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Rostyslav Chaus, Uliana Marushchak

PROSPECTS OF THE USE OF RUBBER CRUMB IN CONCRETE: A REVIEW

Department of Building Production,
Lviv Polytechnic National University,
uliana.d.marushchak@lpnu.ua

The growing global problem of waste tire disposal is prompting the quest for environmentally friendly rubber recycling solutions to support the principles of a circular economy. The development of rubber concrete is a promising aspect. The review highlights the impact of using waste tire rubber in concrete, assesses the advantages and limitations for optimizing material characteristics, as well as environmental benefits. Results of the role of rubber content, size, and additives on the workability, strength, dynamic properties, and durability of rubber concrete are presented. It is shown that rubber crumb increases ductility and energy absorption, but reduces compressive strength and workability of concrete. However, the strategic use of additives such as nanosilica and steel fibers eliminates the loss of strength. Practical applications and environmental assessments show the practicality and environmental safety of rubber concrete.

Keywords: crumb rubber, crumb rubber concrete, aggregate, workability, mechanical properties, eco-friendly concrete.

Introduction

Globally, rubber waste, most of which comes from discarded tires, is a major environmental problem. About 1.5 billion tires are produced annually, driven by population growth and rapid urbanization. Unfortunately, the problem of worn tires is based on the traditional concept of “make-use-dispose” of the linear economy (Chittella, Yoon, Ramarad & Lai, 2021). One billion tires reach the end of their useful life each year, with about half of them being recycled and the rest ending up in landfills (Tahami, Mirhosseini, Dessouky, Mork & Kavussi, 2019). Used tires account for 2 % of the total global solid waste generated annually (Sabbrojjaman, Liu & Tafsirojjaman, 2024). Worn tires accumulate in large quantities in landfills, often dumped uncontrollably, which creates a growing danger to the environment (Rigotti & Dorigato, 2022).

The problems of tire recycling are caused by the fact that under normal conditions, rubber is characterized by a stable three-dimensional structure of cross-linked polymer chains, obtained as a result of the vulcanization of raw rubber. The destruction of this complex structure occurs when heated to high temperatures. Initial losses are observed in the temperature range of 300–419 K, which corresponds to the separation of residual volatile substances contained in the rubber structure. Deep destructive and thermo-oxidative processes begin at temperatures above 483 K (Nagurskyy, Khlibyshyn, Grynyshyn & Kochubei, 2020). The stable structure and composition of rubber make it resistant to natural degradation, so the process of tire decomposition lasts about 100 years. When stored in landfills, tires pollute the environment, in particular soil and groundwater due to the leaching of toxic substances, in particular antioxidants and antiozonants, as well as heavy metals, and at elevated air temperatures in summer, highly toxic compounds are released into the atmosphere (Valentini & Pegoretti, 2022). In addition, tires can retain rainwater for long periods, creating favorable conditions for the breeding of mosquitoes and other pests (González et al., 2020). To eliminate the problem of storing worn tires in landfills, it is necessary to find ways to recycle them, transforming waste into valuable raw materials or energy (Goevert, 2023). This path is consistent with the principles of the circular economy, which forms a closed product cycle and is based on a sustainable production method by reducing raw material consumption and waste generation, implementing recycling and resource reuse practices while minimizing waste and greenhouse gas emissions (Jorgensen & Remmen, 2018). With the implementation of the EU Landfill Directive 1999/31/EC, which banned the landfilling of whole tires in the EU in 2003 and shredded tires in 2006, the issue of recycling and reuse of rubber waste is becoming increasingly relevant (Goevert, 2023).

The most common way to use rubber waste is incineration for energy recovery. In Europe, around 1.5 million tires are incinerated each year (European Tyre and Rubber Manufacturers Association, 2021), mainly in the firing of Portland cement clinker. However, research is needed to determine the impact of using tires as a fuel on the ecosystem in the context of setting limits in the EU for cement kilns in co-incineration of waste.

However, technological advances are being developed for chemical and thermal methods, such as devulcanization and pyrolysis, to convert these wastes into raw materials and energy. Efforts are being made to innovatively utilize waste rubber in other sectors, including construction. The most common building material in the world is cement concrete, which has no alternative in the near future. However, the production of concrete requires a huge amount of natural raw materials and energy, which results in a significant carbon footprint of the material. Therefore, on the way to climate neutrality of the construction industry, it is necessary to implement resource- and energy-efficient technologies (Van den Heede, & De Belie, 2012). The growing global problem of waste tire recycling, along with the depleting resource of raw materials, has led to extensive research into environmentally friendly alternatives in concrete production. Aggregates for concrete have a significantly lower primary energy consumption and carbon footprint than Portland cement, yet their content in concrete is around 70–80 % by volume. Given the growing global concrete production of 14 billion m^3 per year, the consumption of natural aggregates has a significant environmental impact. One of these promising areas is the application of rubber crumb from waste tires as a replacement for mineral aggregates in concrete to create so-called concrete rubber concrete.

For use in concrete, life-end tires are crushed. Depending on the degree of crushing, crumb sizes of 20–30 mm, 1–10 mm or powder with a particle size of less than 1 mm are obtained. Rubber crumb from life-end tires can be used in concrete for replace of natural aggregate, and the rubber powder can be used as a substitute for cement (Strukara, Kalman Šipoša, Miličevićb, & Bušic, 2019).

In the present paper, the effects of adding waste tire rubber to concrete, considering both the advantages and disadvantages of this approach to environmental problems and concrete optimization are reviewed.

Properties of rubber concrete

Fresh concrete properties. High-quality compaction of fresh concrete determines the maximum strength of concrete and depends on workability. The workability of rubberized concrete, which measures how easily it can be mixed, placed, compacted and handled, is affected by the amount and type of rubber particles used. According to several studies, the workability of rubberized concrete decreases with increasing percentage of rubber content. This is because rubber particles have a larger surface area than traditional aggregates and require more water to achieve the same level of workability (Abdelmonem, El-Feky, El-Sayed, & Kohail, 2019; Youssf, Mohamed & Julie, 2015; Feng, Liu, Yang, Li, & Jing, 2018). The reduction of slump of rubberized concrete occurred regardless of the tire rubber particle size, which is associated with the higher water absorption of the rubber particles (Su, Yang, Ling, Ghataora, & Didar, 2015). A decrease in slump was also observed with a decrease of the rubber particle size. Azevedo, Pacheco-Torgal, Jesus, Barroso de Aguiar, & Camões (2012) also report that the addition of rubber crumb reduces the workability of concrete. They explain that the inclusion of rubber aggregates requires the use of a higher superplasticizer content to obtain concrete with the same workability as the control concrete. Youssf, Mohamed & Julie, 2015 noted that the workability of rubberized concrete can be controlled by using superplasticizer in amount 1–3 % by weight of cement. This indicates that the use of rubber crumb in concrete may increase the cost of materials due to the increased need for superplasticizers. However, some studies report different results. For example, workability can be slightly improved when rubber crumb is used as a partial substitute for coarse or fine aggregate (Abdelmonem et al., 2019; Feng et al., 2018). This decrease may be due to reduced friction between rubber particles and other components. This suggests that the size and shape of the rubber particles may also play a role in workability, along with the percentage of rubber.

Studies have shown that the introduction of rubber allows you to prepare lighter concrete. The density of rubberized concrete was lower by 2–11 % compared to the control samples of the mixture. While the decrease in density occurred with an increase of the amount of rubber crumb. In addition, smaller rubber crumb had a stronger effect on the decrease in density (Feng, Liu, Yang, Li, & Jing, 2018).

Mechanical properties and durability. Studies have shown that the addition of rubber particles can lead to a decrease in compressive strength (Thomas, Gupta, & Kalla, 2014). Youssf, Mills & Hassanli (2016) explain that this is due to the lack of strong adhesion between the rubber crumb and the cement material, which is caused by the low polarity and smooth surface of the rubber particles. Wang, Lin, & Lee (2013) observed that the decrease in compressive strength is directly proportional to the amount of rubber added. They also found that the size of the rubber crumb affects the compressive strength. They explain that coarse granulation of the rubber crumb reduces the compressive strength compared to finer granulation (Wang et al., 2013). This may be due to the fact that coarse rubber crumb creates more voids in the concrete than fine rubber crumb. The increasing the size of rubber particles reduces the loss of compressive strength in the range of rubber crumb sizes of 0.15–2.36 mm (Youssf et al., 2020; Khan, Ashraf, Ali, & Khan, 2023). The authors indicate that replacing up to 15 % of fine aggregates with rubber crumb can slightly improve the workability of concrete and increase the compressive strength by over 5 % (Malik, & Singh, 2021). However, they also note a decrease in tensile strength and splitting modulus with increasing RC content. This improved compressive strength and non-brittle failure is attributed to better stress dissipation, increased strain at failure and a higher modulus of toughness (up to 15 % at 15 % rubber crumb replacement), which shifts the failure mode from typical brittle to a more ductile (plastic) one. Atahan and Yucel, 2012 also found that increasing the amount of rubber in concrete leads to a decrease in the modulus of elasticity. It was be noted that decrease in tensile strength and modulus of elasticity at break with increasing rubber crumb content (Malik, & Singh, 2021). However, studies have also shown that the inclusion of steel fibres can help mitigate this decrease and even increase the shear strength and toughness of rubberised concrete beams (Ismail & Hassan, 2017). The size and distribution of rubber particles also play a role in determining the workability and strength of concrete (Su, Yang, Ling, Ghataora & Didar, 2015).

The dynamic properties of rubberized concrete, which refer to its behavior under dynamic loads such as seismic activity or impact, are also affected by the addition of rubber particles. Studies have shown that rubber particles can improve the dynamic properties of concrete by increasing its damping coefficient and energy absorption capacity (Marushchak, Sydor & Chaus, 2024). This is because rubber particles can deform and absorb energy during dynamic loads, reducing the load on the concrete matrix. This property is especially important for structures located in earthquake-prone areas or those subjected to impact loads (Abdelmonem et al., 2019; Youssf et al., 2015; Feng et al., 2018). In addition, Atahan and Yucel (2012) explain that rubber crumb concrete has greater ductility and energy absorption capacity than conventional concrete. They argue that it is an ideal material for concrete safety barriers because it softens the concrete, giving greater plastic deformation on impact and less braking force.

The size and shape of rubber particles play a crucial role in determining the properties of rubberized concrete. Angelin, Miranda, Dos Santos, Lintz, & Gachet-Barbosa, 2019 investigated the use of two types of rubber waste from tires: spheroid and fiber. They discovered that rubberized mortars with fiber particles exhibited higher mechanical strengths than those made with spheroidal rubber. Additionally, the rubberized mortars with fiber particles demonstrated higher sound velocity for P-waves and greater sound attenuation (Angelin et al., 2019).

The structural behaviour of rubberized concrete has been investigated in various studies, including the shear behaviour of large steel fibre reinforced rubberized concrete beams (Ismail & Hassan, 2017) and the flexural behaviour of rubber fibre reinforced rubber chip beams (Mendis, Al-Deen, & Ashraf, 2018). These studies have provided valuable information on the performance of rubberized concrete in structures, highlighting the importance of factors such as rubber content, steel fibre reinforcement and particle size distribution.

The durability of rubberized concrete, a critical factor in its long-term performance and ability to resist weathering, chemical attack, abrasion and other deterioration processes, is a crucial factor to consider. Studies on the abrasion and freeze-thaw resistance of precast concrete containing waste rubber have shown that the use of rubber can significantly improve these properties (Gesoğlu & Güneyisi, 2014). Studies have shown that rubber particles can increase the durability of concrete by improving its resistance to abrasion, impact and chloride ion penetration. This is due to the fact that rubber particles can act as crack confining agents, preventing the propagation of cracks and increasing the ability of concrete to absorb energy. In addition, the effect of NaOH treatment on the frost resistance of rubber concrete has been investigated, showing that treated rubber particles can further improve the durability of concrete(Si, Guo, & Dai, 2017). In addition, rubber particles can improve the frost resistance of concrete, which is important for structures exposed to cold climates (Abdelmonem et al., 2019; Youssf et al., 2015; Feng et al., 2018).

Methods of increasing efficiency

The researchers also studied methods to improve the properties of rubber crumb concrete. The pretreating rubber crumb with NaOH and using microsilica as a mineral admixture improves workability and strength compared to conventional and untreated rubber crumb (Rajagopal, Ganta & Pamu, 2024; Sanytsky, Marushchak, Olevych, & Novitskiy, 2020). This is in line with the results of the study (Shahrul, Mohammed, Wahab, & Liew, 2021; Rajagopal et al., 2024), which demonstrated that the addition of nanosilica improves the mechanical properties of rubber crumb. The combination of rubber concrete with other additives, such as carbon nanotubes, steel and glass fibres, has also been investigated. The authors showed that the incorporation of multi-walled carbon nanotubes into rubber crumb modified concrete improved flexural and compressive strengths (Gill, Jangra, Roychand, Saberian, & Li, 2023; Khan et al., 2023). The positive impact of steel fibres on the mechanical performance of rubberized concrete has seen confirmed in several studies (Gill, Jangra, Roychand, Saberian, & Li, 2023; Tahwia, Noshi, Abdellatief, & Matthana, 2024; Ghoniem & Aboul Nour, 2024). Steel fibres bridge developing cracks and enhance the stress transfer between the rubber particles and the cement matrix, which improves toughness and shifts the failure mode brittle to ductile. Similarly, highlight the positive impact of steel fibres on improving the mechanical properties of rubber concrete is observed (Tahwia, Noshi, Abdellatief, & Matthana, 2024; Ghoniem & Aboul Nour, 2024). To improve the physical and mechanical properties of concrete the adding crumb rubber, it is promising to introduce complex organo-mineral additives containing a polycarboxylate superplasticiser and an active mineral additives.

Potential drawbacks

However, some studies point to potential drawbacks. While additives such as cement and fibres can improve performance, they can reduce the environmental friendliness of rubberised geopolymer concrete (Gill et al., 2023; Khan et al., 2023). In addition, the use of rubber crumb can lead to an increase in the deflection of concrete slabs (Tahwia et al., 2024; Gill et al., 2023, Youssf et al., 2020).

Practical Applications and Environmental Impact

In addition to laboratory tests, the practical application of crumb rubber concrete is being investigated. However, data of the use of this type of concrete for structural applications (columns, frames and beams) is still limited and needs to be detailed. The authors describe in detail the design, processing and actual application of CRC in residential construction (Youssf et al., 2020, Tahwia et al., 2024). These studies emphasize the importance of reproducing laboratory results in practical conditions, taking into account factors such as workability, ease of use and durability (Youssf et al., 2020; Youssf et al., 2022). Recycled rubber aggregate can be used to produce self-compacting concrete in structural elements to reduce the risk of spalling of the concrete surface and concrete cover in structural elements resistant to seismic actions (Wang, Lin, & Lee, 2013).

The environmental benefits of using CR in concrete are obvious, as it provides a solution for the disposal of waste tyres (Shahrul et al., 2021; Rajagopal, Ganta & Pamu, 2024). However, a comprehensive environmental assessment must also consider the impact of additional materials and processes. The life cycle assessment showed that the incorporation of microsilica into CRC did not significantly increase the environmental impact compared to conventional concrete (Rajagopal, Ganta & Pamu, 2024; Ghoniem & Aboul Nour, 2024; Gill et al., 2023).

Conclusions

The addition of rubber crumb to concrete has a double benefit: it solves the environmental problem of waste tire disposal and modifies the properties of concrete. The use of waste tyres in concrete production is a promising approach to sustainable construction, offering several benefits, including reduced waste tire accumulation, as well as improved strength, dynamic, thermal and acoustic properties of concrete. Although rubber crumb may lead to a reduction in certain strength parameters, it increases ductility, toughness and energy absorption. However, it can also lead to reduced workability and compressive strength. The extent of these effects depends on the size and shape of the rubber particles, as well as the water/cement ratio, workability of the concrete and the use of admixtures. The strategic use of additional materials such as nanosilica, steel fibres and microsilica can effectively mitigate the reduction in strength and optimize the performance of concrete. It is therefore essential that these factors are carefully considered when developing rubberized concrete mixes to ensure that they meet the specific requirements of the project. By carefully considering the type and amount of rubber used, as well as adding steel fibres and optimizing the particle size distribution, rubberized concrete with improved mechanical properties, durability and structural characteristics can be produced. The practical application of CRC in residential construction has demonstrated its feasibility and ease of use. In addition, environmental assessments indicate that CRC can be a sustainable alternative to conventional concrete. Overall, the use of rubber from waste tires in concrete is a promising sustainable solution that can help solve the global environmental problem of waste tire disposal. Further research and development in this area will pave the way for the wider use of rubber crumb concrete, contributing to a more sustainable and environmentally friendly building environment.

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Р. Т. Чаус, У. Д. Марущак
Національний університет "Львівська політехніка",
кафедра будівельного виробництва

ПЕРСПЕКТИВИ ВИКОРИСТАННЯ ГУМОВОЇ КРИХТИ В БЕТОНІ: ОГЛЯД

Загострення глобальної проблеми утилізації відпрацьованих автомобільних шин та обмеженість природних ресурсів спонукають до пошуку екологічно чистих альтернативних рішень у будівництві. Використання гумової крихти із відпрацьованих шин у бетоні як часткової заміни природних заповнювачів є перспективним напрямом, що поєднує вирішення екологічних проблем та покращення властивостей будівельного матеріалу. У статті описано вплив гумової крихти на властивості бетону, проаналізовано переваги та недоліки такого підходу. Висвітлено проблеми оптимізації характеристик бетону з урахуванням екологічних аспектів і технічних вимог до будівельних матеріалів. Проаналізовано дослідження впливу гумової крихти на легковкладальність бетонної суміші, міцність, динамічні властивості, довговічність та структурну поведінку затверділого гумобетону. Розглянуто вплив розміру і форми гумових частинок, кількості гумової крихти на властивості гумобетону. Введення гумової крихти до бетону є ефективним способом вирішення проблеми утилізації відпрацьованих шин та покращення певних властивостей бетону, таких як пластичність, ударна в'язкість та звукоізоляція. Однак це може призвести до зниження міцності на стискання і модуля пружності. Досліджено методи підвищення міцності та екологічних характеристик гумобетону, а також практичне застосування матеріалу в житловому будівництві. Проаналізовано використання додаткових матеріалів (мікро- та нанокремнезему, сталевих волокон), а також хімічного оброблення поверхні частинок гуми для зменшення їх негативного впливу на показники гумобетону. Практичне застосування гумового бетону в житловому будівництві підтверджує його перспективність. Оцінювання життєвого циклу показує, що використання гумового бетону є екологічно прийнятним.

Ключові слова: гумова крихта, гумобетон, заповнювач, легковкладальність, механічні властивості, екологічний бетон.