Toward Sustainable Lightweight Concrete: Reviewing the Role of Sewage Sludge Ash, Wood Ash, and Metakaolin in Performance Improvement

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Abstract: This review paper examines the novel and sustainable utilization of industrial and agricultural waste materials in the production of Lightweight Concrete (LWC), offering a transformational strategy to tackle environmental and resource efficiency issues in the construction industry. In particular, it looks into using Sewage Sludge Ash (SSA) as a partial replacement for fine aggregate, Wood Ash (WA) as a partial replacement for cement, and Metakaolin (MK) as an extra cementitious material. By incorporating these byproducts, the study emphasizes how they could improve LWC's durability, mechanical qualities, and environmental sustainability. A systematic assessment of existing research critically analyses key performance indicators, including compressive strength, flexural strength, density, water absorption, and resistance to environmental stresses. This thorough examination reveals growing trends, ongoing obstacles, and critical research deficiencies, highlighting the unexploited potential of waste material valorization in promoting sustainable construction practices. The results demonstrate the combined advantages of minimizing environmental impact and ensuring economic feasibility, establishing waste-derived LWC as a crucial solution for a resource-efficient and sustainable building sector. This assessment leads to the development of new, sustainable, and high-performance concrete technologies.

Keywords: *Lightweight Concrete, Sewage Sludge Ash, Wood Ash, Metakaolin, Sustainable Construction.*

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I. INTRODUCTION

The building industry is notorious for its high levels of waste, greenhouse gas emissions, and resource depletion; it is also one of the most ecologically destructive industries. One third of all industrial greenhouse gas emissions come from the production of Portland cement, a ubiquitous building ingredient [1]. In response to these growing concerns about climate change, resource scarcity, and waste buildup, the construction industry is shifting its focus to more sustainable practices in an effort to meet these challenges. This shift must include the use of innovative materials and techniques that strike a balance between performance and environmental stewardship. To improve sustainability and solve important waste management problems, this is where agricultural and industrial byproducts shine. In this review, we will look at a new way to make lightweight concrete (LWC) that uses sewage sludge ash (SSA) instead of fine aggregate, wood ash (WA) instead of cement, and metakaolin (MK) as an additional cementitious element. For building projects that prioritise energy conservation and structural weight reduction, LWC has been a great choice [2]. Low-Width Construction (LWC) is useful in situations where minimising foundation and support structures is essential, such as in tall buildings or regions with poor soil conditions [3]. It's an efficient and practical choice for certain structural and environmental purposes, and it works well in places where lightweight aggregates are easily accessible [4]. We need long-lasting, energy-efficient construction materials, and we need to reduce our waste output and save the environment; our concept aims to address both of these issues simultaneously. There are a few advantages to using partially treated sewage sludge rather than sand. It enables us to dispose of massive volumes of sewage sludge safely; this sludge is then usable to create lightweight aggregate, an essential component of LWC. When the density of aggregates is less than 2000 kg/m³, we classify them as lightweight [5]. We can't make several varieties of LWC without these. Municipal sewage treatment plants produce a byproduct known as sewage sludge [6]. In addition to its pozzolanic properties, this innovative element can serve as a supplementary cementitious material. For example, the dried-out material that is left over from sewage treatment in Japan is turned into Portland cement, which is a clever use of approximately 20% of this waste [7–11]. Binder

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(cement) is the next ingredient; it acts as glue to bind the aggregate particles together, making concrete. Reducing our reliance on pure cement and its environmental impact is possible through the large substitution of WA for cement. Strengthening construction materials is achieved by adding WA to cement. The compressive strength of concrete and mortar produced using this mixture is very high, according to tests, especially after extended curing times [12]. Concrete with wood ash added to it is also resistant to sulphate attack, so it can be used in areas where sulphate exposure is present. As a result of its pozzolanic properties, wood ash filled in spaces and decreased porosity, which decreased permeability and increased durability. Further, MK is thought of as an additional cementitious material to maintain a balance among the materials utilised in LWC production. An overall reduction in hydration steam, improved workability, durability, and early strength are some of the benefits of using MK in concrete. A more circular system can be constructed with the aid of recycling these waste items. Rather than just discarding them, we are repurposing them into useful construction materials. This makes building less harmful to the environment and more cost-effective while simultaneously improving the concrete [13]. This literature review summarises previous work on the topic of how LWC's mechanical characteristics, durability, and ecological sustainability are affected by waste-derived components. Compressive and flexural strengths, density, water absorption, and microstructural changes are among the significant elements that are thoroughly evaluated. The durability of these materials is demonstrated through the use of cutting-edge analytical techniques, including X-ray diffraction (XRD) and scanning electron microscopy (SEM). This review aims to establish a strong foundation for developing efficient, high-performance concrete solutions by integrating findings from existing studies and identifying areas that require additional investigation. Sustainable construction techniques are on the rise, and these solutions aim to fulfil that demand. By combining waste reuse with cutting-edge building technologies, this project finally takes a big step towards creating a built world that is better for the environment and lasts longer.

➢ *Lightweight Concrete (LWC)*

LWC emerges as a promising option, underscoring its significance through the connections it fosters among structural engineering, material science, and sustainability. For an extended period, LWC has been utilised in structural applications. The density of LWC generally ranges from 1400 to 2000 kg/m3, whereas normal-weight concrete (NWC) has a density of 2400 kg/m³.Natural lightweight aggregates like pumice, diatomite, volcanic cinders, and SSA are employed in the production of LWC. LWC has demonstrated its effectiveness as a construction material in scenarios that require significant reductions in structural dead loads and energy conservation, particularly when there is an abundance of local lightweight aggregates [14]. LWC preserves the essential characteristics of conventional concrete, including its compressive strength and durability, while offering advantages like decreased weight, improved thermal insulation, and better acoustic properties. The demand for lightweight concrete in contemporary construction projects is on the rise, as reduced density results in load-bearing components with smaller cross-sections and a subsequent decrease in foundation dimensions [15]. LWC exhibits an extended lifespan compared to conventional concrete, necessitating reduced maintenance and fewer replacements. The composition and qualities of LWC contribute to enhanced durability and weather resistance. Moreover, the application of LWC can enhance the durability and weather resistance of building materials. The unique composition and characteristics of this material can reduce the risk of freeze-thaw damage, corrosion, and various types of degradation, establishing it as a favoured option for numerous construction applications.

On the other hand, the reduced density of LWC can enhance a structure's seismic performance. The capacity of the material to absorb and dissipate energy during seismic events contributes significantly to the resilience of buildings and infrastructure in earthquake-prone areas [16]. Structures situated in regions with severe weather can significantly benefit from this feature, enabling regulation of internal temperature and reducing energy usage for heating and cooling. It helps to make construction more sustainable and energy-efficient [17].

II. CHARACTERISTICS OF WOOD ASH

➢ *Physical Properties*

Particle dimensions exhibit significant variation depending on the combustion temperature of the biomass. According to the report by Etiegni and Campbell et al. [18], the majority of particles in wood waste ash (WWA) are less than 1 mm in size, comprising 80% of the total, while the remainder consists of unburned wood. Approximately 25% of the WWA consists of fine material, specifically particles smaller than 75 micrometres. This ash is absorbent due to its large surface area. The material exhibits a specific gravity of 2.41, a pH of 12.57, an average particle size of 0.223 mm, and a bulk density ranging from 663 to 997 kg/m³. Naik et al. conducted a study on the feasibility of incorporating wood ash in the production of controlled low-strength material (CLSM). Ash samples were collected from five locations in Wisconsin, designated as W1 through W5.The study focused on particle size, specifically the percentage of ash retained on a 45μm sieve. The variation among the samples was significant, with percentages ranging from 23% to 90%. Two sources, W1 and W5, exhibited particle sizes that conformed to the American Society for Testing and Materials (ASTM) standard, with a maximum retention of 34%. Conversely, the remaining three sources, W2, W3, and W4, failed to meet this criterion due to an excessive presence of large particles [19]. Abdullahi and Elinwa conducted an investigation of the physical characteristics of WA in order to determine whether or not it could partially replace cement. The findings of their investigation are summarised in Table 1 [20,21].

➢ *Chemical Properties*

Wood ash exhibits high alkalinity, characterised by a pH range of 9 to 12. The residual ash quantity after combustion diminishes by approximately 45% as the burning temperature increases from 538°C to 1093°C. Increased burning temperatures alter the chemical composition of the ash. The levels of calcium, iron, magnesium, manganese, and

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phosphorus increase, whereas the levels of zinc, potassium, and sodium decrease. Naik et al. [19] analyzed the chemical composition of wood ash from five distinct sources to investigate its applicability in the production of CLSMs. Table 2 presents the chemical composition of the five ash sources analysed. The loss on ignition (LOI) values for these ashes ranged from 6.7% to 58.1%, indicating significant variability in the composition. Stanislav et al. [22] examined peer-reviewed data regarding the chemical composition of 86 types of biomass, including traditional and complete neighbouring, ultimate, and ash analyses. In comparison to coal, natural biomass exhibits higher levels of moisture, volatile matter, calcium, chlorine, hydrogen, potassium, magnesium, manganese, sodium, oxygen, and phosphorus. Consequently, it typically has lower levels of ash, fixed carbon, aluminium, carbon, iron, nitrogen, sulphur, silicon, and titanium. The predominant elements in biomass, listed in descending order, are Mn, K, P, Cl, Ca, followed by Mg and Na, O, moisture, and volatile matter. In contrast, the highest depletion typically indicates S > (ash, Al, Ti) > fixed carbon > (Fe, Si) > C. Jamaluddin and Munirwan [23] examined the chemical composition of WA using X-ray diffraction (XRD) and determined that the primary components were CaO and SiO2 in maximum percentages, while Fe2O3 was present in the least percentage. Furthermore, the ash exhibited a loss on ignition (LOI) of 2.7%, as demonstrated in Table 2.

Table 1 Physical Properties of Wood Ash

Data	**Abdullahi (2006) [20]**	**Etiegni & Campbell et al. (1991), [18]**	**Elinwa & Mahmood (2002). [21]**	**Naik et al. (2004). Sources, (%), [19]**				
				W1	**W2**	**W3**	**W4**	**W5**
Specific gravity	2.13	2.41	2.29	2.26	2.41	2.60	2.26	2.33
Bulk Density kg/m^3	760	663–997	830	-	-	-	-	-
Water requirement, %	-	-	-	115	155	115	126	130
ph	-	12.57	10.10	-	-	-	-	-
Unit weight, kg/m^3	-	-	-	545	412	1376	509	162

Table 2 Chemical Composition of Wood Ash

Elements	**(Stanislav et al. 2010).**	**Jamaluddin & Munirwan (2022)**	**Naik et al. (2003). Sources, (%)**				
			W_1	**W_2**	**W_3**	**W_4**	**W_5**
SiO_2	53.15%	25.8%	32.4	13.0	50.7	30.0	8.1
TiO_2	0.57%	-	-	-	-	-	-
Al_2O_3	12.64%	14.72%	17.1	7.8	8.2	12.3	7.5
Fe_2O_3	6.24%	0.95%	9.8	2.6	2.1	14.2	3.0
CaO	11.66%	29.8%	3.5	13.7	19.6	2.2	25.3
MgO	3.06%	5.25%	0.7	2.6	6.5	0.7	4.5
Na_2O	4.47%	7.5%	0.9	0.6	2.1	0.5	3.3
K_2O	4.85%	9.55%	1.1	0.4	2.8	2.0	2.7
P_2O_5	1.37%	-	-	-	-	-	-
SO_3	1.99%	-	-	-	-	-	-
LOI	-	2.7	31.6	58.1	6.7	35.3	32.8

III. STRENGTH CHARACTERISTICS OF CONCRETE USING WA AS A PARTIAL REPLACEMENT

The mechanical properties of concrete that have been increased with WA as an SCM are investigated in this section. These properties have been the subject of much research and significance. The discussion is founded on a comprehensive examination of previous research, which encompasses a diverse range of investigations into the application of WA in both conventional and LWC concrete formulations. Key mechanical properties that are evaluated include water absorption capacity, flexural and compressive strength, and susceptibility to alkali-silica reactions. The objective of this review is to offer a nuanced comprehension of how wood ash affects these critical parameters in concrete performance.

➢ *Water Absorption*

Elinwa and Ejeh [24] investigated the impact of incorporating wood waste ash (WWA) as a partial replacement for cement in mortar mixtures, with a specific focus on water absorption characteristics. Two distinct mortar formulations were prepared, maintaining identical mix proportions except for the binder composition. The first mixture utilized cement as the sole binding agent, while the second replaced 15% of the cement by weight with WWA. Experimental findings demonstrated that the integration of WWA at a 15% substitution level effectively reduced the water absorption capacity of the mortar. The average water absorption rates for the mixtures containing 15% WWA and those without WWA were recorded at 0.75% and 1.30%, respectively. Notably, both formulations exhibited water absorption values well below the 10% threshold, which is considered the upper limit for acceptable performance in this context. This suggests that WWA not only serves as a viable supplementary cementitious material but also enhances the durability of mortar by mitigating water absorption.

Wa=M2−M1÷ M1× 100, where Wa=water absorption; M1andM2=mass of the specimen before and after water immersion.

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Fig 1 Percentage of Water Absorption Versus Ash Content of WWA Concrete. [25]

➢ *Flexural Strength*

Udoeyo et al. [25] evaluated the flexural strength of concrete mixtures incorporating waste wood ash (WWA) as a partial replacement for cement at varying percentages (5%, 10%, 15%, 20%, 25%, and 30% by weight of cement). The results, presented in Table 3, indicate a link between the trends in flexural strength and those in compressive strength. The flexural strength showed a steady decrease with increasing WWA concentration, although the reduction rate was less significant than that of the compressive strength. The 28-day flexural strength of concrete containing 5% WWA was recorded at 5.20 N/mm², which diminished to 3.74 N/mm² with 30% WWA concentration. The flexural strength of WWA-modified concrete was observed to be between 67% and 93% of the strength attained by the control mix (without WWA) during comparable curing durations and replacement ratios. These findings emphasise the promise of WWA as a sustainable additive and its impact on the mechanical properties of concrete.

Table 3 Flexural Strength of Concrete Incorporating WWA as an Additive [25].

WWA (%)	3 d	7 d	14 d	21 d	28 d
0	4.45 ± 0.04*	4.93 ± 0.15	5.44 ± 0.42	5.46 ± 0.03	5.57 ± 0.05
5	4.34 ± 0.02	4.67 ± 0.27	5.04 ± 0.20	5.18 ± 0.01	5.20 ± 0.01
10	3.81 ± 0.02	3.92 ± 0.07	3.99 ± 0.03	4.08 ± 0.09	4.28 ± 0.09
15	3.75 ± 0.06	3.91 ± 0.03	3.97 ± 0.04	4.01 ± 0.15	4.04 ± 0.04
20	3.64 ± 0.04	3.76 ± 0.04	3.79 ± 0.05	3.80 ± 0.05	3.85 ± 0.08
25	3.51 ± 0.02	3.53 ± 0.07	3.55 ± 0.04	3.57 ± 0.03	3.73 ± 0.03
30	3.65 ± 0.06	3.66 ± 0.02	3.69 ± 0.03	3.71 ± 0.05	3.74 ± 0.03

Note: Values Represent Mean ± Standard Deviation.

The experimental findings demonstrate a consistent linear relationship between compressive and flexural strength, indicating a proportional interdependence between these two mechanical properties. This relationship was further quantified through regression analysis, which established a predictive model linking the two parameters.

$$Ff = 0.234fcu - 0.908 \quad (R2 = 0.94)$$

Where Ff is the flexural strength, and Fcu is the compressive strength in N/mm2.

➢ *Compressive Strength*

Abdullahi [20] examined the compressive strength characteristics of concrete utilising WA as a partial replacement for cement. The study entailed substituting cement with WA at different percentages (0%, 10%, 20%, 30%, and 40%) in a concrete mixture with a ratio of 1:2:4. Compressive strength tests were performed at 28 and 60 days of curing, with results presented in Table 4. The results indicated that the control mix, comprising 0% WA, attained the maximum compressive strength. The 20% WA mix exhibited more strength than the 10% WA mix at both 28 and 60 days. This behaviour was attributed to the inadequate silica content in the 10% WA mixture, which limited its ability to react completely with the calcium hydroxide produced during cement hydration.

Nevertheless, when the WA concentration exceeded 20%, a reduction in compressive strength was observed at both curing ages. This reduction was associated with an excess of silica in the mixture, which, above the ideal threshold, ceased to facilitate pozzolanic processes and functioned solely as an inert filler. The 20% WA mix demonstrated a substantial improvement in compressive strength at 60 days, indicating that extended curing durations improve the material's performance. The study determined that a 20% cement replacement level with WA is ideal, achieving a balance between pozzolanic reactivity and mechanical characteristics.

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Table 4 Compression strength of WA concrete, [20].

WA content (%)	28-day (N/mm²)	60-day (N/mm²)
0	23.96	24.15
10	13.09	14.06
20	14.13	18.6
30	9.02	7.91
40	8.59	7.82

➢ *Alkali–Silica Reaction (ASR)*

Baxter and Wang [34] examined the expansion behaviour of mortar mixtures influenced by alkali-silica reaction (ASR), employing a highly reactive opal aggregate and a high-alkali cement. The study included three distinct types of fly ash (FA), with WA being a specific type of FA produced from the combustion of coal or burning coal in power plants. With the exact amounts of each item, four different mortar combinations were made. Portland cement was the only component of the first mixture, which served as the control and was used as the sample for comparison. The other three mixtures incorporated various types of fly ash as a partial replacement for cement, maintaining a consistent dosage of 35% by weight of the total mixture. Experimental results demonstrated that coal fly ash exhibited a greater concentration of alkaline components in comparison to Class C fly ash. The inclusion of coal fly ash in mortar mixtures effectively reduced ASR-induced expansion to below 0.1% (the ASTM C33 threshold) at 180 days, in contrast to the 0.27% expansion recorded in the control mixture utilising only Portland cement as the binder and in terms of reducing expansion caused by ASR, coal fly ash outperformed all other types of fly ash tested, suggesting that it could be a sustainable ingredient that cementitious materials can use to last longer.

IV. CHARACTERISTICS OF SEWAGE SLUDGE ASH

➢ *Chemical Properties of SSA*

Azarhomayun et al. [34] reported that the chemical properties of sewage sludge ash (SSA) as a partial replacement for sand in concrete production were extensively analysed. SSA is primarily composed of silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO), which are key components contributing to its pozzolanic and cementitious properties. These elements enable SSA to participate in secondary hydration reactions with calcium hydroxide ($Ca(OH)_2$) formed during cement hydration, thereby enhancing the mechanical performance and durability of concrete. Table 5 presents the results of previous authors regarding chemical properties.

Table 5 Chemical Properties of Sewage Sludge Ash (SSA), [35-38]

Elements	Chang et al. (2010)	Maozhe et al. (2013)	Kazberuk, (2011)	Azarhomayun et al. (2023)
SiO_2	20.10%	30.10%	34.65%	25.3%
TiO_2	1.90%	0.71%	0.41%	0.77%
Al_2O_3	4.47%	26.30%	6.32%	7.7%
Fe_2O_3	17.20%	5.63%	10.32%	6.12%
CaO	30.49%	7.35%	15.42%	23.7%
MgO	12.98%	4.30%	2.65%	2.86%
Na_2O	1.57%	2.53%	0.70%	1.23%
K_2O	0.06%	10.90%	1.30%	1.81%
P_2O_5	0.25%	11.80%	18.17%	13.6%
SO_3	1.83%	0.13%	0.60%	5.9%
LOI	-	-	8.65%	10.02%

➢ *Physical Properties of SSA*

Al-Sharif and Attom [39] conducted a detailed analysis of the granular and morphological characteristics of sewage sludge ash (SSA). Their findings indicated that SSA possesses a fine, granular consistency, with particle sizes typically falling within the range of 10 to 100 micrometres and a specific gravity of 2.60; this size distribution aligns it closely with fine sand or cement, making it a feasible alternative in construction applications. The study also highlighted the porous nature of SSA, which enhances its surface area and reactivity, thereby promoting its interaction with cementitious materials. However, this porosity contributes to a reduced bulk density compared to conventional natural sand, which may affect the workability and overall density of concrete mixes. Additionally, other researchers analyzed the physical properties of SSA and listed them in Table 6.

Table 6 Physical Properties of Sewage Sludge Ash (SSA), [39-42].

Parameters	Al-Sharif & Attom (2014)	Chen & Poon (2017_	Cyr et al. (2007)	Coutand et al. (2006)
Specific gravity	2.60	2.33	-	-
Moisture content, %	0.28	-	-	-
Bulk specific gravity	1.82	-	-	-
Mean diameter(μm)	-	60	26	26
BET surface area (m^2/g)	-	13293	19000	19000
Density	-	-	2.64	2.64

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V. STRENGTH CHARACTERISTICS OF CONCRETE USING SSA AS PARTIAL REPLACEMENT FOR SAND

The investigation into the effects of SSA on concrete has examined multiple methodologies, such as utilizing it as a partial replacement for the primary binder, incorporating it directly without removing fine aggregate, and partially substituting fine aggregate. Research indicates that the inclusion of SSA in concrete or mortar may lead to a decrease in durability, as noted by Chen et al. [40]. According to Halliday et al., substituting 10% of the primary binder with sewage sludge ash (SSA) results in a slight reduction in strength, ranging from 4% to 8% compared to the standard mix. When the SSA content is increased to 20%, a notable decrease in strength is observed, with reductions ranging from 23% to 29% [44]. The compressive strength of concrete incorporating SSA as fine aggregates exhibits a direct correlation with the quantity of SSA utilised. It has been reported that an increased proportion of SSA as a partial replacement results in reduced strength [45]. During the curing process, the compressive strength of the concrete progressively increases. The standard control sample demonstrates this tendency, as it does not include any sewage sludge ash (SSA). When the curing time is extended appropriately, the durability of SSA-mixed concrete closely resembles that of the control samples, exhibiting only minor discrepancies between the two [46]. Perez et al. found that replacing 10% of the aggregate with SSA resulted in a 25% increase in compressive strength compared to conventional concrete mixtures. The findings outlined in this document demonstrate that SSA-based materials possess the potential for use in construction applications, as their characteristics—including strength, thermal conductivity, and water resistance—align with the established performance standards [47]. The negative impact of SSA on concrete strength is likely attributed to the pozzolanic reaction. This reaction takes place when the chemicals present in SSA interact with cement, resulting in the formation of a binder that enhances the overall binding material. In instances where SSA exhibits a low calcium oxide (CaO) percentage, the incorporation of pozzolanic cement into the concrete mix serves as a viable solution. For instance, incorporating 3% SSA (containing 6.2% CaO) into the entire new concrete mass, without removing any aggregate, resulted in hardened samples exhibiting nearly double the strength of control samples produced with pozzolanic cement. This illustrates the capability of SSA to enhance concrete durability when utilised correctly [48]. The mechanical properties of concrete can be enhanced by incorporating a small amount of sewage sludge ash (SSA) into the cement mixture. As the SSA content increases, the mixture necessitates a higher water content during preparation, resulting in a noticeable shrinkage of the final product as it cures. This suggests that although SSA can enhance concrete performance in moderate quantities, higher levels may lead to practical difficulties. Chen and Poon [40].

Furthermore, the incorporation of SSA into concrete utilised for prefabricated elements or blocks results in a reduction of thermal conductivity. This phenomenon occurs due to the decreased porosity and increased compactness of the mixture, which enhances its insulating characteristics [49]. In summary, Figure 2 illustrates the compressive strength characteristics of concrete incorporating SSA as a partial sand replacement, as reported by various researchers across different binder types. However, an increase in the quantity of sewage sludge ash (SSA) resulted in a more significant decrease in compressive strength. After 28 days, the compressive strength of mortar samples decreased by up to 65%, 47%, and 38% when the proportion of SSA in the mix was 50%, 30%, and 20%, respectively. Replacing more than 20% of cement with SSA in mortar may result in considerable difficulties in preserving strength [50].

➢ *Permeability*

Azarhomayun et al. [35] The data indicate that concrete mixtures containing sewage sludge ash (SSA) demonstrated lower permeability than the control specimen with 0% SSA. The mixture with the highest SSA content (30%) exhibited the lowest water penetration, suggesting that the incorporation of SSA particles significantly improves the impermeability of the concrete. Figure 4 illustrates that the reduction in permeability was more significant in mixtures with 10%, 20%, and 30% substitutions of SSA compared to those with 5% and 15% substitutions. This trend suggests that increased SSA content significantly enhances the concrete's resistance to water penetration, a crucial characteristic for applications requiring water-resistant properties. The incorporation of up to 5% SSA demonstrated a minimal impact on permeability, underscoring the necessity of optimising SSA levels to attain targeted performance results. The findings highlight the potential of SSA as a sustainable additive to improve the durability and functionality of concrete in water-resistant environments. Figure 3 illustrates the results of the permeability tests.

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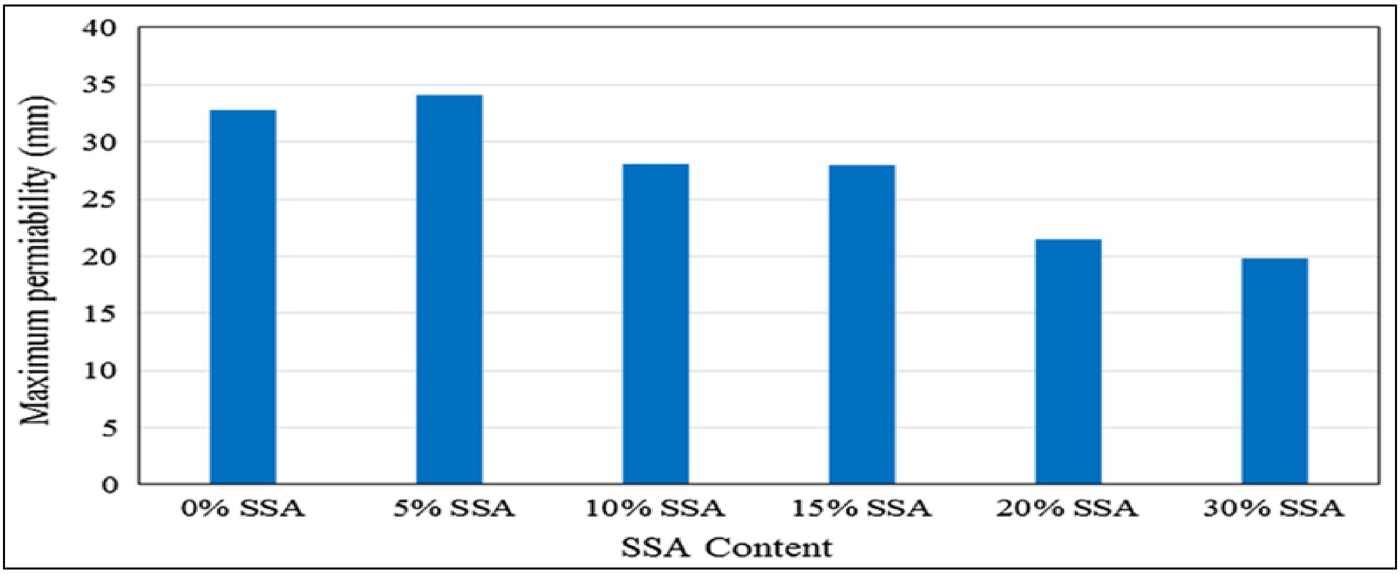


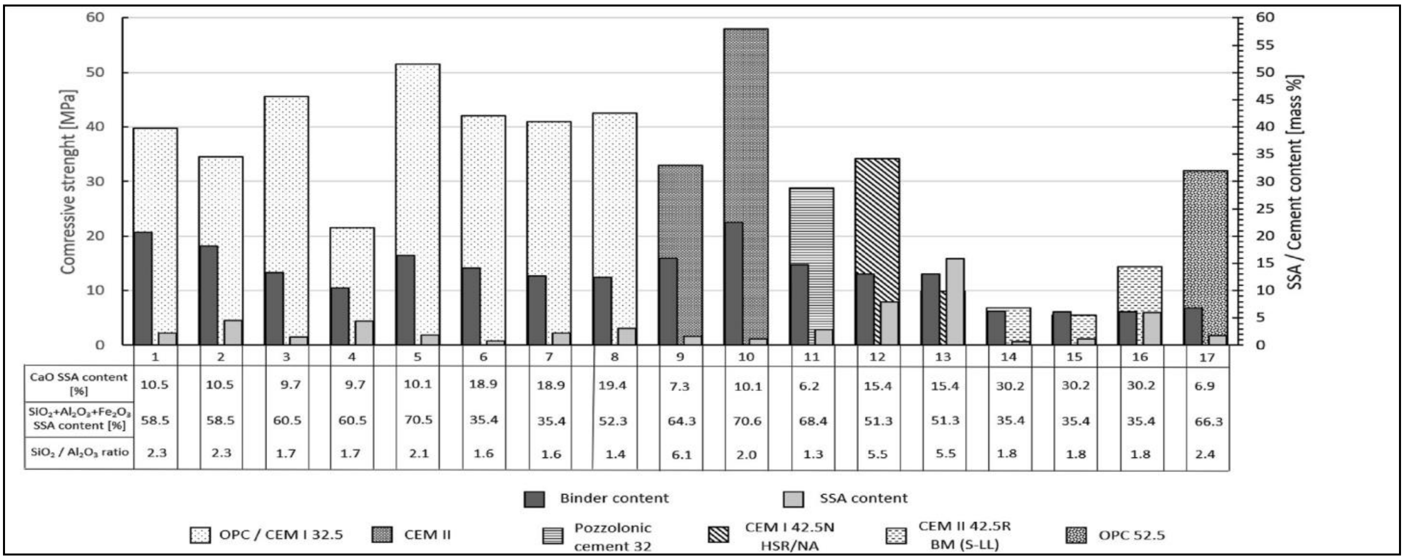
Fig 2 Results of the Water Permeability Test

VI. CHARACTERISTICS OF METAKAOLIN AS SUPPLEMENTARY CEMENTITIOUS MATERIAL

➢ *Compressive Strength*

The incorporation of MK as a partial substitute for cement improved the compressive strength of concrete. The optimal long-term strength performance was achieved by substituting approximately 20% of ordinary Portland cement (OPC) with MK. Beyond this perspective, the benefits seemed to decrease [51]. Jin and Li demonstrated that the incorporation of metakaolin into concrete markedly enhances its strength and modulus of elasticity, particularly during the initial curing phase. Metakaolin significantly enhances the mechanical properties of young concrete relative to alternative materials [52]. Poon et al. found that concrete incorporating MK components in proportions ranging from 0% to 20% exhibited a notable pattern of strength variations when exposed to high temperatures of up to 800°C. The compressive strength of MK concrete initially increased at 200°C, but then experienced a significant decline. All high-strength concrete (HSC) samples, except those subjected to 400°C, exhibited a notable reduction in compressive strength, accompanied by extensive cracking and explosive spalling. In the temperature range of 400-800°C, MK-based concrete exhibited greater strength loss and lower residual strength compared to other types of concrete [53,54].

Ramezanianpour and Jovein [55] examined the impact of metakaolin, utilised as a supplementary cementing material, on the strength and durability of concrete. The compressive strength of the samples was assessed at various curing durations: 7, 28, 90, and 180 days of water curing. Three samples were tested for each curing duration, and the average results are presented in Figure 4. The compressive strength of concrete improved with an extended curing period and a reduced water-to-binder (w/b) ratio. This study found optimal results with metakaolin replacing 12.5% of cement at a water-to-binder ratio of 0.4 and 10% at a ratio of 0.35. The identified replacement levels achieved an optimal balance for strength enhancement.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
CaO SSA content [%]	10.5	10.5	9.7	9.7	10.1	18.9	18.9	19.4	7.3	10.1	6.2	15.4	15.4	30.2	30.2	30.2	6.9
$SiO_2+Al_2O_3+Fe_2O_3$ SSA content [%]	58.5	58.5	60.5	60.5	70.5	35.4	35.4	52.3	64.3	70.6	68.4	51.3	51.3	35.4	35.4	35.4	66.3
SiO_2 / Al_2O_3 ratio	2.3	2.3	1.7	1.7	2.1	1.6	1.6	1.4	6.1	2.0	1.3	5.5	5.5	1.8	1.8	1.8	2.4

Fig 3 Compressive Strength and Shares of Binders and SSA in Concretes Based on Various Cement Binders after 28 Days of Curing [44-50]

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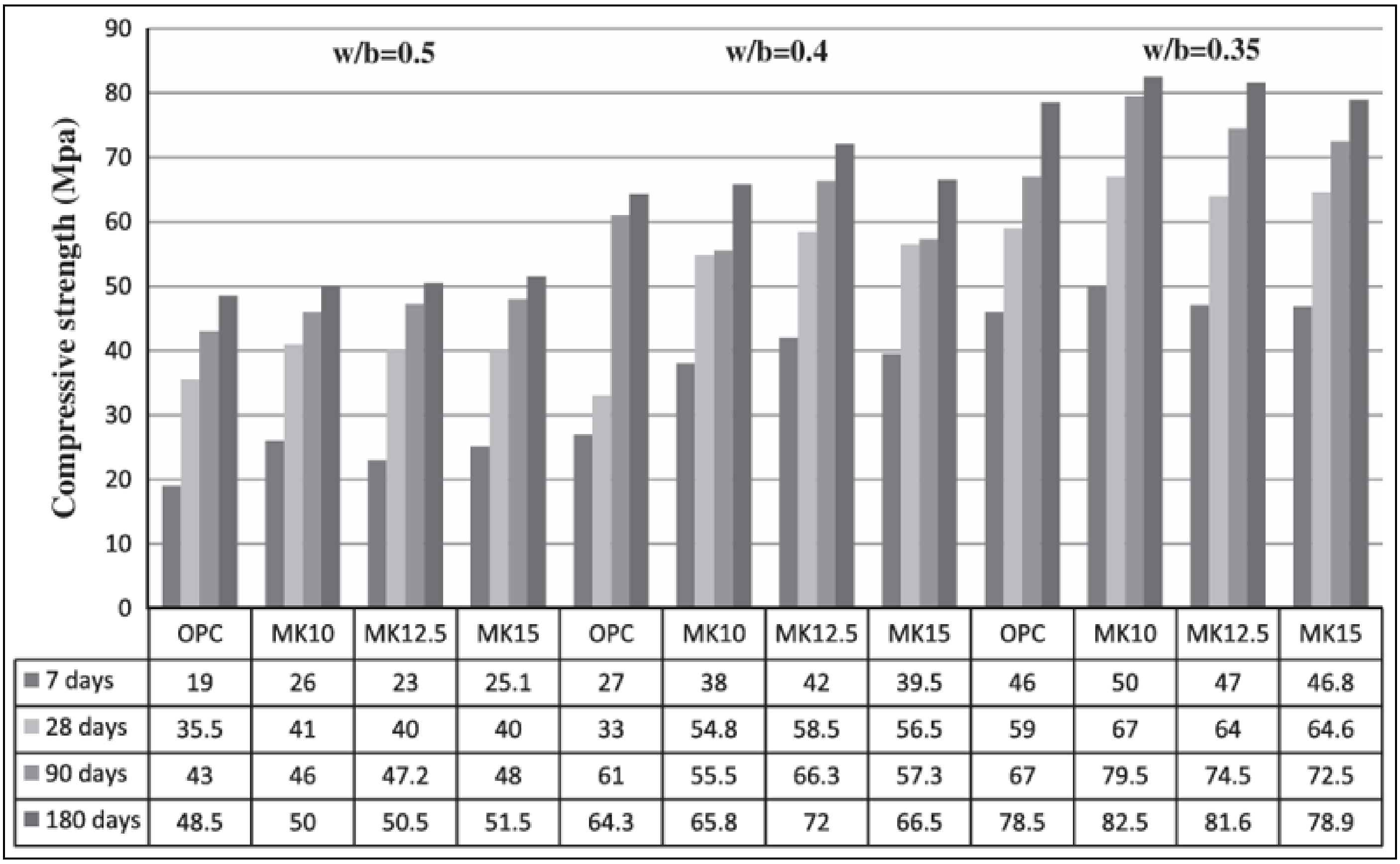

Fig 4 The Effect of MK on the Compressive Strength at Various Ages.

➢ *Tensile Strength*

In their study [56], Qian and Li investigated the degree to which the tensile strength of concrete was affected by substituting metakaolin for cement at 0%, 5%, 10%, and 15% levels. As the amount of metakaolin in the material increased, they observed that the tensile strength improved consistently. The bending strength was not significantly affected by a 5% replacement; however, greater replacements of 10% and 15% led to considerable improvements, resulting in increases of 32% and 38%, respectively, in the 28-day bending strength. Dinakar et al. [57] found that their metakaolin-based concrete had an average 28-day tensile strength of 4.85 MPa, which was approximately 5.15% of its compressive strength at the same mix proportions and metakaolin content. Table 6 contains a summary of both sets of findings.

Table 7 Tensile Strength of Concrete with Different MK Substitution

Metakaolin contents (% mass) at 28 Days				
Name	**0%**	**5%**	**10%**	**15%**
Qian & Li [56]	3.35 Mpa	3.58 Mpa	3.88 Mpa	4.29 Mpa
Dinakar et al. [57],	4.76 Mpa	4.78 Mpa	5.19 Mpa	4.69 Mpa

➢ *Sulphate Resistance*

Khatib and Wild [58] investigated the effect of metakaolin (MK) on the sulfate resistance of mortar. They found that adding metakaolin to two types of cement—one with high C3A content and another with intermediate C3A content—gradually reduced mortar expansion as the MK content increased (ranging from 5% to 20%). Similarly, Roy et al. [59] observed that replacing cement with MK improved the chemical resistance of mortars compared to those made with standard Portland cement. These findings highlight the potential of metakaolin to enhance the durability of cement-based materials.

➢ *Flexural Strength*

Pillay et al. [60] conducted a study to investigate the effect of varying metakaolin (MK) substitution levels on the flexural strength of concrete. They found that all mixes containing MK showed higher flexural strengths at 28 and 56 days compared to the control mix with 0% MK. The 10% MK mix achieved the highest flexural strength at 7 days, while the 5% MK mix performed best at 28 and 56 days. The differences between the highest and lowest flexural strengths were 0.76 MPa (6.38–5.62) at 7 days, 0.6 MPa (7.93–7.33) at 28 days, and 0.67 MPa (8.35–7.68) at 56 days, indicating minimal variation in the results. This consistency may be due to the curing process, where concrete beam samples were removed from the curing bath after 7 days and then moist cured under damp sacks until 28 and 56 days. As shown in Fig. 5, the results indicate that MK has a slight but noticeable effect on enhancing both the short-term and long-term flexural strength of concrete.

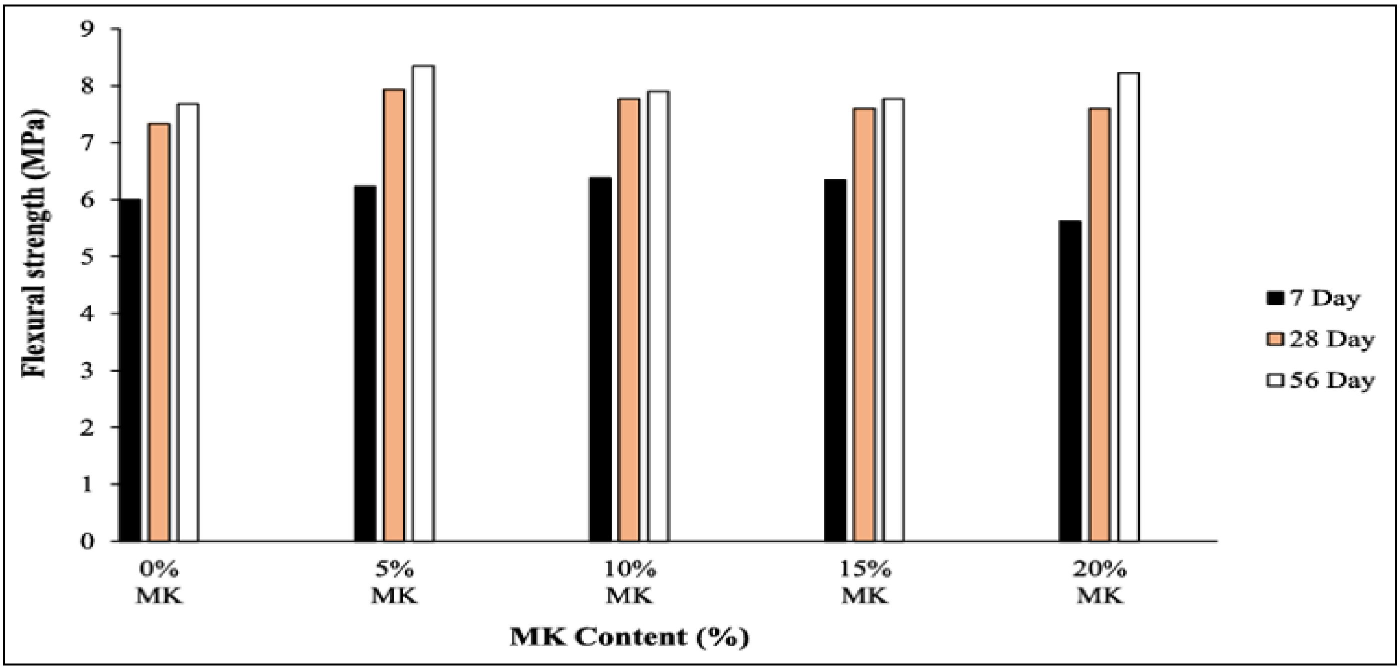

Fig 5 Flexural Strength Results in Different MK Substitutions at (7, 28 & 56 Days).

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VII. OBSERVATIONS AND CONCLUSIONS

This review presents a novel method, investigating the integrated use of SSA, WA, and MK in lightweight concrete—a combination that remains underexplored in existing research. Current research endorses SSA as a viable alternative for fine aggregate and WA as a partial substitute for cement, both of which enhance sustainability through the recycling of industrial wastes. When utilised separately, these materials encounter challenges including diminished mechanical performance, heightened porosity, and potential durability issues. To mitigate these drawbacks, MK serves as an auxiliary cementing component, enhancing strength, improving the microstructure, and augmenting durability over time due to its pozzolanic properties.

This study underscores the necessity of conducting additional experimental research to validate the theoretical advantages of this material combination, particularly in optimising mix proportions, assessing durability under various environmental conditions, and determining the long-term reliability of the structure.

This research examines the impact of different waste materials on the technical properties of lightweight concrete (LWC), namely its strength, durability, and microstructure, based on extensive tests. A thorough assessment of previous studies has been conducted, yielding essential characteristics for each of these three drugs.

Research consistently indicates that the partial substitution of concrete with MK enhances its compressive and flexural strength, particularly at replacement levels of 5-20%.

While SSA improves thermal conductivity and density in lightweight concrete, it may weaken strength at elevated replacement ratios.

When utilised as a partial cement alternative, WA contributes to sustainability; nevertheless, it must be optimised to prevent considerable reductions in strength.

REFERENCES

[1]. O. Zaid, R.M. Garcia, and F. Aslam, "Influence of Wheat Straw Ash as Partial Substitute of Cement on Properties of High-Strength Concrete Incorporating Graphene Oxide," in *Journal of Materials in Civil Engineering,* Vol.34, (2022) https://doi.org/10.1061/(ASCE)MT.1943-5533.0004415

[2]. S.A. Nia, and M.N. Chari, "Applied development of sustainable-durable high-performance, lightweight concrete: Toward low carbon footprint, durability, and energy saving," in *Results in Materials,* Vol.20, (2023) https://doi.org/10.1016/j.rinma.2023.100482

[3]. A.M. Mohamed, B.A. Tayeh, Y.I.A. Aisheh, and M.N.A. Salih, "Exploring the performance of steel fibre reinforced lightweight concrete: A case study review," in *Case studies in Construction Materials,* Vol.18, (2023) https://doi.org/10.1016/j.cscm.2023.e01968

[4]. Z. Dong, T. Han, B. Zhang, H. Zhu, G. Wu, Y. Wei, and P. Zhang, "A review of the research and application progress of new types of concrete-filled FRP tubular members," in *Construction and building materials,* Vol.312, (2021) https://doi.org/10.1016/j.conbuildmat.2021.125353

[5]. I. Sims, J. Lay, and J. Ferrari, "Concrete Aggregates," in *Lea's Chemistry of Cement and Concrete,* Vol. 5, pp. 699-778. (2019) https://doi.org/10.1016/B978-0-08-100773-0.00015-0
[6]. B.L.A. Tuan, C.L. Hwang, K.L. Lin, Y.Y. Chen, and M.P. Young, "Development of lightweight aggregate from sewage sludge and waste glass powder for concrete," in *construction and building materials,* Vol.47, pp. 334-339. (2013) https://doi.org/10.1016/j.conbuildmat.2013.05.039
[7]. A. Gherghel, C. Teodosiu, and S.D. Gisi, "A review on wastewater sludge valorisation and its challenges in the context of circular economy," in *Journal of cleaner production,* Vol.228, pp. 244-263. (2019) https://doi.org/10.1016/j.jclepro.2019.04.240
[8]. C.J. Lynn, R.K. Dhir,G.S. Ghataora, and R.P.West, "Sewage sludge ash characteristics and potential for use in concrete," in *construction and building materials,* Vol.98, pp.767-779, (2015) https://doi.org/10.1016/j.conbuildmat.2015.08.122
[9]. P.W. Ken, M. Ramli, and C.C. Ban, "An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products," in *construction and building materials,* Vol.77, pp. 370-395, (2015) https://doi.org/10.1016/j.conbuildmat.2014.12.065
[10]. V. Mymrin, and S.M. Correa, "New construction material from concrete production and demolition wastes and lime production waste," in *construction and building materials,* Vol.21, pp. 578-582, (2007) https://doi.org/10.1016/j.conbuildmat.2005.09.007
[11]. L. M. Ottosen, I. M.G. Bertelsen, P. E. Jensen, and G.M Kirkelund, "Sewage sludge ash as resource for phosphorous and material for clay brick manufacturing," in *construction and building materials,* Vol. 249, (2020) https://doi.org/10.1016/j.conbuildmat.2020.118684
[12]. B.D. Ikotun, and A.A. Raheem,"Characteristics of Wood Ash Cement Mortar Incorporating Green-Synthesized Nano-TiO_2," in *International Journal of Concrete Structures and Materials,* (2021) https://doi.org/10.1186/s40069-021-00456-x
[13]. M.Behera,S.K. Bhattacharyya, A.K. Minocha, R. De oliya, and S. Maiti, "Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review," in *construction and building materials,* Vol.68, pp. 501-516. (2014) https://doi.org/10.1016/j.conbuildmat.2014.07.003
[14]. M.J. Shannag, "Characteristics of lightweight concrete containing mineral admixtures," in *construction and building materials,* Vol.25, pp. 658-662, (2011) https://doi.org/10.1016/j.conbuildmat.2010.07.025
[15]. B. Chen, and J. Liu, "Experimental application of mineral admixtures in lightweight concrete with high strength and workability," in *construction and building materials,* Vol.22, pp. 1108-1113, (2008) https://doi.org/10.1016/j.conbuildmat.2007.03.001
[16]. O. Hamdy, A. Elghandour, M. Nabil, and M. Lasheen, "Moment Redistribution and Ductility of Self-Compacting Lightweight Reinforced Concrete Continuous Beams," in *Iabse Conference, Sharm el Sheikh,* (2012).
[17]. J. Lee, T. Lee, J. Jeong, and J. Jeong, "Sustainability and performance assessment of binary blended low-carbon concrete using supplementary cementitious materials," in *Journal of Cleaner Production,* Vol. 280, (2021) https://doi.org/10.1016/j.jclepro.2020.124373
[18]. L. Etiégni, and A.G. Campbell, "Physical and chemical characteristics of wood ash," in *Bioresource Technology,* Vol. 37, pp.173-178, (1991) https://doi.org/10.1016/0960-8524(91)90207-Z
[19]. T.R. Naik, R.N. Kraus, R. Siddique, and Y.M. Chun, "Properties of Controlled Low-Strength Materials Made with Wood Fly Ash," in *Journal of ASTM International,* Vol.1, pp.1-10, (2004) https://doi.org/10.1520/JAI11871
[20]. M. Abdullahi, "Characteristics of wood ash/OPC concrete," in *Leonardo Electronic Journal of Practices and Technologies,* Vol.8, pp. 9-16, (2006).
[21]. A.U. Elinwa, and Y.A. Mahmood, "Ash from timber waste as cement replacement material," in *Cement & Concrete Composites,* Vol. 24, pp.219-222, (2002) https://doi.org/10.1016/S0958-9465(01)00039-7
[22]. S.V. Vassilev, D. Baxter, L.K. Andersen, and C.G. Vassileva, "An overview of the chemical composition of biomass," in *Fuel,* Vol.89, pp. 913-933, (2010) https://doi.org/10.1016/j.fuel.2009.10.022
[23]. K. Jamaluddin, and R.P. Munirwan, "Improvement of geotechnical properties of clayey soil with saw dust ash stabilization," in *E3S Web of Conferences,* Vol.340, (2022) https://doi.org/10.1051/e3sconf/202234001009
[24]. A.U. Elinwa, and S.P. Ejeh, "Effects of the Incorporation of Sawdust Waste Incineration Fly Ash in Cement Pastes and Mortars," in *Journal of Asian Architecture and Building Engineering,* Vol.3, (2004) https://doi.org/10.3130/jaabe.3.1
[25]. F.F. Udoeyo, H. Inyang, D.T. Young, and E.E. Oparadu, "Potential of Wood Waste Ash as an Additive in Concrete," in *Journal of Materials in Civil Engineering,* Vol.18, (2006) https://doi.org/10.1061/(ASCE)0899-1561(2006)18:4(605)
[26]. K. Ohenoja, P. Tanskanen, V. Wigren, P. Kinnunen, M. K¨orkk¨o, O. Peltosaari, J. ¨Osterbacka, M. Illikainen, "Self-hardening of fly ashes from a bubbling fluidized bed combustion of peat, forest industry residuals, and wastes," in *Fuel,* Vol. 165, pp.440-446, (2016) doi.org/10.1016/j.fuel.2015.10.093
[27]. J. Fort, J. ˇ S´ al, R. ˇ Sevˇ cík, M. Doleˇzelov´ a, M. Keppert, M. Jerman, M. Z´ alesk´ a, V. Stehel, R. ˇ Cerný, "Biomass fly ash as an alternative to coal fly ash in blended cements: Functional aspects," in *construction and building materials,* Vol.271, (2021) doi.org/10.1016/j.conbuildmat.2020.121544

[28]. S. Maschio, G. Tonello, L. Piani, E. Furlani, "Fly and bottom ashes from biomass combustion as cement replacing components in mortars production: Rheological behaviour of the pastes and materials compression strength," in *Chemosphere,* vol.85, pp.666-671, (2011) https://doi.org/10.1016/j.chemosphere.2011.06.070

[29]. M. Berra, T. Mangialardi, A.E. Paolini, "Reuse of woody biomass fly ash in cement-based materials," in *construction and building materials,* Vol. 76, (2015) https://doi.org/10.1016/j.conbuildmat.2014.11.052

[30]. M. da L. Garcia, J. Sousa-Coutinho, "Strength and durability of cement with forest waste bottom ash," in *construction and building materials,* Vol. 41, (2013) https://doi.org/10.1016/j.conbuildmat.2012.11.081

[31]. M. Pavlíkov´a, L. Zemanov´a, J. Pokorný, M. Z´ alesk´a, O. Jankovský, M. Lojka, D. Sedmidubský, Z. Pavlík, "Vaporization of wood chips ash as an eco-friendly mineral admixture in mortar mix design," in *Waste Management,* Vol. 80, pp.89-100, (2018) https://doi.org/10.1016/j.wasman.2018.09.004

[32]. E.R. Teixeira, A. Cam˜oes, F.G. Branco, "Valorisation of wood fly ash on concrete," in *Resources, conservation and Recycling,* Vol.145, (2019) https://doi.org/10.1016/j.resconrec.2019.02.028

[33]. J. Monzo, J. Paya, M.V. Borrachero, and I. Girbes, "Reuse of sewage sludge ashes (SSA) in cement mixtures: the effect of SSA on the workability of cement mortars," in *Waste Management,* Vol.23, pp.373-381, (2003) https://doi.org/10.1016/S0956-053X(03)00034-5

[34]. S. Wang, and L. Baxter, "Comprehensive study of biomass fly ash in concrete: Strength, microscopy, kinetics and durability," in *Fuel Processing Technology,* Vol.88, pp.1168-1170, (2007) https://doi.org/10.1016/j.fuproc.2007.06.016

[35]. F. Azarhomayun, M. Haji, M. Kioumarsi, and A. Kheyroddin, "Combined Use of Sewage Sludge Ash and Silica Fume in Concrete," in *International Journal of Concrete Structures and Materials,* vol.17, (2023) https://doi.org/10.1186/s40069-023-00593-5

[36]. C. Maozhe, B. Denise, G. Mathieu, M. Jacques, and G. Rémy, "Environmental and technical assessments of the potential utilization of sewage sludge ashes (SSAs) as secondary raw materials in construction," in *Waste Management,* Vol. 33, pp. 1268-1275, (2013) https://doi.org/10.1016/j.wasman.2013.01.004

[37]. M.K. Kazberuk, "Application of SSA as Partial Replacement of Aggregate in Concrete," in *Polish J. of Environ. Stud.* Vol. 20, No. 2 (2011), 365-370.

[38]. F.C. Chang, J.D. Lin, C.C. Tsai, and K.S. Wang, "study on cement mortar and concrete made with sewage sludge ash," in *Water Science and Technology,* Vol. 62, (2010) https://doi.org/10.2166/wst.2010.459

[39]. M.M. Al Sharif, and M.F. Attom, "A geoenvironmental application of burned wastewater sludge ash in soil stabilization," in *Environmental Earth Science,* Vol.71, pp.2453-2463, (2014) http://dx.doi.org/10.1007/s12665-013-2645-z

[40]. Z. Chen, and C.S. Poon, "Comparative studies on the effects of sewage sludge ash and fly ash on cement hydration and properties of cement mortars," in *construction and building materials,* Vol.154, pp. 791-803. (2017) http://dx.doi.org/10.1016/j.conbuildmat.2017.08.003

[41]. M. Cyr, M.Coutand, and P. Clastres, "Technological and environmental behavior of sewage sludge ash (SSA) in cement-based materials," in *Cement and Concrete Research,* Vol.37, pp.1278-1289, (2007) https://doi.org/10.1016/j.cemconres.2007.04.003

[42]. M.Coutand, M. Cyr, and P. Clastres, "Use of sewage sludge ash as mineral admixture in mortars," in *Construction Materials,* Vol.159, pp. 153-162, (2006) https://doi.org/10.1680/coma.2006.159.4.153

[43]. P. Garces , M. Pérez Carrión , E. García Alcocel , J. Payá , J. Monzó , M.V. Borrachero, "Mechanical and physical properties of cement blended with sewage sludge ash," in *Waste Management,* Vol. 28, (2008) https://doi.org/10.1016/j.wasman.2008.02.019

[44]. J. E. Halliday, M.R. Jones, and T. D. Dyer, "Potential use of UK sewage sludge ash in cement-based concrete," in *Waste and Resources Management,* Vol. 165, pp. 57-66, (2012) https://doi.org/10.1680/warm.2012.165.2.57

[45]. A. Jamshidi, M. Jamshidi, N. Mehrdadi, A. Shasavandi, and F.P. Torgal, "Mechanical Performance of Concrete with Partial Replacement of Sand by Sewage Sludge Ash from Incineration," in *Materials Science Forums,* Vol. 730-732, (2012) https://doi.org/10.4028/www.scientific.net/MSF.730-732.462

[46]. G. Rutkowska, P. Wichowski, M. Franus, M. Mendryk, and J. Fronczyk, "Modification of Ordinary Concrete Using Fly Ash from Combustion of Municipal Sewage Sludge," in *Materials,* Vol. 13, (2020) https://doi.org/10.3390/ma13020487

[47]. M. P. Carrion, F. B. Brotons, J. Paya. J. M. Saval. E. Zornoza, M.V. Borrachero, and P. Garces, "Potential use of sewage sludge ash (SSA) as a cement replacement in precast concrete blocks," in *Materials de Construccion,* Vol. 64, (2014) http://dx.doi.org/10.3989/mc.2014.06312

[48]. F. D. Lima, D. Ingunza, and M. D. Pilar, "Effects of Sewage Sludge Ashes Addition in Portland Cement Concretes," in *Proceedings of the 2nd International Conference on Civil, Materials and Environmental Sciences,* Atlantis Press, Paris, France, pp. 189e191. https://doi.org/10.2991/cmes-15.2015.55.

[49]. T. Lu, H. Yuan, Y. Wang, H. Huang, and Y. Chen, "Characteristic of heavy metals in biochar derived from sewage sludge," in *Journal of Material Cycles and wastes Management,* Vol. 18, pp. 725-733, (2016) https://doi.org/10.1007/s10163-015-0366-y.

[50]. I.J. Chiou, K.S. Wang, C.H. Chen, and Y.T. Lin, "Lightweight aggregate made from sewage sludge and incinerated ash," in *Waste Management,* Vol.26,

pp. 1453-1461, (2006) https://doi.org/10.1016/j.wasman.2005.11.024

[51]. S. Wild, and J. M. Khatib, "Portlandite consumption in metakaolin cement pastes and mortars," in *Cement and Concrete Research,* Vol. 27, pp. 137-146, (1997) https://doi.org/10.1016/S0008-8846(96)00187-1

[52]. X. Jin, and Z. Li, "Effects of Mineral Admixture on Properties of Young Concrete," in *Journal of Materials in civil Engineering,* Vol. 15, (2003) https://doi.org/10.1061/(ASCE)0899-1561(2003)15:5(435)

[53]. C. S. Poon, S. Azhar, M. Anson, and Y. L. Wong, "Performance of metakaolin concrete at elevated temperatures," *in Cement and concrete composites,* Vol. 25, pp. 83-89, (2003) https://doi.org/10.1016/S0958-9465(01)00061-0

[54]. C. S. Poon, S. C. Kou, and L. Lam, "Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete," in *Construction and building materials,* Vol. 20, (2006) https://doi.org/10.1016/j.conbuildmat.2005.07.001

[55]. A.A. Ramezanianpour, and H. B. Jovein, "Influence of metakaolin as supplementary cementing material on strength and durability of concretes," in *construction and building materials,* Vol.30, pp. 470-479. (2012) http://dx.doi.org/10.1016/j.conbuildmat.2011.12.050.

[56]. X. Qian, and Z. Li, "The relationships between stress and strain for high-performance concrete with metakaolin," in *Cement and Concrete Research,* Vol. 31, (2001) https://doi.org/10.1016/S0008-8846(01)00612-3

[57]. P. Dinakar, P.K. Sahoo, and G. Sriram, "Effect of Metakaolin Content on the Properties of High Strength Concrete," in *International Journal of Concrete Structures and Materials,* Vol. 7, (2013) https://doi10.1007/s40069-013-0045-0

[58]. J. M. Khatib, and S. Wild, " Pore size distribution of metakaolin paste," in *Cement and Concrete Research,* Vol. 26 (1996) https://doi.org/10.1016/0008-8846(96)00147-0

[59]. D. M. Roy, P. Arjunan, and M. R. Silsbee, "Effect of silica fume, metakaolin, and low-calcium fly ash on chemical resistance of concrete ," in *Cement and Concrete Research,* Vol. 31, (2001) https://doi.org/10.1016/S0008-8846(01)00548-8

[60]. D.L. Pillay, O.B. Olalusi, M.W. Kiliswa, P.O. Awoyera, J.T. Kolawole, and A.J. Babafemi, "Engineering performance of metakaolin based concrete," in *Cleaner engineering and Technology,* Vol.6, (2022) https://doi.org/10.1016/j.clet.2021.100383