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Dynamic response of rubberized concrete columns with and without FRP confinement subjected to lateral impact

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HIGHLIGHTS

- Impact response of rubberized concrete columns.
- FRP-confined rubberized concrete columns.
- Energy absorption of rubberized concrete under lateral impact.
- Progressive failure under impact loads.

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ABSTRACT

This study experimentally investigates the impact response of rubberized concrete columns subjected to lateral impact. A pendulum impact testing apparatus was used to test the concrete columns with varied rubber contents including 0%, 15%, and 30%. Fine and coarse aggregates were replaced by crumb rubber with particle sizes of 2–5 mm and 5–7 mm, respectively. The experimental results have shown that the rubberized concrete columns significantly reduce the peak impact force (27%–40%) and thus mitigate the risk of injury and even death if rubberized concrete is used in roadside barriers. In addition, the rubberized concrete columns were more flexible than the normal concrete columns. They could deflect twice the reference columns before failure. Rubberized concrete significantly increased the impact energy absorption. The columns with 15% and 30% crumb rubber showed an increase in the impact energy absorption by 58% and 63% as compared to the reference columns. The rubberized concrete column confined with FRP outperformed the reference columns in terms of both the energy absorption and load carrying capacity. Therefore, rubberized concrete is a better alternative and recommended for the use in roadside barriers to achieve better impact energy absorption capacity and reduce the maximum impact force under vehicle collisions.

1. Introduction

Used tires are among the largest and most problematic sources of waste in modern societies due to their durability. Millions of used tires are being discarded every year, which contain a number of environmentally damaging constituents, while only a small portion goes through recycling processes [1]. Tires typically require huge dumpsites as more than 75% of a tire volume are void. Furthermore, dumps can be turned into fertile grounds for proliferation of insects and on top of this microorganisms may also take more than 100 years to biodegrade the tires [1]. Therefore, it is necessary to find alternative solutions to recycle used tires and turn them into useful products.

Crumb rubber produced from used tires have been successfully utilized to replace aggregates in order to create new concrete, namely rubberized concrete [2–5]. Previous studies have shown that partially using rubber as aggregates in concrete increases its ductility, toughness, energy absorption, and damping ratio [1,6–8]. However, previous studies also concluded that replacing normal aggregates by rubber reduces the structural strength properties of rubberized concrete [1,9–11]. The reduction in these

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properties depends on many factors, such as the replacement of fine and/or coarse aggregates, the percentage of rubber replacement, and the use of any supplementary cementitious material such as silica fume. Elchalakani [1] recommended adding silica fume to the mix to improve the mechanical properties of rubberized concrete including the axial compressive strength, the flexural strength, and the modulus of elasticity. The author suggested that silica fume has enhanced the bonding at the interfacial transition zone so that it is beneficial to rubberized concrete.

Previous studies have shown that rubberized concrete can absorb more energy than conventional concrete [6,7,12]. The high energy absorption capacity of rubberized concrete can be utilized in structures where the energy absorption capacity is required rather than high strength, for example, roadside barriers [1,3,6] and pedestrian pathways [13]. The impact resistance, defined as the combination of strength and dynamic energy absorption [14], was examined in previous studies on rubberized concrete [3,8,11,15–17]. The impact resistance can be studied by well-established impact tests that are the weighted pendulum, Charpy-type impact, drop-weight, constant strain-rate test, projectile impact, split Hopkinson pressure bar, explosive test, and instrumented pendulum impact [14]. Most of the studies in the open literature examine the impact resistance of rubberized concrete by using simple drop-weight tests according to ACI 544.2R-17 [14]. The simplest and common method of the above impact tests is the repeated drop-weight impact test. The testing apparatus includes a 4.54 kg steel ball dropping from 0.45 m height. The steel ball is dropped multiple times on a specimen until the occurrence of the first crack and the ultimate failure. The energy absorption is measured from this type of impact test but not the strength. However, results of this type of impact tests are very scattered as mentioned by ACI 544.2R-17 [14]. There are studies in the literature investigating the axial impact resistance capacity of rubberized concrete [8,15–17], however, no studies examined rubberized concrete columns against lateral impact. In addition, as rubberized concrete is utilized in roadside barriers, the lateral impact response of the structures become crucial to understanding the behaviour of roadside barriers under vehicle collisions while the axial impact resistance is relatively less relevant in this circumstance.

Beside unconfined rubberized concrete, Youssf et al. [18] investigated the structural behaviour of confined rubberized concrete columns under lateral cyclic loads. The authors concluded that using confined rubberized concrete slightly increased the peak strength and slightly decreased the ultimate drift compared to those of unconfined rubberized concrete. Meanwhile, the rubber particle sizes were found to have an insignificant effect on the energy dissipation and viscous damping of rubberized concrete. Xue and Shinozuka [19] conducted shaking table tests on rubberized concrete columns. The authors found that the damping coefficient of the rubberized concrete columns increases by 62% as compared to normal concrete. In addition, the seismic response acceleration of rubberized concrete decreases by 27% as compared to normal concrete. Sukontasukkul et al. [20] recommended using rubberized concrete as a cushion layer in bulletproof concrete panels. The authors combined a soft rubberized concrete layer and a hard layer of steel fiber reinforced concrete to resist impact loads. The soft layer of rubberized concrete was designed to absorb energy and then transfer less impact energy to the hard layer. In another application, the impact response of real scale roadside barriers made of rubberized concrete was investigated by Atahan and Sevim [6]. The safety barriers had the height, base width, top width, and length of 1 m, 0.45 m, 0.25 m and 1 m, respectively. The authors used a 4-wheel vehicle with the weight of 500 kg for the impact tests and concluded that the energy absorption increased with the rubber content. Besides, rubberized concrete has another advantage of significantly reducing acceleration induced by an impact event thus mitigated injury risk to human occupants. The above studies have made a consensus that rubberized concrete yields higher energy absorption but lower strength than the corresponding conventional concrete. To propose rubberized concrete with higher energy absorption as well as higher strength, FRP confinement can be used since this technique has shown a significant increase in strength and energy absorption of conventional concrete under impact loads [21–23].

As far as the authors are aware, no study has been carried out to investigate the impact response of rubberized concrete columns under lateral impact. Since understanding the performances of the column subjected to lateral impact loads is essential for application of the column in roadside barrier constructions, pendulum impact tests were performed to investigate the impact response of rubberized concrete columns in this study. In total, 7 rubberized concrete columns were cast and tested with 800 mm height and 100 mm square section. Two different rubber contents including 15% and 30% were examined. A steel impactor weighing 300 kg was lifted to certain heights before releasing to generate the impact loading on the mid-height of the columns. The progressive damage, the impact force time histories, the displacement time histories, and energy absorption capacity were examined and discussed.

2. Experimental program

In this study, seven reinforced rubberized concrete columns were cast and tested at the concrete laboratory of the University of Western Australia. Six columns were made of unconfined rubberized concrete and one column (15% rubber content) was wrapped with one layer of FRP. Among the six columns associated with unconfined rubberized concrete, there were three pairs including two columns with normal concrete (0% rubber), two columns with 15% rubberized concrete and the other two columns with 30% rubberized concrete. The columns were tested under pendulum impact until failure.

2.1. Mix design and pre-treatment

Three concrete mixes were designed to examine the effects of varying rubber contents on the impact resistance of reinforced concrete columns. The conventional concrete served as a baseline had the compressive strength of 50 MPa. Normal fine and coarse aggregates of the rubberized concrete were replaced by rubber at 15% and 30%, in which conventional aggregates were replaced by two types of rubber aggregates including 2–5 mm diameter crumbed rubber and 5–7 mm diameter crumb rubbers. The crumbed rubber was manufactured and supplied by tyre cycle [24]. The crumb rubber has the specific gravity of 540 kg/m^3 [1]. The sieve tests were carried out and the particle size distribution is shown in Fig. 1. All the specimens had the ratios of cement, water and total aggregate remain unchanged. The ratio of water to cement was 0.5 for all the mixes. It is noted that the rate at which water was added to the mix had a large impact on the slump and mixing of the concrete. Gradually adding water to the mixer produced the best result as it reduced clumping of material and ensured a good distribution of water. The water absorbed by rubber through the water soaking process was accounted for when producing rubberized concrete by deducting the overall water required for the mix by the amount of absorbed water. Details of the mixture design of the rubberized concrete are presented in Table 1. The compressive strength of rubberized concrete was tested at 28 days according to AS 1012.9 [25]. The compressive strengths of 0%, 15%, and 30% rubberized concrete were 50.3 MPa, 25.0 MPa, and 14.4 MPa, respectively. The density of the specimens was 2271 kg/m^3, 2086 kg/m^3, and 1943 kg/m^3, respectively.

According to a previous study by Mohammadi [26], rubber aggregates for the two mixes were soaked for 24 h in a 10% sodium hydroxide solution (NaOH). This process allows the aggregates to absorb a certain amount of water, improving the interfacial bonding and reducing the possibility of rubber aggregate floating in the mix. After the treatment, the rubber was drained, then soaked and rinsed three times in clean water to neutralize the pH. As mixing the concrete, the rubber aggregates and the conventional aggregates were mixed for 1 min with 10% of the required water, then cement was added and the substances are mixed for 1 min. Next, a half of the remaining water was added and mixed for 1 min. Lastly, the remaining amount of the water was added and mixed for 1 min before adding superplasticizer and mixing for 1 min. Details about the mixing procedure can be found in the previous study by Elchalakani [1]. Slump tests were carried out for each mix and the slump of normal concrete, 15% rubberized concrete and 30% rubberized concrete was 150 mm, 180 mm, and 165 mm, respectively.