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Effect of Bottom Ash on Rheological and Physico-Mechanical Properties of High Early Strength Self-Compacting Brick (HES-SCB)

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ABSTRACT

This study delves into the environmentally responsible application of bottom ash (BA), a prevalent waste product from coal combustion in power plants, which constitutes 15% – 25% of total coal ash in Malaysia. The improper disposal of BA is a significant environmental hazard, with the potential to contaminate groundwater and soil, thereby affecting biodiversity and land usability. This study focuses on the novel application of BA in high early strength-self compacting brick (HES-SCB), known for its rapid strength development and satisfactory flow properties, eliminating the requirement for mechanical vibration during placement. The research meticulously evaluates the substitution of BA for sand in HES-SCB, with a special focus on its influence on the fresh and physico-mechanical characteristics of the bricks. Among various mixes, the 20% BA replacement level emerged as the most significant, demonstrating a superior balance of rheological and physico-mechanical properties, thereby underscoring BA's viability as a sustainable fine aggregate substitute in HES-SCB production. This mix is designated as HES-SCB due to its distinct properties: achieving high early strength essential for rapid construction processes and exhibiting self-compacting qualities that ensure ease of use and uniformity in application.

INTRODUCTION

There are about 8,500 coal-fired power plants with a total capacity of more than 2,000 gigawatts (Birol & Malpass, 2021). The major fuel used in thermal power plants to produce electricity is coal. Power plants generate nearly a third of the electricity used in the world (Abu Bakar et al., 2023). An alternative to a fossil fuel power station is one that burns coal (Bhoi et al., 2023). Thermal power plants produce coal ash that is

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classified into two types fly ash (FA) and bottom ash (BA). BA typically has larger, popcorn-like particles (Tahir et al., 2021).

According to Tamanna et al. (2023) and Park et al. (2016), a common coal combustion by product from power plants, coal bottom ash has a shape like that of sand and clay. Over the past ten years, the US and EU produced around 14 and 4 million tons of bottom ash annually (Kim, 2015). In the civil engineering sector, about 50% of them have been used as substitutes for conventional soil and gravels for embankments, structural fill, road building, and various cement-based composites like concrete and mortar (Apandi et al., 2021; Apandi et al., 2023). Consuming BA in the building sector is one of the effective initiatives to solve the many environmental issues. Some of the earlier investigations have compiled the different management strategies for BA (Guan et al., 2023).

In the world of construction, self-compacting concrete (SCC) has brought revolution in the current construction sector due to several advantages. Concrete that spreads overcrowded reinforcing bars, seals the corners of the formwork, and compacts under its weight is known as SCC. SCC is a recently created high-performance concrete with effective rheology that can fully compact under its weight without the help of internal or external vibration. In recent years, self-compacting bricks (SCB), have garnered a lot of interest as a more environmentally friendly alternative to conventional bricks. Because of their better physico-mechanical qualities, smaller carbon footprint, and simplicity of use, structural insulated boards (SIB) are an excellent option for use in contemporary building endeavours. It is a particularly workable variety of concrete that can also be applied to huge sections of formwork. Filling capacity, passage ability, and improved segregation resistance are the essential requirements for innovative SCB characteristics to display this behaviour.

According to Zainal Abidin et al. (2015), in the observation of mechanical properties of SCC, in most of the earlier studies, the optimum percentage of BA has been found up to 20% as a replacement for natural fine aggregates (NFA). The advantageous effect of CBA has been witnessed in a few studies as most of the physico-mechanical behaviour of SCC prepared with 10% – 20% of NFA replaced with BA has been improved. High early strength-self compacting brick (HES-SCB) is a subcategory of SCB that is characterized by significant early strength growth. This trait makes HES-SCB an attractive option for applications for quick strength development with self-compacting properties.

MATERIALS AND METHOD

Materials selection

In this study, the materials used were according to the specification that meets the requirement of appropriate Malaysian and British Standards. Ordinary Portland cement (OPC) is a synonym of the cement type used for producing concrete. In concrete, the cement acts as a binder, and the composition of the cement strengthens the concrete (LeBow, 2018). OPC is typically grey and is utilized extensively worldwide in civil engineering activities and projects. The OPC is made up of argillaceous substances like alumina and laterite as well as calcareous substances like limestone and calcium.

Water was used as the liquid agent of concrete. The water utilized must be free from chemical composition and organic matter. In Malaysia, the quality of water was referred to the Public Work Department of Malaysia (PWD) and BS EN 1008:2002 for specifications of concrete (The European Standard, 2002). Sand and other uncrushed aggregates with particle sizes smaller than 6 mm ended up being used as fine aggregates, in accordance with BS EN 12620:2002 (The European Standard, 2002). Sand is particularly significant since it acts as a filler component, despite its small particle size.

Almost 50% of bottom ash particles have dimensions less than 250 µm, which makes a greater amount of fine elements available in the concrete. Fine elements could be used as fillers in concrete to enhance its

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properties and performance and could improve the strength, durability, and other physico-mechanical properties of the mixture, making it more suitable for specific applications. Coal bottom ash particles are typically larger and more irregular in shape compared to sand particles. With a particle size of 0.3 mm or less, the fine fraction of BA, or 12% of the total bottom ash at the incineration plant, was used for the studies (Haberl & Schuster, 2019).

Quarry dust was also used in this study. It is a by-product of quarrying operations. Instead of being discarded, quarry dust is often recycled and used in various applications due to its physical and chemical properties. Quarry dust primarily consists of fine particles and small rock fragments. The size of quarry dust that has been used in this study is 5 mm and has been sieving to get this specified size. The type of super-plasticizer used in this study is MasterGlenium SKY 8611. It is a superplasticizer based on polycarboxylate ether (PCE) that produces self-consolidating concrete with low particles for everyday usage. They are used in the mixture to increase its rheological properties including flowability and workability without reducing its strength. This superplasticizer can provide great durability and has high initial and ultimate strengths as well as low permeability. Reduced retreat rate, no segregation, or bleeding, and create a nice surface finish.

EXPERIMENTAL METHOD

In this study, two different phases of testing were done, rheological properties and physico-mechanical properties. The sand acts as a fine aggregate and was replaced with various percentages of CBA, 10%, 15%, 20%, 25%, and 30%, with 0% of replacement acting as a control sample. With controlling all the materials, the mould dimension with the dimension of 210 x 100 x 65 mm was prepared for the compression test, for 1, 3, 7, and 28 days. The tests that have been carried out for fresh properties were slump flow test, T500, and L-box test while, physico-mechanical properties were compression strength test, density test, and water absorption test.

Mix proportions

Prior to casting the specimens, the HES-SCB combinations' proportioning was agreed upon due to the significant difference between the specific gravity of natural sand and bottom ash, volumetric replacement was preferred. The volume approach for concrete mixture refers to the method of proportioning the ingredients of concrete based on its volumes rather than its weights. This approach was commonly used in small-scale projects. Table 1 gives specifics on the control sample of HES-SCB with 0% replacement of coal bottom and named M0. Five (5) HES-SCB combinations of bottom ash were created and the proportion of fine aggregate replaced with bottom ash ranged from 10% to 30%. These mixtures represent different combinations of CBA and sand to achieve the desired properties for HES-SCB based on the specified percentages. The notation provided suggests different mixtures labelled as M0, M10, M15, M20, M25, and M30, with the numbers indicating the percentage of CBA in each mixture. Table 1 provides details of the characteristics of the various HES-SCB mixtures made with different percentages of replacement coal bottom ash as a fine aggregate. The water-to-cement ratio was maintained at 0.45.

Casting and curing

The preparation of the mixtures included: (1) and, bottom ash, quarry dust, OPC, Masterglenium SKY 8611 and water was weighed with 10% of wastage to avoid any humans error during weighing; (2) material such as sand, bottom ash, quarry dust was put into mixer for 30s at low rotation speed (60 rpm). Then, OPC was mix with other materials while water and Masterglenium SKY 8611 was mixed and put into the mixer; (3) the mixture was mixed for about 2 or 3 minutes at the same low speed and, (4) fresh HES-SCB mixture needs to be tested as soon as possible to avoid bleeding and hardening. It can also help get more accurate

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results for fresh properties. The casting of the brick was implemented on the 215 x 101 x 65 mm mould as it was tested on the compressive strength, density, and water absorption of the sample. In this study, water curing was taken to be the curing regime. The samples were put in the water, at room temperature, for a certain time to make sure they were ready on the day of testing. The samples were flooded, and this process is known as water curing. The curing ages monitored in this study are 1, 3, 7, and 28 days. Although high early strength was expected, an increase in compressive performance over additional curing days was also anticipated.

Table 1. Mixture Proportion of HES-SCB specimens

Type of mixture	Cement	Superplasticizer	CBA (Sand replacement)		Water	Quarry dust	Sand	
	kg/m^3	kg/m^3	%	kg/m^3	kg/m^3	kg/m^3	%	kg/m^3
M0 (0% CBA)	561	2.8	0	-	252	593	100	670
M10 (10% CBA)	561	2.8	10	67.0	252	593	90	822
M15 (15% CBA)	561	2.8	15	100.5	252	593	85	777
M20 (20% CBA)	561	2.8	20	134.0	252	593	80	731
M25 (25% CBA)	561	2.8	25	167.5	252	593	75	685
M30 (30% CBA)	561	2.8	30	201.0	252	593	70	640

Test procedures

The self-compacting mixture is exceptionally workable and flows through packed reinforcement under its weight alone, filling the formwork with a void-free structure without segregation of its constituent materials and allowing it to be placed without vibration. The main fresh qualities must be met when making HES-SCB mixes in order to achieve self-compacting properties in terms of flowability, passing ability, strength, and segregation resistance. In the fresh state of the mixture, the slump flow test, T500 test, and L-box test were conducted to determine the rheological properties of the mix such as flowability, viscosity, and passing ability. The test was applied to the procedure according to the European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC) (The European Project Group, 2005). Using the standard as the guide, the testing was performed based on the specification highlighted in the procedure and the testing was repeated three times.

For the density test, all samples were having their density tested, computed, and recorded (Zailani et al., 2024). The measurements for the density of hardened concrete were done after 1, 3, 7, and 28 days after curing. All the processes for the density test were followed from the standard BS EN 771-3:2011+A1:2015 (The European Standard, 2011). According to BS EN 772-1:2011+A1:2015, a brick of 215 x 101 x 65 mm had its compressive strength tested using a Universal Testing Machine (UTM) at 1, 3, 7, and 28 days after curing (The European Standard, 2011). The machine then applied loads to the brick at a different rate depending on the expected compressive strength until the brick failed. Therefore, during water curing, the impact of bottom ash content on the compressive strength of the HES-SCBs was investigated. Each value for compressive strength was the average of three samples.

The International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (RILEM) standard served as the foundation for the water absorption test. For each batch, the brick samples were examined after 1, 3, 7, and 28 days. The main goal of this test is to determine how much water each specimen can absorb; the results will be presented as a percentage. A higher rate of water absorption resulted in more water filling the specimen's pore volume. The procedure for the water absorption test, as outlined by RILEM, involves the following steps. Initially, the specimens are dried in an air oven at 105 ℃ for 24 hours until a constant mass is achieved, and this dried mass is recorded as W1. Once the bricks have cooled to room temperature, the bricks are put in the water for 10 minutes. After that, the brick was removed from the water tank and let it be in a temperature room until the surface was dried.

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Following this, the brick specimens were weighed again, and recorded as *W2*. The percentage of water absorption was calculated by using Equation (1).

$$Water\ absorption = \frac{W2 - W1}{W1} \times 100\% \qquad (1)$$

where *W1* is the mass of brick specimens after drying with an air oven for 24 hours and *W2* is the mass of brick after being immersed in water for 10 minutes.

RESULTS AND DISCUSSION

Fresh properties of HES-SCB

Flowability, viscosity, and passing ability were important to the fresh properties of materials, particularly in the context of SCB or other construction materials. These fresh properties were important considerations in construction practices to ensure that the material can be easily handled, placed, and compacted, leading to a high-quality and durable product.

The analysis based on the results of the experiment was displayed by a bar chart in Fig 1(a) illustrating the diameter of the slump cone test decreases. This means that the flowability or slump of the fresh self-compacting brick decreases with a higher percentage of bottom ash replacement. This reduction in slump occurs because the angular and irregular shape of bottom ash particles increases the internal friction within the mixture, hindering the movement of particles and reducing the ability of the concrete to flow (The European Project Group, 2005). The effect of using CBA as a fine aggregate on viscosity characteristics reveals that the percentage substitution of CBA increases, and it takes longer for the fresh mortar to reach a slump flow of 500 mm in the T500 test. The viscosity of the mortar increases with a higher substitution of CBA. Based on the information in the bar chart in Fig 1(c), it seems that the higher the replacement percentage of bottom ash in the SCC, the lower the flow spread ratio observed in the L-box test. This suggests that increasing the replacement of bottom ash with fine aggregate has a negative effect on the passing ability and flowability of the SCB. A lower flow spread ratio indicates a reduced ability of the SCB to flow and pass through narrow or congested sections, which can be attributed to increased viscosity or decreased workability caused by the higher replacement of bottom ash.

Based on the specification from EFNARC (2005), it seems that the slump flow test has determined that the mixtures M0, M10, and M15 meet the standards for class SF3, which typically refers to a slump range of 760 mm - 850 mm. Besides, for M20 and M25 to meet the specifications the range is between 660 mm - 750 mm for the SF2 class and M30 belongs to class SF1 (The European Project Group, 2005). In addition, in the slump flow time (T500) test, all the mixtures achieved a flow that reached a diameter of 500 mm in less than 5 seconds as shown in Fig 1(b). This indicates that the flowability of the mixtures is within an acceptable range. As a result, all the mixtures were classified in the VS2 class. The VS2 class is typically suitable for reducing formwork pressure or enhancing segregation resistance (The European Project Group, 2005). This suggests that these mixtures, despite having slower flow due to the presence of bottom ash, offer advantages in terms of reducing the pressure on formwork or improving resistance to material separation. Moreover, the value of the passing ability of SCB decreased with the increase in bottom ash content. It was considered to be due to the aggregate bridging at the area between the clear space and the steel bar, resulting from the inter-particle reaction between aggregates. There are two classes, PA1 and PA2, for the L-box test. The L-box ratio H2/H1 for all mixes was above 0.8 except M30 which complies with standards (The European Project Group, 2005).

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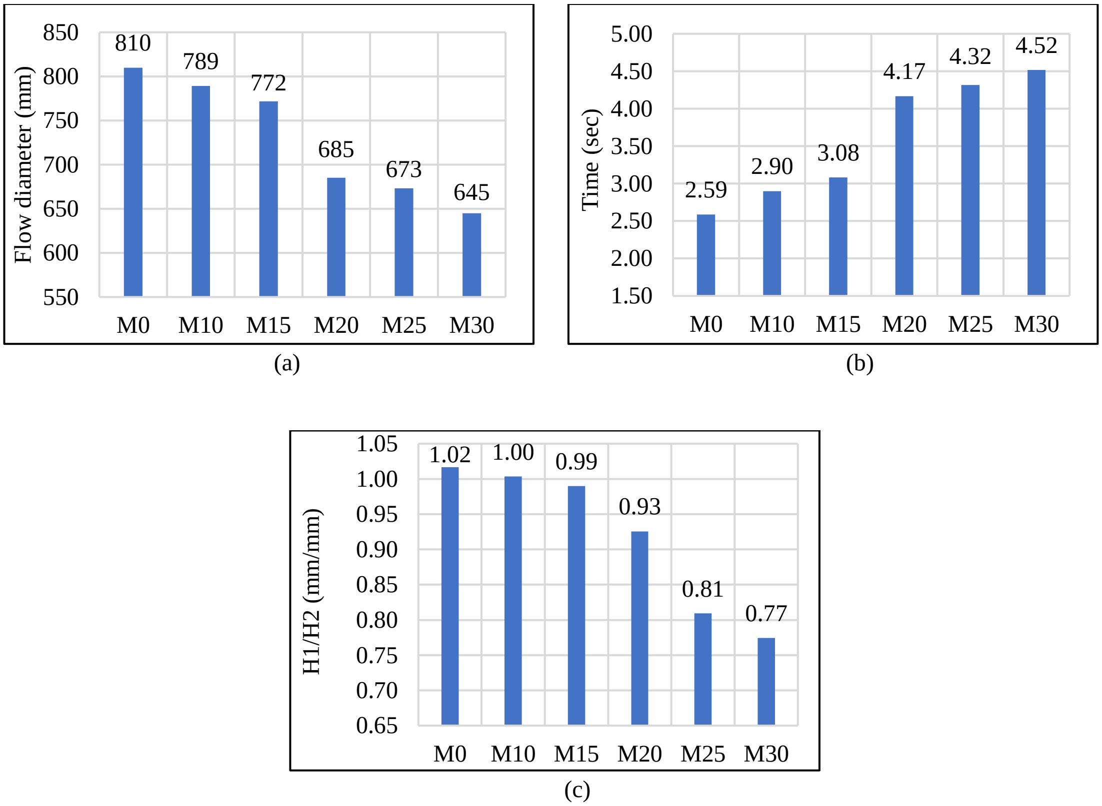

Fig. 1. Fresh properties of HES-SCB; (a) Slump flow test, (b) t500 test, and (c) L-box test.

Bulk density of HES-SCB

Fig 2 shows a consistent increase in density from sample M0 to M20, reaching a peak at sample M20 for curing durations of Day 1, Day 3, Day 7, and Day 28. The result illustrates a decline in density beyond sample M20, indicating a decrease after reaching the maximum value. This suggests that the replacement of bottom ash up to 20% contributes to the density enhancement of the material. However, further increases in sand replacement, specifically up to M30, result in a diminishing effect on density. The findings highlight the importance of optimizing bottom ash as fine aggregates to achieve the maximum density of the concrete, while prolonged curing may not yield additional improvements and may even lead to a reduction in density (The European Standard, 2011).

Concrete will reduce its density as ground bottom ash content rises (The European Standard, 2011). This also has been supported by other researchers, which is that said low density, an uneven, spherical shape, and a complex texture can be seen in the bottom ash (Rafieizonooz et al., 2016). When used in place of sand, bottom ash particles are more porous and brittle than natural sand particles, requiring more water during the mixing process and lowering the density of brick, especially for more than 30% of sand replacement.

There are six (6) types of brick mixes with different replacements of bottom ash were considered for density tests with various curing durations. From the result that has been obtained from the density test, The curing trend reveals slight fluctuations in density values across all mixes over different curing durations.

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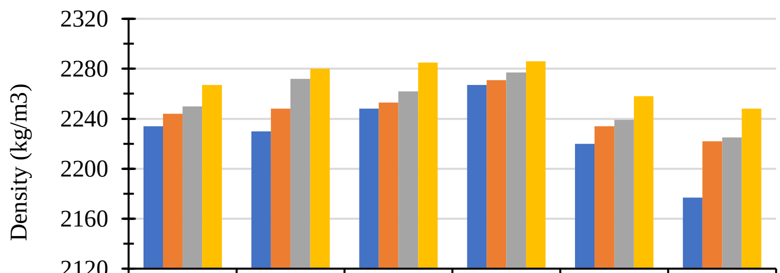

	M0	M10	M15	M20	M25	M30
1 Day	2234	2230	2248	2267	2220	2177
3 Day	2244	2248	2253	2271	2234	2222
7 Day	2250	2272	2262	2277	2239	2225
28 Day	2267	2280	2285	2286	2258	2248

Fig. 2. Density of HES-SCB at different curing duration.

The analysis of the research data across all six samples (M0, M10, M15, M20, M25, and M30) indicates a consistent increase in density from the first day of curing to the 28th day. Notably, all blends exhibit a rise in density, with sample M20 demonstrating the most substantial enhancement. The density increase ranges between 30% and 40% for both the initial curing day (Day 1) and the 28th day of curing. This suggests that the curing process has a pronounced positive impact on the density of the materials, particularly evident in the M20 sample. The observed percentage increase in density highlights the effectiveness of the curing process, emphasizing its role in promoting material density, and underscores the significance of the 28-day curing period in achieving optimal density improvements across the various blends. This implies that several variables, such as the mix's composition and the curing procedure, have an impact on density. This finding is in line with the previous research reported by Rafieizonooz et al. (2016).

Comparing all the density values, it is important to note that the differences in density among the mixes are relatively significant. On curing day 1, Mix M20 has the highest density at 2267 kg/m^3, followed closely by Mix M15 and Mix M10. Mix M30 has the lowest density at 2177 kg/m^3. At 2271 kg/m^3 on Day 3, Mix M20 has the highest density, followed by Mix M15. The lowest density is Mix M30, with 2222 kg/m^3. On Day 7, Mix M20 also has the highest density at 2277 kg/m^3, followed by Mix M10. Mix M30 has the lowest density at 2225 kg/m^3. On the last curing day which is 28 days, Mix M20 has the highest density at 2286 kg/m^3, followed closely by M15. Mix M30 has the lowest density at 2248 kg/m^3. In this analysis, it can be observed that the composition yielding the highest density exhibits variability as a function of the curing duration.

The effects of ground CBA in concrete are clearly seen in the graphs for the density of each mix. On 28 days of curing, when the addition of ground CBA is increased, the density of the brick gradually increases and starts to decrease after 20% sand replacement. When using bottom ash, the density of all mixtures increased at all curing periods as compared to the control mixture except for M10, where the 1 Day density is lower than the control mix (M0). The reason for this unpredictable change is not known, it may be the result of some error during the experiment. For control samples, the density increases during the first 7 days of curing and keeps increasing until 28 days of curing. It was found that the density of HES-SCB containing 20% of bottom ash was the optimum.

The effect of bottom ash on density can be specifically related to the use of bottom ash in brickmaking. The inclusion of bottom ash in brick production can affect the density of the final product. The addition of

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bottom ash can be optimized to clarify the test result. Compared to clay or small particles, bottom ash often has a higher porosity. The greater porosity of bottom ash can cause a decrease in density when used to make bricks (Rafieizonooz et al., 2016). The bottom ash particles' voids may cause a less compact structure, which lowers the brick's overall density. Bottom ash's interaction with other components and particle size distribution affects the mix's packing density. If the bottom ash particles are reasonably small and evenly dispersed, they can fill in gaps and raise the brick's overall density. However, an uneven distribution or too much sand replacement which is more than 20% may result in a reduction in density and overall performance of self-compacting brick.

Compressive strength of HES-SCB

The research analysis reveals a progressive increase in compressive strength from sample M0 to M20, indicating a positive correlation with the escalating content of bottom ash. However, samples M25 and M30 exhibit a decline in compressive strength for curing durations of Day 1, Day 3, Day 7, and Day 28. The graphical representation of the data underscores the optimum compressive strength achieved in sample M20. The incorporation of bottom ash as a replacement for sand demonstrates significant potential for the production of self-compacting bricks. This finding suggests that the utilization of bottom ash positively influences compressive strength up to a certain threshold, with M20 representing the peak performance in terms of strength. The research underscores the promising prospects of employing bottom ash as a viable alternative in the development of self-compacting bricks, with the need for careful consideration of the optimal proportion for enhanced compressive strength.

According to Zainal Abidin et al. (2014), bottom ash has been used to produce self-compacting concrete, which has boosted the compressive strength of the concrete to a 20% replacement level. The outcome demonstrates that when the bottom ash content rises, the amount of air voids in the concrete decreases, leading to an increase in compressive strength. This idea has been supported by Patankar et al. (2015) who employed fly ash as the binder in their study. It has been established that adding more bottom ash makes concrete more compressible. Furthermore, Park et al. (2016) demonstrated that class C fly ash, a high-calcium material, can achieve a maximum compressive strength of 42.5 MPa.. As a result, it is anticipated for this study that the compressive strength will rise as the bottom ash level rises.

In addition, the results indicate that bottom ash during early stages exhibits a comparable strength development pattern to control brick at all degrees of bottom ash replacement for sand. For mix M20, which likely contains 15% bottom ash, demonstrates an increase in compression strength values over the curing days. It shows the highest compression strength values compared to other mixes, indicating that the inclusion of 20% bottom ash contributes to enhanced early strength development. The compression strength values for Mix M20 are particularly notable, reaching 56.44 N/mm^2 on curing day 28. Overall, it shows higher compression strength values compared to the control mix which is M0. It can be seen clearly, the development of the compressive strength of HES-SCB containing CBA and normal HES-SCB.

Based on the results, the development trend of compressive strength for each series of HES-SCB mixes containing bottom ash is higher compared to the control sample (HES-SCB without the bottom ash). Based on the results that have been obtained at 28 days for each mixture of M0, M10, M15, M20, M25, and M30 and as shown in Fig 3, all specimens of HES-SCB that have been replaced 10%, 15%, 20%, 25% and 30% of sand with bottom ash and normal HES-SCB without bottom ash after 1 day of curing were achieved the target strength for this study which exceeds the value of standard strength of engineering brick that is 35 N/mm^2. In Malaysia, the standard value of compression strength for engineering bricks is typically specified by the Malaysian Standards (MS) which is MS 7.6: Part 1. According to MS 7.6: Part 1, the minimum average compressive strength requirement for engineering bricks is 35 N/mm^2. This means that the average compression strength of the engineering bricks should not fall below 35 N/mm^2. This achieves the target of this study to produce high early-strength brick.

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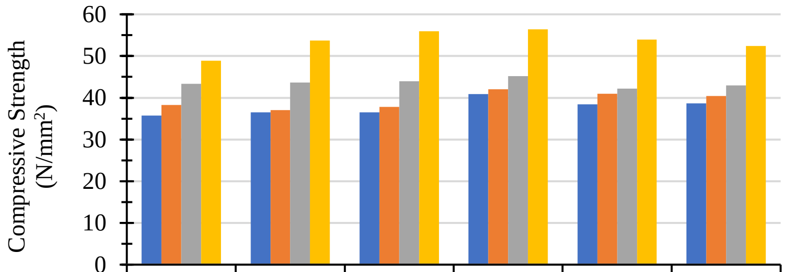

	M0	M10	M15	M20	M25	M30
1day	35.77	36.52	36.53	40.91	38.41	38.69
3day	38.26	37.02	37.81	42.02	40.95	40.41
7day	43.37	43.69	43.95	45.21	42.17	42.96
28day	48.84	53.74	55.93	56.44	53.93	52.42

Fig. 3. Compressive strength of HES-SCB at different curing duration.

It can be seen clearly that all the values of these HES-SCB exceed the standard strength of engineering brick. The presence of bottom ash in the mixtures influences the compression strength. Mixes containing higher percentages of bottom ash, such as M15, M20, M25, and M30, demonstrate higher compression strength compared to mixes M0 and M10. There is an optimal percentage of bottom ash that enhances the compression strength of the self-compacting bricks. The optimum or the best bottom ash replacement to get the optimum compression strength is by replacing 20% of sand with bottom ash. The table allows us to observe the early development of brick mixtures. It is notable that Mix M20 shows the highest compression strength among all the mixtures, particularly on Curing Day 28.

The particle size distribution and packing arrangement of the bottom ash particles, along with the other constituents in the mix, can influence the strength. The specific particle characteristics of the bottom ash in Mix M20 appear to contribute to a favourable packing density, resulting in enhanced compression strength. Chemical reactions between the bottom ash particles, cement, and other constituents during the curing process also might lead to the formation of stronger cementitious phases. These interactions play a crucial role in the overall development of the bricks. The impact of bottom ash on the strength properties of the bricks can be evaluated by comparing the compression strength values across various mixtures and curing days. A crucial factor in determining the structural integrity and load-bearing capacity of bricks is compression strength.

The inclusion of bottom ash in brick production for construction can offer several benefits. Bottom ash, being a by-product of coal combustion, can be a sustainable alternative to traditional brick-making materials. It can contribute to improved strength properties, such as higher compression strength, which is crucial for load-bearing structures. Additionally, utilizing bottom ash in brick production can help reduce waste and environmental impact. The compression strength test results provide insights into the impact of bottom ash on the strength characteristics of self-compacting bricks. The presence of bottom ash generally enhances the early strength development of the bricks, as seen in the improved compression strength values. This compression strength test and previous researchers mostly got the same result that the most suitable percentage of bottom ash in the brick composition to optimize strength, durability, and other properties is by replacing 20% of sand with bottom ash. The use of bottom ash in brick production holds promise for sustainable and resilient construction practices.

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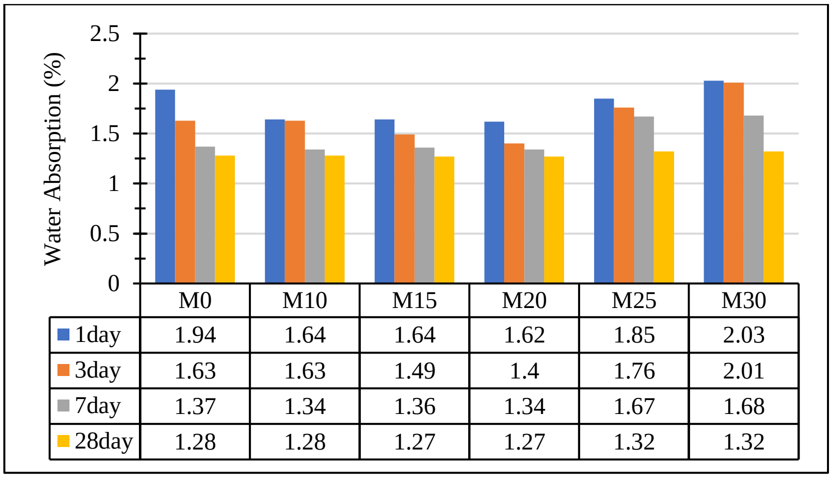
Water absorption of HES-SCB

Water absorption tests for HES-SCB were performed on various curing days to check the relationship between the curing period and water absorption for different bottom ash mix proportions. Fig 4 shows all the values derived for the water absorption test during the experiment. This study followed BS EN 772-11:2011 to conduct a water absorption test utilizing an HES-SCB that contains CBA and a standard HES-SCB. On HES-SCB with CBA and regular SCLFC aged 1, 3, and 7 days, measurements of water absorption values were made.



	M0	M10	M15	M20	M25	M30
1day	1.94	1.64	1.64	1.62	1.85	2.03
3day	1.63	1.63	1.49	1.4	1.76	2.01
7day	1.37	1.34	1.36	1.34	1.67	1.68
28day	1.28	1.28	1.27	1.27	1.32	1.32

Fig. 4. Water absorption of HES-SCB at different curing days.

The experimental results revealed that the inclusion of bottom ash generally led to a decrease in water resistance, as evidenced by the observed water absorption values. These findings provide valuable insights into the effects of incorporating bottom ash into brick compositions, highlighting the importance of considering its impact on water resistance during the manufacturing process. This is because increased porosity increases the bricks' capacity to absorb water. Furthermore, water absorption values tend to decrease or stabilize as the curing days progress. This indicates that the curing process enhances the water-resistance properties of the bricks.

In addition, bottom ash in HES-SCB has a significant effect on water absorption. The changes in water absorption behaviour can be seen by comparing the lines that represent each mix. Different patterns and levels of water absorption are shown for Mixes M0, M10, M15, M20, M25, and M30 at various curing days. Sample Mix M10 shows a relatively consistent decrease in water absorption values as the curing days progress followed by M15 and M20. This suggests that the curing process itself improves the water resistance properties of the bricks, even without the inclusion of bottom ash. This is due to the hydration reaction between cement and water which then produces highly dense brick.

On Curing Day 3, the water absorption for Mix M10 somewhat decreased, and then it gradually decreased over the next few days. This can be a sign that the curing process has temporarily changed how much water is absorbed. In comparison to Mix M0, Mix M10, M15, and M20 generally exhibit lower water absorption values. As the number of curing days increases, the water absorption of Mixes M15, M20, M25, and M30 is reduced to variable degrees. Mix M0 has greater initial water absorption values, but by Curing Day 3, it has significantly decreased and continues to have comparatively low values. While Mix M25 and Mix M30 initially have higher water absorption values, they later demonstrate a decline and stabilization.

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Throughout the curing process, Mix M30 continuously displays the greatest water absorption values of any mix, indicating the need for additional optimization.

However, data does not show any clear distinction between the increase in water absorption and with increase in coal ash content as shown by previous research studies (Patankar et al., 2015; Rafieizonooz et al., 2016; Zainal Abidin et al., 2015). The results of several researchers' studies indicate that using bottom ash with partial replacement of sand significantly reduces the density of concrete and requires additional mixing water. Because bottom ash has a smaller unit weight and a more porous structure than natural sand, bottom ash concrete has a lower density and high-water absorption. The need for more water during the mixing of the bottom ash concrete, which results in more formation of calcium silicate hydrate (CSH), is another element that contributes to filling in the pores within the bottom ash surface (Izwan et al., 2023).

The effect of bottom ash on the water absorption values of HES-SCB for different mixes at various curing days was clearly observed. All the mixes consistently demonstrate relatively lower water absorption values throughout the curing days. This also shows a decrease in water absorption values after the initial curing days, indicating the potential benefits of bottom ash in reducing porosity. Bottom ash is more porous than natural aggregates, which is the primary factor impacting the maximum water absorption properties of HES-SCB with CBA. Due to its porous nature and the dry pore space state of both the CBA and its microcracks, as well as the pore space present in the new hydrated cement mixture, water can enter the bottom ash through absorption (Singh & Singh, 2016). When compared to regular HES-SCB, the HES-SCB that contains CBA absorbs more water because of these factors overall.

Comparing water absorption values across mixes and curing durations highlights the role of bottom ash in minimizing water uptake in bricks. Generally, lower water absorption indicates better quality and improved resistance to moisture penetration. The results indicate that as the curing period progresses, the water absorption values tend to decrease or remain relatively stable for most mixes. This trend suggests that the curing process helps enhance the strength and reduce the porosity of the bricks (Tahir et al., 2019).

It is evident that the bottom ash content of the concrete consistently increases with an increase in the water absorption value. Due to CBA's porous nature, this results in a higher percentage of bottom ash content and bottom ash content in brick. As a result, it increases the amount of pore space that is accessible for water to fill, and it increases the rate at which water is absorbed.

CONCLUSION

In conclusion, the investigation into incorporating coal bottom ash (CBA) as a fine aggregate substitute in High Early Strength Self-Compacting Concrete Bricks (HES-SCB) has yielded critical insights, with the most impactful results summarized as follows:

(i) Rheological challenges are indicated by increased viscosity with higher CBA substitution levels, as evidenced by extended T500 slump flow times.

(ii) Optimal density and compressive strength are achieved with 20% CBA substitution represented by M20, marking it as the ideal proportion for balancing rheological properties and structural integrity in HES-SCB.

(iii) Different mix proportions (M0, M10, M15, M20, M25, M30) exhibit varying water absorption behaviors over the curing period. The study highlights the nuanced influence of CBA on water absorption characteristics, with Mix M20 showing optimal performance in reducing water absorption while maintaining compressive strength.

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(iv) Significantly, the Mix M20 emerges as the most promising formulation, adeptly balancing enhanced density, strength, and reduced water absorption, underscoring its potential in sustainable construction applications. These findings advocate for the judicious use of CBA in HES-SCB production, paving the way for further exploration and optimization of sustainable building materials.

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CONTRIBUTIONS OF AUTHORS

The authors confirm equal contributions to each part of this work. All authors reviewed and approved the final version of this work.

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CONFLICT OF INTERESTS

All authors declare that they have no conflicts of interest.

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