Recycle and Reuse of Crumbed Rubber as Construction Material to Reduce Environmental Pollution

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***Abstract*—The crumbed pieces of the rubber from worn out tires are used as an additive with concrete to develop a novel construction material. The physical, mechanical and durability tests are conducted on concrete with 0%, 1% and 2% of crumbed rubber with respect to weight of cement. Concrete cubes with 2% crumbed rubber show a higher slump value, less air voids, lower water absorption and higher compressive strength in comparison with conventional concrete. The crumbed rubber fills the voids present in the conventional concrete cubes results in increase in dry density and decrease in water absorption. The workability and compressive strength of the concrete increases with the increase in the percentage of crumbed rubber to 2%. The novel construction material developed in this research is sustainable and green compared to conventional concrete as it reduces the release of Carbon Dioxide (CO_2) and fuel consumption based on energy simulation results from design builder software.**

***Keywords*—crumbed rubber, green concrete, additive, cementitious material, mechanical strength, durability study**

I. Introduction

Concrete is the most widely used construction material. Manufacturing of cement which is the main component of concrete is responsible for the emission of 1.7 billion metric tons of CO_2 [1]. Almost a pound of CO_2 is emitted for every pound of cement manufactured [2]. Concrete is a durable building material that provides environmental benefits due to its longevity [3] and at the same time, it is impacting the environment in two ways: emission of carbon dioxide in cement making and emission of heat energy as infra-red radiations from concrete used in building, roads, bridges etc.

The environmental impact can be reduced by partial or complete replacement of cement in concrete with the eco-friendly materials. Currently, approximately one billion five hundred million used and worn-out tires are accumulated each year that could increase to 5 billion by 2030 [4–7]. The tires are manufactured from synthetic rubber which are generally disposed of in landfills, burned or stored which causes tremendous environmental issues such as land and air pollution and releases harmful gases [8–11]. The main aim of this research is to find an alternative method to recycle the non-biodegradable waste material -rubber from worn out tires.

II. Literature Review

Synthetic rubber is a thermosetting polymer which has a cross link formed between polymer chains and once these chains are broken in melting, they cannot reform. The major possible recycle option is to create Tire Derived Fuel (TDF). This recycling method emits chemicals into the air which causes more environmental pollution [12]. Several studies are available to replace part of fine and coarse aggregate with crumbed and fine rubber. It is found that the crumbed rubber of size less than 1mm used in concrete failed to yield promising results. At the same time, when crumbed rubber of size greater than 1mm is used as replacement of aggregate increases the ductility, damping ratio, energy dissipation, toughness, and impact resistance but, the modulus of elasticity, compressive and tensile strength are limited [13–17]. The rubber particles act as a filler and help to reduce the water demand of the cement paste, which can increase the strength of the cement. In addition, it also improves the durability of cement. Rubber particles can form a network of air voids in the cement, which can reduce the permeability of the material and make it more resistant to weathering and other environmental impacts [14]. Additionally, the rubber particles can act as a buffer to prevent cracking, which can reduce the risk of material failure [18–19]. It is found that adding waste rubber to cement can also improve the workability of the material. Rubber particles can help to reduce the viscosity of the cement paste [20]. Bala and Gupta [21] reported rubber particles act as an insulator which reduces the heat transmission rate through the cement.

Based on the literature review, worn out tires are used to make TDF which releases heat and causes environmental pollution. The crumbed tires are used as replacement of fine and coarse aggregates. There are no prior studies of using crumbed rubber as additive with cement. This article uses different percentage of crumbed rubber as additives with cement without any chemical treatment. The size of the crumbed rubber varies from 4.75 mm to 1mm and added as an additive with cement in the ratio of 1% and 2% with respect to weight of the cement. The physical, mechanical and durability aspect of the concrete with crumbed rubber is studied. In addition, energy simulation is carried out to show the effectiveness of the newly developed crumbed rubber concrete.

III. Methodology

The physical, mechanical and durability tests are conducted on concrete cubes with 0%, 1% and 2% of crumbed rubber with respect to weight of cement. Energy simulation is carried out using the design builder software to check the energy performance of the building constructed with conventional concrete and concrete with rubber.

A. Physical Tests

The physical tests are conducted on cement, fine aggregates and coarse aggregates to ensure the quality of the materials used in the research. The physical tests conducted on the cement are fineness test, initial and final setting time. The physical tests conducted on fine and coarse aggregates are sieve analysis, fineness modulus and specific gravity. Water absorption and abrasion value are determined for coarse aggregates.

1) Fineness test on cement

The fineness of cement is measured by dry sieving as per ASTM A370 [22] and ASTM C786-10 [23]. The fineness of the cement is also measured as specific surface by air permeability method (Blaine method). Specific surface is expressed as the total surface area in square centimeter of all the cement particles in per gram of cement. The fineness of cement is high with high specific surface.

2) Initial and final setting time of cement

Initial and final setting time of cement is measured from Vicat apparatus conforming to ASTM C 187 [23].

3) Sieve analysis of fine and coarse aggregate

The particle size distribution of coarse aggregate is obtained by passing a sample of coarse aggregate weighing 5000g through a set of sieves of size 80 mm, 40 mm, 20 mm, 12.5 mm, 10 mm and 4.75 mm confirming to ASTM C 187 [24]. The particle size distribution of fine aggregate is obtained from a sample of 1375g through a set of sieves of size 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.3 mm and 0.15 mm. Fineness modulus of fine and coarse aggregate is calculated from the sum of cumulative percentage of materials retained in the sieve.

4) Specific gravity and water absorption of coarse aggregate

Specific gravity and water absorption of coarse aggregates is determined as per ASTM C 127 [25].

5) Abrasion value of coarse aggregate

The abrasion value of coarse aggregate is measured from Los Angles testing machine as per ASTM C 131-06 [26].

B. Mechanical Tests on Fresh Concrete

Mechanical tests were conducted on fresh concrete both with and without crumbed rubber to assess its workability and air voids using a slump cone and pressure meter.

1) Slump cone test

The workability of the fresh concrete test was conducted in the laboratory using a slump cone. The slump cone test is conducted per ASTM C143-78 [27].

2) Pressure meter or air meter

Pressure meter is used to determine the air voids of normal-weight fresh concrete as per ASTM C231 [28]. The air content is read at the dial, which is calibrated for each apparatus.

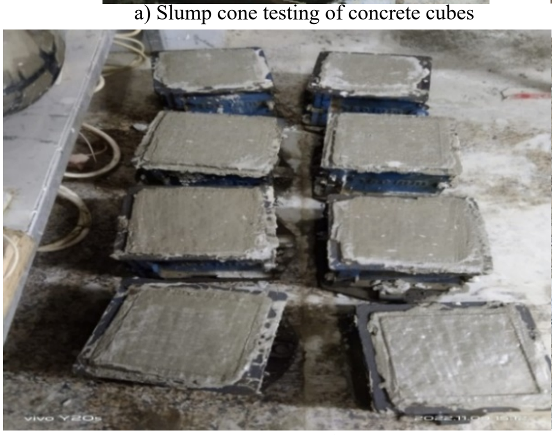
C. Compressive Strength Test on Hardened Concrete

Crumbed rubber is added with concrete and mortar cubes as 0%, 1% and 2% with respect to weight of cement. Based on the literature [29–30], it is found that if the percentage of crumbed rubber is more than 2%, it reduces the hydration and adhesion which in turn causes significant reduction in interfacial bonding. Therefore, the study is restricted up to 2% only. The compressive strength of concrete and mortar cubes is checked on the 7th day and the 28th day. Three specimens are cast for each percentage and average value is calculated.

The size of the concrete cube specimen is 150 mm×150 mm×150 mm. The Compressive strength test on the concrete cubes is conducted on the 7th and the 28th day as per ASTM C109 [31]. The steps involved in making and testing the concrete cubes are shown in Fig. 1.

a) Slump cone testing of concrete cubes

b) Compression test of concrete cubes



c) Concrete cubes

d) Failed concrete specimen

Fig. 1. Process involved in casting and testing concrete cubes.

D. Durability Tests on Concrete Cubes

The durability of concrete and mortar cubes (with and without crumbed rubber) are determined from dry density and water absorption tests.

1) Dry density

The dry density is calculated by measuring the dry weight of the cubes and volume of the cubes.

2) Water absorption

Water absorption is calculated as per ASTM C 158 [32].

E. Energy Simulation

A single-story building with window openings of 30% of gross wall area located in Jeddah, Saudi Arabia is taken into account to study its environmental performances by changing the materials used for the construction of the wall as conventional concrete and concrete with rubber: The following parameters are studied for both materials: energy consumption, carbon emissions, comfort conditions (heat gain through walls) and size of the cooling equipment (design cooling load) using SBC 601 (2018) [33].

Cooling design calculations are carried out to determine the capacity of mechanical cooling equipment required to meet the hottest summer design weather conditions likely to be encountered at the site location. These design calculations are traditionally carried out using periodic steady-state external temperatures calculated using maximum and minimum design summer weather conditions and includes solar gains through windows, walls, and roof.

The simulation is based on half-hourly temperature data and energy flow measurements of the building is based on the design cooling capacity. The cooling is available throughout the year and the thermostat cooling temperature is set to 22 °C [34]. The building is set to generate the simulation without any occupants.

IV. Results and Discussions

A. Physical Tests Results

1) Fineness of cement

Fineness of cement is calculated for 10g of cement. The weight of the cement retained in 90-micron sieve is 0.3 g. The percentage fineness of cement from sieve analysis is found as 3%. As per ASTM C786-10 [22]. The fineness of the cement should be less than 10%.

The fineness of the cement is also calculated by using air permeability apparatus and is found to be 3475 cm^2/g. Minimum requirement of fineness of cement from ASTM C204-18e1 [35] should be greater than 2800 cm^2/g.

2) Initial and final setting time

The minimum initial setting time of cement is 45 minutes and the maximum final setting time of cement is 375 minutes as per ASTM C 403 [36]. From the test results, the initial and final setting time of the cement is 164 minutes and 233 minutes respectively.

3) Sieve analysis of fine aggregate

Table 1 shows the weight retained, cumulative weight retained, cumulative percentage retained and percentage passing of fine aggregates in each sieve.

Table 1. Sieve analysis test results of fine aggregates

Sieve size (mm)	Weight retained (g)	Cumulative weight retained (g)	Cumulative % retained	% passing
4.75	9.76	9.76	0.71	99.29
2.36	59.63	69.39	5.04	95
1.18	94.67	164.06	11.93	88.07
0.6	386.14	550.2	40.01	60
0.3	528.36	1078.56	78.44	21.56
0.15	234.82	1313.38	95.51	4.5
Pan	61.62	1375	100	0
Sum			331.63	

Fineness modulus of fine aggregate = (Sum of cumulative % retained) / 100 = 331.63/100= 3.31.

4) Sieve analysis of coarse aggregate

Table 2 shows the weight retained, cumulative weight retained, cumulative percentage retained and percentage passing of coarse aggregates in each sieve.

Table 2. Sieve analysis test results of coarse aggregates

Sieve size (mm)	**Weight retained (g)**	**Cumulative weight retained (g)**	**Cumulative % retained**	**% passing**
80	0	0	0	100
40	0	0	0	100
20	0	0	0	100
12.5	1519	1519	30.39	69.62
10	3444	4963	99.20	0.740
4.75	37	5000	100	0
Pan	0	5000	100	0
Sum			329.65	

Fineness modulus of coarse aggregate is found to be 3.3.

5) Specific gravity of fine and coarse aggregate

The specific gravity of fine aggregate and coarse aggregate used in this study is 2.53 and 2.9.

The specific gravity of the aggregates should be in the range of 2.5–3.0 as per AASHTO T 85 [37], and the analysis result of the aggregates used in this research is within the range.

6) Water absorption of coarse aggregate

The water absorption of coarse aggregates used in this research is 5% which shows that the texture of aggregates used have more roughness and angular shape. The abrasion value of the coarse aggregates used in this study is 13%.

B. Mechanical Test Results on Fresh Concrete

Slump value is higher in concrete cubes with 2% crumbed rubber than cubes with 0% (conventional cubes) and 1% crumbed rubber (Fig. 2). It shows there is an increase in workability of concrete with the addition of crumbed rubber.

Air voids in fresh concrete with and without crumbed rubber are measured by using an air meter. The result shows less air voids and anhydrate phases in concrete cubes with 1% and 2% rubber compare to conventional cubes (Fig. 3). This may be due to filling of voids with crumbed rubber.

C. Compressive Strength Test on Hardened Concrete

Compressive strength of concrete cubes with 2% crumbed rubber shows an increase of 3.5% compared to conventional concrete cubes and 9% increase compared to concrete cubes with 1% crumbed rubber on the 28th day.

On the 7th day the compressive strength of concrete cubes with 2% crumbed rubber remains same as conventional cubes and is greater than cubes with 1% crumbed rubber (Fig. 4). The crumbed rubber particles fill the gaps between the cement, fine aggregates and coarse aggregates that increases the compressive strength of the concrete cubes. It is also found that the cubes with crumbed rubber gain strength with time.

The average failure load of concrete cubes with and without crumbed rubber is shown in Fig. 5, the cubes with 2% crumbed rubber has high failure load compared to conventional cubes and cubes with 1% crumbed rubber.

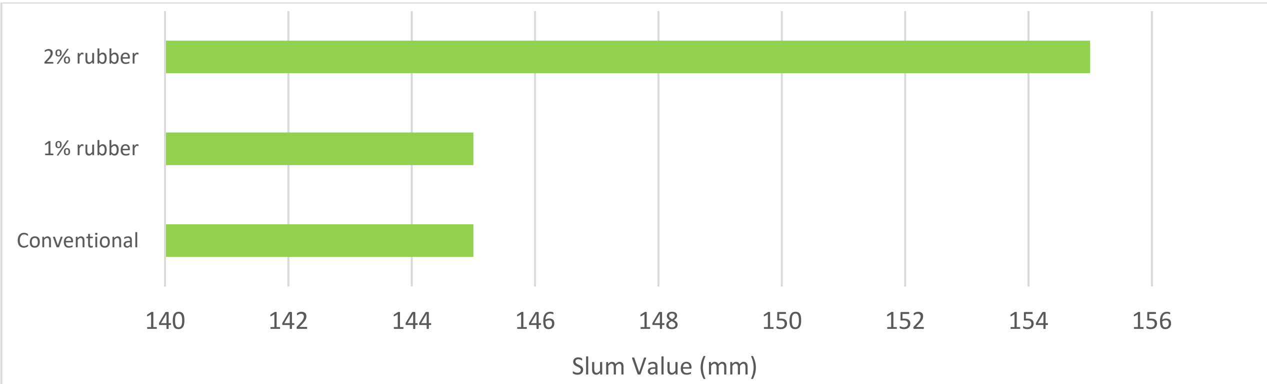


Fig. 2. Slump value of fresh concrete with and without crumbed rubber.

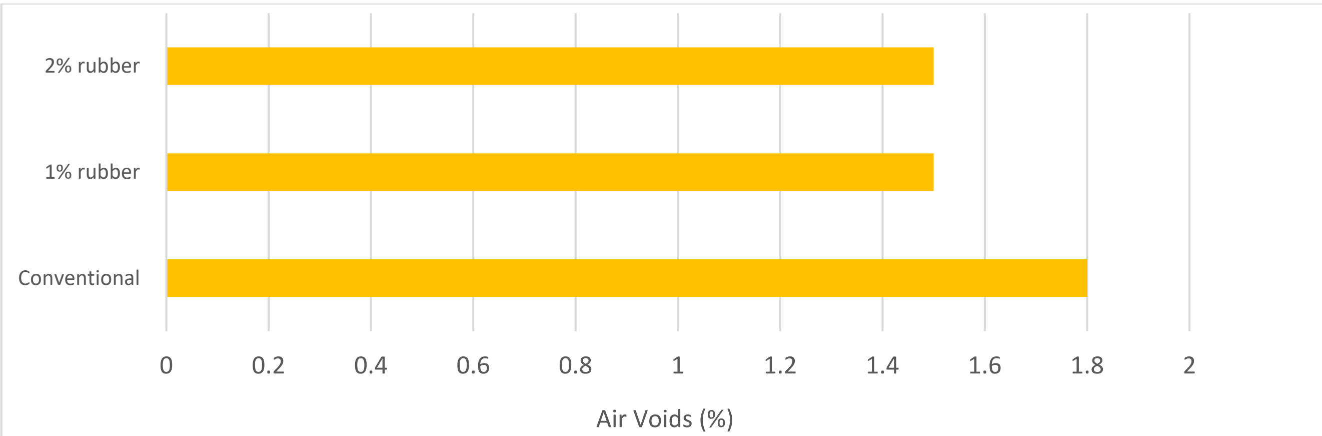


Fig. 3. Air voids of fresh concrete with and without crumbed rubber.

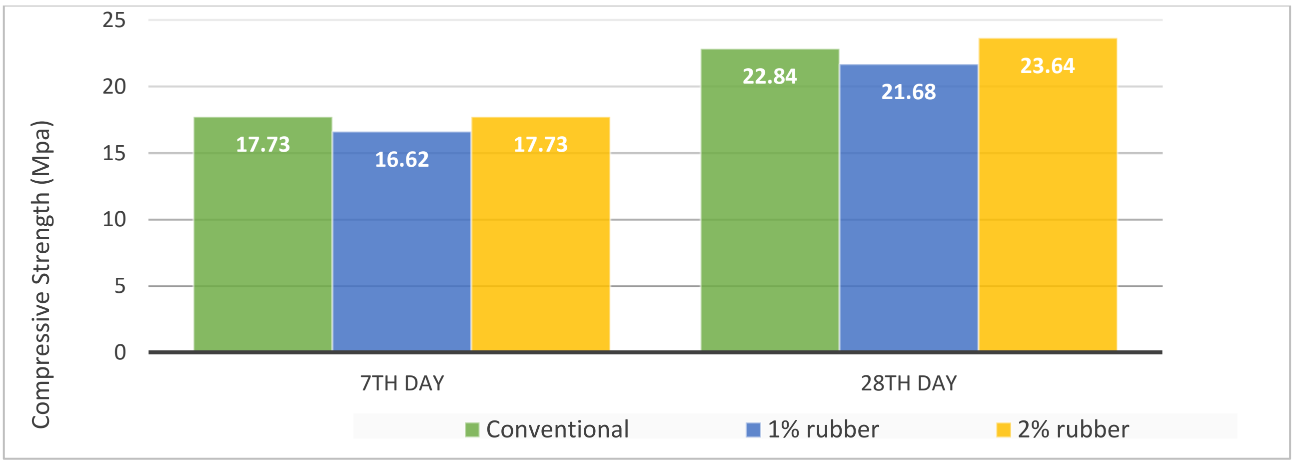


Fig. 4. Compressive strength of concrete cubes with and without crumbed rubber.

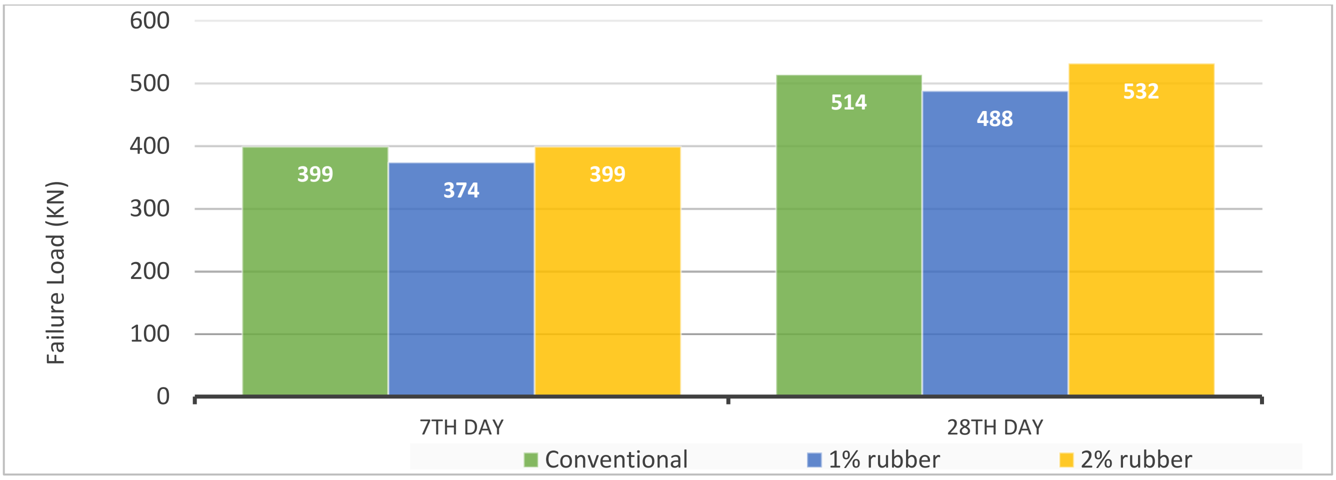


Fig. 5. Failure load of concrete cubes with and without crumbed rubber.

D. *Durability Test Results*

The wet density of concrete cubes with 2% crumbed rubber is less than cubes with 1% crumbed rubber and conventional concrete cubes on the 0th, 7th and 28th day (Fig. 6) The dry density of concrete cubes with 2% crumbed rubber is less than cubes with 1% crumbed rubber and conventional concrete cubes on the 7th and 28th day. This shows the crumbed rubber occupies the voids in cubes which reduces the weight of the concrete cubes with 2% crumbed rubber (Fig. 7). The water absorption of concrete cubes with 2% crumbed rubber is less than cubes with 0% (conventional) and 1% crumbed rubber on the 7th and 28th day (Fig. 8). This proves that concrete cubes with 2% crumbed rubber has less voids as they are filled with crumbed rubber particles which is hydrophobic. Rubber is hydrophobic and has water resistant property, when mixed with cement or concrete it will reduce the amount of free water penetrating in the cement matrix (concrete cube), and this reduces the water absorption.

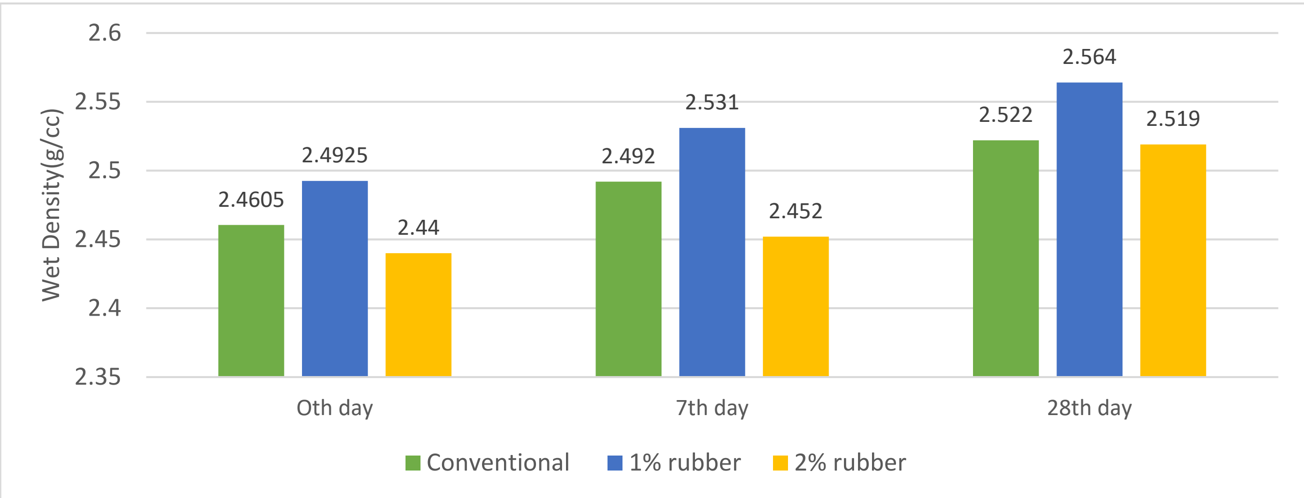


Fig. 6. Wet density of concrete cubes with and without crumbed rubber.

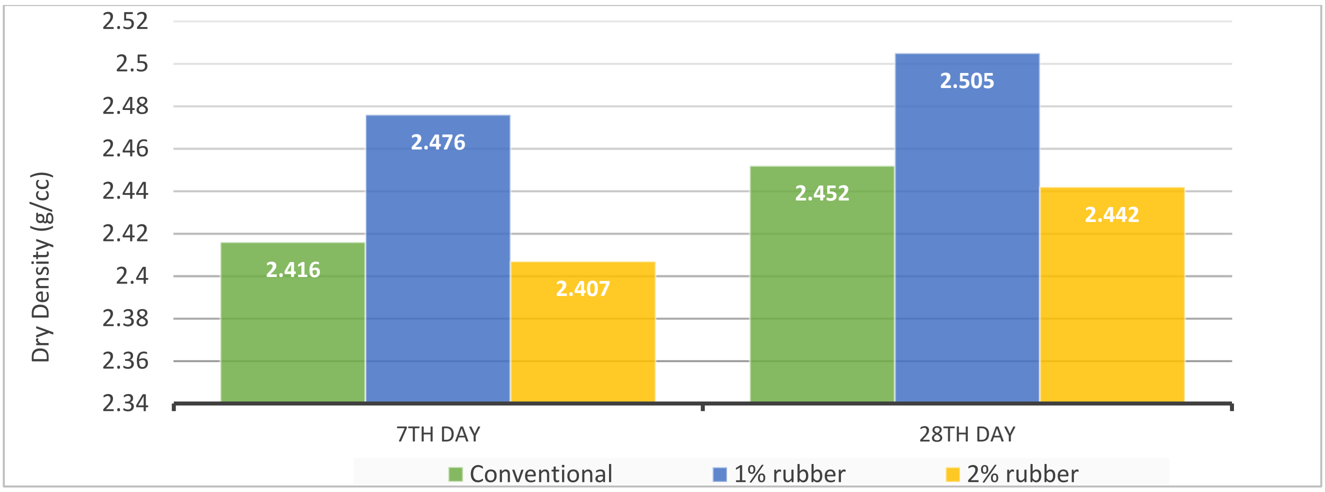


Fig. 7. Dry density of concrete cubes with and without crumbed rubber.

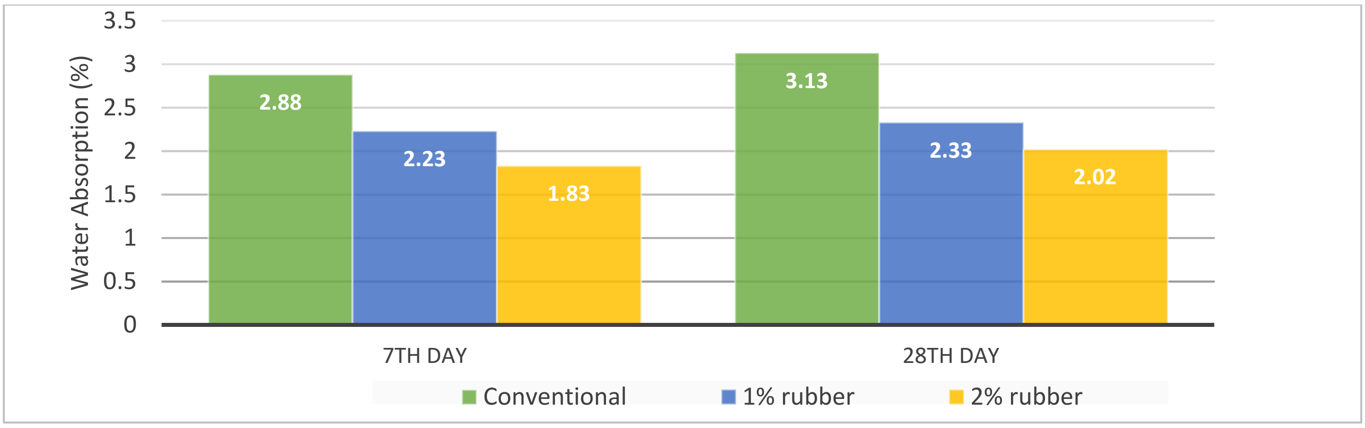


Fig. 8. Water absorption of concrete cubes with and without crumbed rubber.

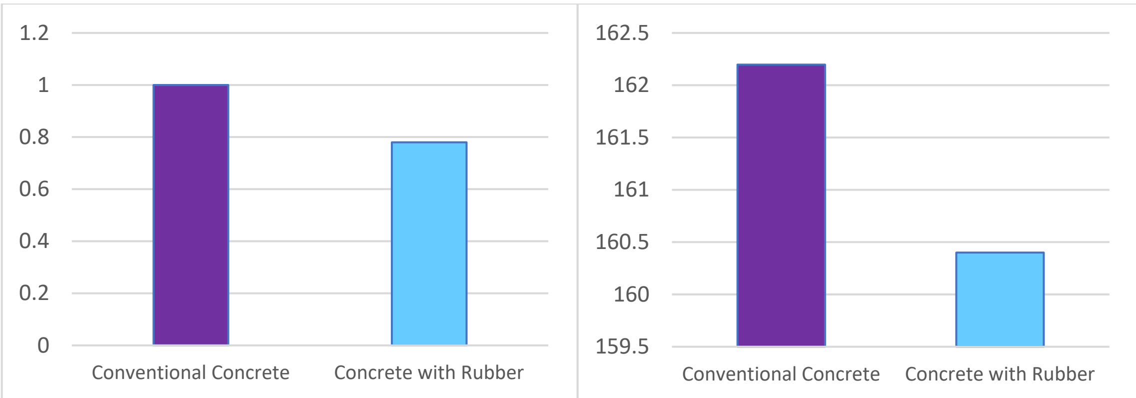
The rubber particles have low density and fill the voids within the concrete. Concrete, by nature, has a porous structure, and water is absorbed in these voids in a conventional concrete. When rubber particles are incorporated as additives, they occupy some of these voids, reducing the total volume of pores available for water to enter. The rubber does not create new porosity but replaces the part of the matrix, which lowers the overall porosity [38].

E. Energy Simulation Results

From the simulation results of a single-story building using energy plus, it is found that the heat gained through the walls constructed with concrete with rubber is reduced by 20% compared to the wall constructed with conventional concrete (Fig. 9). It is reflected in the design capacity of the cooling plant of the building. The building constructed with crumbed rubber concrete requires less energy capacity to cool the building with the set point of 22 °C compared to the building constructed with conventional concrete.

In Jeddah, Saudi Arabia, the peak summer period is from May till August, and the hottest month is found to be July. Fig. 10 shows the emission of Carbon Dioxide (CO_2) from building for a year, and Fig. 11 shows the consumption of fuel for a year from both the buildings. It is found that the building constructed with concrete released less carbon dioxide and consumed less energy compared to the one constructed with conventional concrete.

From the energy simulation study, it is found that buildings constructed from concrete with rubber show high comfort, less cooling plant capacity, less fuel consumption and CO_2 emission. The limitation of the simulation result is, the rubber is added as a new layer not as the rubber from waste and not as particles. This will increase the life cycle cost and embodied carbon of the building compared to the building constructed with conventional concrete.



a) Heat gained through walls as ratio b) Design cooling capacity (Kw)

Fig. 9. Energy simulation results for conventional concrete and concrete with rubber.

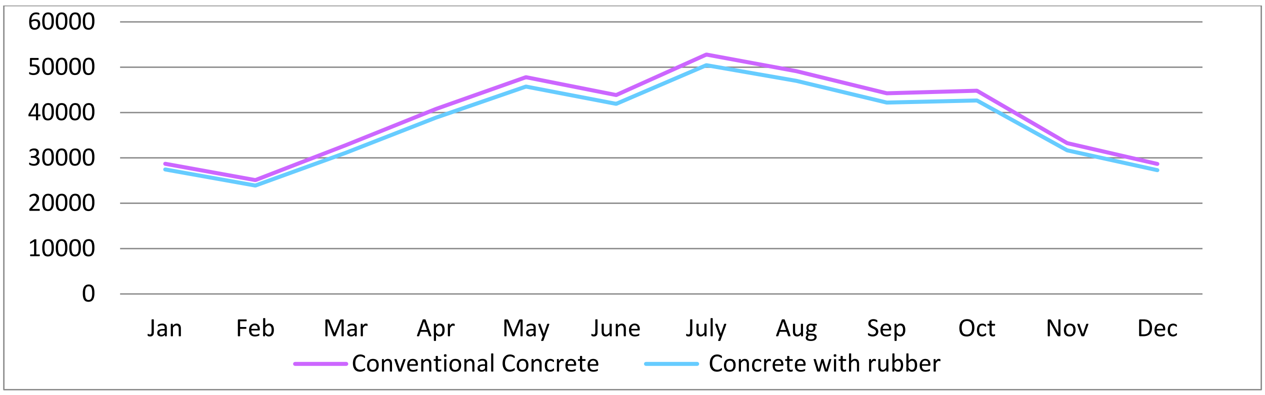


Fig. 10. Emission of CO_2 (kg) from the buildings for a typical year.

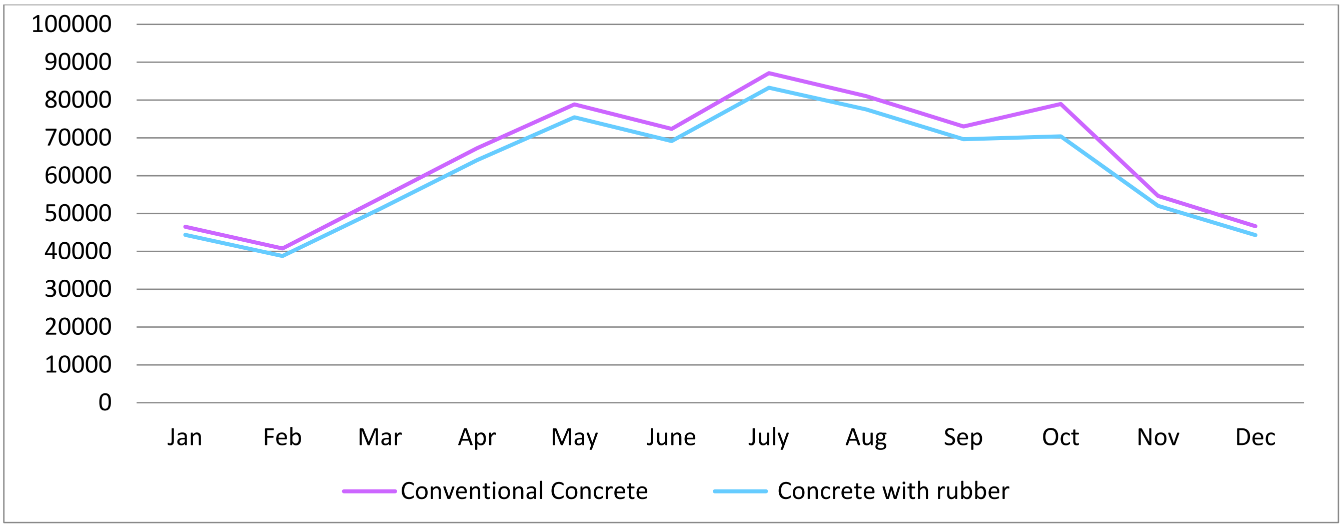


Fig. 11. Energy consumption (kWh) of a building for a year.

V. CONCLUSION

From the mechanical tests conducted on hardened concrete and mortar cubes, it is found that the cubes with 2% crumbed rubber from used tires performs better than conventional cubes and cubes with 1% crumbed rubber in terms of dry density, wet density, water absorption and compressive strength.

From the mechanical tests conducted on fresh concrete, it is found that the workability of the concrete with 2% crumbed rubber is higher than cubes with 0% and 1% crumbed rubber with same water cement ratio. The porosity of concrete cubes with 2% crumbed rubber is less than conventional cubes and cubes with 1% crumbed rubber, due to less water absorption.

The experimental study gives promising results with the use of crumbed rubber in concrete which reduces the amount of cement used in conventional construction. It reduces the greenhouse gas emission from cement production. The energy simulation study shows promising results in terms of comfort, cooling plant size, fuel consumption and emission of carbon dioxide.

The use of crumbed rubber in concrete is sustainable and green compared to conventional concrete. It reduces the accumulation of nonbiodegradable waste thus protects the environmental pollution. Further studies are required to establish threshold percentages of crumbed rubber (e.g., 3%, 5%, 10%) on long-term durability (acid resistance test, s alt water resistance test and rapid chloride penetration test), workability and thermal properties (thermal conductivity and insulation). It is suggested to include the cost and ecotoxicology risk involved in making crumbed rubber concrete.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

The first author conducted the literature review, crumbed rubber collection, conducting mechanical and durability experiments in coordination with the solutions, mining laboratory and initial draft of the article. The second author contributed to the literature review, conducted physical test for the materials and durability tests on concrete and reviewed the initial draft of the article. All authors had approved the final version.

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REFERENCES

[1] B. Tracy and A. Novak. (January 2023). Cement industry accounts for about 8% of CO_2 emissions. One startup seeks to change that. *CBS News*. [Online]. Available: https://www.cbsnews.com/news/cement-industry-co2-emissions-climate-change-brimstone/

[2] K. P. Robinson. (2023). The climate-positive benefits of concrete in outdoor architecture: Recent innovations in the composition, manufacture, and use of this resilient material. [Online]. Available: https://continuingeducation.bnpmedia.com/courses/unilock/the-climate-positive-benefits-of-concrete-in-outdoor-architecture/2/

[3] Frederickson. (2023). Concrete innovations: Reducing the carbon footprint with new technologies that meet future challenges. [Online]. Available: https://continuingeducation.bnpmedia.com/courses/NRMCA/concrete-innovations-1/

[4] B. S. Thomas and R. C. Gupta, "A comprehensive review on the applications of waste tire rubber in cement concrete," *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 1323–1333, 2016. https://doi.org/10.1016/j.rser.2015.10.092

[5] G. Malarvizhi, N. Senthil, and C. Kamaraj, "A study on recycling of crumbed rubber and low-density polyethylene blend on stone matrix asphalt," *International Journal of Scientific and Research Publication,* vol. 2, no. 10, pp. 1–16, 2012. http://www.ijsrp.org/research-paper-1012.php?rp=P10324

[6] F. Azevedo, F. Pacheco-Torgal, C. Jesus, J. B. D. Aguiar, and A. Camões, "Properties and durability of HPC with tyre rubber wastes," *Construction and Building Materials,* vol. 34, pp. 186–191, 2012. http://dx.doi.org/10.1016/j.conbuildmat.2012.02.062

[7] A. Mohajerani, L. Burnett, and J. V. Smith *et al.*, "Recycling waste rubber tyres in construction materials and associated environmental considerations: A review," *Resources Conservation and Recycling*, vol. 155, 104679, 2020. http://dx.doi.org/10.1016/j.resconrec.2020.104679

[8] M. Elkadi, A. Pillay, S. C. Fok, F. Feghali, G. Bassioni, and S. Stephen, "Depth profiling (ICP-MS) study of toxic metal buildup in concrete matrices: Potential environmental impact," *Sustainability*, vol. 2, no. 10, pp. 3258–3269, 2010. https://doi.org/10.3390/su2103258

[9] M. M. Ghobashy and G. Bassioni, "pH stimuli-responsive poly (acrylamide-co-sodium alginate) hydrogels prepared by γ-radiation for improved compressive strength of concrete," *Advances in Polymer*

Technology, vol.37, no. 6, pp. 2123–2133, 2018. https://doi.org/10.1002/adv.21870

[10] A. Pillay, M. Elkadi, F. Feghali. S. C. Fok, G. Bassioni, and S. Stephen, "Tracking chloride and metal diffusion in proofed and un proofed concrete matrices using ablative laser technology (ICP-MS)," *Natural Science,* vol. 2, no. 8, pp. 809–816, 2010. http://dx.doi.org/10.4236/ns.2010.28102

[11] G. Bassioni, A. E. Pillay, M. E. Kadi, F. Fegali, S. C. Fok, and S. Stephen, "Tracking traces of transition metals present in concrete mixtures by inductively coupled plasma mass spectrometry studies," *European Journal of Mass Spectrometry*, vol. 16, no. 6, pp. 679–692, 2010. https://doi.org/10.1255/ejms.1104

[12] M. Sienkiewicz, J. Kucinska-Lipka, H. Janik, and A. Balas, "Progress in used tyres management in the European Union: A review," *Waste Management*, vol. 32, no. 10, pp. 1742–1751, 2012. https://doi.org/10.1016/j.wasman.2012.05.010

[13] R. Saputra, R. Walvekar, M. Khalid, N. M. Mubarak, and M. Sillanpaa, "Current progress in waste tire rubber devulcanization," *Chemosphere*, vol. 265, 129033, 2021. https://doi.org/10.1016/j.chemosphere.2020.129033

[14] R. Hassanli, O. Youssf, and J. E. Mills, "Experimental investigations of reinforced rubberized concrete structural members," *Journal of Building Engineering*, vol. 10, pp. 149–165, 2017. http://dx.doi.org/10.1016/j.jobe.2017.03.006

[15] O. Youssf, M. A. ElGawady, and J. E. Mills, "Static cyclic behaviour of FRP confined crumb rubber concrete columns," *Engineering Structures*, vol. 113, pp. 371–387, 2016. http://dx.doi.org/10.1016/j.engstruct.2016.01.033

[16] B. S. Thomas, R. C. Gupta, and V. J. Panicker, "Experimental and modelling studies on high strength concrete containing waste tire rubber," *Sustainable Cities and Society*, vol. 19, pp. 68–73, 2015. http://dx.doi.org/10.1016%2Fj.scs.2015.07.013

[17] H. Mostafaei, M. Kelishadi, H. Bahmani, C. Wu, and B. Ghiassi, "Development of sustainable HPC using rubber powder and waste wire: Carbon footprint analysis, mechanical and microstructural properties," *European Journal of Environmental and Civil Engineering*, pp. 1–22, 2024. https://doi.org/10.1080/19648189.2024.2400485

[18] A. Sofi, "Effect of waste tyre rubber on mechanical and durability properties of concrete—A review," *Ain Shams Engineering Journal,* vol. 9, no. 4, pp. 2691–2700, 2018. https://doi.org/10.1016/j.asej.2017.08.007

[19] A. M. Aly, M. S. El-Feky, M. Kohail, and E. S. A. Nasr, "Performance of geopolymer concrete containing recycled rubber," *Construction and Building Materials*, vol. 207, pp. 136–144, 2019. http://dx.doi.org/10.1016/j.conbuildmat.2019.02.121

[20] M. Sambucci and M. Valente, "Influence of waste tire rubber particles size on the microstructural, mechanical, and acoustic insulation properties of 3D-printable cement mortar," *Civil Engineering Journal*, vol. 7, pp. 937–952, 2021. http://dx.doi.org/10.28991/cej-2021-03091701

[21] A. Bala and S. Gupta, "Thermal resistivity, sound absorption and vibration damping of concrete composite doped with waste tire rubber: A review," *Construction and Building Materials*, vol. 299, 123939, 2021. https://doi.org/10.1016/j.conbuildmat.2021.123939

[22] *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, ASTM A370-2017.

[23] *Standard Test Method for Fineness of Hydraulic Cement and Raw Materials by the 300-µm (No. 50), 150-µm (No. 100), and 75-µm (No. 200) Sieves by Wet Methods*, ASTM C786-10-2016.

[24] *Standard Test Method for Amount of Water Required for Normal Consistency of Hydraulic Cement Paste*, ASTM C 187-2023.

[25] *Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*, ASTM C127-10-2016.

[26] *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*, ASTM C 131-06-2010.

[27] *Standard Test Method for Slump of Portland Cement Concrete*, ASTM C143-78-2017.

[28] *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*, ASTM C231/C231M-2022.

[29] R. Abirami and S. P. Sangeetha, "Effect of surface modification on the characteristics of sisal fiber reinforced concrete treated with Na_2CO_3," *Nature Environment and Pollution Technology*, vol. 21, pp. 289–295, 2022. https://doi.org/10.46488/NEPT.2022.v21i01.034

[30] D. A. Singaravel, P. Veerapandian, S. Rajendran, and R. Dhairiyasamy, "Enhancing high-performance concrete sustainability: Integration of waste tire rubber for innovation," *Sci. Rep.,* vol. 14, p. 4635, 2024. https://doi.org/10.1038/s41598-024-55485-9

[31] *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens),* ASTM C 109-2020.

[32] *Standard Test Methods for Measurement of Rate of Absorption of Water by Hydraulic Cement Concretes*, ASTM C1585-2020.

[33] *The Saudi Building Code National Committee, The Saudi Building Code (SBC)—Section 601: Energy Conservation,* Kingdom of Saudi Arabia, 2018

[34] U.S. Department of Energy. (2022). Ansi/ashrae/iesna Standard 90.1-2022. [Online]. Available: https://www.energycodes.gov/sites/default/files/2024-02/Standard_90.1-2022_Final_Determination_TSD.pdf

[35] *Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus*, ASTM C 204-18e1-2023.

[36] *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*, ASTM C 403-2017.

[37] *Standard Method of Test for the Specific Gravity and Absorption of Coarse Aggregates*, AASHTO T 85-2022.

[38] P. Martauz and V. Vaclavik, "Review of the use of waste tires in concrete," *IOP Conference Series: Earth and Environmental Science,* vol. 900, 012023, 2021. https://doi.org/10.1088/1755-1315/900/1/012023