International Journal of GEOMATE, Oct., 2025 Vol.29, Issue 134, pp.85-92
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.134.5027
Geotechnique, Construction Materials and Environment

ENVIRONMENTAL AND COMPRESSIVE STRENGTH EFFECTS OF COAL BOTTOM ASH AS PARTIAL SAND REPLACEMENT IN CONCRETE: A LEACHING ASSESSMENT STUDY

**Fauzan[1,2], Sharifah Salwa Mohd Zuki[1], Shahiron Shahidan[1], Herlina Suciati[2] and Panusunan[2]

[1]Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, Malaysia
[2]Faculty of Civil Engineering, Universitas Batam, Indonesia

*Corresponding Author, Received: 25 April 2025, Revised: 06 July 2025, Accepted: 09 July 2025

ABSTRACT: One coal waste is coal bottom ash (CBA), which has an environmental impact due to its heavy metal content. This study reveals the dual role of CBA as a partial sand replacement in concrete through leaching ability analysis to assess mechanical performance and environmental safety. The concrete mixture was prepared by placing CBA at 0%, 30%, 40%, 50%, and 60%, and then a compressive strength test was carried out at the periods of 7 and 28 days. Using the Synthetic Precipitation Leaching Procedure and ICP-MS analysis, the leaching behavior was evaluated. The results showed that adding CBA up to 50% increased the 28-day compressive strength by 6.42% compared to the control concrete. In comparison, higher replacement (60%) caused a decrease in strength due to increased porosity and unburned carbon, which prevented hydration. Leaching tests showed that adding CBA reduced the mobility of Cr, Pb, Zn, and Cd in concrete by combining physical encapsulation in the cement matrix and chemical stabilization by forming calcium silicate hydrate (C–S–H) gel. The maximum reduction was observed at 50% CBA: Cr (27.9%), Pb (67.9%), Zn (1.5%), and Cd (10.2%) compared to control concrete. However, using CBA in concrete needs to be controlled because the concentrations of Cr and Pb in some mixtures exceed the USEPA threshold, indicating potential risks for soil and groundwater. This study is beneficial for sustainable construction.

Keywords: Coal Bottom Ash, Concrete, Compressive Strength, Heavy Metal Leaching, Environmental Impact

1. INTRODUCTION

Concrete is becoming the primary construction material for structural applications, primarily due to its economic advantages compared to alternatives such as steel [1]. However, concrete production has some limitations because of its high dependence on natural resources for fine aggregates such as river sand, the main component of concrete is facing critical depletion globally [2]. The demand for concrete is increasing the need for alternative materials with the same performance as conventional aggregates but environmentally friendly [3].

Coal-fired power plants are major sources of energy industrial waste, producing large amounts of coal combustion residues, including fly ash and bottom ash [4-6]. One coal-fired power plant is estimated to produce more than 50,000 metric tons of coal ash monthly. In Malaysia, approximately 8,000 metric tonnes of coal bottom ash (CBA) is produced monthly, and this waste is typically stored in disposal sites, leading to long-term environmental and health hazards. Although CBA has been explored for various secondary uses, such as soil stabilization and brick manufacturing, a large proportion remains unused, posing ongoing ecological challenges [7-8]. Some efforts have been made to utilize the increasing amount of waste, including utilizing CBA for soil improvement, brick manufacturing, and other applications [9-10].

The construction industry, particularly concrete production, has been scrutinized for its high environmental footprint, including significant greenhouse gas emissions and excessive exploitation of natural resources [11]. As sustainability becomes a central concern, utilizing industrial byproducts such as CBA offers a dual benefit: reducing solid waste and conserving natural aggregates [12]. Reusing CBA in concrete aligns with circular economy principles and represents a viable step toward reducing the construction sector's environmental impact. Using CBA on the concrete can reduce solid waste and solve the problem of alternative source regarding the decreasing number of natural materials used in concrete. The long-term application will affect deterioration processes, in which the durability possibility will be affected physically, mechanically and chemically.

Several studies have demonstrated that CBA can enhance concrete properties as a partial replacement for fine or coarse aggregates, improving strength and durability under certain conditions [13–15]. However, most of this existing research has predominantly focused on mechanical performance, with limited investigation into the long-term environmental implications, particularly regarding the leachability of harmful heavy metals contained in CBA. This limitation raises questions about the ecological safety of CBA-modified concrete, especially in exposed or structural applications.

In response to this gap, the present study aims to comprehensively evaluate the mechanical performance and environmental safety of concrete containing CBA. Specifically, it investigates the compressive strength at curing ages 7 and 28 days and assesses leaching behavior using the Synthetic Precipitation Leaching Procedure (SPLP). By integrating strength assessment with heavy metal leachability analysis, this research provides a more holistic understanding of CBA's viability as a sustainable sand substitute in concrete.

2. RESEARCH SIGNIFICANCE

This study comprehensively evaluates coal bottom ash (CBA) as a partial fine aggregate replacement in concrete by combining compressive strength testing with leachability analysis using SPLP and ICP-MS. While previous studies focused mainly on mechanical properties, this research fills a key gap by addressing environmental safety. The study highlights the potential risks of chromium and lead leaching, offering practical guidelines for safe use in non-exposed or enclosed structural applications. These insights contribute to sustainable construction practices by promoting industrial waste utilization and reducing reliance on depleting natural sand resources.

3. RESEARCH METHODOLOGY

3.1 Material Preparation

This study used Coal Bottom Ash (CBA) sourced from the Tanjung Bin Power Plant in Pontian, Johor, Malaysia, as shown in Figure 1.

Fig.1 CBA disposal area at Tanjung Bin Power Plant in Johor

Both natural sand and Coal Bottom Ash (CBA) were tested prior to use in the concrete mix to ensure compliance with BS 882:1992, the British Standard for fine aggregates in concrete [16]. A sieve analysis confirmed that CBA falls within the acceptable grading limits for fine aggregates, as shown in Table 1.

Table 1. Comparison of sand and CBA

Sieve Size	Sand Cumulative Passing (%)	CBA Cumulative Passing (%)	Standard Range Fine aggregate (BS 882: Table 4) (%)
10.00 mm	100	100	100 – 100
5.00 mm	99.6	92.63	89 – 100
2.36 mm	94.4	72.41	60 – 100
1.18 mm	52.6	42.374	30 - 100
600 µm	23.2	23.206	15 – 100
300 µm	5.2	10.964	5 – 70
150 µm	1.6	4.792	0 - 15
75 µm	0.4	1.982	-
Pan	0	0	-
Total	-	-	-

Over 92% of the CBA particles passed the 5 mm sieve, surpassing the JKR (2014) minimum requirement of 80%. CBA exhibited fewer fine particles than natural sand, with a fineness modulus of 2.48 compared to sand’s 2.77, both within the acceptable range of 2.3–3.0 [17].

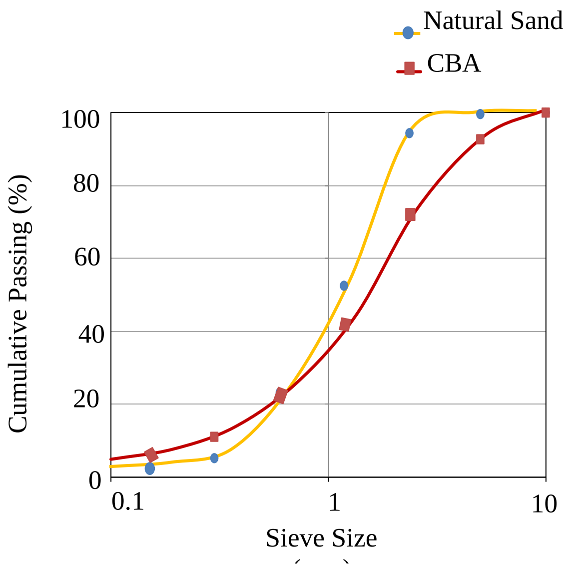

Fig.2 Particle size distribution (gradation curve) for natural sand and Coal Bottom Ash (CBA).

Based on the sieve analysis results, the particle size distribution curve is presented in Figure 2. This graph shows the difference in gradation between natural sand and Coal Bottom Ash (CBA). D50 for sand is 1.13 mm, and for CBA, it is 1.48 mm.

This indicates that CBA has a coarser gradation with larger particles than sand. Lower fines content can reduce packing density, increase porosity, and reduce workability. Consequently, higher CBA content can result in lower slump values and require water or admixture adjustments to maintain mix consistency. The lower specific gravity and bulk density of CBA suggest higher porosity, which can affect workability and long-term performance [21].

Specific gravity and bulk density tests were also conducted to better understand material properties as illustrates in Table 2.

Table 2. Physical properties of sand and CBA

Properties	Sand	CBA	Standard range	Reference
Fineness Modulus	2.77	2.48	2.3-3.0	[15]
Specific Gravity	2.64	2.00	2.50-2.7	[16]
Bulk Density (kg/m3)	1617.4	1185.19	928-1750	[19-20]

Table 2 shows that CBA has a lower fineness modulus, specific gravity, and bulk density than sand. This indicates that CBA is finer, lighter, and more porous, affecting mix workability and water demand in concrete applications.

To complement the physical measurements, microscopic surface characteristics were examined through Scanning Electron Microscopy (SEM). SEM imaging was used to observe the particle surface morphology (Figure 3 and Figure 4) qualitatively. While SEM provides helpful visual cues of surface texture and pore presence, it does not quantify porosity. The study acknowledges that future work should incorporate Mercury Intrusion Porosimetry (MIP) or BET surface area analysis for accurate pore-size distribution.

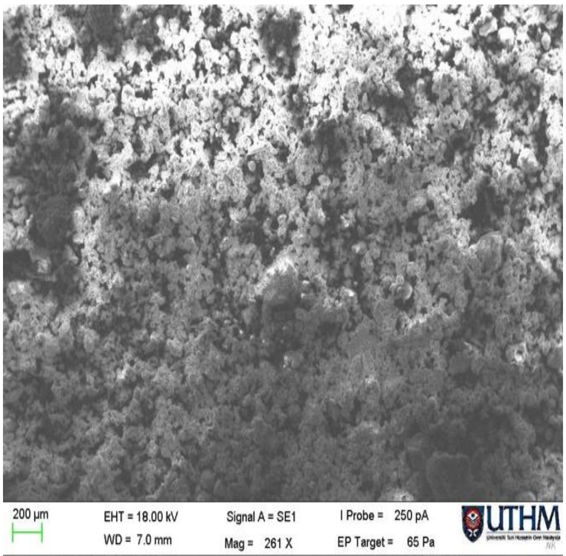

Fig.3 Scanning Electron Microscopy (SEM) images of Coal Bottom Ash (CBA) showing rounded and porous particles

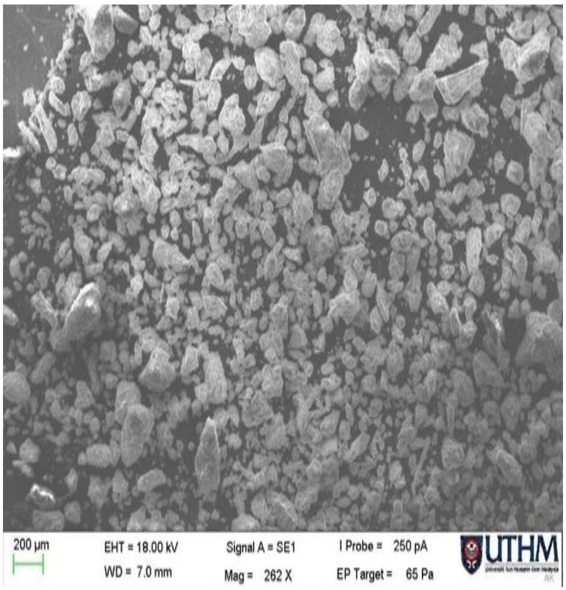

Fig.4 Scanning Electron Microscopy (SEM) images of Natural sand with angular and denser particle morphology.

3.2 Specimen Preparation

Concrete samples were prepared using five different mix proportions with CBA replacing sand at 0%, 30%, 40%, 50%, and 60%. Each mix produced three 100 mm × 100 mm × 100 mm cubes for testing. CBA's higher water absorption was calculated during mix design through water adjustments based on trial batches to maintain consistent workability without altering the water-cement ratio. No chemical admixtures were used. Mix details are shown in Table 3.

Table 3. Mix design concrete per m^3

Name of Sample	Cement (kg)	Water (L)	Coarse Aggregate (kg)	Fine Aggregate (kg)	CBA (Kg)
CCBA0	473	213	835	869	0
CCBA30	473	213	835	608.3	260.7
CCBA40	473	213	835	521.4	347.6
CCBA50	473	213	835	434.5	434.5
CCBA60	473	213	835	347.6	521.4

3.3 Testing Method

This study assessed (i) mechanical performance via compressive strength and (ii) environmental safety through leachability using the SPLP method.

3.3.1 Compressive Strength Test

Concrete curing was evaluated at 7 and 28 days. Before the process of casting, slump tests were conducted to verify workability. Despite the drop in slump at higher CBA content, no compaction issues were observed [22]. Concrete was molded into 100 mm cubes and tested under compressive loading using a universal testing machine at UTHM (Figure 5). A constant load rate of 7 kN/s was applied. The average of three samples was recorded for each age.

Fig.5 Testing of concrete cubes under compression using a universal machine

3.3.2 Leaching Test

Leachability is an important parameter for assessing the environmental acceptability of materials. It involves examining the potential release of soluble contaminants or substances from a solid matrix into a surrounding liquid phase, simulating conditions that may occur in natural or disposal environments. Meanwhile, this test will describe chemical properties of concrete CBA, which evaluation from chemical properties will describe the heavy metal contamination [23]. The leachability test followed the Synthetic Precipitation Leaching Procedure (SPLP), regulated by the USEPA, to simulate acid rain exposure [24]. Samples (100 g) were crushed to 5–10 mm, agitated for 18 hours in sulfuric/nitric acid solution (pH 4.20 ± 0.05), and filtered through 0.7 µm glass fiber. The leachate was acidified to pH < 2 and refrigerated at <4°C.

Fig. 6 Agitation of concrete sample during leaching test (SPLP method)

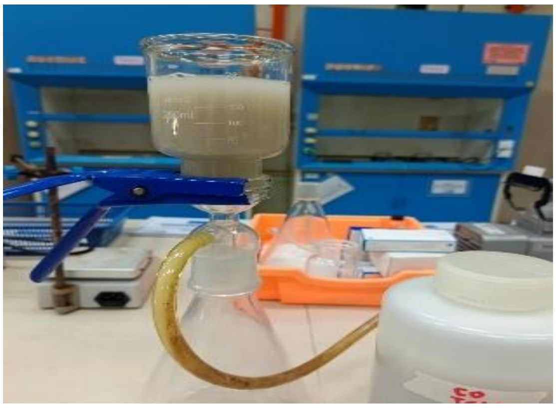

Fig.7 Filtration of leachate through 0.7 µm glass fiber

Fig. 8 pH adjustment of filtered leachate prior to ICP-MS analysis.

Figures 6, 7, and 8 illustrate the main steps in the leaching process conducted under the SPLP method, visually supporting the previously described procedure for assessing heavy metal release from CBA-based concrete.

Heavy metal content was analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), a high-precision technique for detecting trace metals. The measured values were then compared against USEPA regulatory limits (Table 4).

Table 4. USEPA guidelines for waste concentration limits

Element / substance	Symbol / formula	USEPA Limit (Environmental) (mg/L)(14)
Chromium	Cr	5
Zinc	Zn	250
Arsenic	As	5
Lead	Pb	5
Cadmium	Cd	1

This methodology enables a robust assessment of potential environmental risks and supports sustainable practices by promoting industrial waste reuse in concrete production.

4. RESULTS AND DISCUSSION

4.1 Workability (Slump Test)

The slump test is used as the primary method for evaluating the workability and consistency of fresh concrete, indicating how easily the concrete can be mixed, placed, and compacted. Higher slumps usually indicate increased workability, often due to higher water content, and compromising compressive strength. Thus, controlling the water-cement ratio is essential to maintaining strength and durability [25].

CBA's higher water absorption than natural sand significantly reduces slump values as its proportion increases [26]. Despite this, all mixes with up to 60% CBA substitution retained slump values within the acceptable 30–60 mm (Figure 9). The water content was carefully adjusted during trial batches to maintain consistent workability, with no chemical admixtures were used.

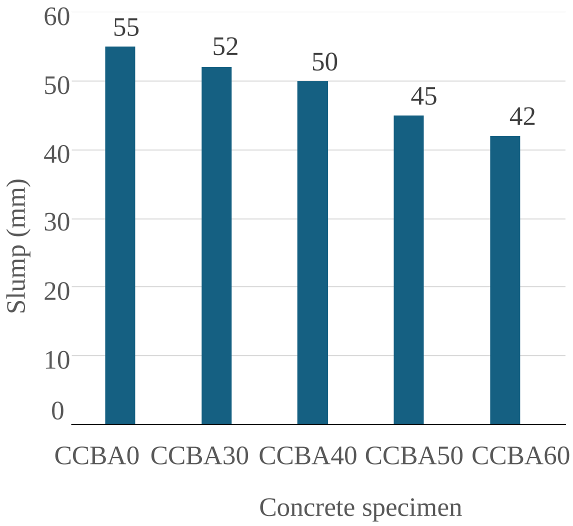

Fig.9 Slump values for different CBA percentages

While the slump decreased with increasing CBA, no compaction issues were reported during mixing or casting. However, CBA particles' high porosity and surface roughness—previously confirmed through SEM imaging—contributed to lower flowability.

4.2 Compressive Strength

Three concrete cube specimens (100 mm × 100 mm × 100 mm) were tested for each mix design, and the average value was used to represent the compressive strength. The control mix reached 36.3 MPa. CCBA30 achieved a similar value at 34.5 MPa, while CCBA40 dropped to 31.6 MPa. CCBA50 and CCBA60 both had 31 MPa in 7 days. This early-age strength reduction is attributed to unburnt carbon in CBA, which can delay cement hydration and slow the development of strength [27].

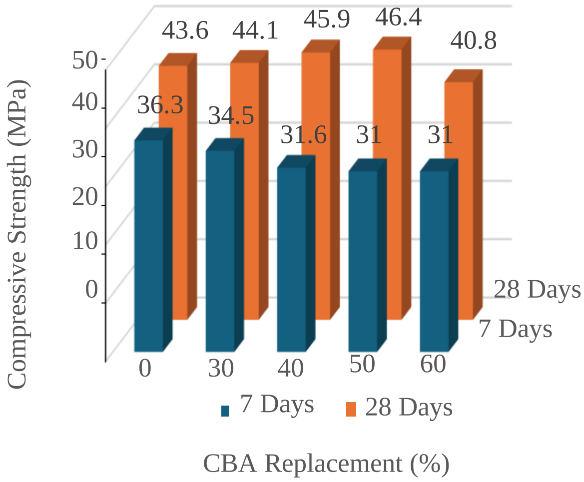

Fig.10 The compressive strength test based on curing age

At 28 days, concrete containing 30%, 40%, and 50% CBA surpassed the control strength, indicating improved performance from pozzolanic reactions and internal curing. However, at 60% CBA, strength declined, aligning with prior studies [28]. The drop at high replacement levels is linked to increased porosity and carbon content, which inhibit densification and hydration—validating the observation of equal 7-day but diverging 28-day results for CCBA50 and CCBA60.

4.3 Leaching Test (SPLP)

Concrete samples from the 28-day strength test were used for SPLP leaching evaluation. Each sample was crushed to 5–10 mm, leached in an acidified solution (pH 4.2), and analyzed via ICP-MS to measure Cr, Zn, As, Pb, and Cd concentrations. Results are presented in Table 5-6.

Table 5. Heavy Metal Concentrations Determined by ICP-MS Analysis (1)

Heavy Metal	Name of samples (mg/L)				USEPA Limit (mg/L)
	CBA	Sand	CCBA0	CCBA30	
Chromium (Cr)	2.98	1.54	79.3	75.4	5
Zinc (Zn)	67.2	102	33.3	34.5	250
Arsenic (As)	1.65	0.595	0.361	0.445	5
Lead (Pb)	10.7	9.47	18.4	16.4	5
Cadmium (Cd)	0.104	0.394	0.156	0.191	1

Table 6. Heavy Metal Concentrations Determined by ICP-MS Analysis (2)

Heavy Metal	Name of samples (mg/L)			USEPA Limit (mg/L)
	CCBA40	CCBA50	CCBA60	
Chromium (Cr)	71.2	58.7	57.1	5
Zinc (Zn)	33.6	32.8	48.8	250
Arsenic (As)	0.488	0.515	0.566	5
Lead (Pb)	7.6	5.9	11.8	5
Cadmium (Cd)	0.19	0.14	0.24	1

Chromium (Cr) and Lead (Pb) concentrations exceeded USEPA thresholds in all CBA mixes. However, their levels declined significantly as CBA content increased—suggesting that heavy metals are immobilized within the concrete through chemical stabilization (via C–S–H gel formation) and physical encapsulation in the cement matrix. For instance, Cr dropped by 28% and Pb by 67.9% in CCBA50 relative to the control as shows in Table 7. Zinc remained well below limits, although CCBA60 showed a spike to 48.8 mg/L. Arsenic and Cadmium remained within safe levels across all mixes, though Cd increased slightly at 60% CBA, indicating reduced stability at high replacement ratios [29-30].

Table 7. Percent reduction in heavy metal concentrations

Heavy Metal	CCBA0	CCBA 50	% Reduction
Chromium (Cr)	79.3	58.7	-27.9%
Zinc (Zn)	33.3	32.8	-1.5%
Arsenic (As)	0.361	0.515	-0.154%
Lead (Pb)	18.4	5.9	-67.9%
Cadmium (Cd)	0.156	0.14	-10,2%

While CBA incorporation effectively reduces leachability for several metals, the exceedance of Cr and Pb in all mixes requires caution. For environmental safety, such concrete should be restricted to non-exposed or sealed applications, pending further treatment or long-term testing.

5. CONCLUSION

Incorporating Coal Bottom Ash (CBA) into concrete mix presents a solution to reduce coal combustion waste posing to environmental risks and utilization for the environmentally friendly construction industry. This study integrates mechanical testing with leachability assessment to evaluate CBA-incorporated concrete's performance and environmental safety. Based on the Design of Experiments (DOE) framework with a 30 MPa minimum design strength and a 43 MPa target strength, several key findings emerged:

1. Physical characterization confirmed that CBA meets the criteria for fine aggregate, with a fineness modulus of10.5% and a specific gravity 24.2% lower than natural sand. Its bulk density is 26.7% lower due to higher porosity, which correlates with reduced workability. As CBA content increases, slump values decrease due to greater water absorption and surface irregularities.
2. Mechanical performance analysis showed that all concrete mixes with CBA met the minimum design strength. At 7 days, strength was reduced due to unburnt carbon, which delays hydration. By 28 days, mixtures up to 50% CBA (particularly CCBA50) exhibited optimal strength—surpassing the control mixes by 6.42%. However, at 60% replacement, performance deteriorated due to increased porosity and hydration inhibition.
3. Environmental assessment via SPLP showed that chromium (Cr) and lead (Pb) levels in CBA are initially high but decrease in concrete as CBA content increases. This is due to heavy metal immobilization through chemical stabilization (e.g., C–S–H gel formation) and physical encapsulation within the cement matrix. In CCBA50, Cr decreased by 27.9% compared to control concrete. However, Cr concentrations remained above USEPA limits across all mixes.
4. Heavy metals such as Zn, Cd, and As exhibited varying trends. While sand contained higher initial levels of Zn and Cd, CBA mixtures at higher percentages sometimes showed increased levels of these metals in leachate, indicating that higher porosity or matrix instability may reduce binding efficiency. Arsenic remained within safe limits but increased with CBA content.
5. A strength–leaching relationship was observed. In CCBA60, lower compressive strength corresponded with reduced heavy metal binding, notably for Zn, Pb, and Cd. Although Zn, As, and Cd concentrations were within USEPA limits, Cr and Pb exceeded permissible levels in all mixes, signaling potential environmental risks if used in exposed applications.
6. CCBA50 emerged as the optimal mix, balancing mechanical and environmental performance. It demonstrated a 6.42% increase in compressive strength and reduced Pb by 67.9%, Cd by 10.2%, and Zn by 1.5% compared to conventional concrete.

This study confirms the feasibility of using CBA as a multifunctional additive in concrete to enhance performance while minimizing environmental impact.

However, exceeding 50% replacement can compromise structural integrity and leaching stability. Given that Cr and Pb concentrations surpassed USEPA regulatory limits, CBA-concrete should be restricted to non-exposed or sealed applications until further mitigation strategies are developed. These findings lay a strong foundation for using industrial waste in environmentally responsible and structurally viable construction materials.

6. ACKNOWLEDGMENTS

Thank you to University Tun Hussein Onn Malaysia (UTHM) for providing the funds for this research. Communication of this research is made possible through monetary assistance from the University Tun Hussein Onn Malaysia and the UTHM Publisher's Office via Publication Funds E15216. And we express our sincere and profound gratitude to Tanjung Power Plant for their invaluable support in providing the CBA samples.

7. REFERENCES

1. Bikash L., Pramod, S., Bikram B., Anish S., and Bikram R., Structural Performance of Concrete: Exploring the Limits of Steel Fiber Reinforcement. International Journal For Multidisciplinary Research, vol. 6, Issue 3, 2024, pp. 0–7.
2. Jagan I., Naga Sowjanya P., and Naga Rajesh K., A review on alternatives to sand replacement and its effect on concrete properties. Materials Today: Proceedings, 2023, pp. 1–6.
3. Htun TP, Thansirichaisree P, Poovarodom N, Ejaz A, Hussain Q. Mechanical properties of environmentally friendly green concrete made with natural and recycled fine aggregates. International Journal of GEOMATE 2024;27:146–53.
4. Sani MSHM, Jaafar MR, Nindyawati, Muftah F. Compressive Strength Of Washed Bottom Ash And Waste Paper Sludge Ash Mortar Filled In Cold-Formed Steel Column. International Journal of GEOMATE 2025;28:9–18.
5. Meh KMFK, Shahidan S, Shamsuddin SM, Zuki SSM, Senin MS. An Experimental Investigation Of Coal Bottom Ash As Sand Replacement. International Journal of GEOMATE. 2022;23(99):17–24.
6. Abdullah M. H., Abuelgasim R., Rashid A. S. A., and Mohdyunus N. Z., Engineering properties of tanjung bin bottom ash. MATEC Web of Conferences, vol. 250, 2018, pp. 1-9.
7. Ramzi Hannan N. I. R., Shahidan S., Ali N., Bunnori N. M., Mohd Zuki S. S., and Wan Ibrahim M. H., Acoustic and non-acoustic performance of coal bottom ash concrete as sound absorber for wall concrete. Case Studies in Construction Materials, vol. 13, 2020, pp. 1-9.
8. Tyszka R., Pędziwiatr A., Pietranik A., Kierczak J., Ettler V., Mihaljevič M., and Zieliński G., A long-term perspective on coal combustion solid waste interacting with urban soil. Applied Geochemistry, vol. 166, 2024, pp. 1-11.
9. Sharma V., and Singh S., Modeling for the use of waste materials (Bottom ash and fly ash) in soil stabilization. Materials Today: Proceedings, vol. 33, 2019 pp. 1610–1614.
10. Sutcu M., Erdogmus,E., Gencel O., Gholampour A., Atan E., and Ozbakkaloglu T., Recycling of bottom ash and fly ash wastes in eco-friendly clay brick production. Journal of Cleaner Production, vol. 233, 2019, pp. 753–764.
11. Pal S., Shariq M., Abbas H., Pandit A. K., and Masood A., Strength characteristics and microstructure of hooked-end steel fiber reinforced concrete containing fly ash, bottom ash and their combination. Construction and Building Material, vol. 247, 2020, pp. 1-14.
12. Tambara Júnior L. U. D., Taborda-Barraza M., Cheriaf M., Gleize P. J. P., and Rocha J. C., Effect of bottom ash waste on the rheology and durability of alkali activation pastes. Case Studies in Construction Material, vol. 16, 2021, pp. 1-12.
13. Simran S., Dar A. R., Kumar R., Adil Dar M., and Raju J., Improved performance of coal bottom ash co-mixtured concrete. IOP Conference Series: Materials Science and Engineering, vol. 561, Issue 1, 2019, pp. 1-6.
14. Kirthika S. K., and Singh S. K., Durability studies on recycled fine aggregate concrete. Construction and Building Materials, vol. 250, 2020, pp. 1-14.
15. Kim H. K., and Lee H. K., Use of power plant bottom ash as fine and coarse aggregates in high-strength concrete. Construction and Building Materials, vol. 25, Issue 2, 2011, pp. 1115–1122.
16. Numan H. A., Yaseen M. H., and Al-Juboori H. A. M. S., Comparison Mechanical Properties of Two Types of Light Weight Aggregate Concrete. Civil Engineering Journal, vol 5, Issue 5, 2019, pp. 1105-1118.
17. Kim H. K., and Lee H. K., Coal bottom ash in field of civil engineering: A review of advanced applications and environmental considerations. KSCE Journal of Civil Engineering, vol. 19, Issue 6, 2015, pp. 1802–1818.
18. Ullah A., Kassim A., Abbil A., Matusin S.,

Rashid A. S. A., Yunus N. Z. M., and Abuelgasim R., Evaluation of Coal Bottom Ash Properties and Its Applicability as Engineering Material. IOP Conference Series: Earth and Environmental Science, vol. 498, Issue 1, 2020, pp. 0-6.

19. Soofinajafi M., Shafigh P., Akashah F. W., & Mahmud H. Bin., Mechanical Properties of High Strength Concrete Containing Coal Bottom Ash and Oil-Palm Boiler Clinker as Fine Aggregates. MATEC Web of Conferences, vol. 66, Issue 34, 2016, pp. 1-8.
20. Malathy R., Ramachandran S., Sentilkumar R., and Prakash A. R., Use of Industrial Silica Sand as a Fine Aggregate in Concrete — An Explorative Study. Multidisciplinary Digital Publishing Institut, vol. 12, Issue 1273, 2022 pp. 1–27.
21. Gashahun A. D., Investigating sand quality effect on concrete strength: a case of Debre Markos and its vicinities. International Journal of Construction Management, vol. 22, Issue 12, 2022, pp. 2234–2242.
22. Selçuk Levent, and Gökçe H. S., Estimation of the Compressive Strength of Concrete under Point Load and Its Approach to Strength Criterions. KSCE Journal of Civil Engineering, vol. 19, Issue 6, 2015, pp. 1767–1774.
23. Yu S., Tao R., Tan H., Zhou A., Deng S., Wang X., and Zhang Q., Leaching characteristic and migration simulation of hazardous elements in recycled aggregates as subgrade scenario. In Fuel, vol. 333, 2023, pp. 1-9.
24. Rafieizonooz M., Khankhaje E., and Rezania S., Assessment of environmental and chemical properties of coal ashes including fly ash and bottom ash, and coal ash concrete. Journal of Building Engineering, vol. 49, Issue 104040, 2022, pp. 1-10.
25. Ding Y., She A., and Yao W., Investigation of Water Absorption Behavior of Recycled Aggregates and its Effect on Concrete Strength. Materials, vol. 16, Issue 13, 2023, pp. 1–17.
26. Amat R. C., Rahim N. L., Mohamed S. A., Ibrahim N. M., Matagi A. B. H., Muhamad N., Raischi M., and Bahatin M., Effect of Incorporating Coal Bottom Ash on the Properties of Concrete. IOP Conference Series: Earth and Environmental Science, vol. 1216, Issue 1, 2023 pp. 1-7.
27. Rani N. H. A., Mohamad N. F., Onn M., Jalil M. J., and Muda N., Coal Bottom Ash as a Potential Adsorbent for CO2 Capture Coal Bottom Ash as a Potential Adsorbent for CO 2 Capture. IOP Conference Series: Materials Science and Engineering, vol 1176, Issue 012001, 2021, pp.1-7.
28. Hasim A. M., Shahid K. A., Ariffin N. F., and Nasrudin N. N., Properties of high volume coal bottom ash in concrete production. Materials Today: Proceedings, vol. 48, 2022, pp. 1861–1867.
29. Firasath Ali M., Talha Rashed M., Abdul Bari M., and Mohammed Razi K., Effect of Zinc Oxide Nanoparticle on Properties of Concrete. International Journal of Science Technology & Engineering, vol. 7, Issue 2, 2020, pp. 1026–1029.
30. Raj K., and Das A. P., Lead pollution: Impact on environment and human health and approach for a sustainable solution. Environmental Chemistry and Ecotoxicology,vol. 5, 2023, pp. 79–85.