

Comparative assessment of the effects of furnace bottom ash and fly ash on mortar performance

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Abstract. The increased reuse and recycling of industrial waste could significantly reduce resource footprint and greenhouse gas emissions. Furnace bottom ash (FBA) is a by-product of thermal power plants and recycling it in the construction industry could have substantial environmental and economic benefits. This study aimed to compare FBA-based mortar with that of FA as a partial substitute for cement in the production of sustainable mortar. Three mixtures with 10%, 20%, and 30% FBA were created, and their workability, compressive strength, and water absorption properties were examined. The workability of the mixtures decreased with an increase in the FBA percentage. The compressive strength of the FBA-containing mixtures was similar to the control mix at early ages, but as curing time increased, the strength of FBA-containing mortars increased considerably due to pozzolanic reactivity. Additionally, the FBA-containing mixes had lower water absorption than those containing fly ash (FA) and the control mixture. As the proportion of FBA in the mixture increased, the amount of water absorbed by the mortar cube decreased. The findings proposed that 10% is the optimal proportion of FBA to substitute cement, as it showed a comparable compressive strength to the control mixture at 7 and 28 days and surpassed the strength of the control sample by 14% after 56 days. This work is anticipated to pave the way to foster new research opportunities by enabling detailed comparisons between emerging and standardized cementitious materials. It will help minimize performance uncertainties and assist in incorporating emerging materials into those standards, enhancing their overall applicability and reliability.

1 Introduction and background of study

Furnace bottom ash is one of the most significant products of industrial waste produced by coal-fired thermal power plants [1]. Currently, coal ashes are either stacked simply or placed in landfills, monofills, and ponds [2,3]. According to the NSW Legislative Council report on remediation costs for these repositories [4], one issue raised is the potential for the leaching of heavy metals from coal combustion products (CCPs) repositories. Therefore, the additional reuse of CCPs could assist with mitigating the potential for leaching. Previous literature has shown that the fine particles of FBA possess a satisfactory pozzolanic reactivity potential, making it a promising replacement for cement in concrete production [5–7]. This reinforces efforts to mitigate the negative effects of cement production. Besides, several advantages of using FBA as both cement and sand replacement have been reported, especially with regard to durability performance compared to the conventional concrete [8,9]. When it comes to the performance of strength, previous research, as depicted in Fig. 1, has shown varied results concerning the compressive strength of cementitious composites that incorporate 5–40% FBA as a substitute for cement in the early ages. As illustrated in Fig. 1, the variation in

compressive strength typically fell within a 30% decrease and a 10% increase at 28 days, relative to the control samples. It's noteworthy that most research indicated that the compressive strength performance at replacement levels of 10 and 15% was largely comparable to that of the control samples at 28 days, while a decrease was noticeable at higher replacement levels (30%). However, a notable improvement in compressive strength was reported at later ages (56, 90, and 180 days), with FBA-containing samples significantly outperforming the control samples [10,11]. A comparison of FBA with a thoroughly researched pozzolanic material like FA can offer valuable insights into the efficacy of FBA as an applicable cementitious material. Consequently, this study seeks to compare the performance of mortar mixtures made from FBA with those made from FA to fill this gap. Mortar mixtures containing various FBA contents were prepared and compared with the mixtures containing similar amounts of FA. A control mix contains no mineral content was also made for comparison. The mortar samples were subjected to various tests, including the flow table test, compressive strength test, and water absorption test.

2 Materials and methodology

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2.1 Materials

The mortar binder was developed from Portland cement, fly ash/bottom ash as shown in Fig.2. The cement used

in this research conforms to the specifications of AS 3972 [22] for cement type GB.

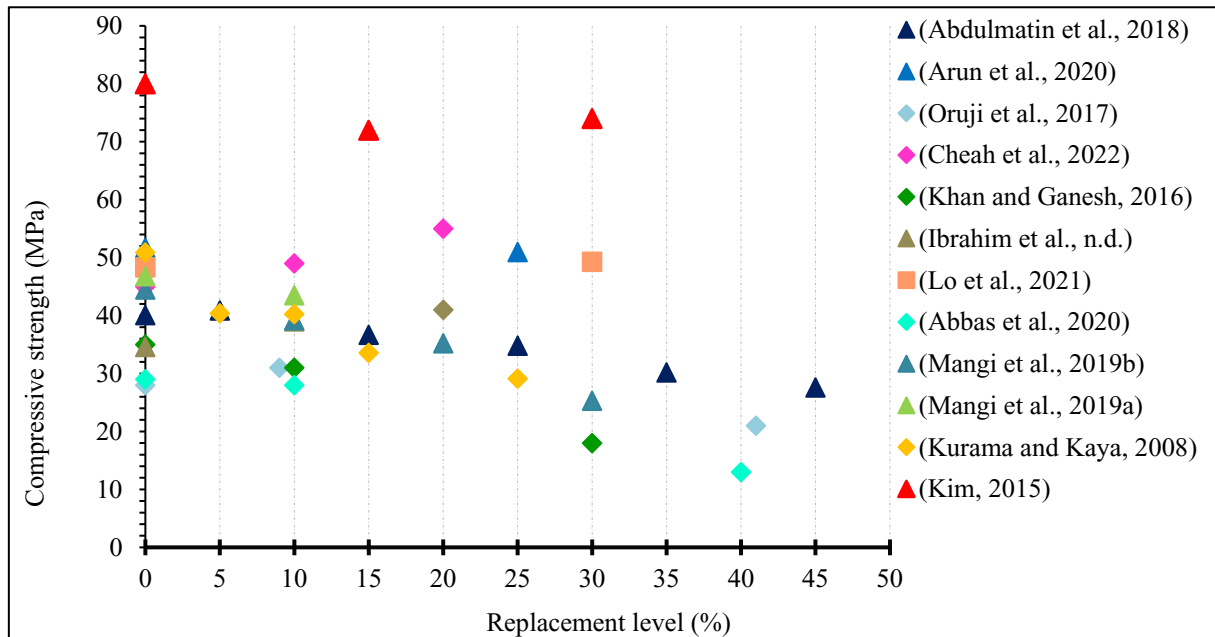


Fig. 1. Compressive strength of FBA-based composites at 28 days (for cement replacement). Raw data obtained from [10–21].

Similarly, the grade II fly ash used in this study was in accordance with AS 3582.1 [23]. Both cement and FA were obtained from Boral Australia. The raw FBA was obtained from Vales Point Coal Power Station, which is

situated in Lake Munmorah, New South Wales. Table 1 shows the chemical composition of raw materials.

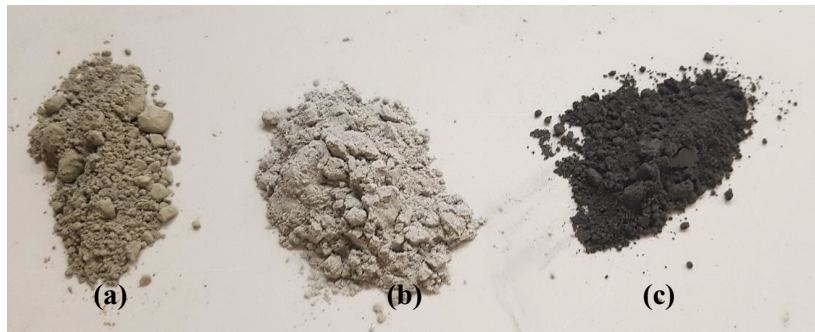


Fig. 2. Binder components used in the mortar mix; (a): Portland cement, (b): FA and (c): FBA

Table 1. Chemical composition of the raw materials.

Oxide (%)	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	MgO	MnO	Na ₂ O	P ₂ O ₅	SiO ₂	TiO ₂	SO ₃	Cl	LOI
FBA	20.5	4.96	10.64	1.82	–	0.22	–	0.48	58.56	0.79	0.23	0.78	–
FA	22.52	4.21	2.97	1.74	–	–	–	0.66	66.17	0.98	0.36	0.17	–
OPC	4.91	69.46	3.33	0.7	–	0.23	–	–	16.47	0.32	4.31	–	–

The FBA underwent a sieving process, and particles larger than 3mm were subjected to further grinding using a planetary Ball Mill Machine (Fig. 3). The Ball Mill machine spins unidirectionally at 450rpm for 120 minutes using jars that contain balls of varying sizes, including 1 x 20mm, 80 x 10mm, 110 x 6mm, and 240 x 4mm. The aim is to obtain particles less than 150µm in size. The crushed fine aggregates used in the mortar mix

range from fine silt to gravel, with a water absorption of 3%. To improve the flow properties of the mix, High Range Water Reducing (HWR) from type Master Glenium SKY 8100, that meets the AS1478.1-2000 [24], is added at a dosage of 10ml (0.0042L/100kg binder) for each mixture

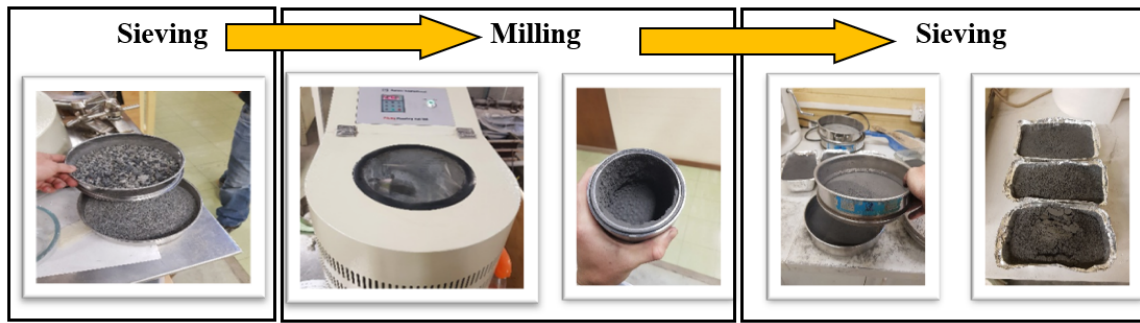


Fig. 3. The treatment process of FBA

2.2 Methodology

Table 2 displays concrete mix design ratios. To make the mortar mixes, the mixing process followed the guidelines in AS 2701 [25]. Before mixing, the moulds were oiled to prevent the mixture from sticking to them. A mortar mixer was used for mixing, and after the dry

materials were fully mixed, the mixture of water and SP was added. The flow table test was then performed on the fresh mortar to check its flow value in accordance with 2701.5 [26]. After recording the flow value, the mixtures were poured into 70×70×70 mm cube moulds and left to cure for 24 hours at room temperature.

Table 2. Mix Proportions.

Mix notation	Crushed fines (kg/m ³)	Cement (kg/m ³)	Water (kg/m ³)	Fly Ash (kg/m ³)	FBA (kg/m ³)	Superplasticizer (L)
Control	1200	400	200	0	0	0.01
FA10	1200	360	200	40	0	0.01
FA20	1200	320	200	80	0	0.01
FA30	1200	280	200	120	0	0.01
FBA10	1200	360	200	0	40	0.01
FBA20	1200	320	200	0	80	0.01
FBA30	1200	280	200	0	120	0.01

The cubes were then taken out of the moulds and kept in a fog room until the testing days. The compressive strength and water absorption were tested according to AS 1012.9 [27] and AS1012-2014 [27], respectively.

3 Results and discussion

3.1 Flow table test

Fig. 4 depicts the results obtained from flow table test. It can be seen that the workability exhibited a reduction trend with the increase in the percentage of FA and FBA. The flow value was 260 mm for the control mixture and mixture with 10% of FA, while it slightly dropped to 250 and 245 mm when the FA content increased to be 20 and 30% of the total binder weight, respectively. More reduction of flow values was observed when FBA was included. The flow values of the specimens containing of 10, 20 and 30% of FBA were 235, 230 and 230 mm, with reductions of 9.6%, 11.5% and 11.5%, respectively, compared to the control mixture. These outcomes align with Torkittikul et al. [28] who reported that the mortar

workability decrease by the increase of replacement level, where the author recorded a linear reduction in table flow test values from 3 to 16%, compared to the control mixture, when FBA content increased from 10 to 100%. According to Mangi et al. [19] the ground FBA with a higher fineness modulus showed lower workability due to higher fineness and a higher specific surface area that required more mixing water to wet.

3.2 Compressive strength

Fig. 5 shows the compressive strength at 7, 28 and 56 days for control, FA, and FBA mixes. At the age of 7 days, the mixtures containing 10%, 20%, and 30% FBA achieved a compressive strength equivalent to 99.6%, 79.3%, and 67.93% of the compressive strength for the control sample respectively. After 28 and 56 days, the compressive strength of samples containing 10% FBA exceeded that of the control sample. Specifically, the FBA10 specimen showed the highest increase in compressive strength by 4.1% and 10.2% at 28 and 56 days, respectively, compared to the control sample.

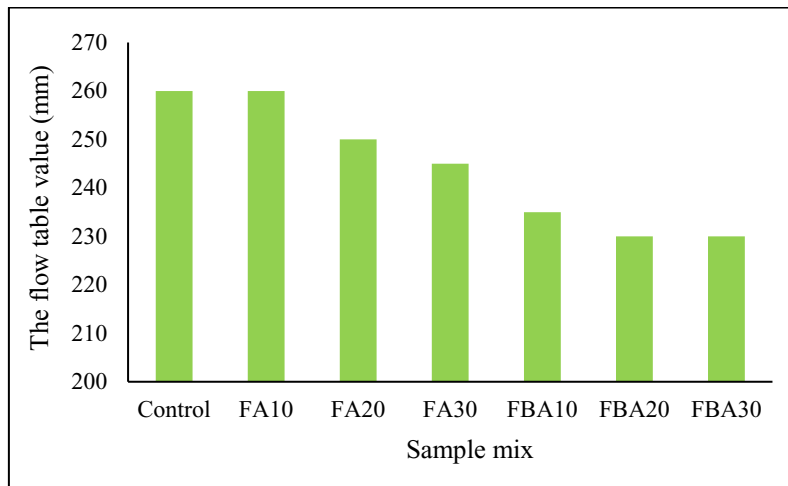


Fig. 4. Flow table values of synthesized mixture.

On the other hand, and with the exception of the compressive strength of the FA20 sample at 28 and 56 days, the samples containing FBA demonstrated higher performance over their counterpart's containing FA in terms of replacement ratios at all testing ages. That reveals that the pozzolanic reactivity of FBA was slightly higher than their counterpart's containing FA. Mangi et al. [19] revealed that the grinding treatment

enhances the reactivity of FBA particles, which could be a contributing factor to the improved compressive strength observed in this study. In general, it was reported that the inclusion of finer pozzolanic materials improve the mechanical strength of cementitious composites due to their contribution in pozzolanic reaction [29], or due to their act as fillers [30].

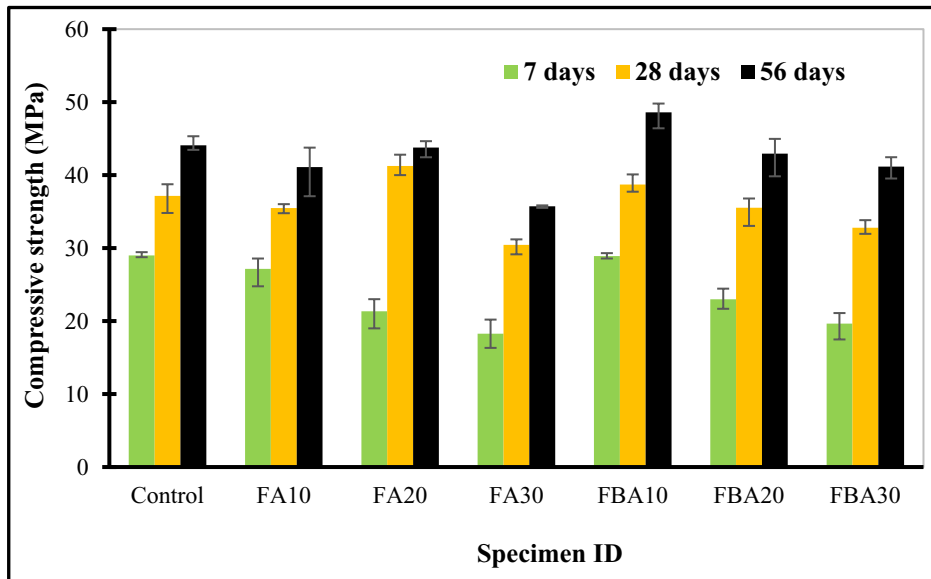


Fig. 5. Compressive strength.

3.3 Water absorption

Fig. 6 shows the average values of water absorption (WA) at 28 days of all the designed mixes. In general, samples designed with FA and FBA exhibited a lower WA% compared to the control sample. In addition, it can be seen that the trend of the WA values for FA-containing samples and FBA-containing samples decreases linearly with increase replacement level. However, it can be observed that the water absorption values for samples containing FBA were lower than their counterparts in

terms of the replacement amount containing FA. The mortar containing 30% FBA achieved the lowest value, which is 30.75% lower than that of the control sample. This improvement in water absorption resistance can be attributed to both the pozzolanic reaction and the filling action by the fine particles. It can be claimed that the high fineness boosted the pozzolanic reactivity of FBA particles, which resulted in the C-S-H gel filling the pores, hence, reducing water absorption [21]

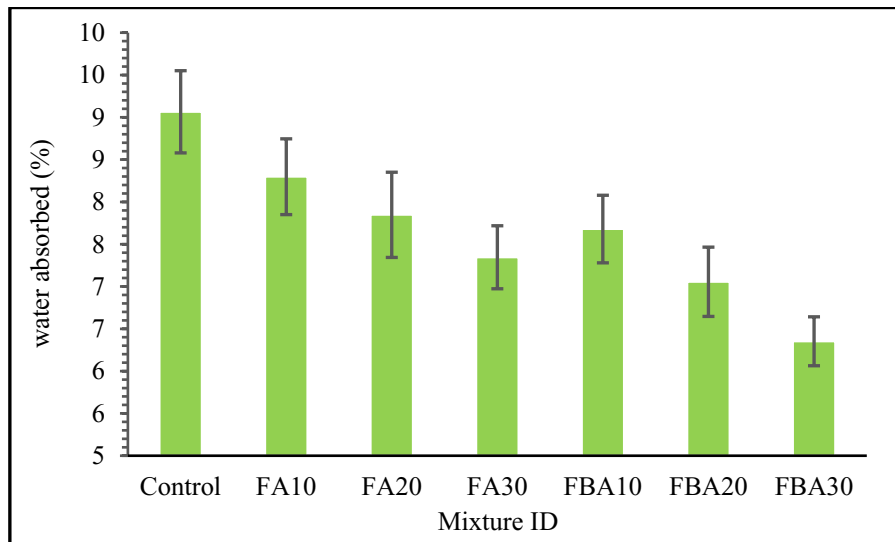


Fig. 6. Water absorption of mortar samples.

4 Conclusions

This study presents a short comparison between FBA and FA in terms of their impact on the fundamental properties of mortar when utilized as cement substitutes. The parameters considered in this comparison are confined to workability, compressive strength, and water absorption characteristics. Despite the observed reduction in workability of mixtures containing FBA as opposed to those designed with FA, the findings demonstrate that FBA outperforms FA in terms of achieving higher compressive strength and exhibiting lower water absorption ratios. The conclusions drawn from the experimental analyses are as follows:

- The FBA-containing mixtures were less workable than FA-containing mixtures. That could be due to its high specific surface area, and the angular and irregular shape of the ground FBA particles, increasing the friction effect between the mixture particles, thus reducing the mixture's workability. Microscopic studies such as particle size analyser and scanning electron microscope can be done to reveal their particle size and appearance.

- The compressive strength test showed that an increase in the replacement level of FBA led to a decrease in compressive strength. However, the gaining strength increases with the increase of curing age.

- The optimal portion of FBA as a cement alternative was determined to be 10% of binder weight, whereas the compressive strength of the mortar mixture containing 10% of FBA was similar to that of the control mixture after 28 days. After 56 days, it surpassed the control sample by approximately 14%.

- The results of the water absorption test indicate that as the proportion of FBA in the mixture increases, the amount of water absorbed by the mortar cube decreases. This can be explained by the pozzolanic reactivity potential of FBA, which enhances the formation of additional C–S–H gel, filling the pores and reducing water absorption.

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