Reinforced Crumb Rubber Concrete for Residential Construction

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ABSTRACT: In this paper, we have moved our research from “the lab to the slab”. While there are extensive data now available for the performance of crumb rubber concrete (CRC) in laboratory mixes, it is essential that we understand whether satisfactory performance can be replicated in real world structures. This is particularly the case for the area of residential construction, which is often characterised as having the lowest common denominator of workmanship and quality. To replicate the real world situation, two large-scale reinforced concrete residential slabs were constructed, each 4 m × 9 m, with an edge beam and one internal beam across the short dimension. One was cast with CRC and the other with a standard residential mix of conventional concrete. Both 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 included the effect of using rubber on concrete mixing, delivery, workability, pump-ability, surface finish-ability, and curing. The contractors reported easy screeding and less physical effort to do so, with no difference reported when finishing the concrete surface by helicopter for both slabs. Other factors have been investigated through laboratory testing on a combination of cylinders cast at pouring, and cored samples from a one metre cantilever section of each slab, as well as detailed observations and reporting of the slab conditions. These include shrinkage, compressive strength, modulus of elasticity, structure deformation, fresh and hardened density, edge dampness effect, carbonation effect, surface abrasion, chloride effect, corrosion development, and water sorptivity. The results to date show that CRC in residential slabs is a promising and potentially viable alternative to conventional concrete.

Keywords: Residential footing, Rubber concrete, Concrete market, Strength, Workability, Durability.

1. Introduction

What to do with end-of life (EOL) tyres is a global and growing problem. Globally, approximately 1.5 Billion vehicle tyres are discarded annually but only a tiny proportion are recycled, and the rest are dumped in landfills or are unaccounted for [1]. In 2013, the number of equivalent passenger units of EOL tyres in Australia (where a standard car tyre is 1 EPU but a bus tyre is 5 EPU) was 51 million (more than two per person), but only 5% were recycled domestically, 32% were exported, 16% were sent to licensed landfills, and the fate of the remaining 47% was either unknown or unverified disposal in landfill on mining sites [2]. 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]. The cost of exporting the waste is similar to the landfill levy. The cost of economically inefficient allocation of end-of-life tyres in Australia was assessed in 2006 as approximately $350 million over a 10 year period [3].

The tyre industry is keen to develop a market for recycled tyre products and to achieve this has formed Tyre Stewardship Australia (TSA). At the same time, 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 becoming depleted worldwide, including in Australia. The ultimate aim of the current research
program reported in this paper is to determine the optimal use of crumb rubber produced from end-of-life tyres as a partial replacement for natural sand aggregate in concrete, thus generating a new product known as crumb rubber concrete (CRC). 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, and account for ~40% of all premix concrete consumption in Australia. The application of reinforced CRC in residential construction has great potential to reduce the environmental impacts of both waste tyres and exploitation of natural material resources.

Sand is now the most widely consumed natural resource after fresh water. The annual world consumption of aggregate (sand and gravel) for concrete is ~40bn tonnes, twice the natural renewal rate [4]. Sand mining is impacting significantly on rivers, deltas, coastal and marine ecosystems, resulting in erosion problems and decreased sediment supply. The construction industry is the most significant user of sand, which is an essential component in the manufacture of concrete. Australia’s annual production of 24M m³ of pre-mixed concrete consumes some 20M tonnes of sand. However, for larger metropolitan markets such as Sydney and Brisbane, natural sand in close proximity to the main locations of concrete production is becoming increasingly difficult to source.

The use of recycled rubber in construction materials began with rubber-modified asphalt binders in pavement engineering in the 1960–1970s [5]. In the early 1990s, rubberised concrete was first developed by introducing rubber particles into Portland cement concrete as a partial replacement for the aggregate component [6, 7]. Compared with traditional concrete, rubberised concrete can have some superior characteristics such as lighter weight, higher damping ratio, greater toughness and impact resistance, and better ductility and acoustic and thermal insulation. However, adding rubber particles into a concrete mix results in compressive strength reduction, which limits the structural applications of rubberised concrete. Hence rubberised concrete was initially recommended for non-structural applications under vibration or impact situations, e.g. foundation pads under machinery or railway stations, trench filling, pipe heads, paving slabs, railway buffers, traffic barrier shock absorbers and noise absorbers [8-10].

Recent research has shown that higher-strength rubberised concrete 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. These results indicate that high-strength rubberised concrete could be used as structural members under modest loading [11]. Experimental tests on rubber-filled reinforced concrete columns [12], wall panels [13, 14], beam-column joints [15], composite slabs [16, 17], and a recent experimental study on CRC columns at UniSA [18] have shown that using rubberised concrete has significant potential to improve ductility and impact resistance of structural components. Rubberised concrete is achieved by shredding the recycled tyres into particle sizes (rubber chips/fibres) or shredding then grinding into granular-sized particles (crumb). Using rubber chips/fibres to produce high-strength rubberised concrete has been investigated [19-21]. However, in a concrete mix there is a larger compressive strength reduction with rubber chips/fibres than crumb rubber. These results have presented widely variable findings due to inconsistent mix designs, rubber particle sizes, origins, and processing, which has limited the structural application of CRC to date.

This project aims to develop a framework to optimise the CRC mix design in terms of rubber size, chemical composition, surface treatments and mix additives. The characterisation of the mechanical properties of the optimal mix in terms of compressive strength, modulus of elasticity, flexural-tensile strength will draw a complete picture about the performance of this concrete class. For residential construction applications, issues of long-term durability and behaviour such as creep are equally important, because serviceability and maintenance are critical for the design life of these structures. In addition, this research hopes to show that reinforced CRC is an economically viable and sustainable alternative to conventional reinforced concrete for residential structural engineering applications. This will provide the tyre industry with a viable market for end-of-life tyres, and the premix concrete industry with a green product for the residential construction market.
2. Residential footing market and needs

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 15% replacement of the natural sand aggregate by crumb rubber in a standard concrete mix of a strength adequate for the residential market, the entire amount of tyres currently being landfilled or disposed of in an unknown manner could be used as crumb rubber for this purpose, and still only provide 1.7M m$^3$ of the estimated annual 9.6M m$^3$ of concrete used annually in the residential sector [22].

The Australian Standard AS 2870, Residential slabs and footings [23], provides guidance on the design and construction of these structures in Australia. While some areas of Australia with non-reactive soils can use the tabulated “deemed-to-comply” footing designs provided in the standard, many areas of Australia have expansive soils combined with climatic conditions that require structurally designed footings to take into account the impacts of expected soil movement as a result of both seasonal moisture changes and the influence of tree growth. The commonly used design methods in accordance with the code require designs to satisfy both flexural capacity and stiffness requirements. While CRC has been shown to have lower compressive strength than equivalent conventional concrete mixes, this issue is not as critical when considering flexural behaviour in ductile designs with very small compressive zones. Similarly the impact of CRC on the Elastic Modulus properties is not as significant as compressive strength reduction, and hence with appropriate mix design it is likely that these concerns can be overcome. However, even if the requirements for flexural strength and stiffness are satisfied, the long term performance of any residential footing is often more influenced by durability factors, and hence improving crack control and moisture ingress to prevent problems such as salt damp, spalling and rusting of reinforcement are critical, particularly in aggressive soils.

The final area of concern in residential footing construction relates to the issues that arise due to the nature of the housing construction workforce and economic model. In a market dominated by high volume, low margin project home builders, subcontractors responsible for footing construction operate in high pressure, low return environments, as do frequently the consulting engineers responsible for designing and inspecting the footings. Consequently there can be an unfortunately high number of poorly qualified workers involved in construction, with limited quality control both in terms of reinforcement fixing and concrete placement. If a CRC readymix product does not meet this particular industry sector’s needs for an easily workable, easily finished product, then the “just add water” and “she’ll be right” philosophy of the workforce might lead to poor outcomes.

Consequently 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.

3. CRC pathway to residential footing market

To increase the likelihood of acceptance of CRC by the concrete market as a new class of concrete for residential footings the following characteristics must be achieved: 1. Good workability and pump-ability to provide easy concrete pouring, 2. Using only inexpensive and common admixtures to keep the final cost of the product appropriate for the customer, 3. Practical mix designs in which no uncommon material or procedures are required to prepare and deliver the ready mix, 4. Adequate flexural strength and modulus of elasticity, 5. No penalties related to the bond length or reinforcement requirements, and 6. No unacceptable durability or shrinkage performance.

Based on the required characteristics and for large-scale residential applications, two concrete mixes were designed and tested for this research (following numerous trials of a range of mix designs). One was a conventional concrete mix with 20 MPa target strength and the other was the corresponding CRC mix with 20% rubber content as a partial replacement of sand aggregate by volume. The materials used in this study were selected based on the common materials being utilized by ready mix concrete companies in Australia and the designs were developed in consultation with an industry partner. The binder material used was General Blended (GB) cement with a specific gravity of 3.08, in accordance
with Australian Standard (AS) AS 3972 [24]. The coarse aggregate was dolomite stone with nominal maximum sizes of 10 mm and 20 mm, while the fine aggregate was river sand with a maximum size of 5 mm. Crumb rubber, which was used as partial replacement of the river sand by volume, had a product name of 2-5mm with particle sizes ranging between 1.18 mm and 2.36 mm. Figure 1 provides the sieve analysis for all of the aggregates used. The specific gravity and unit weight were 2.73 and 1590 kg/m³, respectively for dolomite; 2.63 and 1420 kg/m³, respectively for sand; and 0.97 and 530 kg/m³, respectively for rubber. Polycarboxylic ether type water reducer (WR) and Air-entraining (AE) admixture with specific gravities of 1.075 and 1.002 were used in these mixes. The proportion of the mixes used in the residential slabs are shown in Table 1.

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

Two large scale residential slabs were poured at the Mawson Lakes Campus, University of South Australia, Adelaide, Australia in October 2018. One slab was made out of CC20 conventional concrete and the other one was made out of CC20R rubberised concrete. Figure 2 shows the dimension details of each slab. As shown in the figure, each slab had 4 m × 8 m with surrounded 0.3 m × 0.5 m external beam and one internal beam across the short direction. At the eastern end of the each slab, a 1m cantilever was cast as well to allow for concrete coring and other destructive durability tests. 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. Figure 3 shows the procedures of slabs casting and concrete coring on site.

### Table 1: Mixes proportion used in the residential slabs per 1m³.

<table>
<thead>
<tr>
<th>Mix</th>
<th>20 mm Stone (kg)</th>
<th>10 mm Stone (kg)</th>
<th>Concrete Sand (kg)</th>
<th>Cement (kg)</th>
<th>Rubber (kg)</th>
<th>Water (kg)</th>
<th>WR (kg)</th>
<th>AE (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC20</td>
<td>557</td>
<td>482</td>
<td>986</td>
<td>259</td>
<td>0.0</td>
<td>158.0</td>
<td>0.691</td>
<td>0.314</td>
</tr>
<tr>
<td>CC20R</td>
<td>548</td>
<td>474</td>
<td>810</td>
<td>255</td>
<td>74.2</td>
<td>156.6</td>
<td>0.680</td>
<td>0.309</td>
</tr>
</tbody>
</table>
Figure 2: Dimension details of the residential slab poured in Mawson Lakes, UniSA.
Many standard specimens were taken from each mix to measure different short and long term concrete properties. The concrete slump, fresh and hardened density, compressive strength, modulus of elasticity, drying shrinkage, hydration temperature development, concrete core strength, curing effect, screeding ability, edge dampness development, corrosion development, surface abrasion, water sorptivity, chloride ingress, and carbonation development were all evaluated, with some of the longer term property tests still ongoing. Surveying measurements were also taken at several locations in the slabs to record any change in elevation level of the slabs over time.

The concrete slump was measured using a standard slump cone at four times during the construction process; at the concrete plant (0.0 min), at concrete truck arrival (30 min), at pump end, and at truck discharge end. The fresh and hardened density were measured using the filled cylinders for the compressive strength test. The screeding ability was measured using a helicopter machine and recording the feedback of the contractor in terms of how ease to finish the concrete surface. The compressive strength and modulus of elasticity tests were measured using standard 100 × 200 mm cylinders (three cylinders for each measurement). The drying shrinkage was measured using standard 75 × 75 × 280 mm beams with two end studs. 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 Figure 4.

Concrete cores (three at each measurement) were taken from the slab cantilevers using a 100 mm diameter corer. The curing effect was measured at 28 day concrete age by keeping three cylinders without any water curing or covering for 7 days, compared with cylinders cured by spraying water on them 24 hrs after slab pour and covering them using plastic sheets for 7 days. This was to simulate exactly what happened in half of the slabs. The edge dampness development was measured by covering a 300 × 500 mm surface area of concrete slab surface at its south edge using a plastic tub with small openings in the side walls of the tube to keep the covered area dry all the time. This experimental setup was done at two locations in each slab. At the first location was the plastic membrane laid underneath the slab and the beam sides by the contractor before concrete pouring was kept in place. However, in the other location, that plastic sheet was manually removed from the slab/beam side for the
whole depth and 1 m width to secure a full contact between the concrete and the soil for increased dampness effect.

Long term corrosion development is being measured using 60 × 60 × 470 mm beams with a N10 deformed bar centrally embedded in them. In total, 18 beams of each mix were cast; half of them had the 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 bar was centred using wooden formwork with holes in which the bar went along the whole 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. Half of each mix set of beams (nine beams) are being tested in three different environments. One set was embedded to a depth of half their length close to the residential slabs in the Mawson Lakes campus, UniSA. The second set was buried to half their length in high saline soil in the Port Adelaide area. The third set was fully soaked in 5% sodium sulphate solution. The slab carbonation development was measured by cutting a 70 × 200 mm fresh piece of concrete from the slab cantilever edge and spraying carbon dioxide indicator to determine the carbon dioxide depth, as shown in Figure 5. The surface abrasion, water sorptivity, chloride ingress, and accelerated carbonation of slabs concrete mixes were also measured.

The results to date are shown in Table 2. The ready mix company did not report any issues related to the mixing and delivery of CRC. In addition, the contractors reported easy screeding and less physical effort to do so, with no difference reported when pumping or finishing the concrete surface by helicopter for both CC20 and CC20R slabs. After about 1 hr from first mixing, CC20R showed negligible slump losses in which only 10 mm (6%) decrease in slump was recorded, compared with relatively higher slump losses of 45 mm (28%) recorded for conventional concrete. This was attributed to the lower rate of water absorption of the rubber aggregates with time compared to that of the replaced sand which kept the concrete mix at a higher moisture content for a longer time. No significant effect was observed on the concrete compressive strength when curing it for 7 days by covering using plastic sheet. Only 6% and 10% increase was measured in the 28 day compressive strength of CC20 and CC20R slabs, respectively. The CC20R compressive strength determined through concrete cores showed constant strength values compared with increasing strength for CC20. This might be attributed to many factors related to the core diameter/height ratio, existence of steel in the cored concrete, shape and location of steel in the cored concert.

Figure 6 shows the drying shrinkage measured at different concrete ages for the slab mixes. As shown in the figure, the concrete drying shrinkage increased with concrete age. CRC showed similar shrinkage values to that of the counterpart conventional concrete throughout the concrete age, with slightly lower long-term values. Therefore, using rubber in concrete has an overall insignificant effect on the concrete shrinkage. The highest hydration temperature recorded for CC20 mix was 33.2 °C and occurred at 11.16 hr (from mixing completion); while the CC20R mix was showing 27.9 °C at the same time, see Figure 7. The recorded highest hydration temperature for the CC20R mix was less and later than that of the CC20 mix with a maximum value of 29.2 °C occurring at 17.50 hr; when the CC20 mix was showing 27.9 °C at the same time. The rubber particles have lower thermal conductivity than that of the replaced sand. This can reduce the overall concrete thermal conductivity which decreases the heat transfer rate within
the concrete matrix, and hence less and delayed hydration temperature. Up to 3 month concrete age, the measured carbonation depth for both CC20 and CC20R slabs was zero, showing that there was no adverse effect of using rubber in concrete in developing the carbon dioxide penetration into the concrete cover, as shown in Figure 5. Likewise conventional concrete, no visual deteriorations were observed on rubber concrete slab surface up to 3 month concrete age as shown in Figure 8. Monitoring of longer term properties is continuing.

<table>
<thead>
<tr>
<th>Mix</th>
<th>CC20</th>
<th>CC20R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>At the plant</td>
<td>160</td>
<td>165</td>
</tr>
<tr>
<td>At truck arrival (30 min)</td>
<td>150</td>
<td>160</td>
</tr>
<tr>
<td>At truck pump outlet</td>
<td>120</td>
<td>160</td>
</tr>
<tr>
<td>At truck discharge end (1hr)</td>
<td>115</td>
<td>155</td>
</tr>
<tr>
<td>Fresh Density (kg/m³)</td>
<td>2380</td>
<td>2240</td>
</tr>
<tr>
<td>Hardened Density (kg/m³)</td>
<td>2317</td>
<td>2166</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>19.24</td>
<td>11.16</td>
</tr>
<tr>
<td>28D - Cured</td>
<td>27.8</td>
<td>18.42</td>
</tr>
<tr>
<td>28D - Not cured</td>
<td>26.1</td>
<td>16.66</td>
</tr>
<tr>
<td>56D - Cured</td>
<td>25.23</td>
<td>14.25</td>
</tr>
<tr>
<td>91D - Cured</td>
<td>28.19</td>
<td>16.15</td>
</tr>
<tr>
<td>28D Mod of E (MPa)</td>
<td>28.30</td>
<td>21.20</td>
</tr>
<tr>
<td>Core compressive strength (MPa)</td>
<td>28.98</td>
<td>21.11</td>
</tr>
<tr>
<td>28D</td>
<td>31.11</td>
<td>21.60</td>
</tr>
<tr>
<td>91D</td>
<td>35.06</td>
<td>21.38</td>
</tr>
<tr>
<td>Shrinkage (Microstrain)</td>
<td>14 Day</td>
<td>417</td>
</tr>
<tr>
<td>14 Day</td>
<td>536</td>
<td>591</td>
</tr>
<tr>
<td>28 Day</td>
<td>672</td>
<td>652</td>
</tr>
<tr>
<td>56 Day</td>
<td>838</td>
<td>781</td>
</tr>
<tr>
<td>Highest hydration temp (°C)</td>
<td>Occurred after 11.16 hr 33.2</td>
<td>27.9</td>
</tr>
<tr>
<td>33.2</td>
<td>30.7</td>
<td>29.2</td>
</tr>
<tr>
<td>29.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slab carbonation depth (mm)</td>
<td>Occurred after 17.50 hr 30.7</td>
<td>29.2</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 6: Drying shrinkage for slabs mixes.

Figure 7: Concrete hydration temperature.

Figure 8: Development of slab surface with time.
4. Summary and conclusions

In this research, a wide range of experimental investigations was carried out aiming at moving crumb rubber concrete (CRC) from the lab to the slab. Two 4 m × 9 m large-scale reinforced concrete residential slabs have been constructed. One was cast with CRC and the other with a standard residential mix of conventional concrete. A large range of factors have been investigated and compared. The main findings of this investigation are summarized in the following points:

1. The biggest crumb rubber size available in the Australian market showed 43% enhancement in concrete slump compared with conventional concrete and showed the best compressive strength compared with smaller crumb rubber sizes.
2. The ready mix company did not report any issues related to the mixing and delivery of CRC. In addition, the contractors reported easy screeding and less physical effort to do so, with no difference reported when pumping or finishing the concrete surface by helicopter for both CC20 and CC20R slabs.
3. CC20R showed negligible slump losses with only 10 mm (6%) decrease in slump was recorded, compared with relatively higher slump losses of 45 mm (28%) recorded for conventional concrete. No significant effect was observed on the concrete compressive strength when curing it for 7 days by covering using plastic sheet. CRC showed similar shrinkage values to that of the counterpart conventional concrete throughout the concrete age. Therefore, using rubber in concrete has an overall insignificant effect on the concrete shrinkage.
4. The recorded highest hydration temperature for CC20R mix was less and later than that of the CC20 mix which indicates that the rubber particles can decreases the heat transfer rate within the concrete matrix.
5. Up to 3 months concrete age, the measured carbonation depth for both CC20 and CC20R slabs was zero, showing that there was no adverse effect of using rubber in concrete in developing the carbon dioxide penetration into the concrete cover. No visual deteriorations were observed on rubber concrete slab surface up to 3 month concrete age.

While further tests are still being conducted, these large scale results provide promising evidence that CRC has potential for application in the residential footing market.

5. Acknowledgment

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6. References