Structures 36 (2022) 837–853

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

Practical Application of Crumb Rubber Concrete in Residential Slabs

Osama Youssf [a,c,*], Julie E. Mills [a], Mark Ellis [a], Tom Benn [a], Yan Zhuge [a], Xing Ma [a], Rebecca J Gravina [b]

[a] UniSA-STEM, University of South Australia, Adelaide, Australia
[b] School of Engineering, RMIT University, Melbourne, Australia
[c] Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt

ARTICLE INFO

Keywords:
Residential footing
Residential ground slab
Rubber concrete
Concrete market
Dampness
Durability

ABSTRACT

While there is extensive data now available for the performance of crumb rubber concrete (CRC) in laboratory mixes, it is essential to understand whether satisfactory performance can be replicated in real-world structures. This is particularly the case for the area of residential construction, which is a sector that is sometimes characterised by fairly average outcomes due to a sometimes-low skilled workforce operating with minimal supervision. To replicate a real-world situation, CRC research has been moved from "the lab to the slab" in this paper. Two large-scale (4 × 8 m each) reinforced concrete residential footing slabs were constructed. One was cast with CRC and the other with a standard residential mix of conventional concrete (CC). In addition, two reinforced concrete residential ground slabs of different dimensions were constructed out of CRC and CC mixes to assess abrasion resistance. These ground slabs were poured in high traffic entrances of a civil engineering laboratory. All mixes were provided by a commercial ready-mix company and the construction was undertaken by an experienced footing contractor. A large range of factors have been investigated and compared. Those related to construction requirements, included the effect of using rubber on concrete mixing, delivery, workability, pumpability, ease of surface finishing, and curing. The contractors reported easy screeding and less physical effort to do so, with no difference reported when finishing the concrete surface when using a concrete power trowel for footing slabs. Other factors that were investigated included: fresh and hardened density, compressive strength, modulus of elasticity, shrinkage, carbonation, chloride ingress, abrasion resistance, rising damp, and corrosion. The results show that CRC is a potentially viable and promising alternative to conventional concrete in the residential concrete market.

1. Introduction

Accumulation of end-of life (EOL) tyres is a global and growing problem. Globally, approximately 1.5 billion vehicle tyres are discarded annually but only a small proportion are reused, and the rest are unaccounted for or dumped in landfills [1]. Current methods of recycling or disposal in Australia include re-use/re-treading, use as fuel, civil engineering uses (<1%), disposal to licensed landfill, stockpiles, or dumping on mine sites. The export of EOL tyres overseas has increased from 18% to 33% in the past four years, primarily for use as alternative fuels in the international energy market. However, the environmental consequences of this continuous waste production and disposal are unsustainable. Due to the recent drop in commodity prices and the Australian dollar, combined with a global decline in demand for tyre-derived fuels, Australian tyre recyclers are now making a loss when exporting their product, which is leading to increased local stockpiling and landfill [2].

Crumb rubber concrete (CRC) has some superior properties over conventional concrete such as: higher impact resistance and toughness, higher damping ratio, lighter weight, higher ductility, better thermal and acoustic insulation. On the other hand, CRC has lower compressive strength that initially limited its use to non-structural applications resisting impact forces or vibration such as: railway sleepers, pipe heads, and traffic barriers [3–6].

The recommended rubber replacement percentage of sand by volume is up to 20%. Replacement percentages exceeding 20% increase the adverse influence on concrete characteristics [7] and usually result in more than 30% strength loss compared with CC of same mix design [8]. Eldin and Senouci [9] studied the effect of size (38, 25, 19, 6.4 and 2 mm) and percentage volume (0, 25, 50, 75 and 100%) of untreated rubber aggregates on the compressive strength of concrete. They observed a 45% loss in strength at 28 days with 25% tyre rubber content

* Corresponding author at: UniSA-STEM, University of South Australia, Adelaide, Australia.

https://doi.org/10.1016/j.istruc.2021.12.062
Received 8 September 2021; Received in revised form 5 December 2021; Accepted 21 December 2021
Available online 29 December 2021

as coarse aggregate, which increased to 82% loss at 100% replacement level. They found a similar trend in loss of strength with fine rubber aggregates, but the 28-day strengths with fine rubber aggregates were considerably higher than those of coarse rubber aggregates. They noticed a 32% loss in strength at 28 days with 25% tyre rubber content as fine aggregate, which increased to 60% loss at 100% replacement level. A similar trend in the reduction in compressive strength due to the effect of particle size and percentage volume of tyre rubber was observed by many other researchers [10–14].

Mohammadi and Khabaz [15] studied the effect of soaking crumb rubber in water for 24 h on the crumb rubber concrete at the fine aggregate replacement levels of 10, 20, 30 and 40%. The strength results showed a reduction of 14.1, 29.7, 51 and 63.7% in the compressive strength at the corresponding replacement levels. Youssf et al. [16] investigated the comparative effect of treating rubber particles with different chemical solutions of NaOH, $KMnO_4$ + $NaHSO_4$, H_2O_2, $CaCl_2$, and H_2SO_4 on the mechanical properties of rubber concrete, containing rubber of 20% by sand volume. They observed that the treating the rubber particles with H_2O_2, H_2SO_4 and a combination of $KMnO_4$ and $NaHSO_4$, did not bring about any considerable change in the compressive strength results of the treated rubber concrete in comparison to the untreated rubber concrete. However, treating the rubber particles with NaOH and $CaCl_2$ solutions brought about a similar but small strength improvement of ~7% compared to that of the untreated rubber concrete. Similar small improvement in the compressive strength results of NaOH treated rubber concrete was reported by Najim and Hall [17]. However, another study by Youssf et al. [18] found that NaOH rubber treatment for more than 0.5 h had an adverse effect on the compressive strength of the treated rubber concrete.

Other researchers used different methods that are uncommon to improve the crumb rubber concrete performances. Huang et al. [19] could increase the concrete strength by 110% when using silane coupling agent as a rubber pre-treatment followed by coating the rubber particles by cement paste. However, Dong et al. [20] reported only 10–20% increase in compressive strength when using similar method. An improvement in the adhesion between rubber and cement paste was noted using silane coupling agent in pre-treating rubber [21]. The crumb rubber mortar compressive strength was doubled when rubber has been treated by sulfuric acid (H_2SO_4) [22]. More effects on CRC mechanical properties using untreated and pre-treated rubber have been studied by Roychand et al. [23].

Recent research has shown that higher-strength CRC can be achieved through a range of measures such as rubber pre-treatment, using silica fume, steel fibre and chemical admixtures, optimal rubber content and using rubber additions of well-graded size [18]. These results indicate that high-strength CRC could be used for structural members under modest loading [24,25]. Experimental tests on rubber-filled reinforced concrete columns [26], reinforced concrete slabs [13,27], wall panels [28–30], large-scale beams [31], beam-column joints [32], composite slabs [33–36], and a recent experimental study, on CRC columns at the University of South Australia [37,38], have shown that using CRC has significant potential to improve ductility and impact resistance of structural components. However, all these tests were carried out in the laboratory, which shows the need to move CRC to more practical and in situ research.

The tyre industry is keen to develop a market for recycled tyre products and to achieve this, Tyre Stewardship Australia (TSA) has been formed. In addition, supplies of natural sands that have the necessary consistency and chemical properties for use as fine aggregate in concrete (usually beach and river sands) are being depleted worldwide, including in Australia. The Australian residential construction industry is a huge market, big enough to consume most recycled rubber from Australian waste tyres if CRC could gain even a small market share. Based on 20% replacement of the natural sand aggregate by crumb rubber in a standard concrete mix of a strength adequate for the residential market, all the tyres currently being sent to landfill or disposed of in an unknown manner could be used as crumb rubber aggregate in residential concrete. This would still only provide enough material for 1.7 M m^3 of the estimated annual 9.6 M m^3 of concrete used annually in the residential sector in Australia [39].

If CRC is to be accepted as a viable alternative in the residential footing market, there are a large range of factors that must be explored, from the material, design and construction viewpoints. To increase the likelihood of acceptance of CRC by the concrete market, as a new class of concrete for residential footings, many characteristics must be achieved such as: good workability and pumpability, using only inexpensive and common admixtures, practical mix designs, adequate flexural strength and modulus of elasticity, and acceptable durability or shrinkage performance.

The ultimate aim of the current research reported in this paper is to determine the practical use of crumb rubber produced from EOL tyres as a partial replacement for natural sand aggregate in concrete. The research is focussed on the use of CRC in residential construction applications, since residential footings and slabs generally do not require high-strength concrete (20 MPa is commonly used for these applications in Australia), and account for approximately 40% of all premix concrete consumption in Australia. The application of reinforced CRC in residential construction has great potential to reduce the exploitation of natural material resources and decrease the environmental influences of EOL tyres. To test the feasibility of CRC for this application, large-scale CRC residential footing slabs were poured for several on-site and durability tests. A set of measurements were carried out on the slabs including concrete mixing, delivery, workability, pumpability, surface finishing, curing, shrinkage, compressive strength, modulus of elasticity, carbonation, chloride ingress, abrasion, rising damp, and corrosion. In addition to the residential footings, ground slabs were poured in high traffic entrances of a civil engineering laboratory to investigate the CRC durability, with particular reference to abrasion resistance, in residential construction. This research is the first to test this type of residential slab and it aims to show that for residential structural engineering applications, reinforced CRC is a sustainable and economically viable alternative to conventional reinforced concrete. This will provide the tyre industry with a viable market for EOL tyres, and the premix concrete industry with a green product for the residential construction market.

2. Experimental program

2.1. Mixes and materials

To investigate the required characteristics for large-scale residential applications, four concrete mixes were designed and tested in the initial stage of this project following numerous trials of a range of mix designs [40]. Two mixes were conventional concrete with 20 MPa and 32 MPa target strengths and the other two were the corresponding CRC mixes with 20% rubber content as a partial replacement of sand aggregate by volume. The selection of materials in this study was selected based on the common materials used by ready-mix concrete companies in Australia and the designs were developed in consultation with an industry partner. General Blended (Type GB) cement was the binder material with a specific gravity of 3.08 for the 20 MPa concrete, and General Purpose (Type GP) cement and Fly-ash with specific gravities of 3.15 and 2.57, respectively, for the 32 MPa concrete. Both cements satisfied the requirements of Australian Standard (AS) AS 3972 [41]. Dolomite stone was the coarse aggregate with 10 mm and 20 mm maximum sizes, while river sand was the fine aggregate with 5 mm maximum size. Crumb rubber, which was used as partial replacement of the river sand by volume, had a product name of 2–5 mm with particle sizes ranging between 1.18 mm and 2.36 mm. Fig. 1 shows the particles distribution for all the aggregates used. For dolomite, the unit weight and specific gravity were 1590 kg/m^3 and 2.73, respectively; for sand they were 1420 kg/m^3 and 2.63, respectively; and for rubber they were 530 kg/m^3 and 0.97, respectively. Air-entraining (AE) admixture and

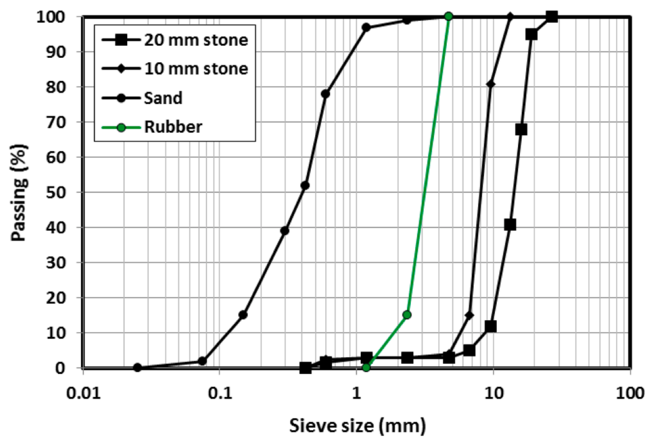


Fig. 1. Particle distributions of the aggregates used.

Polycarboxylic ether type water reducer (WR) with specific gravities of 1.002 and 1.075, respectively, were used in these mixes. The proportion of the mixes used in the residential slabs are shown in Table 1. While mixing CRC, the rubber was dealt with in the same way as the sand, in that it was added at the same time as the sand and stone using the material hopper in the concrete plant.

The selection of crumb rubber size of 2–5 mm was based on a comparative preliminary experimental investigation that assessed all the available crumb rubber sizes in the Australian market in the initial stage of this project [40]. The sizes tested were #40mesh with rubber particle sizes that ranged from 0.150 mm to 0.425 mm, #30mesh with rubber particle sizes that ranged from 0.30 mm to 0.60 mm, 1–3 mm with rubber particle sizes that ranged from 0.60 mm to 1.18 mm, and 2–5 mm with rubber particle sizes that ranged from 1.18 mm to 2.36 mm. Compared to conventional concrete, the biggest crumb rubber size showed 43% enhancement in concrete slump and achieved the best compressive strength of all the trialled rubber sizes. In addition, this crumb rubber size is the most economical size compared to the other smaller sizes, due to less energy and time needed to transform a complete EOL car tyre to that relatively large crumb rubber size.

2.2. Large-scale slab preparation

Two large scale residential footings slabs were poured at the University of South Australia. One slab was made of CC20 conventional concrete and the other one was made of CC20R rubberised concrete. Fig. 2 shows the dimensions of each slab. Each slab was 4 m × 8 m with a 0.3 × 0.5 m external perimeter beam and one internal beam across the short direction. The beams were reinforced by 3 N20 longitudinal top and bottom bars. At the eastern end of each slab, a 1 m cantilever was cast as well to allow for concrete coring for destructive durability tests. The slab thickness was 100 mm and it was reinforced by square reinforcing mesh having 9.5 mm diameter bars with 200 mm spacing in both directions. The residential slab surfaces were finished using a power trowel. The eastern halves of both residential footing slabs were cured by covering the concrete surface with plastic sheets for 7 days; however, the western halves of both slabs were left for air curing (modelling best practice (covered) and unfortunately common practice (no curing) in industry). The soil type at the construction site was a reactive clay/silty clay, classified as H1-D with a maximum surface movement, $y_s = 47$ mm. The area is known for the salinity and relatively aggressive nature of its soils. The footing was designed by a consulting engineering company with a significant market share in the residential footing industry in South Australia. Fig. 3 shows the procedures of slab casting, curing, and coring.

Two ground slabs were also poured at two vehicle entrances of the civil engineering laboratory at the University of South Australia. These laboratory entrances experience high traffic loads of heavy vehicles including; fork-lift, light utility vehicle, and heavy trollies. One slab had dimensions of 3.6 × 2.9 m and the other one had dimensions of 3.1 × 1.4 m, as shown in Fig. 4. These slabs replaced old deteriorated conventional concrete slabs that were removed using a concrete saw. The base soil underneath the slabs was mixed with demolished concrete rubble and then compacted and isolated using plastic sheets, as shown in Fig. 5. At each entrance, the eastern half of the slab was poured using rubberised concrete CC32R and the western half of the slab was poured using conventional concrete CC32. The slab thickness was 125 mm and they were reinforced by square reinforcing mesh having 9.5 mm diameter bars with 200 mm spacing in both directions. The surfaces of the ground slabs were roughly finished using a broom, while the slab edges were smoothly finished with 4-inch steel edger. All ground slabs were left for air curing. Fig. 6 shows the ground slabs after casting and surface finishing.

Many standard specimens were taken from each mix while pouring to measure different short and long term concrete properties. The concrete slump, screeding ability, fresh and hardened density, compressive strength, modulus of elasticity, curing effect, drying shrinkage, hydration temperature development, edge dampness development, normal and accelerated carbonation development, chloride ingress, surface abrasion, and corrosion development were all evaluated.

The concrete workability was measured using a standard slump test at four intervals during the construction process of footing slabs according to Australian Standard (AS) AS 1012.3.1 [42]; at the concrete plant (0.0 min), when the truck arrived (30 min), at the discharge end of the pump line, and at the end of the truck discharge. The fresh and hardened density were measured using the filled cylinders for the compressive strength test. The ease of finishing was assessed using a power trowel by recording the verbal feedback of the contractor. The modulus of elasticity and compressive strength tests were measured using standard 100 × 200 mm cylinders (three cylinders for each mix/measurement). The compressive strength test was conducted using a 1500 kN capacity testing machine with a constant loading rate of 20 ± 2 MPa/min according to AS 1012.9 [43]. Determination of the modulus of elasticity was conducted using an 1800 kN capacity testing machine with a constant loading rate of 15 ± 2 MPa/min according to AS 1012.17 [44]. The drying shrinkage was measured using standard 75 × 75 × 280 mm beams with two end studs according to AS 1012.13 [45]. The hydration temperature development was measured using a 0.5 × 0.5 × 0.5 m concrete block by embedding a thermocouple at the concrete block centre and recording the temperature change for 7 days, as shown in Fig. 7. The effect of the different curing regimes was measured 28 days after casting the concrete. This involved keeping three cylinders exposed to the ambient conditions for 28 days without applying any water curing or covering. They were compared with cylinders that were sprayed with

Table 1
Mix proportions used in the residential slabs per 1 m^3.

Mix	20 mm Stone (kg)	10 mm Stone (kg)	Concrete Sand (kg)	Cement (kg)	Fly-ash (kg)	Rubber (kg)	Water (kg)	WR (kg)	AE (kg)
CC20	557	482	986	259	0.0	0.0	158.0	0.69	0.31
CC20R	557	482	789	259	0.0	73.0	158.0	0.69	0.31
CC32	691	563	848	307	76	0.0	88.0	1.33	0.0
CC32R	691	563	678	307	76	62.0	88.0	1.33	0.0

WR – Water reducer, AE – Air-entraining admixture.

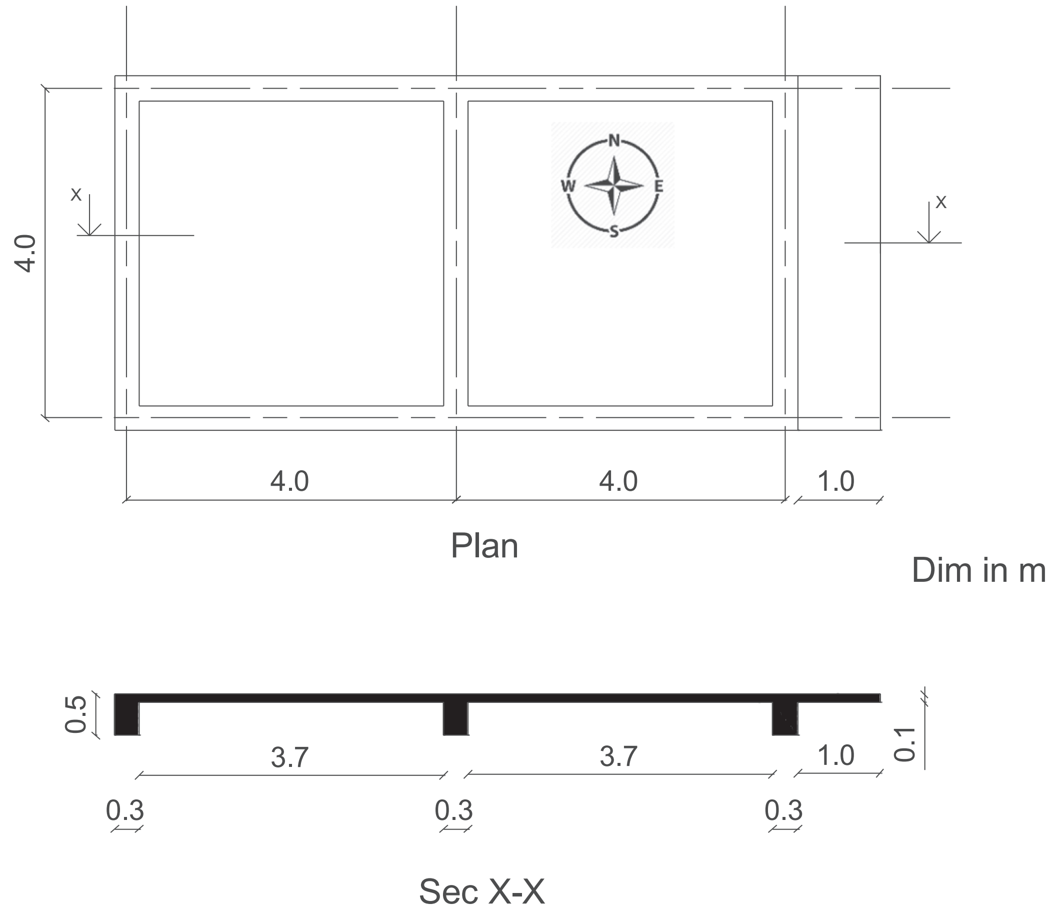


Fig. 2. Dimension details of the residential footing slabs.

water 24 h after the slab was poured, covered with plastic sheets for 7 days and then left exposed to ambient conditions up to 28 days. This was to simulate exactly what happened in half of each slab.

2.3. Carbonation

The carbonation development in the slab was measured by cutting a 70 × 200 mm fresh piece of concrete from the slab cantilever edge and spraying indicator (phenolphthalein 0.5% solution in 50% ethanol) to determine the carbon dioxide (CO_2) depth, as shown in Fig. 8. The fresh concrete cut was taken from the slab edge to check the CO_2 penetration from both slab sides exposed to the air (top surface and vertical side).

Concrete specimens were cast to undertake accelerated carbon dioxide ingress testing of the concrete used for the slab construction in accordance with the recommendations of Zhou and Papworth [46]. Four 100 × 100 × 250 mm prisms were cast for both the CC and CC20R mixes. The prisms were cast in a vertical position (similar to a standard concrete cylinder) to minimise concrete segregation. Approximately 24 h after the prisms were cast, they were carefully removed from the moulds and placed in a lime bath for another 6 days. After this time, the prisms were removed and allowed to air cure for a further 21 days in accordance with the recommendations of Zhou and Papworth [46]. Each prism was placed on a drying rack with timber supports at each end of the prism to ensure full curing of all the prism faces. Care was taken to avoid handling the middle section of the prism as this is where the carbon dioxide ingress would be measured. All four prisms were then placed into the environmental chamber with plastic supports at each end of the prism, see Fig. 9(a). This allowed the carbon dioxide to fully circulate around the prisms. The environmental chamber was set to a temperature of 23 ± 3 °C, relative humidity of 65 ± 5%, and carbon dioxide concentration of 2 ± 0.2% as recommended by Zhou and Papworth [46] which are similar to those suggested by FIB Bulletin #34 [47].

After 28 days, one prism was removed from the chamber and split in two halves using a three-point bending testing machine. The exposed surface of each half was then sprayed with phenolphthalein indicator (same mixture as used for the residential slabs). The sprayed indicator was allowed to dry, and the depth of carbonation ingress measured on all four faces for both halves of the prism at 10 mm intervals. The first measurement was taken at distance of 20 mm away from the corner to avoid any edge effects, see Fig. 9(b). This procedure was repeated at 56, 119, and 182 days of concrete age for the other three prepared prisms.

2.4. Chloride ingress

To better understand the impact of the typical industry curing practice and the surface finish of the concrete on durability, 100 mm diameter specimens were cored from the cantilever section of the slabs at each testing age. The top portion of the cores were trimmed with a saw cut to leave a 50 mm thick specimen with the trowelled surface left intact. The cored specimens were then tested for chloride ingress and surface abrasion. From each slab and at each testing age, four cores were used for the chloride ingress test and ten for the abrasion test. Tests were carried out at 28, 56, and 91 days to determine if the age of the concrete impacted the test results.

The chloride ingress test procedure followed a modified Nordtest Method NT Build 492 [48]. The cored specimens were saturated in a lime bath for a period of 24 h before commencing the test. The trowelled surface of each specimen was placed downward in the test setup and a power supply was used to force chloride ions into the concrete specimen

Fig. 3. Residential slab casting, curing, and coring.

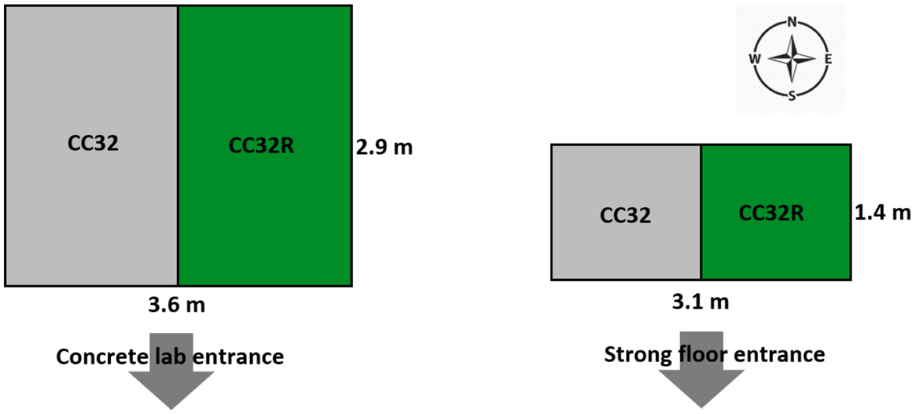


Fig. 4. Dimension details of the ground slab.

Fig. 5. Removing old ground slab and preparing for new replacement.

Fig. 6. The ground slab after casting and surface finishing.

Fig. 7. Recording of hydration temperature.

Fig. 8. Normal carbonation depth measurement.

(a) (b)

Fig. 9. Accelerated carbon dioxide ingress; (a) specimens in environmental chamber, and (b) measuring of carbonation depth.

for a duration of 24 h. After the test had finished, the test specimens were removed from the test setup and split into two halves using a splitting tensile test machine. The exposed surface of the flatter half was painted with silver nitrate ($AgNO_3$) solution (in accordance with the test method) and the depth of the chloride ingress was determined at various locations across the width of the specimen, see Fig. 10. The outer 20 mm were excluded from the measurements to avoid edge contamination.

2.5. Abrasion resistance

Abrasion of the concrete surface was tested according to the test method for masonry pavers AS 4456.9 [49]. The core specimens were dried in an oven (105 ± 5 °C) for 24 h, cooled for 4–5 h, and then the pre-test mass was determined. Eight of the cored specimens from each slab were clamped to the square-sided rotating drum and two specimens were used as controls. The drum was filled with 600 ball bearings having 16 mm diameter and the drum was rotated for 60 min at a speed of 60 rpm. After the test was completed, each specimen was removed, vacuum cleaned to remove any loose dust, and then the post-test mass was determined. The specimens were placed into a water bath for a period of 24 h then their mass was determined while they were under water, and then the saturated surface dry mass was determined. Each specimen was carefully inspected for defects such as side wall damage or missing pieces of aggregate. If any significant defects were found in a specimen, its data was removed from the calculation. From these measurements, the Abrasion index, V_a, was determined. Fig. 11 shows some details of the surface abrasion test.

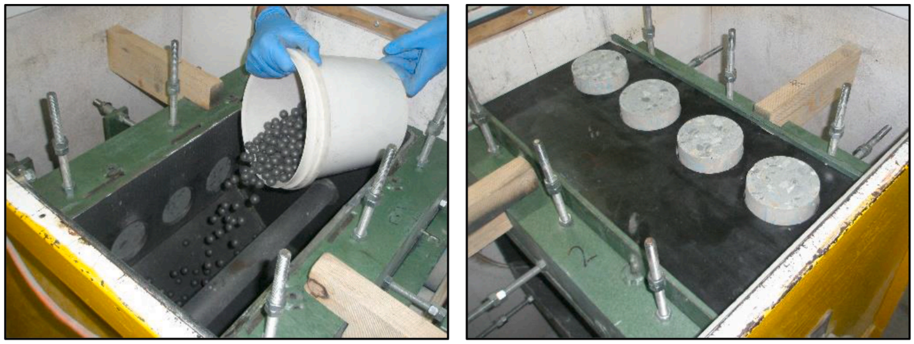
Fig. 10. Determination of the chloride ingress depth.

2.6. Long term dampness and corrosion development

Long term dampness and corrosion development was measured using 60 × 60 × 470 mm beams with a deformed bar centrally embedded in each beam. In total, eighteen beams of each mix were cast; half had N10 steel bar centred using plastic chairs to keep 25 mm cover constant from all bar sides including the bar ends. However, in the other half of the beams, the N12 steel bar was centred using wooden formwork with holes in which the bar went along the whole concrete beam length with 20 mm projection from each end. The bars were then trimmed at the beam edge surfaces and the beam edges were covered by two-part waterproof epoxy to isolate the steel bar from water at the beam edges. Fig. 12 shows the preparation of the dampness and corrosion beams. The eighteen beams of each mix were divided into three sets of six beams (three with N10 and three with N12). These three beam sets were tested in three different environments/conditions. One set was embedded to a depth of half their length close to the residential slabs (clay/silty soil). The second set was buried to half their length in a highly saline sandy soil in the Port Adelaide area (South Australia). The third set was fully soaked in 5% sodium sulphate solution. This resulted in twelve beams (six of each mix) in each testing environments/conditions. The beams were secured in an upright position using horizontal square reinforcing mesh welded to four legs of long reinforcing bar that were embedded into the soil as shown in Fig. 13. The concrete dampness was measured by visually investigating the outer surfaces of the beams. The reinforcement steel corrosion development was measured by determining the mass loss in the embedded bars due to corrosion according to ASTM G1-03 [50]. Each reinforcement bar was cleaned of the corrosion products using 12% hydrochloric acid (density of 1.19 gm/cm^3) solution after demolishing the surrounding concrete according to ASTM G1-03 [50]. The cleaning process commenced by removing the corrosion products initially by using a hammer and steel brush, then by chemically soaking the bars in the HCl solution for 25 min at 23C. The bars were then washed with distilled water by lightly brushing the corrosion products using a non-metallic brush. The cleaned bars were oven dried at 50C for 30 min before measuring the mass loss.

2.7. Edge dampness test

The edge dampness development was measured by covering a 400 × 600 mm surface area of concrete slab surface at its southern edge using a plastic tub (250 mm depth) with small openings in the side walls of the tub to keep the covered area dry at all times. This experimental setup was done at two locations in each footing slab. At the first location, the plastic membrane laid by the contractor underneath the slab and the



(a) (b)

Fig. 11. Details of the surface abrasion test; (a) Insertion of ball bearings, and (b) insertion of test specimens.

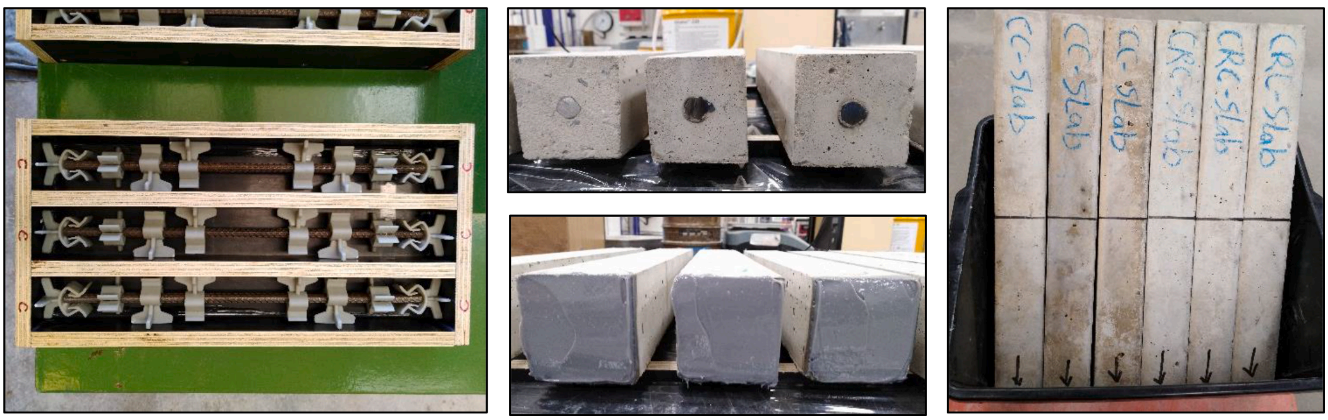


Fig. 12. Dampness and corrosion development beams and test setup.

Fig. 13. Dampness and corrosion development beams buried.

beam sides before concrete pouring, was kept in place (isolated concrete edge). However, in the other location, that plastic membrane was manually removed from beneath the slab/beam side for the whole depth and 1 m width (naked concrete edge) to ensure full contact between the concrete and the soil to increase the edge dampness effect. Fig. 14 shows the locations of the edge dampness test setup.

3. Results and discussion

3.1. CRC practicality

The ready-mix companies did not report any concern related to CRC delivery and mixing. They recommended that if CRC became a common type of concrete with high demand, concrete plants would need to prepare storage areas for rubber aggregate that could feed the materials hopper. They also reported easy wash out of the concrete truck mixer as the rubber is lighter than sand and hence can be easily removed. The contractors reported no difference between CRC and CC when pumping

Fig. 14. Edge dampness test setup.

or finishing with a power trowel. The CRC was easy to screed and required less physical effort to do so due to its relatively light weight. However, they recommended that CRC should not have a slump higher than 100 mm when manually finished as with a higher slump, the rubber particles tended to move to the surface due to their relatively light weight, and hence could be easily removed from the concrete matrix when the surface was finished with tools like the broom.

3.2. CRC mechanical and durability properties

Several mechanical and durability properties were measured in this study including; slump, compressive strength modulus of elasticity, drying shrinkage, corrosion, carbonation, chloride ingress, and surface abrasion. Tables 2 and 3 show the results of the measured mechanical and durability properties for the residential footing slabs and ground slabs in this study.

3.2.1. Slump

Fig. 15 shows the concrete slump losses with time for all mixes. About 1 h after completing the mixing, the CC20R mix had a negligible decrease in slump of only 10 mm (6%), compared with relatively higher slump losses of 45 mm (28%) recorded for mix CC20. This was attributed to the lower rate of water absorption and hydrophobic nature of the rubber aggregates with the size used in this study (1.18–2.36 mm) compared to that of the replaced sand, thus keeping the concrete mix at a higher moisture content for a longer time. This was explained by Youssf et al. [40] in which the rubber size controls its water absorption and hence governs the concrete slump. They showed that the rubber sizes of 0.15–0.425 mm and 0.3–0.6 mm adversely affect the concrete slump; however, sizes of 0.6–1.18 mm and 1.18–2.36 mm increase the concrete slump. The slump losses recorded for all mixes at the time of the truck's arrival at the construction site was not significant and did not cause any issue for the contractor when they handled and finished the concrete. However, it was more pronounced in the 32 MPa concrete mixes. At the time of the truck's arrival, the slump losses were 16% and 12% for CC32 and CC32R mixes, respectively, and were 6% and 3% for CC20 and CC20R mixes, respectively. This was due to the relatively low water content and the existence of the fly-ash in the 32 MPa concrete mixes.

3.2.2. Density

The density of the CC20 mix was 2380 kg/m^3 in the fresh state, which decreased to 2317 kg/m^3 in the hardened state indicating a 3% decrease in density due to the water evaporation. The same evaporation percentage was recorded for CC20R mix as its density was 2240 kg/m^3 in fresh status and 2166 kg/m^3 in hardened status. The hydrophobic nature of rubber particles that repels water helped in not affecting the

Table 2
Measured properties for residential footing slabs.

Mix	*CC20*	*CC20R*	*Mix*	*CC20*	*CC20R*
Slump (mm)			***28 days Mod of E (GPa)***	28.3	21.2
At the plant	160	165	***Highest hydration temp (C°)***		
At truck arrival (30 min)	150	160	Occurred after 11.16 hr	33.2	27.9
At truck pump outlet	120	160	Occurred after 17.50 hr	30.7	29.2
At truck discharge end (1hr)	115	155	***Shrinkage (Microstrain)***		
Fresh Density (kg/m^3)	2380	2240	14 Day	417	447
Hardened Density (kg/m^3)	2317	2166	21 Day	536	591
Compressive strength (MPa)			28 Day	672	652
7 day - Cured	19.24	11.16	56 Day	838	781
28 day - Cured	27.8	18.42	***Normal carbonation depth (mm)***		
28 day - Not cured	26.1	16.66	28 day	2.5	2.5
2 month - Cured	25.23	14.25	3 months	2.5	2.5
3 month - Cured	28.19	16.15	6 months	2.5	2.5
6 month - Cured	27.67	16	9 months	2.5	2.5
9 month - Cured	27.5	15.38	12 months	7	6
12 month - Cured	33.1	18.2	18 months	8	6.5
18 month - Cured	33.3	18.6	***Accelerated carbonation depth (mm)***		
Chloride ingress coefficient (×10^{-12} m^2/s)			28 day	13.1	13.2
28 day	14.9	13.7	56 day	18.9	18.8
56 day	15.6	14.4	119 day	23.5	23.2
91 day	13.6	12	182 day	33.2	34.1
Dampness development in beams after 18 month – affected length (mm)					
Beams with N10 – clay soil	No sign	No sign	Beams with N10 – sand soil	30-70	25-40
Beams with N12 – clay soil	No sign	No sign	Beams with N12 – sand soil	70-185	75-130
Corrosion development in beams after 18 month – mass loss (%)					
Beams with N10 – sodium sulphate	4.78	4.54	Beams with N10 – clay soil	4.62	4.55
Beams with N12 – sodium sulphate	4.25	3.95	Beams with N12 – clay soil	4.12	4.29
Beams with N10 – sandy saline soil	4.95	4.82	***Abrasion index***		
Beams with N12 – sandy saline soil	4.59	5.15	28 day	4	9.9
Edge dampness level in footings after 18 months			56 day	2.3	8.8
Isolated edge	No sign	No sign	91 day	2.2	9.3
Naked edge	No sign	No sign			

water transfer within the concrete matrix when it changed from wet to dry status.

3.2.3. Compressive strength

The compressive strength decreased when replacing 20% of concrete sand by rubber regardless of the concrete grade as shown in Fig. 16. This was because of the weak inherent strength of the rubber particles and the poor bond performance at the rubber/cement interface. In addition, rubber stiffness is much lower than that of the surrounding cement paste which causes relative deformation and early cracking combined with strength reduction.

Both 7 and 28 day compressive strengths had the same trend with having rubber in concrete. However, when rubber presented in concrete, the 7-day/28-day strength ratio decreased by 13% for the 20 MPa mix and by 2% for the 32 MPa mix, compared with the conventional corresponding concrete. This might be due to the existence of zinc stearate in the tyre formulation [51]. The migration and diffusion of this zinc

Table 3
Measured properties for ground slabs.

Mix	Slump (mm)		Hardened Density (kg/m^3)	Compressive strength (MPa)							
	At the plant	At truck arrival (20 min)		7 day	28 day	2 mth	3 mth	6 mth	9 mth	12 mth	15 mth
CC32	120	100	2312	21.1	29.2	38.6	36.5	33.2	35.4	35.6	34.7
CC32R	160	140	2273	16.8	23.8	26.3	26.8	25.6	26.3	29.9	29.0

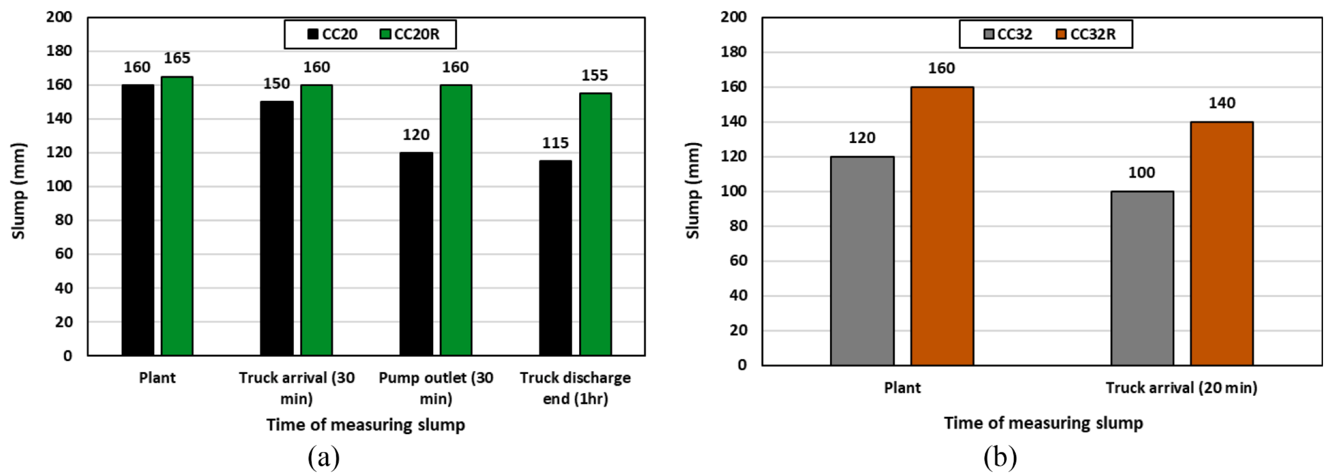


Fig. 15. Slump losses of the mixes used; (a) CC20 and CC20R, (b) CC32 and CC32R.

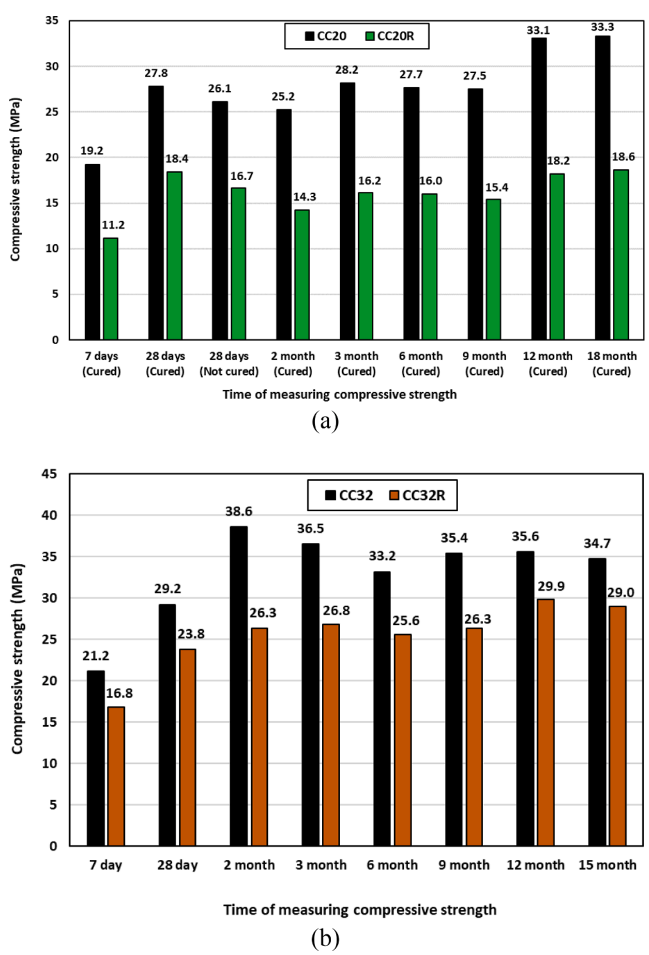


Fig. 16. Compressive strength of the mixes used; (a) CC20 and CC20R, (b) CC32 and CC32R.

stearate while mixing rubber in concrete creates a soap layer around the rubber particles that could affect the interaction between water and cement, which delays the hydration reaction. Compared with sand, rubber particles have lower thermal conductivity which can reduce the overall concrete thermal conductivity [52]. This decreases the heat transfer rate within the concrete matrix, and thus lowers the heat of hydration. The different effects of rubber between 20 MPa and 32 MPa mixes is attributed to each mix composition and proportions. Mix 32 MPa had higher cementitious materials and much lower water/binder ratio. In addition, it had higher water reducer dosage which helped in better spreading of cement particles and hence higher rate of hydration reaction.

The effect of 7 days concrete curing by covering it using plastic sheet showed 6% and 10% increases in the 28 days compressive strength of CC20 and CC20R mixes, respectively as shown in Fig. 16(a). The rubber concrete showed higher strength enhancement due to the hydrophobic nature of the rubber aggregates that helps in keeping the concrete mix moist for longer time and hence led to better internal curing and higher results when covering by plastic sheets. From after 28 days until the end of the testing period of this study, conventional concrete and rubber concrete showed different behaviours and strength developments over time. From 28 days up to 18 months, the CC20R compressive strength remained constant at ≈18 MPa with only 4 MPa variation in the strength throughout the time. Similarly, CC20 showed constant compressive strength at ≈27.5 MPa with 3 MPa variation in the strength up to 9 months; however, for unclear reason the strength jumped to 33 MPa at 12 month and remained constant up to 18 months. The compressive strength of both CC32R and CC32 varied with time from 28 days and up to 15 months as shown in Fig. 16(b). That variation was obvious in CC32 in which the compressive strength increased by 9.5 MPa at 2 months, decreased by 5.4 MPa at 6 months and increased again at 15 months by 2.0 MPa. However, CC32R showed a tendency of increase with time that reached to 5.7 MPa strength increase at 15 months. It is well known that the concrete compressive strength develops rapidly up to 28 days and after that, the strength development and variation is unclear and depends on many factors related to the surrounding environment of concrete [53]. From the above results, it is clear that a combination of factors has affected the long-term strength of the different concrete used. Al-Khaiat and Fattuhi [53] reported a fluctuated compressive strength of concrete up to 18 months with unclear reason. The changing of weather seasons and how concrete is exposed to that change, and the wetting-–drying cycles due to rain can affect the long-term compressive strength. The residential footing slabs in this study were built in an open area and the nearest building to them was about 100 m away. However, the ground slabs were built just in front of structural laboratory with many close by buildings. This also might be another reason of the different behaviours observed between the concrete mixes used. The resultant water repelled by rubber particles in rubber concrete mixes due to the rubber hydrophobic nature can also add to the factors affecting the rubber concrete strength at late ages, in which this can increase the voids within the concrete matrix when concrete gets dry due to high external weather temperature.

3.2.4. Drying shrinkage

Fig. 17 shows the measured drying shrinkage for the concrete footing slab mixes (CC20 and CC20R) at different concrete ages. As shown in the figure, the concrete drying shrinkage increased with concrete age due to the evaporation of water from concrete with time. CRC showed similar shrinkage values to that of the counterpart CC at all ages, with slightly lower long-term values. This was attributed to the hydrophobic nature of rubber particles that repel water and caused no significant effect on the water transfer within the concrete matrix while drying. The differences between the measured shrinkage for both CC20 and CC20R ranged between only 3% and 10%. Therefore, using rubber in concrete has an overall insignificant effect on the concrete shrinkage.

3.2.5. Hydration temperature

The highest hydration temperature recorded for the CC20 mix was 33.2C and occurred 11.16 h after completion of mixing; while the CC20R mix reached 27.9C at the same time, see Fig. 18. The recorded highest hydration temperature for the CC20R mix was less and later than that of the CC20 mix with a maximum value of 29.2C at 17.50 h; when the CC20 mix was showing 27.9C at the same time. Compared with sand, rubber particles have lower thermal conductivity [52]. This can lower the overall thermal conductivity of concrete which reduces the rate of heat transfer within the concrete matrix. In addition, CRC has relatively higher specific heat [54] which means that it needs more heat and time to reach a given temperature compared with CC.

3.2.6. Carbonation depth

3.2.6.1. Natural carbonation. Up to 9 months, the measured natural carbonation depth for both CC20 and CC20R footing slabs was constant at 2.5 mm, as shown in Table 2. However, the carbonation depth increased by about 2.8 times and 2.4 times, respectively for CC20 and CC20R slabs when measured at 12 months. At 18 months, the carbonation depth increased by about 3.2 times and 2.6 times, respectively for CC20 and CC20R slabs compared to those measured during the first 9 months. The mechanism of CO_2 penetration of concrete surface is mainly dependent on the number of concrete pores and their moisture conditions. If the pores are completely full of water or completely dry, carbonation of concrete would be difficult due to the absence of the necessary conditions [55]. Although the existence of rubber in concrete would increase the pores due to the relatively bad adhesion between rubber and surrounding cement paste, the rubber hydrophobic nature makes the surrounding pores full of water and hence no additional CO_2 penetration occurs due to the existence of rubber. It is worth noting that the CO_2 penetration of concrete was observed at the footing vertical side, but not at the top surface. This might be due to the different concrete finishing techniques between the top surface, power trowelled, and the concrete sides, with no applied finishing. Concrete surface finishing is a type of concrete vibration which helps in reducing the number of pores that are close to the concrete surface, and hence lowers the ability of CO_2 penetration. The CO_2 penetration depth was clear and constant (7 mm at 12 months and 8 mm at 18 months) in the CC; however, this was not the case in the CRC with the CO_2 penetrating the CRC to a maximum of 6 mm at 12 month and 6.5 mm at 18 month, as shown in Fig. 19. This implies that there was no adverse effect of using rubber in concrete in developing the carbon dioxide penetration into the concrete cover and that the use of crumbed rubber could possibly reduce the CO_2 attack.

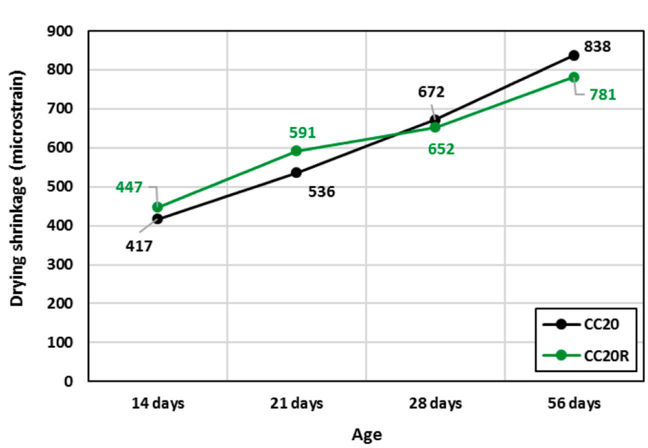


Fig. 17. Drying shrinkage for footing slab mixes.

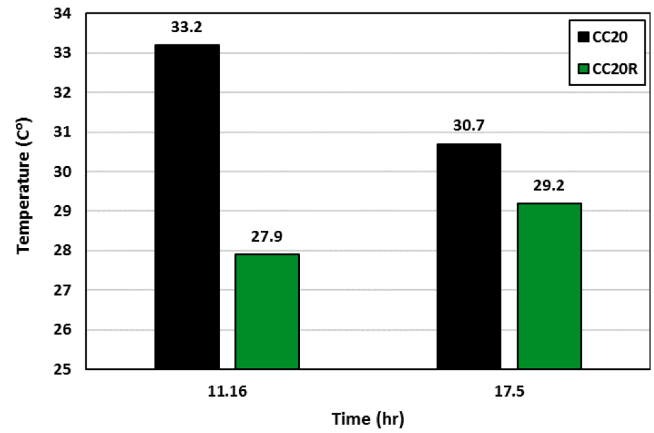


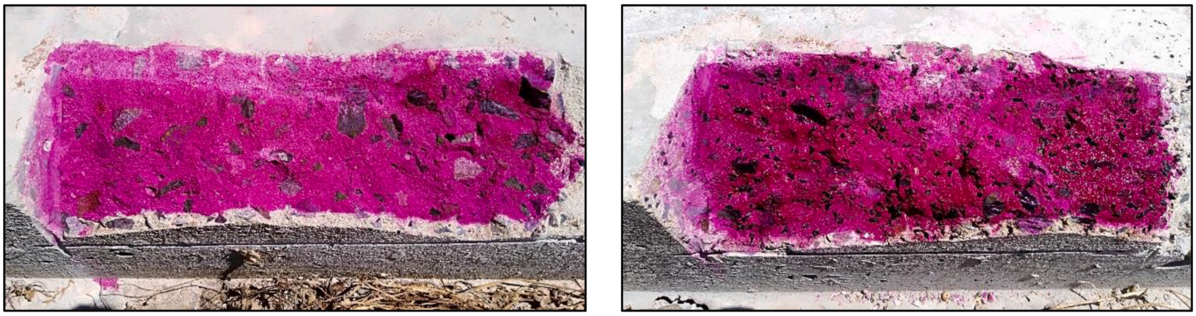
Fig. 18. Concrete hydration temperature.

3.2.6.2. Accelerated carbonation. The accelerated carbonation test was completed over a period of 6 months with a carbon dioxide concentration of 50 times that of natural carbon dioxide level. The carbon dioxide ingress was measured on four sides of each specimen and the average ingress of each specimen was plotted against the square root of time (years$^{1/2}$) in Fig. 20. A linear regression analysis was performed on the data with the carbonation rate equal to the fitting line slope.

Similar to what was recorded in the natural carbonation on the slabs and for the same reasons, there was very little difference between the ingress for the CC and CC20R mixes, suggesting that the rubber has no impact on carbon dioxide ingress through the concrete. The carbonation rate for CC was determined as 45.24 mm/year$^{1/2}$ which was almost the same carbonation rate as that of CC20R (45.68 mm/year$^{1/2}$). These results further confirmed that the rubber has no adverse impact on the concrete carbonation.

3.2.7. Chloride ingress

The non-steady-state migration coefficient (D_{nssm}) for chloride ingress was determined for CC and CC20R at 28, 56, and 91 days using



(a) CC20 (b) CC20R

Fig. 19. CO_2 penetration of concrete.

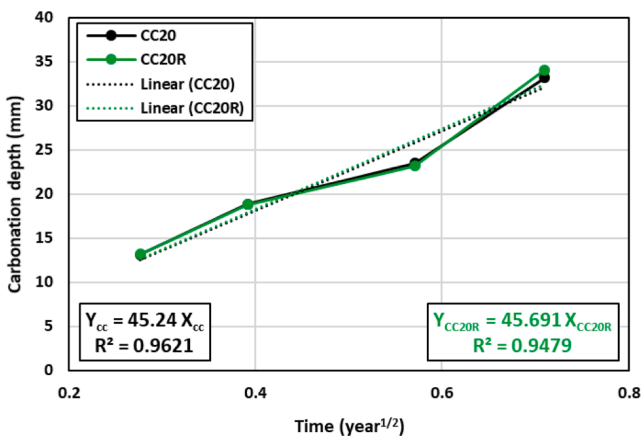


Fig. 20. Accelerated Carbonation Rate for footing slabs mixes.

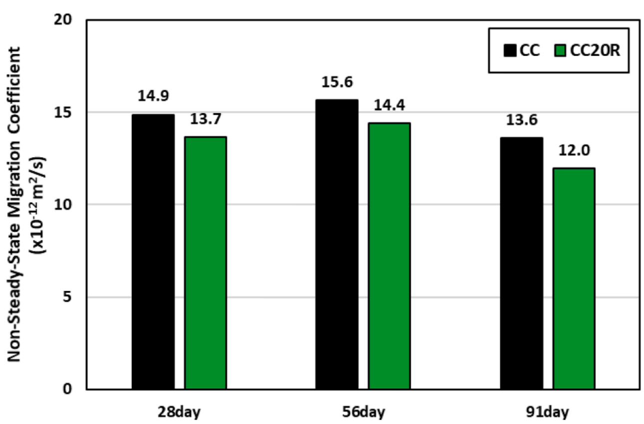


Fig. 21. Chloride ingress at different ages.

the cored specimens and according to Eq. (1). The average test results are shown in Fig. 21. For both CC and CCR20, D_{nssm} increased slightly between 28 and 56 days then decreased again at 91 days to a result lower than at 28 days. This trend may be due to the very dry weather that the slabs experienced for the first two months after being poured, preventing both slabs from fully curing. Importantly, D_{nssm} was lower for CC20R than CC at all ages. This indicates that rubber does not have an adverse effect on concrete resistance to chloride ingress and could reduce the chloride ingress by about 10%. Chloride ingress is largely influenced by the water/cement ratio and the aggregate volume fraction ratio [56]. As the rubber has a larger size than the replaced sand, the effective aggregate volume fraction would increase slightly in the rubberised concrete reducing the overall chloride migration coefficient.

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right) \tag{1}$$

where; D_{nssm} is the Non-Steady-State migration coefficient ($\times 10^{-12}$ m^2/s), U is the absolute value of the applied voltage (V), T is the average value of the initial and final temperatures in the NaOH solution (°C), L is the thickness of the specimen (mm), x_d is the average depth of penetration across the sample (mm) and t is the test duration (hours).

3.2.8. Surface abrasion

The Abrasion index (V_a) was determined for CC and CC20R at ages of 28, 56, and 91 days using Eq. (2). The results are shown in Fig. 22. The V_a for CC almost halved between 28 and 56 days and remained relatively constant up to 91 days. However, CC20R did not follow the same trend in that the V_a decreased slightly up to 56 days and increased slightly up to 91 days. In addition, the V_a for CC20R was significantly higher than that of CC at all test ages. This shows that the rubber had a significant negative impact on the abrasion index using this test method. The main reason for the negative performance of rubber concrete in abrasion resistance is the relatively bad adhesion of rubber particles with the surrounding cement paste which make it easy for rubber to be detached from the concrete matrix when subjected to this aggressive type of abrasion test. The abrasion index is not considered particularly critical for residential slabs, but it was included here for completeness.

$$V_a = \frac{m_1 - (m_2 - C)}{B_d} \tag{2}$$

where; m_1 is the pre-test weight, m_2 is the post-test weight, C is the correction mass and B_d is the bulk density of the specimen.

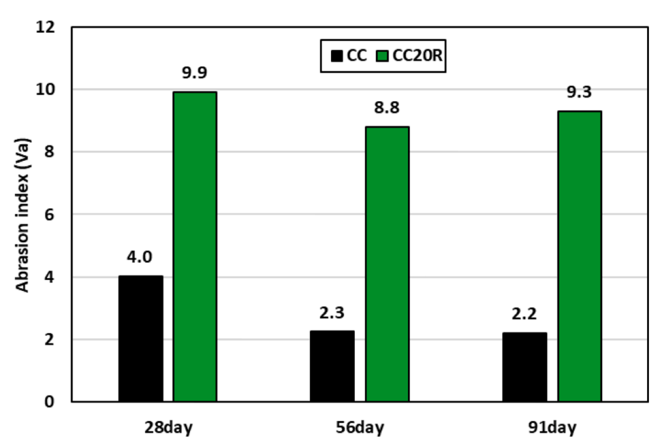


Fig. 22. Abrasion index at different ages.

3.2.9. Surface deterioration and cracking

The concrete surfaces of both residential footings slabs and ground slabs were monitored to report any visual deterioration and cracking with time. As observed in the CC, no visual deterioration or cracking was detected on the CRC surface up to 18 months for the residential footing slabs that were surface finished by the power trowel method. For the ground slabs, outside the laboratory, observations up to 15 months showed no adverse effect of using rubber in the concrete generally. Only some minor voids were observed on the surface of the CRC ground slabs at the perimeters that were smoothly finished by a steel edger, as shown in Fig. 23. This was due to the bad adhesion between rubber particles and cement paste which caused easy detaching of the rubber particles leaving some surface voids. However, this was much lower in the surfaces that were roughly finished using a broom. The rough CRC surface finishing might provide better containment of the rubber particles at the surface which increased its adhesion to concrete. Therefore, it is recommended to avoid smooth surface finishing of CRC when utilising it in ground slabs subject to high traffic of vehicles and walkers. These observations also demonstrated that from a practical perspective, there was no concern with abrasion of the ground slabs and that this test was more realistic and useful than the standard ball bearing abrasion test in predicting the actual behaviour of the CRC from a surface wearing perspective.

3.2.10. Reinforced beams dampness and corrosion

The rising damp and corrosion development were measured for both CC and CRC used in the footing slabs. For each mix, beams with N10 bar and others with N12 bar were exposed to different environments/conditions. The rising damp in the concrete was measured by visual investigation of the outer surfaces of the beams, and the reinforcement steel corrosion development was measured by determining the mass loss in the embedded bars due to corrosion.

The visual inspection of beams soaked in sodium sulphate solution, that contained N10 bars, showed concrete edge spalling regardless of the concrete type, see Fig. 24. However, no evidence of concrete spalling was observed in beams with N12 bars. This was due to the existence of the plastic chairs in beams, containing N10 bars, that eased the way for the solution to penetrate the concrete surface. The visual investigation showed no sign of dampness in beams buried in clay/silty soil, regardless of the concrete type or bar diameter. However, beams buried in the sandy saline soil showed clear signs of dampness. In the dampness affected locations, the concrete surface had clear surface erosion with relatively porous surface compared with the non-affected locations. These marks were more obvious in beams containing N12 bars compared to beams with N10 bars, see Fig. 25, due to the relatively less concrete cover around the N12 bars which helped to absorb high saline water from the sand soil. Because the surface concrete dried out more quickly than in thicker concrete cover, the effect of dampness was more visible. Fig. 26 shows the affected length, in mm, of beams buried in sandy soil. CC20 beams containing N10 bars showed sections of 30–70 mm in length. This value jumped to 70–185 mm in CC20 beams with N12 bars. However, the affected length of the CC20R beams was lower in both cases (25–40 mm with N10 bars and 75–130 mm with N12 bars). This indicates that CRC has higher ability to resist the rising damp effect than CC due to the hydrophobicity nature of rubber that helps in repelling water and causes less water to penetrate the concrete, and hence a lower rising damp effect.

The mass loss in the embedded bars due to corrosion is shown in Fig. 27. Small mass loss values ranging between 3.95% and 5.15% were recorded in all beams under different conditions. The average mass loss in both N10 and N12 bars for beams buried in sandy soil were higher than those in clay/silty soil and sodium sulphate solution. The average mass loss in CC20R-N10 beams was 3% less than that in CC20-N10 beams; however, it was 3% higher in CC20R-N12 beams compared with that in CC20-N12 beams. For beams soaked in sodium sulphate solution, CCR20 beams had 5–7% less mass loss in both N10 and N12

Fig. 23. Surface of CRC ground slabs at different locations.

(a) CC20-N10 beams. (b) CC20R-N10 beams.

Fig. 24. Concrete edge spalling in beams soaked in sodium sulphate solution.

(a) N10 beams. (b) N12 beams.

Fig. 25. Dampness signs in beams buried in sandy soil.

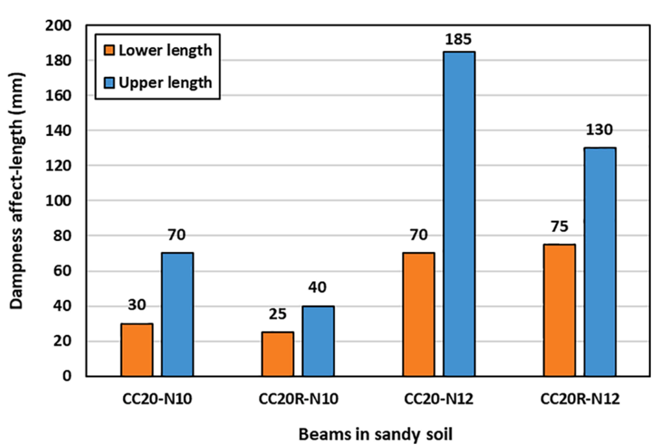


Fig. 26. Dampness effect – sandy soil.

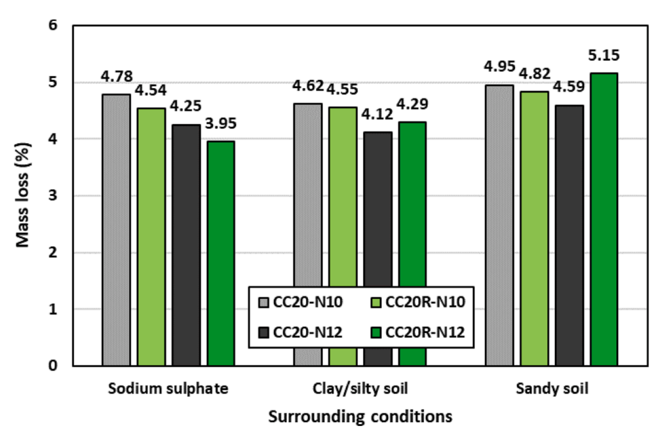
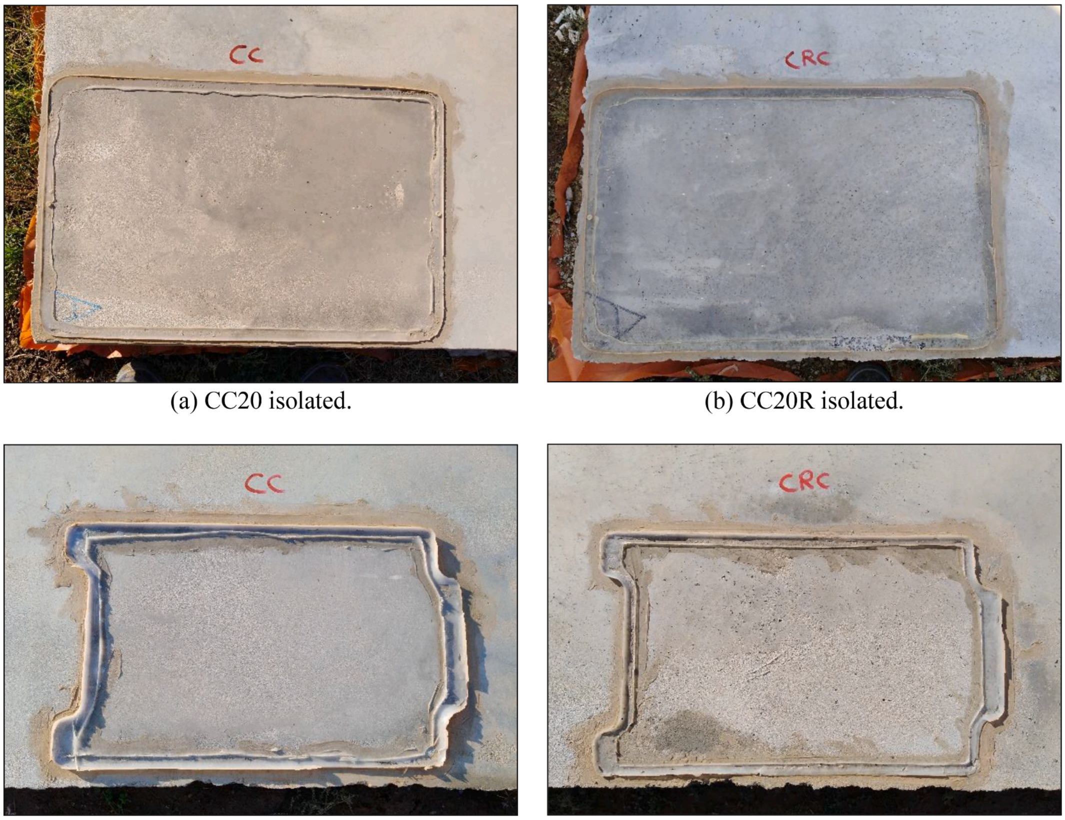


Fig. 27. Mass loss due to corrosion.

bars than was recorded by the corresponding CC20 beams. For beams buried in clay/silty soil, CCR20 beams showed only 1.5% less mass loss in N10 bars, but 4% higher mass loss in N12 bars. For beams buried in sandy soil, CCR20 beams showed only 2.6% less mass loss in N10 bars, but 12% higher mass loss in N12 bars. From the above results, it can be concluded that CRC performs similarly to CC in resisting steel reinforcement corrosion as no significant difference was observed.

3.3. Footing slabs edge dampness

The footing slabs edge dampness was checked at 18 months. An area of 400 × 600 mm of the concrete slab surface was covered 28-days after casting, using 250 mm depth plastic tubs with side openings to create a dry environment inside the covered area. The dry environment inside the covered area was intended to create a wicking effect that would draw water up from the surrounding relatively wet environment, and hence cause slab edge dampness conditions. This test was carried out at two different locations on each slab; namely, concrete isolated from the soil by a plastic membrane and concrete in direct contact with the soil.



(a) CC20 isolated. (b) CC20R isolated.

(c) CC20 naked. (d) CC20R naked.

Fig. 28. Edge dampness of CC20 and CC20R footing slabs at different locations/conditions.

For CC20 and CC20R slabs, there was no sign of slab edge dampness at either the isolated or the non-isolated concrete edges, as shown in Fig. 28. A relatively dark discoloration of concrete surfaces was observed at the isolated locations for both footing slabs. These isolated locations had relatively much less water to absorb from the surrounding environment compared with that at the uncovered locations. This relatively decreased the continuous cement hydration after 28 day concrete age which affects the cement ferrites, and hence leads to a darker grey colour compared with the lighter grey colour of surrounding well hydrated concrete [57]. From the above observations, it can be concluded that crumb rubber concrete performs in a similar manner to conventional concrete under severe conditions in residential footing slabs.

4. Summary and conclusions

In this research, a wide range of experimental investigations were carried out, with the aim of moving crumb rubber concrete (CRC) from the lab to the slab for the residential construction sector. Two 4 × 9 m large-scale reinforced concrete residential footings were constructed. One was cast with CRC and the other with a standard residential mix of conventional concrete (CC), both with nominal 20 MPa strength. In addition, two reinforced ground slabs with different dimensions were constructed out of CRC and CC mixes, with nominal 32 MPa strength. All mixes were provided by a commercial ready-mix company and the construction was undertaken by an experienced footing contractor. A large range of factors have been investigated and compared. The main findings and recommendations of this investigation are summarised in the following points:

1. The ready-mix companies did not report any concern related to the CRC batching, delivery and mixing, with easy wash out of the concrete truck mixer also reported. The contractors reported no difference between CRC and CC with respect to pumping, screeding or finishing the concrete surface using a power trowel, in fact less physical effort was required for all aspects. They recommended that CRC should not have slump higher than 100 mm when manually finished.
2. CC20R mix showed negligible slump losses (6%), compared with relatively higher slump losses (28%) for CC20 mix at 1 h after batching. At the time of truck arrival, the slump losses were 16% and 12% for CC32 and CC32R mixes, respectively, and were 6% and 3% for CC20 and CC20R mixes, respectively.
3. The 7-day/28-day strength ratio decreased by 13% and 2% for 20 MPa and 32 MPa mixes, respectively when the rubber presented. The compressive strength of all CC and CRC mixes displayed some variations with time (18 month), and CRC did not show any tendency to reduce with time.
4. CRC showed similar shrinkage values to that of the counterpart CC with slightly lower long-term values.
5. The recorded highest hydration temperature for the CC20R mix was less and later than that of the CC20 mix.
6. No adverse effect of using rubber in concrete in developing the carbon dioxide penetration into the concrete cover was observed and rubber could possibly reduce the CO_2 attack.
7. No visual deteriorations were observed on the CC or CRC surface up to 18 months for the residential footing slabs that were surface finished using a power trowel. Only some minor voids were observed on the surface of the CRC ground slabs at the perimeters that were smoothly finished by hand using a steel edger.
8. No sign of rising damp was observed in beams buried in clay/silty soil regardless of the concrete type or bar diameter. Clear marks of dampness were observed in beams buried in sandy saline soil. CRC showed higher ability to resist the rising damp effect in beams than CC. CRC performed similarly to CC in resisting slab

edge dampness effect and reinforcement corrosion. No sign of dampness was observed at both isolated and non-isolated concrete edges for either type of concrete. Small mass loss values (3.95–5.15%) due to reinforcement corrosion were recorded in all beams under different conditions.

9. Of the four accelerated durability tests that were performed, CCR20 only performed below CC20 in the abrasion resistance test. However, in the slab subjected to practical abrasion from heavy traffic over 15 months, no difference in performance was noted.
10. Chloride diffusivity and carbonation showed almost identical results between CC and CCR20.

Overall and from the results of a wide range of tests carried out on a large-scale residential footing slab in this study, crumb rubber concrete can be promoted as a viable alternative to conventional concrete in the residential construction concrete market with no significant issues of concern.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to acknowledge the funds provided by the Australian Research Council (ARC-LP160100298) and industry partners for this project. The industry partners are; Tyrecycle Pty Ltd, Tyre Stewardship Australia, ResourceCo Pty Ltd, FMG Engineering Pty Ltd, and Ancon Beton. The material donations by ResourceCo Pty. Ltd., Adelaide Brighton Cement Pty. Ltd., and Tyrecycle Pty. Ltd., are greatly appreciated. The authors also would like to thank the laboratory staff members who helped in this work: Mr. Tim Golding, Mrs. Michelle Plew, Dr. Henry Senko, Mr. Ian Whitehead, Mr. Shane Kakko, Mr. Rohan Muscher, Mr. Craig Sweetman, and Mr. Chris Rust.

References

[1] Tyre Stewardship Australia, Tyre Stewardship Australia "https://www.racv.com.au/membership/member-benefits/royalauto/archive/old-tyres-a-new-local-solution-to-a-global-challenge.html", 2019.
[2] Hyder Consulting Pty Ltd, Stocks-and-fate-end-life-tyres-2013-14-study:final report, 2015.
[3] Fattuhi NI, Clark LA. Cement-based materials containing shredded scrap truck tyre rubber. Constr Build Mater 1996;10(4):229–36.
[4] Topçu IB, Avcular N. Collision behaviours of rubberized concrete. Cem Concr Res 1997;27(12):1893–8.
[5] Siddique R, Naik TR. Properties of concrete containing scrap-tire rubber-an overview. Waste Manage 2004;24(6):563–9.
[6] Eltayeb E, Ma X, Zhuge Y, Xiao J, Youssf O. Composite walls Composed of profiled steel skin and foam rubberised concrete subjected to eccentric compressions. J Build Eng 2021:103715.
[7] Khatib ZK, Bayomy FM. Rubberized Portland cement concrete. J Mater Civ Eng 1999;11(3):206–13.
[8] Li D, Mills J, Benn T, Ma X, Gravina R, Zhuge Y. Review of the performance of high-strength rubberized concrete and its potential structural applications. Adv Civil Eng Mater 2016;5(1):149–66.
[9] Eldin NN, Senouci AB. Measurement and prediction of the strength of rubberized concrete. Cem Concr Compos 1994;16(4):287–98.
[10] Reda Taha MM, El-Dieb AS, Abd El-Wahab MA, Abdel-Hameed ME. Mechanical, fracture, and microstructural investigations of rubber concrete. J Mater Civ Eng 2008;20(10):640–9.
[11] Gesoglu M, Güneyisi E, Hansu O, İpek S, Asaad DS. Influence of waste rubber utilization on the fracture and steel–concrete bond strength properties of concrete. Constr Build Mater 2015;101:1113–21.
[12] Raffoul S, Garcia R, Pilakoutas K, Guadagnini M, Medina NF. Optimisation of rubberised concrete with high rubber content: an experimental investigation. Constr Build Mater 2016;124:391–404.
[13] Li D, Zhuge Y, Gravina R, Mills JE. Compressive stress strain behavior of crumb rubber concrete (CRC) and application in reinforced CRC slab. Constr Build Mater 2018;166:745–59.
[14] Youssf O, Elchalakani M, Hassanli R, Roychand R, Zhuge Y, Gravina RJ, et al. Mechanical performance and durability of geopolymer lightweight rubber concrete. J Build Eng 2022;45:103608. https://doi.org/10.1016/j.jobe.2021.103608.
[15] Mohammadi I, Khabbaz H. Shrinkage performance of Crumb Rubber Concrete (CRC) prepared by water-soaking treatment method for rigid pavements. Cem Concr Compos 2015;62:106–16.
[16] Youssf O, Hassanli R, Mills JE, Skinner W, Ma X, Zhuge Y, et al. Influence of mixing procedures, rubber treatment, and fibre additives on rubcrete performance. J Compos Sci 2019;3(2):41. https://doi.org/10.3390/jcs3020041.
[17] Najim KB, Hall MR. Crumb rubber aggregate coatings/pre-treatments and their effects on interfacial bonding, air entrapment and fracture toughness in self-compacting rubberised concrete (SCRC). Mater Struct 2013;46(12):2029–43.
[18] Youssf O, Mills JE, Hassanli R. Assessment of the mechanical performance of crumb rubber concrete. Constr Build Mater 2016;125:175–83.
[19] Huang B, Shu X, Cao J. A two-staged surface treatment to improve properties of rubber modified cement composites. Constr Build Mater 2013;40:270–4.
[20] Dong Q, Huang B, Shu X. Rubber modified concrete improved by chemically active coating and silane coupling agent. Constr Build Mater 2013;48:116–23.
[21] Xiong G, Luo B, Wu X, Li G, Chen L. Influence of silane coupling agent on quality of interfacial transition zone between concrete substrate and repair materials. Cem Concr Compos 2006;28(1):97–101.
[22] Abdulla AI, Ahmed SH. Effect of rubber treated by acidic solution on some mechanical properties of rubberize cement mortar. Eng Technol J 2011;29(13).
[23] Roychand R, Gravina RJ, Zhuge Y, Ma X, Youssf O, Mills JE. A comprehensive review on the mechanical properties of waste tire rubber concrete. Constr Build Mater 2020;237:117651.
[24] Najim KB, Hall MR. A review of the fresh/hardened properties and applications for plain-(PRC) and self-compacting rubberised concrete (SCRC). Constr Build Mater 2010;24(11):2043–51.
[25] Hassanli R, Youssf O, Mills JE, Karim R, Vincent T. Performance of segmental self-centering rubberized concrete columns under different loading directions. J Build Eng 2018;20:285–302.
[26] Son KS, Hajirasouliha I, Pilakoutas K. Strength and deformability of waste tyre rubber-filled reinforced concrete columns. Constr Build Mater 2011;25(1):218–26.
[27] Li D, Xiao J, Zhuge Y, Mills JE, Senko H, Ma X. Experimental study on crumb rubberised concrete (CRC) and reinforced CRC slabs under static and impact loads. Aust J Struct Eng 2020;21(4):294–306.
[28] Ghaly AM. Flexural performance of rubberized concrete panels reinforced with polymer grid. J Green Build 2006;1(2):99–117.
[29] Sukontasukkul P, Jamnam S, Rodsin K, Banthia N. Use of rubberized concrete as a cushion layer in bulletproof fiber reinforced concrete panels. Constr Build Mater 2013;41:801–11.
[30] Eltayeb E, Ma X, Zhuge Y, Youssf O, Mills JE, Xiao J. Structural behaviour of composite panels made of profiled steel sheets and foam rubberised concrete under monotonic and cyclic shearing loads. Thin-Walled Structures 2020;151:106726.
[31] Gravina RJ, Xie T, Roychand R, Zhuge Y, Ma X, Mills JE, et al. Bond behaviour between crumb rubberized concrete and deformed steel bars. Structures 2021;34:2115–33.
[32] Ganesan N, Bharati R, Shashikala AP. Behavior of self-consolidating rubberized concrete beam-column joints. ACI Mater J 2013;110(6):697–704.
[33] Yi O, Zhuge Y, Ma X, Gravina R, Mills JE, Youssf O. Push-off and Pull-out Bond Behaviour of CRC Composite Slabs – An Experimental Investigation. Eng Struct Accepted October 2020, 2020,;25:110448.
[34] Mohammed BS. Structural behavior and m–k value of composite slab utilizing concrete containing crumb rubber. Constr Build Mater 2010;24(7):1214–21.
[35] Holmes N, Dunne K, O'Donnell J. Longitudinal shear resistance of composite slabs containing crumb rubber in concrete toppings. Constr Build Mater 2014;55:365–78.
[36] Yi Ou, Mills JE, Zhuge Y, Ma X, Gravina RJ, Youssf O. Performance of crumb rubber concrete composite-deck slabs in 4-point-bending. J Build Eng 2021;40:102695. https://doi.org/10.1016/j.jobe.2021.102695.
[37] Youssf O, ElGawady MA, Mills JE. Static cyclic behaviour of FRP-confined crumb rubber concrete columns. Eng Struct 2016;113:371–87.
[38] Youssf O, ElGawady MA, Mills JE. Experimental investigation of crumb rubber concrete columns under seismic loading. Structures 2015;3:13–27.
[39] ANCON Beton Pty Ltd, Recycled Tyre rubber in concrete: Economic and research assessment report, (2014).
[40] Youssf O, Mills JE, Benn T, Zhuge Y, Ma X, Roychand R, et al. Development of crumb rubber concrete for practical application in the residential construction sector – design and processing. Constr Build Mater 2020;260:119813.
[41] Standards Australia, General purpose and blended cements, AS 3972., 2010.
[42] Standards Australia, Methods for testing concrete, Determination of properties related to the consistency of concrete—Slump test AS 1012.3.1, 2014.
[43] Standards Australia, Methods of testing concrete – Compressive strength tests – Concrete, mortar and grout specimens, AS 1012.9, 2014.
[44] Standards Australia, Methods for testing concrete, Determination of the static chord modulus of elasticity and Poisson's ratio of concrete specimens, AS 1012.17, 1997.
[45] Standards Australia, Methods for testing concrete, Part 13: Determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory, AS 1012.13, 2015.
[46] Zhou S, Papworth F. Concrete Durability Series - Z7/05 Durability Modelling - Recommended Practice. Concrete Institution of Australia 2014.
[47] F.I. du Beton, Model code for service life design, Bulletin 34 (2006).

[48] Build N. 492. Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments. Nordtest method 1999;492(10).
[49] Standards Australia, Masonry units, segmental pavers and flags, Method 9: Determining abrasion resistance AS/NZS 4456.9, 2003.
[50] ASTM-G1-03, Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens, 2017.
[51] Ganjian E, Khorami M, Maghsoudi AA. Scrap-tyre-rubber replacement for aggregate and filler in concrete. Constr Build Mater 2009;23(5):1828–36.
[52] Fadiel A, Al Rifaie F, Abu-Lebdeh T, Fini E. Use of crumb rubber to improve thermal efficiency of cement-based materials. Am J Eng Appl Sci 2014;7(1):1–11.
[53] Al-Khaiat H, Fattuhi N. Long-term strength development of concrete in arid conditions. Cem Concr Compos 2001;23(4-5):363–73.
[54] Jedidi M, Gargouri A, Daoud A. Effect of rubber aggregates on the thermophysical properties of self-consolidating concrete. Int J Thermal Environ Eng 2014;8(1):1–7.
[55] Saetta AV, Schrefler BA, Vitaliani RV. The carbonation of concrete and the mechanism of moisture, heat and carbon dioxide flow through porous materials. Cem Concr Res 1993;23(4):761–72.
[56] Li L-Y, Xia J, Lin S-S. A multi-phase model for predicting the effective diffusion coefficient of chlorides in concrete. Constr Build Mater 2012;26(1):295–301.
[57] N. Greening, R. Landgren, Surface discoloration of concrete flatwork, Portland Cement Association, Research and Development Laboratories, 1966.