The viability of rubberised concrete in the South African construction industry

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ABSTRACT

This paper describes the results of an investigation to determine the viability of using waste rubber chips as a substitute for natural aggregate in producing structural concrete. The rubber chips used were obtained from shredded scrap tyres, which are costly to discard at landfill sites and often constitute undesirable environmental and health risks. A major focus of the investigation was to identify whether treatment of the rubber chips before batching would result in an improved rubberised concrete to be used in structural applications. Concrete mixes consisting of 0% rubber chips, were compared with those incorporating, 5%, 10% and 20% rubber replacement percentages for natural coarse aggregate. The water to binder ratio of 0.45 and cement content were kept constant for all mixes. The results showed no significant difference in slump values for the differing rubber replacement values. The strength test results suggest that rubberised concrete has potential for use in structural applications, provided the level of replacement is below 17.5%, for untreated and treated samples, respectively. Dynamic test results suggest that high rubber replacements could be utilised for making concrete elements that do not experience high levels of mechanical stress but rather for elements that experience high levels of fatigue and dynamic loading.

Keywords: Rubberised Concrete, pre-treatment, compressive strength, dynamic loading.

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This paper describes the results of an investigation to determine the viability of using waste rubber chips as a substitute for natural aggregate in producing structural concrete. The rubber chips used were obtained from shredded scrap tyres, which are costly to discard at landfill sites and often constitute undesirable environmental and health risks. A major focus of the investigation was to identify whether treatment of the rubber chips before batching would result in an improved rubberised concrete to be used in structural applications. Concrete mixes consisting of 0% rubber chips, were compared with those incorporating, 5%, 10% and 20% rubber replacement percentages for natural coarse aggregate. The water to binder ratio of 0.45 and cement content were kept constant for all mixes. The results showed no significant difference in slump values for the differing rubber replacement values. The strength test results suggest that rubberised concrete has potential for use in structural applications, provided the level of replacement is below 17.5%, for untreated and treated samples, respectively. Dynamic test results suggest that high rubber replacements could be utilised for making concrete elements that do not experience high levels of mechanical stress but rather for elements that experience high levels of fatigue and dynamic loading.

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1. INTRODUCTION
In modern society, most importantly in the construction industry, the control and management of waste is a key facet in ensuring sustainable development. This sustainability not only should encompass environmental aspects, but also economic and social environments. Incorporating the widespread use of waste materials in the construction industry as a replacement for the current waste management act can help alleviate the stress put on the environment and landfill sites, while also creating employment opportunities. Dumping tyres in landfills requires a lot of space and acts as a breeding space for mosquitoes and other vermin. Besides this, there is economic value to be obtained through the reuse and recycling of waste tyres, creating a circular economy from cradle to cradle of tyre management [1]. Circular Economy can be seen as the process of reusing, recycling and remanufacturing products to keep them circulating within the economy [2].

The use of rubber in concrete as a replacement for aggregate has been progressing since the mid 90's. Al-Fadhli, M. [3] carried out extensive testing on the static and mechanical properties of rubberised concrete and has found that current methods do not allow for rubberised concrete to be used as a substitute for load bearing structural elements [3]. His results indicate an indirectly proportional relationship between loss of compressive strength of concrete and increased percentages of rubber as an aggregate replacement [3]. Little to no research has been done with regards to the static and dynamic properties of rubberised concrete in a South African context. Furthermore, most research that has been done has focused on replacing the fine aggregate and not the coarse aggregate in concrete. This provides a motive to further investigate both the static and dynamic properties of concrete with rubber particles as a coarse aggregate replacement from a South African perspective. This will help to deduce the feasibility thereof in terms of methods to create a structural concrete from chipped rubber particles, whilst examining the changes in dynamic properties and durability that will arise from replacing stone content with chipped rubber.

The study reported in this paper addresses the need for greater research to be conducted within this field, to further push sustainability in civil engineering and assuage the negative effects that waste tyres have on the environment.

2. AIM
The aim of this study is to identify a working range of rubber replacement percentages that can produce structural concrete. A second aim is to investigate the effect of soaking the rubber chips in a sodium hydroxide bath and coating the chips in metakaolin as a pre-treatment method to help mitigate the inevitable loss of compressive strength in rubberised concrete. Lastly, examining the dynamic properties of a rubberised concrete in comparison with a plain concrete control sample.

3. METHODOLOGY
3.1 Mix Design
Before the mix designs were finalised, 3 trial mixes were done in accordance with the South African Concrete & Cement Institute (C&CI) design method, to determine the optimum moisture content to theoretically achieve a 75mm slump for the control mix design. Three different mix designs with water contents ranging between 225 kg/m^3; 215 kg/m^3 and 205 kg/m^3, were done using a principle of ratios. This method was used to ensure that no material was wasted, and excess water used whilst conducting three different slump tests each having different water contents. The method of ratios consisted of designing the initial mix in accordance with the C&CI method, and then performing numerous ratio calculations to determine the new quantities. The recorded slumps can be seen in Figure 1.

With reference to the C&CI method as well as the new optimum water content, the mix designs were scaled to the required volumes for each batch consisting of cubes for compressive strength tests and beams for dynamic loading tests. A constant w/c ratio of 0,45 was used throughout the seven different batches, with the batch quantities

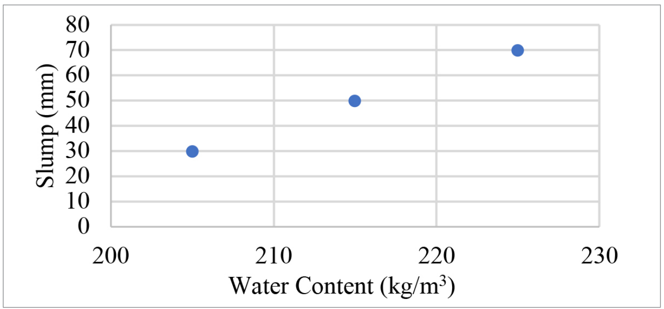

Figure 1: Trial cement mix with subsequent slump

Table 1: Finalised mix Designs

	Plain Concrete	5% Rubber	10% Rubber	20% Rubber
Water (kg/m^3)	230	230	230	230
w/c Ratio	0.45	0.45	0.45	0.45
Cement (kg/m^3)	505	505	505	505
CBD (kg/m^3)	1670	1670	1670	1670
Sand FM	3.26	3.26	3.26	3.26
Stone K	0.94	0.94	0.94	0.94
Stone (kg/m^3)	1040	985	935	830
Rubber (kg/m^3)	-	50	105	210
Sand (kg/m^3)	755	675	590	510
Density (kg/m^3)	2530	2445	2365	2285
Density (kg/m3)	2530	2445	2365	2285

for the treated and untreated rubber staying constant. Table 1 shows the final mix designs for the four different batches.

3.2 Rubber Treatment

The rubber was first rinsed in a water bath and sieved multiple times to get rid of excess nylon leftover from the shredding process and any excess dirt that may still be on the rubber. The sieving process also enabled the rubber to be sorted in a size range between 4.75 and 19 mm, rendering it in a coarse aggregate range.

After the rubber had been sufficiently sorted and cleaned, an appropriate quantity of rubber to meet the batch requirements for the treated rubber concrete was taken and soaked in a sodium hydroxide solution. The solution was a 20% sodium hydroxide diluted with water. The pH of water containing the rubber before the sodium hydroxide was recorded and found to be between 7 and 8. After adding the sodium hydroxide, the pH of the solution was again measured and recorded as 13 before the testing kit was promptly dissolved by the solution. After sitting for twenty minutes, the solution was drained, and the rubber thoroughly rinsed multiple times to bring the pH back to its original state of around 8. After the treated rubber had been air dried, the rubber was then coated in a fine metakaolin coating to assist with the binding when in the concrete matrix. Going forward, the treated rubber will be referred to as TR and the untreated rubber referred to as UR.

4.RESULTS AND ANALYSIS

4.1 Compressive Strength

All results obtained in Figure 2 were achieved by taking an average of three cubes crushed per mix over 3, 7 and 28 days after initially being cast.

The control mix, which contained a 52.5 MPa rapid hardening cement, was designed to achieve a target strength of 59 MPa after 28 days. The control mix achieved a 28-day compressive strength of 72.4 MPa, far outperforming the expected compressive strength. This increase in strength can be possibly attributed to the use of a water to binder ratio of 0.45. A lower water content in relation to cement content is known to result in higher achievable compressive strengths in concrete.

There is a general trend that can be seen in Figure 2 that an increase in rubber replacement percentage results in a significant loss in strength. Neither of the 20% replacement mixes achieved a 28-day strength higher than the structural concrete target of 25 MPa. There was also no discernible difference in the compressive strength values of the 20% treated and untreated rubber mixes over the 3, 7 and 28-day tests. This alludes to the possibility that treating the rubber has no positive benefits to mitigating strength loss when using rubber as a coarse aggregate replacement.

The 5% and 10% rubber replacement mixes showed promising results. Both replacement values achieved 28-day compressive strength results far greater than the 25 MPa target. The 10% untreated and treated mixes reached a 28-day strength of 38.3 MPa and 42.5 MPa, respectively. Despite those strengths falling way short of the strengths witnessed by the control, reaching only 53% and 59% of the control mix's 28-day strength, we observed a significant strength increase over the treated mix when compared to the untreated mix. Treating the rubber before mixing and casting resulted in an increase of 4.2 MPa when compared to its untreated counterpart at 28-days. This increase in strength in the 10% treated mix however only occurred sometime after 7 days of curing.

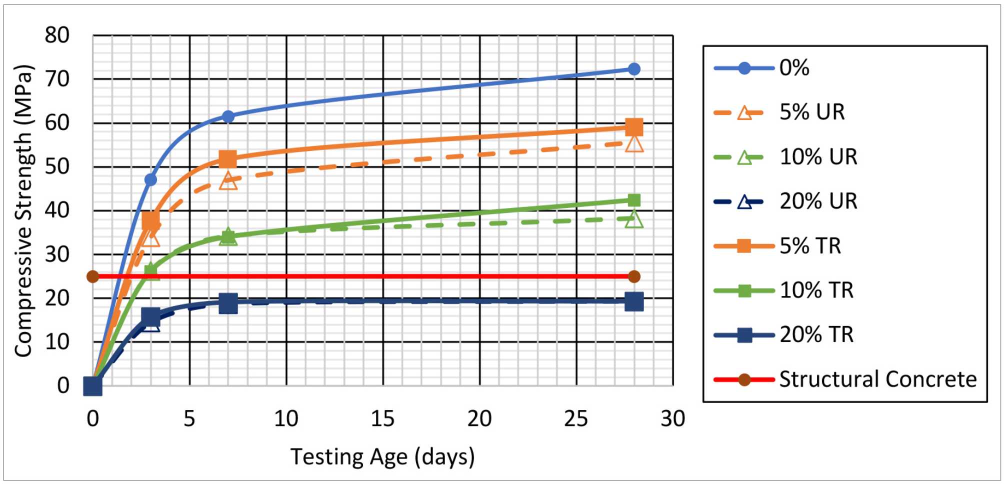

Figure 2: Compressive strength gain over 28 days

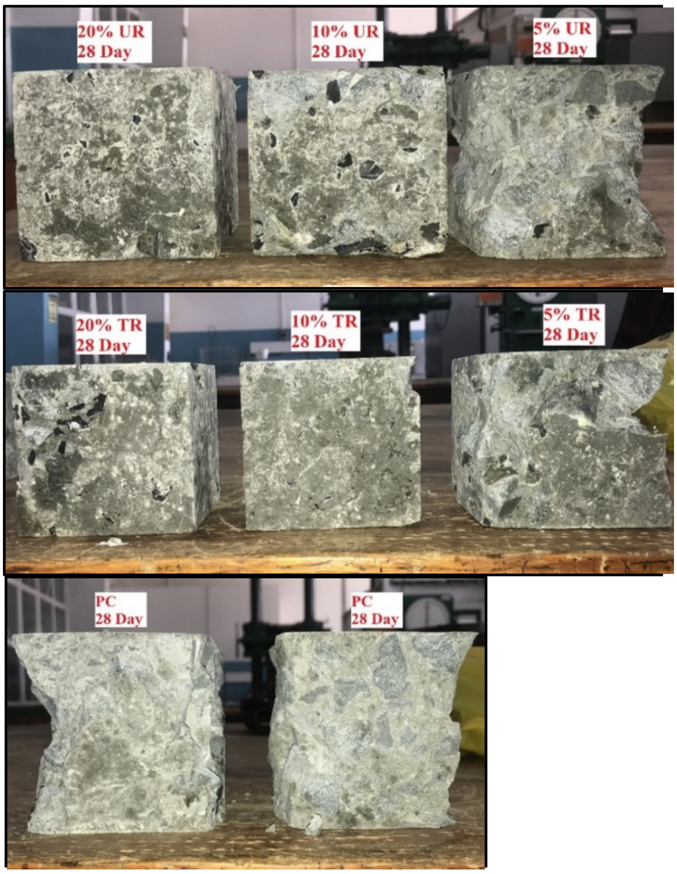

Figure 3: Post crushing failure patterns

At 28-days, the 5% treated and untreated mixes produced compressive strengths of 59.1 MPa and 55.6 MPa, respectively. Similar to the 10% mixes, we see a significant increase in compressive strength after treating the rubber before mixing and casting in comparison to the untreated mix. Promisingly though, the 5% treated and untreated mixes achieved 77% and 82% of the control mix's 28-day strength.

An interesting observation, as can be seen in Figure 3, was how the rubber seemed to hold the testing cubes together post crushing. The plain concrete samples exhibited the textbook hourglass failure pattern. However, the higher the rubber replacement, the less superficial the failure patterns became. It is thus assumed that the rubber within the cement matrix absorbs the tensile stress that the cubes undergo whilst being crushed. Therefore, rubberised concrete does not seem to experience the same brittle failure that plain concrete does.

4.2 Dynamic Analysis

Two separate methods were used to calculate the damping ratio of the beam specimens in order to assess the accuracy of the results. Three tests per beam were conducted to achieve an average damping ratio per beam specimen. It is known that plain concrete has a damping ratio of approximately 5% and that when replacing the aggregates with a percentage of rubber, this damping ratio would increase. This means that the time it takes for the load to oscillate through the structure and to be absorbed, returning to the equilibrium state would be less in a rubberised concrete than that of plain concrete. Figure 4 shows the setup of the dynamic analysis.

In brief, an impact load was applied to the concrete specimens and the logarithmic decay of the amplitude of the oscillations due to the force was measured. From this, the damping ratio was then calculated and can be seen in Table 2.

It should be noted that an average damping ratio was calculated for each of the 5% and 10% rubber replacement for treated and untreated samples. This was done as due to the mixing and batching process; we cannot confidently specify the exact percentage of rubber as a mass replacement per specimen. There is no indication to believe that the treatment of rubber would result in results different to that of an untreated rubber specimen. Therefore, by taking the average over the treated and untreated damping ratios, we aim to mitigate the variability in results due to the possibility of varying rubber replacement percentages through samples of the same replacement values.

Taking the average of the treated and untreated beam specimens results in a linear relationship. That linear relationship being an increase in rubber replacement percentage will result in a higher damping ratio in the specimen. This can be attributed to rubber having a higher damping ratio than the other constituents in the concrete matrix, therefore the scrap rubber will have an influence over the damping of the concrete. Most noteworthy is the similarity of the results between the two different methods used to calculate the damping ratio of the different beam specimens. Two methods providing similar values helps solidify the validity of the results.

The 20% rubber replacement prism results were mitigated from the results as the values produced did not match the trend produced by the 5% and 10% replacement results. The reasoning behind the rogue 20%

Table 2: Average damping ratio using the MIT and INV methods

	Average Damping Ratio (%)	
% Rubber Replacement	INV-Method	MIT-Method
0	5.2	5.4
5	8.9	9.3
10	10.8	10

Figure 4: Setup of the dynamic analysis

damping ratios can be attributed to the lack of precision in ensuring exact replacement percentages were met.

4.3 Analysis of Results

The compressive strength results followed what literature had deemed to be the norm when replacing coarse aggregate with rubber. There is a clear linear relationship between increasing the percentage of rubber as a replacement and the loss of compressive strength. Along with that, there is also a linear relationship with increasing the rubber percentage and increased damping in the samples. With these two relationships, the optimum rubber replacement percentage can be calculated to still meet the minimum compressive strength requirements to meet the standard of structural concrete. Using the linear relationship developed from the treated and untreated rubber samples, the maximum rubber replacement percentage to still meet a compressive strength of 25 MPa for this particular mix design is 17.48% and 16.87% respectively.

As seen evident from the results of the compressive strength tests, treating the rubber significantly mitigates the strength lost when using rubber as a coarse aggregate replacement. By mitigating the strength, a higher rubber replacement percentage is attainable before falling below the limit of compressive strength required to be used as a structural concrete.

By increasing the rubber replacement percentage, the dynamic performance of the concrete greatly improves when compared to a plain concrete mix. The results in Table 3, using both methods and the values from the untreated rubber and treated rubber samples, the damping ratio of the specimens were all more than two and a half times that of plain concrete.

Table 3: Maximum Rubber Replacement and Resultant Damping Ratios

		INV Method	MIT Method
	Max Rubber (%)	Damping Ratio (%)	Damping Ratio (%)
UR	16.87	14.86	13.66
TR	17.48	15.2	13.94

The greatest benefit of using rubber as a coarse aggregate replacement, beyond the environmental benefits, is the increase in dynamic performance. It is thus recommended to use a rubberised concrete mix where concrete strength performance is not a paramount aspect of the project and where dynamic loading is great or occurs often. This will allow for high percentage replacements of rubber, greatly improving the dynamic properties and possibly increasing the fatigue life of the concrete.

Another benefit is the lower density of rubberised concrete in comparison to plain concrete. The lower density will result in a lower self-weight and in turn lower dead load on the concrete structure. This will allow for a higher imposed load to be added and still meet the factor of safety requirements.

Beyond the physical properties of rubberised concrete, the strongest driving factor for adopting rubberised concrete into the construction industry is that of sustainability. With the ability of recycling 100% of waste tyres on a large-scale, the construction industry will be able to significantly reduce the impact that waste tyres are creating on the environment. Just considering the lowest percentage replacement of 5%, that equates to 51.89 kg of rubber per cubic metre of concrete. That is equivalent of using six average 15-inch tyres [381 mm diameter] per cubic metre of concrete.

For a sustainable future, the onus is on large industries to lead the way forward. Sustainable engineering and construction has the potential to alleviate current environmental concerns as well as ensuring these concerns are not prevalent for future generations. Rubberised concrete provides a viable means to tackle the issue of waste tyres and the threat they pose to the environment as well as introducing a cost-effective process to increase the dynamic properties of concrete.

It is from these results that we believe with further testing and researching, a rubberised concrete mix is not only sustainable but viable for use in the construction industry.

5. CONCLUSIONS

The results and data obtained over the various experiments conducted further reinforces what has been stated in literature beforehand. These statements being that introducing rubber into concrete as a percentage replacement for coarse aggregate will greatly reduce the compressive strength of concrete, whilst improving the dynamic properties of said concrete.

- The 5% and 10% replacement mixes registered strength greater than the minimum value of 25 MPa associated with structural concrete whereas the 20% replacement mix fell below this minimum.
- Soaking the rubber chips in sodium hydroxide and coating it with a layer of metakaolin resulted in a significantly higher 28-day compressive strength when compared to the untreated rubber mixes of equal percentage replacement.
- Replacing coarse aggregate with chipped rubber greatly increases the damping ratio of concrete, critically resulting in better performance under shock loading.
- It is recommended that rubberised concrete be utilised where strength performance is not critical and where the loads being applied are mainly dynamic in nature.
- To ensure that mix designs and percentage replacements are accurate and performance across the board is normalised, precast sections of rubberised concrete should be employed.
- Scenarios whereby rubberised concrete will have best performance include, roadside barriers, industrial warehouse flooring, platforms supporting mining machinery and railway sleepers. **CB**

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