Jurnal Kejuruteraan 36(6) 2024: 2693–2700
https://doi.org/10.17576/jkukm-2024-36(6)-38

Physico-Mechanical Properties of GGBS based Geopolymer Mortar for Semi-Rigid Binder: Impact of Crumb Rubber Replacement

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Received 29 February 2024, Received in revised form 5 August 2024
Accepted 6 September 2024, Available online 30 November 2024

ABSTRACT

Geopolymer mortar presents a promising alternative to traditional cementitious materials, with the potential to significantly reduce CO2 emissions and support the development of sustainable construction materials. This study investigates the use of waste rubber tyres as a partial sand replacement in rubberised geopolymer mortar, addressing the environmental issue of tyre disposal. Annually, approximately one billion tyres reach the end of their life cycle, with only about 50% being recycled and the rest ending up in landfills. The research evaluates the effects of substituting sand with crumb rubber (CR) at 20%, 40%, 60%, and 80% proportions in geopolymer mortar, focusing on compressive strength, tensile strength, and workability. Results from workability tests revealed that increasing CR content reduced the slump flow by up to 30%. Furthermore, compressive and split tensile strength tests showed a decline in strength with higher CR content. The optimal replacement level of CR was found to be 20%, achieving a compressive strength of 33.35 MPa and a split tensile strength of 3.4 MPa using a GGBS-WCT mix. These findings underscore the potential of utilizing recycled waste materials as aggregate replacements, with significant implications for improving the sustainability and mechanical performance of construction materials.

Keywords: Geopolymer mortar; compressive strength; split tensile strength; crumb rubber

INTRODUCTION

The increasing amount of waste tyres generated globally has raised the public's concern regarding environmental issues, particularly the space needed for landfilling waste tyres without proper disposal. An estimated one billion waste tyres are generated yearly, with over half disposed of in landfills (Abd Allah Abd-Elaty et al. 2022; Roychand et al. 2020). The yearly number may increase to 1.2 billion by 2030. The landfilling of tyres presents a significant ecological risk, as it not only creates ideal conditions for an increase of rats and other rodents but also offers a fire hazard and pollutes the environment and natural resources with highly toxic pollutants (Guelmine et al. 2016). In addition to landfilling, burning is also used as a technique of disposing for these end-of-life tyres, however both procedures potentially present significant environmental hazards (Shen et al. 2013). Therefore, it is crucial and urgent to suggest a suitable solution to dispose of this substantial quantity of wasted tyres annually. Consequently, there has consistently been a requirement to utilise discarded tyre materials sustainably across many businesses. On top of that, it can be utilised to enhance the sustainability of construction materials by substituting a certain amount of waste rubber with natural aggregates, whether coarse or fine.

Roads play a crucial role in facilitating transportation and supporting economic activities. Crumb rubber (CR) and reclaimed asphalt pavement are commonly employed in pavement engineering due to their capacity to enhance significantly the high-temperature durability and resistance to rutting in asphalt mixtures (Zhao et al. 2023). CR is produced from various scrap tyres and may contain many metals (e.g., Cu, Co, Fe, and Zn) and chemicals used as stabilizers and additives (Li et al. 2023). An essential aspect of rubberized concrete is that more rubber content in mortar or concrete leads to decreased compressive strength and certain other mechanical properties.

Furthermore, the demand for construction aggregates worldwide is expected to increase by 2.3% annually to 47.5 billion tons in 2023 (Abd Allah Abd-Elaty et al. 2022), up from 40 billion tons in 2014 (Tam et al. 2018), as a result of the continuous significant expansion in global construction activity that drives the consumption of natural resources. CR serves as a partial replacement for fine aggregate. Compared to fine aggregate, it has a lower specific gravity (0.51-0.2), bulk density (524 kg/m^3 and 1,273 kg/m^3), and reduced water adsorption, strength, and stiffness (Shahrul et al. 2021). The gradation pattern will shift to gap-graded when the fine aggregate is partially replaced with CR. Moreover, CR can absorb water in the range of 2% to 4.3%, whereas fine aggregate can only absorb water to a percentage of less than 2%. Increasing the proportion of fly ash (FA) and using CR as part of the fine aggregate has improved the mechanical properties.

The main binder for concrete pavement is ordinary portland cement (OPC), which has serious environmental issues, and the production of OPC through the combustion process requires high energy. The environmental effects of OPC on concrete pavements include high carbon dioxide (CO_2) emissions and resource consumption (Althoey et al. 2023). An alternative to replacing traditional cement-based concrete with a new green cement called geopolymer is crucial and significant to the construction industry.

Geopolymer is an environmentally friendly alternative, highlighting its use of industrial by-products and waste materials, reducing CO_2 emissions. The production of geopolymers requires geopolymers to be made up of two components: reactive alumino-silicate-containing raw materials (such as FA, silica fume (SF), and ground granulated blast furnace slag (GGBS)) and an alkali activator (sodium hydroxide and sodium silicate) (Chanakya Varma et al. 2023). Geopolymer is a relatively new material that has gained attention in the construction industry, particularly pavement applications. Geopolymer concrete pavement construction has been discovered to offer significant benefits over traditional concrete pavements (Singh et al. 2022). Geopolymer is proposed as a sustainable solution for pavement applications, contributing to environmental conservation by diminishing the demand for natural resources and minimising waste sent to landfills.

The current research mainly emphasises the mixed development of GGBS, FA class F, and waste clay tiles (WCT) based geopolymer for semi-rigid binder use in pavement. The term “geopolymer” was coined in 1979 by French research scientist Joseph Davidovits, who attributed it to the tri-dimensional alumino-silicates that can be created by alkali interaction with containing natural alumino-silicate substances at low temperatures and in a short amount of time (Chanakya Varma et al. 2023). Due to its extremely short hardening time, the geopolymer exhibits high early strength. The physical properties of the geopolymer are superior to those of the fast-setting cement, but in this regard, their strength characteristics are comparable. In this study, different percentages of 20%, 40%, 60% and 80% CR are used to determine the effect of CR as sand replacement on physical and mechanical properties of geopolymer mortar based on workability test, compressive strength test and tensile strength test.

METHODOLOGY

MATERIALS & MIX PROPORTIONS

The sample mix proportion produced in this study contains GGBS, FA class F, WCT, sodium silicate, sand, CR, and water. The amount of GGBS, FA class F and WCT were 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. A previous study (Migunthanna et al. 2021) referred to this mix as the GGBS optimum value replacement value. Next, water was added to the mixture at a binder-to-water ratio of 0.35. All the specimens were cured at ambient temperature at the laboratory. GGBS-FA and GGBS-WCT are various sand replacements for each mix consisting 0%, 20%, 40%, 60% and 80% with CR, as shown in Figure 1. Table 1 shows a mixing ratio for sample preparation of geopolymer mortar

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

MIXTURE		GGBS (kg/m^3)	FA/WCT (kg/m^3)	Sodium Silicate (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	CR (kg/m^3)
Mix 1	GGBS + 0% CR	2.416	1.04	0.864	1.512	2.16	0
Mix 2	GGBS-FA/WCT + 20% CR	2.416	1.04	0.864	1.512	1.728	0.432
Mix 3	GGBS-FA/WCT + 40% CR	2.416	1.04	0.864	1.512	1.296	0.864
Mix 4	GGBS-FA/WCT + 60% CR	2.416	1.04	0.864	1.512	0.864	1.296
Mix 5	GGBS-FA/WCT + 80% CR	2.416	1.04	0.864	1.512	0.432	1.728

FIGURE 1. Concrete specimens of different mixes

TESTING PROCEDURE

For the workability of various mixes, a flow table test was conducted following the guidelines outlined in the ASTM C1437-20 standard. The flow table test is a common method for determining the workability of geopolymer mortar. The flow table test determines the fluidity or consistency of the geopolymer mortar. The compressive strength of geopolymer mortar cubes was determined according to the guidelines of BS EN 12390-3:2019. Compression testing at the Concrete Laboratory at UiTM Shah Alam, Selangor, determined the maximum compressive loads. Compressive strength was determined by using a standard cube (50mm×50mm×50mm). Cylinders of (50×100) mm were used to determine split tensile strength according to the specifications of ASTM C496/ C496M-17 (ASTM C496/C496M). For each batch, 3 mortar specimens of cube and cylinder samples were prepared tested for 3, 14, and 28 days. Therefore, each mix consists of 0% crumb rubber, 20% crumb rubber, 40% crumb rubber, 60% crumb rubber and 80% crumb rubber.

RESULTS AND DISCUSSIONS

WORKABILITY

The workability of mortar is an important property, demonstrating that geopolymer mortar at various binder-to-sand ratios is suitable for specific repair applications. The results obtained for the 5 mixes GGBS-FA and GGBS-WCT with various 0% CR, 20% CR, 40% CR, 60% CR, and 80% CR are shown in Figure 2. The result shows that the sample with 0% CR is the most fluid with the highest spread width, indicating favourable workability, and the sample with 80% CR is the most viscous lowest spread width, signifying reduced workability for both GGBS-FA and GGBS-WCT. Workability is reduced due to challenges in effectively incorporating CR into the mix during the blending process, along with the irregular shape and rough surface texture of rubber particles impeding cohesive flow (Eisa et al. 2020; Hesami et al. 2016). As mentioned previously, most rubber particles are recovered from the mechanical shredding process of waste tyres, and the surface texture of the crumb rubber is highly dependent on the manufacturing process. Some studies found that the workability of geopolymers was improved in the presence of crumb rubber due to the relatively smooth surface texture of CR compared to sand or the presence of more free water caused by the hydrophobicity of CR (Youssf et al. 2022; Zhong et al. 2019). The choice of mortar to be used in the repair work depends on the pavement failure type. This means that less viscous mortar can be used for narrow cracks. Likewise, for pavements that experience serious distress or fault, a thicker or more viscous mortar shall be used. The data obtained so far indicates that the test adopted in this study to determine geopolymer mortar physical and mechanical properties with various compositions of CR as sand replacement for semi-rigid binders for road applications is sufficient. The workability test also indicates that the more the CR is used, the lesser the flow becomes. It indicates that the mortar can be used or applied in real situations depending on the type of pavement failure. For minor fractures, a mix of 20% CR can be used, while a mortar mix of a higher percentage of CR can be used as a new layer on top of existing road pavement to improve the skid resistance.

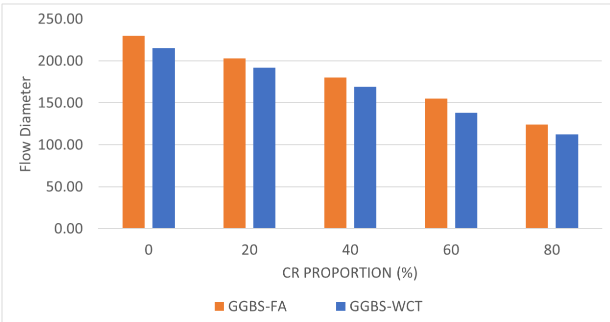

FIGURE 2. Flowability of geopolymer mortar with various composition of crumb rubber as sand replacement

COMPRESSIVE STRENGTH

This test investigates the compressive strength of geopolymer mortar using two different mixes: GGBS-FA (Ground Granulated Blast Furnace Slag - Fly Ash) and GGBS-WCT (Ground Granulated Blast Furnace Slag - Waste Ceramic Tile), with varying percentages of crumb rubber (CR) as a replacement for sand at 0%, 20%, 40%, 60%, and 80%. The compressive strength of GGBS-WCT with various CR contents at 3,14 and 28 days, indicating that, the control sample (without CR) held the highest compressive strengths of 38.96 MPa, 52.47 MPa and 56.14

MPa, respectively, compared with GGBS-FA. Irrespective of curing age, the content of CR lowered the compressive strength of GGBS-WCT and GGBS-FA and the reduction was higher when more sand was replaced with CR. The 28 days compressive strengths of GGBS-WCT CR10, CR20, CR30 and CR40 were approximately 41 %, 57 %, 73 % and 79 %, while GGBS-FA was 52 %, 60 %, 68 % and 81% lower than that of CR0, which is consistent with most of the existing studies on cementitious and geopolymer materials. It can be explained by the fact that the compressive cracks are more likely to appear near the CR as it can be deformed more easily due to its lower stiffness stiffened and higher elastic deformation of CR (Mohammed et al. 2018; Wang et al. 2019). Hence, when the sand replacement dosage by CR in GGBS-FA and GGBS-WCT was appropriate (e.g., 20 %), GGBS-WCT could still have an acceptable compressive strength. The mix with 20 CR showed a slight reduction in early strength but achieved parity with the control mix at 28 days, suggesting a harmonious blend of strength and recycled material utilization. Higher percentages of CR consistently displayed decreasing early strength. In sustainable applications, considerations for higher crumb rubber percentages could contribute to waste material recycling. Ultimately, the GGBS-WCT mix, ranging from 0 to 20 CR, emerged as a viable choice for superior early and long-term compressive strength, aligning with AASHTO guidelines concrete should achieve a minimum of around 13.8 MPa compressive strength prior to opening to the traffic (Migunthanna et al. 2021). Figure 3 illustrates the compression strength of geopolymer mortar with varying amounts of crumb rubber as sand replacement.

(a)

(b)

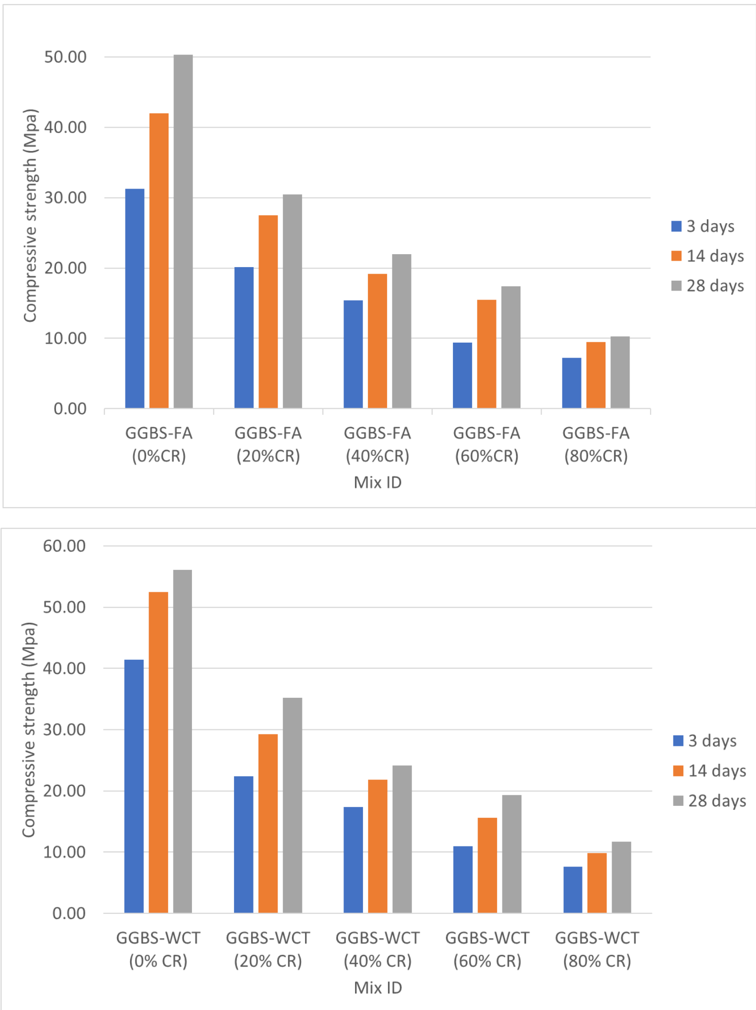

FIGURE 3. Comparison of compressive strength development in geopolymers with binary blends of a) GGBS - FA ; and b) GGBS - WCT, with various CR replacement

SPLIT TENSILE STRENGTH

The bar chart in Figure 4 shows the split tensile strength of samples with different percentages of CR as sand replacement, corresponding to each test age at 3, 14 and 28 days. All the samples are cured at ambient temperature. The same pattern decreased as compressive strength with increasing CR content is observed in the reduction of tensile strength of the mortar throughout the test. With the increasing amount of CR, strength has been lost. The failure in crumb tyre rubber samples was not ductile, and cylindrical samples remained intact even after failure, as mentioned in a previous study (Onuaguluchi & Panesar, 2014). The loss in tensile strength was due to the smooth surface of crumb tyre rubber, which has weak bond characteristics (Appa Rao & Raghu Prasad, 2011). The lowest values for split tensile strength were observed for 80% CR replacement value for 3, 14 and 28 days. The 28 days compressive strengths of GGBS-WCT CR10, CR20, CR30 and CR40 were approximately 7 %, 29 %, 50 % and 61 %, while GGBS-FA was 12 %, 26 %, 43 % and 54% lower than that of CR0. The split tensile strength percentage losses were lower than the counterpart percentage losses in compressive strength. This can be attributed to CR acting as a link between the two fractured surfaces, which helps prevent the crack from widening. The split tensile strength of all concrete mixes increased with age due to the formation of calcium alumina silicate hydrate (C-A-S-H) and Sodium alumina silicate hydrate (N-A-S-H) gel from the geopolymerization and filler effect from FA and WCT (Ahmad Zailani 2023).

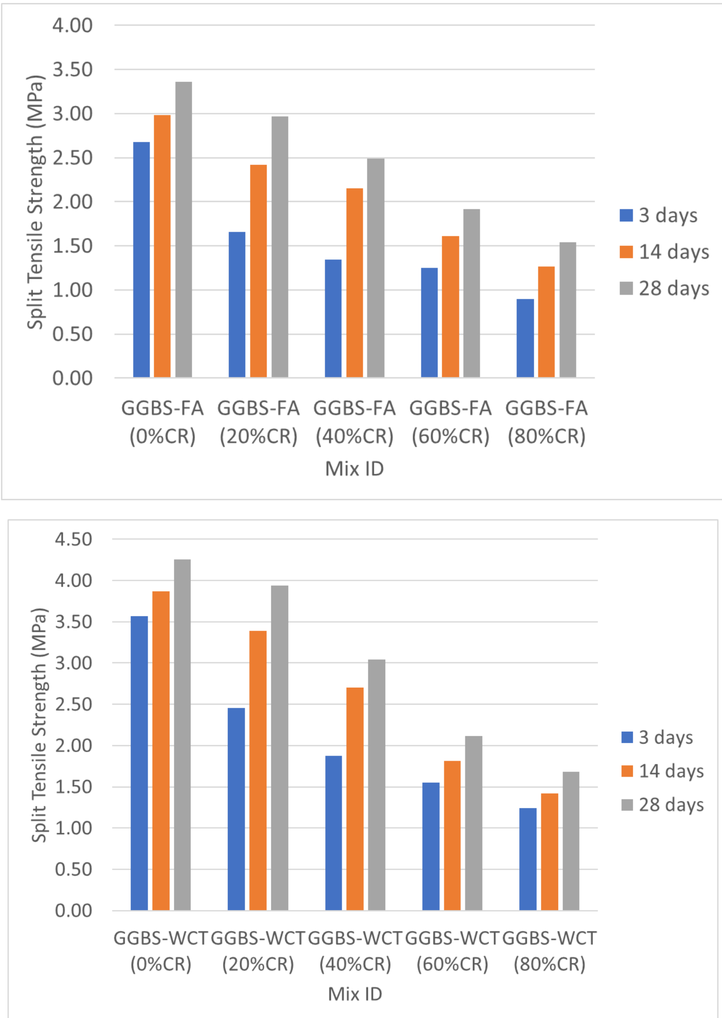

FIGURE 4. Comparison of split tensile strength development in geopolymers with binary blends of a) GGBS - FA ; and b) GGBS - WCT, with various CR replacement

CONCLUSION

Implementing CR technology in Malaysia signifies a substantial transition toward environmentally conscious construction methodologies, incorporating recycled CR from tyres into diverse building materials. Beyond its contributions to roadworks by enhancing asphalt quality and longevity, CR is utilized in concrete and insulating products, promoting improved energy efficiency and noise reduction in buildings. Malaysia dedicated focus on extensive research and development endeavours aims to fine-tune the characteristics of CR for specific applications, aligning with established construction practices. The success of CR in the market relies on targeted strategies that underscore its ecological advantages, cost-effectiveness, and adherence to industry standards. The analysis of geopolymer mortar with CR as a sand replacement indicates a decrease in workability as CR content rises, attributed to particle size variations. Optimal workability is observed within the 20% to 40% CR range. Increasing the crumb rubber content reduced the workability, primarily due to the irregular particle size, lower density of CR and increased air content inside geopolymer mortar. The compressive strength of all geopolymer mortar mixes herein ranged from about 7.24 MPa to 56.14 MPa. The compressive strength of geopolymer mortar gradually weakened when sand was partly replaced with CR. Thus, replacing 20 % of sand with CR can still lead to an acceptable compressive strength requirement for construction and regular traffic. The introduction of CR in mortar reduces tensile strength, with a more significant impact at higher percentages of CR. Although the reduction is less severe compared to compressive strength tests, higher percentages, ranging from about 0.90 MPa to 4.25 MPa, especially 80% CR, result in lower tensile strength readings. This indicates an increased susceptibility to breaking or fracturing with higher CR content. These findings underscore the influence of crumb rubber on mechanical properties, emphasizing the need for careful consideration and optimization of CR composition in mortar mixes to strike a balance between environmental concerns and material performance.

ACKNOWLEDGEMENT

Authors acknowledge the College of Engineering and Universiti Teknologi MARA for funding under the Geran Insentif Penyeliaan (GIP) 600-RMC/GIP 5/3 (084/2023).

DECLARATION OF COMPETING INTEREST

None.

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