Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 3, Issue 8, 2025

OPTIMIZING WHEAT STRAW ASH FOR USE AS A SUSTAINABLE POZZOLAN IN CEMENT

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DOI: https://doi.org/10.5281/zenodo.21257695

Keywords
wheat straw ash, strength activity index, weight loss, calcination, XRD

Article History
Received: 24 June 2025
Accepted: 06 July 2025
Published: 21 August 2025

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Abstract
This study was conducted to determine the optimal conditions for producing pozzolanic ashes from wheat straw for use as cement substitute materials. When the Wheat straw is turned into ash, it develops a pozzolanic character due to the presence of silica. However, the transformation of silica from amorphous to crystalline and its associated pozzolanic reactivity depends on the calcination temperature, duration, and grinding. In this research the Wheat straw were calcined at three different calcination temperatures (300°C, 400°C, and 800°C) for 2-, 4-,6- and 8-hours duration. The obtained ashes were ground for 30 minutes and replaced by 20% with cement. The samples containing ashes were tested for compressive strength, X-ray diffractometry (XRD), weight loss, and strength activity index (SAI). It was observed that the WSA is the most favorable calcination condition in terms of strength development was obtained at 600°C for 6 hours duration. The highest SAI was achieved for the mortar samples containing WSA calcinated at 600°C for 6 hours duration (WSA600-6H). The materials ground for the higher duration is recommended for higher SAI.

INTRODUCTION

Among all construction materials, concrete remains the most extensively used, and the demand for it shows no sign of slowing down [1]. Cement, being the key binder in concrete, plays a major role in environmental degradation its clinker production alone accounts for 8–10% of worldwide CO2 emissions [2], [3]. More broadly, the construction industry as a whole contributes upwards of 20% of total CO2 released into the atmosphere. Given the energy-intensive nature of cement production, incorporating supplementary cementitious materials (SCMs) as a partial replacement has emerged as a practical pathway toward greener, more sustainable binding materials [4], [5].

At the same time, the improper handling of untreated waste from industrial and agricultural sources continues to pose serious environmental risks, largely due to open-air landfilling practices [6]. With usable land for waste disposal becoming scarcer by the day, much of this waste ends up being discharged into rivers and lakes or burned in the open both of which contribute to air pollution and pose health risks to nearby populations [2]. Fortunately, many of these waste streams are rich in silica, making them suitable candidates for cement replacement and offering a dual benefit: expanding the range of sustainable building materials while helping resolve pressing waste disposal issues [6], [7]

In past, several studies have been conducted to investigate the use of industrial by-products and agricultural wastes as a partial alternative to cement [5], [8], [9]. The most used industrial by-products as an alternative to cement are reported to be fly ash, slag, and silica fume [10], [11]. In addition, different agricultural wastes in the form of ash are also widely used in concrete as CRM [12]–[14]. Generally, the common practice for the disposal of agricultural wastes is open-air burning [2]. This open-air burning process not only emits harmful gases but also fades cementitious properties which restrict its use as CRM in the production of cementitious material [6]. In this regard, incineration of agro-wastes in a controlled condition is a promising method to reduce environmental pollution and retain the material properties.
Sahan and Aydin [9] reported the highest strength up to 10 % substitution of RHA cement. Chandra et al., [5] also observed the highest strength development rate at 10% replacement. Overall, the optimum replacement of RHA is selected in the range of 10-20% [15]. The enhanced strength is due to the availability of amorphous silica which increase pozzolanic performance [16], [17]. Other than RHA, many researchers have also utilized WSA as partial cement replacing material and reported enhanced properties [18], [19]. The overall properties of WSA modified concrete depends upon calcination temperature and fineness of the material [19]. In the study of Birick et al. [20], the wheat straw was calcinated at 507°C and 670°C for 5 hours and good quality WSA was obtained at 670°C calcination. Shazim et al. [21] investigate the behavior of WSA at four different calcination temperatures ranging from 500°C to 800°C with an interval of 100°C change in temperature. the calcination duration was fixed at two hours. They reported the optimum burning temperature at 600°C for the better pozzolanic performance. Ataie et al. [22] reported the presence of higher amorphous silica content at 600°C calcination for 1 hour. Many studies agree on the optimum calcination temperature of 600°C to produce WSA having better pozzolanic behavior. However, the effect of calcination duration is not explored yet and remains the topic of discussion.

Methodology

Materials

Type I ordinary Portland cement (OPC) conforming ASTM C150 [25] specifications were utilized in the research. the cement was obtained from a locally available materials supplier in the vicinity of Jamshoro. Natural hill sand passing from the #30 sieve and retained at the #60 sieve was utilized for the preparation of mortar samples. Wheat straw was obtained from wheat-grown areas located in the vicinity of Hyderabad, Pakistan. The maximum fiber length of wheat straw was 25 mm.

Calcination of Ashes

Wheat straw used in the research were subjected to heat treatment, to convert into ashes. The heating was given in an electric muffle furnace. To obtain Wheat straw ash (WSA) the heating was performed at 300°C, 600°C, and 800°C for 2-, 4-, 6- and 8-hours durations. After heating required temperature and duration the sample was allowed to cool in the open air. All the obtained ashes were ground in the ball mill for 30 minutes and sieved from the #200 sieve.

Sample Preparation

The mortar samples of size 50 mm^3 were prepared by substituting 20% of the activated ashes by weight of the cement. The sample was prepared using a cement to a sand ratio of 1:2.75 and the water-to-cement ratio was kept constant at 0.49 (ASTM C 311) [26]. The detail of mortar mixes is presented in Table 1. The nomenclature for mixes is adopted in such a way that it signifies the type of ash used in a mortar mix. For example, the control mix denotes a mix containing only cement without ashes. WSA300-2H, WSA300-4H, WSA300-6H, and WSA300-8H signify wheat straw ash calcinated at 300°C for 2, 4, 6, and 8 hours. WSA600-2H, WSA600-4H, WSA600-6H, and WSA600-8H signify wheat straw ash calcinated at 600ºC for 2, 4, 6, and 8 hours. WSA800-2H, WSA800-4H, WSA800-6H, and WSA800-8H signify wheat straw ash calcinated at 800ºC for 2, 4, 6, and 8 hours. The mixing, compaction, and molding of mortar specimens were performed following ASTM C305 [27] and ASTM C109 [28] guidelines. The samples were demolded after 24 hours and left for 28 days of water curing.

Table 1: Mix Details

Mix No.	Mix ID	Cement	Sand	WSA	w/b
A	Control (Cement)	1	2.75	-	0.49
B	WSA300-2H	0.80	2.75	0.20	0.49
C	WSA300-4H	0.80	2.75	0.20	0.49
D	WSA300-6H	0.80	2.75	0.20	0.49
E	WSA300-8H	0.80	2.75	0.20	0.49
F	WSA600-2H	0.80	2.75	0.20	0.49
G	WSA600-4H	0.80	2.75	0.20	0.49
H	WSA600-6H	0.80	2.75	0.20	0.49
I	WSA600-8H	0.80	2.75	0.20	0.49
J	WSA800-2H	0.80	2.75	0.20	0.49
K	WSA800-4H	0.80	2.75	0.20	0.49
L	WSA800-6H	0.80	2.75	0.20	0.49
M	WSA800-8H	0.80	2.75	0.20	0.49

Testing

X-ray diffraction analysis

Mineralogical analysis on WSA samples calcined at 300, 600, and 800 °C was performed by X-ray diffractometry with a copper tube and a nickel filter.

The compressive strength of the 50 mm mortar cube at 28 days of moist curing was determined following ASTM C109-21 standard [28]. The pozzolanic activity of the ash samples at different calcination temperatures was examined as per ASTM C618 specification [29].

The strength activity Index (SAI) was determined on cubes at 28 days of curing by replacing 20% cement with a weight of the ash. SAI was then calculated as per ASTM C311 [26] using the following formula: SAI = (A/B) × 100, where A = average compressive strength of ash blended cubes, MPa (psi), and B = average compressive strength of control mix cubes, MPa (psi).

Results and Discussion

X-ray diffraction

X-ray diffraction analysis of WSA at different duration and calcination temperatures

The mineralogical phases of silica in wheat straw ash at different combustion temperatures and duration are presented in Figure 1. The intense sharp peaks for the WSA samples at 300, 600, and 800 °C show the crystalline reflections of silica at 2θ =28º, 45º, and 45º. overall, the crystalline structure of silica remains unchanged at the calcination temperature of 300 ºC and 600ºC at all durations (2-8 hours). However, the peak intensity is relatively higher at 2θ = 45º for 300ºC calcination for two hours. A similar pattern was observed for calcination temperature 600ºC at all burning duration (Figure 2b). This is in contrast with the study reported by Shazim et al [30]. In their study, the amorphous phase of silica in WSA was obtained at 600ºC. In our research, the major transformation of crystalline silica into amorphous form was observed at 800ºC calcination temperature with the sharp peak of crystalline silica at 2θ =45º. Some mild peaks were also transformed into amorphous form during the calcination process for longer durations. This shows that the reactive silica is present in WSA at 800°C calcination for 8 hours.

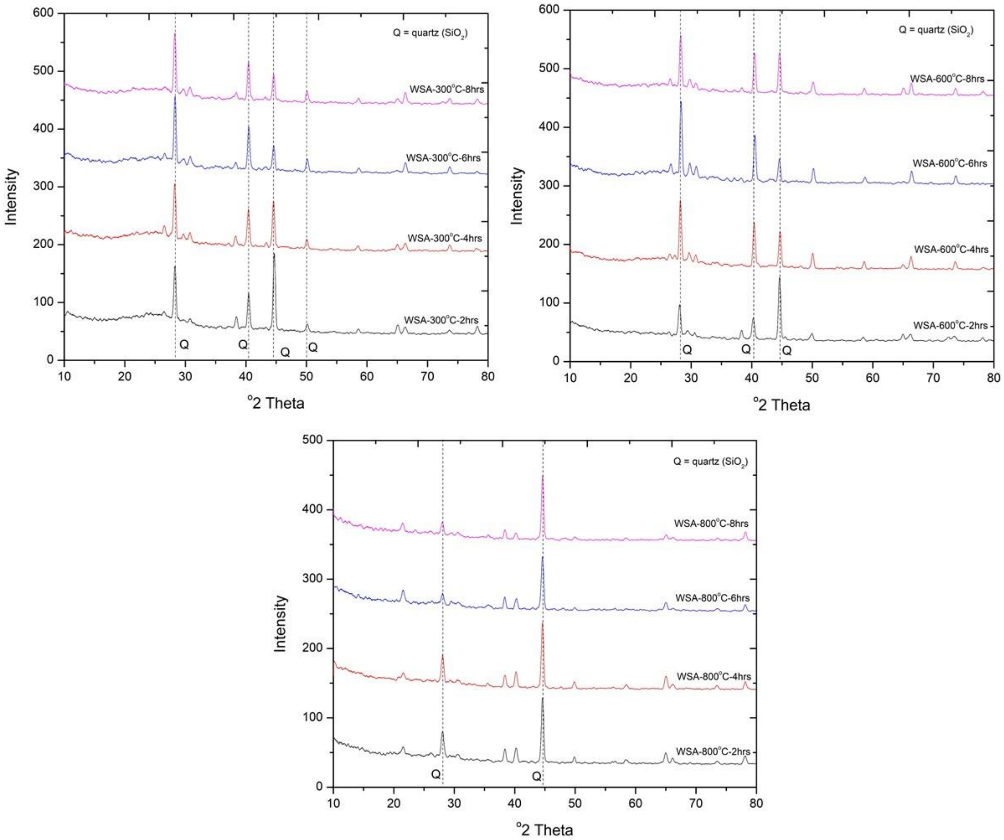

Figure 1: XRD pattern of rice WSA calcinated at a)300°C b) 600°C and c) 800°C

Compressive Strength and Strength Activity Index

Compressive Strength of WSA

The behavior of compressive strength of mortar samples containing WSA at different calcination temperatures and duration is present in Figure 2. It can be observed that the compressive strength of mortar samples containing WSA treated at higher durations during 300°C calcination temperature is continuously increasing. The increase in strength was observed as 6%, 17%, and 34% compared to WSA300-2H. However, a significant drop in strength was observed compared to the control mix containing cement. The drop in strength was between 45%-68%. The highest strength gain was recorded for the WSA sample treated at 600°C for 6 hours (WSA600-6H) compared to the rest of the calcination temperature and durations. The improved pozzolanic performance is attributed to the presence of an amorphous form of silica in higher proportions (Figure 1b and 1c). However, for this mix, a significant drop of 26% in compressive strength was recorded compared to the control mix. The utilization of WSA calcined at 800°C for a higher duration caused a reduction in compressive strength up to 11% compared to samples containing WSA calcined at 600°C for 6 hours. However, the mortar samples containing WSA treated 800°C for 4 hours also showed nearly a similar magnitude for strength as WSA600-6H. The decline in compressive strength is attributed to the poor pozzolanic activity due to the presence of crystalline silica. This can be referred from the XRD graph shown in Figure 1(a-c). the compressive strength obtained in this study for mortar samples containing WSA600-2H is nearly identical with the study of shazim et al [21]. In their study, they only considered the calcination duration for 2H. from the experimental results this can be concluded that the optimum calcination temperature of 600°C is required to obtain high reactive WSA when calcinated for 6 hours (WSA600-6H).

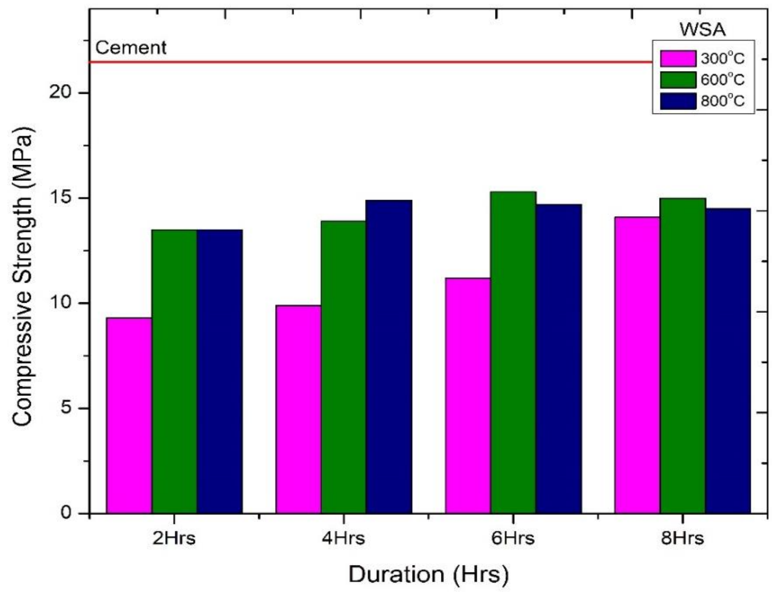

Figure 2: Compressive strength behavior of WSA mortar at different incineration temperatures

Strength Activity Index

Strength activity index (SAI) or pozzolanic activity index (PAI) is one of the most important tests which measures the compressive strength development rate of mixtures containing pozzolans. Figure 3 shows the SAI of WSA calcined at different temperatures for different duration when used as a 20% substitute by weight of the cement. According to ASTM C618, the material can classify as pozzolan when its SAI is equal to or greater than 75%. This means that the mortar mix containing pozzolan should have the compressive strength equal to or greater than 75% of the control mix at 28 days.

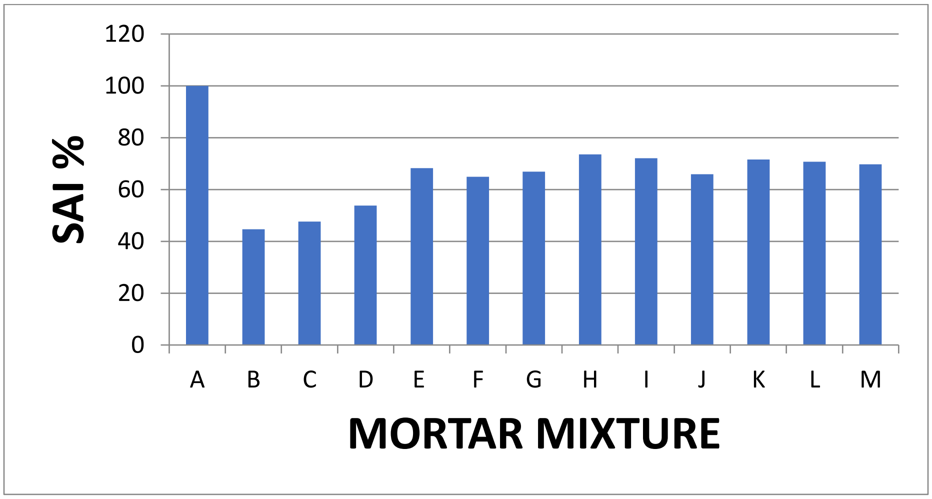

Figure 3: SAI WSA at different incineration temperatures

Weight Loss

Weight loss is an important parameter in terms of obtained mass to be used as a substitute for cement after calcination. The weight loss WSA subjected to different calcination temperatures and durations are shown in Figure 4. The increase in weight loss was observed with the increase in calcination temperature. The highest weight loss of 91%, was obtained during two hours at 800°C calcination temperature for WSA. The WSA content obtained during calcination for two hours at this temperature was in lined with the study of Shazim et al and Xu et al [7], [21]. The weight loss was due to the decomposition of organic matter present the agricultural wastes into carbon [20].

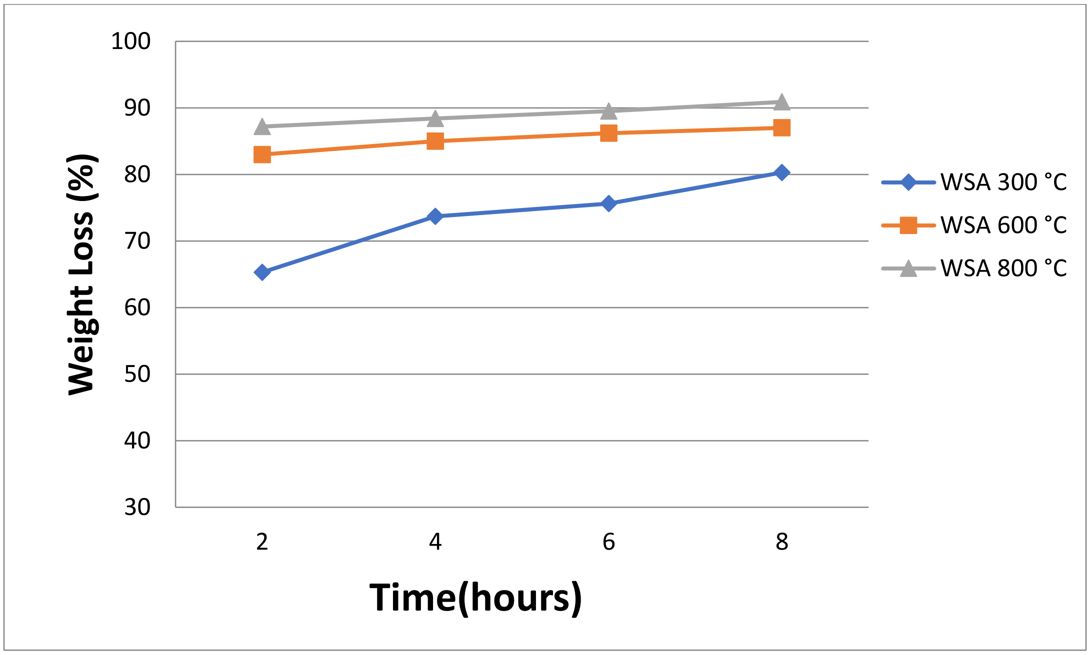

Figure 4: Weight loss (%) WSA at different incineration temperatures

Conclusion

This research was conducted to evaluate the optimum conditions for obtaining different ashes that can be used as a partial substitute to cement. In this research WSA were considered as potential partial cement replacing materials. The prime focus was to find the optimum calcination temperature and duration to obtain highly reactive WSA to be used in cement-based materials. The ashes were prepared at controlled burning temperatures of 300oC, 600oC, and 800°C for 2, 4, 6, and 8-hours duration. Based on the experimental results, the following findings are drawn.

- Based on the XRD patterns the silica was presented in the amorphous state when WSA, were calcinated at 600°C. The optimum calcination duration for producing good quality WSA was recorded as 6 hours.
- The highest compressive strength was obtained for mix (WSA600-6H) containing calcinated WSA at 600°C for 6 hours.
- The highest SAI was achieved for the mortar samples containing WSA calcinated at 600°C for 6 hours duration (WSA600-6H).
- The increase in weight loss was observed with the increase in a calcination temperature.

The highest weight loss of 91%, was obtained during Eight hours at 800°C calcination temperature for WSA.

References
[1] M. Manjunatha, D. Seth, K. Balaji, and S. Chilukoti, "Influence of PVC waste powder and silica fume on strength and microstructure properties of concrete: an experimental study," *Case Studies in Construction Materials*, vol. 15, p. e00610, 2021.
[2] R. Kumar, N. Shafiq, A. Kumar, and A. A. Jhatial, "Investigating embodied carbon, mechanical properties, and durability of high-performance concrete using ternary and quaternary blends of metakaolin, nano-silica, and fly ash," *Environmental Science and Pollution Research*, pp. 1–15, 2021.
[3] R. Kumar, M. Yaseen, N. Shafiq, A. Jalal, and others, "Influence of metakaolin, fly ash and nano silica on mechanical and durability properties of concrete," in *Key Engineering Materials*, 2017, vol. 744, pp. 8–14.
[4] D. B. Viet, W.-P. Chan, Z.-H. Phua, A. Ebrahimi, A. Abbas, and G. Lisak, "The use of fly ashes from waste-to-energy processes as mineral CO2 sequesters and supplementary cementitious materials," *Journal of Hazardous Materials*, vol. 398, p. 122906, 2020.
[5] S. Chandra Paul, P. B. K. Mbewe, S. Y. Kong, and B. Šavija, "Agricultural solid waste as source of supplementary cementitious materials in developing countries," *Materials*, vol. 12, no. 7, p. 1112, 2019.
[6] A. Kumar, R. Kumar, V. Das, A. A. Jhatial, and T. H. Ali, "Assessing the structural efficiency and durability of burnt clay bricks incorporating fly ash and silica fume as additives," *Construction and Building Materials*, vol. 310, p. 125233, 2021.
[7] W. Xu, T. Y. Lo, and S. A. Memon, "Microstructure and reactivity of rich husk ash," *Construction and Building Materials*, vol. 29, pp. 541–547, 2012.
[8] M. Ahad, M. Ashraf, R. Kumar, and M. Ullah, "Thermal, Physico-Chemical, and Mechanical Behaviour of Mass Concrete with Hybrid Blends of Bentonite and Fly Ash," *Materials*, vol. 12, no. 1, p. 60, 2019.
[9] H. \cSahan Arel and E. Aydin, "Use of industrial and agricultural wastes in construction concrete," *ACI Materials Journal*, vol. 115, no. 1, pp. 55–64, 2018.
[10] T. Nochaiya, W. Wongkeo, and A. Chaipanich, "Utilization of fly ash with silica fume and properties of Portland cement–fly ash–silica fume concrete," *Fuel*, vol. 89, no. 3, pp. 768–774, 2010.
[11] M. D. A. Thomas, M. H. Shehata, S. G. Shashiprakash, D. S. Hopkins, and K. Cail, "Use of ternary cementitious systems containing silica fume and fly ash in concrete," *Cement and concrete research*, vol. 29, no. 8, pp. 1207–1214, 1999.
[12] B. S. Thomas, J. Yang, K. H. Mo, J. A. Abdalla, R. A. Hawileh, and E. Ariyachandra, "Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: A comprehensive review," *Journal of Building Engineering*, p. 102332, 2021.
[13] M. Amin, A. M. Zeyad, B. A. Tayeh, and I. S. Agwa, "Effects of nano cotton stalk and palm leaf ashes on ultrahigh-performance concrete properties incorporating recycled concrete aggregates," *Construction and Building Materials*, vol. 302, p. 124196, 2021.
[14] F. Martirena and J. Monzó, "Vegetable ashes as supplementary cementitious materials," *Cement and Concrete Research*, vol. 114, pp. 57–64, 2018.
[15] V. Charitha, V. S. Athira, V. Jittin, A. Bahurudeen, and P. Nanthagopalan, "Use of different agro-waste ashes in concrete for effective upcycling of locally available resources," *Construction and Building Materials*, vol. 285, p. 122851, 2021.
[16] R. Embong, N. Shafiq, A. Kusbiantoro, and M. F. Nuruddin, "Effectiveness of low-concentration acid and solar drying as pre-treatment features for producing pozzolanic sugarcane bagasse ash," *Journal of Cleaner Production*, vol. 112, pp. 953–962, 2016.

[17] E. Arif, M. W. Clark, and N. Lake, "Sugar cane bagasse ash from a high efficiency co-generation boiler: Applications in cement and mortar production," *Construction and Building Materials*, vol. 128, pp. 287–297, 2016.

[18] R. A. Khushnood, S. A. Rizwan, S. A. Memon, J.-M. Tulliani, and G. A. Ferro, "Experimental investigation on use of wheat straw ash and bentonite in self-compacting cementitious system," *Advances in materials science and engineering*, vol. 2014, 2014.

[19] M. N. Amin, T. Murtaza, K. Shahzada, K. Khan, and M. Adil, "Pozzolanic potential and mechanical performance of wheat straw ash incorporated sustainable concrete," *Sustainability*, vol. 11, no. 2, p. 519, 2019.

[20] H. Biricik, F. Aköz, I. Lhan Berktay, and A. N. Tulgar, "Study of pozzolanic properties of wheat straw ash," *Cement and concrete research*, vol. 29, no. 5, pp. 637–643, 1999.

[21] S. A. Memon, I. Wahid, M. K. Khan, M. A. Tanoli, and M. Bimaganbetova, "Environmentally friendly utilization of wheat straw ash in cement-based composites," *Sustainability*, vol. 10, no. 5, p. 1322, 2018.

[22] F. F. Ataie and K. A. Riding, "Thermochemical pretreatments for agricultural residue ash production for concrete," *Journal of Materials in Civil Engineering*, vol. 25, no. 11, pp. 1703–1711, 2013.

[23] D. Ramachandran, V. Vishwakarma, and K. Viswanathan, "Detailed studies of cow dung ash modified concrete exposed in fresh water," *Journal of Building Engineering*, vol. 20, pp. 173–178, 2018.

[24] S. Sahin, B. Kocaman, I. Orung, and S. Memis, "Replacing cattle manure ash as cement into concrete," *Journal of applied sciences*, vol. 6, no. 13, pp. 2840–2842, 2006.

[25] ASTM C150 / C150M - 20, "Standard Specification for Portland Cement," ASTM International, West Conshohocken, PA, 2020.

[26] "ASTM C311/C311M — 18 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency."

[27] "ASTM C305-20 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency."

[28] "ASTM C109 / C109M-21, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens), ASTM International, West Conshohocken, PA, 2021."

[29] ASTM C618-19, "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, PA, 2019, www.astm.org," 2019.