EFFECT OF RECYCLED TYRE AGGREGATE SURFACE TREATMENT BY NAOH SOLUTIONS ON THE SHRINKAGE PROPERTIES OF SUSTAINABLE CONCRETE

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ABSTRACT

Shrinkage in concrete generates tensile stresses that can lead to cracking, thereby compromising its durability, which requires careful investigation. Depleting natural aggregates poses a threat to construction sustainability, necessitating the use of recycled alternatives, such as waste tyre aggregates, to replace traditional materials. However, the smooth surface of tyre aggregates can weaken their bond with cement paste, resulting in reduced strength and increased shrinkage. Treating the tyre surface may improve these properties, which have not been well investigated in the literature. To this aim, this study evaluated the shrinkage behavior of seven concrete mixes: (i) three mixes with 0% (control), 5%, and 15% recycled tyre aggregate (RTA) washed with water, (ii) two mixes with 5% and 15% RTA treated with NaOH for 2 hours, and (iii) two mixes with 5% and 15% RTA treated with NaOH for 72 hours. The shrinkage of the concrete (i.e., longitudinal length change) was monitored on prism specimens (75 × 75 × 285 mm) after 24 hours of casting to 60 days. A data-driven mathematical model was developed from experimental data and later optimised to improve its performance. The drying shrinkage increases with increasing RTA content, reaching approximately 47% for the 5% RTA mix and 151% for the 15% RTA mix compared to the control mix (0% tyre) at 60 days. Concrete made with RTA treated with NaOH for 2 hours and 72 hours exhibited lower shrinkage compared to the one washed with water, which reaches 24% and 121% for 2 hours of treatment and 14% and 95% for 72 hours of treatment of the mixes with 5% and 15% RTA, respectively, higher than the control mix at 60 days. Moreover, at 60 days, the shrinkage of the RTA treated with NaOH was reduced by 16% and 12% for the 5% and 15% RTA mixes, respectively, after 2 hours of treatment, and by 22% for both percentages after 72 hours of treatment, compared to RTA washed with water. The data-driven mathematical model precisely matches the shrinkage profiles (reaches $R^2 \approx 0.9922\text{-}0.9982$), where the optimised model aligns well with experimental results across all stages.

Keywords: *Recycled tyre aggregate, chemical treatment, shrinkage, sustainability, data-driven model*

1. INTRODUCTION

Concrete is the most widely used construction material globally due to its versatility, durability, and cost-effectiveness. The properties of concrete, including its mechanical strength and durability, are determined by its composition, which consists of cement, water, fine aggregates, and coarse aggregates. Among these components, coarse aggregates serve as the primary load-bearing element, providing strength, stiffness, and dimensional stability to the hardened concrete (Domone & Illston, 2010; Mehta & Monteiro, 2006). Typically, coarse aggregates account for 60-80% of the total concrete volume, forming a structural framework that enhances resistance to both compressive and tensile stresses (Mehta & Monteiro, 2006; Miah et al., 2022a). Consequently, the quality, shape, and surface characteristics of coarse aggregates are crucial in determining the overall performance of concrete.

However, the large-scale use of natural coarse aggregates has raised significant environmental and resource-related concerns. These conventional aggregates are commonly sourced from crushed rock or manufactured from clay. The ongoing extraction of natural aggregates through quarrying and mountain excavation leads to extensive environmental degradation, including habitat loss, deforestation, and soil instability. Meanwhile, producing brick aggregates requires burning clay at high temperatures, a process that emits substantial amounts of carbon dioxide (CO_2), further contributing to greenhouse gas emissions (Tam et al., 2018; Miah et al., 2022b; Miah et al., 2021).

With the increasing demand for concrete, reliance on such unsustainable sources is no longer viable. Therefore, developing eco-friendly alternatives that use waste materials as substitutes for aggregates is essential to mitigate environmental impacts, conserve natural resources, and promote sustainable construction practices. Among various waste materials, end-of-life vehicle tyres have emerged as a promising alternative source for aggregate production (Thomas & Gupta 2016; Sofi et al. 2016). The disposal of these waste tyres poses significant environmental challenges due to their non-biodegradability and resistance to natural degradation. Every year, millions of tonnes of tyres reach the end of their service life globally, accumulating in landfills or open dumps. This not only occupies valuable space but also poses fire hazards. Incinerating tyres, while practised for energy recovery, releases toxic gases and high levels of CO_2, negatively impacting air quality (Thomas & Gupta, 2016; Sofi et al., 2016; Khern et al, 2020; Aslani et al., 2016; Khaloo et al., 2008). Incorporating shredded or granulated recycled tyre aggregate (RTA) into concrete offers a sustainable solution to these issues. This approach reduces reliance on natural stone and brick aggregates, lowers CO_2 emissions associated with traditional aggregate production, and mitigates landfill accumulation, aligning with the principles of a circular economy and environmental preservation goals (Khern et al, 2020; Aslani et al., 2016; Khaloo et al., 2008).

Replacing conventional burnt clay brick or stone aggregates with recycled tyre aggregate (RTA) presents several environmental and technical advantages. The use of RTA lowers embodied energy in concrete production, reduces transportation costs in regions without natural stone deposits, and promotes the use of waste (Gigli et al., 2019; Tam et al., 2018; Sofi et al., 2018). Additionally, rubberised concrete demonstrates improved impact resistance, sound absorption, and ductility, making it suitable for both specialised structural and non-structural applications. However, a key limitation of tyre-based concrete is the weak bond at the rubber–cement interface, caused by the hydrophobic and smooth surface of tyre particles, which diminishes mechanical interlocking and overall strength. To overcome this challenge, various surface modification methods—including washing, chemical treatment, and alkaline soaking—have been proposed to enhance roughness and interfacial adhesion (Kashani et al., 2018; Khern et al., 2020; Su et al., 2015; Rivas Vázquez et al., 2015). Despite these promising outcomes, comprehensive studies focusing on the influence of treatment duration and type—particularly sodium hydroxide (NaOH) treatment—on the strength and shrinkage performance of tyre-modified concrete remain limited.

Shrinkage is one of the most critical factors affecting the dimensional stability and long-term durability of concrete. It primarily occurs due to moisture loss, chemical reactions, and temperature variations, often resulting in microcracking, reduced strength, and a decreased service life (Miah et al. 2023a, 2023b). While the shrinkage of conventional concrete has been widely studied, there is limited research on the shrinkage behaviour of rubberised concrete, especially when treated aggregates are incorporated. The addition of flexible rubber particles may alter the internal stress distribution and reduce restraint during drying, thereby influencing shrinkage differently than mineral aggregates. Furthermore, studies addressing the shrinkage of concrete with surface-treated tyre aggregates are scarce, and minimal data is available on predictive mathematical or data-driven models capable of forecasting the shrinkage behaviour of such mixes. Therefore, enhancing the understanding of shrinkage in concrete incorporating both untreated and treated RTA is essential for designing durable and sustainable concrete composites (Kashani et al., 2018; Khern et al., 2020; Su et al., 2015; Rivas Vázquez et al., 2015).

Experimental investigations have played a crucial role in evaluating the mechanical and shrinkage properties of concrete containing tyre-derived aggregates. However, these experiments often require significant time and resources and are limited to specific mix proportions. In contrast, computational and data-driven modelling approaches offer efficient and cost-effective alternatives for performance prediction. Advanced modelling techniques—such as finite element modelling (FEM), machine learning (ML), and artificial intelligence (AI)-based frameworks—enable the simulation of complex interactions between mixed constituents, providing accurate predictions of material behaviour without extensive laboratory testing (Pan et al., 2023; Miah et al., 2025a, 2025b). These approaches have shown great potential for optimising mix design parameters and predicting key properties such as strength, shrinkage, and durability. Nonetheless, there is a notable lack of studies applying such predictive tools specifically to concrete mixes containing untreated and treated RTA.

This study addresses existing research gaps by investigating the shrinkage behaviour of concrete that incorporates 5% and 15% recycled tyre aggregate (RTA) as partial replacements for brick coarse aggregate. The RTA underwent various surface treatments, including simple water washing and alkaline treatment with sodium hydroxide (NaOH) for 2 and 72 hours, respectively. These treatments were aimed at assessing their effects on interfacial bonding and shrinkage characteristics. Additionally, a mathematical data-driven predictive model has been developed to forecast the experimental shrinkage profiles of these concrete mixes. This model utilises optimisation techniques to improve accuracy and establish correlations between material composition, treatment duration, and shrinkage response. Through this combined experimental and computational approach, the research promotes sustainable concrete development by effectively utilising end-of-life waste tyres, reducing environmental impacts, conserving natural resources, and advancing the predictive modelling of material behaviour in sustainable construction systems.

2. METHODOLOGY

This research examined the shrinkage behaviour of concrete in which recycled tyre aggregate (RTA) partially replaced conventional brick coarse aggregate (BCA), as shown in Figure 1. The reference mixture used locally sourced brick aggregate, characterised by a specific gravity of 2.02, a saturated surface-dry (SSD) density of 1065 kg/m³, a fineness modulus of 7.43, and a water absorption rate of 20%. To ensure uniformity across all concrete mixtures, the maximum aggregate size was limited to 20 mm. Fine aggregate consisted of river sand that passed through a 4.75 mm sieve, with a fineness modulus of 3.12 and a specific gravity of 2.66. Both coarse and fine aggregates met the standard grading and quality specifications required for structural concrete, as illustrated in Figure 2. End-of-life vehicle tyres were collected from a local disposal facility and manually cut into intermediate-sized fragments suitable for use as coarse aggregate (see Figure 1). Before being added to the concrete mix, the tyre pieces were carefully washed with water to remove surface contaminants such as dust, oil residues, and other debris. The physical properties of RTA were determined as follows: specific gravity of 1.13, SSD density of 600 kg/m³, fineness modulus of 7.43, and an absorption capacity of 3.63%. It is noted that a similar grading distribution to that of BCA was selected for the RTA particles to eliminate the influence of grading on the measured properties, as shown in Figure 2.

River sand Brick coarse aggeragte Recycled tyre aggregate

Figure 1: Images of river sand, brick coarse aggregate (BCA) and recycled tyre aggregate (RTA).

To improve interfacial bonding between the rubber particles and the cementitious matrix, a portion of the RTA was chemically treated by immersion in a sodium hydroxide (NaOH) solution for 2 hours and 72 hours. After treatment, the aggregates were thoroughly rinsed with clean water to remove any residual alkali, then air-dried before incorporation into the concrete mix.

All concrete mixtures were designed with a fixed water-to-cement (w/c) ratio of 0.55. The reference mix consisted entirely of brick aggregate, while two additional mixtures included water-washed recycled tyre aggregate (RTA) as a replacement for 5% and 15% of the BCA volume. Additionally, four other mixtures contained RTA at the same replacement levels (5% and 15%), but featured particles that had undergone sodium hydroxide (NaOH) treatment for either 2 hours or 72 hours, for both 5% and 15% RTA, to modify their surfaces. The treatment durations of 2 h and 72 h were selected based on the findings reported by Khern et al. (2020). The cement content was consistently maintained at 350 kg/m³ across all mixes. To ensure a uniform distribution of the rubber particles throughout the concrete, all mixtures were prepared using a laboratory-scale drum mixer. The detailed concrete mixture proportions for all mixes are presented in Table 1, in which the amounts of all ingredients at 2 h and 72 h of NaOH treatment remain the same as those for the untreated tyre mixes.

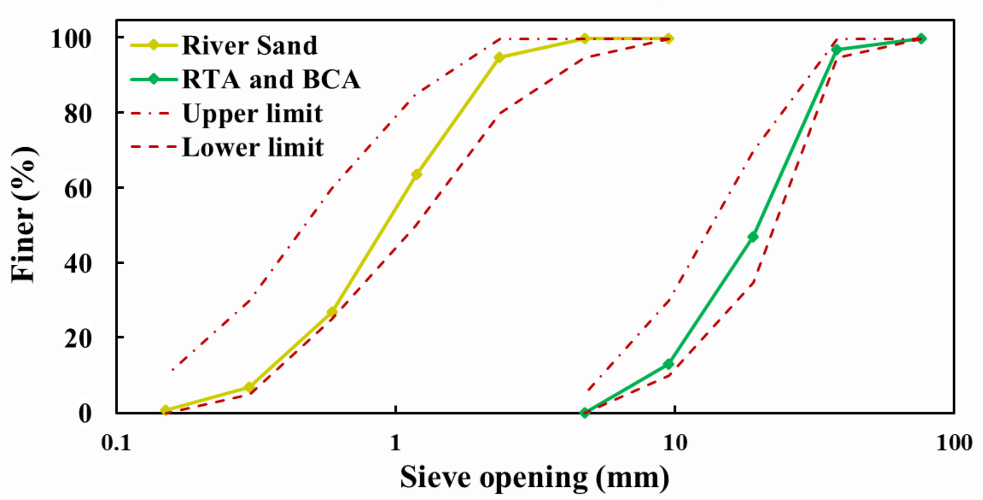


Figure 2: Grading curve of river sand, brick coarse aggregate (BCA) and recycled tyre aggregate (RTA).

Table 1. Mixture proportions of all concrete mixes (kg/m^3)

Mix ID	Cement	Coarse Aggregates BCA	Coarse Aggregates RTA	River sand	Water
Control	350	705	0.0	829	193
Tyre-5%	350	670	20	829	193
Tyre-15%	350	599	59	829	193

The shrinkage behaviour of the concrete mixtures, defined as the longitudinal change in specimen length, was assessed in accordance with ASTM C157. Prism specimens measuring 75 mm × 75 mm × 285 mm were cast and monitored from one day after casting until 60 days later, as illustrated in Figure 3. Before casting, two stainless steel gauge studs were embedded at each end of the mould to align the prism's principal axes with those of the mould, ensuring precise measurement of longitudinal changes. After casting, the prisms were submerged in water maintained at approximately 20 ± 3 °C, as specified in ASTM C157. Shrinkage measurements were taken at frequent intervals, as it was anticipated that specimens containing RTA could exhibit greater shrinkage than those made with conventional BCA, especially at higher RTA replacement levels. A high-precision dial gauge was employed to monitor the length changes of each specimen. The initial measurement was recorded immediately after demoulding and considered as a reference measurement. For each mix, three specimens were tested, and the average shrinkage value was reported.

Figure 3: Fresh concrete with a prism for the shrinkage test (left) and prism specimens with a dial gauge to monitor the axial length change.

3. DATA-BASED MODELLING & OPTIMISATION

A data-driven model is useful for representing the phenomena observed in an experimental dataset. Additionally, such models can be used to identify and predict potential outcomes, helping avoid unnecessary tests and field visits. Since many models are available for selection, including physics-based, non-physics-based, linear, nonlinear, parametric, and non-parametric (Fan, 1996; Miah & Lienhart, 2023), this study opts for a simple polynomial regression model, chosen for its optimal performance (Miah et al., 2018). The general form of this model is presented below as,

$$\alpha = f(t, \gamma) + e \tag{1}$$

where α represents the model output, t is the independent variable, γ represents the unknown coefficients of the model, and e indicates the error term. The above equation can be elaborated based on the studied problem, as shown here,

$$\alpha = \gamma_1 t^3 + \gamma_2 t^2 + \gamma_3 t^1 + \gamma_4 \tag{2}$$

After plugging in the unknown parameters (e.g. $\gamma_1, \gamma_2, \gamma_3$, and γ_4) of the model, it can be rewritten as follows,

$$\alpha = -1.6173e^{-07}t^3 + 2.5085e^{-05}t^2 - 0.0016t^1 - 0.0013 \tag{3}$$

where the shrinkage is represented by α, t is the time in days, $\gamma_1, \gamma_2, \gamma_3$, and γ_4 are the model's parameters.

The model described in Eq. (3) may require proper tuning and adjustment to enhance performance. The aforementioned tuning process can be done manually, which would be time-consuming. Alternatively, this tuning can be performed using optimisation algorithms. In this study, a heuristic-type optimisation algorithm is adopted to search for a global minimum of the defined problem (Lagarias et al., 1998; Miah et al., 2018; Miah, 2020). The optimisation process involves minimising the error of the developed model by optimising its output. To achieve this, the objective function (K) needs to be optimised based on a specific set of data parameters.

$$K = \sqrt{\sum_{i=1}^{N} \frac{|f^{exp} - f^{mod}|^2}{|f^{exp}|^2}} \tag{4}$$

where the experimental data is given by f^{exp}, is the outcome of the model is f^{mod}.

4. EXPERIMENTAL OUTCOMES AND DISCUSSIONS

The axial shrinkage of both the control mix and concretes incorporating untreated (water-washed) recycled tyre aggregates (RTA) was monitored over 60 days, as illustrated in Figure 4. The curves represent the average values of three tests. Because there are many data points, particularly in the initial weeks, error bars are not shown to avoid overcrowding; the same approach is used for subsequent curves. However, almost similar trend was observed among the three tests. It is noted that no shrinkage cracking was observed in any of the test specimens. The data indicate a clear trend: incorporating RTA consistently results in greater shrinkage than the control mixture with 100% BCA. All mixes experience their greatest length reduction during the first two weeks, after which the shrinkage rate slows and continues gradually for about 2 months before stabilising. By the end of the 60-day observation period, mixtures containing 5% and 15% exhibit approximately 47% and 151% more shrinkage, respectively, than the control concrete. Several interacting mechanisms explain why RTA increases shrinkage. The particles of RTA have much lower stiffness and strength than BCA (Gigli et al., 2019; Tam et al., 2018; Sofi et al., 2018). Consequently, they act as soft, compliant inclusions within the cementitious matrix. Their flat, highly flexible geometry (Figure 1) allows them to deform readily, functioning almost like miniature springs dispersed throughout the paste. Rather than restraining the contraction of the cement matrix during moisture loss, these particles deform along with it, providing minimal internal resistance (Tam et al., 2018; Sofi et al., 2018). As a result, the paste experiences a higher net shrinkage strain. Additionally, the interface between RTA and the hardened cement paste is weak due to the rubber's hydrophobic, non-polar surface chemistry and the increased porosity at the aggregate boundary (Gigli et al., 2019; Tam et al., 2018; Sofi et al., 2018). This poorly developed interfacial zone does not effectively transfer stresses between the paste and the RTA particles. During drying, as tensile stresses develop within the matrix, the weakly bonded surfaces permit micro-slip and localised deformation, allowing the cement paste to contract more freely than it would in a well-bonded system. As the RTA content increases, these effects become more pronounced, leading to consistently higher shrinkage values across the mixtures.

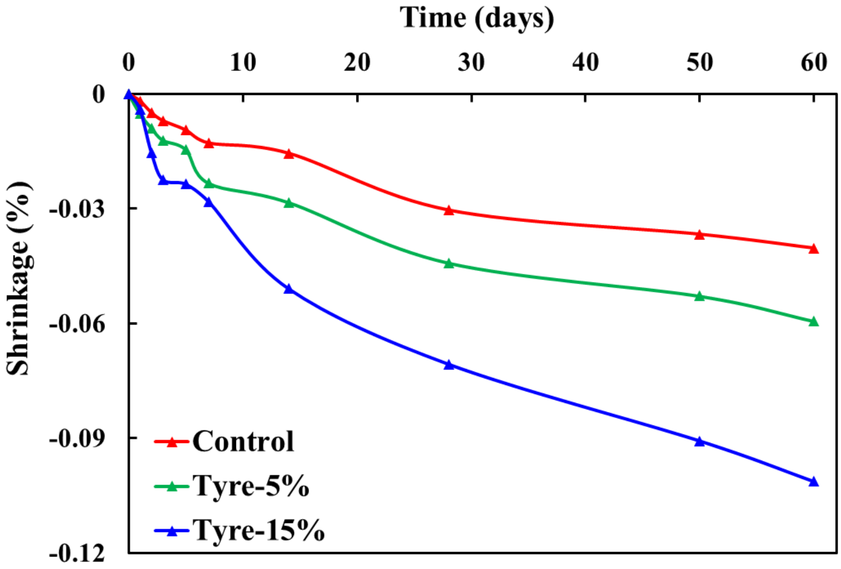


Figure 4: Shrinkage of concrete mixes as a function of time.

The influence of NaOH surface modification of RTA (2 hours and 72 hours) on drying shrinkage was examined over 60 days, as illustrated in Figures 5-7. The measurements indicate that concrete containing chemically treated RTA experiences significantly less shrinkage than concrete made with only water-washed RTA. After 60 days, the mixtures with 2-hour NaOH-treated RTA show approximately 24% and 121% increases in shrinkage at 5% and 15% RTA concrete, respectively, compared to the control mix (100% BCA). In contrast, mixtures containing RTA treated for 72 hours exhibit increases of about 14% and 95% for the concrete mixes with 5% RTA and 15% RTA, respectively. While these values are still higher than those of the control concrete, the shrinkage is considerably lower than that observed with untreated RTA. When compared directly with untreated RTA mixtures, the positive impact of NaOH treatment is more evident. At the 60-day mark, shrinkage is reduced by roughly 16% and 12% for mixtures with 5% and 15% RTA treated for 2 hours. For the 72-hour treatment, the reductions reach around 22% for both replacement levels. These findings confirm that NaOH treatment effectively mitigates the shrinkage-inducing effects of rubber aggregates. The mechanism behind this improvement is related to the chemical action of NaOH on the rubber surface.

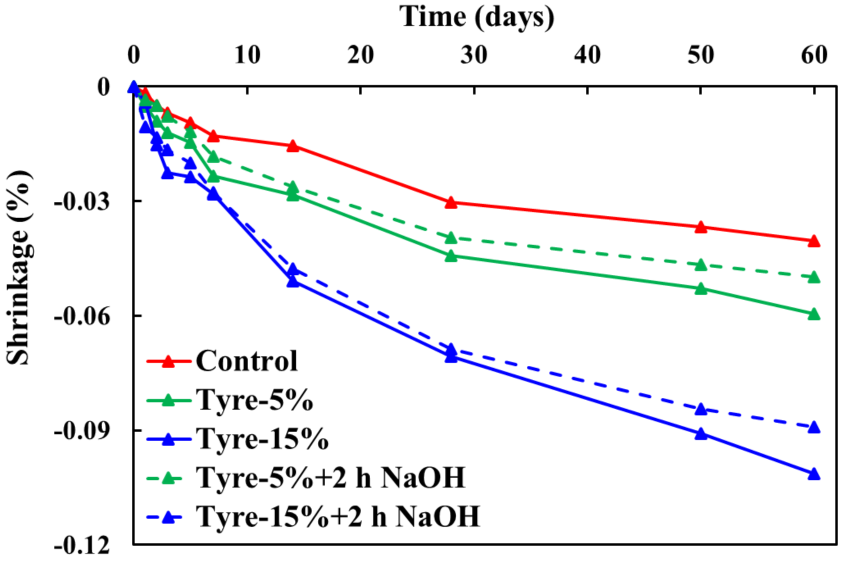


Figure 5: Shrinkage of control and concrete mixes with water-washed and NaOH-treated RTA for 2 h as a function of time.

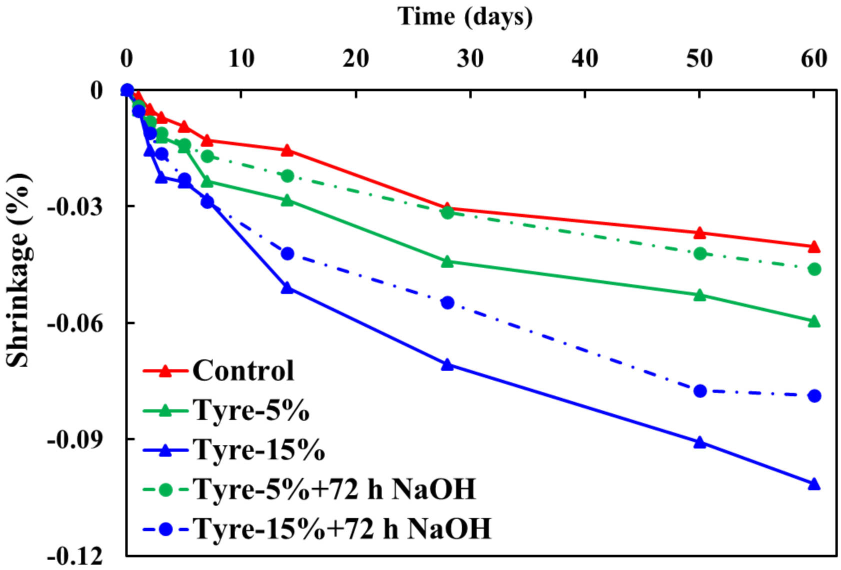


Figure 6: Shrinkage of control and concrete mixes with water-washed and NaOH-treated RTA for 72 h as a function of time.

The alkali treatment partially removes waxy, hydrophobic contaminants and leaches out additives and weak boundary layers from the RTA particles (Kashani et al., 2018; Khern et al., 2020; Su et al., 2015; Rivas Vázquez et al., 2015). This process exposes the underlying polymer chains and creates a microscopically rougher surface texture (Khern et al., 2020; Su et al., 2015; Rivas Vázquez et al., 2015). The increased surface irregularities enhance mechanical interlocking with the cement paste, thereby improving scratch resistance, as the paste can better grip the RTA during relative movement or load transfer. Additionally, NaOH alters the rubber's surface polarity, shifting it from strongly hydrophobic to more hydrophilic (Kashani et al., 2018; Khern et al., 2020). This promotes better wetting during mixing and strengthens the interfacial transition zone (ITZ). The improved ITZ is characterised by reduced porosity, stronger adhesion, and, in some cases, the formation of additional hydrated products from NaOH-induced reactions. This results in greater internal restraint during drying. Consequently, the treated RTA is more effective at limiting paste deformation, resulting in overall smaller shrinkage than the untreated RTA.

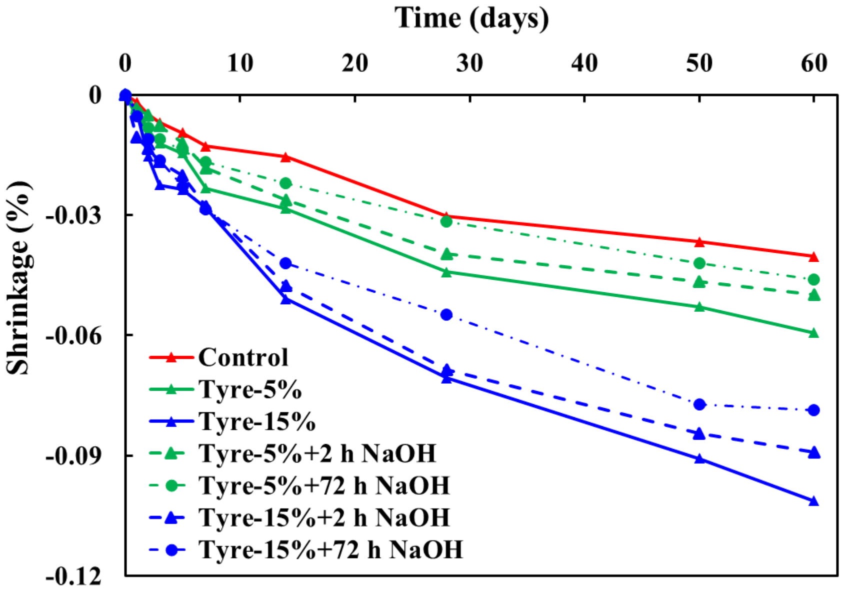


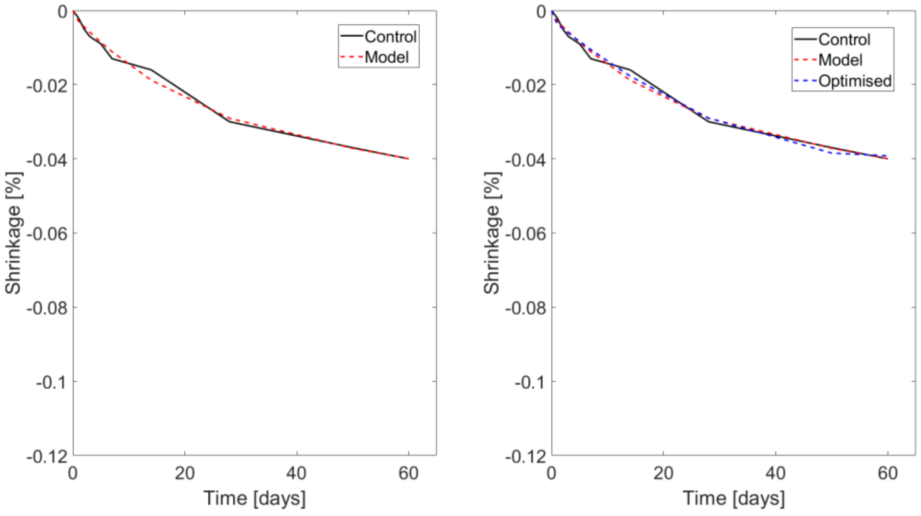
Figure 7: Shrinkage of control and concrete mixes with water-washed and NaOH-treated RTA for 2 h and 72 h as a function of time.

Mixes incorporating RTA treated with NaOH for 72h exhibit a noticeably more substantial reduction in shrinkage than those treated for only 2 h, as shown in Figure 7. When compared directly, the 72h treatment lowers shrinkage by an additional 8% in the 5% RTA mix and 12% in the 15% RTA mix, confirming that longer treatment duration is more effective at mitigating shrinkage. The improved performance of the 72h treatment is linked to more extensive chemical and physical alterations of the rubber surface. With prolonged exposure, NaOH penetrates deeper into the outer polymer layer, dissolving more of the residual oils, processing additives, and hydrophobic films that normally inhibit bonding (Khern et al., 2020; Su et al., 2015; Rivas Vázquez et al., 2015). This extended etching also roughens the surface to a greater degree, creating micro-grooves and pits that increase surface area and promote stronger mechanical interlock with the cementitious matrix. Chemically, the longer treatment increases the number of exposed polar groups on the rubber surface, improving its wettability and allowing the cement paste to spread, adhere, and hydrate more effectively at the interface (Su et al., 2015; Rivas Vázquez et al., 2015). This encourages the formation of a denser, more continuous ITZ, with reduced microporosity and fewer weak planes. In addition, the stronger chemical affinity promotes better stress transfer and reduces microslippage around the aggregate, thereby increasing the stiffness of the surrounding microstructure. Collectively, these effects indicate that the 72 h-treated RTA provides greater internal restraint against volume change in the drying cement paste. As a result, the shrinkage reduction achieved by the 72 h treatment surpasses that of the 2 h treatment and is significantly lower than that of the untreated RTA.

5. DATA-DRIVEN MODEL OUTCOMES AND DISCUSSIONS

Mathematical shrinkage prediction models were developed based on experimentally measured shrinkage data from five concrete mixes: control with 100% BCA, two mixes with water-washed RTA at 5% and 15% replacement of BCA and two other mixes with NaOH treatment for 2 h of RTA at 5% and 15% replacement of BCA. This selection was made under the premise that the shrinkage characteristics of the 72-hour NaOH-treated mixes would follow a similar behavioural pattern, thereby enabling dependable extrapolation of their responses without performing separate simulations. Figure 8 compares experimental and predicted shrinkage profiles of all mixes. The strong correspondence between the experimental results and the predicted values demonstrates the models' effectiveness in accurately replicating the time-dependent shrinkage evolution of the different concrete compositions.

It is important that the developed model effectively replicates the nonlinear shrinkage behaviour of all concrete mixtures, including the control mix, 5% water-washed recycled coarse aggregate (RTA), 15% water-washed RTA, 5% sodium hydroxide-treated RTA for 2 hours, and 15% sodium hydroxide-treated RTA. Notably, it also captured the post-cracking nonlinearity associated with shrinkage-induced microcracking. This phenomenon is inherently complex and difficult to model mathematically because microcrack initiation and propagation occur gradually over time, as the shrinkage increases.



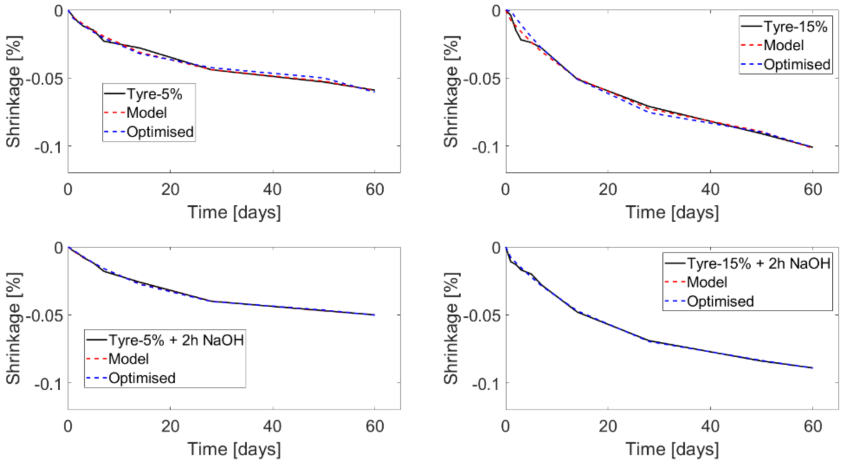


Figure 8: Model performances and optimised results comparison under different tyre percentages with and without NaOH.

The close alignment between the predicted and experimental shrinkage profiles confirms the model's robustness and accuracy in simulating this intricate time-dependent deformation. To assess the predictive framework's accuracy, statistical validation was conducted using the coefficient of determination (R^2). This coefficient represents the degree of agreement between the predicted and observed shrinkage values. The calculated R^2 values were as follows: 0.9922 for the control mix, 0.9931 for 5% water-washed RTA, 0.9938 for 15% water-washed RTA, 0.9982 for 5% NaOH-treated RTA (2 hours), and 0.9977 for 15% NaOH-treated RTA (2 hours). The consistently high R^2 values across all mixes confirm the reliability and predictive accuracy of the models, demonstrating that the time-dependent evolution of shrinkage can be effectively captured using the proposed data-driven approach. An optimisation procedure was employed to refine the initial regression models and minimise residual errors between the predicted and experimental shrinkage data. However, as shown in Figure 8, the improvements after optimisation were marginal, as the baseline models already demonstrated strong agreement with the measured profiles. This finding aligns with established modelling theory, which suggests that further optimisation yields diminishing returns once a model’s accuracy surpasses a very high threshold ($R^2 > 0.99$). Therefore, the baseline models were deemed sufficient for subsequent analyses, achieving a balance between computational efficiency, predictive reliability, and interpretability.

The strong agreement between experimental and predicted shrinkage profiles confirms the robustness of the developed mathematical framework, which can accurately forecast the long-term volumetric stability of rubberised concrete. Beyond replicating experimental data, these models can estimate key shrinkage-related parameters, including drying rate constants, equilibrium strain values, and the shrinkage-mitigation efficiency of surface treatments. Furthermore, incorporating these validated relationships into numerical simulations allows engineers to anticipate time-dependent deformations in structural elements without extensive laboratory testing. This integration of experimental validation with computational prediction promotes a more sustainable, cost-effective, and data-driven approach to designing advanced cementitious materials that incorporate recycled waste components, such as tyre aggregates.

6. CONCLUSIONS

This study investigated the drying shrinkage behaviour of concrete incorporating recycled tyre aggregate (RTA) as a partial replacement for brick coarse aggregate (BCA). It also examined the effects of NaOH surface treatment. Shrinkage was monitored for 60 days, comparing mixes with untreated RTA and RTA treated with NaOH for 2 hours and 72 hours at 5% and 15% replacement levels. The experimental results indicated that untreated RTA exhibits greater shrinkage than conventional BCA concrete. After 60 days, concretes containing 5% and 15% untreated RTA exhibited approximately 47%

and 151% higher shrinkage, respectively. This behaviour is attributed to the low stiffness and high flexibility of RTA, which easily deforms and provides minimal internal restraint. Additionally, the hydrophobic surfaces of RTA weaken the interfacial transition zone (ITZ), allowing for micro-slip during drying. NaOH treatment significantly mitigated these shrinkage effects. The 2-hour treatment reduced shrinkage by 12–16%, whereas the 72-hour treatment lowered it by about 22% for both replacement levels compared to the water-washed RTA. Compared with the 2 h treatment, the 72 h treatment lowers shrinkage by an additional 8% in the 5% RTA mix and 12% in the 15% RTA mix. This reveals that the prolonged exposure to NaOH increases surface roughness, removes hydrophobic contaminants, and exposes polar functional groups. This improves adhesion, mechanical interlock, and ITZ density, creating a stiffer microstructure around the RTA particles. Consequently, this provides greater internal restraint and more effectively limits volumetric contraction than shorter treatments or untreated aggregates. The mathematical, data-driven model was developed to predict shrinkage for the control, untreated, and 2-hour-treated RTA mixes. The model closely matched the experimental results ($R^2 > 0.992$), accurately capturing nonlinear trends and microcracking effects. Its performance also enabled reliable extrapolation to the 72-hour treated mixes, demonstrating its robustness and practical applicability for forecasting time-dependent shrinkage without extensive laboratory testing. Additionally, the optimised model more accurately predicted the entire shrinkage profiles of the concrete mixes measured experimentally. In summary, incorporating RTA increases shrinkage due to particles' compliance and weak bonding. However, NaOH treatment—especially when applied for more extended periods—significantly reduces this shrinkage effect. The combination of experimental data and predictive modelling offers a reliable framework for understanding and controlling shrinkage in rubberised concrete, supporting the sustainable use of tyre waste while maintaining structural performance. However, this study is limited to two NaOH treatment durations, two RTA replacement levels, and shrinkage measured up to 60 days under laboratory conditions. To draw firm conclusions, further study could extend to higher RTA percentages, richer mixes with higher cement content, longer shrinkage measurements (e.g., 120 days or more), and other chemical treatments, such as calcium hypochlorite [$Ca(ClO)_2$] and bleaching powder, at different treatment durations.

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DECLARATION OF USE OF AI

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript. Grammarly software was used solely to improve language style, grammar, and clarity. The software did not contribute to the study design, data analysis, interpretation of results, or generation of scientific content.

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