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RECYCLING WASTE RUBBER TYRES IN ROAD CONSTRUCTION

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Road construction relies on natural material exploitation and it is necessary to find new ways of reducing its negative environmental impact. Simultaneously, number of tyres placed on Croatian (and world) market is constantly growing and the need for waste tyres management will begin to increase due to the wear and tear of tyres in use at the moment. This paper presents a review of latest international and domestic researches on waste rubber application in road construction with special emphasize on Croatian researches within this topic. Preliminary results of ongoing research on waste rubber application in cement bound mixtures are also presented.

Keywords: road construction, pavement, waste rubber, cement stabilized course

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1. Introduction

Sustainable development, circular economy and recycling are terms appearing frequently in recent years in world and domestic researches, which, among other things, are related to civil engineering. All these terms are also incorporated in different ways in the strategic documents of individual countries, in order to create preconditions for improving living conditions. Two of such documents in Croatia are Law on Sustainable Waste Management [1] and Ordinance on waste tyre management [2] which regulate the management of waste tyres. According to Ordinance [2], the term “tyres” is defined as all types of new or used tyres, and rubber tracks used in the household or by registered persons for the transport and transfer of substances, objects and persons, including work, and to waste tyres from these products. The same Ordinance prescribes the annual recovery goal of the waste tyres recycling / recovering of at least 80% of the mass of separately collected waste tyres in that calendar year [2] with prohibition of waste tyres disposal on landfill according to [3]. Given the existing legal framework, there is a clear need to approach the problem of waste tyres in a broader scientific and professional sense, which is the goal of this paper.

During 2018, 5,1 million tons of tyres was produced in Europe and during 2019, 324 million tyres were sold in the EU representing 20% of the world tyre market [4]. In Croatia, there is a continues increase in tons of tyres placed on the Croatian market since 2012 and according to the latest available data, there has been 30 714,05 t of new tyres placed on the Croatian market in 2018 [5]. At the same time, the amount of recovered tyres in Croatia over the years is uniform, about 19,000 tons. As presented in Figure 1 (based on the data from [5]), the difference in tons of tyres placed on Croatian market and recovered is growing. It can be concluded that over time, the need for waste tyres management will begin to increase due to the wear and tear of tyres in use at the moment since they are not allowed to be disposed of in landfills. The magnitude of the problem is also emphasized by the data that the average lifespan of a standard passenger tyre is approximately 4 years (for general use) and that a single passenger tyre equates to 8 kg in weight [6].

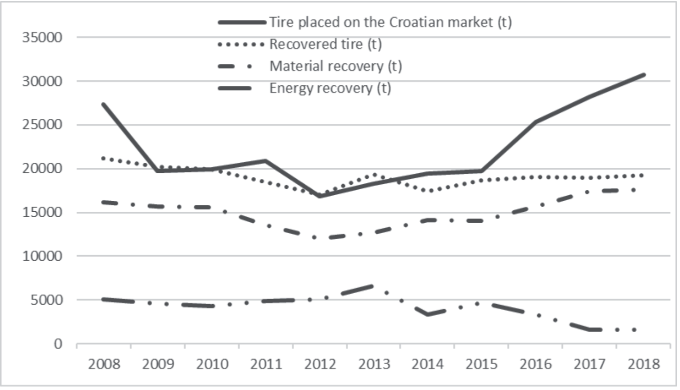

Figure 1. Croatian quantities of tyres placed on the market and recovered

Annual generation of waste tyres is estimated to 1.5 billion whole-tyres worldwide [6]. High volume and slow decomposition (it is a non-biodegradable material) are the main issues of waste tyres management. Landfill disposal is mainly prohibited due to a high endurance and slow decomposition which can result in soil and groundwater pollution while uncontrolled burning results in a carbon release and black smoke which pollutes air. Furthermore, disposed tyres serve as an ideal breeding ground for rodents and mosquitos which are known to be a carrier of various infectious diseases. According to some sources, automobile tyres usage in civil engineering dates back to the 19th century i.e. when automobiles were first invented but only with the increase in waste tyres quantity and environmental protection awareness in 1960s, era of its civil engineering usage begun [7] and one of crumb rubber first usages were for bitumen modification, methodology introduced by Charles McDonalds [8]. Great boost for waste tyres recycling in civil engineering industry, especially in highway construction was given during 1980s and 1990s by major research efforts and significant technology development [7]. Over the years, many ways of sustainable management were found such as waste tyres rethreading, manufacture of rubber-moulded products, tyre pyrolysis to produce carbon black and oil/gas that can be used as a fuel, use as an alternate fuel in cement kilns, in geotechnical applications such as sub-grade fill in roads and embankments, in rubber modified asphalt pavements and as partial replacement of aggregates in concrete [9]. For proper potential application selection, tyre composition can be a key element since it can influence the final product characteristics. Generally, all tyres are made of four basic materials although composition is dependent on tyre purpose (passenger car, truck…). These are 40-45% of rubber (natural and synthetic), 23-27 % of fillers (carbon black, silica, chalk, or carbon), 11-13% reinforcing materials (metals and textiles) and facilitators (plasticisers, vulcanising agents - sulphur and zinc oxide and additives) [6,10]. As for any other waste materials to be used in civil engineering, due to its chemical composition and constituent material toxicity, potential environmental hazard within new tyre rubber application, should be investigated. This is particularly the case for heavy metals leaching potential, particularly zinc [6].

The main scope and purpose of this paper is to present overview of potential application of waste rubber from used tyres in road construction with special emphasize on Croatian researches within this topic. Review of latest international and domestic researches is presented with presentation of newest ongoing research in the field in Croatia.

2. Waste rubber and flexible pavement

In Croatia during 2019 year, 2,62 million tons of hot and warm asphalt mixtures were produced of which 63,7% is surface, 3,8% binder and 32,5 base course [11]. During 2018, in Europe, 297,9 million tons of hot and warm asphalt mixtures were produced and in USA 353 million tons [12].

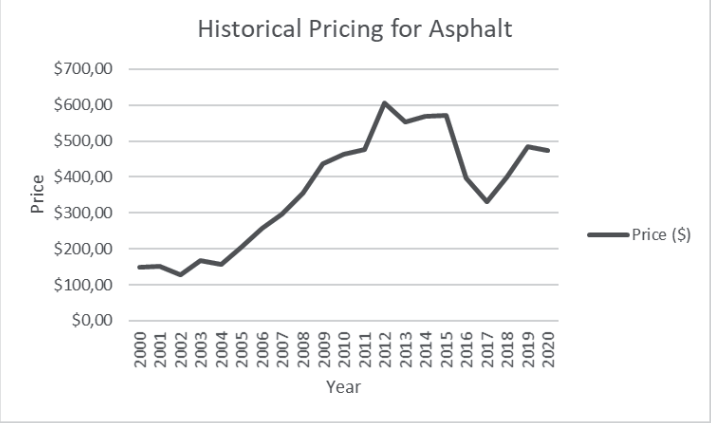

Figure 2. Asphalt price development over last 20 years

The price of asphalt depends on the price of bitumen as a binder, whose price depends on the oil price, from which processing is produced. We are witnessing a constant oil prices rise in the world market, which also caused a significant rise in the price of asphalt produced for road construction. According to The Maryland Asphalt Association the price of asphalt in the last 20 years has increased more than 300%, from $ 150 (January 2000) to $ 473 (January 2020)) (figure 2.). Comparing, diesel fuel price in January 2002 was 1,688 $/gallon and in January 2020 was 3,264 $/gallon or more than 190% [13]. So, it is not surprising that there is a significant number of world researches deals with the possibilities of applying alternative materials in asphalt pavement. One research approach is replacing standard materials with alternative, waste ones, such as waste rubber, and another research approach is expanding pavement life (waste rubber utilization in cement stabilized base course).

One of the most researched and in practice most common application of crumb rubber in pavement design is its application in asphalt. In asphalt mixtures crumb rubber can be used in three main technologies. First, as an addition to the binder in the so-called wet process when fine particles are added to and react with bitumen with the aim of producing an improved binder for asphalt mixtures. Second, in a so-called dry process which includes crumb rubber addition to heated aggregate as a filler at ambient temperature prior to bitumen addition [14]. Third process, so called terminal blend asphalt rubber include fully digested crumb rubber particles in the asphalt binder and blended at the asphalt refinery [15]. According to the [15], wet process includes a minimum of 15% of rubber by weight of the total binder and it is pointed that dry process usually include 3 to 4 % of crumb rubber by weight of total mix.

Addition of crumb rubber to asphalt results in increased viscosity, lower penetration while increasing the softening point and it gives the additional binding strength while increasing elasticity [16]. The addition of rubber to asphalt is equivalent to the addition of the polymer as it reduces fatigue, increases stiffness and the resistance to rutting, retains good behaviour at low temperatures but also when exposed to a warm environment, and reduces traffic noise [7,8,14,17].

Studies show that bituminous binder with crumb rubber, with addition of modifiers, can also be used in the production of warm mix asphalt [18], asphalt mixtures with recycled asphalt aggregates in hot recycling process [14], or in the production of warm asphalt with significant quantities of recycled aggregates [19].

In [20], poroelastic road surface is presented composed of crushed stone aggregate, rubber (20% by weight) and polyurethane binder. It is pointed out that for production and laying and compacting of poroelastic asphalt mixture is possible by ordinary asphalt batch plant and ordinary paving machine and rollers. One of the main features of this wearing course is a potential to reduce pavement noise by at least 10 dB. This innovative material is also applicable for urban roads in cold regions [21]. In [22] it is also emphasized its promising safety issues in a case of spill fuel fires prohibiting the spread of fire and giving a considerable time for the evacuation of passengers.

However, the application of rubber in asphalt also carries negative effects - increasing the cost of production and construction (20-30% more than the cost of conventional mixtures [15]), higher production temperatures, which means higher energy consumption and the problem of bitumen and rubber segregation during transport and storage [7,14]. Also, by applying rubber in the asphalt, due to high temperatures, pollutant emissions are significantly higher than in conventional asphalt [23]. In addition, using it in asphalt layers only a small amount of available waste tyre rubber is used because of limited thickness of these layers [24]. For this reason, the possibility of applying waste tyres in other pavement layers has been investigated.

Li et al. [25] investigated the applicability of crushed rubber in unbound layers from recycled aggregate and crushed stone. Adding crumb rubber to aggregate, as expected led to lower LA values (Los Angeles abrasion test) due to the elastic and deformable behaviour of the material [26]. Measurement of the California Bearing Ratio (CBR) showed that small tyre fractions act as filler increasing CBR value and that the crumb rubber increases failure strain in relation to the control samples. Addition of crumb rubber to the mixture of waste crushed rock results in stiffness reduction but CBR still meet the conditions set for application in base/subbase layers, whereas application in the base layers is not possible only when the 3% by weight of crumb rubber coarse fraction is applied [27].

In the greatest extent, Farhan and his associates [24,28,29] dealt with the application of crumb rubber in cement stabilized layers. Replacing the part of the aggregate with crumb rubber causes a decrease in sample density [24,28]. Namely, this is the result of rubber lower specific weight and high elasticity that absorbs part of the compaction energy resulting in lower compaction effect and consequently lower density. Replacing part of the fine aggregate with rubber and increasing its content results in a drop in compressive, indirect tensile and flexural strength [24,28,29]. Strength decrease upon rubber addition, in relation to the reference mixture, is greater with higher the cement content, that is, the higher the strength and rigidity of the initial reference mixture. For mixtures with lower cement content, such as stabilizations, differences in stiffness are lower and stresses are more uniformly distributed across all mixture components. Although the application of a waste tyre rubber reduces the strength of cement stabilized aggregate, the application of silicon dust or the treatment of waste rubber with sodium hydroxide [30,31] can result in improved interfacial bonding of the rubber granules within the mixture. On the other hand, in stabilized mixtures, due to the compaction, good contact with aggregate particles should be achieved and thus eliminate the problem observed in the application of rubber in concrete mixtures. Aggregate replacement by rubber also results in a less stiff material leading to decrease in ultrasound velocity and dynamic modulus of elasticity [28,29]. Addition of rubber increases capacity for energy absorption, i.e. increases ductility. Cracks that occur at failure are thinner and develop as one major and few smaller cracks leading to greater energy dissipation. It is believed that the addition of rubber particles, having a smaller modulus of elasticity, reduces the propagation of the cracks because it allows the release of part of created local stresses and also due to the distribution of these weak particles, path of the crack lengthens [24]. Toughness and fatigue life are also enhanced and flexural-induced cracks tend to propagate through rubber aggregate [32]. It is found that addition of crushed rubber reduces the stresses that occur in cement stabilization due to material shrinkage [33]. Also, low water capillary absorption of rubberized cement treated aggregates which is favourable characteristic for more durable pavement base layers is pointed out as an advantage [34].

3. Waste rubber and rigid pavement

Considering the dynamic nature of traffic loads, research has also been carried out over the last couple of years to explore the application of rubber in a conventional/normal or roller compacted concrete for pavements.

The application of rubber in concrete presents the addition of elastic material to a rigid concrete matrix that changes its properties [35]. Numerous studies on use of crumb rubber in concrete suggest that the addition of rubber and increase of its amounts in concrete usually has a negative effect on mechanical properties such as compressive, indirect tensile and flexural strength, modulus of elasticity and density [7,25,36]. Strength reduction is described as a result of poor bonds between cement paste and rubber particles and also because rubber with low modulus of elasticity that is imbedded in concrete of high strengths acts like a void [7,35].

But the rubber addition also increases the capacity of concrete for energy absorption and ductility and reduces the possibility of brittle fracture. The addition of rubber to concrete increases the number of load cycles that will lead to fracture or fatigue of the material [37]. The addition of rubber to the mortars makes them hydrophobic and reduces the penetration of water [38], while also improving the resistance to freezing [39]. Applying a fine aggregate of crushed rubber as a volumetric sand replacement in concrete pavement results in satisfactory properties of fresh and hardened concrete with a rubber share of up to 30% [40]. With the addition and increase in rubber share, the drop in compressive and indirect tensile strength was noted, but the samples were ductile, could take higher deformations, and had residual load capacity after failure.

Methodology for measuring the deformations in concrete mixtures with crumb rubber, created to evaluate mixtures for pavements under cyclic loads is presented in [35]. It is found that 20% of rubber aggregate significantly reduces mechanical properties but that up to 10% of the rubber of different granulations achieves better deformability and performance of the material under cyclic load stresses with an acceptable reduction in mechanical properties.

Presence of rubber aggregates in mixtures of roller compacted concrete for pavement application, while decreasing optimum moisture and dry spatial mass, results in more available cement paste that improves workability, consistency and compaction due to lower water absorption [41]. The impact on strength is similar to that of conventional concrete, where significant rubber contents reduce strength and elasticity, but improve the energy absorption potential and the ductility of the material. Small amounts of rubber (5%) can also be beneficial for strength properties. Finally, findings from 100 research studies published in the last 30 years on 25 different rubber treatment methods to improve the mechanical properties of rubber concrete are presented in [9].

4. Waste rubber in Croatian scientific research

Waste tyres application in Croatian road construction is mostly known through research and development of the project RUCONBAR - Rubberized Concrete Noise Barriers. Within this project, absorbing layer of a concrete noise barrier is developed incorporating 40 % rubber granules recycled from waste tyres [42,43] and it was firstly implemented as a noise protection solution for Zagreb ZOO [44]. Another research on waste rubber application in concrete is dealing with substitution of a fine aggregate in normal concrete and self-compacting concrete. When replacing sand by rubber particles 0,5-4 mm, compressive strength is reduced with a linear relation to rubber content, rubberized concrete is more ductile than normal concrete and cracks being narrower and aligned in a mesh, without separation of large parts [45]. For self-compacting concrete, favourable fresh and hardened properties with 28 days compressive strength above 30 MPa can be obtained with up to 15% of crumb rubber and 5% of silica fume [46].

Latest research on waste rubber application in pavement structure is being conducted under scientific project founded by Croatian Science Foundation, Installation Research Project named Cement stabilized base courses (CBC) with waste rubber for sustainable pavements - RubSuPave (UIP-2019-04-8195). As presented earlier, researches in the area of waste rubber application in cement stabilized base layers are limited but there are indications that its application could result in a reduction in shrinkage cracking. However, the optimum mix composition (optimal amount of cement, optimum tyre aggregate content), and in particular the effect on behaviour of asphalt courses in this kind of pavement structure, is not yet fully explored. Within this project, the possibilities for improving behaviour of pavement incorporating CBC will be researched through an analysis of the possibility of recycled rubber replacement for fine aggregate fractions. The results of project activities are expected to have a dual impact: the reduction of the application of natural materials to which road construction traditionally relies on and the extension of pavement life time. The use of waste rubber in CBC has the potential to reduce cracks occurrence which results in reflective cracking on asphalt layers. This will reduce the need for road maintenance and extend its lifespan, which will result in savings of financial resources and reduced energy consumption. The reduction of reflective cracking contributes to the longer lifespan of both the asphalt layers and cement bound bearing course. With the longer road lifespan, less maintenance is needed which saves finances and necessary energy for natural material exploitation. Furthermore, by providing more durable bearing courses, lower requirements are placed on the quality of asphalt layers materials.

Materials which are going to be used within this research are natural river sand and gravel (from the Drava River), Portland cement of grade 32,5 (CEM II B/M (P-S) 32,5R) as a binder and different gradations of a waste rubber (Figure 2). For defining test mixtures composition, grain size distribution was made for available recycled waste rubber and natural aggregate as presented in Figure 3, according to HRN EN 933 - 1:1997 [44].

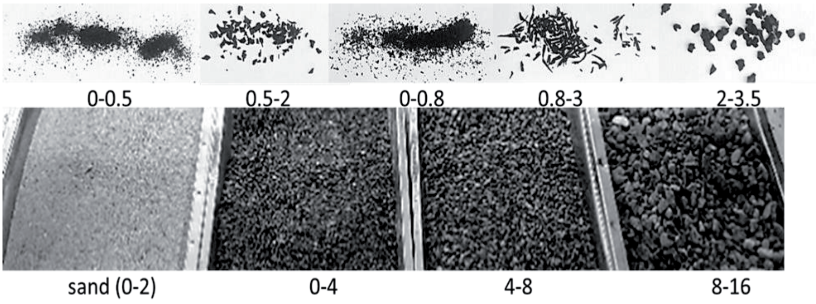

Figure 2. Waste rubber aggregate (up) and natural aggregate (down) - size in mm

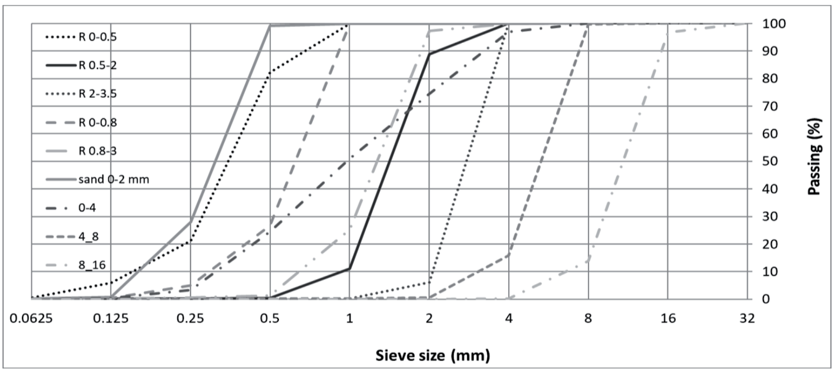

Figure 3. Grain size distribution of waste rubber (R) and natural aggregate (river sand and gravel)

Materials density were determined by pycnometer as prescribed in HRN EN 17892-3:2015 [48]. For sand, 0-4, 4-8 and 8-16 gravel aggregate determined densities were 2,86; 2,96; 2,63 and 2,70 g/cm3 respectively while density of a waste rubber of 1,12 g/cm3 were determine using the same standard but using ethanol instead of water. Density of used cement is 2,92 g/cm^3. Due to a high difference in natural and rubber aggregate densities, volume replacement of sand and gravel fine fractions by rubber particles is going to be implemented for main research phase. Here will be presented preliminary results of this ongoing research.

Laboratory reference density and water content of a mixture with 5% binder content (reference mix) and 60% replacement of a sand by rubber fraction 0-0,5 mm was determined by vibratory hammer method [49] and presented in Table 1. Sand replacement by rubber fraction 0-0,5 mm was selected due to its similar grain size distribution (Figure 3). Compressive strength was determined as average value on three test specimens by standard HRN EN 13286-41:2003 [50]. Sand replacement by rubber in an amount of 60% represent 13,91% of total mixture aggregate volume and 6,13% of total mixture aggregate mass. As presented in Table 1, rubber mixture has 8,4% less optimum water content and 12,15% less maximum dry density due to rubber lower density and water absorption comparing to sand. Compressive strength has dropped by 89,3% comparing to reference mixture. According to [51], a 5% reduction in mixture density causes 40–50% reduction in the mixture strength, which correspond to the obtained laboratory results here presented. Therefore, these preliminary results will be used for main test mixture composition definition in a view of rubber grain size selection and natural aggregate replacement level determination. According to these preliminary results, target mixtures will have 10-40% sand replacement by waste rubber (by volume) in order to achieve target compressive strength values (2,5-6 MPa) but to decrease shrinkage cracks occurrence.

Table 1. Preliminary test results of CBC mix with waste rubber aggregate

Mixture / property	5% binder - reference mix	5% binder + 60% rubber
w_{opt} (%)	5.95	5.45
ρ_d (g/cm^3)	2.4	1.88
Compressive strength (MPa)	4.57	0.49

5. Conclusion

Road construction is an activity mainly based on the application of natural materials, primarily stone, gravel and sand, and binders (bitumen and cement) whose production represents a significant environmental burden. Thus, it is necessary finding new ways of making road construction sustainable and more environmentally acceptable. According to world literature, the use of waste tyres in road construction is possible but not trivial. It is necessary to explore in detail the advantages and disadvantages of its application, which is also the idea of RubSuPave scientific project. Although researches in the area of waste rubber application in cement stabilized base layers of pavement structures are limited, there are indications that its application could result in a reduction in shrinkage cracking. This could on the other hand prolong asphalt wearing course lifespan and reduce need for its maintenance resulting in a significant financial savings, environmental preservation and incorporation of road construction into sustainable development frameworks. However, the optimum mix composition (optimal amount of cement, optimum tyre aggregate content), and in particular the effect on behaviour of asphalt courses in this kind of pavement structure, is not yet fully explored. Also, to gain full insight in potential benefits or disadvantage caused by waste rubber application in road construction, detailed cost-benefit and life cycle assessment is required and should be conducted before making any decision on its practical usage. Results of the research conducted within RubSuPave project will contribute to the creation of new knowledge on the practical application of waste tyres in cement stabilized base layers aiming to solving and improving the practical goal: creating a sustainable roadway through the application of waste material and extending pavement life.

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LIST OF FIGURES AND TABLES:

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