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REVIEW PAPER

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PERFORMANCE OF AGRO-WASTE CEMENTITIOUS MATERIAL IN THE HIGH-STRENGTH REINFORCED CONCRETE APPLICATIONS: A REVIEW

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ABSTRACT

The rapid urbanisation and rising demand for high-performance concrete (HPC) have driven research towards sustainable, environmentally friendly, and cost-effective alternatives to traditional cement. Agricultural waste cementitious materials, such as fly ash, rice husk ash, and bagasse ash, have been used as cementitious material due to their pozzolanic properties. This review explores the feasibility of incorporating these agro-waste materials in high-strength reinforced concrete (HSRC) applications, focusing on their effects on the durability, sustainability and mechanical properties of concrete. Previous studies indicate that the partial replacement of cement (5–10%) with such waste materials can enhance the mechanical strength due to the additional calcium silicate hydrate (C-S-H) gels, which improve its microstructural densification. Moreover, this material's fineness improves the durability by reducing its permeability, enhancing the sulphate and chloride resistance, and mitigating the alkali-silica reaction (ASR). Utilising agricultural waste also significantly lowers the related carbon emissions, minimises industrial waste disposal, and promotes sustainable construction practices. However, challenges such as the variability of the chemical composition, proper processing (grinding and calcination), and standardisation issues must be addressed for broader implementation. This review provides a comprehensive analysis of agro-waste cementitious materials in HSRC, highlighting their benefits and limitations while emphasising the need for further research to optimise their performance and reliability in structural applications.

Keywords: fly ash, rice husk ash, bagasse ash, durability, sustainability, concrete

INTRODUCTION

For almost two centuries, portland cement has been utilised as a binder in concrete and other concrete-related uses. As its use has been increasing in demand over time, its production has also increased, which has inevitably resulted in environmental issues (Gupta & Kashani, 2021). Globally, 8–10% of carbon dioxide (CO_2) emissions are attributed to the manufacturing of cement, which is a cause of many environmental problems. Future increases in cement production will increase atmospheric CO_2 (Poudyal & Adhikari, 2021). The environmental issues associated with cement manufacturing make it necessary to use a variety of industrial and agricultural by-products to reduce the quantity of CO_2 released into the atmosphere. Utilising these types of by-products will increase the development of industrial products as well as sustainable agriculture for

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the global market and lessen the amount of industrial and agricultural trash that is dumped (Jittin, Rithuparna, Bahurudeen & Pachiappan, 2020).

This study was inspired by the widely available and reasonably priced agro-waste as sustainable and workable materials. The data show that in industrialised and developing nations, biomass makes up only 9% to 14% of energy sources (Khan, De Jong, Jansens & Spliethoff, 2009). Studies are being conducted to comprehend the diverse properties of binders from different industrial and agricultural wastes. Due to their high silica content, industrial-agro waste materials like silica fume (SF), ground granulated blast furnace slag (GGBS), bagasse ash (BA), fly ash (FA), rice husk ash (RHA), and waste ash derived from coconuts are widely used in concrete and have been for a few decades. Studies on the usage of a few of the aforementioned by-products have shown that they have several benefits, including improved strength and durability, reduced construction costs due to the use of less cement, decreased carbon dioxide emissions, which benefits the environment, and easier disposal of industrial-agro-waste materials that would otherwise pollute the environment (Thomas et al., 2018). According to Figure 1a, the total amount of garbage produced and cement produced worldwide each year is 4.01 billion and 2.02 billion tonnes, respectively, and both are expected to increase in the upcoming years (Kaza, Yao, Bhada & Woerden, 2018). As seen in Figure 1b, of these waste materials, 44% comes from food and agricultural wastes, while the remaining 56% comes from industrial and other wastes (Kaza et al., 2018).

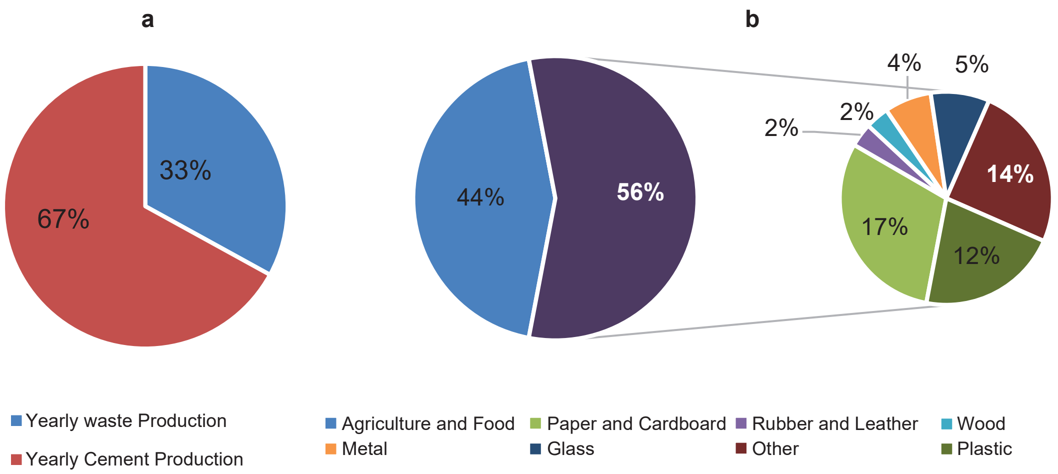

Fig. 1. Waste globally: a – comparison of worldwide production of waste and cement, b – classifications of waste product

Source: Zhang et al. (2015).

About 45.2 million tonnes of ash generated by sugarcane and 30.6 million tonnes of maise stalk ash are produced annually, with the remainder coming from various agricultural and food wastes, as illustrated in Figure 2b. The use of industrial wastes in manufacturing concrete has been the focus of multiple research investigations, both past and present. Reducing or reusing the quantity of waste produced by the industrial and agricultural sectors could be achieved using waste derived from agro-industrial processes in the building sector, which would also offer a long-term solution to the issues brought on by agro-industrial waste disposed of in landfills (Hemlatha & Ramaswamy, 2017). Due to their abundance, these by-products from the agricultural and industrial sectors can be used with cement in the construction industry for less expensive small-scale building projects like grouting, interlocks, plastering, and constructing walkways. It can be used as a substitute for cement in alkali-activated slag mortars or used to replace natural coarse aggregate with greater strength and durability (Zhang et al., 2015). The main disadvantage of using these materials is that they absorb water more quickly due to their vast surface area. Other drawbacks include handling alkali--activating materials poorly, working with large-scale practical applications poorly, and burning wastes to improve their reactivity.

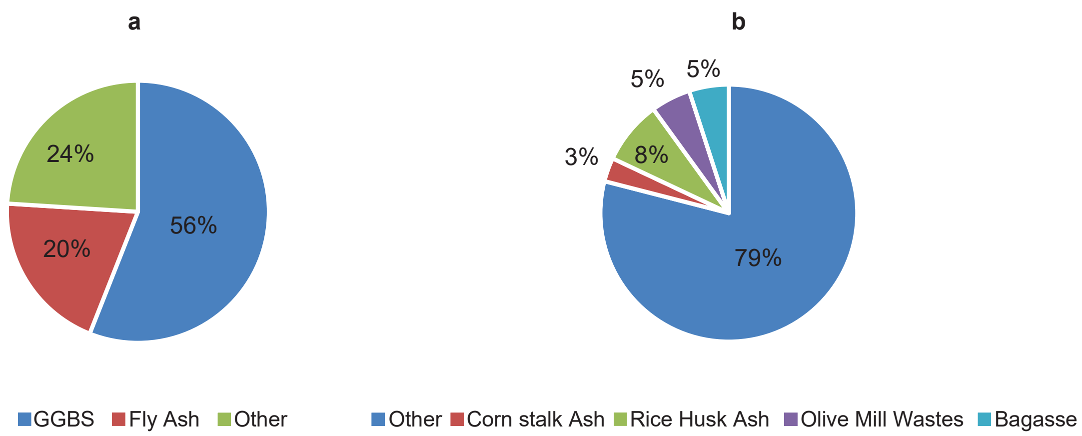

Fig. 2. Wastes: a – produced industrial waste, b – agricultural and food wastes

Source: Kumar, Yaragal and Das (2020).

Burning agro-waste is a significant environmental problem because it negatively affects air quality and risks public health (Bie, Song, Liu, Ji & Chen, 2014). Calcined wastes can improve reactive materials in various ways, depending on the type of waste and its composition, which tends to enhance the pozzolanic properties and aids in optimising the amorphous silica that is already present (Sultana & Rahman, 2013). In contrast, uncalcined waste ashes have a more significant carbon content than calcined ash and are more likely to be in the amorphous phase (Thomas et al., 2021). Consequently, the current review addresses the effects of pozzolanic processes on the characteristics of the binder system in both calcined and uncalcined states, in addition to investigating industrial and agro wastes such as supplementary cementitious materials (SCMs) and alkali-activated binders (AABs) materials.

INFLUENCE OF AGRO-INDUSTRIAL WASTES IN CONCRETE

In nations like China, India, and the US, the agricultural and industrial sectors are significant producers of waste by-products that are often disposed of in landfills (Vaičiukynienė, Nizevičienė, Kantautas, Kielė & Bocullo, 2021). A process called calcination, which occurs at temperatures between 700 and 900°C, converts the amorphous silica found in agricultural and industrial wastes into extremely reactive silica while keeping the ashes. Heating crystalline silica at 900°C yields non-reactive silica. When agricultural wastes are burned to produce biomass fuel, two types of ashes often form: biomass bottom ash (BBA) and biomass fly ash (BFA). Grinding this chemical more will enhance its surface area and reactivity. Adding different active aluminosilicate elements to the blends is another way to increase the BBA precursor's reactivity (Sharma & Sivapullaiah, 2016). The two primary ashes that industries produce are fly ash and GGBS, which are further classified into groups based on the oxide compound and other characteristics (Kaniraj & Havanagi, 1999).

The leftover particles, known as fly ash (FA), from coal-fired power stations can be utilised as an SCM and to make AAB concrete. These are the aluminosilicate materials that, according to the ASTM C618-12a standard (ASTM International [ASTM], 2012), may or may not have a high concentration of calcium oxide. As a result, they are categorised as either Class C or Class F. While sub-bituminous coal containing between 50% and 70% of the components above is used to produce Class C FA, and bituminous coal containing a mixture of SiO_2, Al_2O_3, and Fe_2O_3 concentrations of more than 70% is used to produce the majority of Class F FA. According to the source, the principal chemical composition of the oxide components in Class F and Class C FA varies from highest to minimum values, as illustrated in Table 1. Fly ash is thought to be pozzolanic, with a specific gravity of about 2.15, and exhibits minimal self-hardening qualities when chemical activators like cement or lime are not present (Durdziński, Dunant, Ben & Scrivener, 2015). Fly ash's composition alone is insufficient to explain the behaviour of fly ash because the presence of crystalline or amorphous phases of FA impacts the reactivity of the FA (Hemlatha & Ramaswamy, 2017).

Table 1. Chemical composition of Class C and Class F fly ash

Class	Range	Chemical oxide [%]									
		TiO_2	MnO	SO_3	MgO	Na_2O	K_2O	Fe_2O_3	Al_2O_3	SiO_2	Cao
C FA	max	1.0	0.2	12.9	6.7	2.8	9.3	15.6	20.5	46.4	54.8
C FA	min	0.6	0.03	1.4	0.1	0.2	0.3	1.4	2.6	11.8	15.2
F FA	max	2.6	0.1	4.7	5.2	3.6	4.1	21.2	35.6	62.1	14.0
F FA	min	0.5	0.03	0.02	0.3	0.1	0.1	2.6	16.6	37.0	0.5

Source: ASTM C618-12a standard.

An Indian standard IS 1489:1991 (Bureau of Indian Standards [BIS], 1991) states that the maximum % of fly ash that can be used to make Portland pozzolana cement is 35%. In its natural state, FA cannot enhance the strength properties when used at a rate of more than 35% replacement. The FA-cement binder mix must be altered to increase its strength under such conditions to produce more hydration products (Sanchez & Sobolev, 2010). The modification involves utilising the alkali activation method and nano-modified fly ash in an FA-cement binder mix to speed up early-age hydration. By acting as the cement's nucleus, the nanoparticles quicken the hydration process, thicken the microstructure, and reduce the permeability by densifying the interfacial transition zone (ITZ) (Kalifa, Jalaa & Younes, 2015). The effects of the SiO_2/Al_2O_3 molar ratios (3.25, 3.37, 3.50, and 3.75) on the properties of the FA-based geopolymer with FA (78%, 85%, 92%, and 96%) were examined. The SiO_2/Al_2O_3 ratio of 3.37 yielded the highest compressive strength, primarily attributable to the Al_2O_3–SiO_2 bonding in the amorphous region, which made up a more significant portion of the geopolymer's microstructure. The fly ash does not produce its reactive crystalline phase until calcined. The slump value of concrete prepared by partial substitution with calcined fly ash falls significantly compared to uncalcined FA (Duchesne & Bérubé, 2001). The drop in slump is brought about by the calcined FA's finer particle sizes, which fill the pores in the concrete and increase its density (Fig. 3). However, as seen in Figure 4, the calcined FA's water absorption capacity is greater than that of the uncalcined FA.

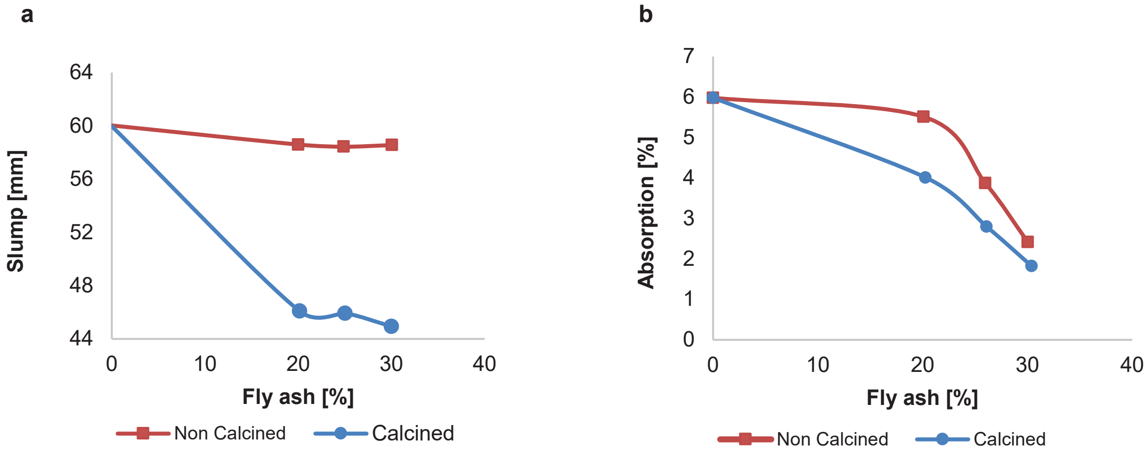

Fig. 3. Slump and water absorption ability of concrete on partial replacement with calcined (a) and uncalcined (b) fly ash

Source: Duchesne and Bérubé (2001).

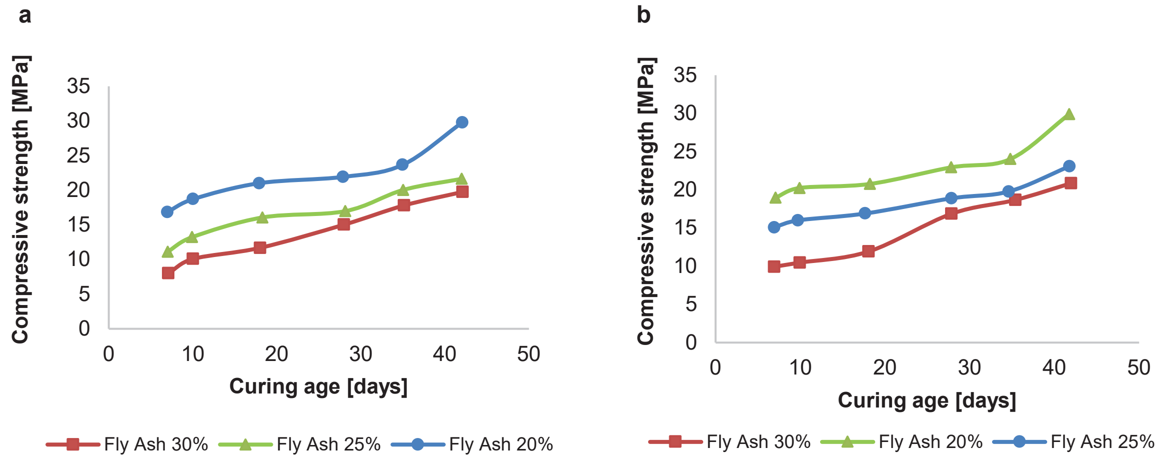

Fig. 4. Effect of partially replaced calcined (a) and uncalcined (b) fly ash on compressive strength

Source: own work.

The narrow pore structure of concrete made with fly ash contributes to its higher resistance to compressive force, hence an improvement in strength was noted regardless of whether calcined or uncalcined fly ash was employed as a partial replacement in the binder (Fig. 4). When compared to uncalcined fly ash, calcined fly ash has been shown to decrease the pore volume of fly ash–cement paste. All organic components are reduced or eliminated during the calcination of fly ash, which could have a negative or nonexistent effect on the strength of the concrete. Class C fly ash's variable and inferior durability to Class F fly ash is one of the key problems with utilising it in portland cement concrete. Class F fly ash has been shown in multiple experiments to be effective in attenuating the alkali-silica reaction; however, because of the lower alkali concentration, its efficacy is better at lower replacement rates (Thomas et al., 2011). Pore refinement, which lowers the permeability and increases the resistance to chloride, is seen in long-term durability investigations of fly ash-based geopolymer concrete.

Influence of rice husk ash in concrete

Rice husk ash is an excellent pozzolana material whose colour changes from black to white-grey based on the kind of incineration, temperature, and burning time (Ha Thanh, 2015). The grinding process determines its fineness; as the grinding energy and duration increase, the RHA's mean particle diameter decreases. Over the course of 0–540 min of grinding, the mean diameter of RHA particles in a ball mill drops from 86.2 to 5.7 μm (Singh & Singh, 2015). Because of its honeycomb structure, its specific surface area typically fluctuates between ten and a hundred times more than cement and five to ten times greater than silica fume. Adequately burnt RHA has Brunauer–Emmett–Teller (BET) values of 100–150 $m^2 \cdot g^{-1}$ (Tong et al., 2018).

A maximum specific surface area of 274 $m^2 \cdot g^{-1}$ can be attained if the RHA is treated. Numerous research demonstrates that RHA can be used to prepare a sodium silicate (Na_2SiO_3) solution and as a binder material. To improve the compressive strength and adequate setting time, fly ash and GGBS are often blended using this sodium silicate (Na_2SiO_3) solution as an alkali activator. Rice husk ash has a specific gravity that ranges from 2.1 to 2.6 and a particle size that varies from 5 μm to 96 μm (James & Rao, 1986). For isothermal heating to destroy the organic components from rice husk, a minimum temperature of 402°C is required to release the silica (Zareei, Ameri, Dorostkar & Ahmadiet, 2017). RHA generated the most reactive silica at a combustion temperature of 500°C.

Amorphous silica on the exterior of RHA particles is attacked by OH ions in the solution, which causes the silica to dissolve in the aqueous solution. The RHA particles absorb water due to the pores created when the amorphous silica dissolves. When silica in the solution combines with Ca and OH, C-(Na, K)-S-H gels are created. These precipitates can then absorb Na, K, and Al ions on the surfaces of RHA particles. Consequently, a pozzolanic reaction rim formation occurs, with RHA particles either fully or partially packed within the rim. The response rim thickens gradually.

Alkalis and silica interact to create alkali-silica reaction gels. These gels subsequently react with Ca ions, absorb water through the pores in RHA particles, and grow. The increasing alkali-silica reaction (ASR) hydrates and enhance the durability of concrete. The primary oxide components of RHA for both calcined and uncalcined rice husk ash (CRHA and URHA), as shown in Table 2, vary in value depending on the available source, from the maximum to the minimum.

Table 2. Chemical composition of calcined and uncalcined rice husk ash

Type	Range	Element oxide [%]									
		TiO_2	MnO	SO_3	MgO	Na_2O	K_2O	Fe_2O_3	Al_2O_3	SiO_2	CaO
CRHA	max	0.70	0.19	0.54	1.57	0.27	4.60	4.00	4.27	99.00	3.90
CRHA	min	0.04	0.11	0.01	0.07	0.10	0.31	0.07	0.06	88.00	0.25
URHA	max	0.70	0.10	0.70	0.80	0.44	5.10	3.90	0.68	82.00	0.92
URHA	min	0.02	0.02	0.01	0.07	0.11	1.66	0.07	0.01	73.68	0.16

Source: James and Rao (1986).

When preparing high-performance concrete, RHA, a pozzolanic reactive material, can be used to increase the surface area of the interfacial transition zone. When 25% of the cement is replaced with RHA, the mixed concrete becomes significantly more impermeable than regular concrete (Gastaldini, Isaia, Hoppe, Missau & Saciloto, 2009). Including rice husk ash (RHA) in geopolymer concrete with ultra-fine slag at room temperature resulted in a noticeable improvement in strength and durability.

The 28th-day and 91st-day compressive strengths of concrete in which 10%, 20%, and 30% of the cement were replaced with RHA are shown in Table 3. The increase in the 28-day compressive strength for concrete containing 10% RHA over the cement-based control concrete was between 15% and 27% for w/b ratios of 0.35, 0.50, and 0.65; on the 91st day, the increase was between 10 and 21%. On days 28 and 91, it was observed that the compressive strengths of 20% RHA concrete were 11–34% and 19–26%, respectively, while the values for 30% RHA concrete ranged from 6 to 26%, and 7 to 27%, respectively (Sathurshan, 2021).

Table 3. Compressive strength of concrete containing rice husk ash

Mixture	w/b ratio	Compressive strength [MPa]	
		after 28 days	after 91 days
Reference	0.35	54	67.9
	0.50	47	51.4
	0.65	28	35
10 RHA	0.35	68	76.4
	0.50	47	62.1
	0.65	32	38.6
20 RHA	0.35	72	85.6
	0.50	51.5	62.9
	0.65	32	41.7
30 RHA	0.35	67	78.9
	0.50	50	65.1
	0.65	30	37.3

Source: Saloni, Pham, Lim, Pradhan and Kumar (2021).

When 10% of the fine aggregate was replaced with unprocessed RHA and 15% with OPC, respectively, for 28 days, the highest compressive strengths of 81 MPa and 75 MPa were achieved (Athira et al., 2021). Except RHA, all other waste ashes often exhibit SiO_2 contents comparable to FA; this greater SiO_2 content helps binders manufactured from RHA build up early and remain exceptionally stable at high temperatures. More broadly, in metakaolin-based geopolymer systems, silica fume and RHA are essential for enhancing the freezing resistance and mechanical qualities of the material by enhancing the pore structure. When calcined RHA's fresh and hardened properties were compared to those of untreated (uncalcined and unground) RHA, it was discovered that calcined RHA had superior qualities while requiring more energy during preparation (Athira, Bahurudeen, Saljas & Jayachandran, 2021).

Influence of sugarcane bagasse ash in the concrete

A by-product of the sugar industry is sugarcane bagasse (SCB). During the sugar processing process, a significant amount of SCB is burned to produce sugarcane bagasse ash (SCBA) and electricity. According to Figure 5, which represents 46.3% of global sugarcane production in 2021, Brazil and India are the two biggest producers (Embong, Shafiq, Kusbiantoro & Nuruddin, 2016). Massive amounts of bagasse trash are accumulated in the landfill, and burned, and roughly 30% of it is turned into ash. Because bagasse ash meets cement's characteristics very well, it represents a significant substitute for cement. Thus, the goal of the current work is to provide a thorough analysis of the application of SCBA in helping SCMs create environmentally friendly concretes. SCBA is prepared by drying and then calcining (600–800°C), grinding, and sieving to form reactive silica. It affects the porosity and water absorption, and enhances concrete's mechanical strength and workability depending on its dosage and fineness. SCBA serves as a sustainable pozzolanic material, improving performance and reducing waste.

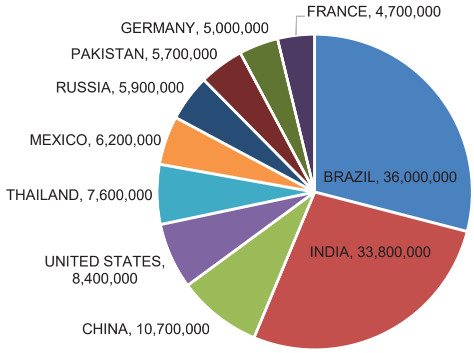

Fig. 5. Production of sugarcane bagasse in 2021 [thousand metric tonnes]

Source: Embong et al. (2016).

It was observed that burning SCB at temperatures between 600°C and 800°C results in SCBA with a large amount of amorphous silica, resulting in excellent pozzolanic qualities (Thomas, 2021). According to Embong et al. (2016), the ashes are determined by the degree and length of burning. Table 4 shows that the SiO_2 concentration rises with the increasing temperature and duration of burning up to 800°C for 2 h. The heating and cooling speeds were considered as 10°C·min^{-1} and 1.67°C·min^{-1}, respectively. The agriculture waste (AW) was heated in a controlled drying oven for 2 h after reaching the necessary temperature (Salim, Ndambuki & Adedokun, 2014).

Table 4. Chemical composition of sugarcane bagasse ash after treatment

Temperature [°C]	Sample number	Chemical composition [%]									
		SiO_2	P_2O_5	CaO	K_2O	Al_2O_3	SO_3	MgO	Fe_2O_3	Na_2O	LOI
600	1	64.9	4.7	1.9	1.9	0.5	0.6	0.7	1.5	0.1	1.8
	2	74.8	6.2	2.1	2.6	2.2	0.7	1.2	0.4	0.3	0.5
	3	71.5	8.3	3.0	3.4	0.6	0.8	1.4	1.4	0.5	0.2
700	1	65.9	7.4	2.6	2.7	1.4	0.7	1.0	1.8	0.3	0.2
	2	72.0	5.9	2.2	2.5	1.0	1.0	1.2	1.4	0.2	0.2
	3	84.8	6.0	2.2	2.6	1.2	1.0	1.2	0.4	0.3	0.2
800	1	84.1	7.3	2.5	2.5	0.9	0.5	1.2	0.4	0.3	0.2
	2	84.3	5.6	1.9	2.9	1.1	0.5	1.4	1.7	0.3	0.1
	3	82.9	5.1	2.0	2.3	1.6	0.3	1.2	3.4	0.2	0.1

Source: Embong et al. (2016).

Table 4 presents the chemical composition of bagasse ashes derived from prior experiments. The collection process, grinding conditions, and treatment process were found to affect the chemical composition of the bagasse ashes.

DISCUSSION

The binding system utilising pozzolanic materials such as bagasse ash, fly ash or rice husk ash works better than any conventional cementitious materials in various respects. During the hydration process, calcium silicate hydrate (C-S-H) is formed, which is responsible for the strength, and calcium hydroxide ($Ca(OH)_2$) is formed, which does not contribute to the strength, but when the pozzolanic material reacts with [$Ca(OH)_2$], it produces additional C-S-H, which leads to long-term strength. While the cement produces the early strength, the pozzolonic materials contribute to a gradual increase in this strength, which makes the concrete stronger later on. The agricultural waste material's pozzolanic reaction refines the pore structure, and this property makes the material less permeable. The pozzolans reduce the alkali content in the concrete, which helps to mitigate the alkali-silica reaction (ASR) and prevent expansive gel formation. Cement production leads to CO_2 emissions, but pozzolanic materials reduce the total CO_2 emissions. Their use also increases waste utilisation, turning by-products (e.g., fly ash, bagasse ash) into valuable construction materials.

FUTURE SCOPE

Further research is required to finalise the optimal replacement percentage of agro-waste cementitious materials to achieve the maximum strength and durability properties, such as the shrinkage and creep behaviour of concrete containing agro-waste cementitious materials. There is a need to study concrete behaviours containing agro-waste in extreme environments (marine, industrial, and high-temperature conditions). There is also a lack of standardised testing methods and specifications for agro-waste-based cementitious materials, which limits their adoption in construction. A detailed life cycle assessment (LCA) should be conducted to determine the environmental benefits of agro-waste in high-strength concrete. Comparative studies on bonding behaviour with reinforcement and fire resistance properties are essential but have not been performed until now.

CONCLUSIONS

The current paper thoroughly evaluates earlier research studies and recent advancements in the use of agro-industrial wastes, industrial plant ashes, and agricultural farming wastes in concrete. The scientific community's task is to find a low-cost, durable, and high-quality building material for which several research studies have been carried out. These studies examine the properties of concrete that have been treated with ashes from agro-industrial waste as a pozzolanic addition. Following are the conclusions reached after looking over research projects that have been completed on agro-industrial wastes.

– It was observed that industrial wastes, including fly ash, provide excellent outcomes. Industrial wastes with smaller particle sizes have more significant surface areas, which would promote more vigorous bond formation in the AAB system.
– It was also observed that agro-based waste has a high concentration of silica, which makes the materials exhibit pozzolanic reactivity. This is advantageous for the growth of concrete's strength over time. It has been noted that a higher percentage of agro-based waste can substitute cement in concrete when there is better treatment, controlled burning, and enhanced particle refinement.
– A thorough review of the literature demonstrates that, while still retaining the necessary properties for building materials, fly ash, rice husk ash, and sugarcane bagasse waste ashes can be utilised as alternative activators in the AAB system or as pozzolanic materials in cement binder systems.
– It was also observed that using portland cement with substitutes of SCBA and RHA in the range of 5–10% by weight gives concrete exceptional mechanical qualities.

Authors' contributions

Conceptualisation and methodology: M.K.; investigation: S.K.; data curation: M.K.; writing – original draft preparation: M.K.; writing – review and editing: S.K.; visualisation: S.K.; project administration: S.K.

All authors have read and agreed to the published version of the manuscript.

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WYDAJNOŚĆ MATERIAŁU CEMENTOWEGO Z AGROODPADÓW W ZASTOSOWANIACH ŻELBETOWYCH O DUŻEJ WYTRZYMAŁOŚCI: PRZEGLĄD

STRESZCZENIE

Szybka urbanizacja i rosnące zapotrzebowanie na beton o dużej wydajności (HPC) skłoniły do badań nad zrównoważonymi, przyjaznymi dla środowiska i opłacalnymi alternatywami dla tradycyjnego cementu. Materiały cementowe z odpadów rolniczych, w tym popiół lotny, popiół z łusek ryżowych, popiół z wytłoków z trzciny cukrowej, ze względu na swoje właściwości pucolanowe coraz częściej są wykorzystywane w budownictwie. W niniejszym przeglądzie zbadano wykonalność integracji tych agroodpadów z zastosowaniami betonu zbrojonego o dużej wytrzymałości (HSRC), z uwzględnieniem wpływu na trwałość, rozwój zrównoważony i właściwości mechaniczne. Poprzednie badania sugerują, że częściowe zastąpienie cementu tymi materiałami odpadowymi (na poziomie 5–10%) może zwiększyć wytrzymałość mechaniczną betonu, dzięki obecności dodatkowych żeli hydratycznych krzemianu wapnia (C-S-H), które poprawiają jego gęstość mikrostrukturalną. Ponadto rozdrobnienie tych materiałów przyczynia się do lepszej trwałości poprzez zmniejszenie przepuszczalności, zwiększenie odporności na siarczany i chlorki oraz złagodzenie reakcji alkaliczno-krzemionkowej (ASR). Utylizacja odpadów rolniczych odgrywa również znaczącą rolę w zmniejszaniu emisji dwutlenku węgla, minimalizowaniu utylizacji odpadów przemysłowych i promowaniu zrównoważonych praktyk budowlanych. Pozostają jednak wyzwania, w tym zmienność składu chemicznego, potrzeba właściwego przetwarzania (mielenie i kalcynacja) oraz kwestie związane ze standaryzacją, które należy rozwiązać w celu szerszego wdrożenia. Niniejszy przegląd zawiera kompleksową analizę materiałów cementowych z odpadów rolniczych w HSRC, w której podkreślono zarówno ich zalety, jak i ograniczenia, jednocześnie zwrócono uwagę na potrzebę dalszych badań w celu optymalizacji ich wydajności i niezawodności w zastosowaniach konstrukcyjnych.

Słowa kluczowe: popiół lotny, popiół z łusek ryżowych, popiół z wytłoków z trzciny cukrowej, trwałość, rozwój zrównoważony, beton