(e)ISSN 2656-8896 (p)ISSN 2656-890X
Journal of Infrastructure and Facility Asset Management – Vol. 2, Supplement 1, December 2020

Effect of Waste Tire Rubber on the Durability Behavior of Cement Composites: A Review

Isyaka Abdulkadir[1,2,a) **& Bashar S. Mohammed**[1,b)]

[1)] Civil and Environmental Eng. Dept., Universiti Teknologi PETRONAS, Seri Iskandar, Malaysia.
[2)] Civil Engineering Department, Bayero University, Kano, Nigeria.

Correspondents : [a)]isyaka_18000638@utp.edu.my & [b)]bashar.mohammed@utp.edu.my

ABSTRACT

A lot of literature reviews exist on the mechanical properties of rubberized cement composites (mortar, concrete and engineered cementitious composite). However, very little of such works exist on the effect of waste tire rubber on the durability of the composites. This paper aims to review how the use of tire rubber in cement composites affects the water absorption, permeability and resistance to aggressive chemicals (sulphates and chlorides). Recent literatures on the use of CR in concrete, mortar, and Engineered Cementitious Composites (ECC) were reviewed to assess how incorporation of rubber influences the water absorption, permeability, and chloride and sulphate resistance of the composites. The findings revealed that CR incorporation consistently enhances the resistance of the composites to the adverse effect of chloride and sulphate ions. However, there are differing opinions by researchers regarding the effect of the CR on water absorption and permeability of the rubberized composites.

Keywords : infrastructure management, crum rubber, durability, cement composite,

INTRODUCTION

The overwhelming rate at which tire waste is generated globally is alarming. This problem is caused by the increase in the production and ownership of automobiles around the world (Mohammed, Achara, Nuruddin, Yaw, & Zulkefli, 2017; Mohammed, Adamu, & Shafiq, 2017; Na & Xi, 2016). The situation leads to significant increase in the world rubber consumption by 3.4% from 29.39 million tonnes in 2018 to 30.12 million tonnes in 2019 as forecasted by International Rubber Study Group (IRSG) (Chen, Li, Zhang, Xu, & Zhang, 2019). This rise in the global rubber consumption is due to increase in tire production as evident from a hike in the waste tire generation; estimated at 3.6 million tonnes in EU by 2013 and 4.9 million tonnes in USA by 2015 (Záleská, Pavlík, Čítek, Jankovský, & Pavlíková, 2019). This problem is considered as one of the most serious environmental challenges in the world as a result of its numerous disadvantages (Gupta, Chaudhary, & Sharma, 2016; Mohammed & Adamu, 2018; S Mohammed et al., 2018). The use of land filling method of discarding waste tire has been banned by many countries because of the negative consequences associated with such practice (Strukar, Kalman Šipoš, Miličević, & Bušić, 2019). Among the problems caused by waste tire disposal is that due to the rapid rate of its generation, large area of useful land is consumed by the tire stockpiles because of its fixed volume and non-biodegradable nature (Mohammed, Hossain, Swee, Wong, & Abdullahi, 2012). The tire stockpiles attract rodents, vermin and disease causing organisms such as mosquitos (Mohammed, Khed, & Nuruddin, 2018; Strukar et al., 2019). Also, in an event of fire outbreak in such stockpiles, it is very difficult if not impossible to extinguish coupled with the poisonous smoke emitted as shown in Fig. 1 (Mohammed et al., 2018; Nacif, Panzera, Strecker, Christoforo, & Paine, 2013). The use of specific waste material is important for the Infrastructure. This will increase the environment sustainability aspect of infrastructure (Suprayitno & Soemitro, 2018).

The need for proper and environmentally friendly ways of reusing discarded waste tires has lead researchers to find feasible means of using the rubber in cement composites as construction material (Gerges, Issa, & Fawaz, 2018; Gonen, 2018; Lakusic, 2019; Mohammed, Awang, Wong, & Nhavene, 2016). Cement composites (chiefly cement mortar and concrete) are the most popular construction materials in the world (Horszczaruk, Mijowska, Kalenczuk, Aleksandrzak, & Mijowska, 2015; Z. Pan et al., 2015). Their popularity and wide spread use in construction is owed to their amazing and versatile properties in fresh and hardened states. Cement composites are produced from locally available and relatively cheaper raw materials. The composites can be formed in to almost any conceivable shape and size while in fresh state and possess a good mechanical strength at hardened state (Reches, 2018). However, despite being very good in resisting compressive stresses in hardened state, cement composites are very weak in tension and that makes them very brittle (Z. D. PAN, Wenhui; LI, Dan; COLLINS, Frank, 2013). Their brittle nature makes them very predisposed to crack development and propagation (Lv et al., 2013). In an attempt to find a solution to this problem, numerous researchers experimented by incorporating discarded tire rubber in various forms to develop rubberized cement composites (AbdelAleem & Hassan, 2018; X. Wang, Xia, Nanayakkara, & Li, 2017).

Figure 1. Discarded waste tires on fire

A lot of research findings revealed that the use of tire rubber in cement composites has many advantages such as enhanced energy absorption capacity (Aiello & Leuzzi, 2010; Corinaldesi & Donnini, 2019), improved tensile and ductility behavior (Aiello & Leuzzi, 2010; Corinaldesi & Donnini, 2019), increased abrasion resistance (Thomas, Gupta, Kalla, & Cseteneyi, 2014), better freeze-thaw resistance (Corinaldesi & Donnini, 2019; Gonen, 2018; Siddique & Naik, 2004), enhanced sound and insulation behavior among others(Corinaldesi & Donnini, 2019). While there are a lot of reviews on the performance of waste tire rubber (in the form of crumb rubber or powdered rubber) in cement composites (Siddika et al., 2019; Xu, Yao, Yang, & Han, 2020), there is however very little such literatures on the influence of the tire rubber on the durability of cement composites despite the high number of research conducted recently focusing on the durability performance of rubberized cement composites. This paper focuses on the durability of all types of cement composites (i.e. mortar, concrete and ECC) incorporating tire rubber in any form (CR, PR, waste tire fiber etc.). In the subsequent sections, discussions on the material (tire rubber) and reviews of recent research findings on its influence on the durability of cement composites follow.

WASTE TIRE RUBBER

As shown in Table 1, tire is made of a combination of natural rubber, synthetic rubber, carbon black steel, and doses of different fillers, accelerators and antioxidants in different weight percentage proportions(Alexander et al., 2018; Khed, Mohammed, & Nuruddin, 2018). Waste tire rubber for cement composite application is usually produced using one of two processes known as ambient or cryogenic grinding process(Alexander et al., 2018). The ambient process of producing crumb rubber usually starts with reducing the waste tire in to 100 mm to 50 mm pieces by mechanical shredding at room temperature(Alexander et al., 2018). Primary granulation process follows in which the pieces are further reduced to sizes ranging from 50 mm to 10 mm. Using magnetic separation technique, steel fibers are removed from the tire rubber and secondary granulation process follows. The rubber chips are then subjected to further grinding using rolling mills in to crumb rubber of various desired sizes(Mohammed et al., 2012) as explained in the following sub-sections.

Table 1. Composition of Tire by Weigth

Composition	Automobile tire (wt. %)	Truck tire (wt. %)
Natural Rubber	14	27
Synthetic Rubber	27	14
Carbon Black	28	28
Steel	14 – 15	14 – 15
Fabric, filler, accelerators and antioxidants	16– 17	16– 17

Source: (Alhumoud, 2020)

RESEARCH METHODS

The general objective is to identify cost components of Green Building projects in government offices from the design stage to the specified age and determine the life cycle cost structure by using a real case The Ministry of Public Works and Housing Main Building. For the first step, data collection methods used in this study includes the preparation stage to formulate the research problem, research objectives, and explore data to the stakeholders involved in the project. The next stage is data collection by taking the field survey of the research location and conduct the permitting process for data collection to the stakeholders which are Bureau of General Affairs Ministry of Public Works and Housing as the owner, SNVT P4SBPUPRL as Construction Project Officer and PT. Airkon Pratama as building management operator. Later Data Analysis was performed after the data was collected to create a life cycle cost calculation using MSExcel, followed by discussion and conclusion to this research.

Building under Study

The Ministry of Public Works and Housing Main Building is situated on Jalan Pattimura 20 Kebayoran Baru, South Jakarta as one of the office building inside the Central Office Complex of the Ministry of Public Works and Housing, an office area with an area of 53.846 m^2 which were designed to be a green site or green campus.

Water Absorption And Permeability

The water absorption behavior of a cementitious composite is usually associated with the porosity of the composite. The moisture transfer behavior within the network of pores in the composite is affected by the nature and the geometry of pores (Zaouai, Tafraoui, Makani, & Benmerioul, 2019). In the same vein, the water absorption is closely linked to permeability which gives the material's resistance to water penetration and hence ions and other potentially harmful substances that could cause a chemical attack (T. M. Pham et al., 2019).

Zaouai et al. (Zaouai et al., 2019), worked on the hardened and transfer properties of self-compacting concrete containing crumb rubber and crushed dune sand. Their results indicated that crushed sand dune pre-coated crumb rubber leads to a higher water absorption. It was revealed that a 5% sand dune used for pre-coating the CR lead to a 10% increase in the water absorption. Zaleska et al.(Záleská et al., 2019), reported that increase in the CR percentage replacement lead to an increase in the porosity of the composite which in turn influences the water transport properties of rubberized concrete. However, their water absorption parameter values did not follow a uniform trend. But the result generally indicated that finer crumb rubber lead to more water absorption than coarser crumb rubber particles (Záleská et al., 2019).

Similarly, Pham et al.(T. M. Pham et al., 2019) worked on the durability characteristics of rubberized lightweight concrete and their findings on initial rate of absorption (IRA) of water test showed that irrespective of rubber pretreatment method used (NaOH and water washing), increase in CR content lead to increase in water absorption. The authors mentioned that for 15% and 30% content NaOH pretreated CR, the water absorption increased to 7.26% and 7.72% respectively from the water absorption value of the control which is 6.96% as shown in Figure 4 (T. M. Pham et al., 2019). Also, Mohammed et al (Liu, Luo, Gong, & Wei, 2018) tested the water absorption of a rubberized masonry brick. They found that the brick has an absorption value of 25.23% which classified it as a 3rd class brick based on the provisions of ASTM C67-14.

After conducting a water absorption test on waste tire rubber concrete, Girkas and Nagrockiene (Girskas & Nagrockienė, 2017) found out that the 20% CR substitution has the highest average water absorption of 4.95% while 3.49% was recorded as the lowest for control specimen. Generally, the trend of the result revealed that there was an increase in water intake with increase in the rubber content. They ascribed that to the nature of the rubber granules creating more pores and taking up more water by capillary suction. Also, it was revealed that finer sized CR led to more water absorption when compared with coarser CR particles. Smaller sized CR (2/4) samples absorb 2.87% more water than the coarser CR (4/6) samples at 5 to 10% replacement levels.

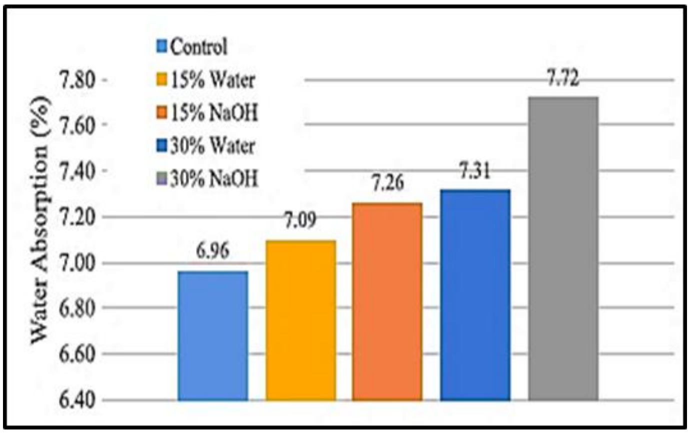

Figure 2. Water Absorption of NaOH and Water Pretreated CR Concrete (T. M. Pham et al., 2019)

Bisht and Ramana (Bisht & Ramana, 2017) similarly reported an increase in CR concrete water absorption and permeability with increase in the rubber content as depicted in Figure 5 (a) and (b) respectively. A water absorption of 3.21% was observed for 5.5% CR (highest) replacement while 1.91% was recorded as the absorption value for the control specimen (0%

CR). This trend is attributed to the increase in the voids due to the CR addition and also to the cracks within the matrix. On permeability, an increase of 3.33% and 6.66% were recorded from 4% and 5.5% CR replacement respectively as compared with the control (0% CR). This increase in the water penetration depth is brought about by the increased between the CR and the cement matrix (Bisht & Ramana, 2017).

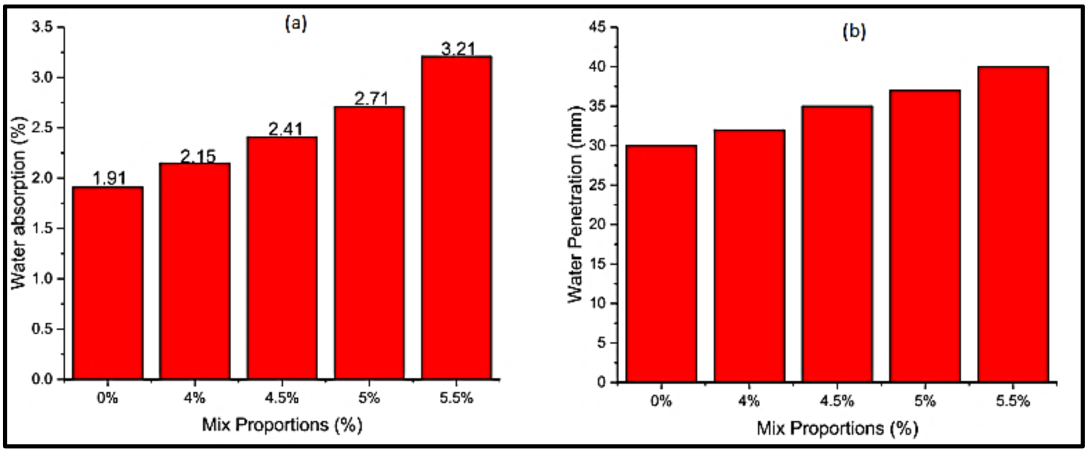

Figure 3. (a) Water Absorption of CR Concrete (b) Water Penetration (permeability) of CR Concrete (Bisht & Ramana, 2017)

However, contrary to the findings of the preceding researchers, Wang et al (R. Wang, Tao, & Li, 2019) in their work on the evaluation of the micro-crack size in rubber concrete ITZ exposed to sulfate attack reported that due to the hydrophobic nature of CR particles, concrete samples with higher CR content exhibited lower water absorption than samples with lower CR content which lead to the weakening of the bond between the rubber and the cement composite in the later (R. Wang et al., 2019). In the same vein, Rahat et al. (Rahat Dahmardeh, Sargazi Moghaddam, & Mirabi Moghaddam, 2019) investigated the influence of waste glass and rubber on the water absorption behavior of self-compacting concrete (SCC) and their result indicated a diminishing water absorption with increasing waste content as shown in Figure 6. They reported that larger CR particles were more effective in reducing the water absorption than smaller CR particles which agrees with the findings of the previous researchers discussed.

Li et al. (Li et al., 2019) reported a general decrease in water absorption with increase in recycled tire aggregate. The researchers attributed the behavior to the hydrophobic nature of the waste tire rubber aggregates affecting their contact angle to be greater than 90° which decreases the penetration force of the water (Li et al., 2019). Similarly, a permeability test result conducted by Reshi et al. (Nayeem Ahmad Reshi, 2019) indicated a reduction of 5.7, 13.30%, 20.9% and 23.5% for 10% to 40% replacement levels of CR with fine aggregate respectively. Li et al. (Li et al., 2019) arrived at a similar finding when they used recycled tire aggregate in self-compacting concrete. They attributed the decrease in the water absorption to the increase in contact angle between the water and the hydrophobic rubber particles thereby reducing the driving force of water in to the specimen.

Pham et al (N. P. Pham, Toumi, & Turatsinze, 2018) reported a decrease in water absorption with the use of rubber aggregate (RA). They attributed the higher absorption of the control mortar to the higher rate of absorption of the sand as compared to the RA and also to the hydrophobic nature of the RA particle which makes it repel water. They stated that the combination of these effects led to the lower water absorption value in the matrix despite higher amount of pores in the RA composites. Also, Dahmardeh et al (Rahat Dahmardeh et al., 2019) reported a reduction in the water absorption of SCC with increase in CR content. They ascribed the reason for the reduction in the water absorption to the nature of the rubber particles that have very negligible water absorption property when compared to natural aggregates.

Mukaddas et al. (A. M. Mukaddas, 2019) worked on the influence of using treated crumb rubber (TCR) and oil palm fruit fiber (OPFF) on water permeability, chloride and sulfate resistance of mortar. Their results revealed that the permeability of the samples was inconsistent at 10% to 30% TCR replacement when immersion method of curing was used. When spray curing method was used however, the permeability depth remain within the medium level except at 30% replacement level. This is attributed to the poor bonding between the rubber particles and the cement paste with the interphase serving as the inlet for the pressurized water(A. M. Mukaddas, 2019).

In the same vein, Liu et al conducted a research to determine the permeability of pervious concrete containing crumb rubber. They concluded that incorporation of CR reduces the permeability of the rubber modified pervious concrete. They attributed the decrease in permeability to the reduction in the porosity of the pervious concrete by the CR. They also reported that the different in size of the CR used does not affect the permeability of the concrete.

Gupta et al (Gupta, Siddique, Sharma, & Chaudhary, 2017) assessed the effect of elevated temperature and cooling regime on the mechanical and durability of concrete containing waste tire fiber. Based on the classification of permeability developed by Ganjiang et al(Ganjian, Khorami, & Maghsoudi, 2009), the authors determined that the rubber fiber concrete samples were all having medium permeability after being subjected to various elevated temperatures. It was after 750°C exposure for 120 minutes that the samples having 15% CR sand replacement reached the high permeability class as can be observed in Figure 7. In this instance, the increase in the permeability is attributed to the decomposition of the waste tire rubber at that temperature thereby increasing the pores within the matrix.

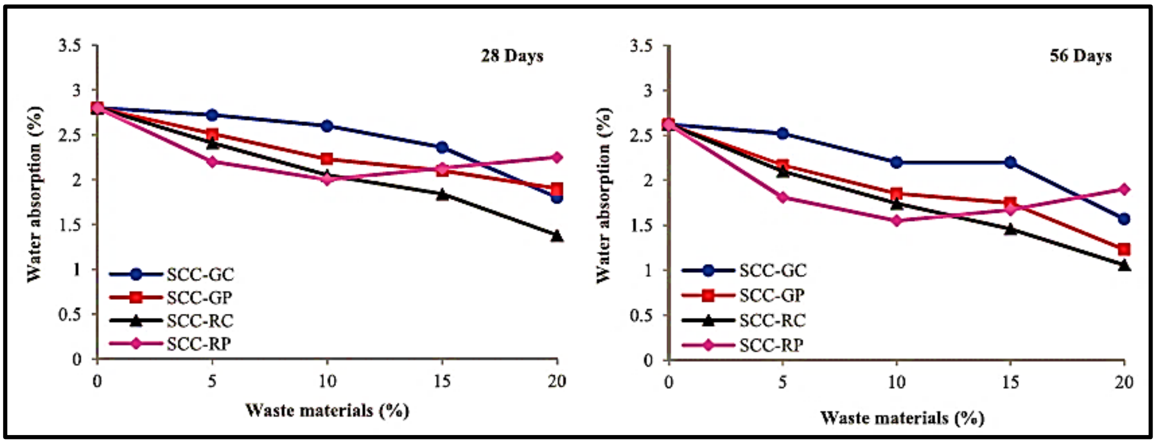

Figure 4. Effects of Waste Materials (Glass and Rubber) on the Water Absorption at 28 and 56 days (Rahat Dahmardeh et al., 2019).

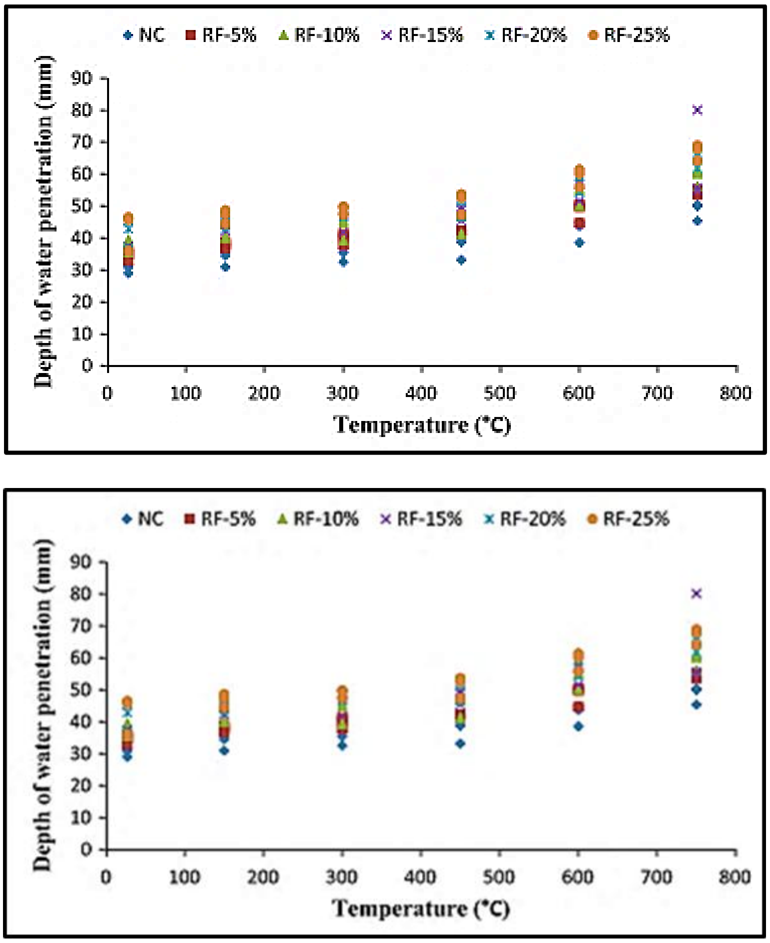

Figure 5. The Water Penetration Depth at 120 minutes Exposure to Elevate Temperature (Gupta et al., 2017)

However, the above findings are directly opposite to the result of (T. M. Pham et al., 2019) who reported an increase in the water absorption of rubberized lightweight concrete with increase in the CR as compared with normal lightweight concrete. The stated that rubberized concrete with 15% and 30% CR content respectively experienced a water absorption of 7.26% and 7.72% in contrast to the 6.96% water absorption value of the control. The higher water absorption behavior of the rubberized concrete was attributed to increased porosity due to the CR addition. This is similar to the findings of (Adamu, Mohammed, Shafiq, Liew, & Alaloul, 2018) which they also attributed to the hydrophobic nature of the CR leading to the entrapment of air voids that eventually increased the porosity of the roller compacted nansilica modified rubberized concrete.

Chloride Permeability And Hydrochloric Acid Attack

The permeability of a cement composite depends on the number and connectivity of pores present within the matrix. The resistance to water and other aggressive chemicals of a cement composite depends on its permeability (Na & Xi, 2016). One of the threats to the durability of reinforcing steel and the concrete generally is the corrosion caused by chloride ion penetration (Pham et al., 2019). The resistance of a cement composite to chloride ion ingress is usually determined usingthe rapid chloride permeability test (RCPT).

Wang *et al* (Wang et al., 2017) reported that increasing the crumb rubber content from 20% to 40% lead to a decrease in chloride ion penetration. Furthermore, their findings revealed that the resistance to chloride ion penetration reduced with the reduction in the crumb rubber size. This behavior is attributed to the low conductivity nature of the crumb rubber. Similarly, Alsaif *et al* (Alsaif, Bernal, Guadagnini, & Pilakoutas, 2018) investigated the durability of steel fiber reinforced rubberized concrete subjected to chloride attack. The influence of the chloride on the concrete was examined after 150 and 300 days wet-dry exposure cycles. A visual inspection revealed that as the days progressed, signs of corrosion became very visible on the samples. However, upon deeper investigation in to the samples, none of the fibers inside the matrix was affected despite the rusty appearance externally. This is attributed to the reduced permeability of the composite owed to the addition of the CR(Alsaif et al., 2018).

Gupta *et al* (Gupta et al., 2017) reported that for all CR replacement levels (5% to 25%) subjected to varying degrees of elevated temperatures (100°C to 800°C), the chloride permeability was not so much different from the control sample (0% CR). As can be seen from Figure 7, the diffusion coefficient drastically started rising at 150°C for the 120 minutes exposure; this is attributed to the onset of CR decomposition creating more pores within the CR concrete and cracks in the normal concrete (0% CR).

Nadine *et al.* (Asroun, De Aguiar, Trouzine, & Medine, 2017) found out that the presence of CR increased the resistance of CR concrete to chloride acid attack. This is attributed to the stable chemical nature of the rubber particles that make them less reactive with the acid

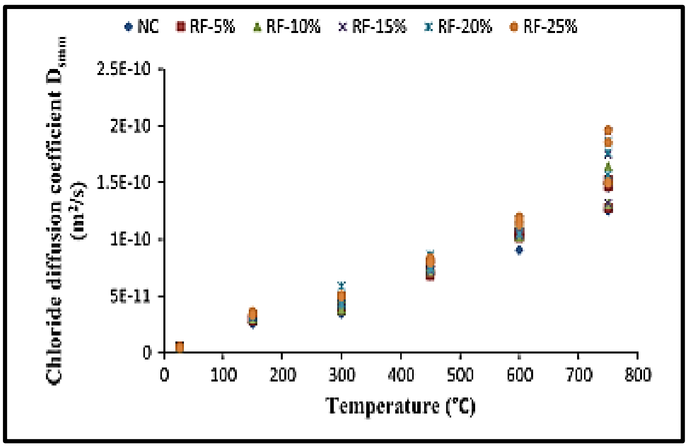

Figure 6. The Chloride Diffusion Coefficient for the CR Fiber Concrete at 120 minutes Exposure to Elevate Temperature (Gupta et al., 2017).

Sulfate Resistence

The presence of sulphuric acid in the environment in which a cementitious composite may be in contact with leads to a lot of durability issues (Thomas, Gupta, & Panicker, 2016). The reaction of $Ca(OH)_2$ in cement composite and sulphuric acid leads to a product known as gypsum ($CaSO_4.2H_2O$) (Rahat Dahmardeh et al., 2019). This product leads to expansion, cracking and spalling in concrete. Furthermore, the gypsum reacts with the CaO in the cement and forms ettringite which is another expansive product. The ettringite leads to further expansion and spalling of the concrete.

(Mohammed et al., 2020) reported that the presence of CR in the ECC reduced the permeability of the composite and hence reducing the ingress of the sulphate leading to lower expansion rate of the sample prims tested.

Mukaddas *et al* (A. M. Mukaddas, 2019) after subjecting rubberized fiber mortar to sulfate resistance test reported that by observation, no residue of corrosion of the mortar was noticed before 56 days of immersion. However, after 56 days, salt precipitate was visible on the specimens as shown in Figure 6. The presence of rubber improves the resistance to sulphate attack with resistance coefficient factor of more than 100%. However, this result does not agree with the findings of (Sabapathy et al., 2020) who reported that CR above 5% in rubberized GO modified ECC has insignificant effect on sulphate attack.

Figure 7. Salt scaling on the mortar samples before and after 56 days of immersion in Na_2SO_4

In a research to assess the durability of 5 years aged lightweight concrete containing rubber aggregate was conducted by Nadine et al (Asroun et al., 2017). Their findings on sulfate attack revealed that the highest value for mass loss was recorded for 5% CR samples. They concluded that the highest mass losses were recorded for the smallest rubber content. A mass loss of 0.26% (the smallest) was recorded for 10% CR. Also, the researchers reported that the CR concrete samples behaved better than the control in terms of sulfate resistance.

The work of Wang *et al* (R. Wang et al., 2019) on the micro crack size of CR concrete exposed to sulphate attack revealed that the CR prevents the presence of sulphate ions (SO_4^{2-}) near the ITZ-R microcracks. Hence as can be seen from Figure 9 less amount of SO_4^{2-} corrosion product was observed as compared to that near the pores of cement base.

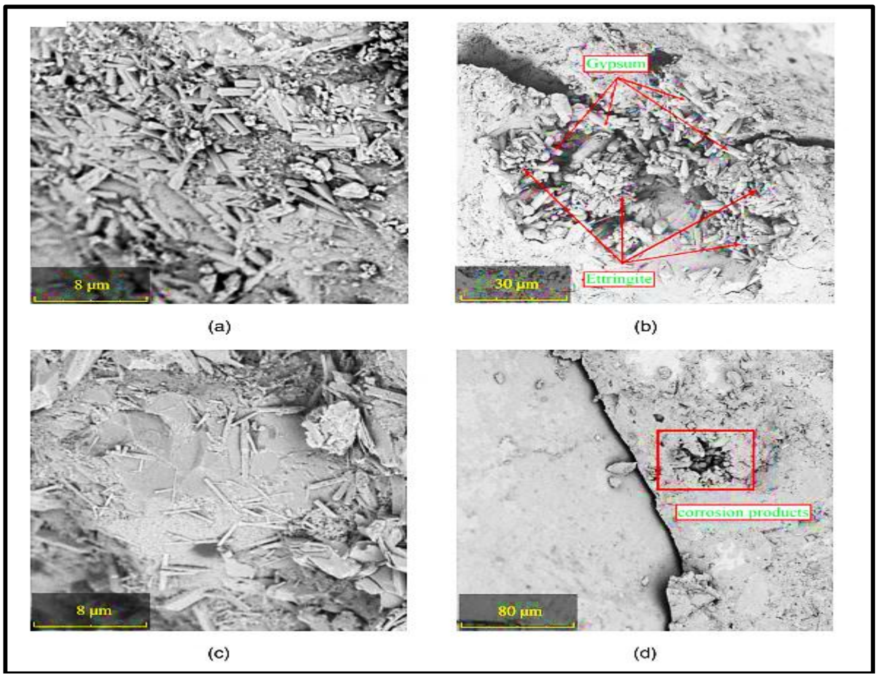

Figure 8. Products of Corrosion (a) Gypsum (b) Gypsum and Ettringite (c) Ettringite (d) The Products Near an ITZ (Wang et al., 2019)

CONCLUSION

This paper aimed to investigate the influence of waste tire rubber in the water absorption behavior and resistance to aggressive chemicals of Cementitious Composites by reviewing recent literatures. After reviewing the findings of research conducted on rubberized cement composites the following conclusions are drawn :

1. There were opposing views regarding the influence of CR on the water absorption of cement composites. Some researchers are of the opinion that the water absorption is increased with increase in the rubber content. On the other hand, other researchers reported a decrease in the water absorption with incorporation of CR.
2. The permeability of cement composite is reported to be affected negatively by most of the researchers. However, there was a small number of researchers that reported an increase in the permeability with the increase in the CR content.
3. Regarding the behavior of rubberized cement composite to aggressive chemicals, there is a consistent trend from all the research reviewed that the higher the content of the CR in the composite, the higher the resistance to the adverse effect of the chemicals.

ACKNOWLEDGEMENT. The Authours wish to acknowledge Universiti Teknologi PETRONAS Malaysia for the provision of the needed support required for this work.

REFERENCES

A. M. Mukaddas, F. N. A. A. A., N.A. Mohd. Nasir, and N. Mohamed Sutan. (2019). "Water Permeability and Chloride and Sulphate Resistance of Rubberised Fibre Mortar". *Journal of Civil Engineering, Science and Technology, 10*(2), 135-146.

AbdelAleem, B. H., & Hassan, A. A. A. (2018). "Development of self-consolidating rubberized concrete incorporating silica fume". *Construction and Building Materials, 161*, 389-397. doi:10.1016/j.conbuildmat.2017.11.146

Adamu, M., Mohammed, B. S., Shafiq, N., Liew, M. S., & Alaloul, W. S. (2018). "Effect of crumb rubber and nano silica on the durability performance of high volume fly ash roller compacted concrete pavement". *International Journal of ADVANCED AND APPLIED SCIENCES, 5*(10), 53-61. doi:10.21833/ijaas.2018.10.008

Aiello, M. A., & Leuzzi, F. (2010). "Waste tire rubberized concrete: properties at fresh and hardened state". *Waste Manag, 30*(8-9), 1696-1704. doi:10.1016/j.wasman.2010.02.005

Alexander, M. G., Mushunje, K., Otieno, M., Ballim, Y., Beushausen, H., Dehn, F., & Moyo, P. (2018). "A Review of Waste Tire Rubber as an Alternative Concrete Consituent Material". *MATEC Web of Conferences, 199*. doi:10.1051/matecconf/201819911003

Alhumoud, A. B. N. a. J. M. (2020). "Properties of Concrete Containing Scrap (Recycled) Tire-Rubber". *Journal of Engineering and Applied Sciences, 15*(2), 653-658.

Alsaif, A., Bernal, S. A., Guadagnini, M., & Pilakoutas, K. (2018). "Durability of steel fibre reinforced rubberised concrete exposed to chlorides". *Construction and Building Materials, 188*, 130-142. doi:10.1016/j.conbuildmat.2018.08.122

Asroun, A., De Aguiar, J. B., Trouzine, H., & Medine, M. (2017). "Durability Properties of Five Years Aged Lightweight Concretes Containing Rubber Aggregates". *Periodica Polytechnica Civil Engineering*. doi:10.3311/PPci.11363

Bisht, K., & Ramana, P. V. (2017). "Evaluation of mechanical and durability properties of crumb rubber concrete". *Construction and Building Materials, 155*, 811-817. doi:10.1016/j.conbuildmat.2017.08.131

Chen, R., Li, Q., Zhang, Y., Xu, X., & Zhang, D. (2019). "Pyrolysis kinetics and mechanism of typical industrial non-tire rubber wastes by peak-differentiating analysis and multi kinetics methods". *Fuel, 235*, 1224-1237. doi:https://doi.org/10.1016/j.fuel.2018.08.121

Corinaldesi, V., & Donnini, J. (2019). "Waste rubber aggregates". In *New Trends in Eco-efficient and Recycled Concrete* (pp. 87-119): Elsevier.

Ganjian, E., Khorami, M., & Maghsoudi, A. A. (2009). "Scrap-tire-rubber replacement for aggregate and filler in concrete". *Construction and Building Materials, 23*(5), 1828-1836. doi:https://doi.org/10.1016/j.conbuildmat.2008.09.020

Gerges, N. N., Issa, C. A., & Fawaz, S. A. (2018). "Rubber concrete: Mechanical and dynamical properties". *Case Studies in Construction Materials, 9*. doi:10.1016/j.cscm.2018.e00184

Girskas, G., & Nagrockienė, D. (2017). "Crushed rubber waste impact of concrete basic properties". *Construction and Building Materials, 140*, 36-42. doi:10.1016/j.conbuildmat.2017.02.107

Gonen, T. (2018). "Freezing-thawing and impact resistance of concretes containing waste crumb rubbers". *Construction and Building Materials, 177*, 436-442. doi:10.1016/j.conbuildmat.2018.05.105

Gupta, T., Chaudhary, S., & Sharma, R. K. (2016). "Mechanical and durability properties of waste rubber fiber concrete with and without silica fume". *Journal of Cleaner Production, 112,* 702-711. doi:10.1016/j.jclepro.2015.07.081

Gupta, T., Siddique, S., Sharma, R. K., & Chaudhary, S. (2017). "Effect of elevated temperature and cooling regimes on mechanical and durability properties of concrete containing waste rubber fiber". *Construction and Building Materials, 137*, 35-45. doi:10.1016/j.conbuildmat.2017.01.065

Horszczaruk, E., Mijowska, E., Kalenczuk, R. J., Aleksandrzak, M., & Mijowska, S. (2015). "Nanocomposite of cement/graphene oxide – Impact on hydration kinetics and Young's modulus". *Construction and Building Materials, 78*, 234-242. doi:10.1016/j.conbuildmat.2014.12.009

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". *IOP Conference Series: Earth and Environmental Science, 140*. doi:10.1088/1755-1315/140/1/012137

Lakusic, S. (2019). "Properties of high strength concrete containing surface-modified crumb rubber". *Journal of the Croatian Association of Civil Engineers, 71*(07), 579-588. doi:10.14256/jce.2312.2018

Li, N., Long, G., Ma, C., Fu, Q., Zeng, X., Ma, K., & Luo, B. (2019). "Properties of self-compacting concrete (SCC) with recycled tire rubber aggregate: A comprehensive study". *Journal of Cleaner Production, 236*. doi:10.1016/j.jclepro.2019.117707

Liu, H., Luo, G., Gong, Y., & Wei, H. (2018). "Mechanical Properties, Permeability, and Freeze–Thaw Resistance of Pervious Concrete Modified by Waste Crumb Rubbers". *Applied Sciences, 8*(10). doi:10.3390/app8101843

Lv, S., Ma, Y., Qiu, C., Sun, T., Liu, J., & Zhou, Q. (2013). "Effect of graphene oxide nanosheets of microstructure and mechanical properties of cement composites". *Construction and Building Materials, 49*, 121-127. doi:10.1016/j.conbuildmat.2013.08.022

Mohammed, B. S., Achara, B. E., Nuruddin, M. F., Yaw, M., & Zulkefli, M. Z. (2017). "Properties of nano-silica-modified self-compacting engineered cementitious composites". *Journal of Cleaner Production, 162,* 1225-1238. doi:10.1016/j.jclepro.2017.06.137

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

Mohammed, B. S., Adamu, M., & Shafiq, N. (2017). "A Review on the Effect of Crumb on the Properties Oof Rubbercrete". *International Journal of Civil Engineering and Technology (IJCIET), 8*(9), 599-165.

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

Mohammed, B. S., Hossain, K. M. A., Swee, J. T. E., 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

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

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 (Basel), 13*(16). doi:10.3390/ma13163516

Na, O., & Xi, Y. (2016). "Mechanical and durability properties of insulation mortar with rubber powder from waste tires". *Journal of Material Cycles and Waste Management, 19*(2), 763-773. doi:10.1007/s10163-016-0475-2

Nacif, G. L., Panzera, T. H., Strecker, K., Christoforo, A. L., & Paine, K. (2013). "Investigations on Cementitious Composites Based on Rubber Particle Waste Additions". *Materials Research-Ibero-American Journal of Materials, 16*(2), 259-268. doi:10.1590/S1516-14392012005000177

Najim, K. B., & Hall, M. R. (2010). "A review of the fresh/hardened properties and applications for plain- (PRC) and self-compacting rubberised concrete (SCRC)". *Construction and Building Materials, 24*(11), 2043-2051. doi:https://doi.org/10.1016/j.conbuildmat.2010.04.056

Nayeem Ahmad Reshi, E. S. M., Er. Sohan Sing. (2019). "Effect of Addition of Crumb Rubber on Physical and Mechanical Properties of M-40 Grade Concrete". *International Research Journal of Engineering and Technology (IRJET), 6*(9), 11782-11786.

Olesen, A. (2018). *Durability and Mechanical Properties Of Portland Cement Concrete that Utilizes Crumb Rubber as an Alternative Fine Aggregate.* (Master of Science (Civil Engineering)), Lakehead University, Lakehead University.

Pan, Z., He, L., Qiu, L., Korayem, A. H., Li, G., Zhu, J. W. & Wang, M. C. (2015). "Mechanical properties and microstructure of a graphene oxide–cement composite". *Cement and Concrete Composites, 58*, 140-147. doi:10.1016/j.cemconcomp.2015.02.001

PAN, Z. D., Wenhui; LI, Dan; COLLINS, Frank. (2013). USA Patent No.: W. I. P. Organization.

Pham, N. P., Toumi, A., & Turatsinze, A. (2018). "Rubber aggregate-cement matrix bond enhancement: Microstructural analysis, effect on transfer properties and on mechanical behaviours of the composite". *Cement and Concrete Composites, 94*, 1-12. doi:10.1016/j.cemconcomp.2018.08.005

Pham, T. M., Elchalakani, M., Hao, H., Lai, J., Ameduri, S., & Tran, T. M. (2019). "Durability characteristics of lightweight rubberized concrete". *Construction and Building Materials, 224*, 584-599. doi:10.1016/j.conbuildmat.2019.07.048

Rahat Dahmardeh, S., Sargazi Moghaddam, M. S., & Mirabi Moghaddam, M. H. (2019). "Effects of waste glass and rubber on the SCC: rheological, mechanical, and durability properties". *European Journal of Environmental and Civil Engineering,* 1-20. doi:10.1080/19648189.2018.1528891

Reches, Y. (2018). "Nanoparticles as concrete additives: Review and perspectives". *Construction and Building Materials, 175,* 483-495. doi:10.1016/j.conbuildmat.2018.04.214.

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.

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 (Basel), 13*(14). doi:10.3390/ma13143125.

Si, R., Guo, S., & Dai, Q. (2017). "Durability performance of rubberized mortar and concrete with NaOH-Solution treated rubber particles". *Construction and Building Materials, 153,* 496-505. doi:10.1016/j.conbuildmat.2017.07.085.

Siddika, A., Mamun, M. A. A., Alyousef, R., Amran, Y. H. M., Aslani, F., & Alabduljabbar, H. (2019). "Properties and utilizations of waste tire rubber in concrete: A review". *Construction and Building Materials, 224,* 711-731. doi:10.1016/j.conbuildmat.2019.07.108.

Siddique, R., & Naik, T. R. (2004). "Properties of concrete containing scrap-tire rubber--an overview". *Waste Manag, 24*(6), 563-569. doi:10.1016/j.wasman.2004.01.006

Sofi, A. (2018). "Effect of waste tire rubber on mechanical and durability properties of concrete – A review". *Ain Shams Engineering Journal, 9*(4), 2691-2700. doi:10.1016/j.asej.2017.08.007.

Strukar, K., Kalman Šipoš, T., Miličević, I., & Bušić, R. (2019). "Potential use of rubber as aggregate in structural reinforced concrete element – A review". *Engineering Structures, 188,* 452-468. doi:10.1016/j.engstruct.2019.03.031

Suprayitno, H. & Soemitro, R.A.A. (2018). "Preliminary Reflexion on Basic Principle of Infrastrucutre Asset Management". *Jurnal Manajemen Aset Infrastruktur & Fasilitas, 2(1), Maret 2018.*

Thomas, B. S., Gupta, R. C., Kalla, P., & Cseteneyi, L. (2014). "Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates". *Construction and Building Materials, 59,* 204-212. doi:10.1016/j.conbuildmat.2014.01.074

Thomas, B. S., Gupta, R. C., & Panicker, V. J. (2016). "Recycling of waste tire rubber as aggregate in concrete: durability-related performance". *Journal of Cleaner Production, 112,* 504-513. doi:10.1016/j.jclepro.2015.08.046

Wang, R., Tao, Z., & Li, Y. (2019). "Evaluation of Microcrack Size in Rubber Concrete ITZ Exposed to Sulfate Attack". *Journal of Materials in Civil Engineering, 31*(12). doi:10.1061/(asce)mt.1943-5533.0002986

Wang, X., Xia, J., Nanayakkara, O., & Li, Y. (2017). "Properties of high-performance cementitious composites containing recycled rubber crumb". *Construction and Building Materials, 156,* 1127-1136. doi:10.1016/j.conbuildmat.2017.09.024

Xu, J., Yao, Z., Yang, G., & Han, Q. (2020). "Research on crumb rubber concrete: From a multi-scale review". *Construction and Building Materials, 232.* doi:10.1016/j.conbuildmat.2019.117282

Záleská, M., Pavlík, Z., Čítek, D., Jankovský, O., & Pavlíková, M. (2019). "Eco-friendly concrete with scrap-tire-rubber-based aggregate – Properties and thermal stability". *Construction and Building Materials, 225,* 709-722. doi:10.1016/j.conbuildmat.2019.07.168

Zaouai, S., Tafraoui, A., Makani, A., & Benmerioul, F. (2019). "Hardened and transfer properties of self-compacting concretes containing pre-coated rubber aggregates with crushed dune sand". *Journal of Rubber Research*. doi:10.1007/s42464-019-00030-x