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Effect of Treated Crumb Rubber on Mechanical Properties of GGBS-WCT Based Rubberised Geopolymer Concrete

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ABSTRACT

This study examines the effect of incorporating treated crumb rubber (CR) as a partial substitute for sand on the engineering properties of rubberized geopolymer concrete (RGC) formulated with Ground Granulated Blast Furnace Slag (GGBS) and Waste Clay Tiles (WCT). The primary aim is to assess the impact of different CR content levels (0%, 5%, 10%, 15%, and 20%) on the physical and mechanical properties of RGC. The experimental methodologies encompass water absorption testing, surface abrasion resistance assessment, and compressive strength evaluation. The findings indicate that elevated CR content typically results in greater water absorption due to the porous characteristics of the rubber particles; yet, all measurements were within permissible durability thresholds. The abrasion resistance is enhanced with increased CR content, with 10% and 15% exhibiting optimal resistance attributable to the elastic properties of rubber. The compressive strength diminished with increased CR percentages; however, the 10% CR mixture maintained a strength exceeding 42 MPa, rendering it appropriate for structural application. In summary, a 10% CR replacement provides the optimal equilibrium of strength, durability, and sustainability. This supports the use of recycled rubber and industrial by-products in the production of eco-friendly concrete.

Keywords: Geopolymer concrete; water absorption; abrasion resistance; compressive strength; treated crumb rubber

INTRODUCTION

The construction sector greatly contributes to global carbon emissions, mostly because of the prevalent usage of Ordinary Portland Cement (OPC). The production of OPC is extremely energy-intensive and generates substantial carbon dioxide CO_2 emissions, hence worsening climate change and environmental damage. There is an urgent necessity to identify and implement environmentally friendly alternatives to OPC to mitigate the environmental impacts associated with conventional construction practices (Luhar et al. 2021). Different industrial by-products, including fly ash, slag, and silica fume, have been studied as possible alternatives to OPC. These materials not only mitigate the carbon footprint but also enhance the engineering properties and durability of concrete. Utilisation of sustainable resources is crucial for the building sector to shift towards environmentally friendly practices and attain global sustainability objectives.

Geopolymer concrete (GPC) has arisen as a viable substitute for OPC concrete owing to its superior mechanical properties, improved chemical resistance, decreased drying shrinkage, and decreased creep under prolonged loading conditions Abd Allah Abd-Elaty et al. 2022; Luhar et al. 2021). GPC is an alkali-activated binder system created by the polymerization of aluminosilicate materials in the presence of alkaline solutions, usually comprising sodium silicate and/or sodium hydroxide Davidovits 1991; Provis et al. 2015). Typical precursors encompass geologically sourced elements such as metakaolin and industrial by-products like fly ash and Ground Granulated Blast Furnace Slag (GGBS), which are abundant in silica (SiO_2) and alumina (Al_2O_3) Cong and Cheng, 2021; Ma et al. 2022). In contrast with Ordinary Portland Cement (OPC), the manufacture of Geopolymer Cement (GPC) yields markedly reduced CO_2 emissions, thereby providing a more sustainable construction material and facilitating the valorization of diverse industrial byproducts Andrew 2018; Lamaa et al. 2024).

Besides reducing carbon emissions, the utilisation of alternatives instead of OPC can help with waste management issues. Industrial byproducts that would typically be sent to landfills can be recycled in concrete manufacturing, fostering a circular economy. Research suggests that these alternative materials can enhance concrete performance, increasing its resistance to external influences and increasing its lifespan. The incorporation of these materials into conventional construction techniques requires cooperation among researchers, industry players, and regulators to set up standards and guidelines that guarantee their safe and successful application. By adopting these environmentally friendly options, the construction industry may significantly aid in easing climate change and promoting sustainable growth.

The global production of waste tires is a rising environmental issue, with around a billion metric tonnes generated each year (Abd Allah Abd-Elaty et al. 2022). Waste tires are non-biodegradable and can result in significant pollution if not properly handled. Existing waste disposal methods, including landfilling and incineration, are unsustainable due to their detrimental environmental effects, such as soil and air contamination. Consequently, new recycling and repurposing solutions are crucial in reducing the problem of waste tyre accumulation. A promising method involves integrating waste tyre materials into construction uses, including the utilisation of crumb rubber in concrete. This not only improves the management of waste tires but also enhances the characteristics of construction materials, rendering them more durable and resilient.

Efficient waste tyre management is crucial for reducing environmental damage and encouraging sustainable development. The recycling of waste tires into construction materials can substantially minimise the quantity of waste tires in landfills and lessen the dependency on natural resources. The incorporation of crumb rubber in asphalt and concrete has demonstrated enhancements in material performance, yielding advantages such as higher flexibility, less cracking, and improved resistance to wear and strain. To scale these solutions, it is essential to establish regulations and incentives that promote the utilisation of recycled tyre parts in construction initiatives. By confronting the challenge of waste tyre management via new recycling techniques, we can progress towards a more sustainable and eco-friendly future.

The current research mainly emphasises the mixed development of GGBS and waste clay tiles (WCT) based geopolymer for semi-rigid binder use in pavement. In this study, different percentages of 0%, 5%, 10%, 15% and 20% treated CR are used to determine the effect of CR as sand replacement on physical and mechanical properties of geopolymer mortar based on water absorption test, abrasion test, and compressive strength test.

METHODOLOGY

MATERIALS & METHODS

The sample mix proportion produced in this study contains GGBS, WCT, sodium silicate, sand, CR, and water. The amount of GGBS and WCT was adjusted to be different for all 5 mixtures, while the amount or weight of sodium silicate and water was fixed. The mixing was conducted in the Laboratory of Civil Engineering, UiTM Shah Alam. It should be noted that a previous study (Bakar et al. 2024) referred to this mix as the GGBS optimum value replacement value. In the step, water was added to the mixture at a binder-to-water ratio of 0.35. All the specimens were cured at ambient temperature in the laboratory. GGBS-WCT was prepared varying sand replacement for each mix consisting of 0%, 5%, 10%, 15% and 20% treated Crumb Rubber (CR). Treated CR was soaked into NaOH solution for 24 hours. NaOH solution (5%) was prepared in a glass beaker using distilled water and laboratory-grade NaOH flakes. After the soaking process is completed within the stipulated time and conditions, the CR was washed with tap water three times over a # 100 sieve and dried in an oven at 50 ◦C for 24 h.

Table 1 shows a mixing ratio for the sample preparation of geopolymer mortar with varying the incorporation of treated crumb rubber ranging from 5% to 20% replacement.

TABLE 1. Different percentages of treated CR as sand replacement with the material

Sample	GGBS (g/cm³)	WCT (g/cm²)	Sodium Metasilicate (g/cm²)	Water (g/cm²)	Chipping stone (g/cm²)	Sand (g/cm²)	Crumb Rubber (g/cm²)
GGBS + WCT (0% CR)	3.0	1.3	0.5	1.7	6	2.40	0.0
GGBS + WCT (5% CR)	3.0	1.3	0.5	1.7	6	2.28	0.12
GGBS + WCT (10% CR)	3.0	1.3	0.5	1.7	6	2.16	0.24
GGBS + WCT (15% CR)	3.0	1.3	0.5	1.7	6	2.04	0.36
GGBS + WCT (20% CR)	3.0	1.3	0.5	1.7	6	1.92	0.48

TESTING PROCEDURE

For the evaluation of the physical and mechanical properties of geopolymer mortar, several standard tests were conducted. Firstly, the water absorption test was performed to assess the porosity and durability characteristics of the mortar, following the procedures outlined in ASTM C642-13. This test determined the amount of water absorbed by the mortar specimens, indicating the material's permeability. Secondly, the abrasion resistance test was carried out by ASTM C944/C944M-19 to evaluate the surface wear resistance of the geopolymer mortar. For this test, cuboid moulds measuring (55 mm × 90 mm × 10 mm) were used to prepare the specimens. The abrasion test results reflect the material's ability to withstand surface wear under mechanical action. Lastly, the compressive strength test was conducted following BS EN 12390-3:2019 guidelines. Compressive testing was performed at the Concrete Laboratory at UiTM Shah Alam, Selangor, using standard cube specimens (50 mm × 50 mm × 50 mm) to determine the maximum compressive loads. For each batch, 3 mortar specimens of cube and cylinder samples were prepared and tested for 3 and 28 days. Therefore, each mix consists of 0%, 5%, 10%, 15% and 20% treated CR.

RESULTS AND DISCUSSIONS

WATER ABSORPTION

The water absorption characteristics of rubberized geopolymer concrete (RGC), including treated crumb rubber, were assessed under air-dry curing conditions at 3 and 28 days, with sand replacement levels of 0%, 5%, 10%, 15%, and 20% by volume. The results shown in Figure 1 exhibited a consistent trend, with absorption values between 5.36% and 6.33%, signifying effective resistance to water penetration despite the use of crumb rubber as a partial substitute for sand.

After three days, water absorption values varied from 5.36% (0% rubber) to 6.19% (5% rubber), with slight variations for mixtures with increased rubber content, ranging from 5.76% to 5.40%. As expected, the incorporation of crumb rubber, which is less dense and more porous than natural sand, created micro-voids that marginally elevated water absorption. Moreover, da Silva et al. (2015) indicated that inadequate adhesion between crumb rubber and the cementitious binder generates micro-channels that promote water movement, hence enhancing water absorption. The surface treatment provided to the crumb rubber particles significantly enhanced the adhesion between the rubber and the geopolymer matrix, minimizing the occurrence of interfacial gaps. Guo et al. (2017) found that alkali treatment of crumb rubber can improve the hydration of slag in rubberized mixtures, resulting in decreased porosity in the interfacial transition zone (ITZ). This results in reduced water absorption, corroborating the study's conclusions that treated crumb rubber mitigates the negative permeability effects commonly linked to rubber incorporation.

At 28 days, water absorption slightly increased in all mixtures, attaining values between 6.26% and 6.33%, with no significant variation among different crumb rubber concentrations. This aligns with the standard behaviour of geopolymer concrete under air-dry curing circumstances, where the lack of heat or moist curing extends the geopolymerization process, permitting additional time for water to infiltrate the forming pores. Furthermore, as noted by Aly et al. (2019), the reduced density of crumb rubber enhances the likelihood of particle migration to the surface during compaction. This may result in agglomeration and localized voids or micro-cracks, hence increasing the possibility of moisture penetration. The utilization of treated crumb rubber in this study certainly mitigated adverse impacts, as demonstrated by the uniform and constant water absorption values at all rubber replacement levels.

The findings of the water absorption test demonstrate that the addition of treated crumb rubber to geopolymer concrete does not substantially diminish its resistance to water penetration. Despite minor increases in water absorption with elevated crumb rubber amounts, all readings remained within a limited range (5.36%–6.33%), indicating that the geopolymer matrix preserved its integrity. The slight discrepancies noted are probably attributable to the intrinsic porosity of crumb rubber and its propensity to create micro-voids within the mixture. Among all crumb rubber percentages, a 10% CR replacement exhibited a comparatively consistent performance over both the 3-day and 28-day curing periods, yielding values of 5.76% and 6.26%, respectively. This suggests that 10% CR content may provide an ideal balance between sustainability and satisfactory durability in air-dry environments. Additionally, the application of surface-treated crumb rubber significantly enhanced the interfacial adhesion between the rubber particles and the geopolymer binder, thereby mitigating the risk of permeability concerns. These findings confirm prior research and indicate that treated crumb rubber can be effectively utilized in geopolymer concrete without markedly impairing water absorption efficiency, even under air-dry curing circumstances. This facilitates its utilization in sustainable construction, where durability and ecological advantages must be reconciled.

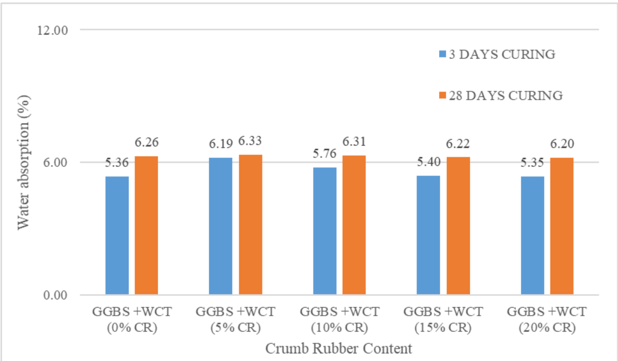

FIGURE 1. Effect of different amounts of CR on the water absorption.

ABRASION RESISTANCE

The abrasion resistance of GGBS-WCT rubberized geopolymer concrete containing different proportions of crumb rubber (CR) was assessed under 3-day and 28-day curing conditions. The findings are illustrated in Figure 2.

The findings indicate that the control mix (0% CR) exhibited the greatest abrasion resistance, with measurements of 7.101 mm²·hr/g for 3-day curing and 6.647 mm²·hr/g for 28-day curing. This indicates that the geopolymer concrete matrix, without rubber, was originally more robust and resistant to surface abrasion. Nonetheless, the incorporation of CR resulted in a reduction in abrasion resistance with up to 10% replacement. The minimum abrasion resistance was seen at 10% CR, with measurements of 6.093 mm²·hr/g (3-day) and 6.257 mm²·hr/g (28-day).

This decrease can be attributed to the inadequate adhesion between the hydrophobic surface of the crumb rubber and the geopolymer binder, potentially resulting in micro-voids and compromised interfaces. This aligns with the findings of Bisht and Ramana (2017), who indicated that rubberized concrete exhibits diminished mechanical performance due to interfacial deficiencies resulting from untreated rubber particles.

Notably, after a 10% CR content, the abrasion resistance began to increase once more. At a 15% conversion rate, the resistance increased to 6.541 mm²·hr/g (3-day) and 6.363 mm²·hr/g (28-day). This increase can be attributed to the elastic and energy-absorbing characteristics of crumb rubber, which facilitate the distribution of abrasion forces and mitigate surface damage. Feng et al. (2021) showed the same findings, indicating that rubber particles functioned as a cushioning layer under abrasive stresses, hence improving resistance despite reduced compressive strength.

The tendency persisted moderately at a 20% CR; however, the abrasion resistance values experienced a minor decline relative to the 15% CR mixture. This highlighted that whereas a moderate rubber concentration enhances surface wear resistance, excessive quantities may compromise matrix integrity, leading to reduced performance. This aligns with Thomas et al. (2016), who emphasized the necessity of optimizing rubber composition to achieve a balance between durability and mechanical qualities.

A key observation is that the difference between 3-day and 28-day curing results is minimal across all mixtures. This suggests that the geopolymerization process probably transpired swiftly, with most of the mechanical development stabilizing within the initial days. The marginal advantage of the 3-day cured samples at reduced CR concentrations may result from residual curing water enhancing matrix compaction during the initial phase.

To conclude this discussion, the test findings indicate that the use of 10% crumb rubber in geopolymer concrete achieves the optimal equilibrium between abrasion resistance and sustainability. Consequently, this replacement level seems to be the ideal juncture where the benefits of rubber elasticity surpass the disadvantages of diminished interfacial strength. Thus accordingly samples with 15% CR may be advisable for applications subjected to moderate abrasive conditions, such as pavements, drains, or low-load hydraulic components.

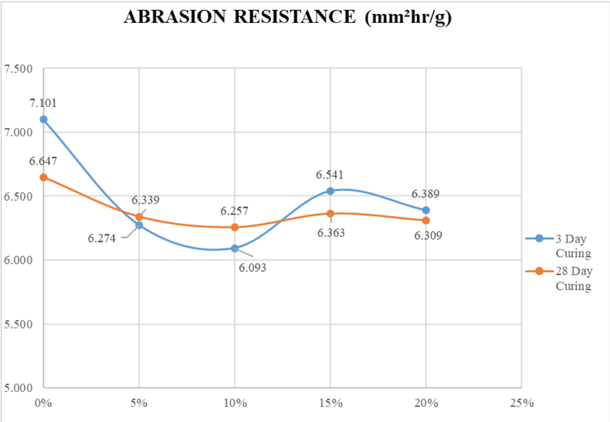

FIGURE 2. Effect: Abrasion resistance.

COMPRESSIVE STRENGTH

The compressive strength results for GGBS-WCT rubberised geopolymer concrete with different crumb rubber (CR) content as sand replacement (0%, 5%, 10%, 15% and 20%) are given in Figure 3. It clearly illustrated a decreasing pattern in strength with increasing CR replacement. This pattern is shown at both 3 days and 28 days of curing.

At 3 days of curing. The control sample (0%) recorded a strength of 49.37 MPa, while the 5% CR mix followed closely at 47.24 MPa. Subsequent mixes with higher crumb rubber replacement exhibited further declines, reaching 43.00 MPa (10% CR), 35.25 MPa (15% CR), and 31.61 MPa (20% CR).

Likewise, a similar pattern was observed at 28 days, where the control sample (0% CR) reached the highest compressive strength at 70.72 MPa, followed by the 5% CR mix at 65.54 MPa, representing an approximate 8.74% decrease. It is also observed that as the crumb rubber content increases beyond 5%, the compressive strength continues to decline significantly, reaching 52.80 MPa (10% CR), 43.25MPa (15% CR), and 38.86 MPa (20% CR), respectively. All of the samples exhibited an average of 8% reduction in strength, with 20% CR losing almost half its strength, with a 45.05% reduction in strength compared to the control.

These results suggest that while the inclusion of crumb rubber may contribute to sustainability efforts by recycling waste materials, it compromises the mechanical performance of the concrete. These findings are consistent with previous research, which also reported strength reductions with increased crumb rubber content as sand replacement in sample mixtures. According to Zhao et al. (2023), when the solid activator and precursors were combined with water simultaneously during the geopolymer sample preparation process, the geopolymerization reaction began right away. As a result some of the solid activators react with the precursors before their modulus reaches the intended modulus. Hence, it significantly reduces the compressive strength of the samples.

Furthermore, Raut et al. (2024) suggested replacing sand with CR reduces solid material, creating interior spaces that can be considered macro-porosity. Therefore, the increase in CR could lead to a reduction in strength. Azmi et al. (2016) also added that due to the lack of bonding between crumb rubber and precursor with alkaline activator, porosity or weakness points in the mix increased, hence owing to a corresponding decrease in strength. Aside from this, Luhar et al. (2021) stated that a high Poisson ratio and large deformability of CR particles are attributed to the low strength microcracks in rubberised concrete.

The compressive strength data clearly shows a gradual decrease with the increase of crumb rubber (CR) content in the GGBS-WCT rubberised geopolymer concrete. The incorporation of CR as a partial sand substitute enhances environmental sustainability but negatively impacts the mechanical properties of concrete, especially its compressive strength. It can observe that the most substantial decrease occurred at 20% CR, with strength diminishing by more than 45% relative to the control group. This decline is ascribed to multiple variables, such as heightened porosity, insufficient interfacial adhesion between CR and the geopolymer matrix, and the malleable characteristics of CR particles. These findings confirm prior research and underscore the necessity of optimizing CR content to acquire a balance between strength and sustainability. This test indicates that lower CR concentrations, such as 5%, may be suitable for applications requiring moderate strength; however, greater CR proportions should be restricted in structural applications where high compressive strength is essential.

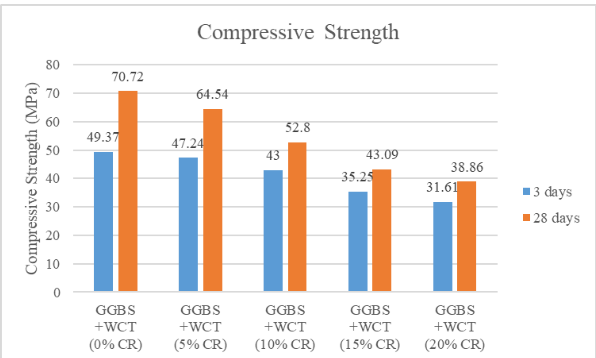

FIGURE 3. Effect of different amounts of CR on the compressive strength.

CONCLUSION

This study systematically investigated the impact of treated crumb rubber (CR) as a partial sand replacement on the microstructural and physico-mechanical properties of RGC made with GGBS and WCT. CR was incorporated at volume ratios of 0%, 5%, 10%, 15%, and 20% to assess its influence on water absorption, compressive strength, abrasion resistance, and microstructure development.

The findings highlighted that the water absorption values, which ranged from 5.36% to 6.33%, stayed comparatively constant, suggesting that the permeability resistance of the concrete was not harmed by the addition of treated CR. This was explained by the reduced interfacial gaps caused by better adhesion between the treated rubber particles and the geopolymer matrix.

Because rubber particles are less stiff and have a weaker link, compressive strength values for mechanical performance indicated a predicted reduction with increasing CR amount. For non-structural applications, materials with 5% to 10% CR amount nevertheless showed respectable strength values.

The abrasion resistance test showed that 15% CR substitution produced the best balance between sustainability and wear resistance, taking advantage of rubber's elastic and energy-absorbing properties to reduce surface deterioration without significantly weakening the concrete matrix.

Among all tested mixes, the 10% CR replacement level provided the most balanced results across physical, mechanical, and microstructural properties. It achieved acceptable compressive strength above 42 MPa, maintained low water absorption within durable limits, and exhibited excellent abrasion resistance suitable for wear-prone applications.

In conclusion, it is evident that the best way to balance sustainability, abrasion resistance, and durability is to utilize treated crumb rubber at a 15% sand replenishment level. This makes it appropriate for moderate-load applications such as drains and pavements. Furthermore, this study supports the possibility of turning industrial waste into environmentally friendly building materials, thus-enabling material innovation and environmental conservation.

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DECLARATION OF COMPETING INTEREST

None.

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