A review on the suitability of rubberized concrete for concrete bridge decks

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Abstract. Road authorities manage a large population of ageing bridges, a substantial number of which fail to meet the current requirements either due to deterioration and other structural deficiencies or as a result of the escalating demands imposed by increased traffic. This problem is related to the dynamic load from vehicles. This problem can be solved by producing a type of concrete that can reduce the amplitude of oscillation or vibration such as rubberized concrete. Green construction has been a very important aspect in concrete production field in the last decade. One of the most problematic waste materials is scrap tires. The use of scrap tires in civil engineering is increasing by producing rubberized concrete. Rubberized concrete is a type of concrete that is mixed with rubber. The purpose of this review is to justify the suitability of rubberized concrete for concrete bridge decks. Several parameters named physical, chemical and mechanical properties were measured to ensure the suitability of rubberized concrete for concrete bridge decks. Rubberized concrete has similar workability to normal concrete. The rubber reduced the density and compressive strength of the concrete while increased the flexural strength, water absorption and damping ratio. The use of rubber in concrete beyond 20% is not recommended due to decreasing in compressive strength. Rubberized concrete recommended to be used in circumstances where vibration damping was required such as in bridge construction as shock-wave absorber.

1. Introduction
Today, many concrete bridge structures are ageing due to large impact load. As a result, the maintenance, upgrading and replacement of existing bridges have become a very challenging task for the construction industry. Complications associated with these tasks are even more critical in urban areas, where the overall cost of the project is often governed by indirect costs due to traffic disruption. New upgrading and refurbishment methods integrated with accurate urban planning minimize the traffic disruption and disturbance in highly populated areas and are therefore very useful for bridge authorities and owners. Engineers need to find a suitable material which has resistance towards the impact, vibration or damping such as rubber material. The United States generates approximately 300 million scrap tires annually, about 40% of which are used as fuel for generating energy, 26% ground into crumb rubber, 13% discarded in landfills and 5.5% used in civil engineering applications [1-4]. There are more that 300 million tires which are currently stockpiled throughout the United State [2, 5]. These stockpiled waste tires occupy large landfill spaces that contain nesting insects and rats. Stockpiles of tires destined for landfills are also known to be flammable. There are many waste
materials which become problematic to the environment [6]. One option to reduce this environmental concern is for the construction industry to consume a high number of recycled tires accumulated in stockpiles. Utilizing waste materials in concrete provides significant contribution to the environment and indirectly helps to generate economic value for some other industries [7]. In the pavement industry, the use of crumb rubber has been initiated with asphalt mixes. However, some difficulties, such as the high viscosity of the rubberized bitumen and the requirement of higher temperature for production of rubberized asphalt have limited its application [8]. Consequently, the introduction of rubber to concrete pavements was the basis of this investigation.

The replacement of fine aggregates with waste tire rubber was done at a volume of 5% whereas the strength was increased up to 10% [9]. The addition of shredded scrap tires to concrete provides some favorable characteristics for concrete and alters some concrete properties. The ordinary cement-based concrete is generally brittle. However, the addition of rubber in the concrete material is able to increase the ductility and impact resistance [10]. The rubberized concrete was recommended to be used in circumstances where vibration damping was required, such as in bridge constructions as a shock-wave absorber [11]. Experimental studies on rubberized concrete materials have shown that using rubber in concrete as partial replacement of mineral aggregates enhances its ductility, toughness, impact resistance, energy dissipation, and damping ratio [12]. Using recycled tire rubber in cement concrete can provide an efficient way of utilizing rubber. In addition to environmental benefits, the use of tire rubber particles could provide a new type of concrete with unique mechanical and fracture characteristics. Although recycled tire rubber has been widely used in highway asphalt, there are limited studies on its application in cement concrete [13].

The current applications of recycling waste tires in civil engineering practice are mainly as follows:

- Used as modifiers for asphalt paving mixtures;
- Used as an additive for Portland cement concrete;
- Used as light weight fillers; and
- Used in whole tires as crash barriers, bumpers, artificial reefs and etc.

The purpose of this review is to justify the suitability of rubberized concrete for concrete bridge decks. There are several parameters which need to be measured such as physical, chemical and mechanical properties before determining the use of rubberized concrete for concrete bridge decks.

2. Waste tires

There are many ways to recycle scrap tires, but the preferred method for recycling tire rubber is by grinding it before converting it into various applications. There are several sizes of rubber particles as shown in Figure 1 after grinding. The different sizes of rubber particles will result in different effects to the concrete. Ganjian et al. [14] have classified scrap tires into two: car tires and truck tires. Car tires are different from truck tires in terms of its constituent materials, especially natural and synthetic rubber content as shown in Table 1. Considering the high production volume of car tires compared to truck tires, the former is usually of more interest to researchers. In most of the researches performed, usually three broad categories of discarded tire rubber are considered such as chipped, crumb and ground rubber:

- Shredded or chipped rubber replaces gravel. To produce this rubber, the tire has to be shredded in two stages. By the end of stage one, rubber has a length of 300-340 mm and a width of 100-230 mm. In the second stage, its dimension changes to 100-150 mm by cutting. If shredding is further continued, particles of about 13-76mm in dimension are produced. These are called “shredded particles”.
- Crumb rubber that replaces sand is manufactured by a special mill in which big rubber is converted into smaller torn particles. In this procedure, different sizes of rubber particles may be produced depending on the kind of mill used and the temperature
generated. Using a simple method, particles are made with high irregularity in the range of 0.4250-4.75 mm.

- Ground rubber that may replace cement is dependent on the equipment for size reduction. The processed used tires are typically subjected to two stages of magnetic separation and screening. Various sizes of rubber are produced using more complex procedures. In the micro-milling process, the particles made are in the range of 0.075-0.475 mm.

Tires are made of rubber (60-65 wt%), carbon black (CB) (25-32 wt%) and the rest consists of accelerators and fillers, which are added during the manufacturing process. The rubbery materials are present in the form of CxHy with some fibrous materials and they are considered as thermoset polymer [15].

| Composition weight (%) | Car tire | Truck tire |
|-----------------------|----------|------------|
| Natural rubber        | 14       | 27         |
| Synthetic rubber      | 27       | 14         |
| Black carbon          | 28       | 28         |
| Fabric, filler, and accelerators, and antiozonants | 16-17 | 16-17 |
| Steel                 | 14-15    | 14-15      |

Table 1 Typical constituent materials of tires [16].

3. Properties of rubberized concrete
One of the possible solutions to reduce waste tire is to incorporate it into concrete by replace the natural aggregates. The properties of the fresh and hardened rubberized concrete had been reviewed.

3.1. Fresh concrete

3.1.1. Workability. Fresh concrete is a plastic concrete that can be molded to any shape. Hundred percent compaction of fresh concrete is an important parameter to enable maximum strength for concrete. A highly workable concrete can ensure full compaction. Workability of concrete is the ease...
with which concrete can be mixed, handled and compacted. Trilok et al. [17] found that the workability of concrete is not affected significantly by adding rubber fibers. Zheng et al. [18] indicated that the mixture made with fine ground rubber is more workable than that with coarse tire chips. Ayman et al. [10] observed the replacement of up to 10% did not affect the workability much; however, an increase beyond 10% caused a severe reduction in workability. Youssf et al. [19] mentioned that the workability of rubberized concrete can be controlled by using an appropriate quantity of super plasticizer (1-3% by weight of cement). Elchalakani [20] explained that rubberized concrete having a combination of rubber powder and crumb rubber exhibited good workability in contrast to plain concrete when an adequate quantity of admixture was used. Rubber particles have acceptable workability when they are used to replace the total aggregate of up to 50% but the strength is reduced proportionally [21].

3.1.2. Bulk density. Gesog Lu et al. [22] prepared the lowest density of 1900 kg/m$^3$ while the highest density was 2240 kg/m$^3$ and found that the finer the rubber particles, the higher the density of the rubberized concrete. This is because the fine rubber played the role of fine aggregate and filled the small gaps among the concrete particles which improve the density and did not affect the permeability coefficient. “K. Nadal Gisbert et al. [23] explained that the increase of the rubber content in the concrete reduces the density of the concrete due to the gaps surrounding the rubber. Gesog Lu et al. [22, 24] discovered that lighter weight concrete was produced by adding rubber to concrete. The rubberized concrete densities were 2-11% lighter than control concrete specimens. Pelisser et al. [25] explained that the density of the rubberized concrete was lesser by 13% compared to normal concrete but only 9% reduction was observed when silica fume was added to rubberized concrete due to the higher densification of the concrete structure. Parheco-Torgal et al. [26] studied tire chips partially replacing coarse aggregates and crumb rubber replacing total mineral aggregate in rubberized concrete. It was observed that the density of the concrete with fine aggregate replacement was reduced by 34% while the coarse aggregate replacement had a reduction of 45%. The combination gave a decrease in density of 33% in total. Kardos et al. [27] found that an increase in air content when crumb rubber was added into the concrete.

3.1.3. Air content. Richardson et al. [28] compared the percentage air entrainment for plain concrete which was 1.9% and the percentage value for <0.5 mm crumb rubber which was 3.3%. The additional air entrained in plain concrete was 74% compared to the <0.5 mm crumb rubber sample. This is a significant difference as a 3% air entrainment is adequate for providing freeze/thaw protection, especially as the mix has evenly dispersed crumb rubber particles that will permit pressure absorption, consisting of a particle size small enough to provide effective freeze/thaw protection. Al-Akhras et al. and Li et al. [29] discovered that the larger the particle of the tire fiber, the higher the air content in the concrete. Benazzouk et al. [30] indicated that increasing rubber volume ratio results in higher air content. Al-Akhras et al. [31] explained that the use of tire rubber ash in concrete can reduce the air content. The air content of tire rubber ash mortar decreased with increasing tire rubber ash content. The air content decreased from 2.6% for the control mortar to 1.5% for the mortar containing 10% tire rubber ash.

3.2. Hardened concrete

3.2.1. Compressive strength. The compressive strength of the rubberized concrete slightly decreased compared to normal concrete [10, 13, 17, 32-35]. However, Obinna Onuaguluchi et al. [36] found a significant improvement in compressive and tensile strength recorded in the mixture containing coated rubber crumb and silica fume. The synergy between limestone powder and silica fume caused this mixture to outperform the reference mixture at 5% and 10% fine aggregate replacement. Gupta et al. [17] explained that the compressive strength of waste rubber tire fiber concrete decreases with the increase in the replacement level of fine aggregates using rubber fiber. However, the strength of
rubberized cement increases upon partial replacement of cement using silica fume. Al-Akhras and Smadi [31] observed an increase in compressive strength when the tire rubber ash replaced the fine aggregates up to 10%. The increase in compressive strength of mortar specimens at 90 days were 14%, 21%, 29%, and 45% where the tire rubber ash content were 2.5%, 5%, 7.5% and 10% respectively. Feng Lie et al. [35] explained that the increase in rubber content in concrete decreases the compressive strength of rubberized concrete. Larger rubber particles reduced the compressive strength of rubberized concrete. Therefore, the finer the rubber particles produced, the higher the compressive strength of rubberized concrete.

3.2.2. Flexural tensile. Matthew et al. [37] have found that rubber particles in rubberized concrete reduce the fracture energy in external macro cracks. Farhan et al. [38] noted that the tensile strength of rubber is reduced due to the inclusion of rubber particles in cement stabilized aggregate mixture due to the weakness of these introduced particles. However, an increase was observed in the post peak behavior which caused an improvement in the toughness of the modified mixtures. In addition, the high stiffness of the original mixtures was mitigated after partial replacement with rubber particles. Gupta et al. [39] pointed out that the flexural strength of concrete containing rubber ash decreased with an increase in the percentage of rubber ash while the flexural strength of modified concrete (containing 10% rubber ash and a varying percentage of rubber fibers) increased with the increasing amount of rubber fiber (aspect ratio 8-10). Al-Akhras and Smadi [31] studied the properties of mortar containing tire rubber ash. An increase in flexural strength was observed when the tire rubber replaced fine aggregates up to 12%, 27%, 32%, and 43% whereas the tire rubber ash content was 2.5%, 5%, 7.5% and 10% respectively compared to the control mix mortar.

3.2.3. Abrasion resistance. The abrasion resistance of concrete may be defined as its ability to resist being worn away by rubbing. Concrete which is more resistant to abrasion can be used for the construction of pavements, floors and concrete highways; in hydraulic structures such as tunnels and dam spillways, or on other surfaces upon which abrasive forces are applied between surfaces and moving object during services. B. Thomas et al. [40] found that rubberized concrete is more resistant to abrasion compared to the control mix. Da Silva et al. [9] observed an improvement in abrasion resistance with the addition of rubber. In their study, the increase in the rubber content decreased the amount of abrasion whereas with 50% replacement, the amount of wear reduction was 18% compared to without rubber.

3.2.4. Water absorption and penetration. Obinna Onuaguluchi et al. [36] discovered that crumb rubber increased the porosity of concrete. Matthew et al. [37] indicated that the rubber in concrete will increase water penetration depth and the water absorption coefficient. Thomas et al. [41] also found the water absorption of rubberized concrete was higher than the control mix concrete. However, Gupta et al. [17] also stated that water permeability increases with an increase in rubber fiber content. However, the permeability of rubberized concrete can be reduced by replacing cement with silica fume.

3.2.5. Damping ratio. Bravo and Brito [42] observed that the damping capacity of rubberized concrete was greater than normal concrete. Xue and Shinozuka [32] explained that the average damping ration of rubberized concrete columns was 7.70%. In contrast, the average damping ratio of normal concrete columns is only 4.75%. Adding rubber crumbs into concrete increases the damping ration by 62%. Zheng et al. [18] indicated that the damping ratios of rubberized concrete increased considerably with the increase of rubber content. However, the relationship between the damping ratio and rubber content is not linear. Since high rubber content would cause dramatic reduction in the modulus of elasticity of rubberized concrete, the optimal content of rubber would be less than 30% to obtain satisfactory static and dynamic properties. Yousif et al. [12] explained that replacing 20% of the concrete sand with rubber aggregates decreased the damping ratio by 49% compared to average
conventional concrete specimens. Gisbert et al. [23] found that a rise in the proportion of rubber also increases the damping ratio of rubberized concrete. The bigger the grain size of rubber, the lower the damping.

4. Discussion and conclusion

Workable rubberized concrete mixture can be made with scrap tires [43]. The workability can be similar to normal concrete by using admixtures without any increase in the quantity of water [10]. The literature made it clear that the density of rubberized concrete decreases with increasing amount of rubber [44]. The loss in density would be severe when powdered rubber is used to replace aggregates. The rubber can also produce light weight concrete for special purposes. The compressive strength of the rubberized concrete would be affected by the use of rubber in concrete. The reduction of compressive strength can be avoided if the replacement of rubber does not exceed 20% of the total aggregate content [8]. Rubber powder reduces the flexural strength but rubber fiber increases the flexural tensile strength. By using any coupling agent, severe loss in compressive strength could be avoided.

Most researchers mentioned that the abrasion resistance got improved with the addition of rubber in cement. Only few researchers found that rubberized concrete reduces the abrasion of concrete [45]. Water absorption and water penetration increase with the increase of rubber content in concrete. The addition of rubber increases the damping ratio of the concrete. Rubberized concrete seems to be suitable to be used for concrete bridge deck as there were positive results. As recommendations for future work, a proper study on the application of rubberized concrete could be performed. Furthermore, a study on carbonation and damping effect of rubberized concrete could be performed. An in-depth study on the properties of tire rubber ash concrete could also be carried out to maximize its applications.

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Acknowledgments
The authors would like to thank the University of Tun Hussein Onn, Malaysia and the Ministry of Education of Malaysia, for their generous grant awarded for this research, Short Term Grant Vot U114.