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Experimental Study of Eco-friendly Concrete by Replacement of Fine Aggregate with Treated Waste Tyre Rubber

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Abstract

Utilizing an alternative fine aggregate in concrete as a replacement for natural fine aggregate is able to preserve river sand from being excessively dredged while maintaining the sustainability of the environment. This understanding has prompted people, especially in the construction industry, to move towards sustainable and green concrete. Currently, a significant portion of discarded tires ends up in landfills. The disposal of waste tyres in landfills produces toxic leachate, including Cadmium, Aluminium, Lead, Mercury, Iron, Zinc, Calcium, and Barium, leading to severe environmental issues. In Malaysia, it is estimated that about 417 thousand tonnes of scrap tires will be produced each year by 2030. To address this issue, tires are being utilized as aggregates in concrete. In this study, crumb rubber is used as a partial substitute for the fine aggregate. The objective of this project is to investigate the impact of incorporating treated waste rubber tires using NaOH solution on the mechanical properties of the concrete, including its workability, compressive strength, and flexural strength. The treatment takes 24 hours by soaking crumb rubber in a 2.5 molarity NaOH solution. Crumb rubber is used in the experiment to partially replace the fine aggregate, with varying percentages by weight of concrete, namely 0%, 5%, 10%, and 15%. The results showed that the workability achieved its highest value when the percentage of treated crumb rubber increased. Additionally, compressive and flexural strength values for treated rubberized concrete showed enhancement compared to untreated concrete. In conclusion, the treatment of crumb rubber helped enhance the mechanical properties of rubberized concrete due to the contact surface between rubber particles and the concrete mixture.

1. Introduction

Concrete is a popular construction material due to its strong durability and cost effectiveness. It is created by combining cement, coarse and fine aggregate, and water. Approximately, 10 billion tons of concrete is produced every year, and it is the most used material after water (Ken Crank and Peter, 2023). Undoubtedly, concrete is the predominant material utilized in construction, ranging from minor infrastructure projects to extensive buildings, and it serves as the primary construction material for over 70% of the global population. However, the extensive use of concrete has resulted in the over-extraction of river sand from riverbeds.

The possibility of utilizing an alternative fine aggregate in concrete as a replacement to natural fine aggregate able to preserve river sand from being excessively dredged as well maintain the sustainability of the environment. This understanding has brought people especially in the construction industry to move towards sustainable and green concrete. Green concrete is typical of eco-friendly concrete manufactured from additional waste or residual materials and requires less energy for production. The eco-friendly concrete has capability to reduce environmental impact of concrete.

Currently, a significant portion of discarded tires are disposed of in landfills. Many landfill operations have prohibited the dumping of whole tires due to the massive fires they can create, and their tendency to rise to the surface over time. Research has shown that discarded rubber tires contain non-decomposable materials that can cause severe environmental issues (Ul Islam et al., 2022). With the increasing amount of waste being produced, managing tire waste in Malaysia has become crucial. One approach to make the most of the waste is to recycle it and create a new useful product. To address this issue, tires can be utilized as aggregates in concrete. This project aims to improve the properties of rubberized concrete by utilizing a retreatment process for rubber with the aid of sodium hydroxide (NaOH).

Prior studies have investigated the possibility of replacing some fine aggregate in concrete with crumb rubber, but research on the effects of re-treating tires using sodium hydroxide has been limited. Consequently, this study aims to determine how treated waste rubber with sodium hydroxide (NaOH) can be utilized as a partial substitute for fine aggregate in concrete to improve its compressive strength, flexural strength, and workability.

Pre-treatment of rubber in rubberized concrete refers to the process of preparing waste rubber particles before incorporating them into the concrete mixture. It involves various methods aimed at improving the properties and compatibility of the rubber with the cement matrix such as acid treatment, alkaline treatment, chlorination treatment, washing treatment using water, thermal treatment, and coating treatment. All treatments have their effect on toward the mechanical properties of rubberized concrete. According to an investigation by Munoz-Sanchez et al., (2017) a solution consisting of 48% H2SO4 (sulfuric acid) and 48% CH3COOH (acetic acid) was found to be effective in treating waste rubber. When this treatment was used instead of untreated ELT rubber in Rubberized Concrete Mixtures (RCM), the strength loss was recovered by roughly 43% and 13%, respectively.

Besides, Abdullah and Ahmed (2011) discovered that treating rubber with HCl did not result in significant improvement in Rubberized Concrete Mixtures (RCM). ~~In fact,~~ the strength of RCM was negatively affected when using a 35% HCl solution. The researchers suggested that the strong HCl acid reduced surface irregularities that could have acted as mechanical interlocking sites in addition to dissolving dirt, oils, and rubber particle corners. Meanwhile, alkaline treatment such as sodium hydroxide is usually used in the pre-treatment of rubber. The alkaline solution helps to remove impurities and surface oxidation from the rubber particles, improving their compatibility with the concrete matrix. According to Guo et al., (2017) the hydrophilicity of waste rubber's surface can be increased by treating it with NaOH, which will reduce the water film that surrounds the rubber. As a result, this treatment may lessen the interfacial transition zone's (ITZ) porosity, improving the bonding of the rubber particles with the cement matrix.

In contrast, Segre et al. (2006) demonstrated that the presence of zinc stearate, an additive used in tire manufacturing, has a harms impact on adhesion because of its diffusion onto the rubber's surface. It is hypothesized that applying NaOH treatment will efficiently remove zinc stearate from rubber surfaces, change their surface chemistry, and improve surface homogeneity. Data from several investigations show that treating rubber with NaOH improves the rubber's adherence to the hydrated cement matrix. In addition, there is a study by Dong et al., (2013) that investigated the performance of rubberized concrete after the modification of the rubber surface using silane coupling agent. In this investigation, two samples of crumb rubber are prepared, one with untreated crumb rubber and the second treated of rubber using silane coupling agent. The rubber particles size is in the range 0.425 - 4.75 mm. The investigation's findings showed that while treated crumb rubber somewhat raised the air content of concrete, it did not affect the material's workability. The results showed that treated rubber concrete had 10–20% higher compressive strength and split tensile strength than untreated rubber concrete.

Other than that, a study by Najim and Hall (2013) found that the Unconfined Compressive Strength (UCS) of waste rubber particles could rise by up to 15% when they are washed with water before being mixed. Concrete's workability is preserved because less water is absorbed into the mixture following the removal of dust and fine particles.

From all research that has been done regarding treatment methods, it gives a comprehensive overview to the mechanical properties of concrete when fine aggregate is partially substituted with treated rubber. Based on the comprehensive overview, Sodium Hydroxide (NaOH) solution is a better treatment than other treatments such as acid treatment, thermal treatment, and coating treatment. The NaOH solution is safe to handle, easy to get in the market, and less expensive compared to other treatments.

2. Experiment details

2.1 Materials

In this study, material used is Ordinary Portland Cement Type 1 accordance with BS EN 197-1: 2011. Additionally, coarse aggregate with nominal size at 20 mm and fine aggregate with size less than 5 mm. Besides, a solution of sodium hydroxide (NaOH) is used to treat crumb rubber, which has a size range of 2-4 mm. For 24 hours, the crumb rubber is immersed in 2.5 molarity of NaOH. It will next be given a water rinse and left to air dry for 24 hours.

2.2 Mix proportions

For applications, the ratios of cement, aggregates, and water are adjusted to produce the required qualities and performance. There are four different mixes of crumb rubber used in the concrete mixture by weight: 0%, 5%, 10%, and 15%. There are a total of 36 samples—24 of them are cubes shaped. The cube samples will undergo a compressive strength test after the 7th and 28th days of curing. A 28th day curing period will be observed in 12 additional rectangular samples prior to their flexural strength test. A cube mould measuring 100 mm × 100 mm is used, and a rectangular mould measuring 100 mm × 100 mm × 400 mm is used. The water cement ratio, 0.54, was used for both the cube and rectangular samples. The mix proportions of cube and rectangular samples are shown in Table 1 and Table 2.

Table 1. *Mix proportions of cube samples*

Mix design (%)	Cement (kg)	Water (kg)	Coarse Aggregate (kg)	Fine Aggregate (kg)	Crumb Rubber (kg)
0	2.32	1.25	6.38	5.89	0
5	2.32	1.25	6.38	5.59	0.12
10	2.32	1.25	6.38	5.30	0.23
15	2.32	1.25	6.38	5.00	0.35

Table 2. *Mix proportions of rectangular samples*

Mix design (%)	Cement (kg)	Water (kg)	Coarse Aggregate (kg)	Fine Aggregate (kg)	Crumb Rubber (kg)
0	4.65	2.51	12.75	11.77	0
5	4.65	2.51	12.75	11.19	0.23
10	4.65	2.51	12.75	10.60	0.46
15	4.65	2.51	12.75	10.01	0.70

2.3 Test methods

All samples are mixed according to ASTM C305. The samples were cast in 100 mm × 100 mm cube mould and 100 mm × 100 mm × 400 mm rectangular mould. Then, demolding after 24 hours and curing in water tank for 7 days and 28 days before testing. Compressive strength test using ASTM C109 while flexural strength test using ASTM C348.

To simplify the methodology of the research, the crumb rubber will undergo pre-treatment process. The crumb rubber is soaked in 2.5 molarity of Sodium Hydroxide (NaOH) solution for 24 hours and then, it will be rinsed with water and air-dried for 24 hours. Concrete mix design can be proceeded after rubber been treated properly by replacing of fine aggregate with 0%, 5%, 10% and 15% of treated crumb rubber. Cube samples are cured in water tank for 7th days and 28th days while rectangular samples are cured for 28th days before conducting compressive strength test and flexural strength test. The results achieved then compared with untreated rubberized concrete to analyze the effect of rubber after treated using NaOH solution.

3. Results and discussion

3.1 Workability

Slump test is a common test used to determine the consistency and workability of newly mixed concrete. It entails pouring freshly mixed concrete into a conical mould, removing the mould, and letting the concrete slump or settle. It was measured how much the slump concrete's height differed from the mold's initial height. The slump of the mixture may change if crumb rubber which is made from recycled tire is added to concrete. The results of the slump test of treated rubberized concrete for cube and rectangular sample at 0%, 5%, 10% and 15% are shown in Fig 1.

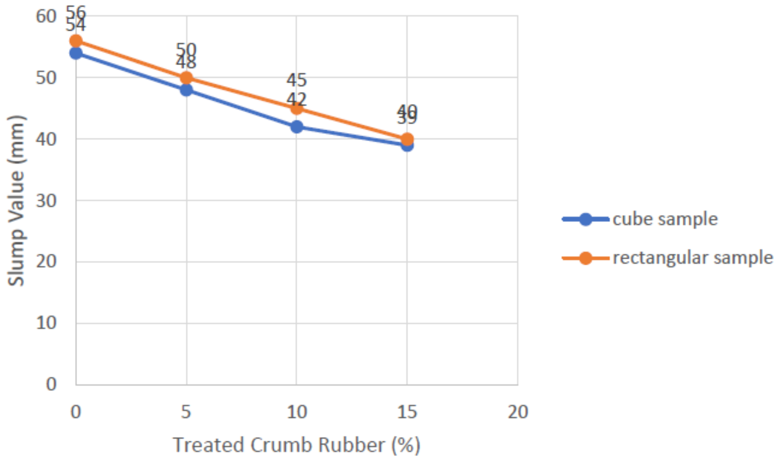

Fig 1. *Slump value containing different percentages of treated crumb rubber*

As a results, the control sample slump is 54 mm and 56 mm for cube and rectangular sample respectively with the experiment's usage of a water-cement ratio of 0.54. The workability of treated crumb rubber concrete increased as the percentage of treated crumb rubber increased. The lowest drop in slump value achieved higher of workability. The highest workability is 39 mm for cube sample mixing at 15% replacement of fine aggregate with treated crumb rubber. Even though all slump value showed reduction, all samples have slump value which fell within 30-60 mm of design slump range. However, there might be a higher slump value for cube sample mixing compared to rectangular sample mixing due to human mistakes since the mixing is conducted manually. Hand mixed of rectangular sample which large amount of kg might take too much time and caused nature water absorption.

There are a few possible explanations for why adding treated crumb rubber could result in a lower slump test. The surface of crumb rubber is affected by pretreatment, becoming smoother. As a result, the concrete mix can move across the crumb rubber surface more easily. Additionally, Shahzad & Zhao (2022) discovered that treated crumb rubber has a fineness modulus that is 1.57 times higher than sand, which increased workability.

3.2 Compressive Strength

For compression testing, cube specimens with dimensions of 100 mm × 100 mm × 100 mm were employed. Throughout the testing procedure, applied loads were applied to the specimens. The compressive strength test, as depicted in Fig 2, was conducted in this study.

Fig 2. *Compressive strength test in laboratory*

Table 3. *Compressive strength value*

Treated Crumb Rubber (%)	Compressive Strength (MPa) 7th days	Compressive Strength (MPa) 28 days
0	24.1	34.3
5	19.6	36.9
10	17.4	35.2
15	14.2	31.7

Based on Table 3, it illustrates that compressive strength of treated crumb rubber concrete decreased when percentage of treated crumb rubber is added. Control specimen at 7 days and 28 days are 24.1 MPa and 34.3 MPa respectively. At 5% replacement of treated crumb rubber after 28 days, compressive strength achieved 36.9 MPa more than control specimen and slightly decreased at 10% and 15%. The analysis of result for compressive strength are shown in Fig 3.

However, if compared the result of compressive strength between treated crumb rubber concrete and untreated crumb rubber concrete, compressive strength for treated is higher than untreated. Tudin & Rizalman (2020) investigated that pretreatment of crumb rubber improved surface contact between the cement mixture and crumb rubber. Since there is less space between the rubber particle and cement mixture in treated crumb rubber, it is clear the interfacial transition zone (ITZ) is preferred. Therefore, compared to untreated rubber, treated rubber with cement mixture has a better bond.

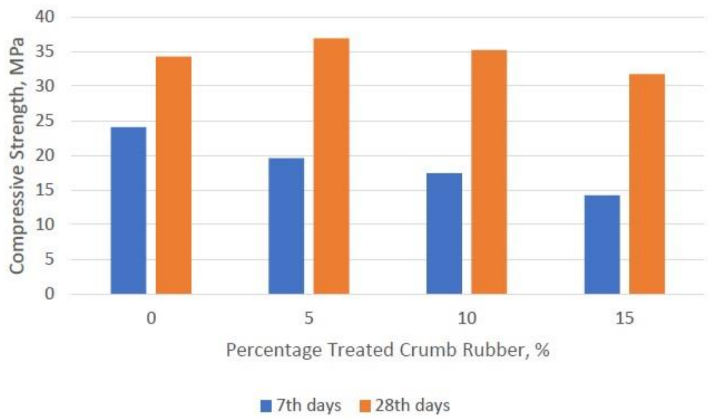

Fig 3. *Analysis of compressive strength at 7th and 28th days*

As shown in Fig 3, the analysis of compressive strength show that the compressive strength value tends to reduce slightly after added 10% and 15% of treated crumb rubber. Alwi et al., (2021) investigated that reduction of compressive strength of concrete can be lessened with adding treated crumb rubber into cement mixture. Even the compressive strength value of treated crumb rubber concrete showed reduction, but it was still higher compared to untreated crumb rubber concrete.

Besides, Si et al., (2017) studied that pretreatment of crumb rubber with $NaOH$ solution can make weak alkaline conditions encircling rubber particles and improved cement hydration around rubber when mixed into cement mixture. Other than that, the treatment helped strengthen adhesion between rubber and cement mixture. Therefore, the compressive value for treated is higher than untreated.

3.3 Flexural Strength

For the evaluation of flexural strength, rectangular samples measuring 100 mm × 100 mm × 400 mm used for testing as in Fig 4.

Fig 4. *Flexural testing in laboratory*

The result after 28^{th} days is depicted in Table 4. The flexural strength obtained from testing as in Table 4 showed moderate reduction when adding percentage of treated crumb rubber. Mohammadi et al., (2016) found that 5% enhancement of flexural strength for 24 hours treated crumb rubber using $NaOH$ solution compared to untreated crumb rubber.

Table 4. *Results of flexural strength*

Treated Crumb Rubber (%)	Flexural strength (MPa) 28^{th} days
0	3.22
5	3.10
10	2.90
15	2.82

Research by Tudin & Rizalman (2020), the study found flexural strength decreased when percentage of crumb rubber increased. Treated crumb rubber enhanced the flexural strength of rubberized concrete at all percentages of replacement compared to untreated crumb rubber concrete. Flexural strength at 5% substitution of treated crumb rubber is 6.2 MPa same as control specimen. Meanwhile, experimental result for flexural strength at 5% substitution of treated crumb rubber is 3.10 MPa which is less than control specimen, 3.22 MPa. The analysis result is illustrated as in Fig 5. The difference happened might be because of human error during preparing the sample such as spend much time in mixing the concrete, consistency on falling the stamp rod and mix proportion. However, all percentages replacement whether experimental or previous study, it showed moderate reduction when percentage substitution of treated crumb rubber increased. The flexural strength value for treated crumb rubber concrete is higher than untreated crumb rubber concrete.

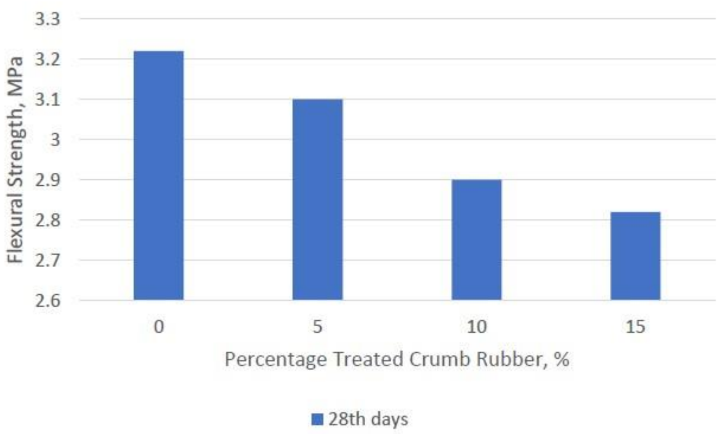

Fig 5. *Analysis of flexural strength at 28th days*

4. Conclusion and recommendations

The study's findings suggest that adding waste tyre rubber to concrete can affect the material's compressive strength in both favourable and unfavourable ways. Additionally, rubberized concrete's compressive strength was increased by pretreating the rubber with a NaOH solution. A few variables, including the molarity of the NaOH solution, the duration of treatment, the amount of treated crumb rubber, the size of the particles, and the mix proportions, affect the result.

From the outcomes of this research, the pretreatment of crumb rubber using NaOH solution able to smoothen rubber surface and create better bond with cement mixture. Besides, Mohammadi et al., (2022) investigated that NaOH solution used to treat crumb rubber able to remove oil and other pollutants or chemicals that might stick to its surface, weakening the binding and lowering the composites' strength. Therefore, compressive strength of treated rubberized concrete shows better result compared to untreated rubberised concrete. Also, the addition of treated crumb rubber in rubberised concrete enhanced its flexural strength. In this study, the addition of treated crumb rubber leads to higher value of flexural strength compared to untreated crumb rubber.

Some conclusions can be drawn in this research which the workability and the percentage of treated crumb rubber have an inverse relationship: the workability increases as the percentage of treated crumb rubber increases. These followed the same pattern as a study conducted by Raj et al., 2020), and the author claimed that this was because rubber had been treated to create a smooth surface that surrounded the rubber and made it easier to move in cement mixtures.

It is evident from the compressive strength test results that the percentage of treated crumb rubber and compressive strength are negatively correlated. In other words, the compressive strength falls as the percentage of treated crumb rubber rises. According to Murugan et al. (2017), this phenomenon is caused by the fact that rubber has a lower stiffness and more air content in its particles than river sand (fine aggregates).

The outcome of flexural strength test indicates that there is a negative correlation between the percentage of crumb rubber and the tensile strength; that is, the tensile strength decreases as the percentage of crumb rubber increases, but the reduction is still greater than the tensile strength of untreated crumb rubber. Onuaguluchi et al. (2016) found that the rubberized concrete displayed a ductile failure mode for the specimen with a rubber content of more than 10%. This ductile behaviour is due to the resistance of microcrack propagation at the interfacial zone between the rubber particle and the cement mixture.

Last but not least, there are several suggestions to improve the research. To increase the testing period, it is advised to add a 14th day of curing. Furthermore, it is advised to increase the number of percentage replacements by up to 20% in order to achieve more accurate and consistent results. Future tests should take the concrete's tensile strength into account as well, as this will help us better understand the mechanical properties of rubberized concrete. A more thorough understanding of the mechanical behaviour of rubberized concrete will be possible with the help of this additional test. Moreover, rubber was treated exclusively with NaOH for a 24-hour period in this study. In order to obtain a more thorough comprehension of the impact of pretreatment rubber, it is advised to carry out pretreatment for varying durations, such as 2 hours, 2 days, and 4 days. This more extensive testing will yield important information about how these rubber substitutes perform differently.

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