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An Overview of Recycling of Crumb-Rubber in Asphalt and Concrete Structures

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Abstract - Waste tires pose significant health and environmental concerns if not recycled and/or discarded properly. Over the years, recycling waste tires into civil engineering applications, especially into asphalt paving mixtures and portland cement concrete, has been gaining more and more interests. This review summarizes the recent advances in the use of waste tire rubber in asphalt and portland cement concrete. The use of crumb rubber in asphalt paving mixture has long been proven successful due to good compatibility and interaction between rubber particles and asphalt binder, leading to various improved properties and performance of asphalt mixtures. The rubberized asphalt mixtures also have shown good compatibility with two widely used sustainability technologies in asphalt paving industry – reclaimed asphalt pavement (RAP) and warm-mix asphalt (WMA). In comparison with its use in asphalt paving mixtures, recycling of waste rubber in Portland cement concrete has not been so successful due to two factors: (1) incompatibility in chemical property between rubber and cement paste and (2) the significant difference in stiffness resulting in stress concentrations. Various methods have been proposed to overcome the barriers to improve the performance of rubberized Portland cement concrete, some of which have shown to be promising.

***Keywords*:** Waste tire rubber, asphalt and Portland cement concrete

I. INTRODUCTION

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, 5.5% used in civil engineering applications. More and more environmental awareness has led people to seek alternative usage of scrap tires. The use of waste automobile tires in civil engineering applications dates back to the very early ages when automobiles were first invented. Waste tires became natural candidates for construction materials, such as landfills and cushion materials. However, large scale recycling of waste tires in civil engineering applications did not happen until the 1960s, which was stimulated by both an ever-increasing number of scrap tires and a stronger environmental awareness movement.

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

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(1) Used as modifiers to asphalt paving mixtures;
(2) Used as an additive to Portland cement concrete;
(3) Used as light weight fillers; and
(4) Used in whole tires as crash barriers, bumpers, and artificial reefs, etc.

During the late 1980s and early 1990s, the US Department of Transportation (USDOT) and Federal Highway Administration (FHWA) launched several major studies related to utilizing recycled tire products in highway constructions. Recycling scrap tires was even mandated by the US Congress and was written into both the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 and the Resource Conservation Recovery Act, which states that any highway project funded by the federal government has to use certain percentages of recycled tire project, otherwise the funds will be withheld. Section 1038 of the ISTEA (Use of Recycled Paving Material) addresses the use of scrap tires in asphalt concrete mixtures and contains three primary requirements including: (a) the federal regulations regarding the use of scrap tires should be relaxed; (b) the performance, recycling and environmental impact related to the use of scrap tire must be studied; and (c) each state must satisfy a minimum waste tire utilization requirement. However, Section 1038(d) was repealed by the US Senate in 1995. Nevertheless, the major research efforts during the 1980s and 1990s have brought significant technology development and stimulated greater applications of waste tire products in civil engineering, especially in highway constructions.

1) research objectives

Use of waste tyre rubber particle in concrete can gives a efficient way of utilizing rubber and by using rubber in concrete gives better environmental benefits(1).The waste tyre rubber provides a concrete with good engineering properties by partial replacement of waste tyre crumb rubber particle to the fine aggregate in concrete.

II. LITERATURE REVIEW:

1. Xiang Shu and Baoshan Huang (2014) "Recycling of waste tire rubber in asphalt and portland cement concrete: An overview" said that Use of waste tire rubber in asphalt paving mixtures and Portland cement concrete has been gaining more and more attention in civil engineering area due to the associated economic, technical, and environmental benefits. Recycling of crumb rubber into asphalt paving mixtures, especially the asphalt rubber

technology has been proven successful for decades. The addition of crumb rubber into asphalt binder can lead to the increased resistance to the three major modes of asphalt pavement distress, rutting, fatigue cracking, and low-temperature cracking. Once properly constructed, rubberized asphalt pavements can perform much better than conventional asphalt roads. One technical problem that still needs to be addressed is storage stability – how to store crumb rubber modified Asphalt at high temperatures for as long as possible without phase Separation.

2. Niall Holmes, et al (2014) "Longitudinal shear resistance of composite slabs containing crumb rubber in concrete toppings " investigated that structural application of crumb rubber from discarded car tyres in concrete toppings on composite metal deck slabs. CRC composite slabs produce similar longitudinal shear capacities due to its ductile behaviour and greater capacity to absorb higher tensile stresses. The interface between the concrete and steel maintains shear interaction under vertical loading while also resisting longitudinal slip at higher loads. The longitudinal end slip results here also satisfy the recommendations within Eurocode 4 with all slabs displaying ductile behaviour. With further improvements to the compressive, flexural and tensile strengths of CRC, based on the results here, these slabs have the potential to be a structurally viable form of construction while successfully addressing the environmental problem created by tyre rubber.
3. Mehmet Gesog˘lu et al (2014) "Investigating properties of pervious Concretes containing waste tire rubbers "investigated that Rubberized pervious concretes with local resources of material can be obtained either with the highest compressive strength or the best permeability, depending on the type, size, and amount of the rubber material used. Rubber incorporated pervious concretes had lower compressive strength, splitting tensile strength, and modulus of elasticity.

- Since the compressive strength of the pervious concretes ranges from3 to 30 MPa, rubberized pervious concretes produced in this study fulfill this requirement as the minimum compressive strength being 6.45 MPa in the mix 10TC10CR.
- Permeability coefficients (K) of the rubberized pervious concretes fell between 0.025 and 0.61 cm/s which are recommended limits for pervious concretes. Therefore, they seem to assure the capability of pavements to collect the first-flush rainfall and to drain it immediately into the ground despite the observed reduction in the K values of the rubberized pervious concretes.
- Fracture energy of the pervious concretes increased with tire chips and/or coarse crumb rubber while using fine crumb rubber decreased the fracture energy.
- Since the acceptable results obtained in this research, it may be possible to utilize such kind of pervious concrete in constructing parking areas, walkways and road shoulders, etc.

Table: 1- Physical properties and chemical compositions of Portland cement

Chemical analysis (%)	Portland cement
Cao	62.58
Sio_2	20.25
Al_2O_3	5.31
Fe_2O_3	4.04
MgO	2.82
So_3	2.73
K_2O	0.92
Na_2O	0.22
Loss on ignition	1.02
Specific gravity	3.15
Blaine specific surface area (m^2 / kg)	3.26

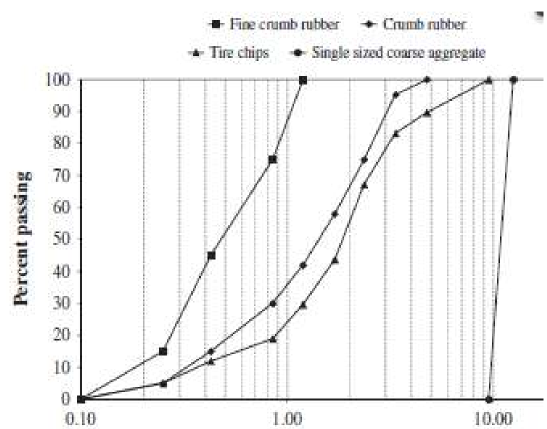

Fig.1. Gradation curve of aggregate, tire chips, crumb rubber, and fine crumb rubber

1) *Recycled tires in asphalt paving mixtures*

The processes of applying crumb-rubber modifier (CRM) in asphalt mixtures can be divided into two broad categories dry process and wet process. In the dry process, crumb rubber is added to the aggregate before the asphalt binder is charged into the mixture. In the wet process, asphalt cement is pre-blended with the rubber at a high temperature and specific blending conditions. Crumb rubber particles in the dry process are normally coarser than those in the wet process and are considered as part of the aggregate gradations (called ''rubber–filler'') whereas, in the wet process, fine crumb rubber powders fully react with asphalt binders (called ''asphalt–rubber'') and improve the binder properties. According to Tahmoressi, crumb rubber has usually been applied in asphalt paving mixtures in the following forms:

(1) Chip Seal Coat: In this application asphalt rubber is used as the binder for the seal coat, which is the finished pavement layer. This application is also known as SAM (Stress Absorbing Membrane).
(2) Under seal: In this application asphalt rubber is used as the binder for chip seal application. After construction of chip seal layer asphalt overlay is applied on the chip seal layer. The function of this under seal is to waterproof the existing pavement and retard reflective cracking. This application is also known as SAMI (Stress Absorbing Membrane Interlayer).
(3) Hot Mix: Asphalt rubber is used as the binder for hot mix.
(4) Porous Friction Course (PFC): Asphalt rubber is used as the binder for open graded porous friction course.

2) Asphalt–rubber interaction

The interaction of crumb rubber and asphalt binder plays an important role not only in the performance of crumb rubber modified asphalt mixtures, but also in the processing and storage of crumb rubber modified asphalt binder. The asphalt–rubber interaction involves two opposite mechanisms that occur simultaneously: particle swelling and dissolution

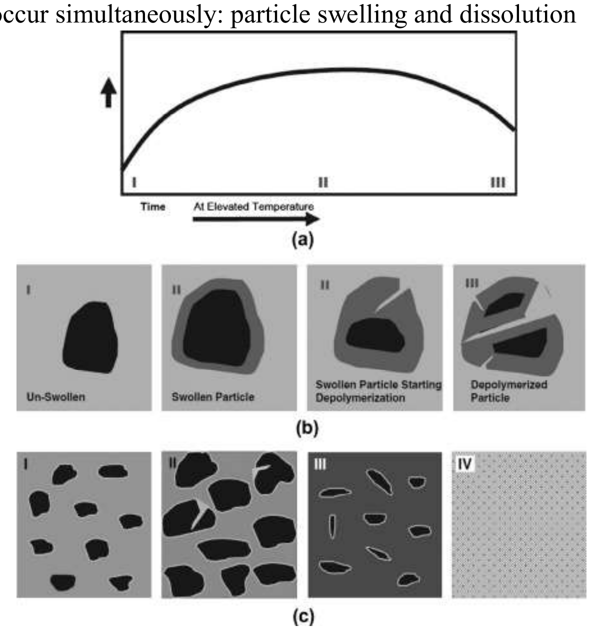

Fig.2. Progression of asphalt–rubber interaction at elevated temperature: (a) change in binder viscosity over time at elevated temperature, (b) change in particle size over time at elevated temperature, and (c) change in binder matrix over time at elevated temperature

III. RECYCLED WASTE TIRES IN PORTLAND CEMENT CONCRETE (PCC)

Compared to their applications in asphalt paving mixtures, the use of recycled tires in Portland cement concrete (PCC) has been limited. The size of waste tires used in PCC ranges from rubber chips (25 mm to 50 mm) to crumb rubber powders (4.75 mm to 0.075 mm). When used in PCC, waste tire materials replace part of coarse or fine aggregates. The addition of waste tire rubber into PCC significantly alters the properties of the concrete. Due to the hydrophobic nature of rubber, the bond between the untreated rubber and hydrated cement is weak, which results in the significant reduction of both compressive and tensile strength of rubber modified PCC On the other hand, concrete becomes more ductile, as illustrated by the limited viscoelasticity and higher post failure toughness.

1) Review of literature

Eldin and Senouci investigated the strength and toughness of concrete with a portion of coarse aggregates replaced by waste tire chips. They observed that the compressive strength and split tensile strength were reduced, while its toughness and ability to absorb fracture energy were enhanced significantly. They also provided an explanation of the fracture mechanisms of rubber-filled concrete based on the theory of strength of materials.

Topcu investigated the size and amount of tire rubbers on the mechanical properties of concrete. He found that although the strength was reduced, the plastic capacity was enhanced.

Lee et al. investigated the flexure and impact strength of crumb rubber-filled concrete. They found that crumb rubber-filled concrete had higher flexure and impact strength than conventional Portland cement concrete and latex-modified concrete. They attributed the increased strength to an improved interfacial bonding between crumb rubber particles and cement paste due to the existence of styrene-butadiene rubber (SBR) latex.

Goulias and Ali used nondestructive testing (NDT) to evaluate crumb rubber-filled concrete. They attempted to establish a relation correlating the strength and elastic modulus with parameters from NDT results.

Khatib and Bayomy used fine crumb rubber and tire chips to replace a portion of fine or coarse aggregates. They found that the rubber-filled concrete showed a systematic reduction in strength, while its toughness was enhanced. They also proposed a regression equation to estimate the strength of rubber-filled concrete.

2) Concerns of using waste tires in PCC

Throughout the literature, the most common negative comment of the use of waste tires in PCC has been the significant reduction of strength. Generally, the addition of 15% rubber chips to replace coarse aggregate results in a 5% reduction of compressive strength and 25% reduction in split tensile strength

3) Applications of PCC with waste tires

Most applications of PCC with waste tires have been on secondary or non-critical structures. Zhu et al. reported the use of adding crumb rubber into exterior wall materials. Sukontasukkul and Chaikaew reported the successful application of crumb rubber modified PCC on pedestrian blocks in Thailand. Pierce and Blackwell studied the potential of using crumb rubber as lightweight aggregate in flowable fill for both PCC and trench bedding materials. Potential uses of rubber modified PCC have also been reported for highway sound walls, residential drive ways, and garage floors, etc.

4) Advantages of rubber modified PCC

In addition to environmental benefits, the most significant advantages of rubber modified PCC have been their excellent energy absorbing characteristics. Researchers have found that rubber modified PCC can effectively increase the ductility and prevent brittle failures. Potential applications of the ductile rubber modified PCC could be structural components subjected to impact and dynamic load (such as bridge approach slabs and airport runways). However, the significant reduction of strength has prohibited these applications.

Another benefit of rubber modified PCC is the light weight. Rubber has much lower specific gravity than aggregates, so the replacement of aggregates with rubber consequently reduces the overall specific gravity of the rubber modified PCC Most researchers reported the improved freeze and thaw resistance of rubber modified PCC. However, some researchers indicated that a higher percentage of rubber content compromises the freeze-thaw durability of rubber modified PCC.

5) Modified concrete in slab

The modified rubber concrete is used in the CRC slabs have higher deflections than the control due to the enhanced ductility, lower rigidity and higher modulus of elasticity.

6) Latest research of PCC with rubber

Researchers have been working to improve the properties of rubber modified PCC so that it could be suitable for more applications.

Two approaches have been adopted by researchers to prevent the significant loss of strength of rubber modified concrete. The first approach is to reduce the size of rubber particles. Since rubber chips produce flaws in concrete mass and generate stress concentrations, the reduction in size of ‘‘holes’’ would effectively reduce the stress concentration. However, only if the rubber particles can be reduced to the dimension that is comparable to cement particles (around 20 lm) can a significant increase of both compressive and tensile strength be expected.

The processing of extremely fine rubber powder will inevitably increase the cost, which should be considered along with the benefit of improved performance of the modified concrete.

However, none of the surface treatments so far have shown significant effect in preventing the huge strength loss due to the incorporation of rubber particles/chips. While surface treatment does have the potential to help improve the bond, it will not change the fundamental fact of stiffness incompatibility between the rubber and other constituents of PCC. Reducing the size of rubber particles (down to the same order of magnitude of cement powders) will both reduce the ‘‘flaw’’ induced by the rubber and increase the stiffness of the particles. Combining the surface treatment and reducing the particle size might produce PCC that can be used in varieties of applications. Reduction of processing cost will be a key issue. Recently, Chou et al. performed a theoretical analysis to explain the effect of rubber additives on the properties of rubber modified concrete. They found that rubber particles block water diffusion in rubberized concrete, leading to insufficient and imperfect cement hydration in some regions and thus the reduced properties of concrete. In order to improve the mechanical properties of rubber modified concrete, they proposed to modify the surface properties of rubber particles and change them to hydrophilic [78]. Two ways they used to enhance the hydrophilic characteristics are partial oxidation at elevated temperatures and treating crumb rubber with waste organic sulphur. Both have shown to be successful in improving the mechanical properties of rubber modified cement mortar and concrete.

7) Tests were conducted in modified concrete

Compressive test, Splitting tensile strength, Young’s modulus, Flexural strength, workability test

IV. Preparation of Concrete and Testing Samples

The 130 mm thick concrete toppings were directly cast on top of the metal deck in three equal depths compacted with a poker vibrator. The surface of the fresh concrete after compaction was troweled level. Ganjian et al. [14] highlighted the issue of rubber particles moving to the top of their testing moulds after vibrating. Non-uniform distribution of the rubber crumb in the concrete could result in failure at lower stresses. To avoid this, the top surface of the slab was initially levelled with a smooth length of timber to produce a rough finish and then trowelled level. Curing of the concrete was provided by placing the slabs under polythene sheets for 24 h after mixing as shown in. Six 150 mm thick cubes were cast for compression strength testing at 7 and28 days for each mix and one for Young’s modulus analysis. The cubes were cast in 50 mm thick layers with each compacted with a poker vibrator and placed under plastic sheeting for 24 h. Following remoulding, they were placed in a curing tank at 20 ± 2 _C until testing.

1) Test set-up

The study involved two sets of full scale composite slabs with a 130 mm thick concrete topping, one with crumb rubber (7.5% fine aggregate replacement level)and one without. The composite slabs were simply supported on a testing frame with a 2500 mm clear span. The overhang distance ‘Lo’ for each support was 100 mm with two symmetrically applied equal point loads over the full width of the slab. the arrangement before testing. Strain gauges were attached to the underside of the steel deck soffit and on top of the concrete slab at mid-span to monitor the structural behaviour of the test specimens during loading. The gauges were applied by firstly sanding down the zinc coating on the metal deck, cleaned and then glued onto the steel surface. The strain gauge at the top of the concrete slab at mid-span was attached in the same matter as shown in for the Young’s modulus test. A nominal reinforcement of A142 mesh (0.1% of the cross-sectional area of the concrete slab) was cast with a 25 mm cover all around

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the perimeter of the slab. Crack inducers were placed across the full width of the specimen in the tension zone of the concrete. They were fabricated from 0.6 mm steel sheeting and cut into the trapezoidal shape of the profiled steel deck. The crack inducers extended from the bottom of the deck to the underside of the mesh above. The inducers were rubbed down with de-bonding agent before the fresh concrete was poured into the shutter to define the shear span length (Ls) under loading. They also eliminated the tensile resistance provided by the concrete in the zero shear area under load. Presents the arrangement before the concrete was poured.

2) Loading arrangements

Similar to the fresh and hardened concrete tests, the structural testing regime employed on the composite slabs for this study followed the recommendations in Eurocode 4 [12] to provide confidence to the results, particularly for the CRCslabs. Eurocode 4 recommends that the specimens be subject to cyclic loading to remove the chemical bond between the steel and concrete interface prior to static loading. By having the interface removed, slip is initiated and the shear bond strength value can be calculated from the static loading data between the slab and the metal deck. However, according to Marimuthu et al., the cyclic loading proposed in Eurocode 4 does not affect the load carrying capacity of the slab and found a minimal difference between the shear bond strength of a composite slab subjected to cyclic loading followed by static loading to failure than static loading alone. Research conducted into the shear bond capacity of composite slabs using this procedure found that cyclic loading beforehand had a negligible effect on the eventual load carrying. It was therefore decided not to conduct cyclic testing before the static tests.

Table: 2

Mix identifications and proportions of materials (in kg/m^3).

Mix ID	Cement	Water	Aggregate	Tire chips	Crumb rubber	Fine crumb rubber
Control	450	121.5	1594	0	0	0
10TC	450	121.5	1434.6	59.8	0	0
20TC	450	121.5	1275.2	119.6	0	0
10CR	450	121.5	1434.6	0	48.6	0
20CR	450	121.5	1275.2	0	97.3	0
10FCR	450	121.5	1434.6	0	0	28.1
20FCR	450	121.5	1275.2	0	0	56.2
5TC5CR	450	121.5	1434.6	29.9	24.3	0
10TC10CR	450	121.5	1275.2	59.8	48.6	0
5TC5FCR	450	121.5	1434.6	29.9	0	14.1
10TC10FCR	450	121.5	1275.2	59.8	0	28.1

3) Test specimens

Cubic specimens of 150 * 150 * 150 mm dimensions were produced for testing compressive strength and modulus of elasticity. Three point bending tests were conducted on notched 100 * 100 * 500 mm prisms such that the 40-mm notch of the beam was cut by sawing before testing. Moreover, cylinder specimens of£100 * 200 mm were utilized for determining splitting tensile strength and permeability. Each experimental parameter was determined by averaging the results of three samples. All of the tests were performed at the end of 28 day curing period.

4) Test methods

Compression test was carried out on the concrete cube samples as per ASTMC39 by means of a 3000 kN capacity testing machine. Modulus of elasticity was also determined on the same concrete cube before the compression test in accordance with ASTM C469. Splitting tensile strength of the concrete was measured by applying a diametric compressive force on a cylindrical specimen placed with its horizontal axis between the plates of a testing machine with respect to ASTM C 496

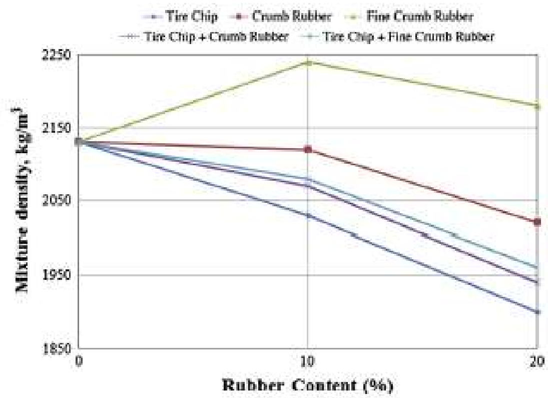

Fig.3. Fresh density of the pervious concretes versus rubber content

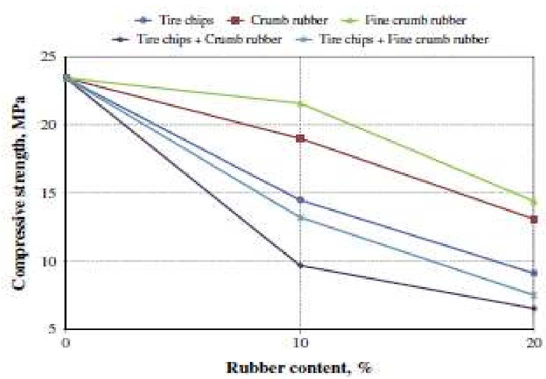

Fig.4. Compressive strength of pervious concretes versus rubber content

V. Results and Discussions

1) Bulk density of the mixtures

The control pervious concrete has a density of 2130 kg/m3which is about 80% the weight of the traditional normal concrete [14]. Adding rubber in different rates shows lighter weights of concretes as shown in such that the rubberized pervious concrete densities are lesser than that of the control mix by about2–11%. The lowest density of 1900 kg/m3 was from the mix 20TCwhile the highest density of is 2240 kg/m3 belongs to the mix 20FCR, respectively. It was pointed out that the rubberized concrete mixtures were workable to a certain degree and resulted in lighter weight concretes [7]. The fine particles from FCR are oppositely increased the density by about 2–5%. Fine crumb rubber played the role of fine aggregate and filled the small gaps among the concrete particles which improved the density and not affected more the permeability coefficient ''K''.

2) Compressive strength

A noticeable negative effect of rubber particles on the compressive strength of the pervious concrete can be seen in Fig. 7. The control mix had the compressive strength of 23.4 MPa decreasing with using rubber. The compressive strength was further affected by rubber particle size such that the smaller size had lesser effect on that property of pervious concrete. The minimum compressive strength of 6.45 MPa was obtained at the mix 10TC10CR in which CR and TC were used together. The test result of compressive strength revealed that the use of the rubber remarkably decreased the compressive strength of pervious concrete. Moreover, the rate of reduction in the compressive strength increased with increasing the rubber content [24]. In general, the reduction in strength was between 16% and 68% according to the type and the ratio of rubber replaced the total aggregate volume.

3) Splitting tensile strength

There is general reduction in the splitting tensile strength of the concretes as the rubber has been used, as shown in. Rubber aggregates appeared to have two kinds of role on the tensile strength of the pervious concrete. Firstly, the small particles of rubber played the role of isolating the aggregates between each other's well as with the cement paste leading to weaker bonds between the mixture particles. For this, splitting tensile strength of 2.1 MPa of control mix reduced to 0.7 MPa (66% loss) by replacing rubber in the mix 10TC10FCR. Secondly, the bigger rubber particles (TC) played as reinforcing fibres in pervious concrete so that the strength loss was as low as 22% in mix 10TC. Visual observation of the broken concrete surface indicated that that splitting occurred along the paste and/or through the aggregates rather than interfacial transition zone (ITZ) due to the strong bond between the cement paste and the aggregate particles [26,27]. Moreover, unlike plain concrete, the failure state in rubberized concrete occurred gently and uniformly, and did not cause any separation in the specimen in line with the literature [28].

4) Flexural strength

The average flexural strength results are presented in with the CRC yielding an increased flexural strength. This does not concur with previous work in this area by Li et al. and Aiello and Leuzzi [19,2] who both report a reduction in flexural strength with the addition of CRC and concluded that it can undergo larger deformations before failure compared to conventional concrete control samples.

5) Young's modulus

The results from the Young's modulus tests. As may be seen, the Young's modulus of the control concrete (19.76 kN/mm2) is higher than the 7.5% CRC sample (12.96 kN/mm2). This reduction in Young's modulus has been observed previously [19, 3].

VI. Conclusions

The following conclusions can be drawn in accordance with the experimental results presented in this research:

Use of waste tire rubber in asphalt paving mixtures and Portland cement concrete has been gaining more and more attention in civil engineering area due to the associated economic, technical, and environmental benefits. Recycling of crumb rubber into asphalt paving mixtures, especially the asphalt rubber technology has been proven successful for decades. The addition of crumb rubber into asphalt binder can lead to the increased resistance to the three major modes of asphalt pavement distress, rutting, fatigue cracking, and low-temperature cracking. Results from a number of small and full-scale tests have shown that CRC composite slabs produce similar longitudinal shear capacities due to its ductile behaviour and greater capacity to absorb higher tensile stresses. The longitudinal end slip results here also satisfy the recommendations within Eurocode 4 with all slabs displaying ductile behaviour. Permeability coefficients (K) of the rubberized pervious concretes fell between 0.025 and 0.61 cm/s which are recommended limits for pervious concretes. Rubberized pervious concretes with local resources of material can be obtained either with the highest compressive strength or the best permeability, depending on the type, size, and amount of the rubber material used. Rubber incorporated pervious concretes had lower compressive strength, splitting tensile strength, and modulus of elasticity. Fracture energy of the pervious concretes increased with tire chips and/or coarse crumb rubber while using fine crumb rubber decreased the fracture energy.

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