World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

Check for updates

Rubbercrete as a sustainable solution for recycling waste tires in concrete: An overview

Bashar S Mohammed *

Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia.

World Journal of Advanced Research and Reviews, 2024, 24(01), 1126–1135

Publication history: Received on 29 August 2024; revised on 05 October 2024; accepted on 08 October 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.24.1.3112

Abstract

Due to the rapid growth of the automotive industry, the number of waste tires has been rising dramatically each year. This increase is causing a strain on landfills, as the bulky nature of waste tires, with about 75% of their volume being void, quickly depletes available space of landfills. Furthermore, waste tires are non-biodegradable and, due to their concave shape, provide an ideal breeding ground for insects and harmful rodents, posing a public health risk. Given the limited range of products that can be produced from recycled tires, it is crucial to find economically viable solutions to recycle these tires and use them in mass production of useful materials, such as concrete. Concrete has been chosen by researchers as it is the second most consumed material per capita, after water. Researchers have produced crumb rubber from recycled tires and used it to partially replace fine aggregates in concrete, creating a material known as rubbercrete. Compared to conventional concrete, rubbercrete has better thermal and acoustic properties, is lighter in weight, and more ductile. However, it also shows a reduction in mechanical strengths. This paper provides an overview of rubbercrete, highlighting its key challenges, advantages, and properties.

Keywords: Waste tires; Crumb rubber; Concrete; Rubbercrete

1. Introduction

The global expansion of the automotive industry has resulted in a significant increase in the number of waste tires. According to the Ohio EPA, a waste tire is defined as any tire no longer serving its original function as a vehicle tire. Each year, millions of tons of waste tires are generated, often disposed of improperly due to insufficient enforcement of regulations and poor waste management practices. This improper disposal contributes to environmental challenges, including occupying vast landfill space and creating potential breeding grounds for mosquitoes, rats, and rodents. Moreover, waste tires are highly flammable, and illegal burning releases thick, toxic black smoke, further harming the environment [1, 2,3,4,5].

Burning waste tires releases heavy metals such as iron, lead, zinc, chromium, and cadmium, posing a threat to nearby living organisms. Both controlled and uncontrolled tire burning emits various mutagenic and carcinogenic chemicals. In landfills, leachate from burning scrap tires can seep into the soil, contaminating groundwater. Additionally, scrap tires are bulky, with 75% of their volume being void, which consumes valuable landfill space [6, 7, 8, 9]. Burying scrap tires in landfills reduces the service life of these sites, as tires tend to float to the surface, damaging the anti-leakage cover due to their inability to compress. During rainfall, water can infiltrate torn landfill caps, mixing with waste to produce leachate that contaminates nearby waterways, posing health risks to consumers. The damaged caps also allow rodents and insects to enter, causing further health and environmental issues. Therefore, a holistic and environmentally friendly disposal method is necessary to address the challenges of waste tire management. Classified as special solid

* Corresponding author: Bashar S Mohammed

waste due to the difficulties in their treatment, storage, and disposal, waste tires require special handling. Recycling provides a valuable resource for creating sustainable, eco-friendly products while offering an economic viable solution for managing scrap tires properly [10, 11, 12].

2. Recycling of waste tires and production of crumb rubber

In practical application, waste tires can be recycled mainly through two methods. In the first method, the whole waste tire can be used for applications such as slope stability, boat bumpers and infill materials for embankment. In the second method, recycling waste tires to produce several products such as moulded rubber products, electrical coating, rubber product, rubberized sport field and playground surface. In the United States, the distribution of utilizing waste tires includes 7% for civil engineering applications, 26% ground rubber, 11% land disposal, 49% tire-derived fuel and 7% miss-used [13,14]. Waste tires consist of rubber, steel wire and textile. To produce crumb rubber from the waste tires, two methods which are mechanical and cryogenic process are available. The cryogenic process requires liquid nitrogen to freeze tire chips prior to size reduction. While in the mechanical process, waste tires are to be collected and sent to the recycling factory for processing. Those tires are then sorted based on their size and the process starts by separating the steel wires from the sidewalls of the tires by using rotating corrugated steel drums or cracker mill. As shown in Figure 1, in the mechanical process, waste tires are to be collected and sent to the factory for processing. The process starts by separating the steel wires from the sidewalls by using rotating corrugated steel drums or cracker mill. The shredding process of tires reduced the size of rubber into 100 mm to 50 mm. In the primary and secondary granulation process then further reduced the size from 50 mm to 10 mm. The screen and gravity separator are used to remove the steel fiber, then tires chips are grinded to smaller size to produce crumb rubber. Generally, the processed scrap tires are classified according to size such as rubber chips with size ranges between 25 mm to 50 mm and crumb rubber with size ranges between 4.75 mm to 0.075 mm. As rubber chips size is equivalent to coarse aggregates size and crumb rubber size is equivalent to fine aggregate size, therefore, rubber chip and crumb rubber have been used in concrete industry as replacement to coarse and fine aggregates. The inclusion of crumb rubber into the concrete leads to various effects on the properties of the concrete depending on several factors such as the size and amount of aggregate replaced [15,16,17,18].

Figure 1 Process of producing crumb rubber

3. Utilization of crumb rubber in concrete

Crumb rubber is being used in a wide range applications in the civil engineering idustry like asphalt pavement, breakwater, retaining wall, artificial turf field, concrete and for architectural purposes. Asphalt pavement containing crumb rubber particles to ease the noise pollution in urban area. While utilizing crumb rubber in backfill materials in retaining structures application leads to about 60% cost reduction. The rubberised artificial turf field for playground floor exhibits various advantages over the traditional playground surface as it requires less maintenance, durable, long lasting and safer. However, to achieve a successful waste management of waste tires, research trend is focusing on utilizing crumb rubber from waste tires as replacement to fine aggregate in concrete production [19,20, 21]. This is justified by several facts such as the global annual production of 3820 billion cubic meter of concrete which puts it next to water consumption per capita providing an opportunity to utilise significant quantities of waste tires. The crumb rubber particles can be produced in size is comparable to size of natural fine aggregate uses in concrete production as shown in Figure 2. In addition, replacing the natural aggregate in concrete with crumb rubber help in preserving the natural resources. Finally, concrete containing crumb rubber exhibits several advantages in comparison to conventional concrete such as lighter in weight, more ductile, higher electrical resistivity, and as well as better thermal and acoustic properties [22, 23, 24].

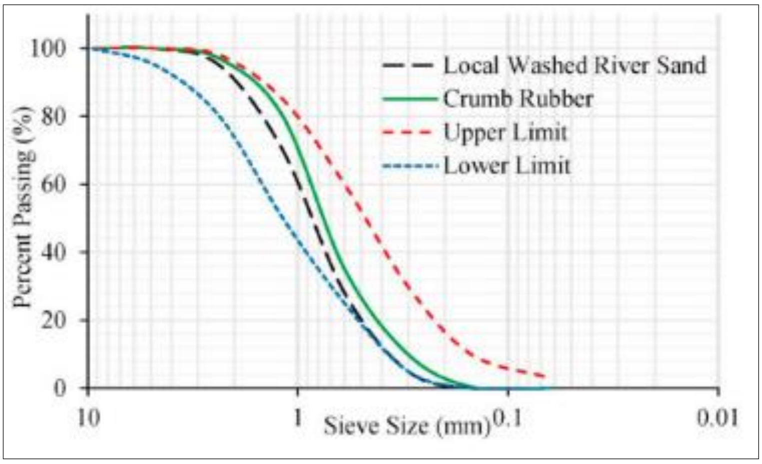

Figure 2 Grading curves of fine sand and crumb rubber (59)

4. Challenges and mitigation of utilizing Crumb Rubber in Concrete

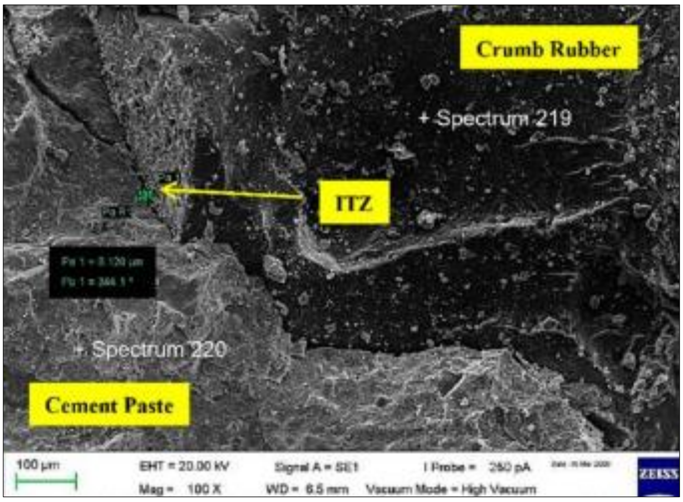

Figure 3 Microstructure of rubbercrete due to hydrophobic nature of crumb rubber [60]

Despite the advantages of concrete containing crumb rubber (rubbercrete), the most significant challenge is the reduction in the mechanical strengths in comparison to conventional concrete. This due to the hydrophobic nature of crumb rubber, which tends to repel water and entrap air on its surface during mixing process, thus thickening the interfacial transition zone (ITZ) and increasing the air voids in the hardened rubbercrete as shown in Figure 3. In addition, the irregular shape and impervious surface of crumb rubber particles contributes to reducing the bonding between crumb rubber particles and the hardened cement paste. under loading application on rubbercrete, micro-cracks initiates and propagates at the weak ITZ between crumb rubber particles and hardened cement paste due to difference in strain rates between rubber and hardened cement paste which eventually leads to premature failure. This limits the usage of rubbercrete to non-structural applications. Researchers have addressed this issue through various techniques, including treating the surface of crumb rubber (CR) with water, carbon tetrachloride solvent, and latex admixture; pre-coating CR with cement paste and METHOCEL cellulose ether solution; partially replacing cement with silica fume; treating CR with organic sulfur; using limestone powder as filler combined with an acrylic-based superplasticizer admixture; partially replacing cement with a mixture of silica fume and limestone powder; utilizing fly ash and metakaolin as cement substitutes; treating the CR surface with NaOH and bonding fine aggregate to the CR; and pre-coating CR with limestone. [25, 26, 27]. However, the most effective results in compensating for the strength reduction in rubbercrete have been achieved by incorporating up to 5% nano-silica by weight of cementitious materials and up to 0.08% graphene oxide into the rubbercrete mixture [28, 29, 30, 31, 32,33, 34, 35, 36, 37].

5. Properties of Rubbercrete

Rubbercrete exhibits several advantages over the conventional concrete. In the current research trend, researchers focus on developing rubbercrete containing crumb rubber as partial replacement to fine aggregate. This is justified by research findings which showing that replacing coarse aggregates with rubber chipping leads to dramatical reduction in strengths of the rubbercrete. Therefore, in this paper rubbercrete refers to concrete containing crumb rubber as partial replacement to fine aggregate [38, 39, 40]. The density of rubbercrete is inversely proportioned to the crumb rubber content since specific density of crumb rubber is lower than that of natural fine aggregate, therefore, replacing fine aggregate with crumb rubber leads to reduction in the density of the rubbercrete. Beside the low specific gravity of crumb rubber, the non-polar surface of crumb rubber particles entraps air during the mixing process increasing air voids in the microstructure of the hardening rubbercrete contributes to the lower density. The decreasing in density of the rubbercrete allows the development of lighter concrete [41, 42, 43]. High percentage of crumb rubber in rubbercrete resulting in reduction in the modulus of elasticity. This attributed to the lower elasticity modulus of the crumb rubber particles in comparison to natural fine aggregates. Unlike brittle characteristic of conventional concrete, rubbercrete exhibits higher ductility and gradual failure behaviour [44,45, 46]. Hardened rubbercrete remains intact beyond the failure load due to the elongation and ductile behaviour of the rubber and the ability of rubber to bridge the cracks as shown in Figure 4. This indicates the ability of rubbercrete to absorb dynamic load, resist crack propagation, high ductility and energy dissipation capacity. Ductile behavior of rubbercrete makes it suitable for area prone to earthquake as high energy absorption is required to minimize the structural damage [47,48, 49].

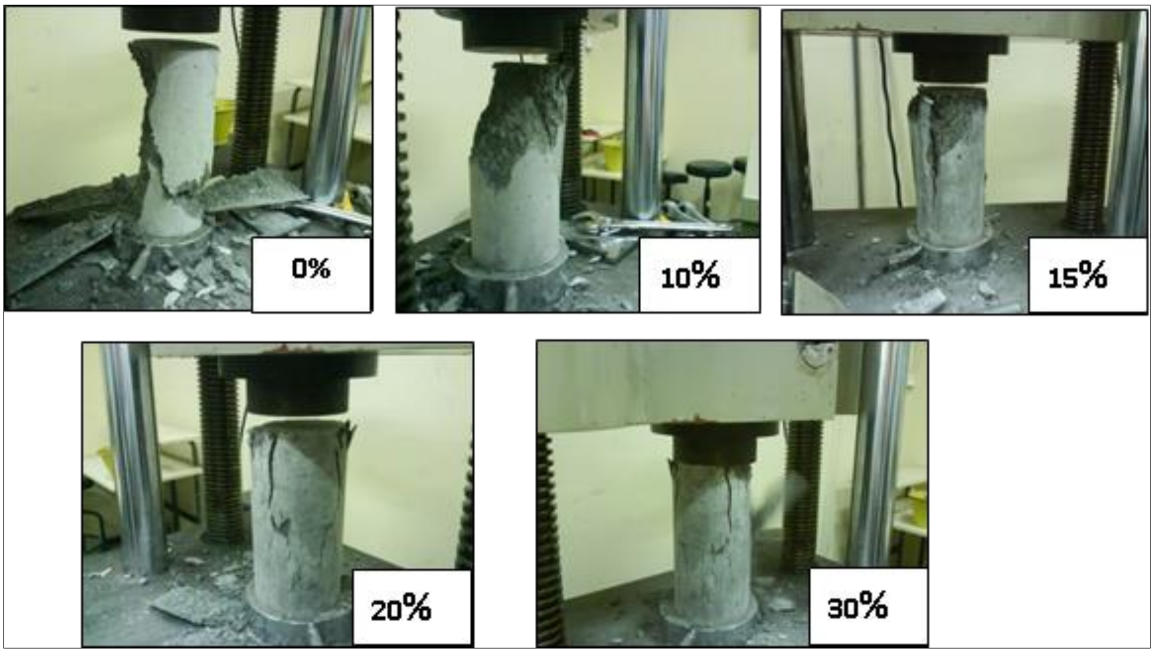

Figure 4 Failure mode of rubbercrete (61)

Compressive strength is one of the most adversely affected property of the rubbercrete. Utilizing crumb rubber in concrete, will lead to a reduction in the compressive strength. As shown in Figure 5, the reduction in the compressive strength increases as the replacement percentage of crumb rubber increasing [50,51,52]. Therefore, to mitigate the adverse effects of inclusion the crumb rubber into concrete, it has been suggested that crumb rubber replacement should not exceed 30%. Beside the weak bonding between crumb rubber particles and hardened cement paste, the reduction in compressive strength is attributed to the soft nature and lower stiffness of crumb rubber particle as compared to natural aggregate. During loading application, the soft crumb rubber particles act as stress concentration points in the composite, thus leading to debonding of crumb rubber and initiation of microcracks [53, 54].

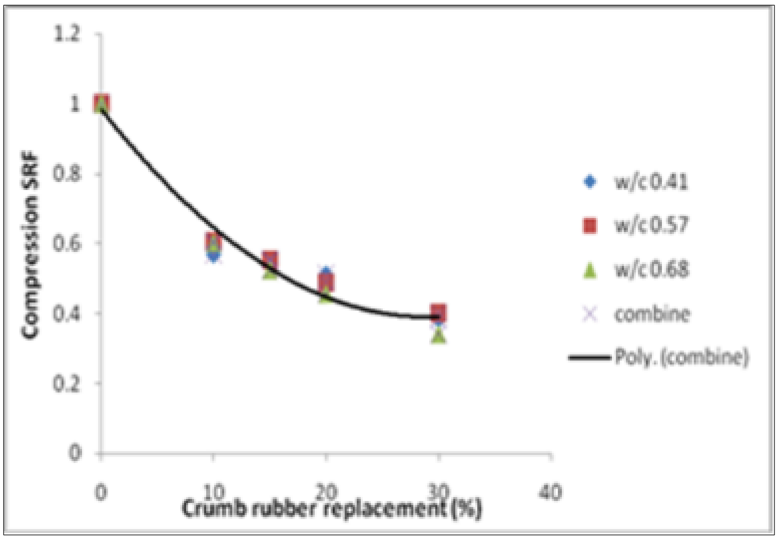

Figure 5 Compressive strength of rubbercrete (64)

In comparison to conventional concrete, rubbercrete exhibits a good sound absorption. Sound absorption is ability of the material to absorb the sound and not reflecting it back. This is due to ability of rubbercrete to absorb sound through the entrapped air on crumb rubber surface inside the microstructure of rubbercrete. Crumb rubber also perform well as a modifier in bituminous binder, allowing better noise reduction [55, 56, 57]. Rubber is essential insulator materials in the electrical industry. Crumb rubber particles offer better electrical insulation property of the rubbercrete compared to the conventional concrete, which makes rubbercrete has a good electrical resistivity [58,59]. In addition, increases the amount of crumb rubber replacement leads to increasing the thermal resistivity, in other words, decreasing the thermal conductivity of the rubbercrete in comparison to conventional concrete. 50% crumb rubber replacement reduce the thermal conductivity up to 50% as depicted in Figure 6 [63,64,65,66,67,68,69].

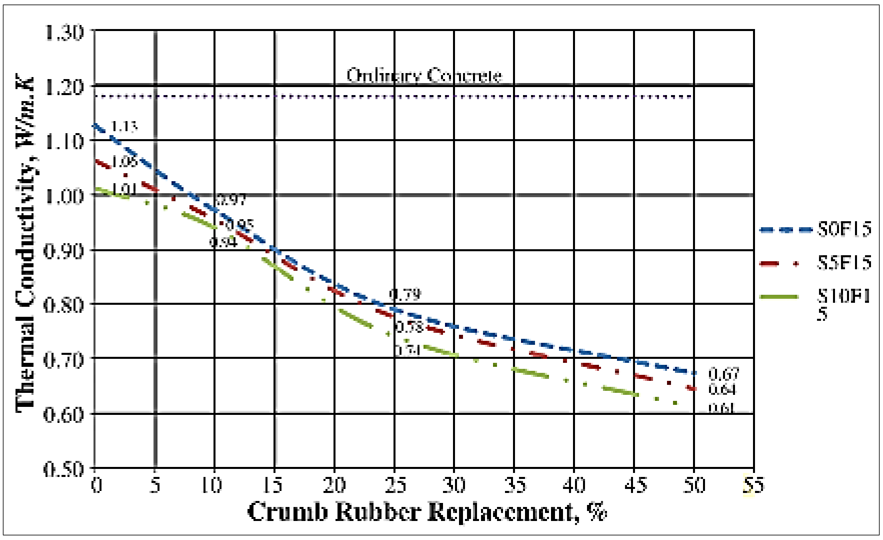

Figure 6 Thermal conductivity of rubbercrete (62)

6. Conclusion

The following conclusions can be drawn from this paper:

- Stockpiles of waste tires have a negative impact on both the environment and public health, as these non-biodegradable materials offer limited recycling opportunities.

- Using crumb rubber from recycled waste tires as a partial replacement for fine aggregate in the concrete industry offers several benefits, such as effective waste management, improved physical properties of rubbercrete compared to conventional concrete, and the conservation of natural resources.
- Various techniques have been explored by researchers to counteract the reduction in strength caused by the inclusion of crumb rubber in concrete. These include surface treatments, coating the rubber particles, adding cementitious materials, and incorporating nanomaterials

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Mohammed, B. S., Abdulkadir, I., Perceka, W., & Djayaprabha, H. S. (2023). The behavior of rubberized engineered cementitious composites under extreme loading: A review. Paper presented at the AIP Conference Proceedings, 2711. doi:10.1063/5.0137929

[2] Al-Fakih, A., Mohammed, B. S., Al-Osta, M. A., & Assaggaf, R. (2022). Evaluation of the mechanical performance and sustainability of rubberized concrete interlocking masonry prism. Journal of Materials Research and Technology, 18, 4385-4402. doi:10.1016/j.jmrt.2022.04.115

[3] Al-Fakih, A., Mohammed, B. S., Al-Shugaa, M. A., & Al-Osta, M. A. (2022). Experimental investigation of dry-bed joints in rubberized concrete interlocking masonry. Journal of Building Engineering, 58. doi:10.1016/j.jobe.2022.105048

[4] Appana, P. M., Mohammed, B. S., Abdulkadir, I., Ali, M. O. A., & Liew, M. S. (2022). Mechanical, microstructural and drying shrinkage properties of NaOH-pretreated crumb rubber concrete: RSM-based modeling and optimization. Materials, 15(7). doi:10.3390/ma15072588

[5] Choo, J., Mohammed, B. S., Chen, P. -., Abdulkadir, I., & Yan, X. (2022). Modeling and optimizing the effect of 3D printed origami bubble aggregate on the mechanical and deformation properties of rubberized ECC. Buildings, 12(12). doi:10.3390/buildings12122201

[6] Al-Fakih, A., Mohammed, B. S., Liew, M. S., Wahab, M. W. A., & Haruna, S. (2021). Utilizing of crumb rubber derived recycled scrap tires in masonry application: A review doi:10.4028/www.scientific.net/MSF.1030.73.

[7] Mohammed, B. S., Xian, L. W., Haruna, S., Liew, M. S., Abdulkadir, I., & Zawawi, N. A. W. A. (2021). Deformation properties of rubberized engineered cementitious composites using response surface methodology. Iranian Journal of Science and Technology - Transactions of Civil Engineering, 45(2), 729-740. doi:10.1007/s40996-020-00444-3

[8] Murali, M., Mohammed, B. S., Abdulkadir, I., Liew, M. S., & Alaloul, W. S. (2021). Utilization of crumb rubber and high-volume fly ash in concrete for environmental sustainability: Rsm-based modeling and optimization. Materials, 14(12). doi:10.3390/ma14123322

[9] Sabapathy, L., Mohammed, B. S., Al-Fakih, A., Wahab, M. M. A., Liew, M. S., & Amran, Y. H. M. (2020). Acid and sulphate attacks on a rubberized engineered cementitious composite containing graphene oxide. Materials, 13(14). doi:10.3390/ma13143125

[10] Al-Fakih, A., Wahab, M. M. A., Mohammed, B. S., Liew, M. S., Wan Abdullah Zawawi, N. A., & As'ad, S. (2020). Experimental study on axial compressive behavior of rubberized interlocking masonry walls. Journal of Building Engineering, 29. doi:10.1016/j.jobe.2019.101107

[11] Hong, D. L. H., Mohammed, B. S., Al-Fakih, A., Wahab, M. M. A., Liew, M. S., & Mugahed Amran, Y. H. (2020). Deformation properties of rubberized ecc incorporating nano graphene using response surface methodology. Materials, 13(12). 1-14. doi:10.3390/ma13122831

[12] Khed, V. C., Mohammed, B. S., Liew, M. S., & Abdullah Zawawi, N. A. W. (2020). Development of response surface models for self-compacting hybrid fibre reinforced rubberized cementitious composite. Construction and Building Materials, 232. doi:10.1016/j.conbuildmat.2019.117191

[13] Adamu, M., Mohammed, B. S., Liew, M. S., & Alaloul, W. S. (2019). Evaluating the impact resistance of roller compacted concrete containing crumb rubber and nanosilica using response surface methodology and weibull distribution. World Journal of Engineering, 16(1). 33-43. doi:10.1108/WJE-10-2018-0361

[14] Mohammed, B. S., & Adamu, M. (2019). Non-destructive evaluation of nano silica-modified roller-compacted rubbercrete using combined SonReb and response surface methodology. Road Materials and Pavement Design, 20(4), 815-835. doi:10.1080/14680629.2017.1417891

[15] Ng, C. Y., Narong, A. R., Kamarul Zaman, A. B., Mustaffa, Z., Mohammed, B. S., & Ean, L. W. (2019). Properties of modified high permeable concrete with a crumb rubber. Open Civil Engineering Journal, 13(1). 82-91. doi:10.2174/1874149501913010082

[16] Adamu, M., Mohammed, B. S., & Liew, M. S. (2018). Effect of crumb rubber and nano silica on the creep and drying shrinkage of roller compacted concrete pavement. International Journal of GEOMATE, 15(47). 58-65. doi:10.21660/2018.47.22082

[17] Adamu, M., Mohammed, B. S., Shafiq, N., & Shahir Liew, M. (2018). Effect of crumb rubber and nano silica on the fatigue performance of roller compacted concrete pavement. Cogent Engineering, 5(1). doi:10.1080/23311916.2018.1436027

[18] Mohammed, B. S., Khed, V. C., & Nuruddin, M. F. (2018). Rubbercrete mixture optimization using response surface methodology. Journal of Cleaner Production, 171, 1605-1621. doi:10.1016/j.jclepro.2017.10.102

[19] Aman, S. S., Mohammed, B. S., & Al-Fakih, A. (2021). Crumb rubber mortar and its properties: An overview. Paper presented at the AIP Conference Proceedings, 2339. doi:10.1063/5.0044262

[20] Mohammed, B. S., Al-Fakih, A., & Liew, M. S. (2021). Characteristics of interlocking concrete bricks incorporated crumb rubber and fly ash doi:10.1007/978-981-33-6311-3_72

[21] Abdulkadir, I., Mohammed, B. S., Liew, M. S., Bin Abdul Wahab, M. M., Zawawi, N. A. W. A., & As'ad, S. (2020). A review of the effect of waste tire rubber on the properties of ECC. International Journal of Advanced and Applied Sciences, 7(8). 105-116. doi:10.21833/ijaas.2020.08.011

[22] Mohammed, B. S., Liew, M. S., S Alaloul, W., Al-Fakih, A., Ibrahim, W., & Adamu, M. (2018). Development of rubberized geopolymer interlocking bricks. Case Studies in Construction Materials, 8, 401-408. doi:10.1016/j.cscm.2018.03.007

[23] Adamu, M., Mohammed, B. S., Shafiq, N., & Shahir Liew, M. (2018). Skid resistance of nano silica modified roller compacted rubbercrete for pavement applications: Experimental methods and response surface methodology. Cogent Engineering, 5(1). doi:10.1080/23311916.2018.1452664

[24] Adamu, M., Mohammed, B. S., & Shahir Liew, M. (2018). Mechanical properties and performance of high volume fly ash roller compacted concrete containing crumb rubber and nano silica. Construction and Building Materials, 171, 521-538. doi:10.1016/j.conbuildmat.2018.03.138

[25] Adamu, M., Mohammed, B. S., & Shafiq, N. (2018). Abrasion resistance of nano silica modified roller compacted rubbercrete: Cantabro loss method and response surface methodology approach. Paper presented at the IOP Conference Series: Earth and Environmental Science, 140(1). doi:10.1088/1755-1315/140/1/012119

[26] Alaloul, W. S., Loganathan, R., Mohammed, B. S., Hasan, E., Nikbakht, Liew, M. S., Adamu, M. (2018). Deformation properties of concrete containing crumb rubber as partial replacement to fine aggregate. International Journal of Civil Engineering and Technology, 9(10), 317-326.

[27] Al-Fakih, A., Mohammed, B. S., Liew, M. S., & Alaloul, W. S. (2018). Physical properties of the rubberized interlocking masonry brick. International Journal of Civil Engineering and Technology, 9(6), 656-664.

[28] Rahim, N. I., Mohammed, B. S., Abdulkadir, I., & Dahim, M. (2022). Effect of crumb rubber, fly ash, and nanosilica on the properties of self-compacting concrete using response surface methodology. Materials, 15(4). doi:10.3390/ma15041501

[29] Al-Fakih, A., Mohammed, B. S., & Liew, M. S. (2021). On rubberized engineered cementitious composites (R-ECC): A review of the constituent material. Case Studies in Construction Materials, 14. doi:10.1016/j.cscm.2021.e00536

[30] Loganathan, R., & Mohammed, B. S. (2021). Properties of rubberized engineered cementitious composites containing nano-silica. Materials, 14(13). doi:10.3390/ma14133765

[31] Rahim, N. I., Mohammed, B. S., & Al-Fakih, A. (2021). Physical properties of rubberized self-consolidating concrete (R-SCC) incorporating nano-silica. Paper presented at the AIP Conference Proceedings, 2339 doi:10.1063/5.0044267

[32] Adamu, M., Mohammed, B. S., Shafiq, N., & Liew, M. S. (2020). Durability performance of high volume fly ash roller compacted concrete pavement containing crumb rubber and nano silica. International Journal of Pavement Engineering, 21(12), 1437-1444. doi:10.1080/10298436.2018.1547825

[33] Abdulkadir, I., & Mohammed, B. S. (2023). Effect of graphene oxide on the long-term modulus of elasticity and poisson's ratio of rubberized ECC. Paper presented at the AIP Conference Proceedings, 2711. doi:10.1063/5.0137930

[34] Abdulkadir, I., Mohammed, B. S., Ali, M. O. A., & Liew, M. S. (2022). Effects of graphene oxide and crumb rubber on the fresh properties of self-compacting engineered cementitious composite using response surface methodology. Materials, 15(7). doi:10.3390/ma15072519

[35] Abdulkadir, I., Mohammed, B. S., Liew, M. S., & Wahab, M. M. A. (2022). Effect of graphene oxide and crumb rubber on the drying shrinkage behavior of engineered cementitious composite (ECC): Experimental study, RSM—Based modelling and optimization, Sustainable Practices and Innovations in Civil Engineering. Lecture Notes in Civil Engineering, 179. doi:10.1007/978-981-16-5041-3_3

[36] Abdulkadir, I., Mohammed, B. S., Liew, M. S., & Wahab, M. M. A. (2021). Modelling and optimization of the mechanical properties of engineered cementitious composite containing crumb rubber pretreated with graphene oxide using response surface methodology. Construction and Building Materials, 310. doi:10.1016/j.conbuildmat.2021.125259

[37] Mohammed, B. S., Yen, L. Y., Haruna, S., Seng Huat, M. L., Abdulkadir, I., Al-Fakih, A., . . . Abdullah Zawawi, N. A. W. (2020). Effect of elevated temperature on the compressive strength and durability properties of crumb rubber engineered cementitious composite. *Materials, 13*(16). doi:10.3390/MA13163516

[38] Al-Fakih, A., Mohammed, B. S., Liew, M. S., Alaloul, W. S., Adamu, M., Khed, V. C., Al-Mattarneh, H. (2018). Mechanical behavior of rubberized interlocking bricks for masonry structural applications. International Journal of Civil Engineering and Technology, 9(9), 185-193.

[39] Khed, V. C., Mohammed, B. S., Liew, M. S., Alaloul, W. S., Adamu, M., Al-Fakih, A., & Karthikeyan, J. (2018). Experimental investigation on pullout strength of hybrid reinforcement of fibre in rubberized cementitious composites. International Journal of Civil Engineering and Technology, 9(7), 1612-1622.

[40] Mohammed, B. S., Azmi, N. J., & Abdullahi, M. (2011). Evaluation of rubbercrete based on ultrasonic pulse velocity and rebound hammer tests. Construction and Building Materials, 25(3), 1388-1397. doi:10.1016/j.conbuildmat.2010.09.004

[41] Khed, V. C., Mohammed, B. S., & Nuruddin, M. F. (2018). Effects of different crumb rubber sizes on the flowability and compressive strength of hybrid fibre reinforced ECC. Paper presented at the IOP Conference Series: Earth and Environmental Science, 140(1). doi:10.1088/1755-1315/140/1/012137

[42] Mohammed, B. S., & Adamu, M. (2018). Mechanical performance of roller compacted concrete pavement containing crumb rubber and nano silica. Construction and Building Materials, 159, 234-251. doi:10.1016/j.conbuildmat.2017.10.098

[43] Mohammed, B. S., & Ahmed Nezri, A. N. S. B. (2015). Durability aspects and bond strength of rubbercrete containing nano silica. Paper presented at the Proceedings, Annual Conference - Canadian Society for Civil Engineering, 2, 888-893.

[44] Mohammed, B. S. (2010). Structural behavior and m-k value of composite slab utilizing concrete containing crumb rubber. Construction and Building Materials, 24(7), 1214-1221. doi:10.1016/j.conbuildmat.2009.12.018

[45] Mohammed, B. S., Nuruddin, M. F., & Shafiq, N. (2016). Development of high strength nano-silica modified rubbercrete. Paper presented at the Proceedings, Annual Conference - Canadian Society for Civil Engineering, 2, 1441-1446.

[46] Adamu, M., Mohammed, B. S., & Shafiq, N. (2016). Nano silica modified roller compacted rubbercrete – an overview. Paper presented at the Engineering Challenges for Sustainable Future - Proceedings of the 3rd International Conference on Civil, Offshore and Environmental Engineering, ICCOEE 2016, 483-488. doi:10.1201/b21942-98

[47] Mohammed, B. S., Adamu, M., & Liew, M. S. (2018). Evaluating the effect of crumb rubber and nano silica on the properties of high volume fly ash roller compacted concrete pavement using non-destructive techniques. Case Studies in Construction Materials, 8, 380-391. doi:10.1016/j.cscm.2018.03.004

[48] Mohammed, B. S., Adamu, M., & Liew, M. S. (2018). Evaluating the static and dynamic modulus of elasticity of roller compacted rubbercrete using response surface methodology. International Journal of GEOMATE, 14(41), 186-192. doi:10.21660/2018.41.42833

[49] Khed, V. C., Mohammed, B. S., Shahir Liew, M., Alaloul, W. S., & Adamu, M. (2018). Hybrid fibre rubberized ECC optimization for modulus of elasticity. International Journal of Civil Engineering and Technology, 9(7), 918-928.

[50] Mohammed, B. S., Adamu, M., & Shafiq, N. (2017). Establishing relationship between modulus of elasticity and strength of nano silica modified roller compacted rubbercrete. International Journal of GEOMATE, 13(39). 103-110. doi:10.21660/2017.39.23401

[51] Adamu, M., Mohammed, B. S., & Shafiq, N. (2017). Mechanical performance of roller compacted rubbercrete with different mineral filler. Jurnal Teknologi, 79(6), 75-88. doi:10.11113/jt.v79.10200

[52] Mahamood, N., Mohammed, B. S., Shafiq, N., & Eisa, S. M. B. (2016). Development of nano silica modified solid rubbercrete bricks. Paper presented at the Engineering Challenges for Sustainable Future - Proceedings of the 3rd International Conference on Civil, Offshore and Environmental Engineering, ICCOEE 2016, 443-446. doi:10.1201/b21942-90

[53] Adamu, M., Mohammed, B. S., & Shafiq, N. (2017). Evaluating the effect of superplasticizer on the properties of roller compacted concrete using response surface methodology. ARPN Journal of Engineering and Applied Sciences, 12(21), 6206-6215.

[54] Mohammed, B. S., Adamu, M., & Shafiq, N. (2017). A review on the effect of crumb rubber on the properties of rubbercrete. International Journal of Civil Engineering and Technology, 8(9), 599-615.

[55] Adamu, M., Mohammed, B. S., Woen, E. L., Yen, L. Y., & Bala, N. (2020). Mechanical performance of engineered cementitious composite containing crumb rubber at elevated temperature. Paper presented at the *IOP Conference Series: Earth and Environmental Science, 476*(1). doi:10.1088/1755-1315/476/1/012023

[56] Al-Fakih, A., Mohammed, B. S., Wahab, M. M. A., Liew, M. S., & Mugahed Amran, Y. H. (2020). Flexural behavior of rubberized concrete interlocking masonry walls under out-of-plane load. *Construction and Building Materials, 263.* doi:10.1016/j.conbuildmat.2020.120661

[57] Mohammed, B. S., Awang, A. B., Wong, S. S., & Nhavene, C. P. (2016). Properties of nano silica modified rubbercrete. Journal of Cleaner Production, 119, 66-75. doi:10.1016/j.jclepro.2016.02.007

[58] Adamu, M., Mohammed, B. S., & Shafiq, N. (2017). Effect of polycarboxylate superplasticizer dosage on the mechanical performance of roller compacted rubbercrete for pavement applications. Journal of Engineering and Applied Sciences, 12(20), 5253-5260. doi:10.3923/jeasci.2017.5253.5260

[59] Al-Fakih, A., Mohammed, B. S., Wahab, M. M. A., Liew, M. S., Mugahed Amran, Y. H., Alyousef, R., & Alabduljabbar, H. (2020). Characteristic compressive strength correlation of rubberized concrete interlocking masonry wall. Structures, 26, 169-184. doi:10.1016/j.istruc.2020.04.010

[60] Shahrul, S., Mohammed, B. S., Wahab, M. M. A., & Liew, M. S. (2021). Mechanical properties of crumb rubber mortar containing nano-silica using response surface methodology. Materials, 14(19). doi:10.3390/ma14195496

[61] Mohammed, B. S., & Azmi, N. J. (2011). Failure mode and modulus elasticity of concrete containing recycled tire rubber. Journal of Solid Waste Technology and Management, 37(1), 16-24. doi:10.5276/JSWTM.2011.16

[62] Mohammed, B. S., Anwar Hossain, K. M., Eng Swee, J. T., Wong, G., & Abdullahi, M. (2012). Properties of crumb rubber hollow concrete block. Journal of Cleaner Production, 23(1), 57-67. doi:10.1016/j.jclepro.2011.10.035

[63] Adamu, M., Mohammed, B. S., & Shafiq, N. (2017). Effect of mineral filler type on strength of roller compacted rubbercrete for pavement applications. Paper presented at the *IOP Conference Series: Materials Science and Engineering, 201*(1). doi:10.1088/1757-899X/201/1/012011

[64] Mohammed, B. S., & Azmi, N. J. (2014). Strength reduction factors for structural rubbercrete. *Frontiers of Structural and Civil Engineering, 8*(3), 270-281. doi:10.1007/s11709-014-0265-7

[65] Mohammed, B. S., Hossain, K. M. A., & Azmi, N. J. (2012). Relationships of mechanical properties for concrete containing crumb rubber as partial replacement to fine aggregate. Paper presented at the *Proceedings, Annual Conference - Canadian Society for Civil Engineering, 3,* 2410-2418. doi: 10.1016/j.proeng.2011.12.445

[66] Mohammed, Bashar S., Abdulkadir, Isyaka, Perceka, Wisena, Djayaprabha, Herry Suryadi. (2023). The behavior of rubberized engineered cementitious composites under extreme loading: A review. *AIP Conference Proceedings*, Volume 2711.

[67] Giri, Yajish Giri A/L Parama; Mohammed, Bashar S.; Liew M.S.; Zawawi, Noor Amila Wan Abdullah; Abdulkadir, Isyaka; Singh,Priyanka; Ravindran, Gobinath. (23). Mechanical and Microstructural Properties of Rubberized Geopolymer Concrete: Modeling and Optimization. Buildings, Volume 13, Issue 8. DOI:10.3390/buildings13082021.

[68] Abdulkadir, Isyaka; Mohammed, Bashar S.; Al-Yacouby, Ahmad Mahamad; Woen, Ean Lee; Tafsirojjaman T. (2024). Tailoring an engineered cementitious composite with enhanced mechanical performance at ambient and elevated temperatures using graphene oxide and crumb rubber. Journal of Materials Research and Technology. Volume 28, Pages 4508 – 4530. DOI: 10.1016/j.jmrt.2024.01.059

[69] Abdulkadir, Isyaka; Mohammed, Bashar S.; Woen, Ean Lee; Sing, Wong Leong; Al-Yacouby, Ahmad Mahamad (2024). Optimizing sulfate and acid resistance in rubberized engineered cementitious composite with graphene oxide-pretreated crumb rubber: A response surface methodology approach. Developments in the Built Environment. Volume 18. DOI: 10.1016/j.dibe.2024.100405.