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Mining and Industrial Wastes in Sustainable Construction: A Synergistic Approach Using Fly Ash, Coal Bottom Ash, and Quarry Dust

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Abstract

This study presents a comprehensive investigation into the synergistic use of fly ash (FA), coal bottom ash (CBA), and quarry dust (QD) as partial replacements for conventional construction materials, aiming to mitigate environmental degradation while enhancing material performance. Individually and in combination, a series of concrete mixes were prepared incorporating these wastes at varying proportions, and were tested for workability, compressive strength, and durability (water absorption and chloride ion penetration). Results indicate that blends of FA, CBA, and QD can effectively substitute up to 40% of cement and fine aggregates without compromising structural performance. The mixes containing 20% fly ash, 10% bottom ash, and 10% quarry dust exhibited superior compressive, split tensile, and flexural strength, and reduced water absorption and chloride ion penetration, demonstrating their potential in aggressive environments.

1. Introduction

The rapid expansion of industrialisation and mining activities across the globe has led to the exponential generation of solid wastes, particularly in the form of fly ash (FA) [1-3], coal bottom ash (CBA) [4-6], and quarry dust (QD) [7-9]. Traditionally viewed as environmental burdens, these by-products are increasingly being re-evaluated through the lens of sustainability and resource efficiency [10, 11]. Their unregulated disposal has triggered a multitude of ecological concerns, including groundwater contamination, air quality deterioration, and loss of productive land. As construction remains one of the largest consumers of natural resources, the integration of such industrial residues into construction materials emerges as both an ecological necessity and a technological opportunity [12, 13]. There are some other agro-industrial by-products which are pozzolanic and are utilised in concrete as

replacements of cement, resulting in both waste management and reduction of carbon footprint [14-17]. FA, a fine particulate residue from coal combustion in thermal power plants, is known for its pozzolanic behaviour and fineness, making it a potential substitute for cementitious materials [18, 19]. CBA, which settles at the base of boilers, offers granular characteristics and thermal stability, lending itself well as a partial replacement for natural aggregates [4, 5, 20]. QD, a by-product of stone crushing operations, possesses angularity and gradation comparable to river sand, making it an alternative fine aggregate in concrete [8, 9]. However, the real promise lies not in their individual applications but in their synergistic combination, where their distinct properties can complement and compensate for one another.

This study seeks to explore a novel integrative approach, blending these three major waste types



in optimized proportions to create concrete with enhanced performance and reduced environmental footprint. The objective is not merely substitution but value-added transformation—turning what was once discarded into components of a high-performance, low-impact building material [6, 9, 21, 22].

By comprehensively assessing the mechanical strength and durability of these blended mixes, the research aims to contribute meaningfully to the evolving paradigm of sustainable construction. Furthermore, the findings hold significance in aligning with global circular economy initiatives and national missions focused on green infrastructure and carbon reduction. This study supports innovation as this work not only provides a viable route for large-scale valorisation of mining-associated wastes but also aligns with circular economy principles and low-carbon development goals. The findings contribute valuable insights for integrating industrial ecology into mining practices, transforming high-volume waste liabilities into eco-efficient construction resources. The proposed methodology encourages regulatory bodies and industry stakeholders to adopt sustainable waste reuse policies, fostering a greener mining and construction ecosystem. The objectives of the study are to systematically investigate the individual physical, chemical, and mineralogical characteristics of FA, CBA, and QD, thereby identifying their suitability as partial replacements for conventional cementitious and fine aggregate materials in concrete production, to develop optimized concrete mixtures using singular and blended combinations of FA, CBA, and QD that can meet or exceed the performance criteria of standard construction materials in terms of strength, workability, and durability, to conduct comprehensive laboratory testing, including compressive, split tensile, and flexural strength,

water absorption, and chloride ion penetration, in order to evaluate the technical feasibility and environmental resilience of the proposed concrete mixes, to demonstrate the potential of waste valorisation in reducing dependency on virgin resources, thus promoting responsible material sourcing and minimizing the ecological footprint of the construction sector, and to contribute actionable knowledge toward the implementation of circular economy strategies within mining, thermal power, and construction industries, supporting policies that emphasize waste minimisation, resource recovery, and low-carbon development.

2. Materials and methods used

2.1. Materials used

Ordinary Portland Cement (OPC) 43 grade was used as the primary binder. FA sourced from a local thermal power station, conforming to IS 3812: Part 1 [23], used as a partial cement replacement. CBA was collected from Rajpura thermal power plant, Punjab, which was then dried and sieved before use, and used as partial sand replacement. QD was procured from a stone crushing plant, utilised as a cement substitute based on its gradation and angularity. River sand conforming to Zone II, following IS 383: 2016 [24], was used as the base fine aggregate. Crushed granite stone of 20 mm maximum size was provided by a local supplier, following IS 2386:2016 [25] was utilised in this study. A polycarboxylate ether-based admixture was added to improve workability as the use of superplasticiser reduces alkaline activator to binder ratio and improves workability [14, 26, 27]. The chemical composition testing of FA, CBA, and QD was done by Raicon Labs, Sonapat, India. Tables 1 and 2 show the physical and chemical properties of FA, CBA, and QD. Figure 1 (a, b) shows the aggregate gradation curves.

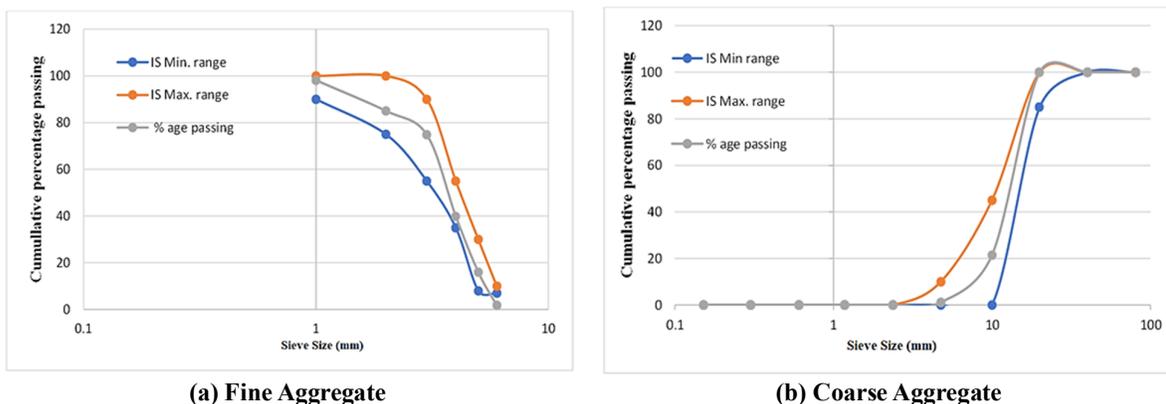


Figure 1. Aggregate grading curves

Table 1. Physical properties of materials

Property	FA	CBA	QD	Cement
Colour	Grey	Dark grey	Whitish	Dark grey
Specific gravity	2.2	2.14	2.7	3
Fineness	2.4	6.5	8	1.8

Table 2. Chemical properties of materials

Chemicals	FA	CBA	QD	Cement
SiO ₂	54	50	59	18
Al ₂ O ₃	20	22	14	4.8
Fe ₂ O ₃	6	8	5	5
CaO	4	3.3	9	62.9
MgO	1.4	2.2	2.4	3.18
SO ₃	0.7	1	0.4	3
LOI	2	3.4	0	3.12
Others	9.7	10.1	10.2	0

2.2. Methodology

This experimental investigation was structured to evaluate the effects of using mining and industrial waste materials—FA, CBA, and QD as partial replacements in cement and sand for concrete production. A total of six concrete mix designs were prepared, including a control mix (OCCM) and five blended variations incorporating different proportions of the selected waste materials. Concrete was mixed using a tilting drum mixer. The dry ingredients were homogenised first, followed by the gradual addition of water and superplasticiser. The fresh concrete was tested for workability using the slump cone method as per IS 1199. Standard cubes (150 mm), cylinders (150 × 300 mm), and beams (100 × 100 × 500 mm) were cast for testing compressive, split tensile and flexural strengths (IS 516:1959) [28], respectively. All specimens were demoulded after 24 hours and cured in clean water at 27 ± 2°C until testing at 7, 28, and 90 days. Water absorption was determined by oven-drying samples and measuring weight gain after immersion, as per ASTM C642:2013 [29]. Rapid Chloride Ion Penetration Test (RCPT) was conducted at 28 days following ASTM C1202:2016 [30] to assess chloride ion permeability. The charge passed in Coulombs was recorded to classify chloride ion penetrability. Table 2 shows the mix proportions of the specimens prepared for this study. Figure 2 shows some of the images of the samples. For the calculation of the non-steady state migration diffusion coefficient (D_{nssm}), equation 1 has been used according to the NT Build 492 which is given below:

$$D_{nssm} = \frac{R \cdot T \cdot L}{z \cdot F \cdot A \cdot \Delta V} \times \frac{Q}{t} \quad (1)$$

Where:

D_{nssm} = chloride diffusion coefficient (m²/s),

R = Universal gas constant = 8.314 J/(mol·K),

T = Temperature in Kelvin (assume 298 K = 25°C),

z = Ionic valence = 1 for Cl⁻,

F = Faraday's constant = 96485 C/mol,

L = Specimen thickness = 0.1 m,

A = Area of sample = π · (0.025)² = 1.9635 × 10⁻³ m²,

ΔV = Applied voltage = 60 V,

Q = Total charge passed (Refer Table 3),

t = Time = 6 hours = 21600 seconds.



Figure 2. Sample image

3. Results and discussion

3.1. Workability

The slump test results indicated in Figure 3 improved workability in waste-based mixes, especially those containing higher percentages of

FA. The spherical shape and fine texture of FA particles provide a "ball bearing" effect, reducing internal friction during mixing [31–33]. Mix F20Q20C10 exhibited the highest slump (92 mm), whereas mixes with increased CBA content (e.g., F20Q20C20) had slightly reduced slump due to the angular, porous nature of CBA which tends to absorb more mixing water [34–36]. Despite this, all mixes remained within acceptable workability limits for practical applications.

3.2. Compressive strength

The compressive strength results across all mixes, as shown in Figure 4, revealed clear trends influenced by the type and proportion of waste materials used. The control mix (OCCM), composed entirely of cement and natural sand, demonstrated a 28-day strength of 36.5 MPa, serving as a benchmark. The modified mix F20Q10C10, which incorporates 20% fly ash and

10% quarry dust as cement replacements and 10% bottom ash as sand replacement, exhibited a higher 28-day compressive strength of 39.2 MPa, increasing further to 42.6 MPa at 56 days. This superior performance is attributed to the pozzolanic reaction of FA, which continues to contribute to strength gain beyond the initial hydration period [32, 37–39]. Additionally, quarry dust—due to its fine and angular particles—enhances packing density, reducing voids within the matrix [7, 8, 40, 41]. Although mixes with higher total replacement (e.g., F20Q20C20) showed lower strength than the optimum blend, they still maintained acceptable values, indicating the feasibility of integrating even higher volumes of waste, provided the balance of binder and filler characteristics is carefully managed. Therefore, these findings confirm that fly ash and quarry dust can synergistically replace a substantial fraction of cement without compromising, and in some cases even improving, the compressive strength of concrete.

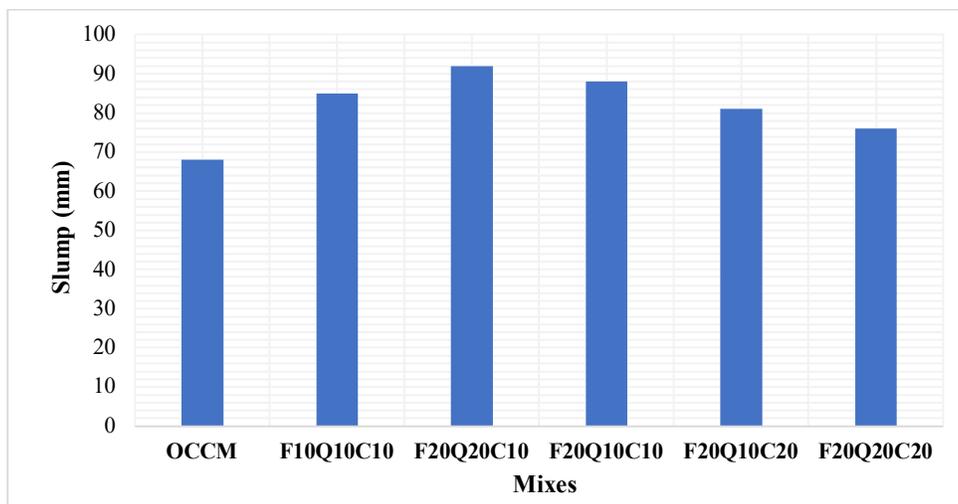


Figure 3. Workability of the blends

3.3. Split tensile strength

The split tensile strength values followed a similar enhancement pattern, though they were slightly more sensitive to the type of material replacing sand, as shown in Figure 5. The control mix registered a 28-day tensile strength of 3.12 MPa, while F20Q10C10 achieved 3.58 MPa, eventually reaching 3.86 MPa at 90 days. The improvement in tensile strength is primarily driven by the refined interfacial transition zone (ITZ) between the aggregate and binder, resulting from the combination of FA's micro-filling capabilities and quarry dust's particle interlock [42, 43]. CBA, despite being more porous, did not negatively affect the strength at 10% replacement; however,

mixes with 20% bottom ash (F20Q20C20) showed reduced tensile strength due to increased internal porosity [6, 22, 44]. This suggests that controlled substitution of sand with CBA up to a certain threshold can be beneficial, but excessive usage may compromise the matrix's cohesiveness under tensile loading. The data confirm that optimised blends can enhance the tensile characteristics of concrete, which is critical for resisting crack formation and propagation in structural applications.

3.4. Flexural Strength

Flexural strength, which reflects the material's capacity to resist bending stresses, displayed

consistent improvements with the inclusion of fly ash and quarry dust as shown in Figure 6. The control mix reported a 28-day flexural strength of 5.10 MPa, while the highest value was recorded for F20Q10C10 at 5.48 MPa, progressing to 5.79 MPa at 90 days. The use of FA contributed to the long-term strength development, while the rigid, angular particles of QD enhanced the internal load-transfer mechanism across the matrix [7, 8, 45, 46]. Moreover, the partial substitution of sand with bottom ash did not impair the flexural capacity at

10% levels; rather, it provided adequate granular structure, provided it was well graded. Mixes with higher CBA content, however, showed marginally reduced flexural strengths, emphasising that the physical quality of CBA (e.g., fineness, water absorption, shape) plays a decisive role [22, 34]. In conclusion, the incorporation of these waste materials not only sustains but, in many cases, improves the flexural strength of concrete, which is vital for beam, slab, and pavement applications where bending forces are dominant.

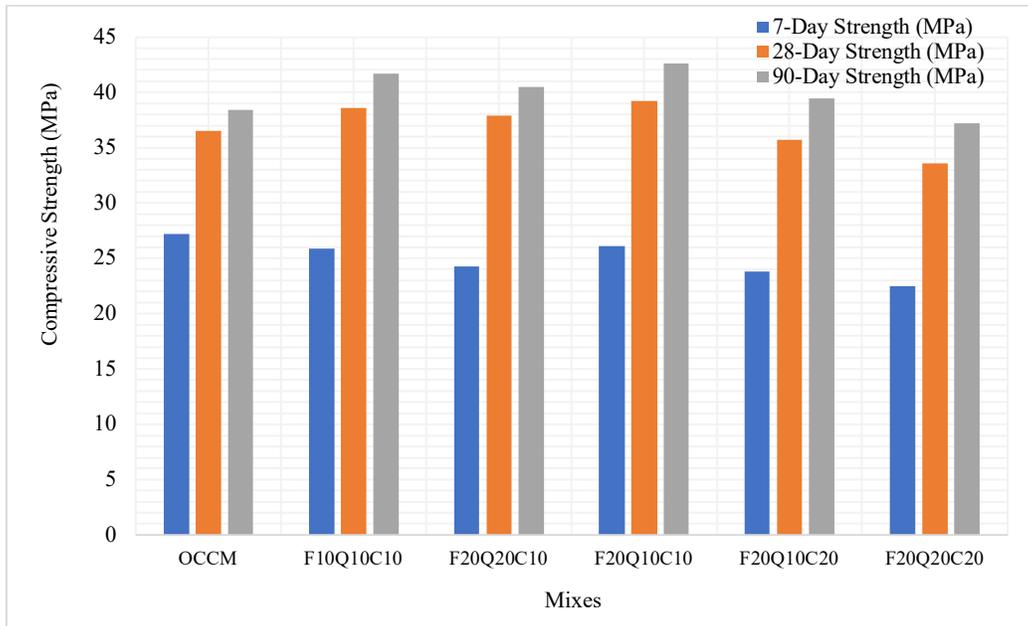


Figure 4. Compressive strength of the blends

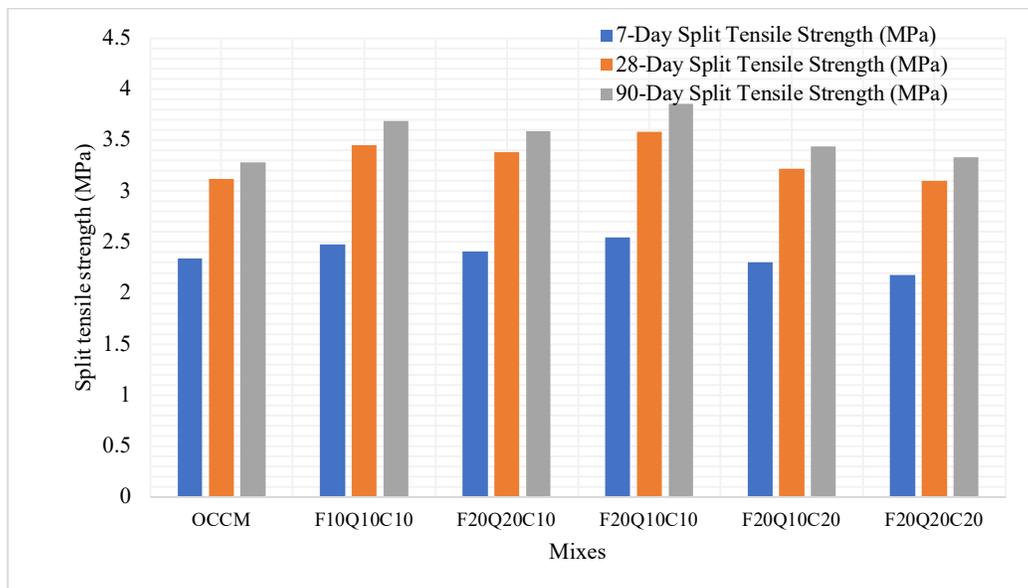


Figure 5. Split Tensile strength of the blends

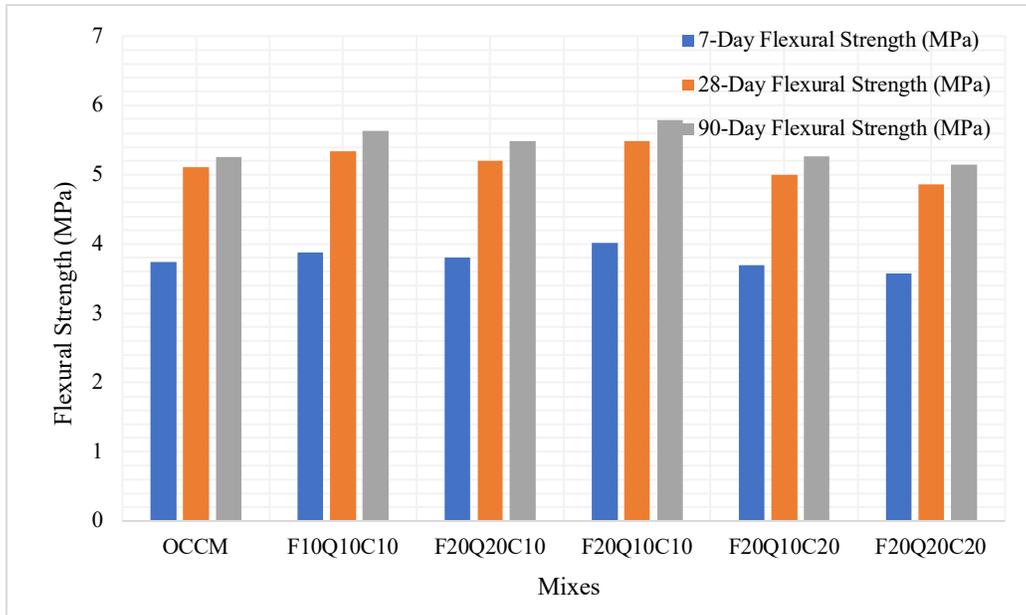


Figure 6. Flexural strength of the blends

3.5. Water absorption

Water absorption is a critical durability parameter that reflects the porosity and permeability of concrete. The results obtained in this study revealed a clear correlation between the incorporation of industrial wastes and the reduction in water absorption values, as shown in Figure 7. The control mix (OCCM) exhibited a water absorption rate of 4.02%, which was comparatively higher than that of all modified mixes. The optimised mix F20Q10C10 recorded the lowest absorption value of 3.31%, signifying a more refined and compact internal microstructure. The reduction in water ingress is primarily due to the fine particles of fly ash and quarry dust that effectively fill voids within the cement matrix,

thereby decreasing capillary porosity [41, 47–50]. Additionally, the partial substitution of cement by fly ash contributes to the formation of additional calcium silicate hydrate (C–S–H) gel over time, further enhancing matrix densification [18, 51]. However, in the mix F20Q20C20, where the replacement of sand by bottom ash reached 20%, a slight increase in water absorption (4.21%) was observed. This is likely due to the porous and irregular morphology of coal bottom ash, which can increase the interconnected pore network if not compensated by adequate paste volume or particle grading [20, 34, 36]. These findings underscore the importance of balanced mix design; while fly ash and quarry dust contribute to pore refinement, excessive use of bottom ash may counteract this benefit unless carefully optimised.

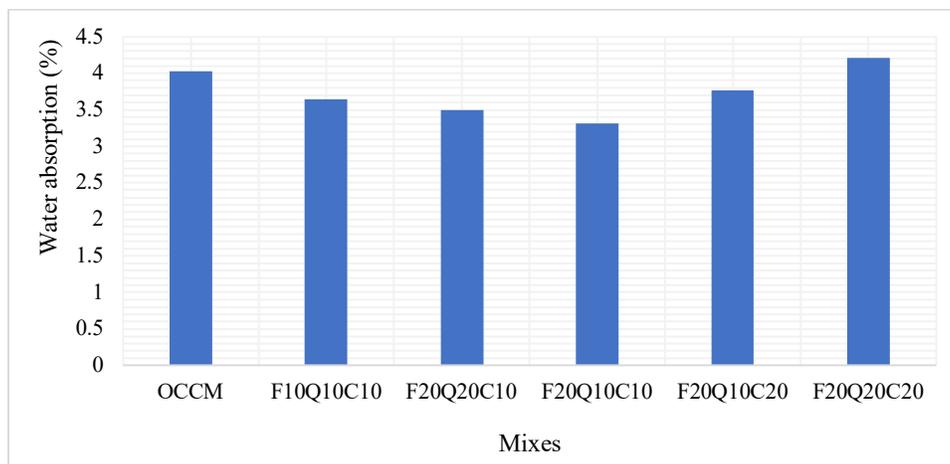


Figure 7. Water absorption of the blends

3.6. Chloride ion penetration

The Rapid Chloride Ion Penetration Test (RCPT) is an established indicator of a concrete's resistance to chloride ingress—a major concern in marine and deicing salt environments. The results clearly demonstrated that mixes incorporating fly ash and quarry dust showed significantly reduced chloride ion permeability compared to the control, as shown in Figure 8. The OCCM mix registered a charge passage of 3100 Coulombs, placing it in the "moderate" category per ASTM C1202. In contrast, the F20Q10C10 mix exhibited only 2290 Coulombs, falling into the "very low" permeability class. This enhancement is largely due to the refined pore structure and pozzolanic reaction of fly ash, which reduces calcium hydroxide content

and leads to a denser cementitious matrix [52–54]. The angular and graded nature of quarry dust further assists in closing capillary pores [7, 55]. While mixes such as F20Q20C10 and F20Q10C20 also performed well, a slight increase in charge passed was noted in F20Q20C20 (2920 Coulombs), suggesting that higher levels of coal bottom ash can marginally compromise the permeability resistance if not properly balanced. Therefore, the reduction in charge passed across all modified mixes validates the positive influence of synergistically blended waste materials in enhancing chloride durability, thereby extending the service life of concrete exposed to harsh environmental conditions. Table 3 shows the limits of RCPT.

Table 3. Standards for RCPT

Charge Passed (Q Coulombs)	> 4000	2000 – 4000	1000 – 2000	100 – 1000	< 100
Chloride Ion Penetrability	High	Moderate	Low	Very Low	Negligible

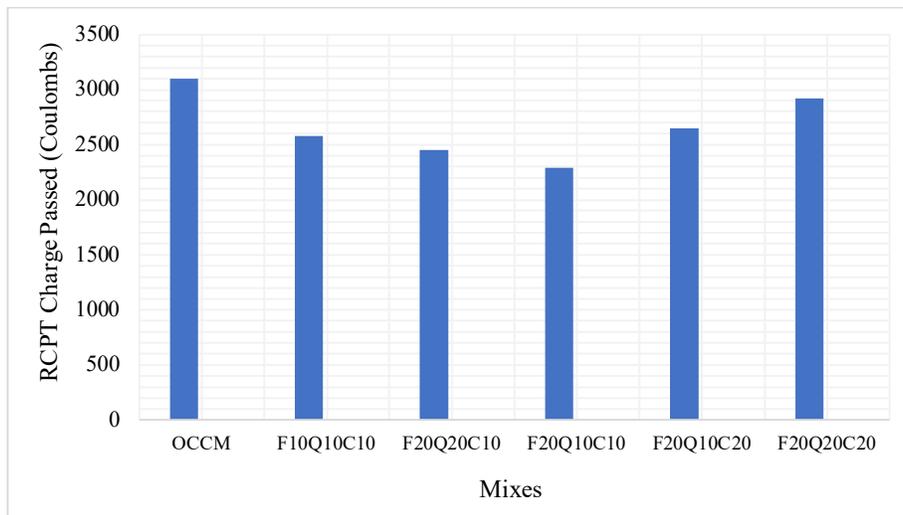


Figure 8. Chloride ion penetration of the blends

The calculated non-steady-state migration coefficients (D_{nssm}) for the various concrete mixes, based on NT Build 492 and the actual specimen dimensions (50 mm diameter and 100 mm thickness), reveal insightful trends in chloride ion permeability as shown in Table 4. The control mix (OCCM) exhibited the highest D_{nssm} value of $3.13 \times 10^{-3} \text{ m}^2/\text{s}$, reflecting the greatest vulnerability to chloride ingress. Compared to, all modified mixes incorporating industrial by-products as partial replacements showed significantly reduced D_{nssm} values, indicating improved resistance to chloride ion penetration [56, 57].

Among the modified mixes, F20Q10C10 demonstrated the lowest D_{nssm} value of $2.22 \times 10^{-3} \text{ m}^2/\text{s}$, highlighting the optimal synergy between 20% fly ash and 10% quarry dust in enhancing microstructural densification and chloride resistance. Similarly, F20Q20C10 and F10Q10C10 recorded D_{nssm} values of $2.47 \times 10^{-3} \text{ m}^2/\text{s}$ and $2.57 \times 10^{-3} \text{ m}^2/\text{s}$, respectively, which are significantly lower than the control. The mix F20Q10C20, with a higher coal bottom ash content, showed a slightly elevated coefficient of $2.67 \times 10^{-3} \text{ m}^2/\text{s}$, while F20Q20C20 returned a value close to the control at $2.93 \times 10^{-3} \text{ m}^2/\text{s}$, suggesting that higher combined replacement levels may begin to offset the beneficial effects if

not properly balanced. Therefore, the empirical results align with the expected performance of blended cementitious systems where supplementary materials such as fly ash, quarry dust, and coal bottom ash refine the pore structure, reduce permeability, and contribute to enhanced

durability. These findings affirm that targeted partial replacements can effectively reduce chloride ion penetration, as quantified through Dnssm, thereby supporting the design of more durable and sustainable concrete for aggressive environments [56–58].

Table 4. Dnssm coefficients according to NT Build 492

Mix ID	Coulombs	Dnssm (m ² /s)	% Reduction in Dnssm vs OCCM (%)	Chloride Permeability Class
OCCM (Control)	3100	3.13×10^{-3}	–	High
F10Q10C10	2550	2.57×10^{-3}	17.91	Moderate
F20Q20C10	2450	2.47×10^{-3}	21.09%	Moderate
F20Q10C10	2200	2.22×10^{-3}	29.07%	Moderate
F20Q10C20	2650	2.67×10^{-3}	14.69%	Moderate
F20Q20C20	2900	2.93×10^{-3}	6.39%	Moderate

4. Conclusions

This study underscores the immense potential of reengineering mining and industrial by-products like FA, CBA, and QD into value-added components for sustainable concrete production. Through a systematic evaluation of mechanical and durability properties, several noteworthy findings emerged:

1. Synergistic blends of FA, CBA, and QD successfully replaced cement and sand without compromising structural performance. The optimized mix F20Q10C10 (20% fly ash, 10% quarry dust, and 10% coal bottom ash) consistently delivered superior strength and durability across all tested parameters.
2. The compressive, split tensile, and flexural strengths of the modified concrete mixes showed steady growth over 7, 28, and 90 days, indicating the prolonged pozzolanic and filler activity of the added materials. Specifically, F20Q10C10 achieved a 90-day compressive strength exceeding that of the control mix, validating its efficacy as a performance-grade concrete.
3. Workability improved significantly in fly ash-based mixes, aided by the use of a polycarboxylate superplasticizer, while maintaining slump values within acceptable construction limits.
4. In terms of durability, the ternary blends recorded lower water absorption and reduced chloride ion penetration, particularly in fly ash-rich combinations. These results confirm enhanced pore refinement and chemical resistance, making the mixes suitable for aggressive environments.
5. Compared to the control mix (OCCM), all modified mixes exhibited a notable reduction in the non-steady-state migration coefficient

(Dnssm), ranging from **6.39% to 29.07%**, shifting the chloride permeability class from **High to Moderate**. The mix **F20Q10C10** demonstrated the highest resistance to chloride ingress, indicating its superior durability.

6. Environmental safety was maintained, as the incorporation of bottom ash and quarry dust did not negatively impact the integrity or leaching characteristics of the concrete, thus promoting eco-responsible reuse of large-scale industrial waste.
7. The findings validate the feasibility of integrating circular economy principles into construction, whereby waste materials from energy and mining sectors are repurposed to reduce natural resource depletion and carbon intensity in infrastructure development.

5. Future scope

Future research should investigate the long-term durability of blended concrete under conditions like marine exposure, freeze–thaw cycles, and acidic attacks. Advanced microstructural tools such as SEM, XRD, and FTIR can help analyse hydration and pore development over time. Environmental assessments like LCA and carbon footprint analyses are crucial to quantify the sustainability benefits of using fly ash, coal bottom ash, and quarry dust. Scaling the mix for precast and pavement applications can promote industrial use. Studies should also explore compatibility with other SCMs and alkali-activated/geopolymer systems to develop cement-free eco-concretes. Future work must include predictive models, performance-based mix design tools, and technical guidelines, while policy and standardisation efforts should support waste valorisation and circular

construction at broader levels. For sustainable development, further research could be enhanced using modern AI and ML techniques, along with optimisations like Taguchi and RSM [59–63].

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انجمن مهندسی معدن ایران

ضایعات معدنی و صنعتی در ساخت و ساز پایدار: رویکردی هم افزایی با استفاده از خاکستر بادی، خاکستر کف زغال سنگ و گرد و غبار معدن

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چکیده	اطلاعات مقاله
<p>استخراج مس پورفیری مقادیر قابل توجهی باطله تولید می‌کند که به دلیل توانایی در تولید اسید و آزادسازی عناصر بالقوه سمی، مخاطرات جدی زیست‌محیطی و بهداشتی برای انسان به همراه دارد. در این مطالعه، ارزیابی یکپارچه‌ای از ریسک‌های زیست‌محیطی و سلامت انسانی ناشی از باطله‌های معدن مس پورفیری سونگون در شمال غرب ایران ارائه شده است. بدین منظور، رویکردی جامع و میان‌رشته‌ای به کار گرفته شد که شامل ترکیب آنالیزهای فیزیکوشیمیایی، کانی‌شناسی و ژئوشیمیایی با روش‌های آماری بود. گونه‌بندی شیمیایی عناصر با استفاده از روش اصلاح‌شده پیشنهادی دفتر مرجع جامعه اروپا انجام شد؛ روشی که در مطالعات متعدد برای ارزیابی تفکیک ژئوشیمیایی و تحرک‌پذیری عناصر به کار رفته است. هدف اصلی این پژوهش، گذار از تحلیل صرف غلظت کل عناصر به سوی ارزیابی دقیق‌تر ریسک مبتنی بر زیست‌دسترس‌پذیری، با بهره‌گیری از چارچوب سازمان حفاظت محیط‌زیست ایالات متحده برای کودکان و بزرگسالان بود. بررسی‌های کانی‌شناسی نشان داد که باطله‌ها دارای پتانسیل خالص تولید اسید هستند، به‌گونه‌ای که مقدار پیریت (حدود ۴ درصد) معمولاً بیش از کانی خنثی‌کننده اصلی، یعنی کلسیت (حدود ۲ درصد)، است. نتایج آنالیزهای ژئوشیمیایی بیانگر غنی‌شدگی قابل توجه مس و مولیبدن و همچنین غنی‌شدگی متوسط آرسنیک و کبالت در باطله‌ها بود. در میان عناصر مورد بررسی، بیشترین ضرایب تحرک به ترتیب متعلق به مس (۸۱،۴۹٪)، سرب (۷۶،۷۱٪)، روی (۷۱،۶۵٪) و مولیبدن (۵۹،۲۷٪) بود. شاخص خطر غیرسرطان‌زایی برای کودکان برابر با ۲،۰۴ به‌دست آمد که از حد ایمنی فراتر است و در این میان، وانادیم زیست‌دسترس‌پذیر به‌عنوان عامل اصلی ریسک شناسایی شد. این یافته‌ها نشان می‌دهد که اتکای صرف بر غلظت کل عناصر بالقوه سمی می‌تواند گمراه‌کننده باشد و بر ضرورت انجام ارزیابی‌های مبتنی بر گونه‌پذیری شیمیایی برای توصیف دقیق رفتار زیست‌محیطی و مخاطرات سلامت ناشی از باطله‌های معدنی تأکید می‌کند.</p>	<p>تاریخ ارسال: ۲۰۲۵/۰۷/۱۲ تاریخ داوری: ۲۰۲۵/۰۷/۱۸ تاریخ پذیرش: ۲۰۲۵/۰۹/۰۶</p> <p>DOI: 10.22044/jme.2025.16387.3196</p> <p>کلمات کلیدی</p> <p>خاکستر بادی خاکستر کف زغالسنگ گرد و غبار معدن ساخت و ساز پایدار استفاده مجدد از ضایعات معدن</p>