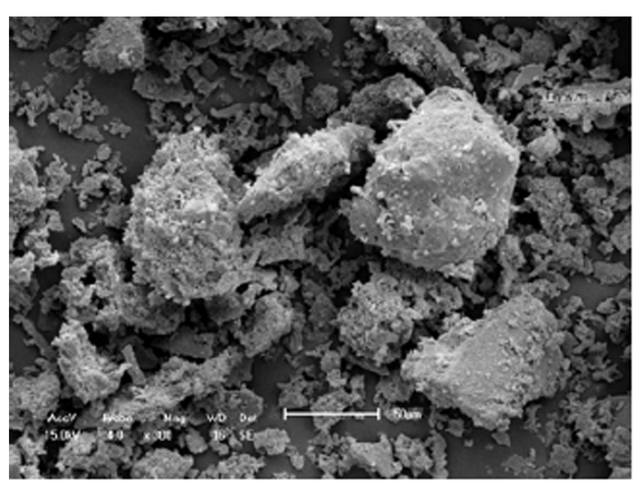

Figure 3: SEM of sewage sludge particles [51].

The workability of mortars containing sewage sludge ash is negatively impacted by this feature (no "lubricant effect" is generated) [52]. A significant amount of water is needed to power hydration operations because the silica fume has a higher specific surface area than cement [53]. The superplasticizer dose was increased to provide the required workability in all silica fume concrete combinations. It should be noted that the flowability of concrete decreased with increasing silica fume substitution. Concrete becomes stiffer and more cohesive and loses flowability when silica fume is substituted with calcium hydroxide because silica interacts with calcium hydroxide when it is in its finely split condition to generate secondary cementitious calcium silicate hydrate (CSH) [54].

3 Strength properties

3.1 Compressive strength (CPS)

Figure 4 shows the CPS with various replacements of ash and sewage sludge. As opposed to the reference mixes, it should be highlighted that incorporating sewage sludge ash increased the compressive capacity. The research reveals that the 5% sewage sludge ash concrete had the maximum strength of 55.85 MPa at 180 days, 9.94% higher than the control strength, while the 20% sewage sludge ash sample had the lowest strength of 30.36 MPa strength at 180 days. Additionally, it is shown that all of the samples' strengths increase throughout the curing process. The concrete age, curing technique, and specimen strength are all significantly correlated. In general, concrete samples exposed to the water curing technique have greater overall strengths than concrete samples subjected to the air curing method. This demonstrates how the concrete's ability to build strength has an impact on the curing process. The concrete samples must function as predicted in terms of strength, and the early volume change must be controlled; thus, it is crucial to use the right curing technique [55].

A study used sewage sludge ash, which was obtained directly from the local sewage treatment facility. The water-to-binder ratio (0.55) remained constant while there were five degrees of cement replacement (2.5, 5, 7.5, 10, and 20%). The finding shows that the CPS of mortar samples decreases as the ash content increases. The control sample with no ash from sewage sludge had the maximum average CPS of 35.31 MPa after 7 days of curing. The mortar sample with sewage sludge ash replacing 20% of the cement had the lowest strength of 32.31 MPa. The average CPS of the cement mortar with the addition of 2.5% sewage sludge ash was 35.65 MPa, which was somewhat higher (by 0.95%) than the value of the control mortar. The average CPS of the mortar containing 5, 7.5, 10, and 20% sewage sludge ash decreases by around 2.1, 5.4, 5.9, and 8.5%, respectively, when compared to the control cement mortar [59]. The maximum CPS was shown by the cement replaced with 5% sewage sludge ash at 28 days (33.09 N/mm^2), while the lowest CPS was demonstrated by the

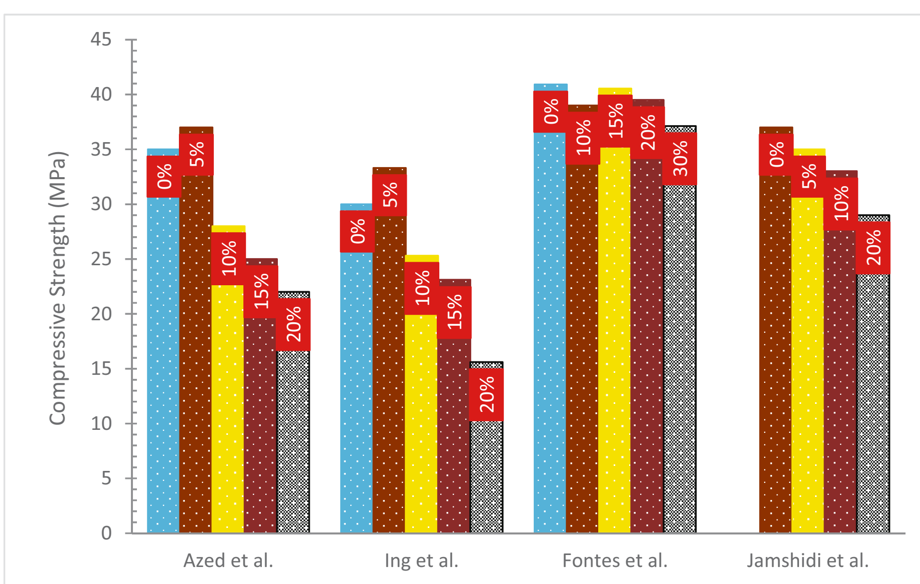

Figure 4: Compressive capacity [55–58].

cement replaced with 20% (15.68 N/mm^2) in comparison to control concrete; the substitution of sewage sludge ash at 5% increased the CPS by up to 10% [56]. When cured for 28 days, the CPS of 20 and 30% sludge ash concrete was less than the intended 28-day CPS. However, the CPS of the concrete made with 20% sludge ash was more than the 28-day CPS. This is due to the sludge ash's probable pozzolanic properties, which causes concrete's CPS to decrease at young ages and increase at older ages. Thus, unreinforced concrete might be used with 10% sludge ash concrete. The 20% sludge ash concrete might also be used for non-structural concrete. CPS and workability are not suitable when cement is replaced with a higher dose (30%) of sludge ash [60].

The CPS decreases as the amount of cement replaced by sewage sludge ash increases. The CPS of sewage sludge ash concrete increases with curing time, and the CPS loss is proportional to the percentage increase in sludge ash [58]. Although the maximum benefit was attained for a replacement level of 10–15%, which shows CPS increased by about 74% in comparison to the reference blend, the increase in CPS was also noticeable for replacement levels of 20% (50% more than the reference blend), and 30% (22% more than the reference blend) [57]. Three days of hydration did not reveal any appreciable changes. The concrete mixture with a 5% sludge ash concentration showed nearly no CPS loss from 7 to 28 days of curing. Mixtures that include 10% sludge ash show a 10% decrease in CPS [58].

The CPS of the composite including 20% sludge ash increases with curing time and, after 90 days, approaches that of the mixture containing merely 10% sludge ash. This may be explained by a negligible pozzolanic impact, as suggested by Cyr et al. [61], or by the possibility that sludge ash particles operate as additional sites for the nucleation and development of hydration products, so accelerating the hydration process as a whole [62]. The pozzolanic activity of sewage sludge ash is affected by the increase in the incineration temperature in two different ways. On the one hand, sewage sludge ash contains more amorphous SiO_2 because of the increasing temperature, and this increase in amorphous SiO_2 promotes the development of CSH gel in the mortar, thereby improving the mortar performance. On the other hand, the performance of mortar is negatively impacted by the sintering bonding phenomena, which arises because with an increase in temperature, the sewage sludge ash's pozzolanic activity may be somewhat increased with grinding [63]. Table 1 depicts the concrete flowability and strength properties of the concrete with varying proportions of sewage sludge ash.

Figure 5 shows the CPS with varied sewage sludge ash concentrations and curing times. The control or reference concrete (blank mix), CPS after 28 days, was selected as reference strength from which different blend mixes with sewage sludge ash are compared. For comparison, the optimum substitution of sewage sludge ash (5%) was selected. Pozzolanic CPS of 5% sewage sludge ash is less than 15% as compared to the reference strength. However, after 28 and 90 days of cure, the CPS is 6 and 28% more than the reference strength with a 5% substitution of sewage sludge ash. This is because the pozzolanic process proceeds at a much slower pace than the cement hydration process [65], in which materials could have had lower early-age strength than expected. Similar studies arrived at the same result, that is, the addition of pozzolanic components enhanced the concrete strength at a later age (beyond 28 days) [13]. Haustein et al. [59] also reported that the gradual and ongoing reactivity of ash from sewage sludge in cement mortars is responsible for the early-age (7 days) poor CPS value. The findings suggest that sewage sludge ash affects the hydration of cement because of its chemical makeup. It probably has little pozzolanic action and mostly functions as an additive. The sewage sludge ash grains may have trapped a lot of water, and only a small quantity of CH was formed from cement hydration to take part in the pozzolanic interactions with the sewage sludge ash and provide strength to the mortar samples.

3.2 Tensile strength

Figure 6 shows the tensile strengths with various binder replacement levels for sewage sludge. It should be highlighted that the tensile strength was not increased while employing sewage sludge ash in comparison to the reference mixes. However, the tensile strength is almost similar to reference mixes up to 5% sewage sludge ash. Furthermore, for high strength, the review recommends the addition of different types of fibers such as jute fiber [66], steel fiber [67], nylon fiber [68], carbon nanofiber [69], glass fiber [70], and basalt fiber [71] to improve its tensile capacity.

Additionally, greater days of curing, better tensile strength, and strength that is similar to the reference mixes up to 5% sewage sludge ash were also reported. The research found that adding sewage sludge ash to polyester dramatically changes the composite's mechanical characteristics. Tensile stress increases in the tensile test results until the weight rate of ash reaches 20%, after which it drops [72]. With up to 5% more sewage sludge

Table 1: Performance of concrete with sewage sludge ash

Reference	Concrete type	Sewage sludge ash	Concrete ingredient	Other materials	W/C	Slump (mm)	Compression strength (MPa)				Split tensile strength (MPa)			Flexure strength (MPa)			Remarks
[60]	Conventional		Cement	—	—	—	**7 D**	**28 D**	**56 D**		—			—			Strength
	concrete	0%					19	24	27								decreased
		10%					18	22	26								
		20%					15	19	23								
		30%					14	16	17								
[64]	Conventional		Cement	—	—		**3 D**	**7 D**	**28 D**					**7 D**	**28 D**		Slump
	concrete	0%				50	31.3	34.3	43.9					5.6	7.7		increased
		5%				55	23.4	26.4	35.6					3.8	5.9		and strength
		10%				55	17.1	20.8	25.3					4.3	5.4		decreased
		15%				60	13.7	15.0	19.1					3.4	4.7		
[50]	High strength		Cement	Fly ash	0.33		**7 D**	**14 D**	**28 D**		**7 D**	**28 D**	**56 D**	**7 D**	**28 D**	**56 D**	Slump
	concrete					180	46.0	53.9	61.1		3.3	3.9	4.1	4.5	5.1	5.2	increased
		0%				195	43.0	45.9	58.9		3.2	3.9	4.0	4.3	5.0	5.1	and strength
		5%				162	27.8	36.7	44.7		2.4	3.3	3.4	3.5	4.3	4.5	decreased
		10%				157	26.3	37.4	43.9		2.4	3.2	3.3	3.4	4.2	4.4	
		15%				151	42.4	44.6	58.1		2.1	2.9	3.1	3.0	3.9	4.1	
[57]	Conventional		Additive	—	0.50	—	**7 D**		**28 D**		—			—			7 D strength
	concrete	0%					20.66		40.92								increased
		10%					36.01		39.00								and 28 D
		15%					35.89		40.55								strength
		20%					30.93		39.50								decreased
		30%					26.50		37.12								
[55]	Conventional		Cement	—	0.51	—	**7 D**	**28 D**	**90 D**					**7 D**	**28 D**	**90 D**	Strength
	concrete	0%					27	35	40					6.4	7.0	8.5	increased
		5%					30	37	45					6.5	7.5	8.0	
		10%					22	28	32					5.8	6.5	7.8	
		15%					20	25	27					5.0	5.8	6.2	
		20%					18	22	24					4.8	5.5	6.0	
[41]	Conventional		Cement	Silica fume and	0.50	—	**3 D**	**7 D**	**14 D**	**28 D**	—			**1 D**	**7 D**	**28 D**	Strength
	concrete	0%		metakaolin			39.3	46.1	54.7	59.4				3.3	6.3	6.8	increased
		10%					41.5	53.2	57.5	66.9				3.1	6.2	7.3	
		20%					33.1	42.5	53.3	59.7				2.5	5.5	7.2	
		40%					14.6	18.2	18.9	20.7				1.2	1.9	4.7	
[56]	Conventional		Cement	—	0.55	—	**1 D**	**7 D**	**28 D**		—			—			Strength
	concrete	0%					7.9	23.2	30.0								decreased
		5%					7.3	21.2	33.3								
		10%					6.8	19.6	25.3								
		15%					6.0	17.0	23.1								
		20%					5.8	14.7	15.6								

(*Continued*)

Table 1: *Continued*

Reference	Concrete type	Sewage sludge ash	Concrete ingredient	Other materials	W/C	Slump (mm)	Compression strength (MPa)		Split tensile strength (MPa)	Flexure strength (MPa)	Remarks
[58]	Conventional concrete		Cement	—	0.45	—	**14 D**	**28 D**	—	**28 D**	Strength decreased
		0%					26	37		6.0	
		5%					25	35		5.1	
		10%					24	33		4.9	
		20%					22	29		4.2	
[51]	Conventional concrete		Additive	—	0.65		**7 D**	**28 D**	—	—	Strength decreased
		0%				180	13.6	16.7			
		5%				125	17.9	25.0			
		10%				30	23.0	28.8			

Note: W/C = water/cement ratio, D = curing days.

ash in both curing procedures, the concrete has stronger properties than regular concrete. After the hydration process in the cement took place, $Ca(OH)_2$ and CSH were produced. The presence of sewage sludge ash in the concrete mixture functions as a pozzolanic material and reacts with these byproducts. The specimen's strength might increase as a result of this interaction. The development of CSH gel was accelerated by the presence of adequate moisture caused by the curing procedure during the hydration phase [55]. The tensile strength of concrete mixes using sawdust ash as a partial replacement for cement was investigated at 7 and 28 days. A reduction in the tensile strength with an increase in the saw dust ash percentage was observed; however, it was less noticeable than a decrease in the CPS. After 7 days, it was seen that the difference in the strength between the blended cement concrete and control mixtures increased. After 28 days, the blended cement concrete mixes with replacement percentages of up to 25% exhibited tensile capacities up to 90% of the strength of the control mixtures [73]. Tensile strength was significantly and just slightly affected by the use of metakaolin and silica fume, respectively. The improved compressive and tensile strength was attained by using the ideal replacement percentage, 15% mixed pozzolan (7.5% metakaolin and 7.5% silica fume) [74]. The optimal dosage of silicon carbide whiskers was 0.1% (by wt), increasing the tensile strength of cement-based materials [75]. Kumar et al. have also shown that the strength significantly decreased at replacement levels of 5, 10, and 15% when 150 µm of smaller sewage sludge ash was replaced compared to concrete samples made with 150 µm of sewage sludge and ash that were reduced to 75 µm [50]. It is possible to conclude that sewage sludge ash with decreasing particle size (below 75 µm) has increased reactivity and, therefore, more efficient strength qualities than sewage sludge ash with greater particle size (150 µm).

3.3 Flexural strength

Figure 7 shows the flexural strength with various replacements of ash and sewage sludge. As opposed to the reference mixes, it should be emphasized that incorporating sewage sludge ash increased the flexural capacity. The flexural strength of the concrete made from sewage sludge and ash is virtually identical to the findings for CPS. When compared to air-cured concrete, the results for sewage sludge and ash concrete were greatest when they were water-cured. This demonstrates why an air-curing

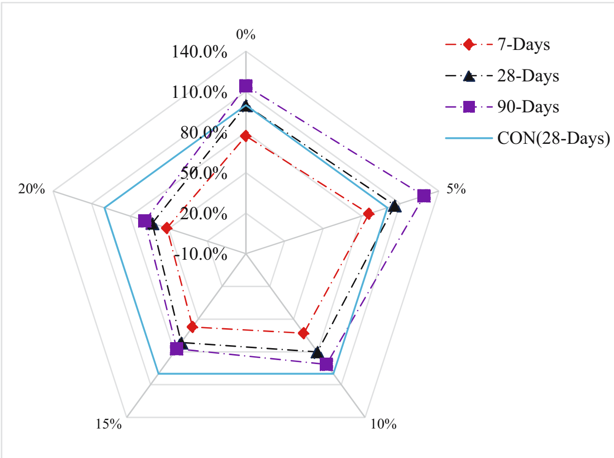

Figure 5: CPS and age relationship [55].

regime is inferior to one that uses water. The best way to stop concrete from losing moisture is to water cure continuously, which will improve the hydration process and pozzolanic reaction [55]. Although excessive amounts of sewage sludge ash concrete may decrease flexural strength due to sample's larger porosity and greater water absorption of the concrete, pozzolanic processes in the concrete may impact the increase of flexural strength [76].

When heated to a medium-high temperature, concrete containing 5% sewage sludge ash had slightly greater flexural strength than the control sample at ages 7 and 28 days. At 7 and 28 days after curing, respectively, the flexural strength of 5% sewage sludge ash heated to a medium-high temperature was 5.64 and 7.91 MPa. In comparison to other samples, the flexural strength of concrete with a 15% replacement of sewage sludge ash is the lowest. When compared to control samples at age 28 days, the flexural strength of the 15% sewage sludge ash concrete was 39.07% lower [64]. The flexural strength of mortar may be increased by adding mineral admixtures like silica fume and metakaolin. Mortar that was blended with 10% silica fume and 20% sewage sludge ash had slightly greater flexural strength than cement mortar. The ideal dose is 10% metakaolin with a 20% sewage sludge ash replacement rate, which results in a flexural strength that is 28.32% more than cement mortar [41]. The source and processing method of sewage sludge ash has a significant impact on the mortar's flexural strength. For instance, when using the same source of sewage sludge ash and a 10% replacement ratio, the mortar made by sewage sludge ash calcined at 700°C has a 28-day flexural strength, which is greater than that of the mortar prepared by sewage sludge ash calcined at 600°C [78]. Because of the coarse particles, Pavlik et al. [79] discovered that the pozzolanic activity of sewage sludge ash was low.

3.4 Elasticity modulus

It is crucial to analyze the results of the modulus of elasticity test since they will show the stiffness properties of

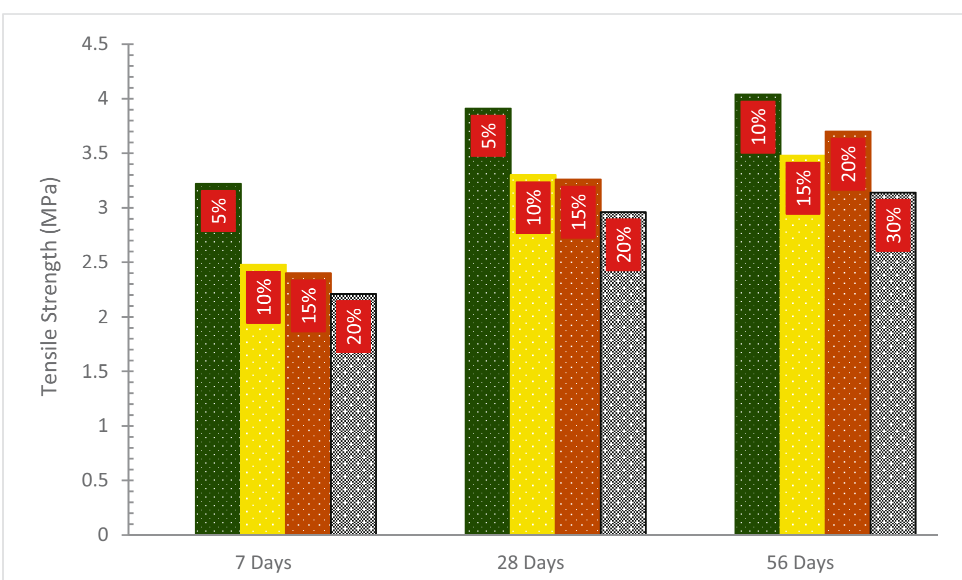

Figure 6: Tensile strength [50].

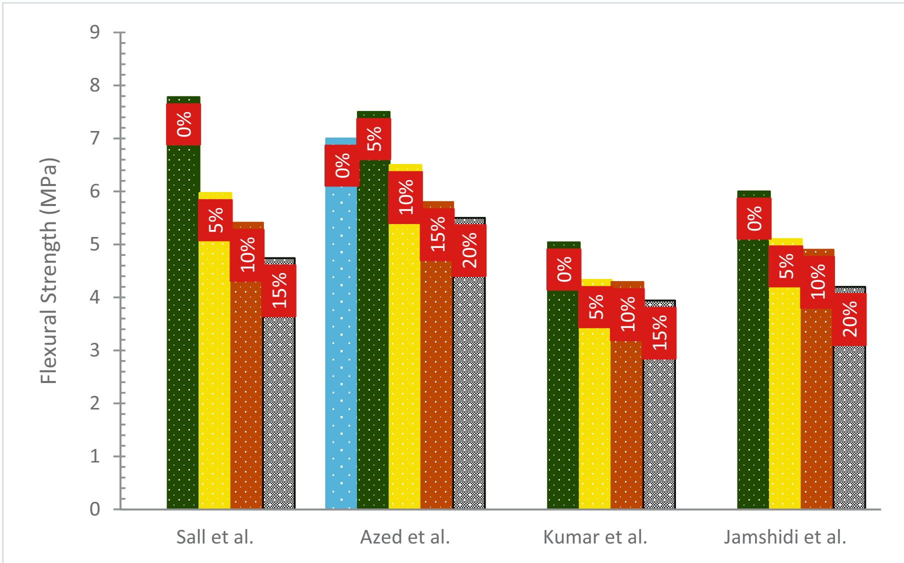

Figure 7: Flexural strength [50,55,58,77].

the specimen material that exhibits elastic behavior. Figure 8 depicts the association between the addition of sewage sludge ash and the modulus of elasticity of the specimen at 28 days. The findings show that adding concrete with a 5% proportion of sewage sludge ash increases the concrete's rigidity. Additionally, the results demonstrate that the value of the elastic modulus decreased as the amount of sewage sludge and ash concrete increased. This implies that the stiffness of the sewage sludge ash concrete would increase with lower percentages of the sewage sludge ash. Additionally, specimens with water curing had better results than those with air curing [55]. The stiffness of the aggregate, cement paste, and concrete's compactness all affect the material's modulus of elasticity [80].

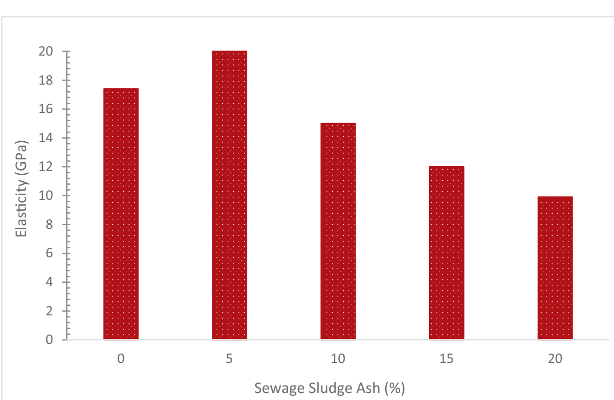

Figure 8: Elastic modulus [55].

A study revealed that the pozzolanic interactions between the binders (ordinary Portland cement [OPC] and wheat straw ash) and continuous hydration caused by the increase in the wheat straw ash concentration increased the elastic modulus of the concrete. According to Katman et al. [81], the potential fine-tuning of the concrete pores may be the cause of the improvement in the elastic modulus of concrete with the buildup of wheat straw ash. This helped the aggregates and the binder, such as wheat straw ash and cement, form stronger interfacial connections [82]. The modulus of elasticity reduced when 150 µm of sewage sludge ash was replaced but it was comparable to the control mix in samples containing 75 µm of downsize sewage sludge ash. The addition of sewage sludge ash resulted in a decrease in elasticity owing to pore structure de-densification. The value of the modulus of elasticity decreases linearly as the sewage sludge ash concentration increases [50].

3.5 Impact strength

Figure 9 displays the impact resistance and energy absorption with varying amounts of sewage sludge ash ranging from 0 to 40%. It should be noticed that the impact resistance and absorbed energy increase until the ash weight rate approaches 10%. This is due to the sludge ash's possible pozzolanic activity, which reduces the CPS of the concrete early on and increases it subsequently. Thus, unreinforced concrete might be used with 10% sludge ash concrete. Additionally, 20% sludge ash concrete might

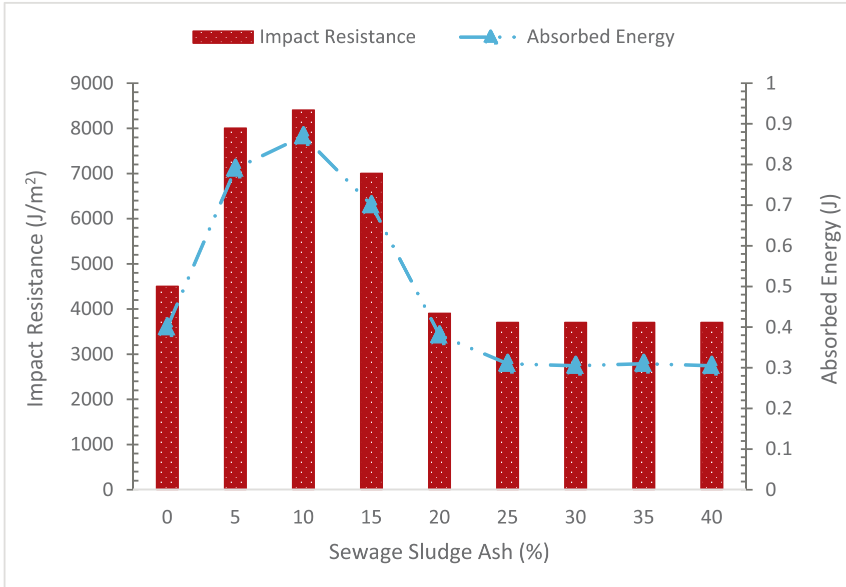

Figure 9: Impact resistance and absorbed energy [72].

be used for the non-structure concrete. For CPS and workability, replacing cement with 30% sludge ash is inappropriate [60].

According to Gonen, when waste crumb rubbers were used in regular concrete at a rate of 4%, the specimen's impact resistance was 200% greater than that of the control concrete [83]. Carmichael and Arulraj compared the impact resistance of concrete with and without the addition of 10–50% of nanomaterial particles and found that the concrete with the nanomaterials had higher impact resistance [84]. More than 20% of sewage sludge ash in concrete exhibits impact resistance and practically constant energy absorption, according to Kutuk and Oguz [72]. Figure 10 compares the impact damage morphologies of standard concrete samples with silica. After being struck, the samples including silica also fractured in half along the impact direction, showing that the inclusion of silica did not improve the concrete specimens' impact damage morphology and that samples blended with silica still experience fragile failures comparable to those of regular concrete.

4 Conclusions

The main objective of this article is to discuss the application of sewage sludge in building materials. Novel properties such as slump flow and setting time as well

Figure 10: (a) Reference sample and (b) 2% addition of silica (pozzolanic materials) [85].

as strength properties such as compressive strength, tensile strength, flexural strength, elastic modulus, impact energy, and absorbed energy are the main aspects of this review.

- Setting time increased with the substitution of sewage sludge ash because the pozzolanic process moves more slowly than OPC hydration. The flowability decreased with sewage sludge ash owing to its spongy nature, which absorbed more water and hence less water is accessible for flowability.
- Strength properties improved with sewage sludge ash due to micro-filling voids and pozzolanic activity, which enhanced the binding properties of the paste. However, optimum substitution is crucial as the higher dose decreased the strength due to a deficiency of flowability, which increased compaction energy, leading to additional cavities. Different studies recommend different optimum doses. However, the typical range for the optimum dose of sewage sludge ash is 5–10% (by wt) of cement.
- It can also be observed that the sewage sludge ash decreased or did not improve early-age strength (up to 7 days). However, improvement was observed with late-age strength (beyond 28 days). It is because the pozzolanic reaction advances more gradually than the hydration of cement, which increases in strength with age.
- This review also concludes that the particle size of sewage sludge ash plays an important role in terms of strength. The lower particle size (75 μm) of sewage sludge ash shows better strength properties as compared to the larger particle size (75 μm).

5 Recommendation

- To increase sewage sludge ash's pozzolanic activity, several techniques like heat activation or alkali activation should be used.
- Less information is available on the impact of particle size of sewage sludge ash on concrete strength. Therefore, this review recommends detailed research on the effect of particle size of the sewage sludge ash on concrete strength.
- Although sewage sludge ash enhanced the concrete strength, the concrete showed low tension. A few studies focus on the tensile capacity of concrete, as shown in Table 1. Therefore, this review also recommends detailed research on the tensile capacity of concrete.

Acknowledgments: The authors are thankful to the Deanship of Scientific Research at Najran University for funding this work, under the Research Groups Funding program grant code (NU/RG/SERC/12/13).

Funding information: The authors are thankful to the Deanship of Scientific Research at Najran University for funding this work, under the Research Groups Funding program grant code (NU/RG/SERC/12/13).

Author contributions: Muhammad Alam: Writing original draft; Hani Alanazi: Review editing and revising; Fadi Althoe: Supervision Review editing and revising; Ahmed Farouk Deifalla: Funding, Review editing and revising; Jawad Ahmad: Methodology, Conceptual, Review editing and revising.

Conflict of interest: Authors state no conflict of interest.

References

[1] Althoey F. Compressive strength reduction of cement pastes exposed to sodium chloride solutions: Secondary ettringite formation. Constr Build Mater. 2021;299:123965.
[2] Smirnova O, Kharitonov A, Belentsov Y. Influence of polyolefin fibers on the strength and deformability properties of road pavement concrete. J Traffic Transp Eng (Engl Ed). 2019;6:407–17.
[3] Smirnova OM, Menéndez Pidal de Navascués I, Mikhailevskii VR, Kolosov OI, Skolota NS. Sound-absorbing composites with rubber crumb from used tires. Appl Sci. 2021;11:7347.
[4] Jani Y, Hogland W. Waste glass in the production of cement and concrete – A review. J Env Chem Eng. 2014;2:1767–75. doi: 10.1016/j.jece.2014.03.016.
[5] Singh Shekhawat B, Aggarwal V. Utilisation of waste glass powder in concrete-A literature review. Int J Innov Res Sci Eng Technol. (An ISO) 2007;3297:2319–8753.
[6] Van Lam T, Bulgakov B, Bazhenov Y, Aleksandrova O, Anh PN. Effect of rice husk ash on hydrotechnical concrete behavior. IOP Conf Ser Mater Sci Eng. 2018;365:032007. doi: 10.1088/1757-899X/365/3/032007.
[7] He Z, Zhu X, Wang J, Mu M, Wang Y. Comparison of CO_2 emissions from OPC and recycled cement production. Constr Build Mater. 2019;211:965–73.
[8] Nelson J, Grayson D. World Business Council for Sustainable Development (WBCSD). In: Corporate Responsibility Coalitions. London: Routledge; 2017. p. 300–17.
[9] Meyer C, Xi Y. Use of recycled glass and fly ash for precast concrete. J Mater Civ Eng. 1999;11:89–90. doi: 10.1061/(asce)0899-1561(1999)11:2(89).
[10] Siddique R. Utilization of industrial by-products in concrete. Procedia Eng. 2014;95:335–47. doi: 10.1016/j.proeng.2014.12.192.
[11] Althoey F, Farnam Y. The effect of using supplementary cementitious materials on damage development due to the formation of a chemical phase change in cementitious

materials exposed to sodium chloride. Constr Build Mater. 2019;210:685–95. doi: 10.1016/j.conbuildmat.2019.03.230.
[12] Brito J, Silva R. Use of waste materials in the production of concrete. Proceedings of the Key Engineering Materials. Vol. 634. Trans Tech Publ; 2015. p. 85–96.
[13] Ahmad J, Majdi A, Deifalla AF, Isleem HF, Rahmawati C. Concrete made with partially substitutions of Copper Slag (CPS): State of the art review. Mater (Basel). 2022;15:5196. doi: 10.3390/ma15155196.
[14] Rahmawati C, Aprilia S, Saidi T, Aulia TB. Current development of geopolymer cement with nanosilica and cellulose nanocrystals. Proceedings of the Journal of Physics: Conference Series. Medan, Indonesia: 2021. p. 1–8.
[15] Alvee AR, Malinda R, Akbar AM, Ashar RD, Rahmawati C, Alomayri T, et al. Experimental study of the mechanical properties and microstructure of geopolymer paste containing nano-silica from agricultural waste and crystalline admixtures. Case Stud Constr Mater. 2022;16:e00792. doi: 10.1016/j.cscm.2021.e00792.
[16] Isler JW. Assessment of concrete masonry units containing aggregate replacements of waste glass and rubber tire particles. Free Download, Borrow, and Streaming: Internet Archive. University of Colorado at Denver; 2012.
[17] Agency IE, Agency IE. Tracking industrial energy efficiency and CO_2 emissions. OECD; 2007. https://doi.org/10.1787/9789264030404-en.
[18] Mermerdaş K, Arbili MM. Explicit formulation of drying and autogenous shrinkage of concretes with binary and ternary blends of silica fume and fly ash. Constr Build Mater. 2015;94:371–9.
[19] Benhelal E, Zahedi G, Shamsaei E, Bahadori A. Global strategies and potentials to curb CO_2 emissions in cement industry. J Clean Prod. 2013;51:142–61.
[20] Ahmad J, Martínez-García R, De-Prado-Gil J, Irshad K, El-Shorbagy MA, Fediuk R, et al. Concrete with partial substitution of waste glass and recycled concrete aggregate. Mater (Basel). 2022;15:430. doi: 10.3390/ma15020430.
[21] Faraj RH, Ali HFH, Sherwani AFH, Hassan BR, Karim H. Use of recycled plastic in self-compacting concrete: A comprehensive review on fresh and mechanical properties. J Build Eng. 2020;30:101283.
[22] Suwanmaneechot P, Nochaiya T, Julphunthong P. Improvement, characterization and use of waste corn cob ash in cement-based materials. Proceedings of the IOP Conference Series: Materials Science and Engineering. Vol. 103. IOP Publishing; 2015. p. 12023.
[23] Sun L, Wang C, Zhang C, Yang Z, Li C, Qiao P. Experimental investigation on the bond performance of sea sand coral concrete with FRP bar reinforcement for marine environments. Adv Struct Eng. 2023;26:533–46.
[24] Sambhaji ZK, Autade PB. Effect of copper slag as a fine aggregate on properties of concrete. Int Res J Eng Technol. 2016;3:410–4.
[25] Balapour M, Joshaghani A, Althoey F. Nano-SiO2 contribution to mechanical, durability, fresh and microstructural characteristics of concrete: A review. Constr Build Mater. 2018;181:27–41.
[26] Rahmawati C, Aprilia S, Saidi T, Aulia TB, Hadi AE. The effects of nanosilica on mechanical properties and fracture toughness of geopolymer cement. Polym (Basel). 2021;13:2178. doi: 10.3390/polym13132178.
[27] Ahmad J, Kontoleon KJ, Majdi A, Naqash MT, Deifalla AF, Ben Kahla N, et al. A comprehensive review on the Ground Granulated Blast Furnace Slag (GGBS) in concrete production. Sustainability. 2022;14:8783. doi: 10.3390/su14148783.
[28] Zeybek Ö, Özkılıç YO, Karalar M, Çelik Aİ, Qaidi S, Ahmad J, et al. Influence of replacing cement with waste glass on mechanical properties of concrete. Mater (Basel). 2022;15:7513. doi: 10.3390/ma15217513.
[29] Karalar M, Bilir T, Çavuşlu M, Özkiliç YO, Sabri MMS. Use of recycled coal bottom ash in reinforced concrete beams as replacement for aggregate. Front Mater. 2022;9:1064604.
[30] Qaidi S, Najm HM, Abed SM, Özkılıç YO, Al Dughaishi H, Alosta M, et al. Concrete containing waste glass as an environmentally friendly aggregate: A review on fresh and mechanical characteristics. Mater (Basel). 2022;15:6222.
[31] Basaran B, Kalkan I, Aksoylu C, Özkılıç YO, Sabri MMS. Effects of waste powder, fine and coarse marble aggregates on concrete compressive strength. Sustainability. 2022;14:14388.
[32] Świerczek L, Cieślik BM, Konieczka P. The potential of raw sewage sludge in construction industry–A review. J Clean Prod. 2018;200:342–56.
[33] Hong J, Hong J, Otaki M, Jolliet O. Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. Waste Manag. 2009;29:696–703.
[34] Mininni G, Blanch AR, Lucena F, Berselli S. EU policy on sewage sludge utilization and perspectives on new approaches of sludge management. Env Sci Pollut Res. 2015;22:7361–74.
[35] Limbachiya MC. Bulk engineering and durability properties of washed glass sand concrete. Constr Build Mater. 2009;23:1078–83. doi: 10.1016/j.conbuildmat.2008.05.022.
[36] Khaloo AR, Dehestani M, Rahmatabadi P. Mechanical properties of concrete containing a high volume of tire–rubber particles. Waste Manag. 2008;28:2472–82.
[37] Frigione M. Recycling of PET bottles as fine aggregate in concrete. Waste Manag. 2010;30:1101–6.
[38] Çelik Aİ, Özkılıç YO, Zeybek Ö, Karalar M, Qaidi S, Ahmad J, et al. Mechanical behavior of crushed waste glass as replacement of aggregates. Mater (Basel). 2022;15:8093. doi: 10.3390/ma15228093.
[39] Karalar M, Özkılıç YO, Aksoylu C, Sabri MMS, Beskopylny AN, Stel'Makh SA, et al. Flexural behavior of reinforced concrete beams using waste marble powder towards application of sustainable concrete. Front Mater. 2022;9:1068791.
[40] Smol M, Kulczycka J, Henclik A, Gorazda K, Wzorek Z. The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. J Clean Prod. 2015;95:45–54.
[41] Vouk D, Serdar M, Vučinić AA. Use of incinerated sewage sludge ash in cement mortars: Case study in Croatia. Teh Vjesn. 2017;24:43–51.
[42] Johari MAM, Brooks JJ, Kabir S, Rivard P. Influence of supplementary cementitious materials on engineering properties of high strength concrete. Constr Build Mater. 2011;25:2639–48.
[43] Pruckner F, Gjørv OE. Effect of CaCl2 and NaCl additions on concrete corrosivity. Cem Concr Res. 2004;34:1209–17.
[44] Ribeiro DV, Labrincha JA, Morelli MR. Potential use of natural red mud as Pozzolan for Portland cement. Mater Res. 2011;14:60–6.
[45] Abdulkareem OA, Ramli M, Matthews JC. Production of geopolymer mortar system containing high calcium biomass wood

ash as a partial substitution to fly ash: An early age evaluation. Compos. Part B Eng. 2019;174:106941.
[46] Rabie GM. Using of wastewater dry and wet sludge in concrete mix. J Civ Env Eng. 2016;6:1–7.
[47] Monzó J, Payá J, Borrachero MV, Girbés I. Reuse of sewage sludge ashes (SSA) in cement mixtures: The effect of SSA on the workability of cement mortars. Waste Manag. 2003;23:373–81.
[48] Lin DF, Lin KL, Chang WC, Luo HL, Cai MQ. Improvements of Nano-SiO2 on sludge/fly ash mortar. Waste Manag. 2008;28:1081–7.
[49] Monzo J, Paya J, Borrachero MV, Bellver A, Peris-Mora E. Study of cement-based mortars containing Spanish ground sewage sludge ash. Stud Environ Sci. 1997;71:349–54.
[50] Kumar M, Prashant S, Kamath MV. Enhancing the sustainability of high strength concrete in terms of embodied energy and carbon emission by incorporating sewage sludge and fly ash. Innov Infrastruct Solut. 2022;7:240.
[51] de Lima F, Ingunza D, del Pilar M. Effects of sewage sludge ashes addition in Portland cement concretes. Proceedings of the 2nd International Conference on Civil, Materials and Environmental Sciences. Atlantis Press; 2015. p. 189–91.
[52] Monzó J, Paya J, Borrachero MV, Córcoles A. Use of sewage sludge ash (SSA)-cement admixtures in mortars. Cem Concr Res. 1996;26:1389–98.
[53] Erdoğdu Ş, Arslantürk C, Kurbetci Ş. Influence of fly ash and silica fume on the consistency retention and compressive strength of concrete subjected to prolonged agitating. Constr Build Mater. 2011;25:1277–81.
[54] Satish K, Kumar S, Rai B. Self compacting concrete using fly ash and silica fumes as Pozzolanic material. J Eng Technol. 2017;6:394–407.
[55] Azed MA, Ing DS. Properties of concrete containing microwaved sewage sludge ash. J Mech Eng Sci. 2021;15:8469–79.
[56] Ing DS, Chin SC, Guan TK, Suil A. The use of sewage sludge ash (SSA) as partial replacement of cement in concrete. ARPN J Eng Appl Sci. 2016;11:3771–5.
[57] Fontes CMA, Barbosa MC, Toledo Filho RD, Goncalves JP. Potentiality of sewage sludge ash as mineral additive in cement mortar and high performance concrete. Proceedings of the International RILEM Conference on the Use of Recycled Materials in Buildings and Structures. Vol. 8. 2004.
[58] Jamshidi A, Jamshidi M, Mehrdadi N, Shasavandi A, Pacheco-Torgal F. Mechanical performance of concrete with partial replacement of sand by sewage sludge ash from incineration. Proceedings of the Materials Science Forum. Vol. 730. Trans Tech Publ; 2013. p. 462–7.
[59] Haustein E, Kuryłowicz-Cudowska A, Łuczkiewicz A, Fudala-Książek S, Cieślik BM. Influence of cement replacement with sewage sludge ash (SSA) on the heat of hydration of cement mortar. Mater (Basel). 2022;15:1547.
[60] Chang FC, Lin JD, Tsai CC, Wang KS. Study on cement mortar and concrete made with sewage sludge ash. Water Sci Technol. 2010;62:1689–93.
[61] Cyr M, Coutand M, Clastres P. Technological and environmental behavior of sewage sludge ash (SSA) in cement-based materials. Cem Concr Res. 2007;37:1278–89.
[62] Torgal FP, Castro-Gomes JP. Influence of physical and geometrical properties of granite and limestone aggregates on the durability of a C20/25 strength class concrete. Constr Build Mater. 2006;20:1079–88.
[63] Pan S-C, Tseng D-H, Lee C-C, Lee C. Influence of the fineness of sewage sludge ash on the mortar properties. Cem Concr Res. 2003;33:1749–54.
[64] Doh SI, Aizat AM, Chin SC, Jing GQ. Mechanical properties of concrete containing microwaved sewage sludge ash as partial cement replacement. Proceedings of the IOP Conference Series: Earth and Environmental Science. Vol. 244. IOP Publishing; 2019. p. 12027.
[65] Ahmad J, Aslam F, Martinez-Garcia R, De-Prado-Gil J, Qaidi SMA, Brahmia A. Effects of waste glass and waste marble on mechanical and durability performance of concrete. Sci Rep. 2021;11:21525. doi: 10.1038/s41598-021-00994-0.
[66] Sivakandhan C, Murali G, Tamiloli N, Ravikumar L. Studies on mechanical properties of sisal and jute fiber hybrid sandwich composite. Mater Today Proc. 2020;21:404–7.
[67] Huang Y, Huang J, Zhang W, Liu X. Experimental and numerical study of hooked-end steel fiber-reinforced concrete based on the meso-and macro-models. Compos Struct. 2023;309:116750. doi: 10.1016/j.compstruct.2023.116750.
[68] Lee G, Han D, Han M-C, Han C-G, Son H-J. Combining polypropylene and nylon fibers to optimize fiber addition for spalling protection of high-strength concrete. Constr Build Mater. 2012;34:313–20.
[69] Shi T, Liu Y, Hu Z, Cen M, Zeng C, Xu J, et al. Deformation performance and fracture toughness of carbon nanofiber-modified cement-based materials. ACI Mater J. 2022;119:119–28. doi: 10.14359/51735976.
[70] Ray S. Effect of marble particle on physico-mechanical behaviour of glass fiber reinforced epoxy composites. Int J Integr Eng. 2019;11:93–102.
[71] Zhang W, Kang S, Huang Y, Liu X. Behavior of reinforced concrete beams without stirrups and strengthened with basalt fiber–reinforced polymer sheets. J Compos Constr. 2023;27:4023007.
[72] Kutuk M, Oguz Z. A research on effect of sewage sludge ash on the mechanical properties of composite material. Proceedings of the World Congress on Civil, Struct., and Environment Engineering (CSEE'16); 2016.
[73] Udoeyo FF, Dashibil PU. Sawdust ash as concrete material. J Mater Civ Eng. 2002;14:173–6.
[74] Sharbatdar MK, Abbasi M, Fakharian P. Improving the properties of self-compacted concrete with using combined silica fume and metakaolin. Period Polytech Civ Eng. 2020;64:535–544.
[75] Shi T, Lan Y, Hu Z, Wang H, Xu J, Zheng B. Tensile and fracture properties of silicon carbide whisker-modified cement-based materials. Int J Concr Struct Mater. 2022;16:1–13.
[76] Baeza-Brotons F, Garcés P, Payá J, Saval JM. Portland cement systems with addition of sewage sludge ash. Application in concretes for the manufacture of blocks. J Clean Prod. 2014;82:112–24.
[77] Sall M, Traoré A, Wade AC, Gueye PM, Diouf S, Dieye G, et al. Potential use of sewage sludge ash in lime-based materials. Adv Mater. 2021;10:12.
[78] da Cunha Oliveira JV, Chagas LSVB, de Andrade Meira FFD, Carneiro AMP, de Melo Neto AA. Study of the potential of adhesion to the substrate of masonry and tensile in the flexion in mortars of coating with gray of the sewage sludge. Proceedings of the Materials Science Forum. Vol. 1012. Trans Tech Publ; 2020. p. 256–61.

[79] Pavlík Z, Fořt J, Záleská M, Pavlikova M, Trník A, Medved I, et al. Energy-efficient thermal treatment of sewage sludge for its application in blended cements. J Clean Prod. 2016;112:409–19.
[80] Silva RV, De Brito J, Dhir RK. Establishing a relationship between modulus of elasticity and compressive strength of recycled aggregate concrete. J Clean Prod. 2016;112:2171–86.
[81] Katman HYB, Khai WJ, Bheel N, Kırgız MS, Kumar A, Khatib J, et al. Workability, strength, modulus of elasticity, and permeability feature of wheat straw ash-incorporated hydraulic cement concrete. Buildings. 2022;12:1363.
[82] Bheel N, Ibrahim MHW, Adesina A, Kennedy C, Shar IA. Mechanical performance of concrete incorporating wheat straw ash as partial replacement of cement. J Build Pathol Rehabil. 2021;6:1–7.
[83] Gonen T. Freezing-thawing and impact resistance of concretes containing waste crumb rubbers. Constr Build Mater. 2018;177:436–42.
[84] Carmichael MJ, Arulraj GP. Impact resistance of concrete with nano materials. Mater Today Proc. 2021;37:677–84.
[85] Zhang P, Sha D, Li Q, Zhao S, Ling Y. Effect of nano silica particles on impact resistance and durability of concrete containing coal fly ash. Nanomaterials. 2021;11:1296.