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The Ideal Percentage of Rubberized Engineered Cementitious Composite (RECC) as Partial Sand Replacement

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ABSTRACT

The demand for materials to retrofit earthquake-prone high-rise buildings and road vehicle tire manufacturing has led to crumb rubber as a partial sand replacement. This trend, in turn, has contributed to the rapid growth of urbanisation. Engineered Cementitious Composite (ECC) comprises sand, cement, fibres, and admixtures as primary materials and does not require the addition of coarse aggregates to the mix. This study aims to determine the ideal percentage of Rubberized Engineered Cementitious Composite (RECC) as a partial sand replacement. The mechanical properties, such as the compressive and splitting tensile strength, were evaluated at varying percentages of crumb rubber (0%, 5%, 10%, 15%, and 20%). Due to the increased percentages of crumb rubber as a partial sand replacement into ECC, the compressive strength and tensile strength of RECC were significantly reduced. Despite these reductions, all the mixture achieved its minimum acceptable compressive strength of 35 MPa, and tensile strength is 2.31MPa. The ideal percentage of crumb rubber as partial sand replacement in ECC or RECC is 5%. However, more extensive tests can be conducted in the future to determine the flexural strength of different percentages of crumb rubber.

1. Introduction

Although Malaysia is located outside the Pacific Ring of Fire, it does not guarantee that Malaysia is safe from earthquakes [1]. For instance, Ranau, Sabah was inflicted by an Mw 6.0 earthquake on 5 June 2015, according to Ferrario *et al.,* [2] and Tongkul [3]. Malaysia earthquake damage is usually assessed through macroseismic intensity and its effect on humans, buildings, and the natural environment. Moreover, the increased demand for automobiles has played a role in the swift growth of urbanisation, leading to a rise in the production of tires. As a result, there is a need for new materials to be utilised for the construction of earthquake-resistant high-rise buildings and the

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production of tires. One of the solutions is to replace the sand with crumb rubber partially. Nonetheless, incorporating a larger proportion of crumb rubber into the concrete mixture can reduce strength, which is undesirable. Despite this drawback, crumb rubber concrete possesses excellent toughness and deformability [4].

The depletion of fine aggregate, a natural resource, and subsequent cost increment can occur if it is exploited excessively, given its limited supply. Furthermore, fine aggregate mining activities in the river and beach will cause environmental issues such as slope slides and lowered water levels. If the demand for fine aggregate in a locality exceeds the country's natural supply, it could lead to a precarious global crisis of limited aggregate availability. As a result, an alternative is required to preempt further deterioration. Simultaneously, the rapid pace of urbanisation has led to a significant surge in the demand for road vehicles. After a certain period or a few years, a tire will wear down, and its torn rubber components must be replaced. Malaysia has an estimated annual total waste tire of 8.2 million or 57 391 tonnes [5].

Kewalramani *et al.,* [6] stated that Engineered Cementitious Composite (ECC) is a distinctive cement blend with a particular composition of low-volume fibres and high brittleness. Its high compressive strength enhances ductility, tensile strength, and repair capabilities while mitigating the crack tendency of conventional concrete. The main constituents of Engineered Cementitious Composite (ECC) are fine aggregate, cement, fibres, and admixtures. Notably, no coarse aggregate is needed for the mixture [7,8].

Using crumb rubber as a sand replacement significantly affects the durability of the Rubberized Engineered Cementitious Composite (RECC). In the absence of moisture, chemical reactions in concrete do not occur. Thus, the durability of Rubberized Engineered Cementitious Composite (RECC) Mortar is also affected by its water absorption [9].

Rubberised composite is an affordable construction material that withstands more pressure and impact than conventional concrete. Therefore, rubberised composite can be used in buildings as an earthquake shock-wave absorber, foundation pad for machinery, highway pavement construction, and airport runways. Tests conducted on structural concrete containing crumb rubber as a crash barrier material are infrequent and have produced conflicting outcomes. Faraz *et al.,* [10] discovered that Crumb rubber concrete reduces its compressive strength. On the contrary, a study by Sherwani *et al.,* [11] stated that incorporating natural rubber or kenaf core powder in PLA composites led to increased loading rate properties and a high percentage of composite absorption. The impact strength may be reduced when kenaf core powder is added. Enhancing polymers' mechanical properties and yield strength is necessary as they tend to be stiff and brittle. Meanwhile, Safan *et al.,* [12] have investigated the optimisation of NaOH solution for rubber treatment. Nonetheless, due to the hydrophobic nature and lower density of discarded rubber, there are insufficient interfacial bonds and uneven rubber distribution within concrete.

Furthermore, railway transportation is getting more popular globally due to its convenience and many other merits. Despite its benefits, the degradation of railway tracks is noticeable as trains operate at higher speeds and carry heavier loads. Hence, the issue could be overcome by including rubber elements and geogrid in the track structure. Furthermore, energy-absorbing shock mats, such as rail pads, under sleeper pads, and ballast mats, may make the tracks resilient [13]. According to Sharul *et al.,* [14], a prestressed concrete sleeper (PCS) is the main structural component in a railway track that transmits the load from the train to the ballast. Therefore, incorporating crumb rubber in railways can help reduce geometric degradation, noise, and vibration.

According to AbdelAleem and Hassan [15], applying rubber particles in concrete can also help to enhance ductility and reduce brittle failure. The property improvement is attributed to the rubber particles' elasticity and elastic deformation capability. Furthermore, the inclusion of RECC in the structure can enhance its resistance to staining, energy dissipation, flexibility, and impact, albeit at the expense of compromising its mechanical properties [16].

Hence, it is essential to investigate the feasibility of using crumb rubber derived from recycled tires as a partial substitute for sand in the construction industry. This research aims to address the issue of high sand demand and consumption. In this study, crumb rubber is evaluated as a partial replacement of sand at the percentages of 5%, 10%, 15%, and 20% mixture, benchmarked with the work of Wang *et al.,* [17]. Compressive and splitting tensile strength tests were conducted to determine the ideal percentage of crumb rubber incorporated in ECC as partial sand replacement.

2. Methodology

2.1 Mechanical Properties of RECC

The RECC was mechanically tested at the different crumb rubber and sand ratios. The amount of crumb rubber used as partial sand replacement in ECC or RECC varied from 5%, 10%, 15%, and 20%, benchmarked with a previous study by Wang *et al.,* [17]. The material has been collected from different sources and processed to create a mixture that can be used for casting the RECC specimen.

2.2 Material Properties

Cement, sand, crumb rubber, polyvinyl alcohol (PVA), fly ash, and superplasticiser is used to create the RECC. The raw crumb rubber was immersed in Natrium hydroxide (NaOH) for two days to remove extra scrape until it turned from alkaline to neutral (7-7.5 pH). As shown in Figure 1, the crumb rubber was tightly and dry-cleaned. Next, the crumb rubber was dried 24 hours before sieving to eliminate excess moisture. Following this, the crumb rubber was passed through a 2mm sieve for 15 minutes to refine its texture, making it more suitable to be used as a partial substitute for sand in ECC and achieving improved outcomes. Then, a chemical admixture known as superplasticiser (SP) is added to the mortar to reduce the water content in the mortar mixture. According to Figure 2, the partial replacement of cement with 40% fly ash was utilised in RECC to improve its mechanical characteristics. In addition, a Polyvinyl Alcohol (PVA) fibre, as shown in Figure 3, was added to enhance the compressive strength and tensile strength of ECC to counterbalance the reduction in mechanical properties of ECC caused by crumb rubber.

Fig. 1. Crumb rubber

Fig. 2. Fly ash

Fig. 3. Polyvinyl Alcohol(PVA) fibre

2.3 Preparation of RECC

This study used an ECC or RECC for 54 cubes of 50mm size and 18-cylinder specimens with 100mm diameter and 200mm height. In this study, crumb rubber is evaluated as a partial replacement of sand by various percentages of 5%, 10%, 15%, and 20% [17]. The details of the mixed proportion employed in this study are discussed in the sub-sections below.

2.3.1 Mix proportion

Before casting ECC or RECC, the material proportion was done under [BS EN196-1(2004)]. The modified mixed design and different percentages of crumb rubber were referred to in the previous study by Wang *et al.,* [17]. Table 1 shows the proportions of the materials in the ECC mix. Different percentages of crumb rubber (0%, 5%, 10%, 15%, and 20%) were utilised to replace the volume of ECC, which was initially made up entirely of sand. Meanwhile, fly ash partially replaces the total weight of cement. Furthermore, the replacement of the entire mixture volume with PVA is required, while the superplasticiser is added in an amount equivalent to the total weight of sand. A fixed volume of cement, water, fly ash, and PVA were added to ECC mixtures.

Table 1
Material proportion

ECC/RECC	Cement (kg)	Sand (kg)	Water (kg)	Fly Ash (kg)	PVA (%)	Superplasticizer (%)	Crumb rubber (kg)
Control	1.0	1.0	0.6	0	2.7	1.5	0
Fly Ash	1.0	1.0	0.6	0.6	2.7	1.5	0
5% CR	1.0	1.3	0.6	0.6	2.7	1.5	0.2
10% CR	1.0	1.2	0.6	0.6	2.7	1.5	0.3
15% CR	1.0	1.2	0.6	0.6	2.7	1.5	0.5
20% CR	1.0	1.1	0.6	0.6	2.7	1.5	0.7

2.4 Experimental Work on ECC

Cement, fine aggregate, and water are the essential components of ECC. ECC was cast, tested, and subjected to compressive and splitting tensile strength tests until failure occurred while using varying amounts of crumb rubber.

The Rubberized Engineered Cementitious Composite (RECC) was cured using the air curing method in the sealed plastics bag for up to 28th days, as shown in Figure 4. Compressive strength and splitting tensile strength tests were carried out using compression testing equipment to assess the strength performance of different proportions of crumb rubber as a partial replacement for sand.

Fig. 4. Curing samples

Crumb rubber is available in various percentages, which are 0%, 5%, 10%, 15%, and 20%. After the 7th, 14th and 28th days, the ECC or RECC specimen was tested using compressive strength test equipment as shown in Figure 5 under [BS EN196-1(2004)] to determine the ideal percentage of crumb rubber as a partial sand replacement. The testing machine's bearing surface was clean, and any loose grit or other irrelevant material on the specimen's surface that might have encountered platens was removed. Then, the specimen was positioned in the middle of the lower platen. The weight, dimensions, and density of the mortar specimen were measured and inputted into the testing machine, and the testing was conducted on a 50mm cube at a rate of 0.9kN/s. The ECC was tested until it failed, as shown in Figure 5.

Fig. 5. Mortar testing on compressive strength test equipment

Meanwhile, the cylinder specimen was tested on the 7th, 14th and 28th days after curing. The tensile splitting strength test was conducted according to [BS EN 12390-6(2009)]. The specimen is placed centrally in the testing machine with the packing strips and loading pieces along the top and bottom of the plane of the loading specimen. The upper platen shall parallel the lower plane throughout the loading. The rate for loading shall be selected within the range between 0.04MPa/s to 0.06MPa/s. The load will be gradually increased until no further significant increase in load is observed. Figure 6 shows the splitting tensile test setup for the cylinder sample.

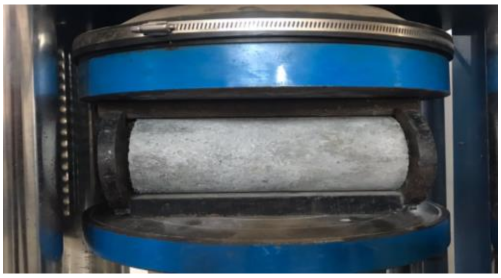

Fig. 6. The splitting tensile test setup

3. Results and Discussion

The strength of the Rubberized Engineered Cementitious Composite (RECC) was evaluated on the 7th, 14th, and 28th day of curing through compressive strength and splitting tensile tests.

3.1 Compressive Strength

Crumb rubber reduces its compressive strength compared to normal ECC. The compressive strength of control ECC or RECC, as well as that with fly ash and varying proportions of crumb rubber, is depicted in Figure 7. The graph shows a decline in the compressive strength of all ECC mixtures, including RECC, on the 28th day of curing. On the 28th day of curing, there is a reduction in the compressive strength of ECC or RECC as the proportion of crumb rubber used as a partial replacement for sand increases. This trend is also observed on the 14th and 7th days, except for the mixture with 5% crumb rubber which exhibits slightly higher compressive strength than the control specimen (0% crumb rubber) on the 14th day.

Nonetheless, on the 28th day, the RECC containing 5% crumb rubber showed marginally lower compressive strength than the control specimen without crumb rubber. Compared to other ECC or RECC, the 20% crumb rubber exhibits the lowest compressive strength. This phenomenon is primarily due to uneven stress distribution caused by a lack of bonding between crumb rubber particles and the other materials. Previous research has linked the decreased compressive strength in the presence of crumb rubber to inadequate adhesion between the rubber particles, leading to more bonding loss. Adding more rubber particles exacerbates this effect, reducing compressive strength [18].

In addition, since crumb rubber tends to be elastic, it tends to weaken the ECC mixture's interface binding strength, ultimately reducing its strength [17]. In contrast, Alaloul *et al.,* [19] stated that the capillary porosity indicates the strength degradation caused by high surface area constituents, such as crumb rubber. Crumb rubber creates pores, allowing water to seep into the specimen more quickly, lowering the bonding and compressive strength of the sample. Moreover, the physical properties of crumb rubber and its compatibility with sand contribute to a decline in strength when rubberised material is used. The hydrophobic behaviour of the crumb rubber particles causes the water to repel and the air to be entrapped on the surface [20].

Additionally, rubber content below 10% increases rubberised concrete's ability to absorb energy. However, the capacity of rubberised concrete to absorb energy declined when the proportion of rubber exceeded 10%, but it remained constant although it was below 10% [21]. Even though using crumb rubber as a partial replacement for sand leads to a decline in the compressive strength of the mortar, the ECC mixtures containing 5% crumb rubber attained the desired compressive strength of over 35 MPa on the 28th day of curing in this study. Hence, the ideal percentage of crumb rubber is 5% replacing the sand in the ECC obtained in this study.

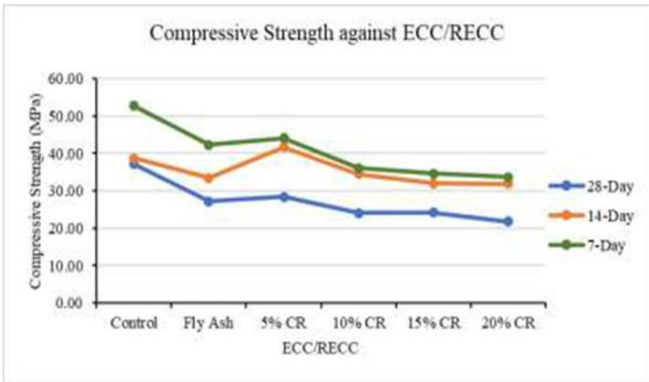

Fig. 7. Compressive strength against ECC/ RECC

3.2 Tensile Strength

Figure 8 shows the result of the tensile strength ratio between ECC and RECC of all mixes on the 28th day. The results were calculated by taking the average of 3 cylinders. The tensile splitting strength test results showed a similar trend as compressive strength. On the 28th day, 5% crumb rubber showed the highest tensile strength compared to normal ECC. The reduction of tensile strength depends on the addition of crumb rubber, but after increasing the added crumb rubber by 10%, 15%, and 20%, it starts to decrease. The decrease in tensile strength could be due to the lower modulus elasticity of crumb rubber particles compared to sand. Another contributing factor is the low density of crumb rubber, which reduces the concrete's tensile strength.

In a previous study, researchers proved that a reduction of tensile strength for 50% of the crumb rubber incorporation in the ECC was a sand replacement. The RECC content has higher porosity due to the hydrophobic rubber effect and reduces strength. The high-water content in the mixture may also increase the void when the excessive water in the RECC evaporates [7].

Moreover, the effect of crumb rubber in composite on split tensile strength is analogous to flexural strength behaviour. As the percentage of rubber increases in rubberised composites, the presence of voids and inadequate adhesion cause a decrease in splitting tensile strength [16].

According to a study by Priyadharshini and Naveen Kumar [22], a mixture of crumb rubber and sand in the concrete would give rise to a split tensile strength of primarily below 2.31 MPa. Meanwhile, in this study, the target tensile strength was achieved on the 28th day with a crumb rubber replacement percentage of 5%, resulting in 14 MPa. This value is greater than the reported value by Priyadharshini and Naveen Kumar [22] by 2.31 MPa.

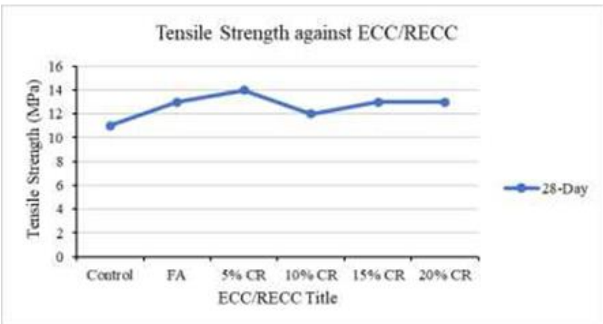

Fig. 8. Tensile strength against ECC/RECC

4. Conclusions

In summary, the experiment investigated the application of crumb rubber at different percentages as a substitute for sand in concrete. Both compressive and tensile strength are anticipated to be decreased. Therefore, the properties are superior to standard ECC. New green materials were produced using recycled tyre rubber to alleviate this problem. Using crumb rubber may also contribute to the Sustainable Development Goals (SDG), i.e., SDG 9 and SDG 11. SDG 9 may promote the building of resilient infrastructure by applying sustainable industrialisation and innovation. The RECC production had reduced the use of sand using crumb rubber from recycled tyres to improve the construction of buildings or railways for transportation, which could extend the structure's service life. Moreover, SDG 11 sets the goal of creating cities and human settlements that are safe, resilient, and sustainable. This work proposed the application of crumb rubber as a partial sand replacement. All mortar specimens had passed the target for compressive strength and tensile strength. Hence, the ideal percentage of crumb rubber as partial sand replacement in the ECC mixture is 5%. This study is mainly focused on the strength of materials. RECC holds great promise as a sustainable alternative material for retrofitting construction buildings or transportation infrastructure such as railways. However, more extended studies involving fatigue and durability are recommended for future endeavours. More extensive tests can be conducted to determine the flexural strength of different percentages of crumb rubber, which need further investigation.

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