Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 07, July, 2025

Enhancing Durability in Recycled Concrete: Investigating Chloride Permeability with Recycled Aggregates and Plastic Waste

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Received 26 March 2025; Revised 18 June 2025; Accepted 23 June 2025; Published 01 July 2025

Abstract

This study investigates the effects of substituting fine aggregates with recycled plastic in recycled concrete, focusing on chloride penetration, compressive strength, workability, and porosity. Recycled plastic was incorporated at 10% (A10) and 20% (A20) by volume, and properties were evaluated across six mix designs. The control mix without plastic (Mix A) achieved the highest 28-day compressive strength (400 KSC), while A10 and A20 showed reduced strengths of 320 and 255 KSC, respectively. The addition of plastic increased mix porosity, resulting in reduced strength and workability due to diminished cement bonding and lubrication. Chloride ingress was assessed under cyclic wetting–drying exposure using a 3.5% NaCl solution. Results revealed progressive surface chloride accumulation over time. Notably, Mix A showed a 137.96% increase in chloride content at a 0–2 cm depth after 280 days, with Mix A20 exhibiting even higher surface concentrations. Chloride content consistently decreased beyond a 4 cm depth, indicating limited long-term penetration into inner layers. These findings highlight the importance of porosity control in mitigating chloride transport in recycled concrete. A clear relationship between plastic content, increased porosity, and enhanced chloride diffusion was observed. While 10% plastic substitution demonstrated acceptable performance, higher levels significantly compromised durability. The study recommends limiting plastic waste incorporation to ≤10% by volume and maintaining a concrete cover of at least 8–10 cm over reinforcement to enhance resistance against chloride-induced corrosion. These findings support the controlled reuse of plastic waste in sustainable concrete development, particularly for non-structural or low-exposure applications. Optimizing mix design and incorporating supplementary cementitious materials are suggested to improve long-term durability.

Keywords: Chloride Permeability; Recycled Concrete; Recycled Aggregates; Plastic Waste; Durability.

1. Introduction

Concrete, the primary construction material used worldwide [1], is a composite primarily composed of cement, water, and aggregates. Aggregates constitute approximately 70–80% of the concrete volume [2], serving as the principal contributors to its strength and durability. In Thailand, concrete roads managed by the Department of Highways and the Department of Rural Roads span approximately 4,555 kilometers [3], highlighting the nation's substantial reliance on this material. However, the extensive use of concrete has significant environmental impacts, particularly from cement production, which contributes approximately 8% of global CO_2 emissions [4–7]. Moreover, the extraction of natural aggregates, such as stone and sand,

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http://dx.doi.org/10.28991/CEJ-2025-011-07-020

has rapidly depleted natural resources, while construction and demolition activities generate substantial amounts of waste—commonly referred to as construction and demolition waste (CDW) [8–10]. Concurrently, plastic waste pollution poses a major environmental challenge. Projections estimate that by 2030, up to 23 million tonnes of plastic waste could enter global water systems annually, while plastic incineration may release up to 53 million tonnes of CO_2 -equivalent gases. Current recycling efforts remain insufficient, with only 27.2% of plastic waste being recycled, while the remainder is either landfilled or incinerated [11–13].

These environmental concerns have prompted efforts to develop alternative construction materials incorporating waste as substitutes for conventional inputs. Numerous studies have focused on recycled materials, which can significantly reduce natural resource consumption and construction waste generation [14]. Among these, recycled coarse aggregate (RCA) and recycled fine aggregate (RFA) are among the most widely used. In particular, plastic waste—such as polyethylene terephthalate (PET)—has been incorporated as aggregate in concrete. When shredded into small particles, recycled PET can replace sand or gravel, reducing concrete density and thermal conductivity but potentially decreasing compressive strength. Research has shown that incorporating plastic increases porosity and decreases density and thermal conductivity, but it also tends to lower compressive strength and adversely affect durability properties, including resistance to the ingress of aggressive agents [15–19].

One of the primary mechanisms of deterioration in reinforced concrete is the ingress of chloride ions, which accelerates the corrosion of steel reinforcement, particularly in marine environments or areas exposed to deicing salts, such as roads and coastal structures [20, 21]. Therefore, chloride penetration is a key indicator for assessing concrete durability. Previous studies have employed tests such as the Rapid Chloride Penetration Test (RCPT) and the Bulk Diffusion Test to evaluate chloride ingress in recycled concrete. Recycled concrete generally exhibits higher chloride penetration than conventional concrete [22, 23] due to its increased porosity and more interconnected pore structure [21, 24–27]. Although numerous studies have investigated the influence of recycled aggregates on chloride ingress, most focus on either RCA or RFA individually [26, 28–31], and these are typically conducted under controlled laboratory conditions that may not reflect actual field environments.

Current research often relies on short-term immersion tests or indirect evaluations of chloride permeability, which limits practical applicability. In real-world applications, structures are frequently exposed to alternating wet–dry cycles that significantly accelerate chloride ingress [30–32]. Furthermore, limited research has examined recycled concrete incorporating both recycled plastics and RCA, particularly regarding how this combination affects pore structure, chloride resistance, and overall service life. To address this gap, the present study investigates chloride ingress in recycled concrete incorporating both RCA and recycled plastic waste as partial replacements for fine aggregate. The experimental design simulates realistic field conditions, including exposure to a 3.5% sodium chloride (NaCl) solution under continuous wet–dry cycles for 280 days. This study aims to provide in-depth insights into the durability of recycled concrete and support the development of more sustainable infrastructure.

2. Materials and Methods

2.1. Materials

The recycled concrete mixtures were produced using five primary materials: recycled coarse aggregates, Type I Portland cement, non-recyclable plastic waste, a cementitious binder (Type I), and water. The recycled aggregates were sourced from the demolition of construction elements, specifically from leftover concrete piles (Figure 1-a). The particle size distribution of the crushed aggregates obtained from the pile heads is shown in Figure 1-a, while the combined particle grading curve is presented in Figure 2.

a) Recycled aggregates sourced from leftover concrete piles

b) Plastics used as a replacement for fine aggregates

Figure 1. Concrete mix materials

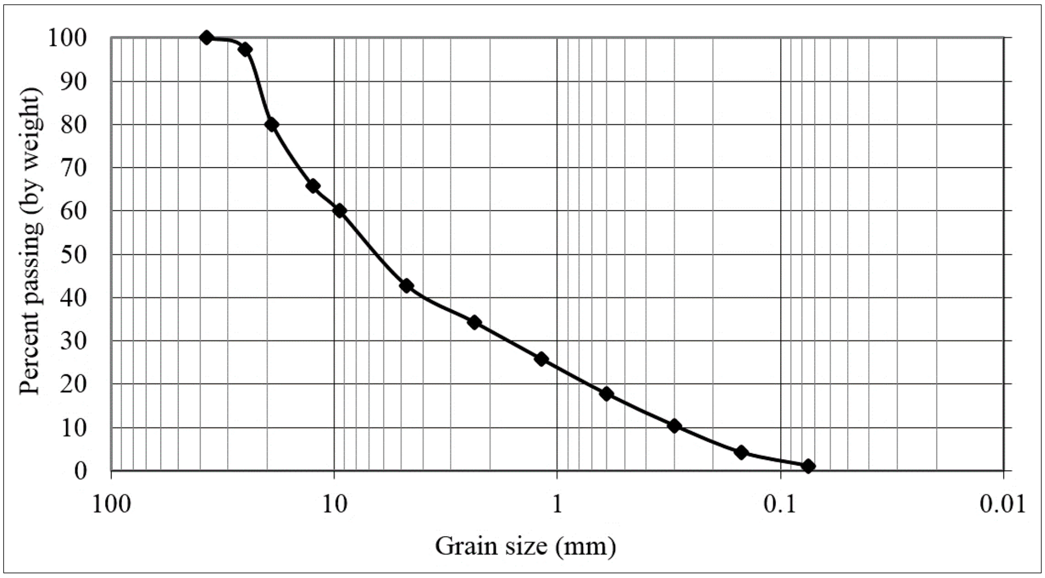


Figure 2. Particle size distribution of recycled concrete materials

Non-recyclable plastic waste was used as a partial replacement for fine aggregate. This plastic was obtained from post-consumer recycling processes, where waste was sorted via water flotation. Only plastics that sank—indicating higher density—were selected and then shredded into particles smaller than 4.75 mm (Figure 1-b).

The cement used in this study was Type I Portland cement, compliant with the Thai Industrial Standard TIS 15-2547 (TIS 2004) [33]. Its primary chemical constituents included calcium oxide (CaO) at 65.5% and silicon dioxide (SiO_2) at 21.0% [34]. The physical properties of the recycled aggregates are summarized in Table 1. These properties—including Los Angeles Abrasion, Flakiness Index, Elongation Index, Unit Weight, and Soundness—were tested in accordance with ASTM and BS standards.

Table 1. Physical properties of recycled composites

Property	Fine Aggregate	Coarse Aggregate	Test Method
Los Angeles Abrasion (%)		18.98	ASTM C131/C131M-20 [35]
Flakiness Index (%)		23.50	BS 812 [36]
Elongation Index (%)		24.70	BS 812 [36]
Unit Weight (kg/m^3)	1,441.1		ASTM C29/C29M-23 [37]
Soundness (Solution of Sodium Sulfate) (%)	10.68	15.90	ASTM C88-13 [38]

2.2. Mix Design and Preparation of Concrete Samples for Testing

The concrete mixtures in this study were composed of Type I Portland cement, water, recycled coarse aggregates sourced from crushed concrete pile heads, and non-recyclable plastic waste used as a partial replacement for fine aggregates. The recycled aggregates were graded as shown in Figure 1a. Plastic waste particles smaller than 4.75 mm were incorporated at replacement levels of 10% and 20% by volume of the fine aggregate fraction. Six sets of concrete mixes were prepared, with proportions summarized in Table 2 and the preparation sequence illustrated in Figure 3.

Table 2. Mix proportions of recycled concrete mixtures incorporating plastic waste and recycled aggregates

RC Round	Type	RC Aggregate (kg m^{-3})	PRC (kg m^{-3})	Water (kg m^{-3})	Cement (kg m^{-3})	W/C
1	A	541.85	-	3.87	126.20	0.505
1	A10	518.13	3.86	3.86	126.20	0.519
1	A20	494.42	3.86	3.86	126.20	0.518
2	B	532.71	7.45	7.45	126.15	0.529
2	B10	532.71	8.47	8.47	126.15	0.517
3	C	532.71	10.65	10.65	126.15	0.525

Note: RC = Recycled concrete, PRC = Plastic Waste (as replacement of fine aggregate), W/C = Water-cement ratio.

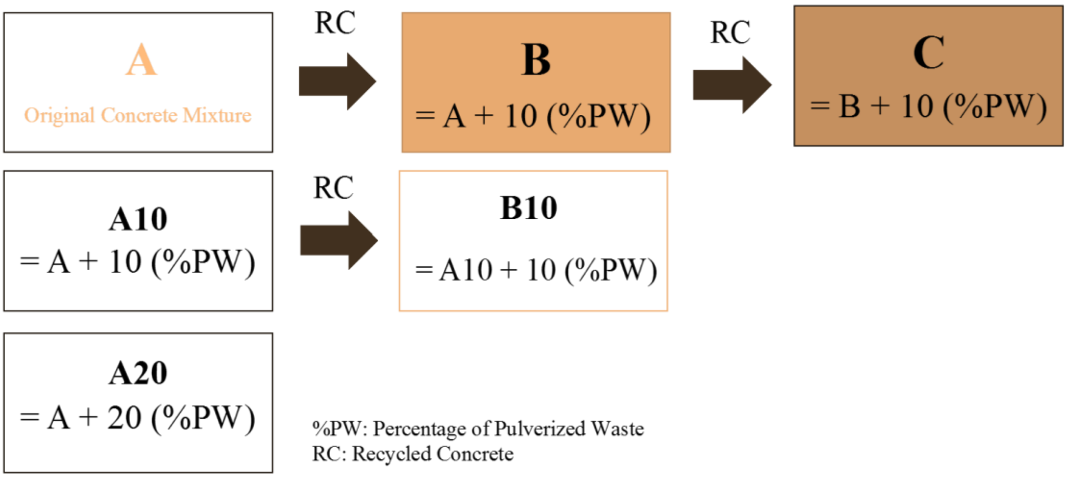


Figure 3. Flow diagram showing the preparation sequence of recycled concrete mixtures for chloride permeability testing

In Set A, recycled aggregates from discarded reinforced concrete were mixed with cement and water to form the base mix. Mixes A10 and A20 were derived from Set A by incorporating 10% and 20% plastic waste by volume of fine aggregate, respectively. For Set B, the hardened concrete from Set A was crushed and reused as recycled aggregate in a new mix, with 10% plastic waste added (B10). Similarly, in Set C, concrete from Set B was crushed and remixed, again with 10% plastic waste by volume of fine aggregate. The complete preparation sequence is depicted in Figure 3 [39]. This progressive recycling approach—recasting and crushing through Sets A to C—enabled the evaluation of durability and performance over multiple recycling cycles while varying the plastic content.

The selection of 20% plastic waste in Mix A20 was guided by prior studies and preliminary trial mixes [39]. Previous research has explored substitution levels between 5% and 30% for fine aggregates using recycled or polymer-based materials, with findings consistently showing that compressive strength losses become more pronounced beyond the 20% threshold. The 20% level was therefore adopted as a practical upper bound. Additionally, trial batches conducted prior to this study revealed that exceeding 30% plastic substitution led to unstable mixes, characterized by excessive bleeding and unacceptable loss of workability. As such, the selected substitution levels of 10%, 20%, and 30% were intended to capture the transition point at which mechanical and durability properties become significantly compromised.

2.3. Testing Procedures and Durability Evaluation

2.3.1. Physical Properties of Aggregates

The physical properties of the recycled coarse aggregates were evaluated through standard procedures, including Los Angeles Abrasion, Flakiness Index, Elongation Index, Unit Weight, and Soundness tests. The soundness test was conducted using a sodium sulfate solution in accordance with relevant ASTM and BS standards.

2.3.2. Compressive Strength and Workability

The compressive strength of concrete samples was determined using a compression testing machine with a load capacity of 2000 kN. Specimens were placed between two 30 mm-thick steel plates and loaded gradually until failure. The procedure followed BS EN 12390-3: 2019 [40]. The ultimate load was recorded, and compressive strength was calculated by dividing the failure load by the cross-sectional area of the specimen.

The workability of fresh concrete was assessed using slump tests in accordance with BS EN 12350-2 [41]. A standard 300 mm cone mold was used, and the slump height was measured after the concrete settled under its own weight. Each test was conducted in duplicate to ensure consistency.

2.3.3. Water Absorption Test

Water absorption tests were conducted on 150 mm × 150 mm × 150 mm concrete cubes following BS 1881-122:2011+A1:2020 [42]. Two sets of specimens were prepared based on the mix proportions in Table 2. One set was cured for 28 days and the other for 90 days. After curing, specimens were oven-dried for 72 hours and cooled to room temperature. The dry mass (M_d) was recorded. The samples were then immersed in water for 10, 20, 30, 60, 120, and 180 minutes. At each interval, the wet mass (M_t) was recorded. Water absorption (W_a) was calculated using the following equation:

$$W_a = \frac{M_t - M_d}{M_d} \times 100 \quad (1)$$

2.3.4. Chloride Permeability Testing

To assess chloride permeability, 150 mm × 150 mm × 150 mm concrete cube specimens were prepared after mixing. After 24 hours, the specimens were demolded and cured in water for 28 days under standard laboratory conditions. Subsequently, they were immersed in a 3.5% sodium chloride (NaCl) solution [43–44]. To simulate field exposure, particularly in marine and coastal environments, specimens underwent a wetting–drying cycle consisting of seven days of immersion in NaCl solution followed by seven days of air drying [45–46]. This cyclic exposure represented a worst-case scenario by accelerating chloride ingress due to the porous nature of concrete [47–50].

For chloride quantification, all specimen surfaces were sealed with epoxy except for one face, which was left uncoated to allow unidirectional chloride diffusion. The specimens were immersed and retrieved for testing after 28, 56, 84, and 280 days of exposure (Figure 4). Upon retrieval, specimens were drilled at five depth intervals: 0–2 cm, 2–4 cm, 4–6 cm, 6–8 cm, and 8–10 cm. The resulting powder from each depth was collected in sealed, labeled bags.

Chloride content was measured according to ASTM C1218 using the titration method. Powdered concrete from each depth was sieved through a No. 4 mesh and dissolved in nitric acid (HNO_3) to extract the chloride ions. The resulting solution was titrated with a standard silver nitrate ($AgNO_3$) solution using potassium chromate (K_2CrO_4) as the indicator. The titration end point was indicated by the formation of a reddish-brown precipitate, signifying complete reaction of the chloride ions.

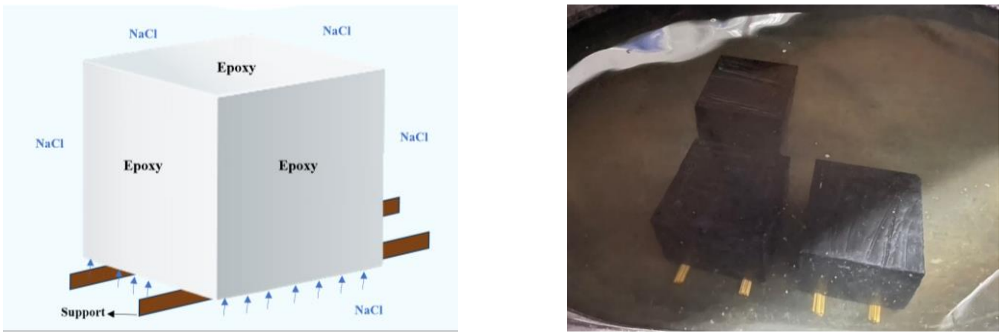


Figure 4. Immersion of concrete specimens in 3.5% NaCl solution during wetting–drying durability cycle

Figure 5. Test setup and equipment used for chloride permeability evaluation of recycled concrete specimens

3. Results and Discussion

3.1. Mechanical Properties of Recycled Concrete

3.1.1. Compressive Strength

The compressive strength of the concrete specimens was evaluated at 7, 14, and 28 days of curing at room temperature. As shown in Figure 6, Mix A developed strength rapidly within the first 7 days, attributed to efficient early-stage hydration. It reached a maximum compressive strength of 400 KSC (≈39.2 MPa) at 28 days, indicating adequate mechanical performance and supporting the feasibility of using recycled concrete aggregates (RCA) in structural applications. With partial replacement of fine aggregates by plastic waste, Mix A10 achieved the highest strength among the plastic-modified mixtures, reaching 320 KSC (≈31.4 MPa) at 28 days. All mixes exceeded the 240 KSC (≈23.5 MPa) threshold, except Mix C, which recorded 215 KSC (≈21.1 MPa)—approximately 10.5% below the minimum target. A noticeable strength reduction was observed with increased plastic content, as seen in Mix A20 (255 KSC), B10 (240 KSC), and C (215 KSC).

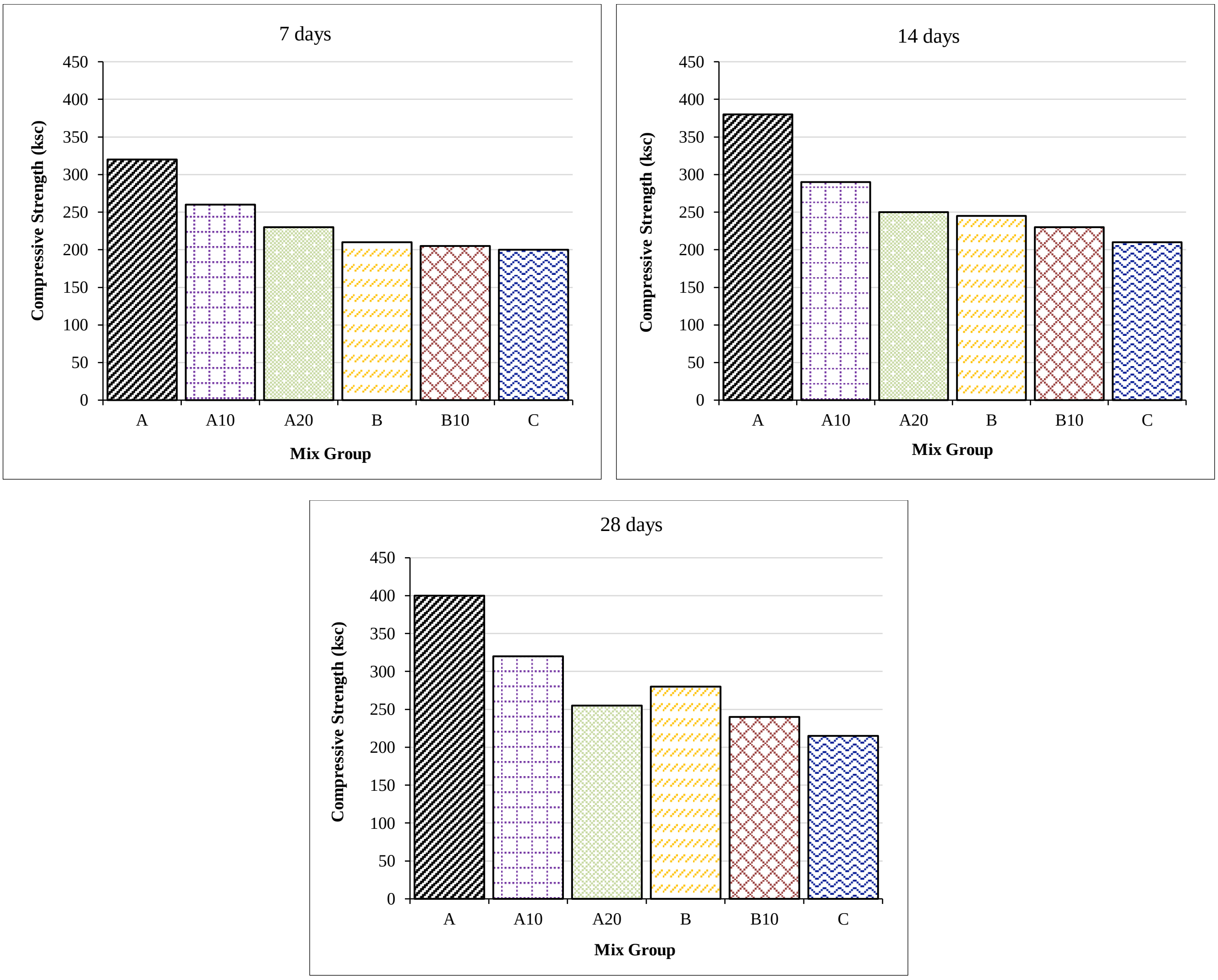


Figure 6. Compressive strength of recycled concrete mixtures at 7, 14, and 28 days

The decline in compressive strength with rising plastic content is attributed to the inert nature of plastic, which impedes cement hydration and weakens the interfacial bond. This trend was consistent across all ages (Figure 7) and aligns with findings from previous studies [15–17], which reported that plastic incorporation reduces concrete density and disrupts paste–aggregate interaction. A comparative analysis across recycling cycles (Mix A → B → C) also showed a gradual strength decline. Additional recycling led to weakened mechanical bonding due to increased angularity and surface roughness of RCA, contributing to the lowest strength observed in Mix C (Figure 7).

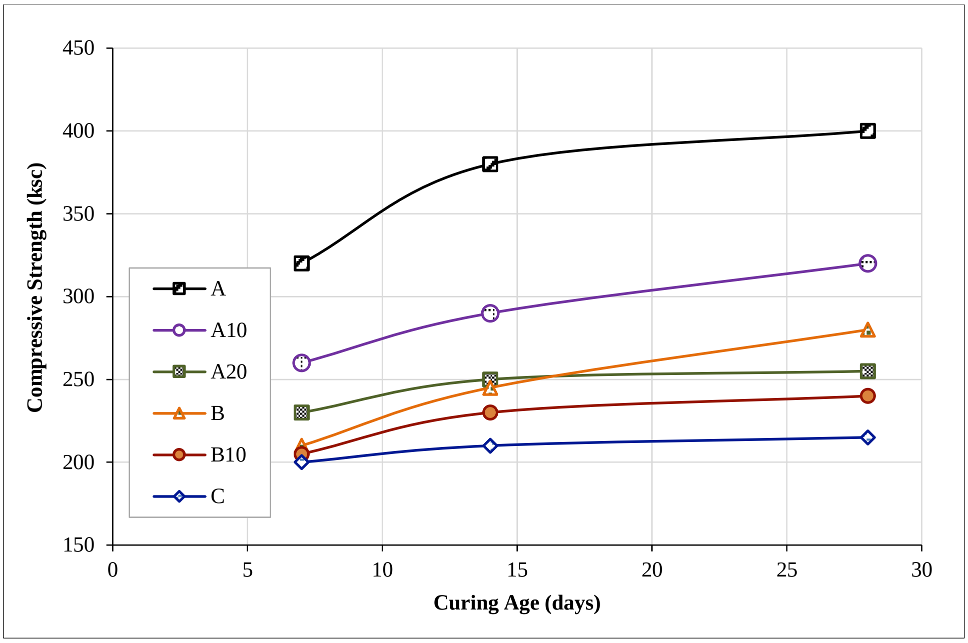


Figure 7. Compressive strength development of concrete with varying recycled content and plastic waste over time

3.1.2. Compressive Strength Loss

To quantify performance degradation, compressive strength losses relative to Mix A were calculated (Figure 8). The most significant reductions occurred within the first 14 days and stabilized by day 28. Mix C, incorporating the highest plastic content and recycled for a third cycle, exhibited the greatest loss at 46.25%. In contrast, mixes with ≤10% plastic content (A10 and B) maintained acceptable strength development. These results suggest that plastic contents above 10%, especially in A20, B10, and C, significantly compromise mechanical performance, with limited strength recovery from continued curing.

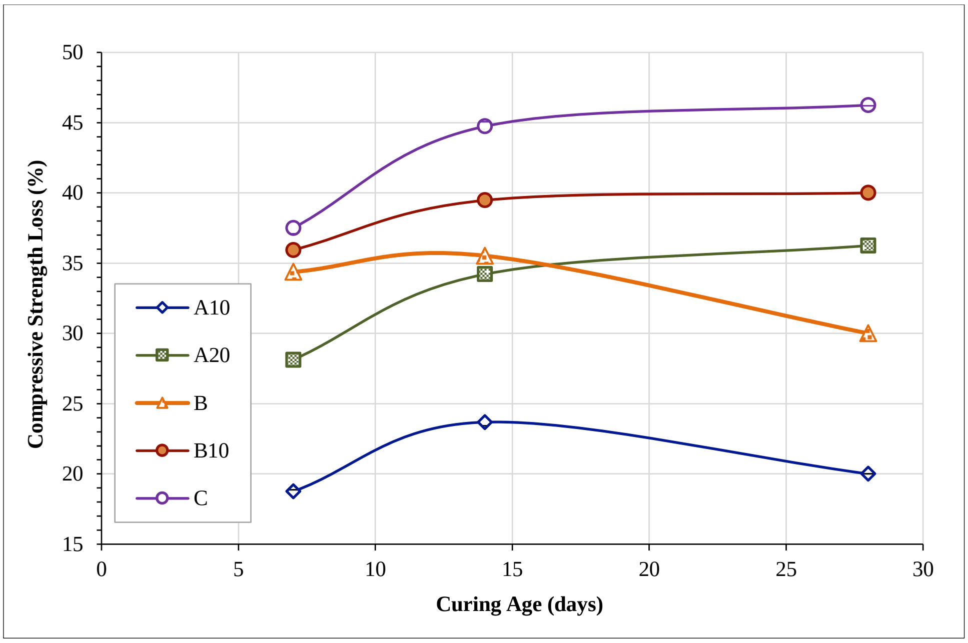


Figure 8. Compressive strength loss of recycled concrete mixtures relative to the control mix (A)

3.2. Workability and Water Absorption

The workability of the recycled concrete mixes, evaluated via slump tests, is shown in Figure 9. All mixes demonstrated slump values within an acceptable range for structural concrete, averaging approximately 8.0 cm. However, workability generally decreased with each additional recycling cycle due to the increased surface roughness, angularity, and water absorption capacity of RCA. These characteristics elevate internal friction during mixing, consistent with observations in previous studies by Qader et al. [17] and Ambrose et al. [51]. Mixes A20 and C exhibited slightly higher slump values of 8.5 cm. This deviation may result from plastic particles acting as inert fillers that reduce internal friction under specific conditions. Nonetheless, the inclusion of plastic typically increases porosity, as reflected in the water absorption results (Figure 10). Increased porosity raises the water demand, reducing the availability of free water for lubrication and lowering overall workability. To maintain adequate fresh concrete performance, mix designs should account for the higher absorption characteristics of both recycled and plastic aggregates and include appropriate water compensation [52, 53].

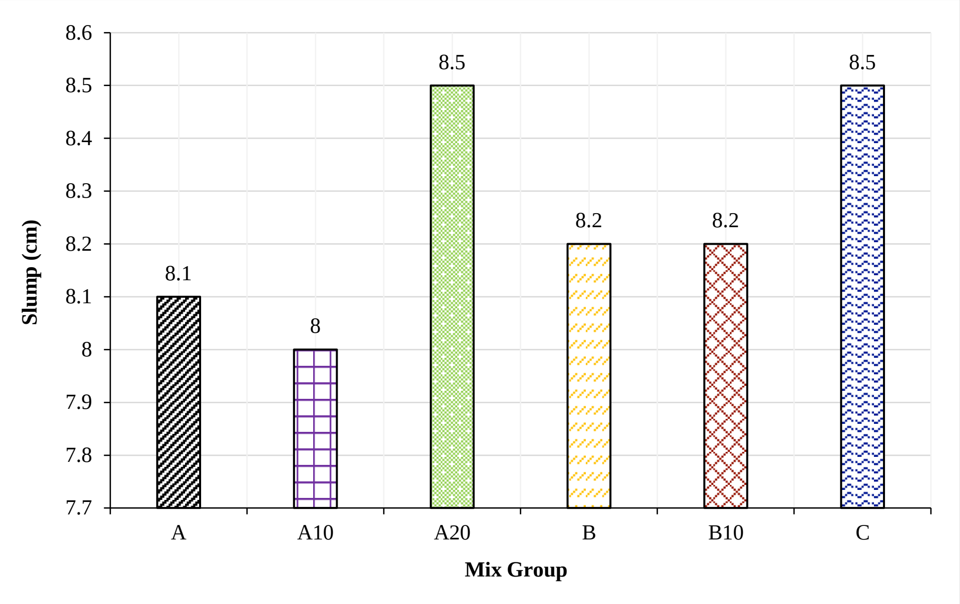


Figure 9. Slump values of recycled concrete mixes containing plastic waste and recycled aggregates

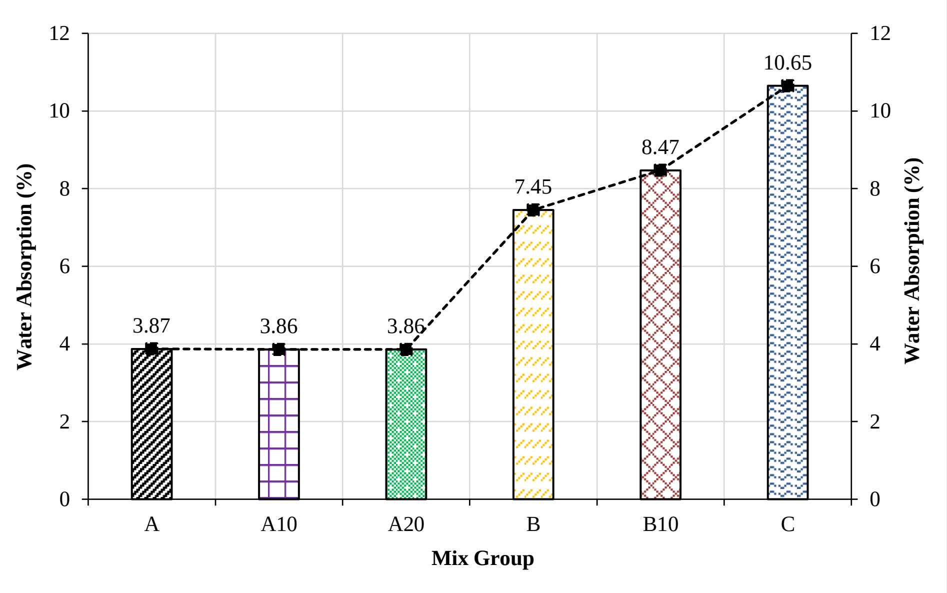
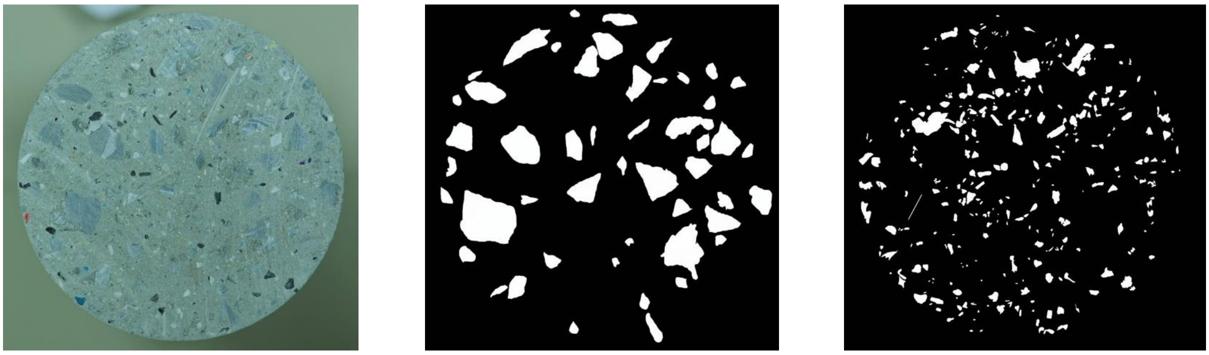


Figure 10. Water absorption of recycled concrete mixes with varying plastic content and recycling stages

3.3. Microstructural Characterization

Microstructural analysis was conducted using cross-sectional image analysis to examine the spatial distribution of coarse aggregates, cement paste, and plastic waste. As shown in Figure 11, the distribution of recycled aggregates and plastic particles varied across the mixtures, particularly with increasing plastic content and recycling cycles. Quantitative evaluation of cross-sectional area proportions (Figure 12) showed that Mix A (no plastic) had a balanced composition: 30.25% coarse aggregate and 69.75% cement paste. This proportion corresponded to the highest compressive strength observed. In contrast, mixes with plastic waste displayed reduced aggregate content. For instance, Mix A10 contained 27.58% aggregate and 4.58% plastic, while Mix A20 showed 21.70% aggregate and 10.98% plastic by area.



Cross-sectional view of concrete Distribution of coarse aggregate Distribution of plastic

Figure 11. Cross-sectional distribution of coarse aggregate, plastic waste, and cement paste in recycled concrete (Set B)

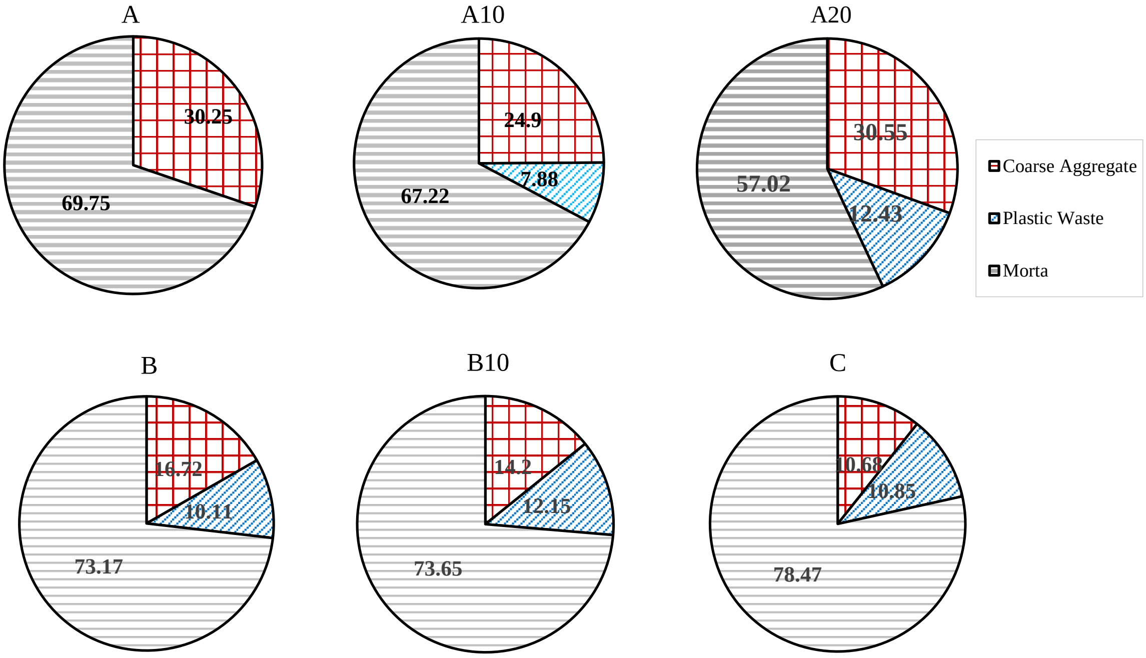


Figure 12. Quantitative analysis of material proportions in recycled concrete based on cross-sectional area distribution

This reduction in coarse aggregate—especially in highly recycled samples like Mix C, which contained only 10.68% aggregate—substantially compromises strength. The decrease in mechanical performance is attributed to both a reduction in aggregate bonding area and the inert behavior of plastic, which does not contribute to cement hydration. These findings are consistent with previous studies by Kang et al. [54] and Du et al. [55], which reported that reducing aggregate content while increasing plastic content lowers concrete density and thermal conductivity, thereby reducing compressive strength.

Additionally, in terms of chloride permeability, studies by de Almeida Ferreira et al. [56] Cheng et al. [57] have shown that increased plastic content leads to more pore spaces in the cement matrix, diminishing resistance to ion ingress. To preserve mechanical performance, an optimal composition is recommended: 30–40% coarse aggregate, ≤10% recycled plastic waste, and 60–70% cement paste by area. This composition supports efficient hydration, reduces interfacial voids, and mitigates strength loss associated with plastic incorporation.

3.4. Chloride Permeability Assessment of Recycled Concrete

3.4.1. Chloride Penetration

Chloride ingress behavior in recycled concrete specimens was evaluated to assess durability under aggressive environmental conditions. The concrete mixes were prepared using recycled aggregates sourced from reinforced concrete beams, with plastic waste used as a partial replacement for fine aggregates. Specimens were exposed to a 3.5% NaCl solution and subjected to cyclic wetting–drying conditions for 28, 56, 84, and 280 days. As shown in Figure 13, chloride content increased with prolonged exposure, particularly within the surface zone (0–2 cm). For example, Mix A exhibited chloride content increases of 5.27%, 17.07%, and 137.96% at 56, 84, and 280 days, respectively—reflecting an average daily increment of 0.59%. Similarly, Mix A10 showed increments of 28.57%, 44.60%, and 84.39%, corresponding to an average daily increase of 0.25%. Comparable trends were observed across Mixes A20, B, B10, and C.

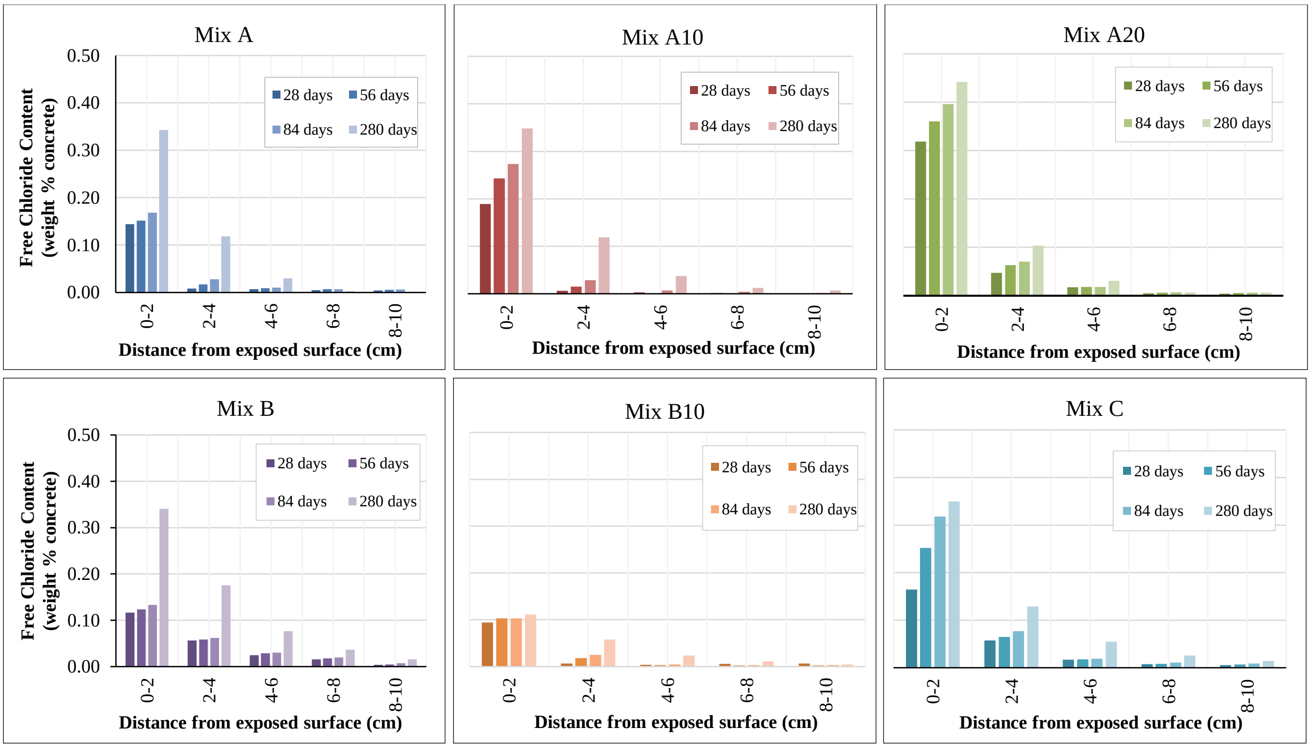


Figure 13. Chloride concentration profiles in recycled concrete mixes at different exposure durations (28–280 days) under cyclic wetting–drying in 3.5% NaCl solution

The data also indicated non-uniform chloride distribution with depth. Chloride concentrations consistently decreased beyond 4 cm, underscoring the protective role of surface layers. These findings highlight that extended exposure significantly compromises the chloride resistance of concrete. Understanding depth-dependent chloride diffusion is critical in designing durable concrete structures exposed to marine or deicing environments. Effective protective measures, such as increasing concrete cover depth or applying surface treatments, are essential to mitigate corrosion risk and prolong structural service life.

3.4.2. Chloride Content Compared to International Standards

Controlling chloride ion content is vital for preventing reinforcement corrosion. International standards such as BS EN 206 [58] and ACI 318R-19 [59] define permissible chloride limits based on exposure conditions and structural type. Proper adherence to these standards ensures long-term durability. Figure 14 compares the chloride contents of all concrete mixes with these standards. At 0–2 cm depth, all mixes exceeded permissible chloride limits at 280 days, with Mix A20 reaching 0.442%, indicating a high risk of reinforcement corrosion. In contrast, chloride contents at depths beyond 4 cm remained below 0.06%, within allowable thresholds for both conventional reinforced and prestressed concrete. This suggests that while deeper layers are resistant to chloride penetration, surface zones remain highly vulnerable and must be prioritized in durability design.

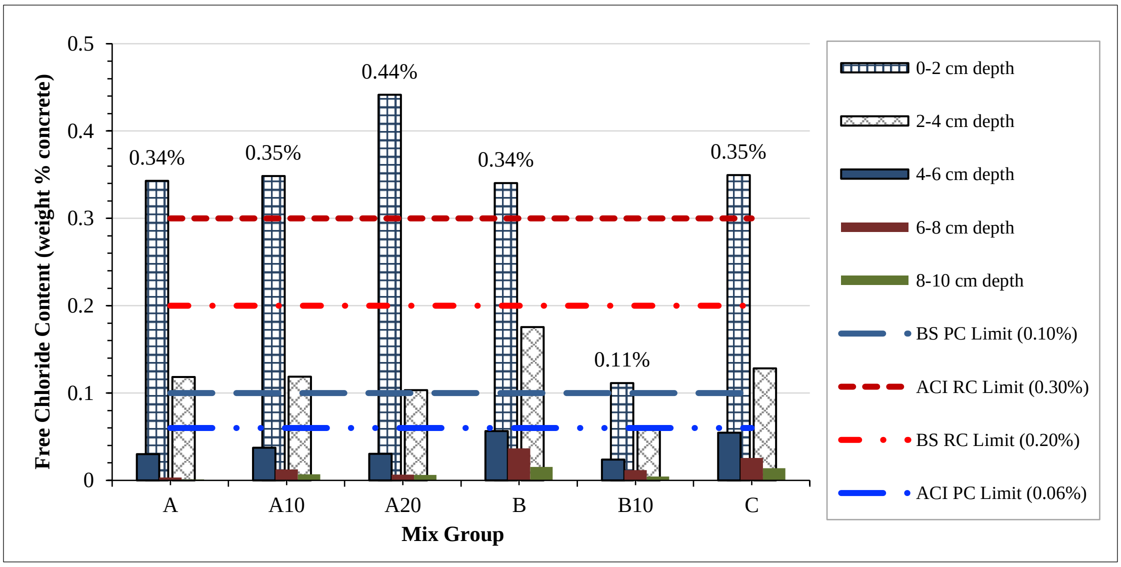
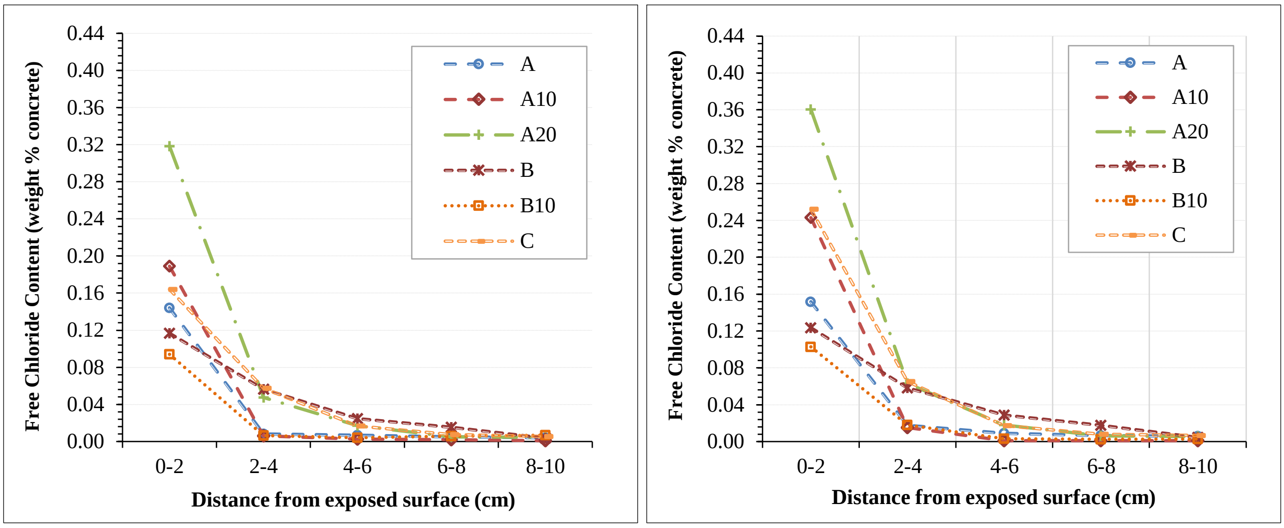


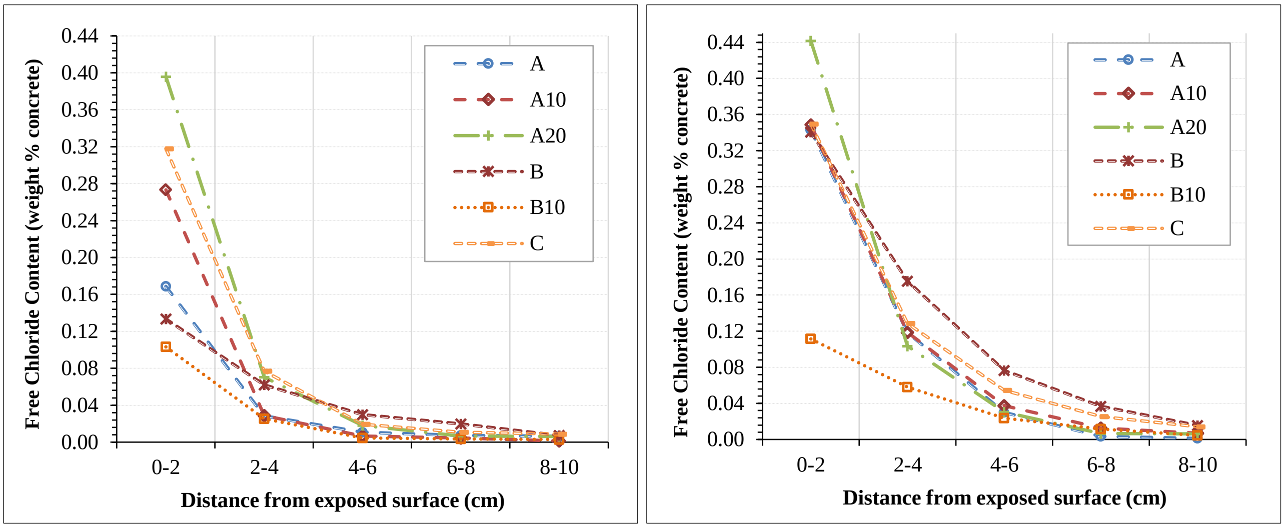
Figure 14. Chloride concentration in recycled concrete mixes at 280 days compared to international standards

3.4.3. Chloride Distribution Across Concrete Depths

Chloride profiles reveal that concentrations are highest near the surface and decrease with depth (Figure 15). This behavior can be divided into two distinct zones: a critical surface layer (0–4 cm) with substantial chloride ingress, and an inner layer (beyond 4 cm) with significantly lower penetration. At 28 days, chloride concentrations at 0–2 cm ranged from 0.094% to 0.318% across all concrete mixes (Figure 15-a). By 280 days, these values increased to between 0.111% and 0.442% (Figure 15d), indicating progressive accumulation over time. Mix A exhibited depth-wise reductions in chloride content of 5.76%, 11.54%, 16.78%, and 34.47% at 28, 56, 84, and 280 days, respectively, corresponding to a median reduction rate of 0.17% per 2 cm depth. Mix A10 showed a similar trend with a median rate of 0.12%, while Mix A20 displayed more variability, with a median reduction of 0.31%. Mix B demonstrated the most pronounced reduction, with a median rate of 0.96%, followed by Mix C at 0.69%. Beyond 4 cm, chloride concentrations remained relatively stable, with variations below 5%, confirming limited further diffusion. These findings align with previous studies [60–62], which also noted the importance of maintaining adequate concrete cover and applying protective surface treatments to prevent long-term chloride ingress.



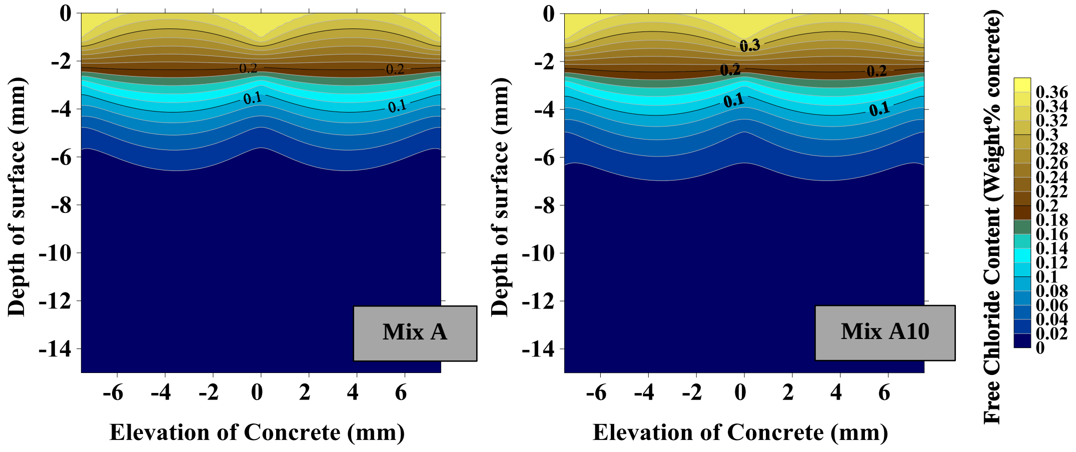
a) after 28 days immersion **b) after 56 days immersion**



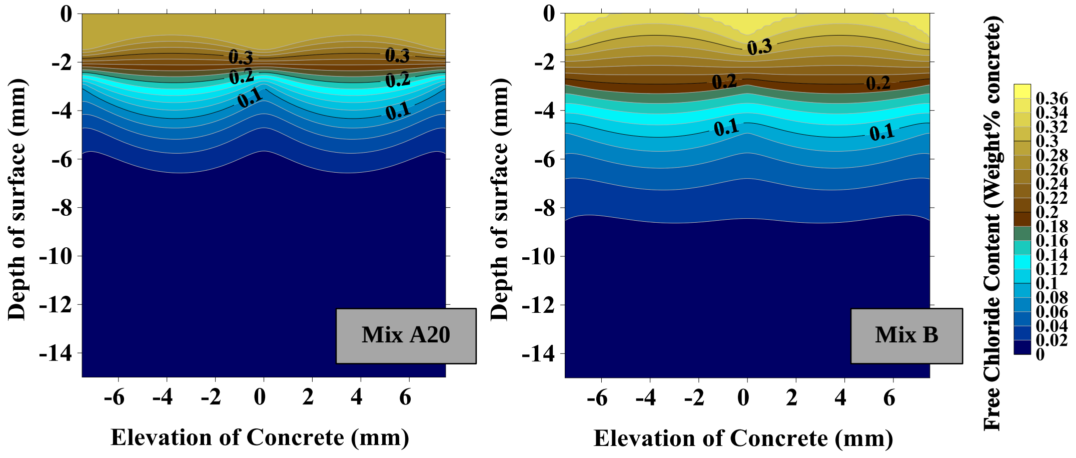
c) after 84 days immersion **d) after 280 days immersion**

Figure 15. Chloride penetration profiles in recycled concrete specimens (Mix A, A10, A20, B, B10, and C) at different exposure durations: (a) 28 days, (b) 56 days, (c) 84 days, and (d) 280 days in 3.5% NaCl solution under cyclic wetting–drying

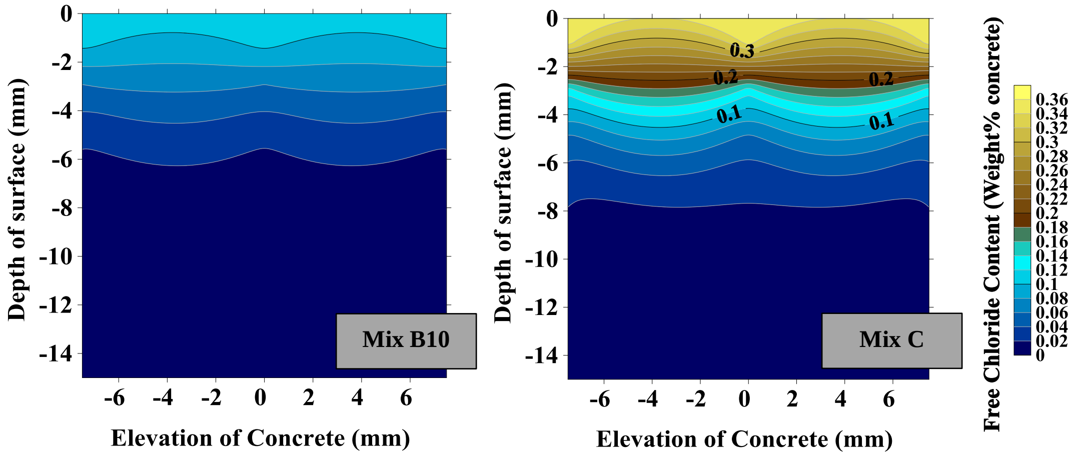
Figure 16 illustrates the simulated chloride diffusion profiles in concrete specimens with dimensions of 150 × 150 × 150 mm after 280 days. The results show that chloride content falls below 0.06% at depths greater than 4 cm in all mix designs. However, repeated recycling combined with plastic waste substitution significantly increased the depth of chloride penetration. This effect is primarily attributed to the weakened interfacial bonding and higher porosity resulting from the use of recycled aggregates. The increased porosity introduces additional internal voids, facilitating deeper chloride ion migration. For instance, chloride presence in Mix C, produced from Mix B concrete, extended to a depth of 8–10 cm, whereas in Mix A, it was limited to approximately 6 cm. These results are consistent with recent studies, which confirm that increased porosity and weaker bonding due to repeated recycling cycles enhance chloride ingress, particularly in the surface zone. Studies by Yang et al. [61] and Jiang et al. [63] further support the observation that chloride transport exhibits non-uniform, depth-dependent behavior, largely influenced by microcracking and heterogeneous aggregate distribution. Similarly, Tong et al. [64] reported that unmodified recycled aggregates reduce the concrete's resistance to chloride ingress in marine environments. These findings emphasize the need for protective strategies such as increasing cover thickness or applying surface sealants to improve the durability and longevity of reinforced recycled concrete in chloride-laden conditions.



a) Mix A b) Mix A10



c) Mix A20 d) Mix B



e) Mix B10 f) Mix C

Figure 16. Chloride distribution across recycled concrete specimen depths after 280 days: (a) Mix A, (b) Mix A10, (c) Mix A20, (d) Mix B, (e) Mix B10, (f) Mix C

3.4.4. Effect of Plastic Waste Substitution on Chloride Ingress

The substitution of fine aggregates with plastic waste significantly affects chloride ingress in recycled concrete. As the replacement ratio increased from 10% to 20%, the chloride content in the concrete specimens also increased. For example, Mix A20, which contained 20% plastic waste, exhibited the highest surface chloride concentration (Figure 16c). This trend is consistent with the porosity results shown in Figure 10, where higher plastic content correlated with greater void formation within the cement matrix. The resulting increase in porosity enhances concrete permeability, allowing chloride ions to migrate more freely through the pore structure. Chloride accumulation also increased with successive recycling cycles, suggesting that the recycling process further compromises the material's resistance to ion ingress. At a 10% plastic replacement level, chloride content at 0–2 cm depth declined from 61.95% to 2.35% between the first and second reuse cycles. Similarly, at a 20% replacement level, chloride content decreased from 238.72% to 68.12% across three cycles. These findings underscore the combined impact of plastic substitution and repeated recycling on concrete durability.

These results are consistent with recommendations from Ismail & Ramli [32], which suggest limiting recycled plastic content to no more than 10% by volume of fine aggregate and maintaining coarse aggregate content between 30–40%. Such adjustments in mix design help preserve the mechanical properties and durability of concrete by minimizing the negative effects associated with elevated porosity and reduced strength. From a durability standpoint, the observed increase in chloride ingress raises critical concerns about reinforcement corrosion. As chloride ions accumulate near the reinforcement zone, the likelihood of corrosion initiation increases, directly compromising the service life of the structure. This deterioration is exacerbated by plastic-induced porosity, which reduces the concrete's impermeability. Therefore, optimizing mix design is essential for recycled concrete incorporating plastic waste. Recommended strategies include limiting plastic content to below 10%, enhancing matrix densification, and incorporating supplementary cementitious materials to offset porosity. Further research is needed to refine these strategies and develop more durable and sustainable plastic-modified recycled concrete.

4. Conclusion

This study evaluated the performance of recycled concrete incorporating plastic waste as a partial replacement for fine aggregates, with a focus on compressive strength, workability, water absorption, and chloride permeability. The results clearly indicate that both the plastic substitution level and the number of recycling cycles significantly affect the mechanical and durability properties of the concrete. Concrete mixes without plastic substitution achieved the highest compressive strength. In contrast, increasing plastic content resulted in a notable strength reduction, primarily due to the inert nature of plastic particles and weak interfacial bonding. Similarly, higher plastic content and multiple recycling cycles led to reduced workability and increased water absorption, reflecting elevated internal porosity. Chloride diffusion was strongly correlated with porosity, with deeper penetration observed in more porous mixes—particularly within the top 2 cm of the concrete surface. Among the tested formulations, the mix with 20% plastic waste exhibited the lowest compressive strength and the greatest chloride ingress. Conversely, limited plastic substitution ($\leqslant$10% by volume) yielded more favorable outcomes in terms of strength retention and chloride resistance, even across multiple recycling cycles. Based on these findings, it is recommended that plastic waste substitution not exceed 10% by volume to preserve an acceptable balance between mechanical performance and durability. Additionally, a concrete cover of at least 8–10 cm is advised for structural elements exposed to chloride-rich environments to ensure adequate protection of embedded reinforcement. To further enhance the performance of plastic-modified concrete, future research should explore the incorporation of supplementary cementitious materials or nano-additives aimed at reducing porosity and improving matrix densification. Such advancements will support the development of durable and sustainable concrete for broader structural applications.

5. Declarations

5.1. Author Contributions

Conceptualization, K.J., S.P., W.Y., W.T., C.T., and S.T.; methodology, K.J., S.P., W.Y, and C.T.; formal analysis, S.T., W.T. and C.T.; visualization, S.T., W.T.and C.T.; writing—original draft preparation, S.T., K.J., and W.T.; writing—review and editing, K.J., S.T., S.P. and W.T; supervision, K.J., S.T.; project administration, K.J., S.T.; funding acquisition, K.J., S.T. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The research was supported by a grant from the Department of Civil Engineering, Faculty of Engineering at Kamphaeng Saen, and Kasetsart University, Kamphaeng Saen campus, Thailand.

5.4. Acknowledgements

The authors express their gratitude to the Department of Civil Engineering at Kamphaeng Saen Kasetsart University, and Rajamangala University of Technology Suvarnabhumi for facilitating in this study. Additionally, the author would like to thank the Faculty of Engineering at Kamphaeng Saen Kasetsart University, Kamphaeng Saen Campus, and Research and Development Institute at Rajamangala University of Technology Suvarnabhumi for its support in the publishing of this research. Thanks to Kasetsart University, for editing this for grammatical and linguistic accuracy.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

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