Effects of Pre-Treated Crumb Rubber as Sand Partial Replacement on Compressive Strength of Engineered Cementitious Composites (ECC)

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ABSTRACT

This study was conducted to determine the surface morphology of crumb rubber (CR) treated with 10% Sodium Hydroxide (NaOH) solution at different periods and the compressive strength of the treated rubberised engineered cementitious composites (R-ECC). R-ECC is a type of engineered cementitious Composite (ECC) with CR as partial sand replacement. In contrast to the quasi-brittle nature of conventional concrete, engineered cementitious Composite (ECC) is distinguished for its tensile strain-hardening behaviour and tensile ductility. However, adding crumb rubber (CR) in ECC as partial sand replacement reduces the composites' compressive strength owing to its smooth surface. The Scanning Electron Microscopy (SEM) test was conducted on the CR samples, which had been treated with 10% NaOH for 1, 2 and 3 days. Meanwhile, the compressive strength test was conducted on 45 cubes consisting of standard ECC, untreated R-ECC and treated R-ECC. The results discovered that 2 and 3 days of 10% NaOH treatment on CR enhanced its surface roughness, and 2 days NaOH treated R-ECC is the optimum duration for the highest compressive strength reduction. Therefore, the enhanced surface roughness of the CR used as partial sand replacement in the ECC can lessen the compressive strength reduction owing to better bonding between CR and cement matrix in the composites.

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Introduction

There are a few problems with normal concrete, including its high brittleness, weakness under tension, and susceptibility to tension cracks [1]-[2]. The use of conventional concrete as the main material for high-rise buildings exposed the structure to crack failure under dynamic loading due to its brittleness. The micro-crack formation on the structure may propagate to crack failure. In an effort to overcome these drawbacks, the engineered cementitious Composite (ECC) was created [3] on the basis of the micromechanical and fracture propositions [4]. ECC is a specific class of high-performance concrete with excellent mechanical qualities and permanence that has received a lot of interest from researchers and engineers [5]. The main ingredients in ECC production are supplementary cementitious materials, sand, polyvinyl alcohol (PVA) fibre, and admixture. Research and development for novel ECC mix using wastes are ongoing to meet the industrial demands for producing green and sustainable ECCs [6].

Meanwhile, rubberised engineered cementitious composites (R-ECC) are a type of ECC in which sand is partially or entirely replaced by crumb rubber (CR). By integrating CR into ECC, concerns caused by the rising waste tyre demolition process, such as unsustainable landfill dumping and an increase in carbon footprint as a result of combustion, may be lessened [7]. CR can be an excellent construction material due to its capability to serve as a vibration damper and enhance the ductility of the composite [8]. However, the addition of CR in the composite can lead to the reduction of the compressive strength of the ECC. As a consequence, a substantial amount of earlier studies explored alternative methods to minimise the strength reduction of ECC brought on by rubber particles. Nonetheless, the research on the ECC incorporating treated CR is still not well explored.

Literature Review

ECC displays many subparallel fine crack growth and tensile strain-hardening, the latter of which cause deformation [3]. Besides that, the ECC can self-consolidate, which derives from the fibre bridge activated during Serviceability Limit State (SLS) [4]. The purpose of ECC is to overcome conventional concrete's high brittleness and crack tendency due to the high compressive strength by enhancing the ductility, tensile strength and repairability as stated by [9]. Furthermore, ECC's ability to absorb energy and seismic load is better than conventional concrete; hence the durability of the structure can be enhanced and prolonged its service life as stated by [10].

[11] verified that the incorporation of CR in the ECC had reduced the compressive strength and stiffness of the specimen; however, the result still fulfils the structural standard and requirement. The CR's smooth surface resulted in less bonding with the cement paste [12], and low-strength CR replaced the high-strength aggregate and reduced composite strength [13]. As a result, adding high-stiffness fibres like steel fibre can increase compressive strength [14], while adding polyvinyl alcohol (PVA) fibre, which has the potential to bridge over composites' crack volumes, can increase the mechanical strength of the R-ECC [11]. According to [15], the ECC is usually reinforced with short PVA, which has a length between 6 to 12 mm and an inconsistent diameter of 10 to 100 µm micro-fibres.

Moreover, previous studies have stated hat the bonding between the CR particles and the cement paste can be enhanced by pre-treating the CR before adding it to the concrete. Hence, the reduction of the composite's mechanical strength can be lessened [16]. According to [17], among the surface treatments done to make the rubber surface more hydrophilic, the usage of sodium hydroxide (NaOH) solution produced the best results. Once treated CR is added to the composite, the cement hydration around rubber particles can be improved as NaOH solution pre-treatment can provide weak alkaline conditions surrounding rubber particles. Additionally, by treating CR with NaOH solution, the hydrophilicity of rubber particles can be enhanced, which lowers the porosity of the interface transition zone (ITZ) between rubber particles and cement matrix. As a result, rubber particles and cement paste may adhere together and become better over time [18]. [26] had investigated the effect of the pre-treatment of CR on rubberised concrete using NaOH solution at 10% concentration under different periods (20 minutes, 2, 24, 48 hours and 7 days). The results showed that the rubberised concrete with 1-day treatment of 10% NaOH pre-treated CR achieved the highest compressive strength with a 20% increment compared to untreated CR [16].

In this study, CR was used as sand partial replacement in the ECC and 10% sodium hydroxide (NaOH) solution was used as a pre-treatment on CR for a different duration (1 day, 2 days and 3 days). Hence, the effect of the CR treatment using 10% NaOH on the CR's surface roughness and compressive strength of R-ECC was investigated. The optimal time for pre-treating CR with 10% NaOH to minimise the compressive strength in R-ECC from deteriorating was established.

Materials and Methods

Materials

The binder used in this study is Composite Portland Cement (CPC), while silica sand and CR are employed as aggregates in the ECC. The average size of silica sand is 1.19 mm to 0.25 mm, whereas the average size of CR is 1 mm to 3 mm. CR was treated with 10% NaOH solution with different durations before blending into the mixture. The ECC is reinforced with the PVA fibre of 6 mm in length, and superplasticiser (SP) was added to the mixture. Figures 1a and 1b show the picture of the CR and PVA used in the ECC, respectively.

(a) (b)

Figure 1: Picture of; (a) CR, and (b) PVA fibres

Crumb rubber treatment

Before the casting process, the 10% NaOH solution must be prepared for CR treatment. 400 g NaOH granules were heated with 1 L distilled water and stirred until the solution became clear. Then, the heat was turned off, and continued to stir the solution for 2 to 3 hours to allow it to cool. After pouring the 10% NaOH solution into the CR container and made it completely soaked, leave it for 1 day, 2 days, and 3 days. Finally, the CR was cleaned with tap water until it reached a pH of 7 ± 0.5, then dried at room temperature. The treatment process was done by modifying the procedure conducted by [19].

Mixture design and sample preparation

Five different ECC mixtures were prepared with the inclusion of 10% CR as a partial silica sand replacement by volume. Normal ECC is employed as the Control, whereas R-ECC is made up of CR that has been untreated (UT) and treated with 10% NaOH solution for 1 day (T1), 2 days (T2), and 3 days (T3). Table 1 shows the modified proportion of materials from Wang et al. (2020) for the ECC. The water-cement ratio, volume of PVA fibre, and superplasticiser (SP) were fixed at 0.35, 1.5% by volume of the mixture, and 0.89% of cement weight, respectively. The control sample is a normal ECC with no CR as partial sand replacement.

When making the R-ECC, the dry ingredients consisting of sand, cement and CR were combined to achieve a uniform and thorough dispersion of constituent materials. The mixture was then filled with half as much water and let to continue rotating. After that, SP and the leftover water were added to the mixture while stirring for another 2 to 3 minutes. Finally, PVA fibres were added to the mixture as the mixing continued until they were blended together. After the mixing process was completed, the wet mixture was immediately cast into cube moulds with 50 mm sides and demoulded after 24 hours. Next, the samples were cured in an airtight bag at room temperature before being tested.

Table 1: Material proportion of ECC

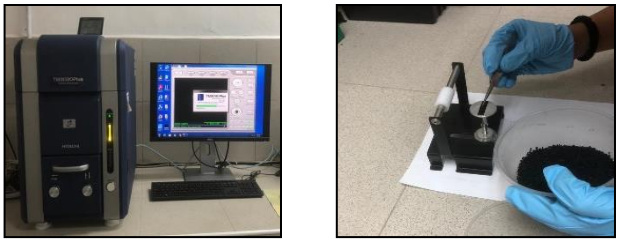
Mix	Cement (kg/m^3)	Sand (kg/m^3)	CR (kg/m^3)	Water (kg/m^3)	PVA (%)	SP (%)
Control	1193	990	0	417	1.5	0.89
UT, T1, T2, T3	1193	891	27	417	1.5	0.89

Methods

The physical properties of untreated and treated CR were determined using Scanning Electron Microscopy (SEM) to get the surface roughness of the material. SEM was carried out using the TM3030Plus Tabletop Microscope, as presented in Figure 2a. The test was conducted on the CR, consisting of untreated, 1 day, 2 days, and 3 days 10% NaOH-treated CR. A small amount of CR was placed on the base using a carbon tape, as shown in Figure 2b. Next, the base with CR was placed inside the chamber to vacuum and centralised the CR under the lens using the manual adjuster. Later, the chamber was closed and the machine was run to obtain the surface roughness of the CR.

The fresh properties of the ECC with and without CR were determined using the flow table test in accordance with ASTM C230/C230M. The flow table test was carried out using the automatic flow table test machine as shown in Figure 3. The mixture was filled inside the mould in two layers and tamped 20 times for each layer using the steel rod. Then, the mould was removed vertically from the mixture, and the plate dropped 25 times. Lastly, the longest diameter of the wet ECC and R-ECC was measured and recorded.

As indicated in Figure 4a, the specimens were put through a compressive strength test utilising NL Scientific apparatus model, NL 4000 X/018U at the intervals of 7, 14, and 28 days. In this investigation, the test was performed on cube specimens with the diameter of 50 mm on each side, as shown in Figure 4b. Before testing, the samples were taken out of the sealed bag and allowed to cure in the open air. The compressive strength test was executed following BS EN 196-1. The cube specimens were positioned in the middle of the lower platen and perpendicular to the load direction. Based on the size of the samples and the equipment's manual, the compressive strength test was carried out at a rate of 0.9 kN/s.



(a) (b)

Figure 2: (a) Scanning Electron Microscopy (SEM) equipment, and (b) base of the sample

Figure 3: Automatic flow table test machine

(a) (b)

Figure 4: Image of (a) compression test machine, and (b) cube specimen

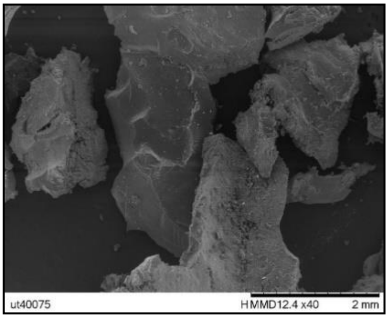
Results and Discussion

Scanning Electron Microscopy (SEM)

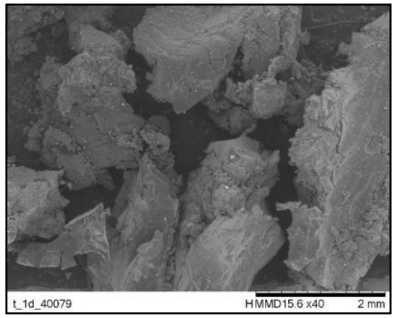
Figure 5 shows Scanning Electron Microscopy (SEM) images of untreated CR, and 10% NaOH-treated rubber particles. The surface roughness of the CR particles treated with 10% NaOH solution is better than untreated CR caused by the corrosion of CR's surfaces by the solution. According to [26], the zinc stearate layer on CR, which is in charge of gives it its hydrophobic characteristics, reacts with NaOH to produce soluble sodium stearate, which may be eliminated by washing CR in tap water [16]. Consequently, the bonding between 10% NaOH-treated CR and the cement matrix can be enhanced. Besides that, [26] affirmed that the NaOH solution treatment on CR discarded the forbid material such as oil and other pollutants or chemicals that may attach to its surface and reduce the bonding as well as weaken the strength of the composites, supported by [16]. Moreover, the NaOH solution can produce the best results among the surface treatments evaluated to improve the hydrophilicity of the rubber surface, mentioned by [17].

Flowability

Figure 6 presents the flowability of the ECC with and without CR. The Control has the lowest flow value, followed by untreated R-ECC mixtures (UT). The inclusion of CR in ECC has an increment in diameter and flowability compared to the normal ECC. The increase in R-ECC flowability may be affected by the low water absorption of CR compared to sand, as stated by [20]. Moreover, the hydrophobic nature of CR, which repelled water, led to an increment of water content in the mixture. However, 10% NaOH-treated R-ECC achieved a higher flowability than untreated R-ECC. The untreated CR particles may have impurities coating on the external surfaces that cause a higher water demand compared to the treated CR particle which had been cleaned [16]. At a two-day duration of CR treatment with 10% NaOH (T2), the R-ECC achieved the highest flow value and flowability of 147 mm and 46.67%, respectively. However, the T3 had a slight reduction of flowability which is 45%. This might be created by the enhancement of CR's surface roughness, which resulted in an increment of flow resistance [21]. The enhancement of surface roughness reduced air trapped on CR surfaces and promoted the adhesion between the cement matrix and CR particles [20].



(a)



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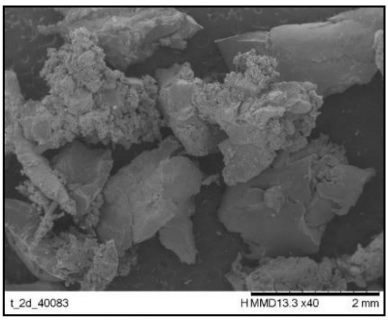
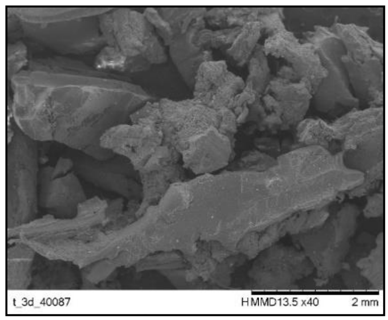


(c)



(d)

Figure 5: SEM image (a) untreated (b) 1 day (c) 2 days, and (d) 3 days 10% NaOH treated CR

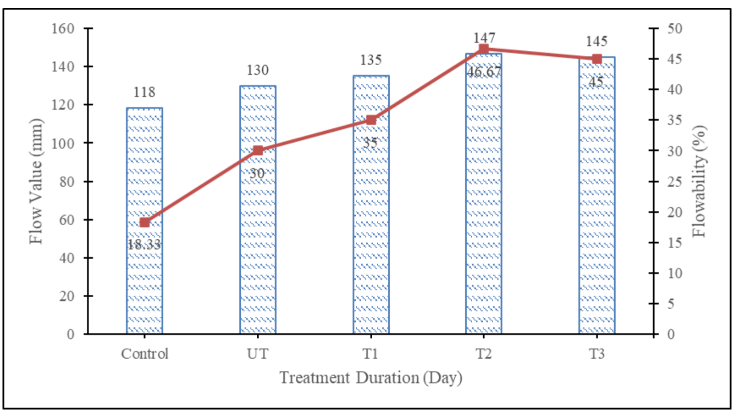


Figure 6: Flowability of ECC/R-ECC

Compressive strength

Figure 7 presents the results of the compressive strength of R-ECC at the age of 7, 14, and 28 days against the duration of 10% NaOH pre-treatment on CR incorporated as a sand partial replacement. Based on the compressive strength of untreated CR (UT) and 10% NaOH-treated CR for 1 day (T1), 2 days (T2), and 3 days (T3), the employment of CR as partial sand replacement in the ECC contributed to the reduction of compressive strength. Since CR was not added to the normal ECC or Control specimens, it obtained the highest compressive strength at 7, 14, and 28 days. The strength reduction of R-ECC may be caused by the smooth surface of CR, which weakened the cement paste's adhesion [12]. Besides that, incorporating CR in ECC reduced strength because there was less bonding with cement paste and lesser stiffness of CR than sand [22]. Nonetheless, the compressive strength achieved by T1, T2, and T3 was greater than UT. Meanwhiles, T2 experienced the highest strength at all ages for R-ECC specimens. UT had the least compressive strength, owing to the hydrophobic nature of rubber particles. Therefore, treatment with 10% NaOH on CR for 2 days is optimal to enhance the compressive strength of the R-ECC. [23] reported that NaOH-treated CR improved the adhesion between its particles and the cement matrix, resulting in less compressive strength reduction, as supported by [24].

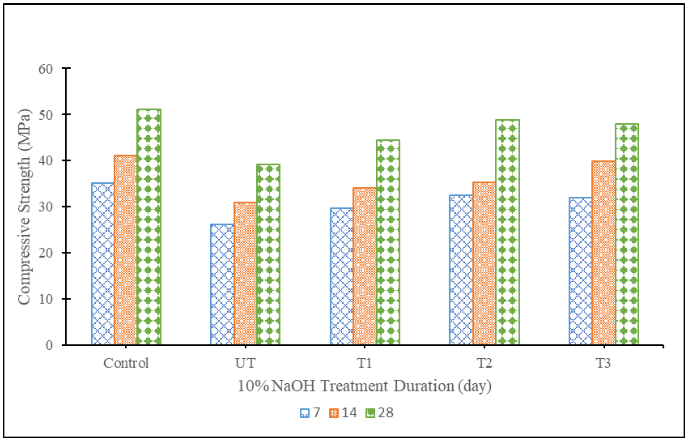


Figure 7: The effect of treatment duration of CR on compressive strength

Figure 8 shows the relative strength determined based on Equation 1 against the age of the rubberised ECC. The line graph displays the relative strength of the Control and R-ECC (UT, T1, T2, and T3). The relative strength of untreated R-ECC (R-UT) achieved the bottommost relative strength of 74.49%, 75.15%, and 76.61% of control at the age of 7, 14, and 28 days respectively, compared to the relative strength of T1 (R-T1), T2 (R-T2), and

T3 (R-T3). The weaker adhesion of CR particles to the blended materials in the ECC might be the reason for the less strength achieved by R-UT due to its smooth surface. According to [20], the probable weak interfacial zone between cement paste and CR may be the source of the reduced ECC's compressive strength. Besides that, the development of voids in the cement matrix may increase due to the incorporation of CR. Therefore, compressive strength reduction occurs due to the nature of those voids. [27] mentioned that the elasticity of CR is anticipated to reduce the bonding strength with the cement matrix, which results in a decrease in compressive strength, as supported by [25]. Additionally, the relative strength of R-T1, R-T2, and R-T3 is better than R-UT, which may have been influenced by the enhancement of surface roughness of the CR, as mentioned by [25]. R-T3 had a slightly lower percentage than R-T2, which may derive from the 10% NaOH solution that permeated the CR particles and reduced its rigidity rather than corroded its outlying surface [25]. Hence, the 10% NaOH solution pre-treatment on CR may be a credible method to minimise the reduction in the compressive strength of the R-ECC.

$$\frac{Strength\ of\ R\text{–}ECC(MPa)}{Strength\ of\ control\ (MPa)} \times 100 = relative\ strength\ (\%) \qquad (1)$$

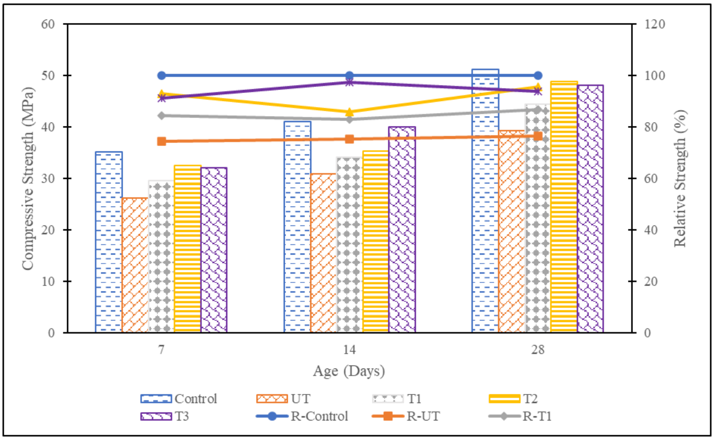


Figure 8: The relative strength of R-ECC

Conclusions

This research presents the effect of utilising untreated CR and 10% NaOH pre-treated CR at different durations to partially replace the sand on the strength of the R-ECC. 10% volume of sand in the mixture was replaced with CR to evaluate compressive strength performance at 7, 14, and 28 days. Based on the results from the experimental study, it can be concluded that 10% NaOH-treated R-ECC obtained a greater compressive strength than the untreated R-ECC due to the reaction between NaOH and zinc stearate layer on the rubber surface, making it hydrophilic and enhancing its surface roughness. Hence, a lesser strength reduction for R-ECC can be obtained owing to the enhancement of the adhesion between the treated R-ECC materials. T2 achieved the highest compressive strength among the R-ECC; therefore, 2 days of CR treatment with 10% NaOH solution is the ideal duration.

Moreover, R-ECC achieved a higher flowability than normal ECC, owing to the low water absorption of the CR particles compared to the sand. 10% NaOH pre-treatment cleaned the impurities on the CR particles' surface, which can hinder the bonding between CR and cement paste. Lastly, CR pre-treated with 10% NaOH-treated for 2 and 3 days had a better surface roughness than untreated CR and 1-day treated CR, leading to a lower compressive strength reduction. Be that as it may, the NaOH may permeate into the CR when a longer duration of CR pre-treatment with 10% NaOH solution takes place. Hence, the strength of R-ECC might be lowered, incurring a decrease in the rigidity of the CR rather than enhancing its surface roughness.

A few recommendations can be proposed, such as to investigate other mechanical properties of the composites like tensile and flexural strength. In addition, the study on the structural behaviour of 10% NaOH-treated R-ECC can be identified by applying the Composite as a structure and testing it under static and dynamic loads. Last but not least, conduct an experiment to study the different concentrations of NaOH solution to treat CR.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest

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References

[1] Q. Wang, M. H. Lai, J. Zhang, Z. Wang, and J. C. M. Ho, "Greener engineered cementitious composite (ECC) – The use of pozzolanic fillers and unoiled PVA fibers," *Construction Building Materials*, vol. 247, 2020, https://doi: 10.1016/j.conbuildmat.2020.118211

[2] L. S. Wee, O. C. Lian, and M. R. M. Zain, "Mechanical properties of engineered cementitious composites using local ingredients," *Journal of Mechanical Engineering*, vol. 16, no. 2, pp. 145–157, 2019, https://doi: 10.24191/jmeche.v16i2.15332

[3] V. C. Li, "Engineered cementitious composite (ecc): Material, structural, and durability performance," in *Concrete Construction Engineering Handbook, Second Edition*, no. June, pp. 1001–1048, 2008.

[4] A. C. Mircea, H. Szilagyi, A. Hegyi, and C. Baera, "Study of self-healing engineered cementitious composites for durable and sustainable infrastructure," *Procedia Manufacturing*, vol. 46, pp. 871–878, 2020, https://doi: 10.1016/j.promfg.2020.05.002

[5] B. H. AbdelAleem and A. A. A. Hassan, "Use of rubberized engineered cementitious composite in strengthening flexural concrete beams," *Engineering Structures*, vol. 262, no. January, pp. 114304, 2022, https://doi: 10.1016/j.engstruct.2022.114304

[6] C. L. Oh, S. W. Lee, N. A. Yahya, G. Pandulu, and M. R. M. Zain, "Tensile Behaviour of Slag-based Engineered Cementitious Composite," *Pertanika Journal of Science and Technology*, vol. 30, no. 1, pp. 303–317, 2022, https://doi: 10.47836/pjst.30.1.17.

[7] B. Zhang and C. S. Poon, "Sound insulation properties of rubberized lightweight aggregate concrete," *Journal of Cleaner Production*, vol. 172, pp. 3176–3185, 2018, https://doi: 10.1016/j.jclepro.2017.11.044

[8] A. Hamdi, G. Abdelaziz, and K. Z. Farhan, "Scope of reusing waste shredded tires in concrete and cementitious composite materials : A review," *Journal of Building Engineering*, vol. 35, no. November 2020, pp. 102014, 2021, https://doi: 10.1016/j.jobe.2020.102014

[9] M. A. Kewalramani, O. A. Mohamed, and Z. I. Syed, "Engineered Cementitious Composites for Modern Civil Engineering Structures in Hot Arid Coastal Climatic Conditions," *Procedia Engineering.*, vol. 180, pp. 767–774, 2017, https://doi: 10.1016/j.proeng.2017.04.237

[10] S. Wang, H. Du, J. Lv, J. Guo, G. Yue, and J. Ma, “Test research on mechanical properties of engineered cementitious composites,” *IOP Conference Series: Earth and Environmental Science*, vol. 647, no. 1, pp. 1-8, 2021, https://doi: 10.1088/1755-1315/647/1/012071

[11] Isyaka Abdulkadir, Bashar S. Mohammed, M.S. Liew, M.M.A. Wahab, “Mechanical and deformation properties of rubberized engineered cementitious composite (ECC),” *Case Studies Constructions Materials*, vol. 13, pp. 1-20, 2020, https://doi: 10.1016/j.cscm.2020.e00385

[12] K. Bisht and P. V. Ramana, “Evaluation of mechanical and durability properties of crumb rubber concrete,” *Construction and Building Materials*, vol. 155, pp. 811–817, 2017, https://doi: 10.1016/j.conbuildmat.2017.08.131

[13] J. Xue and M. Shinozuka, “Rubberized concrete: A green structural material with enhanced energy-dissipation capability,” *Construction and Building Materials*, vol. 42, pp. 196–204, 2013, https://doi: 10.1016/j.conbuildmat.2013.01.005

[14] M. K. Ismail, B. H. Abdelaleem, and A. A. A. Hassan, “Effect of fiber type on the behavior of cementitious composite beam-column joints under reversed cyclic loading,” *Construction and Building Materials*, vol. 186, pp. 969–977, 2018, https://doi: 10.1016/j.conbuildmat.2018.08.024

[15] E. H. Yang, S. Wang, Y. Yang, and V. C. Li, “Fiber-bridging constitutive law of engineered cementitious composites,” *Journal of Advanced Concrete Technology*, vol. 6, no. 1, pp. 181–193, 2008, https://doi: 10.3151/jact.6.181

[16] R. Alwi, M. Rizwan, S. U. Al-dulaijan, and M. Maslehuddin, “Properties of concrete with untreated and treated crumb rubber e A review,” *Journal of Materials Research and Technology*, vol. 11, pp. 1753–1798, 2021, https://doi: 10.1016/j.jmrt.2021.02.019

[17] E. Ganjian, M. Khorami, and A. A. Maghsoudi, “Scrap-tyre-rubber replacement for aggregate and filler in concrete,” *Construction and Building Materials*, vol. 23, no. 5, pp. 1828–1836, 2009. https://doi: 10.1016/j.conbuildmat.2008.09.020

[18] R. Si, S. Guo, and Q. Dai, “Durability performance of rubberized mortar and concrete with NaOH-Solution treated rubber particles,” *Construction and Building Materials*, vol. 153, pp. 496–505, 2017, https://doi: 10.1016/j.conbuildmat.2017.07.085

[19] O. Youssf, J. E. Mills, and R. Hassanli, “Assessment of the mechanical performance of crumb rubber concrete,” *Construction and Building Materials*, vol. 125, pp. 175–183, 2016, https://doi: 10.1016/j.conbuildmat.2016.08.040

[20] A. Adesina and S. Das, “Performance of engineered cementitious composites incorporating crumb rubber as aggregate,” *Construction and Building Materials*, vol. 274, pp. 122033, 2021, https://doi: 10.1016/j.conbuildmat.2020.122033

[21] Z. Chen, L. Li, and Z. Xiong, "Investigation on the interfacial behaviour between the rubber-cement matrix of the rubberized concrete," *Journal of Cleaner Production*, vol. 209, pp. 1354–1364, 2019, https://doi: 10.1016/j.jclepro.2018.10.305

[22] S. Guo, Q. Dai, R. Si, X. Sun, and C. Lu, "Evaluation of properties and performance of rubber-modified concrete for recycling of waste scrap tire," *Journal of Cleaner Production*, vol. 148, pp. 681–689, 2017, https://doi: 10.1016/j.jclepro.2017.02.046

[23] N. Segre and I. Joekes, "Use of tire rubber particles as addition to cement paste," *Journal of Materials Research and Technology*, vol. 30, pp. 1421–1425, 2000, https://doi.org/10.1016/S0008-8846(00)00373-2

[24] T. C. Ling, K. H. Mo, L. Qu, J. Yang, and L. Guo, "Mechanical strength and durability performance of autoclaved lime-saline soil brick," *Construction and Building Materials*, vol. 146, pp. 403–409, 2017. https://doi: 10.1016/j.conbuildmat.2017.04.106

[25] Y. Li, X. Yang, P. Lou, R. Wang, Y. Li, and Z. Si, "Sulfate attack resistance of recycled aggregate concrete with NaOH-solution-treated crumb rubber," *Construction and Building Materials*, vol. 287, pp. 123044, 2021, https://doi: 10.1016/j.conbuildmat.2021.123044.

[26] I. Mohammadi, H. Khabbaz, K. Vessalas, "Enhancing mechanical performance of rubberised concrete pavements with sodium hydroxide treatment," *Materials and Structures*, vol. 49 pp. 813-827, 2016, https://doi.org/10.1617/s11527-015-0540-7

[27] Q. Dong, B. Huang, X. Shu "Rubber Modified Concrete Improved by Chemically Active Coating and Silane Coupling Agent." *Construction and Building Materials*, vol. 48, pp. 116–123, 2013, https://doi.org/10.1016/j.conbuildmat.2013.06.072