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Influence of granulated rubber from waste tires on ASR expansion, microstructure, and mechanical properties of mortars

Abstract: The paper presents the results of research on the effect of partially replacing the sand fraction in cement mortar mixes with granulated rubber (GR) from waste tires on the potential for alkali–silica reaction (ASR) occurrence. ASR is a significant durability issue in cement-based composites, which can lead to substantial expansion and cracking in these materials. The study also analyzed the influence of rubber aggregate on the mechanical properties of mortars, particularly compressive and flexural strength, as well as on the microstructure of the mortars. Additionally, the impact of NaOH on the properties of granulated rubber aggregate was evaluated. Reference mortars were prepared using moderately reactive sand (R1) and highly reactive sand (R3), while in the experimental mixes, rubber aggregate was used as a volumetric replacement for a specific sand fraction at levels of 15% and 30%. ASR-related expansion tests were conducted in accordance with the RILEM AAR-2 guidelines. The results showed that partially replacing sand with rubber aggregate effectively reduced ASR-induced expansion, likely due to the rubber's ability to absorb stress and restrict moisture migration, thereby mitigating the reaction. However, the use of rubber aggregate also led to a decrease in both compressive and flexural strength, which is a typical effect when introducing elastic materials, such as rubber, into cementitious mixes. The findings highlight the potential of granulated rubber from waste tires recycled as a sustainable additive in cement-based materials to control ASR, especially in structures exposed to aggressive environmental conditions. Additionally, the use of this type of aggregate aligns with the principles of the circular economy by utilizing rubber waste and simultaneously delivering both environmental and performance benefits.

Keywords: ASR, durability, internal structure, rubber aggregate, waste tire.

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1. INTRODUCTION

The expansion of road infrastructure worldwide has led to increasing concerns regarding the environmental footprint of pavement materials and construction practices. Traditional road pavements, primarily composed of natural aggregates, bitumen, and cement-based materials, consume vast amounts of raw materials and contribute significantly to greenhouse gas emissions throughout their lifecycle, from extraction and production to construction and maintenance phases [1, 2]. Addressing these challenges is imperative to meet national and international decarbonization targets and to promote sustainable resource management aligned with the principles of a circular economy [3].

One of the key strategies to mitigate the environmental impact of road construction is the incorporation of recycled materials into pavement systems. The depletion of natural aggregate resources necessitates the search for suitable alternatives, while the available options often fall short of the expected performance requirements [4]. Reclaimed asphalt pavement, construction and demolition waste, and granulated rubber derived from end-of-life tires are among the most promising secondary raw materials that can be effectively reused in various pavement applications [5, 6]. In particular, the use of granulated rubber from waste tires (GR) not only diverts significant amounts of waste from landfills but also provides unique mechanical and durability benefits to cement-based materials [7, 8].

The application of GR in cementitious systems has been investigated in several studies focusing on its influence on mechanical properties, such as compressive and flexural strength [9, 10]. Several studies have demonstrated that the incorporation of rubber aggregates into cementitious systems can positively affect a range of material properties beyond strength. Rubberized mortars and concretes exhibit enhanced ductility and impact resistance, which help mitigate brittle failure modes [10-13]. The inclusion of rubber particles has also been shown to improve resistance to shrinkage-induced cracking [10] and provide better vibration damping capacity, making such composites suitable for applications subjected to dynamic loading [12, 13]. Moreover, durability-related benefits have been reported, including improved resistance to freeze-thaw damage, reduced permeability, and better performance under aggressive chemical environments [14, 15].

Moreover, GR has been identified as a potential modifier to mitigate alkali-silica reaction (ASR), a serious durability concern in concrete and mortar structures exposed to reactive aggregates [8, 16]. ASR can cause significant expansion and cracking, undermining the long-term performance of road pavements and other civil infrastructure [17].

Despite these encouraging findings, several critical knowledge gaps persist regarding the mechanisms by which GR mitigates ASR and the factors influencing its performance in cementitious systems. For instance, although some studies have suggested that the elasticity of GR particles may absorb stress concentrations and disrupt ASR gel propagation [7, 16], the detailed microstructural interactions at the interfacial transition zone (ITZ) between GR and the cement matrix remain poorly characterized. The extent to which GR alters local pore structure, moisture transport pathways, and chemical reactions that drive ASR expansion is still not fully understood [18]. Additionally, the influence of GR surface properties, potentially modified by alkaline exposure during cement hydration, on long-term performance requires systematic investigation [12].

Furthermore, the environmental benefits of using GR extend beyond landfill diversion. By partially replacing natural aggregates with GR, the embodied carbon of pavement materials can be significantly reduced, contributing to the decarbonization of road infrastructure. This aligns with the European Union's Circular Economy Action Plan [3], which emphasizes the reuse and recycling of materials in construction sectors to foster resource efficiency and climate resilience.

This paper addresses these issues by investigating the use of granulated rubber as a partial sand replacement in cement mortars intended for road pavement applications. The study evaluates the influence of GR on the mechanical properties, ASR mitigation potential, and microstructural characteristics of mortars prepared with different levels of rubber incorporation. Particular attention is paid to the interplay between mechanical performance and durability to assess the feasibility of adopting GR in modern road pavements with reduced carbon footprints. By combining mechanical testing, ASR expansion evaluation, and microstructural analyses, this research aims to provide valuable insights into the integration of recycled materials into sustainable pavement design.

2. MATERIALS AND METHODS

The mortar compositions were based on ordinary Portland cement CEM I 52.5 R, selected for its high alkali content with Na_2O_e = 0.87% and Blaine specific surface area of 5460 cm^2/g, ensuring suitability for ASR-related testing.

Three types of siliceous sands were used as fine aggregates, each representing a different level of alkali reactivity according to AASHTO R 80-17 [19]:

- Sand No. 1 was classified as moderately reactive, exhibiting a 14-day expansion of 0.13%, corresponding to Class R1;
- Sand No. 2 was categorized as highly reactive, with a 14-day expansion of 0.49%, placing it in Class R3;
- Sand No. 3, considered non-reactive (14-day expansion < 0.10%), was incorporated in selected mixes to assess the influence of inert aggregate substitution.

The granulated rubber was obtained from processed end-of-life tires. It consisted of dry, free-flowing granules with a particle size range of 0.50-1.00 mm, irregular shapes, and a black colour, typical of ground rubber, Fig. 1. Its bulk density was approximately 1.2 g/cm^3, provided by the supplier.

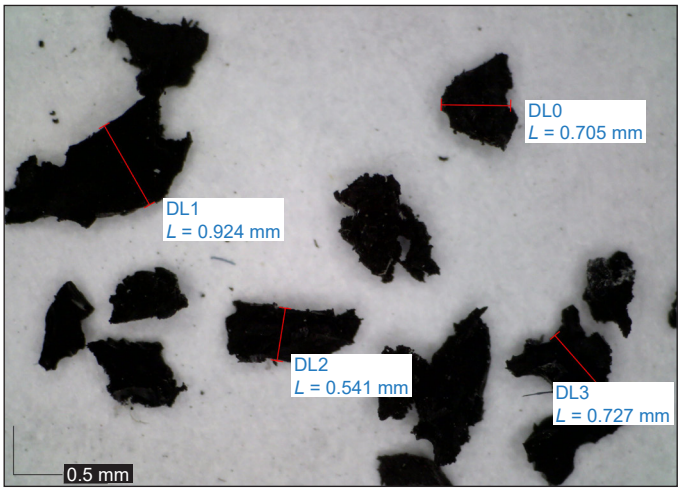

Fig. 1. The granulated rubber from waste tires

A portion of the natural sand retained on the 0.5 mm sieve was replaced with GR on a volumetric basis. Two substitution levels were selected, 15% and 30% volumetric replacement. The substitution approach was designed to preserve the original sand gradation (Fig. 2) and packing density. The matching nominal size between the rubber granulate and the replaced sand fraction ensured structural consistency within the mixtures.

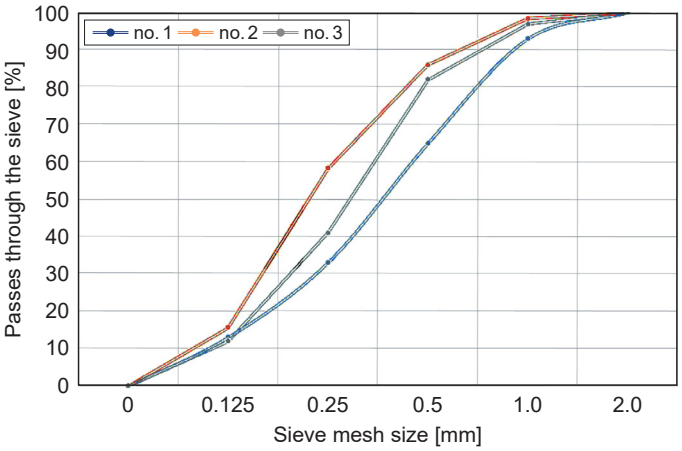

Fig. 2. Sieve curves of the analysed sands

In total, seven mortar compositions were prepared for mechanical and expansion tests, Table 1, differentiated by sand type and GR content.

- M1-0 and M2-0: reference mortars with no rubber addition, prepared respectively with sand no. 1 and no. 2,
- M1-15 and M2-15: 15% volumetric replacement of sand with GR,
- M1-30 and M2-30: 30% volumetric GR replacement,
- M2-30 sand: a comparative mix in which 30% of the reactive no. 2 sand was substituted with non-reactive no. 3, to isolate the effect of reactivity suppression. The water-to-cement ratio was tailored to the testing purpose. A *w/c* of 0.50 was used for mechanical tests and a *w/c* of 0.47 was adopted for ASR evaluation in line with RILEM AAR-2 guidelines [20]. In all mortars, cement content was held constant at 450 g per batch for mechanical testing and 440 g for ASR testing. As the GR content increased, the corresponding sand mass was reduced to ensure equivalent volume substitution.

To assess the chemical stability and potential for surface modification of granulated rubber from waste tires, the granules were subjected to an alkaline conditioning process. The treatment involved immersing 100 g of GR in a 1 M sodium hydroxide solution at room temperature (20 ± 1°C) for 30 min. to affect the surface. Post-treatment, the rubber was divided into two subsets and dried under distinct thermal conditions: one at room temperature at 20° ± 1C and the other in a ventilated oven at 80 ± 1°C, each for a duration of 24 hours. The solid material was then separated from the residual solution by filtration and reserved for further analysis.

Table 1. Composition of mortars intended for ASR testing.

Mix ID	Cement [g]	Water [g]	Sand type (S)	Sand mass [g]	Rubber [g]	Sand S3 [g]	Substitution type
M1-0	440	206.8	S1	990	–	–	–
M1-15	440	206.8	S1	842	37	–	15% GR
M1-30	440	206.8	S1	693	73	–	30% GR
M2-0	440	206.8	S2	990	–	–	–
M2-15	440	206.8	S2	842	37	–	15% GR
M2-30	440	206.8	S2	693	73	–	30% GR
M2-30_sand	440	206.8	S2 + S3	693 (S2)	–	297 (S3)	30% non-reactive sand

To evaluate the impact of alkaline treatment on the mineral and organic phases of GR, a set of analytical techniques was employed: X-ray Diffraction (XRD), thermogravimetric analysis (TGA) and Attenuated Total Reflectance Fourier Transform Infrared spectroscopy (ATR-FTIR).

The crystallographic structure of GR was examined using a Bruker D8 DISCOVER diffractometer operating with Cu Kα radiation. Data collection was performed across a 2θ range of 5°-65°, with a resolution of 0.02° per step and an acquisition time of 1 second per increment. Diffractograms were interpreted using Diffrac.Eva 5.2 software to identify mineralogical components.

Thermal decomposition behaviour was characterized using a PerkinElmer TGA 800 system. The specimens were heated from ambient temperature to 800°C at a ramp rate of 10°C per minute under a nitrogen atmosphere (flow rate ~40 mL/min), enabling the identification of mass loss associated with volatile organics and polymer breakdown.

Functional group composition and chemical transformations at the GR surface were assessed using ATR-FTIR spectroscopy. Ground samples were scanned across the 400-4000 cm^{-1} spectral range using a Spectrum Two spectrometer (PerkinElmer) to detect changes related to hydroxyl, aliphatic, and sulfur-containing moieties.

Compressive and flexural performance of the mortar specimens was evaluated after 28 days of curing, following the procedures outlined in PN-EN 196-1 [21]. For each mortar composition, three prismatic samples (40 × 40 × 160 mm) were cast. After demoulding at 24 hours, the specimens were water-cured at 20 ± 1°C until testing. Flexural strength was determined through a three-point bending test, in which the prism was loaded centrally until failure. The resulting fragments were then subjected to compressive strength testing, using the fractured halves placed vertically between steel plates. Load was applied until failure, and strength values were calculated based on the cross-sectional area and maximum load recorded.

To assess the susceptibility of the mortar mixes to ASR and quantify the influence of GR on expansion behaviour, accelerated mortar bar testing was carried out in accordance with the RILEM AAR-2 protocol. Mortar bars with dimensions of 25 × 25 × 285 mm were prepared with a water-to-cement ratio of 0.47. After an initial 24-hour ambient cure, specimens were immersed in water at 80 ± 1°C for another 24 hours. They were then transferred into a 1 M NaOH solution, maintained at 80 ± 1°C for the duration of the test. Expansion measurements were taken periodically, with a primary evaluation point at 14 days and extended observation up to 28 days to monitor potential reactivity.

Post-ASR exposure, selected mortar specimens were subjected to detailed microstructural analysis. Segments were extracted from the mortar bars, dried at 50 ± 1°C for three days, and embedded in low-viscosity epoxy to preserve the internal structure. Polished cross-sections were obtained using successive grinding and diamond polishing. To ensure conductivity, the samples were carbon-coated prior to imaging.

Scanning Electron Microscopy (SEM) was performed using backscattered electron imaging (BSE) at 15-20 kV to examine matrix-aggregate interfaces, crack development, and ASR gel morphology. Energy-Dispersive X-ray Spectroscopy (EDS) was employed for elemental mapping and point analysis, focusing on ASR gel zones, aggregate boundaries, entrapped air voids, and the interfacial transition zone surrounding GR particles.

3. RESULTS

3.1. CHARACTERIZATION OF GRANULATED RUBBER

XRD analysis (Fig. 3) confirmed that the mineral composition of GR remained largely unchanged by alkali exposure. The diffraction patterns of both untreated and NaOH-treated specimens showed distinct crystalline peaks corresponding to zinc oxide and calcite, common components of recycled rubber. In addition, a broad amorphous peak was observed between approximately 13° 2θ and 30° 2θ. In the original interpretation this was attributed mainly to the carbonaceous organic matrix of the rubber. However, considering that recycled tire rubber typically contains around 15% amorphous silica [22, 23], it is more accurate to assume that the observed hump reflects the superimposed contribution of both the carbonaceous organic phase and the amorphous silica. This combined origin is consistent with the characteristic diffuse signal of amorphous silica reported in the literature [22].

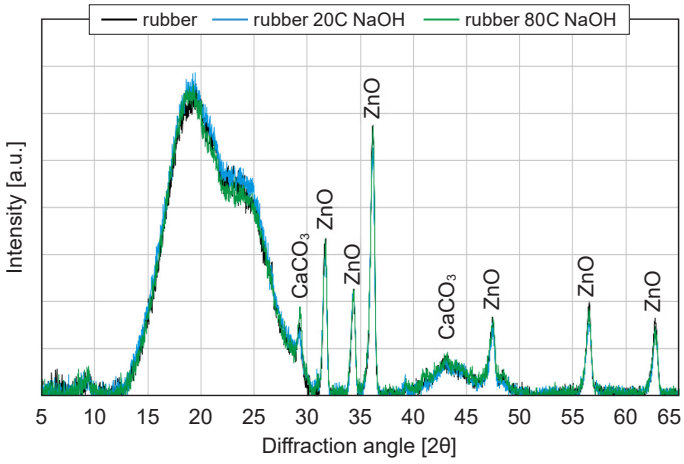

Fig. 3. XRD patterns of granulated rubber: untreated and treated with 1 M NaOH at 20°C and 80°C

The TGA results (Fig. 4a) provided insight into the thermal degradation characteristics of GR. All samples showed significant mass loss between 300°C and 500°C, consistent with the breakdown of the vulcanized polymer network and carbon black fillers. Remarkably, samples treated with NaOH at 80°C showed a more sudden and significant mass loss in this range, indicating accelerated degradation due to the combined effects of chemical and thermal exposure. In contrast, untreated GR showed a more gradual degradation profile, reflecting greater thermal stability. The behaviour of specimens treated at 20°C fell between these two extremes, further emphasizing the effect of elevated temperature on chemical reactivity.

ATR-FTIR spectra (Fig. 4b) revealed the effect of alkali media treatment on the GR specimens. The change that is observed in the range between 3100 and 3600 cm^{-1} relates to the O-H stretching vibrations. The increase of the band intensity can indicate enhanced hydroxylation or polarity of the material. Following changes in the region between 2800-3000 cm^{-1} are characteristic to the vibrations of the C-H bonds. The presence of bands at 2846 cm^{-1} and 2953 cm^{-1} are ascribed to the symmetric and asymmetric vibrations of CH2, while bands at 2915 cm^{-1} and 3002 cm^{-1} relate to symmetric and asymmetric vibrations in CH3 functional groups in the polymer-based matrix. The intensity of these bands increased in the alkali treated GR samples for the surface degradation after the NaOH treatment. Furthermore, the changes of absorption bands in the 1000-1600 cm^{-1} region, associated with C-O, C=C, and C-S bonds, also point out the changes in functional groups within the rubber matrix. Importantly, the band in the 1560 cm^{-1} in GR 80C NaOH and band at 1556 cm^{-1} in GR 20C NaOH that are ascribed to the aromatic ring modes are shifted in both samples compared to the GR 20C specimen (band at 1536 cm^{-1}) what also confirms surface changes of treated samples. Similarly, for GR 20C NaOH and GR 80C NaOH specimens two the increase of the bands at 695 and 715 cm^{-1} can be ascribed to the out-of-plane and aromatic ring bending, respectively [24]. Another change can be observed for in the irregular band about 1424 cm^{-1} for the GR 80C NaOH and two bands at 1424 cm^{-1} and 1440 cm^{-1} possibly related to the −C-H bending (scissoring) and =C-H (rocking) bending, respectively, in GR 20C NaOH compared to the GR 20C specimen [25]. As can be seen, the ratio between these bands and the band around 1370 cm-1 that relates to the umbrella mode of CH3 group increases after the treatment. All these changes confirm that alkaline treatment combined with elevated temperature affect the surface of the recycled rubber exposing additives and promoting surface defects that can enhance binding in the concrete-based composites.

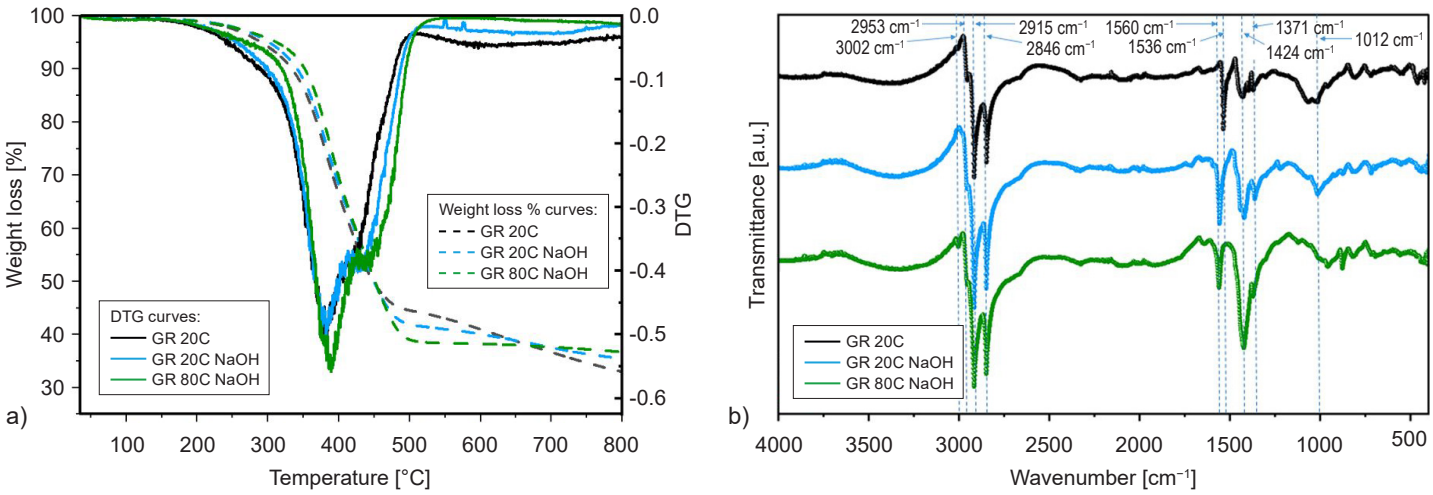

Fig. 4. Characteristic of the recycled rubber, untreated and treated with 1 M NaOH at 20°C and 80°C: a) TGA curves, b) ATR-FTIR spectra

3.2. MECHANICAL PROPERTIES OF MORTARS

After 28 days of curing, mortars incorporating granulated rubber from waste tires exhibited a noticeable reduction in both compressive and flexural strength compared to their respective reference mortars (Fig. 5). In mortars prepared with sand no. 1 (moderately reactive), replacing 15% of the sand with GR resulted in a 12.4% decrease in compressive strength and a 9.9% decrease in flexural strength, while a 30% substitution led to respective reductions of 24.1% and 19.8%. For mortars made with sand no. 2 (highly reactive), compressive strength was reduced by 11.1% and 22.8%, and flexural strength by 9.2% and 18.5%, for 15% and 30% GR replacement, respectively. Additionally, the mortar in which 30% of sand no. 2 was replaced by non-reactive sand no. 3 exhibited a compressive strength of 41.5 MPa and a flexural strength of 7.8 MPa.

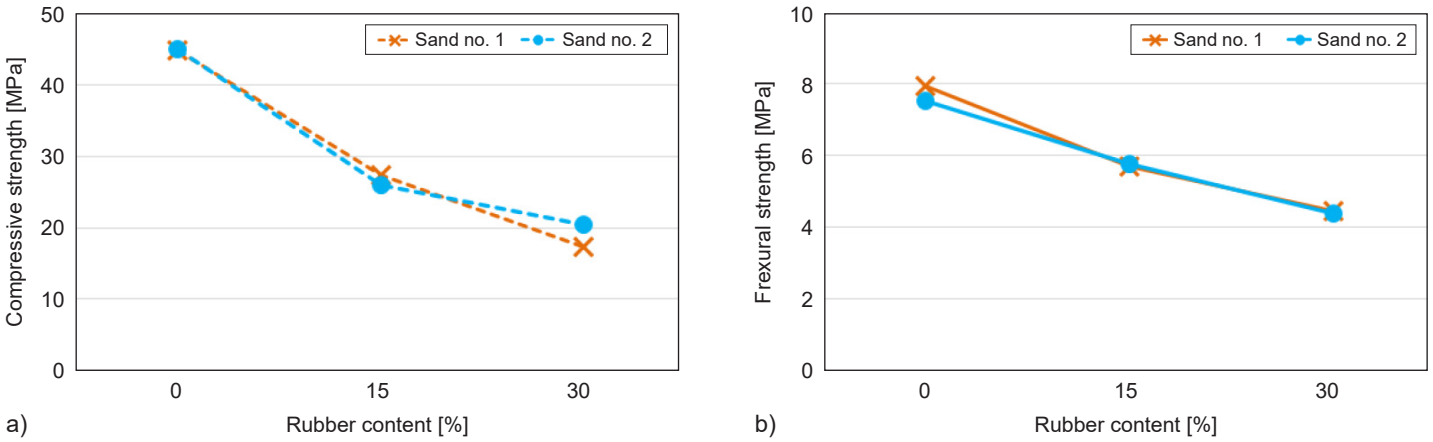

Fig. 5. The mechanical properties of mortars after 28 days of curing: a) compressive strength, b) flexural strength

3.3. ASR EXPANSION BEHAVIOUR

The effectiveness of granulated rubber in reducing alkali-silica reaction-induced expansion is presented in Fig. 6. Mortars containing moderately reactive sand no. 1 showed relatively low expansion values. After 14 days, the reference mortar M1 reached an expansion of 0.13%, while the incorporation of 15% GR reduced this to 0.11%. The 30% GR series reached 0.12%, slightly higher than the 15% GR mix but still below the reference. After 28 days, expansions were 0.30% for the reference, 0.23% for M1-15 GR, and 0.22% for M1-30 GR, corresponding to reductions of 23% and 26%, respectively. A significantly stronger mitigation effect was observed in mortars made with highly reactive sand no. 2. The reference mortar M2 showed a 14-day expansion of 0.49%, while mixes with 15% and 30% GR achieved reductions to 0.43% and 0.32%, equating to 12.8% and 33.0% reductions, respectively. After 28 days, expansions were 0.73% (reference), 0.66% (15% GR, 9% reduction), and 0.46% (30% GR, 37% reduction). In addition to the rubber-modified mortars, a mortar M2-30_sand, in which 30% of the highly reactive sand no. 2 was replaced with non-reactive sand no. 3, was also tested for ASR expansion. After 28 days, this mortar reached 0.48% expansion (34% reduction vs. M2). While both substitutions, GR and inert sand, effectively lowered ASR-induced expansion by reducing the total amount of reactive silica, the M2-30 GR mix achieved the greatest reduction.

3.4. MICROSTRUCTURAL OBSERVATIONS

The SEM micrographs presented in Figs 7-9 illustrate the influence of granulated rubber from waste tires on the microstructure of mortars exposed to alkali–silica reaction conditions, with particular emphasis on crack formation and gel distribution. Fig. 7 compares mortars containing highly reactive sand no. 2 in the reference mix and the mix with 30% GR (M2-30). The reference mortar (Fig. 7a) exhibits widespread ASR-induced cracking and substantial gel accumulation around reactive aggregate particles. In contrast, the mortar modified with 30% GR (Fig. 7b) shows markedly fewer cracks and a noticeable reduction in ASR gel, particularly near rubber inclusions.

Further insight into the dose-dependent effect of GR is provided in Fig. 8, which compares mortars with and without 15% GR (M2-15). A clear difference in crack propagation is observed. In the reference mortar, cracks pass directly through reactive sand grains, indicating severe ASR damage. In the GR-modified mortar, however, cracks are fewer and tend to terminate at the rubber particles instead of penetrating them, indicating that GR functions as a stress-absorbing barrier that interrupts crack development.

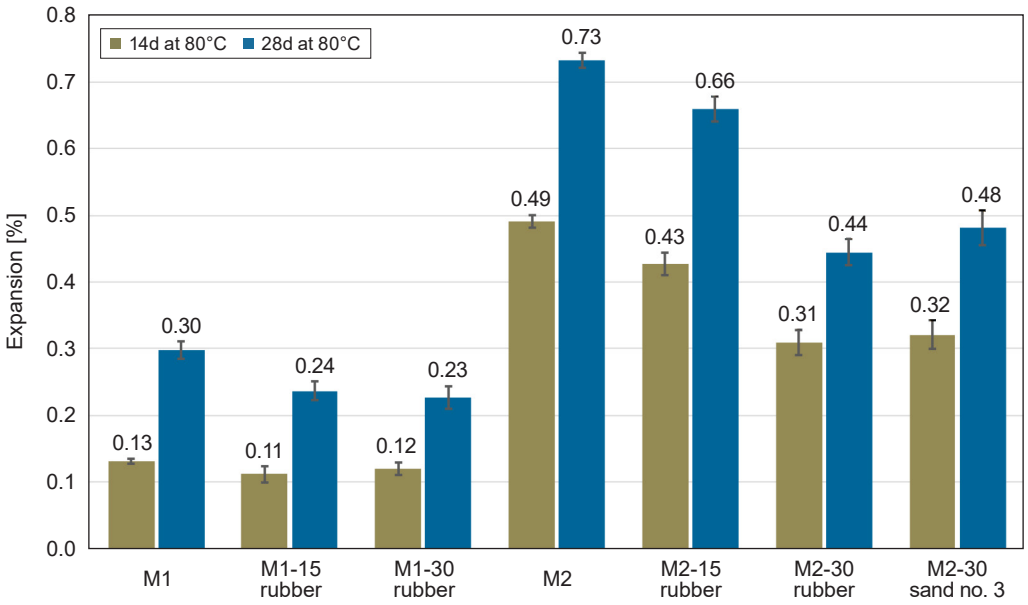

Fig. 6. Expansion of the mortar bars after exposure to 1M NaOH at 80°C

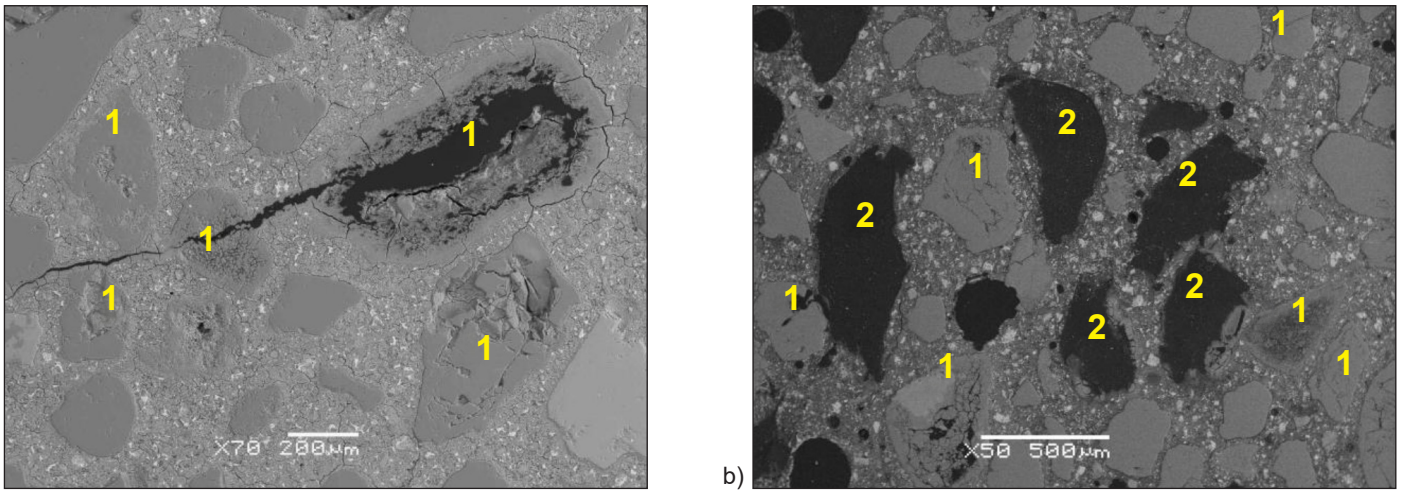

Fig. 7. Microstructure of mortars with highly reactive sand no. 2 after ASR testing: a) reference, b) with 30% of GR; 1 – cracked sand grains, 2 – GR grains

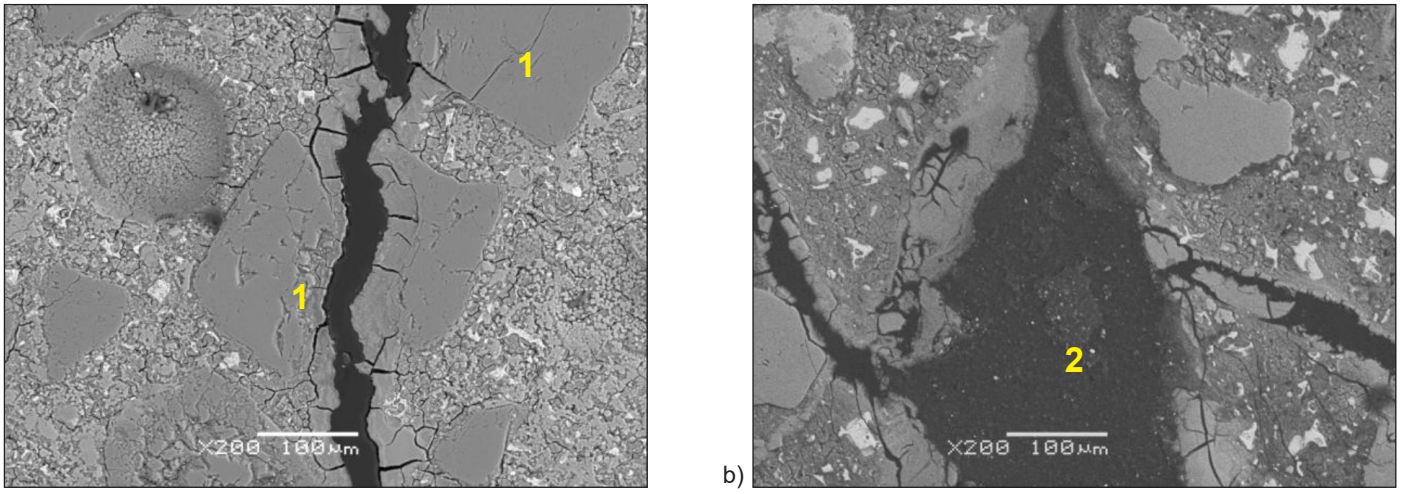

Fig. 8. Microstructure of mortars with highly reactive sand no. 2: a) reference, b) with 15% of GR; 1 – cracked sand grains, 2 – GR grains

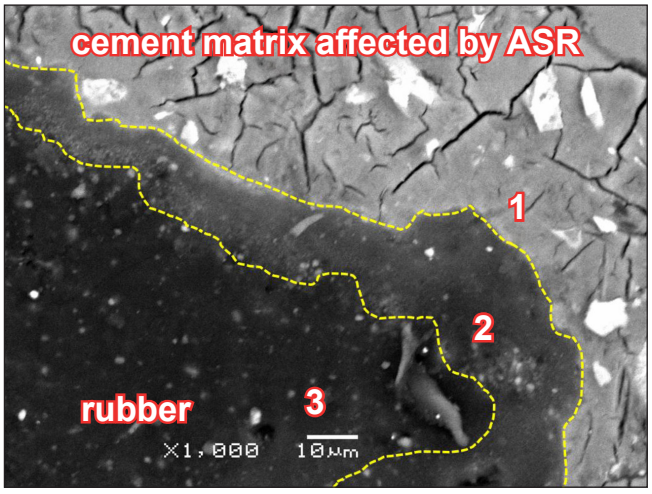

Fig. 9 additionally illustrates the microstructure of mortars modified with rubber. The area marked with number 1 is characteristic of the cement matrix affected by ASR. The region labelled as number 2 corresponds to the interfacial transition zone, where the rubber surface appears modified due to interaction with the surrounding matrix. Finally, area 3 represents the rubber particle itself. These observations are consistent with the mechanical test results, in which mortars with higher rubber content exhibited reduced stiffness but an improved ability to arrest crack propagation.

Fig. 9. SEM microstructure of contact zone between cement matrix and rubber aggregate in mortar M2-30 after ASR test, highly reactive sand no. 2 with 30% of rubber substitute →

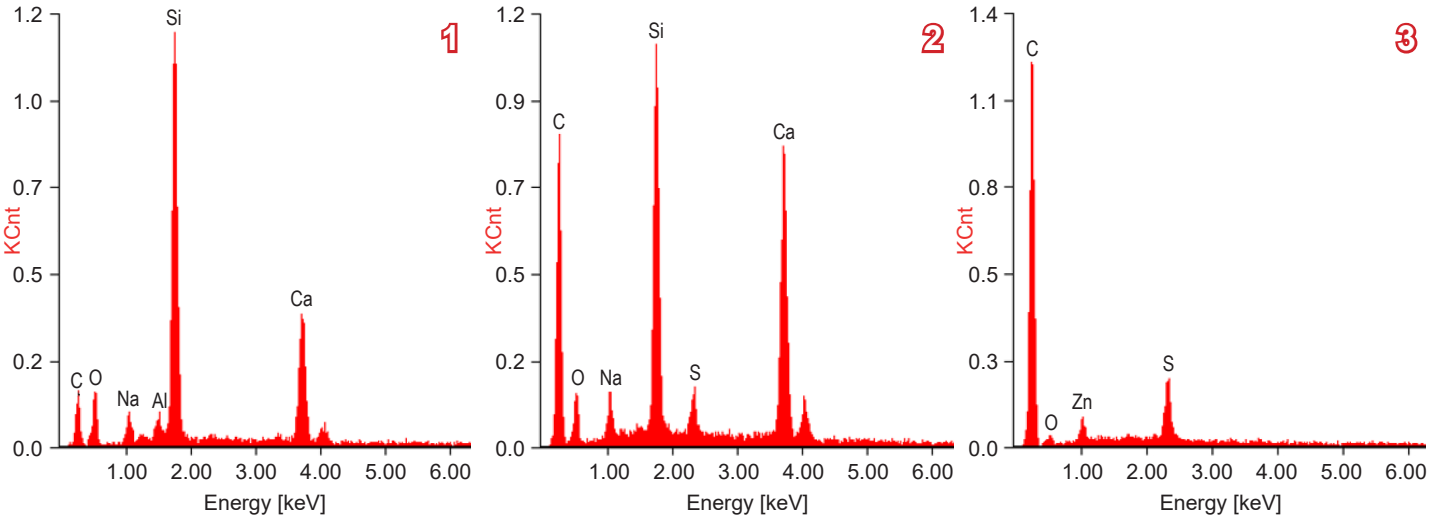

Fig. 9. SEM microstructure of contact zone between cement matrix and rubber aggregate in mortar M2-30 after ASR test, highly reactive sand no. 2 with 30% of rubber substitute; KCnt – counts, peak intensity measured during elemental analysis (EDS)

4. DISCUSSION

The experimental findings demonstrate that granulated rubber from waste tires can be integrated into cement mortars not merely as a waste-derived substitute for natural sand, but as a functional modifier with practical benefits for specific civil engineering applications. This discussion emphasizes performance interpretation within the context of transport infrastructure, environmental durability, and material adaptability – diverging from the conventional focus on strength loss and alkali-silica reaction mitigation alone.

Although reductions in compressive and flexural strength were observed with increasing GR content, these declines should be contextualized rather than viewed strictly as disadvantages. In road and bridge engineering, many structural or semi-structural components are exposed to dynamic loading, thermal cycling, and microcrack-inducing conditions rather than purely axial stress. In such scenarios, the elasticity and energy absorption properties of GR can contribute positively to performance [6, 13].

Potential use cases include bridge expansion joint mortars, vibration-damping elements in abutments, and pavement overlays in regions prone to cracking. These applications benefit from the improved ductility and post-cracking response observed in rubberized mortars, which help mitigate brittle failure modes commonly encountered in conventional mixes [26, 27].

The mitigation of ASR expansion through the use of GR reflects more than a chemical dilution effect. The elastic deformation capacity of GR, its hydrophobic nature limiting internal moisture transport, and its role in disrupting continuous gel propagation collectively contribute to reduced expansion [8, 12]. This positions GR as a strategic component for ASR risk control, especially in structures exposed to aggressive environments, such as road pavements subjected to de-icing salts or bridge elements in marine zones.

The observation that mortars incorporating GR outperformed those containing inert sand in terms of ASR mitigation further supports the notion of a multi-mechanistic action, combining both physical and chemical contributions to durability [14].

Although not explicitly addressed in the current study, the behaviour of GR mortars under environmental cycling, such as freeze-thaw exposure, chloride ingress, and carbonation merits further attention. The hydrophobicity and flexibility of rubber particles suggest potential for enhanced resistance to freeze-thaw-induced cracking and reduced capillary absorption of aggressive agents [15]. These properties may offer extended service life in infrastructure exposed to fluctuating climates and chemical stressors

Conversely, thermal and alkaline degradation of the rubber matrix, confirmed via ATR-FTIR and thermogravimetric analysis, indicates potential long-term softening or interface weakening. While initial oxidation may enhance bond strength at the particle-matrix interface [15], prolonged degradation could alter mechanical continuity. This highlights the need for lifecycle assessments of GR-modified cementitious systems in long-term infrastructure applications.

The granulated rubber from waste tires should not be positioned solely as a volumetric replacement for mineral sand but rather as a hybrid engineering and ecological modifier. Its integration introduces a spectrum of trade-offs reducing stiffness while enhancing ductility, moderating peak strength but improving durability against specific deterioration mechanisms. These characteristics may be strategically harnessed in design approaches that prioritize resilience over maximum static strength [29].

Furthermore, the reuse of end-of-life tires as aggregate aligns with European and global sustainability directives, contributing to reduced extraction of virgin materials and promoting circular construction [3]. The continued development of technical standards and long-term performance benchmarks will be essential to facilitate broader adoption in road and bridge construction practice.

5. CONCLUSIONS

The present study examined the effects of incorporating finely ground rubber from waste tires as a partial replacement for natural sand in cement mortars, with particular attention to its impact on mechanical performance, mitigation of alkali-silica reaction, and microstructural behaviour.

Based on the experimental results and analysis, the following conclusions can be drawn:

1. The inclusion of GR led to a significant decrease in compressive and flexural strength of the mortars. However, the reduction remained within acceptable limits for non-structural or semi-structural applications, particularly those requiring increased toughness, flexibility, or vibration resistance.
2. Granulated rubber contributed to a significant reduction of ASR expansion in mortars with highly reactive sand (from 0.66% to 0.44%). Compared with replacing reactive sand with non-reactive sand (0.48%), the 30% GR substitution achieved a slightly lower expansion (0.44%), though the difference between these two strategies is minor.
3. Scanning electron microscopy revealed a more compliant interfacial transition zone around rubber particles. In mortars with granulated rubber, the ITZ is mechanically weaker compared to the bulk cement matrix. Nevertheless, due to the elastic nature of rubber particles, internal stresses in the composite are redistributed, resulting in fewer visible cracks in the surrounding matrix. This effect reflects stress compensation rather than an inherent increase in the crack resistance of the ITZ.
4. Physicochemical analyses (XRD, TGA, ATR-FTIR) indicated surface transformations in the rubber matrix that may influence the long-term adhesion to the cementitious matrix.
5. The use of GR promotes the valorisation of end-of-life tires, contributing to reduced natural resource consumption and supporting circular economy goals. While mechanical performance must be carefully evaluated, the environmental benefits and durability improvements make GR a promising additive for targeted applications in transport infrastructure.
6. GR-modified mortars are particularly suitable for road and bridge elements such as pavement overlays, expansion joint mortars, and vibration-dampening substructures. Further research is recommended to validate long-term field performance under environmental cycling and mechanical fatigue.

In summary, granulated rubber from waste tires presents a technically feasible and environmentally sound option for modifying cement-based materials. With proper mix design and performance-based criteria, GR can contribute meaningfully to the development of more durable and sustainable civil infrastructure.

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Wpływ granulatu gumowego z odpadów opon na ekspansję spowodowaną reakcją alkalia–krzemionka, mikrostrukturę oraz właściwości mechaniczne zapraw cementowych

Streszczenie: W artykule przedstawiono wyniki badań dotyczących wpływu częściowego zastąpienia frakcji piasku w mieszankach zapraw cementowych recyklingowym kruszywem gumowym na potencjał występowania reakcji alkalia–krzemionka (ASR). ASR jest istotnym problemem trwałości w kompozytach o matrycy cementowej, ponieważ może prowadzić do znacznego pęcznienia i spękań w tych materiałach. Analizowano również wpływ kruszywa gumowego na właściwości mechaniczne zapraw, w szczególności na wytrzymałość na ściskanie i zginanie, oraz na mikrostrukturę zapraw. Dodatkowo przeanalizowano oddziaływanie NaOH na właściwości kruszywa gumowego. Zaprawy referencyjne przygotowano z użyciem umiarkowanie reaktywnego piasku (R1) i wysoko reaktywnego piasku (R3), natomiast w mieszankach eksperymentalnych zastosowano kruszywo gumowe jako zamiennik objętościowy określonej frakcji piasku w ilościach 15% i 30%. Badania rozszerzalności związanej z ASR przeprowadzono zgodnie z wytycznymi RILEM AAR-2. Uzyskane wyniki wykazały, że częściowe zastąpienie piasku kruszywem gumowym skutecznie ograniczało ekspansję wywołaną ASR, prawdopodobnie dzięki zdolności gumy do pochłaniania naprężeń oraz ograniczania migracji wilgoci, co w konsekwencji łagodziło reakcję. Zastosowanie kruszywa gumowego prowadziło jednak do obniżenia wytrzymałości na ściskanie i na zginanie, co jest typowym efektem wprowadzania do mieszanek materiałów elastycznych, takich jak guma. Wyniki badań podkreślają potencjał recyklingowego kruszywa gumowego jako zrównoważonego dodatku do materiałów cementowych, umożliwiającego kontrolowanie reakcji alkalia–krzemionka, zwłaszcza w konstrukcjach narażonych na agresywne warunki środowiskowe. Dodatkowo wykorzystanie tego rodzaju kruszywa wpisuje się w założenia gospodarki o obiegu zamkniętym, poprzez zagospodarowanie odpadów gumowych i jednoczesne przynoszenie korzyści środowiskowych oraz użytkowych.

Słowa kluczowe: ASR, struktura wewnętrzna, kruszywo gumowe, trwałość, zużyte opony.