Proceedings of the 8th International Conference on Civil Engineering for Sustainable Development (ICCESD 2026), 5~7 February 2026, KUET, Khulna, Bangladesh

AXIAL COMPRESSIVE STRESS-STRAIN BEHAVIOUR OF SUSTAINABLE CONCRETE MADE WITH CHEMICALLY TREATED RECYCLED TYRE AGGREGATE: EXPERIMENTAL INVESTIGATION, NUMERICAL MODELLING, AND OPTIMISATION

Md Jihad Miah[1*], Mohammad Shamim Miah[2], Md. Munir Hossain Patoary[3], Md Kawsar Ali[4]

[1] *Lecturer, Civil Engineering, School of Architecture, Technology and Engineering, University of Brighton, Lewes Road, Brighton BN2 4GJ, England, UK, e-mail: M.J.Miah@brighton.ac.uk*
[2] *Senior Researchers, Institute of Engineering Geodesy and Measurement Systems, Graz University of Technology, 8010 Graz, Austria, e-mail: miah@tugraz.at*
[3] *PhD Student, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh, e-mail: 3dcometdesign@gmail.com; 0422044016@ce.buet.ac.bd*
[4] *Materials Engineer, Abdul Monem Limited, Dhaka-1205, Bangladesh, e-mail: kawsar.uap@gmail.com*

***Corresponding Author**

ABSTRACT

Rapid urbanisation increases aggregate demand, depleting natural resources and harming ecosystems. In contrast, waste tyres pollute and contribute to landfill overcrowding, as they persist as non-biodegradable waste. Recycling them into construction materials provides a sustainable solution. Studies show that untreated recycled tyre aggregate (RTA) weakens the bonding with cement paste, while surface treatment can improve performance, a detail not well understood in the literature. Furthermore, data-driven mathematical modelling of stress-strain relationships has not been extensively covered in the literature. To address these issues, this study examines the performance of concrete mixes incorporating RTA as a 5% or 15% replacement for brick aggregate. Seven mixes were created: the control mix without RTA, and the other four mixes with RTA were fabricated as follows: 2 mixes with water-washed RTA at 5% and 15%, while the other four mixes were fabricated with 5% and 15% RTA treated with NaOH for 2 hours and for 72 hours, respectively. The stress-strain behaviour and strength of the mixes were assessed at 28 days. Data-driven mathematical models were developed, and those models were optimised to obtain better relationships. The slope of the stress-strain curves (i.e., modulus of elasticity) decreased with an increase in the content of RTA compared to the control mix (0% RTA). However, an improvement in the stress-strain behaviour was observed for RTA treated with NaOH for both 2 hours and 72 hours, with the 72-hour treatment yielding superior results. Similarly, the compressive strength decreased as the RTA content increased, showing reductions of 21% for 5% and 39% for 15% RTA compared to the control mix. However, the introduction of NaOH-treated RTA improved compressive strength, with decreases of only 18% for the 2-hour treatment and 16% for the 72-hour treatment compared to the control mix. Compared with water-washed RTA, the strength of RTA treated with NaOH increased by 1.5-3.5% after 2 hours of treatment and by 6.5-8.5% after 72 hours for concrete containing 5% and 15% RTA, respectively. The developed mathematical models closely matched the experimental stress-strain profiles, including the more nonlinear regions. The models' accuracy was outstanding, with R^2 values ranging from 0.9957 to 0.9992 across all mixes. The optimised model provided excellent predictive performance across all stages, matching the experimental results.

Keywords: *Recycled tyre aggregate, chemical treatment, stress-strain behaviour, sustainability, data-driven model*

1. INTRODUCTION

Concrete is a fundamental material in modern construction, known for its high strength, resilience, and versatility. It is made from a mixture of cement, water, and aggregates of various sizes, with the coarse aggregates forming the structural backbone of the mix (Domone & Illston, 2010; Mehta & Monteiro, 2006). This component not only provides dimensional stability but also influences many mechanical properties of the material, including stiffness, strength, and durability. Coarse aggregates typically account for 60 to 80 per cent of the total volume of concrete, making their characteristics essential for the performance and sustainability of the final product (Mehta and Monteiro, 2006; Miah et al., 2020). However, conventional sources of coarse aggregates have become increasingly problematic from both environmental and economic perspectives. Natural aggregates, such as crushed rock, gravel, and stone, are finite resources, and their continuous extraction through quarrying and excavation has significant ecological consequences (Shafigh et al., 2014; Mehta & Monteiro, 2006; Miah et al., 2022). These operations can damage landscapes, disrupt habitats, and emit large quantities of carbon dioxide during extraction, processing, and transportation. In some regions, crushed brick aggregates are used as an alternative to stone, but the firing of clay to manufacture bricks requires high temperatures, consumes substantial fuel, and further contributes to greenhouse gas emissions (Debieb & Kenai, 2008; Cachim, 2009; Miah et al., 2022). These issues highlight the urgent need to identify substitute materials that can fulfil similar roles while minimising environmental degradation.

One promising alternative is the reuse of waste materials, particularly those that are difficult to dispose of (Batayneh, 2007; Miah et al., 2025a). Discarded vehicle tyres are a major global concern, as millions of tyres reach the end of their useful life each year and pose a serious challenge due to their non-biodegradability. Stockpiled tyres occupy large areas of land, create fire hazards, and release significant pollutants and carbon dioxide when incinerated. Repurposing waste tyres as a substitute for conventional coarse aggregates in concrete offers a dual benefit: it reduces the environmental burden of tyre disposal while conserving natural resources (Khern et al., 2020; Sofi, A. 2018; Aslani, F. 2016; Khaloo et al., 2008). Incorporating shredded or processed tyre particles into concrete can decrease landfill accumulation, lower embodied carbon, reduce the need for quarrying, and promote circular-economy practices. Additionally, this approach can lower overall material costs, making it an economically attractive option for sustainable construction (Khern et al., 2020; Sofi, A. 2018; Aslani, F. 2016; Khaloo et al., 2008).

The literature has explored the partial replacement of natural or brick aggregates with tyre-derived materials, primarily through experimental testing. These studies have shown that rubber inclusion affects concrete’s workability, density, and mechanical strength, with varying effects depending on the level of replacement. However, limited attention has been paid to enhancing the bond between tyre aggregates and the cementitious matrix. Because rubber surfaces are generally smooth and hydrophobic, poor interfacial adhesion often leads to reduced mechanical performance (Khern et al., 2020; Sofi, A., 2018). Surface modification or chemical treatment of tyre particles may improve bonding with the surrounding mortar, thereby enhancing strength and stiffness (Khern et al., 2020; Aslani, F. 2016; Khaloo et al., 2008). Nonetheless, the available literature on this specific aspect remains limited, leaving room for further exploration. Moreover, most investigations have relied heavily on experimental observations, with comparatively little emphasis on predictive or data-driven approaches. Developing mathematical or computational models that can forecast the behaviour of rubberised concrete would significantly reduce the need for extensive laboratory testing. Advanced analytical tools, such as finite element simulations and machine learning models, can capture complex material interactions, optimise mix designs, and efficiently predict structural responses (Miah et al., 2025a, 2025b, 2025c). These techniques not only save time and costs but also contribute to the broader goal of sustainable material development through data-supported design.

The present study investigates the stress-strain characteristics of concrete in which recycled tyre aggregate (RTA) replaces 5% and 15% of traditional brick coarse aggregates. Seven mixes were created; the control mix without RTA, two mixes with water-washed RTA at 5% and 15% RTA, while the other four mixes were fabricated with 5% and 15% RTA treated with NaOH for 2 hours and 72 hours, respectively. Their impact on mechanical performance was examined. A data-driven mathematical model has been developed to simulate the experimental stress-strain response of these concrete mixtures, with optimisation applied to improve predictive accuracy. By integrating experimental evidence with computational modelling, this research aims to advance sustainable construction practices, demonstrating how end-of-life tyre waste can be transformed into a valuable structural material that minimises environmental impact and supports a circular, resource-efficient economy.

2. METHODOLOGY

This study investigated the mechanical behaviour of concrete incorporating recycled tyre aggregate (RTA) as a partial substitute for brick coarse aggregate, as shown in Figure 1. The control mix utilised locally sourced brick aggregate with a specific gravity of 2.02, a saturated surface-dry (SSD) unit weight of 1065 kg/m³, a fineness modulus of 7.43, and an absorption capacity of 20%. To ensure consistency across all mixtures, the maximum particle size was limited to 20 mm. River sand, screened through a 4.75 mm sieve, was used as the fine aggregate and demonstrated a fineness modulus of 3.12 and a specific gravity of 2.66. Both aggregates met the grading and quality requirements for structural concrete, as illustrated in Figure 2. Discarded vehicle tyres were sourced from a local disposal site and manually cut into medium-sized fragments suitable for use as coarse aggregate, as shown in Figure 1. Before use, the tyre particles were thoroughly washed with water to remove contaminants such as dust, oil, and surface residues. The specific gravity, SSD unit weight, fineness modulus, and absorption capacity of RTA are 1.13, 600 kg/m³, 7.43, and 3.63, respectively. To improve bonding with the cement matrix, portions of the RTA were immersed in a sodium hydroxide (NaOH) solution for surface modification, with two immersion durations being considered: 2 hours and 72 hours. The treated aggregates were rinsed with clean water to remove any remaining alkali, then air-dried before mixing.

River sand Brick aggeragte Recycled tyre aggregate

Figure 1: Images of river sand, brick aggregate and RTA aggregate.

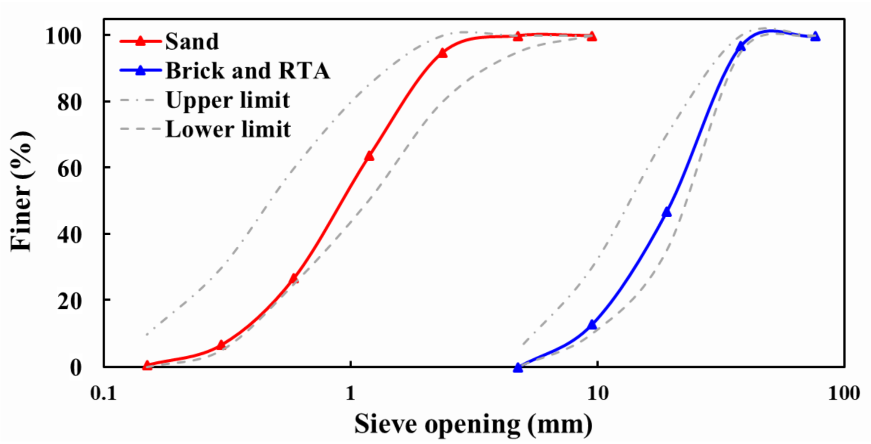


Figure 2: Grain size distribution of river sand, brick and RTA.

The RTA particles were designed to have a similar grading distribution of brick aggeragte in order to eliminate the grading effects on the uniaxial compressive strength of concrete mixes, as shown in Figure 2. All concrete mixes were prepared using a constant water-to-cement ratio (w/c) of 0.55. The control batch consisted solely of brick aggregate, while two other mixes contained 5% and 15% washed RTA by volume. Additionally, four mixes contained 5% and 15% RTA by volume treated with NaOH for either 2 hours or 72 hours. The treatment periods of 2 h and 72 h were chosen based on the findings of Khern et al. (2020). The cement content was kept constant at 350 kg/m³ across all mixtures, and mixing was performed using a laboratory drum mixer to ensure uniform distribution of the rubber particles. Table 1 summarises the detailed mix proportions of all concretes. The ingredient quantities for tyre mixes subjected to 2 h and 72 h NaOH treatment are the same as those used in the untreated mixes.

Table 1. Concrete mix proportions for all mixtures (kg/m^3)

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

Cylindrical specimens measuring 100 mm in diameter and 200 mm in height were cast for each concrete mix. After 24 hours of casting, the specimens were demolded and submerged in water at 27 ± 2 °C for curing. Tests were conducted after 28 days to determine compressive strength and stress-strain characteristics. Three samples were tested for each mix. Axial deformations were recorded using a strain measurement system with a 100 mm gauge length, employing two dial gauges mounted opposite each other at the midsection of the specimen. The collected data were used to develop the stress-strain profiles and to assess the influence of RTA content and NaOH surface treatment on the mechanical response, stiffness, and ductility of the concrete.

3. STRESS-STRAIN BEHAVIOUR MODELLING AND OPTIMISATION

The stress-strain behaviour exhibits a fundamental property of any material, including concrete. Often, the aforementioned behaviour exhibits complex nonlinear phenomena; as a result, it is not straightforward to model such characteristics. Moreover, there are not many models available that can be utilised to render all types of material behaviour. This gap has motivated the development of a model that can capture the stress-train behaviour of experimentally measured data. As a single linear model is not capable of capturing the complex behaviour of stress-strain, a 4th-order polynomial regression has been utilised for its usefulness and robust performance (Fan, 1996; Miah et al., 2018). The studied problem can be written as,

$$\sigma = [\tau_1 \quad \tau_2 \quad \tau_3 \quad \tau_4 \quad \tau_5] \begin{Bmatrix} \epsilon^4 \\ \epsilon^3 \\ \epsilon^2 \\ \epsilon^1 \\ 1 \end{Bmatrix} \tag{1}$$

where the stress is given by σ, the strain is shown by ϵ, while $\tau_1, \tau_2, \tau_3, \tau_4$ and τ_5 are the model's parameters. Using the model parameters, it can be rewritten as,

$$\sigma = -564661762324.25\epsilon^4 + 5022011650.38\epsilon^3 - 16381915.05\epsilon^2 + 27800.06\epsilon^1 + 1.17 \tag{2}$$

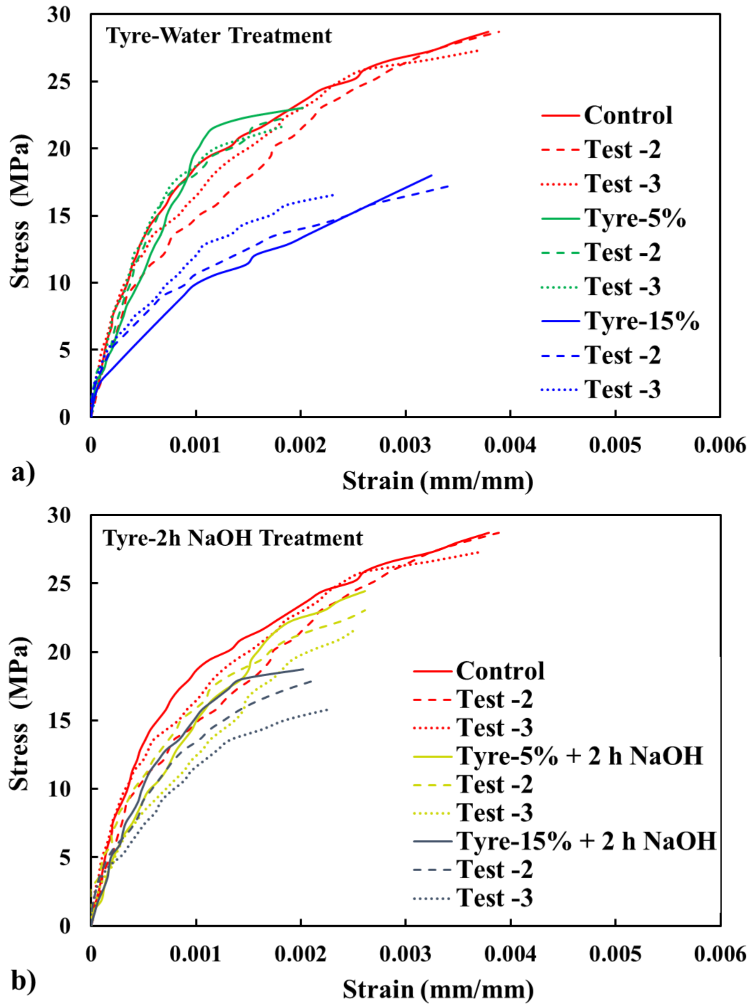
When the model's output does not meet expectations, tuning its parameters is often necessary to improve performance. Model parameters can be tuned manually (which might be time-consuming) or semi-automatically using optimisation algorithms. To achieve this end, a heuristic-type optimisation algorithm is used to enhance the output of the studied problem (Lagarias et al., 1998; Miah et al., 2018; Miah, 2020). The optimisation is done by minimising the error of the model, which is achieved by minimising the objective function (U).

$$U = \left[\sum_{i=1}^{N} \frac{\left| f_{exp}^{stress} - f_{model}^{stress} \right|^2}{\left| f_{exp}^{stress} \right|^2} \right]^{\frac{1}{2}} \tag{3}$$

where the experimental data is given by f_{exp}^{stress}, is the outcome of the model is f_{model}^{stress}. The designers define the above function; hence, there is no specific guideline on what to minimise or how to minimise it. Therefore, optimisation requires some prior knowledge and understanding of how to define the problem and initialise the simulation (Miah, 2020).

4. EXPERIMENTAL OUTCOMES AND DISCUSSIONS

The compressive stress-strain behaviour of all concrete mixes, as illustrated in Figure 3, begins with a distinct linear elastic phase. The slope of this phase corresponds to the material's elastic modulus and reflects its resistance to deformation under load. Concrete mixes containing recycled tyre aggregate (RTA) exhibited a noticeably gentler slope in this initial linear region compared to the control mix, indicating reduced stiffness during the early elastic response. This effect was more pronounced at higher RTA replacement levels. The reduction in elastic modulus is due to the softer, more compliant nature of the tyre particles, which alters the concrete's internal microstructure and reduces its overall load-bearing efficiency (Khern et al., 2020; Sofi, A. 2018; Aslani, F. 2016; Khaloo et al., 2008). Additionally, the presence of tyre aggregates weakens the interfacial transition zones (ITZs), introducing localised compliance that promotes early microcrack formation (Khern et al., 2020; Khaloo et al., 2008).



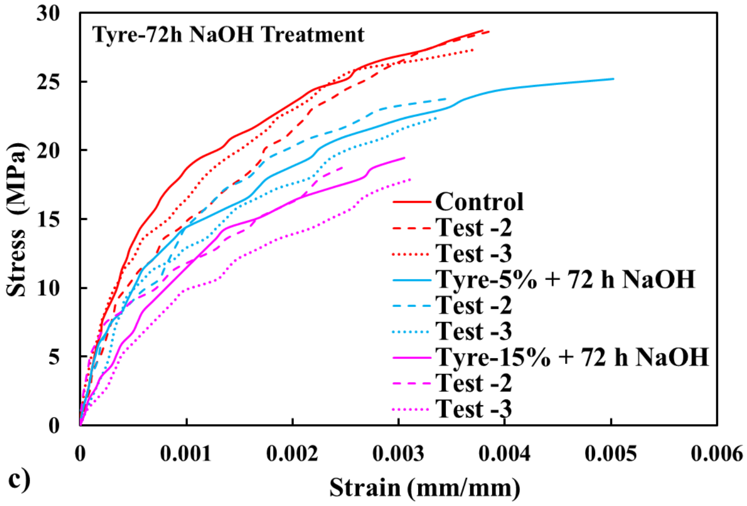


Figure 3: Stress-strain profile of concrete mixes: (a) Tyre-water treatment, (b) Tyre-2h NaOH treatment, and (c) Tyre-72h NaOH treatment.

While the RTA mixes initially displayed a primarily linear response, nonlinear behaviour gradually developed as microcracks propagated, particularly near the interfaces between the particles and the matrix. After reaching peak stress, these mixes exhibited noticeable post-peak strain softening, reflecting energy dissipation through progressive cracking and limited mechanical interlocking at the ITZs surrounding the rubber inclusions. In contrast, the control concrete exhibited a steeper initial slope, indicating higher early-age stiffness and a longer linear-elastic range before nonlinear deformation began. This difference highlights the impact of flexible tyre particles, which reduce load transfer efficiency and increase deformability during the elastic phase (Khern et al., 2020; Sofi, A., 2018).

However, the inclusion of chemically treated RTA significantly improved mechanical performance, as reported in Figures 3-4. Sodium hydroxide (NaOH) treatment modifies the tyre surface both chemically and physically, resulting in a rougher texture that enhances mechanical interlocking with the cement matrix. The alkali solution removes surface contaminants and partially etches the rubber, increasing surface area and friction at the ITZ (Khern et al., 2020; Kashani et al., 2018; Su et al., 2015; Rivas-Vázquez et al., 2015). These changes strengthen the particle-matrix interface, facilitating more efficient load transfer, increasing the elastic modulus, and reducing early-stage compliance. Consequently, concrete made with treated RTA exhibits higher stiffness, improved post-peak ductility, and greater energy absorption than concrete made with untreated tyre particles. It is noted that post-peak ductility and greater energy absorption capacity were not examined or analysed, which is a limitation of this work, as it was primarily based on the stress-strain profiles of the concrete mixes.

Overall, RTA-containing mixes display a characteristic stress-strain profile: lower initial stiffness, extended nonlinear deformation, and gradual post-peak softening. These features reflect the combined effects of microcrack initiation around the tyre particles, ITZ compliance, and the energy-absorbing nature of the rubber inclusions (Sofi, A. 2018; Aslani, F. 2016; Khaloo et al., 2008). It is noted that scanning electron microscopy (SEM) analysis was not performed, which is a limitation of this study and is mainly based on literature findings. In comparison, the control concrete demonstrates higher early-age stiffness, a steeper initial slope, and a more brittle post-peak response. NaOH treatment of RTA effectively mitigates these limitations by roughening the surface and removing contaminants, thereby enhancing interfacial bonding and producing more balanced mechanical behaviour (Kashani et al., 2018; Su et al., 2015; Rivas-Vázquez et al., 2015). These findings highlight the potential of recycled tyre aggregates as a sustainable replacement for conventional coarse aggregates. Untreated RTA tends to reduce early-age stiffness and provides limited bonding. At the same time, NaOH-treated RTA strengthens the particle-matrix interface, increases elastic modulus, improves post-peak ductility, and enhances energy absorption, resulting in concrete with more reliable and resilient structural performance.

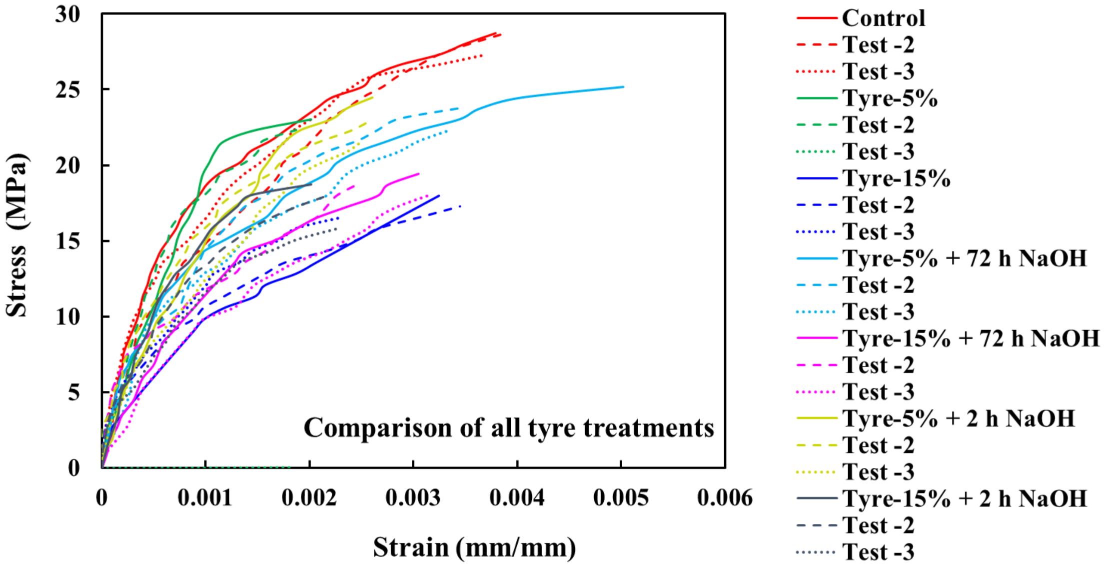


Figure 4: Comparison of the stress-strain profile of all concrete mixes: (a) Tyre-water treatment, (b) Tyre-2h NaOH treatment, and (c) Tyre-72h NaOH treatment.

The results of the compressive strength tests demonstrated a significant impact of RTA content and surface treatment on the mechanical performance of concrete, as reported in Figure 5. Compared to the control mix containing no RTA, both 5% and 15% RTA replacements showed lower compressive strength, with the reduction more pronounced at 15%, resulting in 21% and 39% reductions for 5% and 15% RTA, respectively, compared to the control mix. This suggests that a higher proportion of tyre aggregate further weakens the load-bearing capacity of the mix. The decrease in strength can be attributed to the soft, flexible nature of rubber particles, which tend to deform under load, creating weak ITZs with the surrounding cement matrix (Khern et al., 2020; Sofi, A. 2018; Aslani, F. 2016; Khaloo et al., 2008). Additionally, the smooth and hydrophobic surface of untreated tyre aggregates impairs adhesion, leading to poor stress transfer and early crack initiation under compression (Khern et al., 2020; Khaloo et al., 2008).

In contrast, when the RTA was treated with sodium hydroxide (NaOH), a significant improvement in compressive strength was observed. The concrete containing 5% and 15% NaOH-treated RTA exhibited higher strength than the corresponding untreated mixes, with the greatest improvements observed in aggregates treated for longer durations (72 hours rather than 2 hours). The compressive strength decreased by 18% for the 2-hour NaOH treatment and 16% for the 72-hour treatment relative to the control mix. Compared with concrete containing water-washed RTA, NaOH-treated aggregates led to an increase in strength of approximately 1.5–3.5% after 2 hours of treatment and 6.5–8.5% after 72 hours for mixes with 5% and 15% RTA, respectively. This enhancement is due to the chemical and physical changes enacted by the NaOH treatment. The alkali solution partially dissolves the outer polymeric layer of the rubber, removes surface contaminants, and creates a rough, micro-textured surface (Khern et al., 2020; Kashani et al., 2018; Su et al., 2015; Rivas-Vázquez et al., 2015). This increased roughness enhances the effective contact area between the aggregate and the cement paste, promoting mechanical interlocking. Additionally, improved surface energy increases wettability and bond strength at the ITZ, thereby improving load transfer and delaying crack propagation (Kashani et al., 2018; Su et al., 2015; Rivas-Vázquez et al., 2015). Overall, the improvement in compressive strength resulting from NaOH treatment illustrates that chemical surface modification can effectively counteract the inherent drawbacks of RTA in concrete. While untreated RTA diminishes stiffness and strength due to poor bonding, treated RTA enhances particle-matrix adhesion, resulting in a denser microstructure and a more efficient stress distribution under load. Consequently, NaOH treatment allows for a higher content of tyre aggregate to be incorporated without a significant loss of compressive strength, highlighting the potential of treated RTA as a viable and sustainable substitute for conventional coarse aggregates in structural concrete.

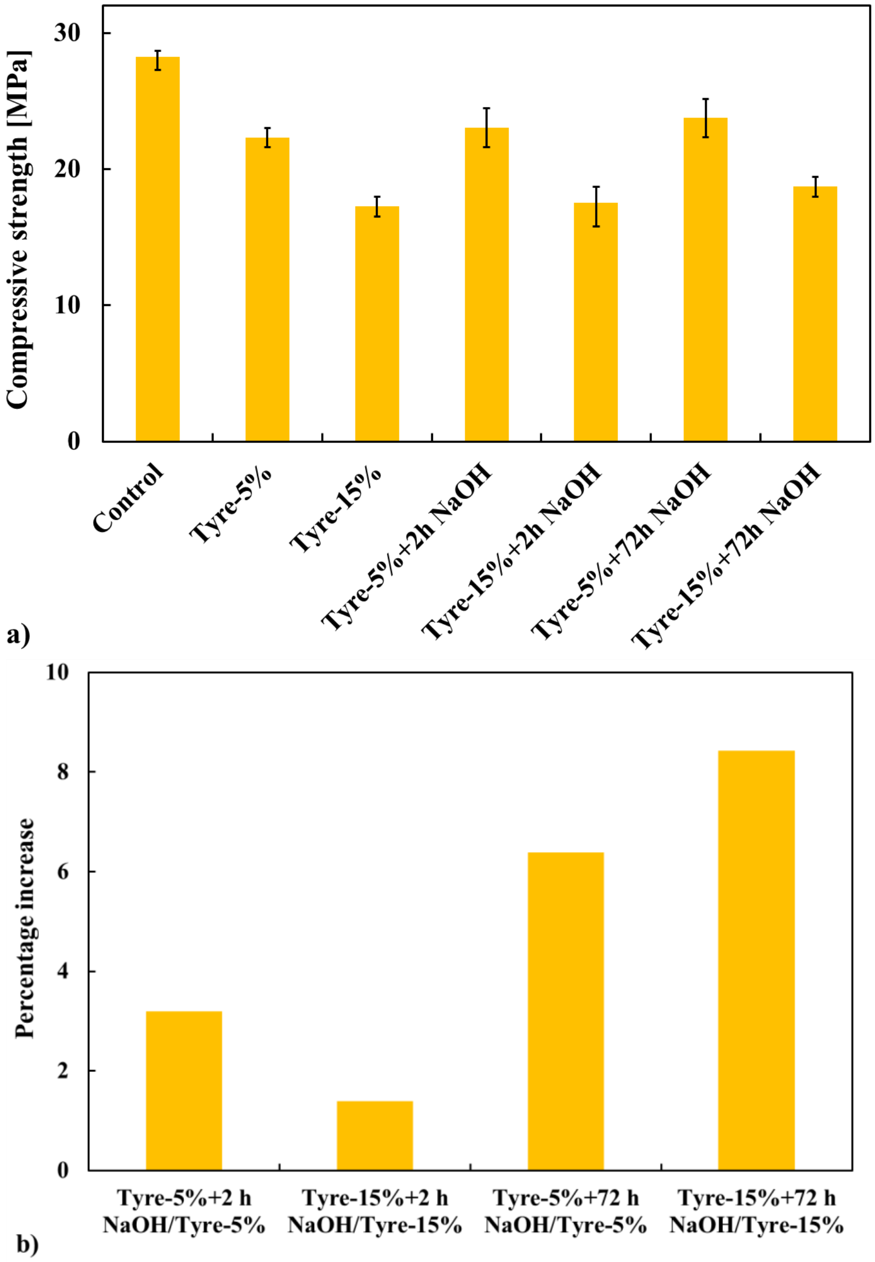


Figure 5: Compressive strength of concrete mixes.

5. DATA-DRIVEN MODEL OUTCOMES AND DISCUSSIONS

Mathematical models were developed using the experimentally obtained stress–strain data for each concrete mixture. These models were created through data-driven regression analysis to capture the nonlinear mechanical behaviour of concrete under compression. The predictive framework was calibrated using the experimental datasets and then validated against the measured stress–strain responses. To ensure computational efficiency and reduce overall simulation time, only five concrete mixtures were selected for modelling: the control mix and mixes containing 5% and 15% RTA washed with water, as well as mixes containing 5% and 15% RTA treated with NaOH for 2 hours. This selection was based on the assumption that the mechanical response of mixes treated for 72 hours would exhibit a comparable trend, allowing for reliable predictions of their behaviour without the need for additional simulations. Figure 6 provides a comparative illustration of the predicted and experimental curves for the control (without RTA), 5% RTA, and 15% RTA, washed in water and treated with NaOH for 2 hours. The close correspondence between the two sets of results confirms that the proposed models successfully replicate the entire loading response—from the initial linear elastic region to the post-peak softening phase that follows extensive cracking.

The nonlinear segment of the stress–strain curve marks a critical stage in concrete deformation, indicating the initiation and propagation of microcracks and the subsequent reduction in material stiffness. This progressive damage reduces the modulus of elasticity; however, it also enhances the material's ability to undergo controlled deformation, providing greater ductility and energy absorption. Such behaviour is desirable in structural systems because it delays catastrophic brittle failure, allowing for the redistribution of internal stresses and improving overall safety margins. The developed models effectively capture this transition, demonstrating their capability to simulate the material's post-elastic response with high fidelity.

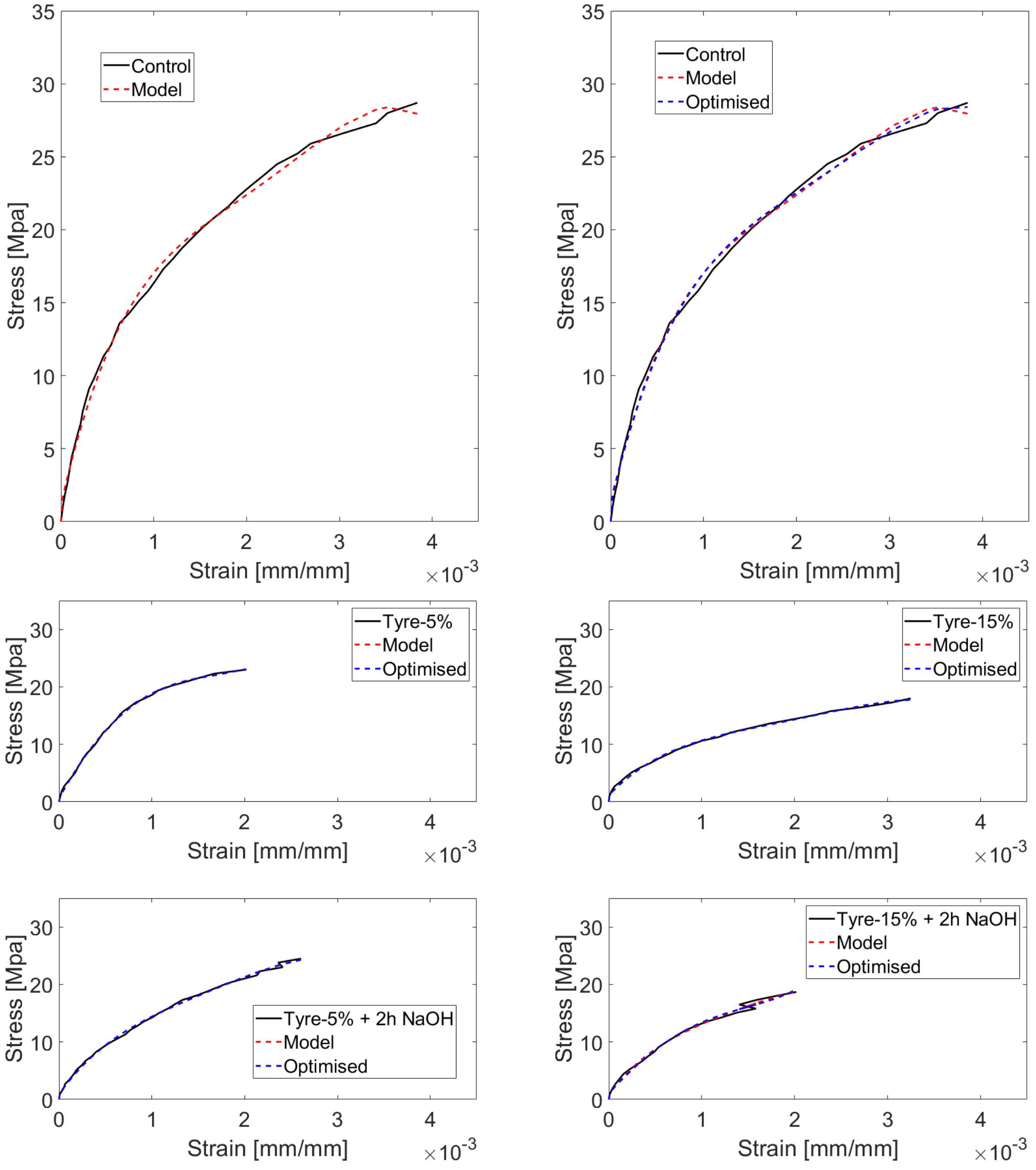


Figure 6: Comparison of models' performances and optimised results under different tyre percentages with and without NaOH treatment.

The statistical reliability of the models was evaluated using the coefficient of determination (R^2), which quantifies the degree of agreement between the predicted and observed data. The R^2 values obtained were 0.9968 for the control mix, 0.9992 for the 5% RTA washed in water, 0.9979 for the 15% RTA washed in water, 0.9986 for the 5% RTA treated with NaOH for 2 hours, and 0.9957 for the 15% RTA treated with NaOH for 2 hours. These consistently high coefficients confirm that the models possess strong predictive accuracy, effectively replicating the experimental results across all curing ages and mix variations.

To enhance the model's predictive performance, an optimisation process was conducted, resulting in a refined version designated as "Optimised," as illustrated in Figure 6. The figure shows that optimisation yielded only marginal gains, as the initial (baseline) model already demonstrated high accuracy. This observation aligns with previously reported trends suggesting that optimisation procedures yield notable benefits primarily when the initial model deviates significantly from the experimental behaviour. In this analysis, the strong correlation between predicted and measured results (R^2 values exceeding 0.99) indicated that further refinement was unnecessary for the stress-strain behaviour of the concrete mixes. Pursuing additional optimisation would have increased computational demands and modelling complexity, extending the processing time without yielding substantial improvements. Therefore, the baseline models were adopted for subsequent analyses, offering an appropriate balance between computational efficiency and predictive reliability in assessing the stress-strain behaviour of concrete mixes.

The reliability and precision of the developed mathematical representations indicate that they can serve as powerful tools for practical and analytical applications in structural engineering. Beyond simply replicating experimental curves, these models can be utilised to estimate key performance parameters such as modulus of elasticity, peak stress, strain capacity, and energy absorption potential. Furthermore, by embedding the constitutive relationships derived from these models into finite element simulations, engineers can predict the behaviour of structural components under various loading conditions without needing extensive physical testing. This integration of validated computational modelling into the design process can substantially reduce costs, time, and material consumption while ensuring accurate performance evaluation. Additionally, these models can aid in optimising concrete mix proportions that incorporate industrial by-products, such as waste tyre, rice husk ash, fly ash, silica fume, and slag, thereby contributing to more sustainable and resource-efficient construction practices.

6. CONCLUSIONS

Concrete mixes were prepared using recycled tyre aggregate (RTA) as a partial replacement for coarse brick aggregate. The RTA underwent two treatments: either water-washing or treatment with sodium hydroxide (NaOH) for 2 or 72 hours to improve surface bonding. Cylindrical specimens were cast, cured, and tested to evaluate their compressive strength and stress-strain behaviour. The data obtained from these tests were used to develop the data-driven models, which were then optimised to tune the outcomes. This study confirms that RTA can serve as an eco-friendly partial substitute for traditional brick coarse aggregate in concrete. Concrete containing untreated RTA exhibits lower initial stiffness and reduced compressive strength, due to the rubber particles' soft, deformable nature and limited bonding with the cement paste. The compressive strength declined with increasing RTA content, with reductions of 21% and 39% at 5% and 15% replacement levels, respectively, relative to the control mix. However, surface modification of RTA using sodium hydroxide (NaOH) significantly enhances its performance. Incorporating NaOH-treated RTA increased compressive strength, resulting in smaller reductions of 18% for the 2-hour treatment and 16% for the 72-hour treatment compared to the control mix. Compared with concrete with water-washed RTA, NaOH-treated aggregates led to strength gains of approximately 1.5–3.5% after 2 hours of treatment and 6.5–8.5% after 72 hours for mixes containing 5% and 15% RTA, respectively. This treatment creates a rougher texture, removes surface impurities, and improves interfacial adhesion with the cement matrix. As a result, concrete with NaOH-treated RTA demonstrates a higher elastic modulus, improved post-peak ductility, and increased energy absorption when compared to mixtures with untreated aggregates. These benefits become more pronounced with longer treatment times. The stress-strain response of all mixes features a distinct linear elastic phase, followed by progressive nonlinear deformation and gradual post-peak softening. Notably, NaOH treatment reduces early-stage compliance and facilitates more effective load transfer. Data-driven models derived from experimental results closely replicate the full stress-strain behaviour and exhibit strong predictive accuracy. The models' accuracy was outstanding, with R^2 values ranging from 0.9957 to 0.9992 across all mixes. Furthermore, additional optimisation only provides marginal gains, confirming the robustness and efficiency of the baseline models. Overall, the results illustrate that NaOH-treated RTA can produce concrete with well-balanced mechanical properties, combining sustainability with enhanced toughness, ductility, and energy absorption. This makes it a promising option for structural applications and supports circular economy strategies.

ACKNOWLEDGEMENTS

The authors acknowledge the facilities provided by the Department of Civil Engineering at the University of Asia Pacific for this research.

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.

REFERENCES

Domone, P., and Illston, J. (2010). *Construction Materials: Their Nature and Behaviour*. 4th ed.; Spon Press 270 Madison Avenue: New York, NY, USA.

Mehta, P.K., and Monteiro, P.J.M. (2006). *Concrete microstructure, properties and materials*. McGraw-Hill, New York, NY, USA.

Miah, M. J., Patoary, M. M. H., Paul, S. C., Babafemi, A. H., & Panda, B. (2020). Enhancement of mechanical properties and porosity of concrete using steel slag coarse aggregate. *Materials, 13*(11), 2865.

Miah, M.J., Babafemi, A.J., Li, Y., Kong, S.Y., Paul, S.C., Jang, J.G. (2022). Impact of overburnt distorted brick aggregate on the performance of concrete at ambient temperature and after exposure to elevated temperatures. *Construction and Building Materials* 349, 128792.

Shafigh, P., Mahmud, H. B., Jumaat, M. Z., & Zargar, M. (2014). Agricultural wastes as aggregate in concrete mixtures – A review. *Construction and Building Materials*, 53, 110-117.

Debieb, F., & Kenai, S. (2008). The use of coarse and fine crushed bricks as aggregate in concrete. *Construction and Building Materials*, 22, 886-893.

Cachim, P. B. (2009). Mechanical properties of brick aggregate concrete. *Construction and Building Materials*, 23(3), 1292-1297.

Batayneh, M., Marie, I., & Asi, I. (2007). Use of selected waste materials in concrete mixes. *Waste Management*, 27(12), 1870-1876.

Miah, M.J., Miah, M.S., Hasan, N.M.S., Sobuz, M.H.R., & Li, Y. (2025a). Role of recycled crushed clay bricks as fine aggregates in enhancing the performance of ferrocement-strengthened RC beams. *Construction and Building Materials,* 478: 141412.

Khern, Y. C., Paul, S. C., Kong, S. Y., Babafemi, A. J., Anggraini, V., Miah, M. J., & Šavija, B. (2020). Impact of chemically treated waste rubber tire aggregates on mechanical, durability and thermal properties of concrete. *Frontiers in Materials, 7*, Article 90.

Sofi, A. (2018). Effect of waste tyre rubber on mechanical and durability properties of concrete – A review. *Ain Shams Engineering Journal, 9*(4), 2691–2700.

Aslani, F. (2016). Mechanical properties of waste tire rubber concrete. *Journal of Materials in Civil Engineering, 28*(3), Article 04015152.

Khaloo, A. R., Dehestani, M., & Rahmatabadi, P. (2008). Mechanical properties of concrete containing a high volume of tire–rubber particles. *Waste Management, 28*(12), 2472–2482.

Kashani, A., Ngo, T. D., Hemachandra, P., & Hajimohammadi, A. (2018). Effects of surface treatments of recycled tyre crumb on cement–rubber bonding in concrete composite foam. *Construction and Building Materials, 171*, 467-473.

Su, H., Yang, J., Ghataora, G. S., & Dirar, S. (2015). Surface modified used rubber tyre aggregates: Effect on recycled concrete performance. *Magazine of Concrete Research*, 67(12), 680–691.

Rivas-Vázquez, L. P., Suárez-Orduña, R., Hernández-Torres, J., & Aquino-Bolaños, E. (2015). Effect of the surface treatment of recycled rubber on the mechanical strength of composite concrete/rubber. *Materials and Structures, 48*(9), 2809–2814.

Miah, M., Miah, M.S. (2025b). Sustainable strengthening of RC beams using ferrocement with recycled clay bricks: Role of areca nut husk and jute fibres. *Structures*, 80:109819.

Miah, M. J., Miah, M. S., Humera, M., & Noor, M. S. H. (2025c). Mitigating environmental impact through the use of rice husk ash in sustainable concrete: Experimental study, numerical modelling, and optimisation. *Materials, 18*(14), 3298.

Fan, J. (1996). *Local polynomial modelling and its applications: From linear regression to nonlinear regression.* Chapman & Hall/CRC. ISBN 978-0-412-98321-4

Miah, M. J., Miah, M. S., Uddin, M., & Suzaudoula, M. (2018). Optimisation of mechanical properties of high performance concrete made with fly ash and blast furnace slag. In 4th International Conference on Advances in Civil Engineering (ICACE 2018), 502–507.

Lagarias, J. C., Reeds, J. A., Wright, M. H., & Wright, P. E. (1998). Convergence properties of the Nelder–Mead simplex method in low dimensions. *SIAM Journal on Optimization, 9*(1), 112–147.

Miah, M. S. (2020). Performance evaluation of tall buildings using optimised tuned mass damper. *Journal of Engineering Advancements, 1*(4), 195–198.