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# Waste Rubber-Modified Cement-Bound Base Course: Laboratory Characterisation and Field Application

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**Abstract:** Within the scientific research project 'RubSuPave', a large number of laboratory tests were carried out to investigate the addition of waste rubber (WR) to mixtures of a cement-bound base course (CBC) for pavement construction. For mixtures consisting of gravel aggregate, sand, cement (at 3%, 5%, and 7% by mass) and various sand replacements with WR (0%, 10%, 20%, 30% and 40% volume) additions, the compaction characteristics, compressive strength, and resistance to freezing and thawing (F/T) were determined. The results show that compressive strength is negatively affected by the addition of WR, while F/T resistance is improved, with mixtures containing 10–20% WR and 5% cement being optimal. The next step was transferring the knowledge gained into field conditions via the large-scale production of such mixtures in concrete plants and the construction of test fields. The CBC reference and WR mixtures (2% mass) were produced in two different concrete plants; the samples were compacted, and compressive strength and F/T resistance were tested. The CBC mixtures made in the first plant were used for the construction of the test field. The results and problems of mixture production in two different concrete plants are presented, along with the experiences of the construction of a test field with such a rubberised base course. The in-plant production of mixtures with 2% WR also resulted in a reduction in compressive strength and improved resistance to freezing, but these significantly values varied between plants. The main reasons for this are that the addition of WR causes issues due to its dosing and during its incorporation into the second plant, difficulty in achieving a homogenous mixture, and the subsequent maintenance of the concrete plant, implying that the technology should be adapted for large-scale production in future. The test field, with both the reference mixture and the WR mixture from the first plant, will be monitored further to determine its behaviour in real conditions.

**Keywords:** cement-bound base courses; waste rubber; sustainable pavement; test field; large-scale production

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## 1. Introduction

The importance of essential functional road networks has been recognised since ancient Roman times. Traditional road construction relies on natural material utilisation and, even today, large quantities of stone, gravel, and sand are still built into kilometres of newly constructed roads. Road traffic is an essential means of transportation globally for passengers and inland freight transport. According to Eurostat [1], in 2022, there were 313 million motor vehicles registered in the EU and the motorisation rate surpassed 1 car per 2 inhabitants. Consequently, more than 3.5 million tons of end-of-life tyres (ELTs) were generated in 2019 [2]. This is a waste material that needs to be sustainably addressed.

On the other hand, the European Commission's strategic plan outlined the creation of a sustainable transport area to reduce transport's impact on the environment as one of its specific objectives. From this, two objectives may be highlighted: making road construction sustainable and environmentally friendly, and solving the problem of ELT accumulation.

With the increase in road traffic and heavy vehicle loads, the task of and requirements for pavement construction have become more demanding. A new trend in pavement construction is the use of new materials with enhanced resistivity to crack occurrence and prolonged service life. Waste rubber (WR), originating from ELTs, is frequently used in the asphalt industry, where its positive effect on the properties of modified asphalt is well known [3–7]. As a potentially limiting feature, its higher production cost is highlighted, ranging from 20 to 30% in comparison to the direct costs of conventional asphalt mixtures [5]. Used as a replacement for the fine aggregate fraction in cement-bound base courses, WR is known to reduce strength (both compressive and tensile) but improve strain capacity, toughness, and fatigue life, reducing the appearance of shrinkage cracks and the velocity of crack propagation [8–11]. WR also improves frost resistance and the tensile-to-compressive strength ratio [12] and it can improve the deformation capacity and fatigue performance of cement-bound aggregate [13]. It improves strain capacity and possesses a lower propensity for cracking, owing to restrained shrinkage and improved sound insulation [11]. To improve the mechanical characteristics of cement-based grouting materials, a 2% concentration of silane coupling agent solution may be used for the surface treatment of waste rubber powder, improving toughness, volume stability, and strength. The solution improves the structural distribution and bonding characteristics of the interface between the rubber powder and cement particles [14]. Adding rubber may also reduce the thermal diffusivity, thermal conductivity, and specific heat capacity of the rubberised cement-stabilised base materials, with the potential to reduce both the temperature and temperature fluctuation within semi-rigid pavement structures [15]. In addition to extensive laboratory research, there will be a need for large-scale experimental and numerical models, as pointed out in [11]. The objectives of this paper are to present laboratory test results of WR-modified cement-bound mixtures based on the requirements set out for CBC construction, and to gain practical experience via a field application (a large-scale experiment). Numerical models dealing with the optimal WR-modified mixture from this research are presented in [16,17].

The greatest advantage of using waste materials in road construction is the reduction in waste being disposed of in landfills. Furthermore, to repurpose waste materials for new applications, a certain amount of energy is required for processing. This typically involves mechanical treatment [18]. Specifically, rubber only requires mechanical processing, such as shredding, which is an established process that does not necessitate additional research or financial investment. Shredded rubber is used for various purposes, with the most common application being the production of surfaces for sports courts and children's playgrounds. The waste rubber used for such purposes is exposed to environmental conditions, leading to the leaching of harmful substances into the environment [19]. Formela [20] emphasised that, due to increasingly stringent regulations regarding the emission of harmful substances into the environment, it is necessary to find an appropriate solution for the utilisation of waste rubber. According to Grynkiewicz-Bylina et al. [21], the use of composite materials for construction represents a method of re-using waste rubber which is safer, in terms of the environment and health. Our research supports this, which proves that rubber incorporated into the base layer of the pavement emits fewer harmful compounds into the environment compared to rubber exposed to atmospheric conditions [12].

A detailed laboratory research programme was conducted to define the properties of cement-bound gravel, modified by WR, within the research project supported by the

Croatian Science Foundation UIP-2019-04-8195: "Cement stabilised base courses with waste rubber for sustainable pavements—RubSuPave". The results of this project revealed the feasibility of using WR for the construction of pavements with enhanced properties [12]; knowledge transfer was carried out by trial section construction and construction technology verification. Some researchers indicate that certain challenges arise during the transfer of the production process from the laboratory to the field [22,23]. Therefore, the scope of this paper is to verify the conclusions of laboratory research and the suitability of standard cement-bound aggregate construction technology for WR-modified mixtures. The main purpose of this paper is to present experience and guidance for the practical application of scientific laboratory research in real-life conditions, using conventional construction materials and technologies, with the aim of promoting the use of alternative materials in sustainable road construction.

## 2. Laboratory Testing Programme

### *2.1. Materials and Test Methods*

As a preliminary research programme, laboratory testing was carried out to investigate the properties monitored during the construction of a cement-bound base course (CBC) within a construction quality control programme. Firstly, the compaction characteristics were determined and analysed following the determination of mechanical properties, in line with a standard field test programme conducted on CBC (7- and 28-day compressive strength test and resistance to freezing and thawing). Within this research, CBC mixtures consisted of equal proportions of three gravel fractions and one fraction of river sand. They were stabilised with various amounts of cement (3%, 5%, and 7% by total aggregate mass) and various amounts of waste rubber (WR) (10%, 20%, 30%, and 40% by sand volume) as a fine fraction (sand) volume substitute. The natural aggregate included gravel and sand from the Sava and Drava rivers, respectively; Portland cement of grade 32.5R (CEM II B/M (P-S)) was used as a binder. The densities of the natural aggregates used (0–4 mm, 4–8 mm, 8–16 mm and sand) were 2.96, 2.63, 2.70, and 2.86 g/cm$^3$, respectively; WR was 1.123 g/cm$^3$, as determined by EN 1097-6:2013 [24]. The reference mixture comprised equal proportions of each natural aggregate fraction (25% mass each) with a volume substitution of sand by WR, as presented in Table 1, due to its similar grain size distributions (Figure 1). A Scanning Electron Microscopy (SEM) image (at a 100 times magnification) of sand and WR is presented in Figure 2.

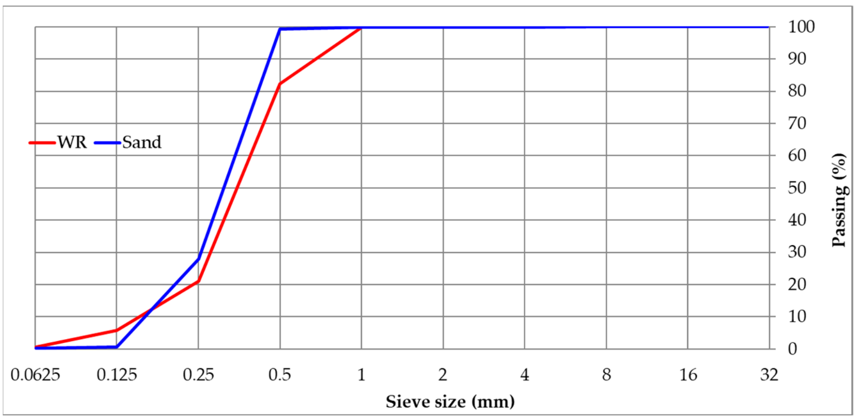
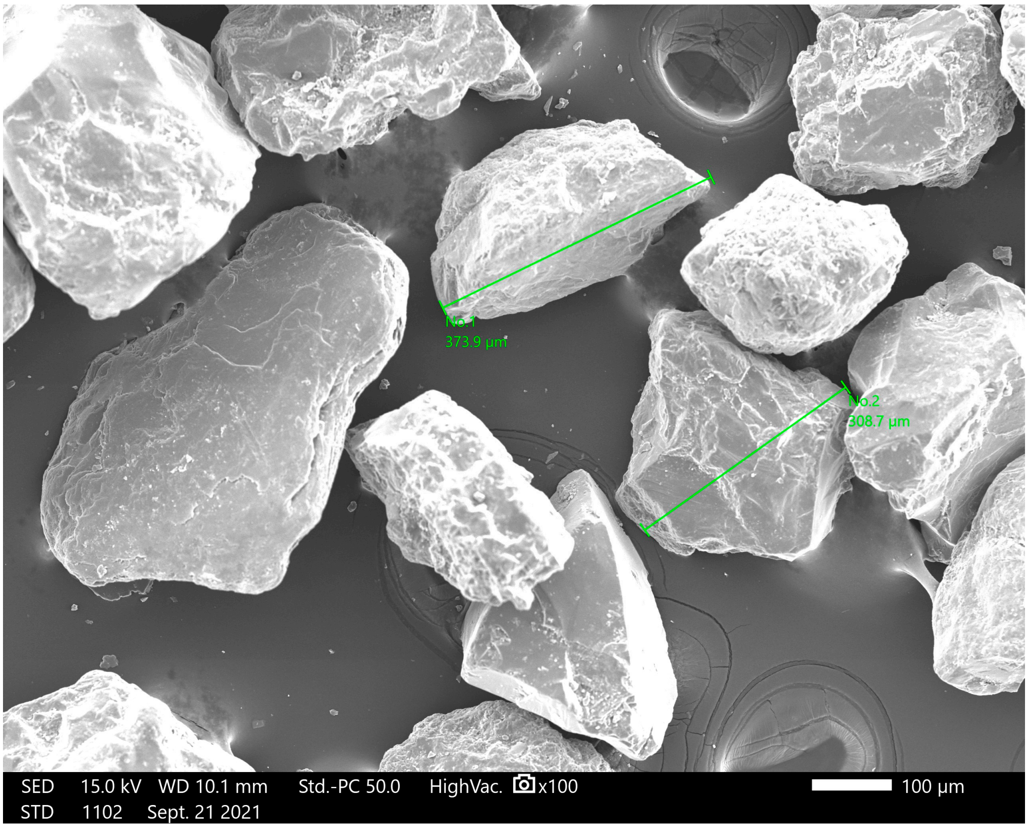



**Figure 1.** Grain size distribution of sand and WR.

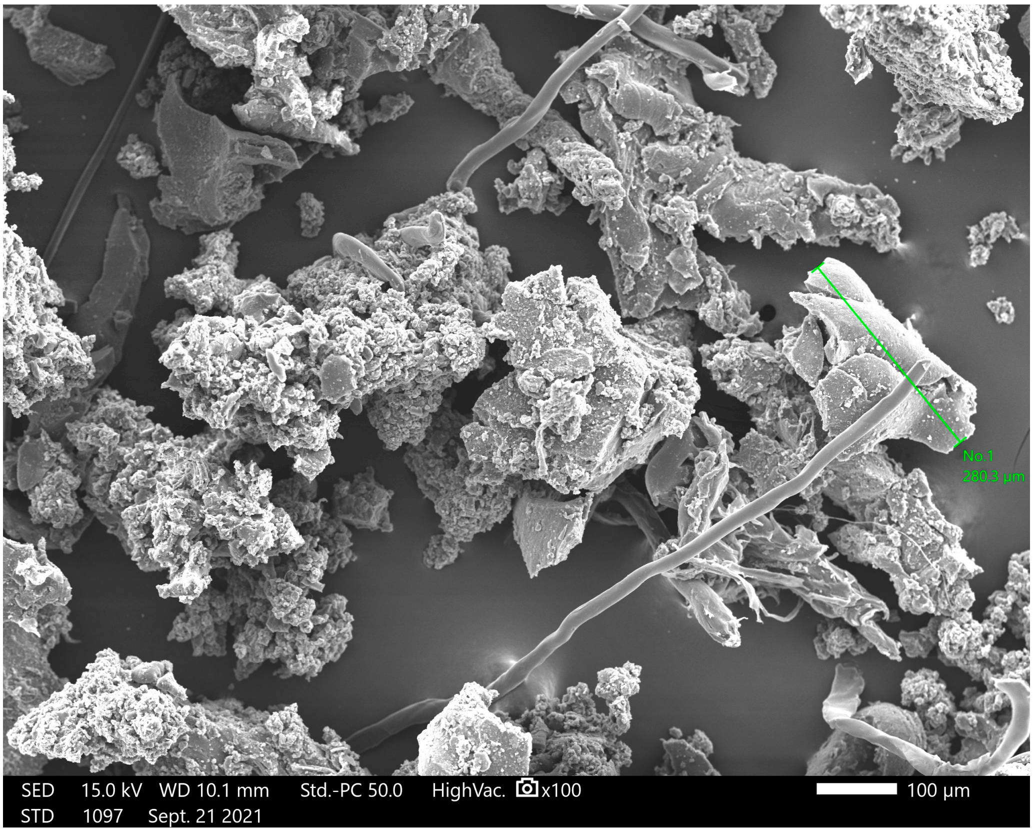
**Table 1.** CBC mix composition.

| Mix | %Vol Sand Replacement by WR | Cement Content (%Mass of Aggregate) |
|---|---|---|
| C0R0 | 0 | 0 |
| C3R0 | 0 | 3 |
| C5R0 | 0 | 5 |
| C7R0 | 0 | 7 |
| C3R10 | 10 | 3 |
| C3R20 | 20 | 3 |
| C3R30 | 30 | 3 |
| C3R40 | 40 | 3 |
| C5R10 | 10 | 5 |
| C5R20 | 20 | 5 |
| C5R30 | 30 | 5 |
| C5R40 | 40 | 5 |
| C7R10 | 10 | 7 |
| C7R20 | 20 | 7 |
| C7R30 | 30 | 7 |
| C7R40 | 40 | 7 |




(**a**)

**Figure 2.** *Cont*.




(**b**)

**Figure 2.** SEM image of sand (**a**) and WR (**b**).

CBC is constructed of well-graded aggregate, a hydraulic binder (cement), and an appropriate amount of water, as determined by a modified Proctor compaction test [25] in laboratory conditions using material compaction parameters. However, in field conditions, granular soils are mostly compacted with vibration compaction using vibrating rollers, potentially making the Proctor test inadequate for obtaining realistic results because it does not use any vibrations during specimen compaction. As an alternative to sample preparation by the Proctor compaction method, the vibratory hammer compaction method [26] was used in this research.

### *2.2. Mechanical Properties of WR-Modified CBC Mixtures*

Six cylindrical test specimens (h = 120 mm, Φ = 100 mm) of each mixture (Figure 3) were prepared by the vibrating hammer method, according to EN 13286-51 [27], for compressive strength determination. The compressive strength was tested according to standard EN 13286-41 [28] for 7 and 28 days curing periods, at 90% humidity and 20 °C temperature conditions, in a climatic chamber. Compressive strength was calculated by Equation (1):

$$f_c = \frac{F}{A_c} \tag{1}$$

$f_c$—compressive strength ($N/mm^2$)
$F$—maximum braking force (N)
$A_c$—sample cross section area ($mm^2$), $A_c = r^2\pi$
$r$—sample radius (mm)


**Figure 3.** Samples for compressive strength and RTF determination.

In addition to the compressive strength test, six specimens of each mixture were compacted for the determination of resistance to frost (RTF). In this procedure, specimens were divided into two groups, one of which was exposed to frost in the presence of de-icing agent, while the other was used as a reference mixture. The resistance to frost was tested according to standard EN 13286-54 [29] using Equation (2):

$$RTF = \frac{f_c(A)}{f_c(B)} \times 100\ [\%] \quad (2)$$

RTF—resistance to frost [%]
$f_c$ (A)—compressive strength of group of specimens exposed to freeze/thaw cycles
$f_c$ (B)—compressive strength of group of specimens cured in water

## 3. Laboratory Test Results

The results of the laboratory tests are presented in Table 2 and Figure 4. The mechanical characteristic was defined as the average value of three samples of a certain kind.

**Table 2.** Laboratory test results.

| mix | OMC (%) | MDD (g/cm$^3$) | $f_{c,7}$ (MPa) | $f_{c,28}$ (MPa) | RTF (%) |
|---|---|---|---|---|---|
| C3R0 | 4.91 | 2.08 | 1.73 | 2.69 | 98.68 |
| C5R0 | 5.35 | 2.12 | 4.11 | 6.45 | 88.98 |
| C7R0 | 5.53 | 2.15 | 6.82 | 8.89 | 94.09 |
| C3R10 | 5.54 | 2.07 | 1.31 | 2.07 | 99.72 |
| C3R20 | 5.64 | 2.04 | 0.94 | 1.15 | 89.37 |
| C3R30 | 5.57 | 2.01 | 0.60 | 0.85 | 65.08 |
| C3R40 | 5.59 | 1.95 | 0.51 | 0.59 | 63.05 |
| C5R10 | 5.27 | 2.13 | 3.54 | 3.99 | 98.61 |
| C5R20 | 5.32 | 2.10 | 2.20 | 3.01 | 98.60 |
| C5R30 | 5.58 | 2.04 | 1.56 | 1.94 | 91.22 |
| C5R40 | 5.92 | 2.00 | 1.32 | 1.51 | 89.63 |
| C7R10 | 4.97 | 2.15 | 6.04 | 7.81 | 80.37 |
| C7R20 | 5.12 | 2.11 | 3.69 | 4.36 | 71.94 |
| C7R30 | 5.28 | 2.05 | 2.84 | 3.32 | 70.96 |
| C7R40 | 5.16 | 1.99 | 1.09 | 1.66 | 67.91 |

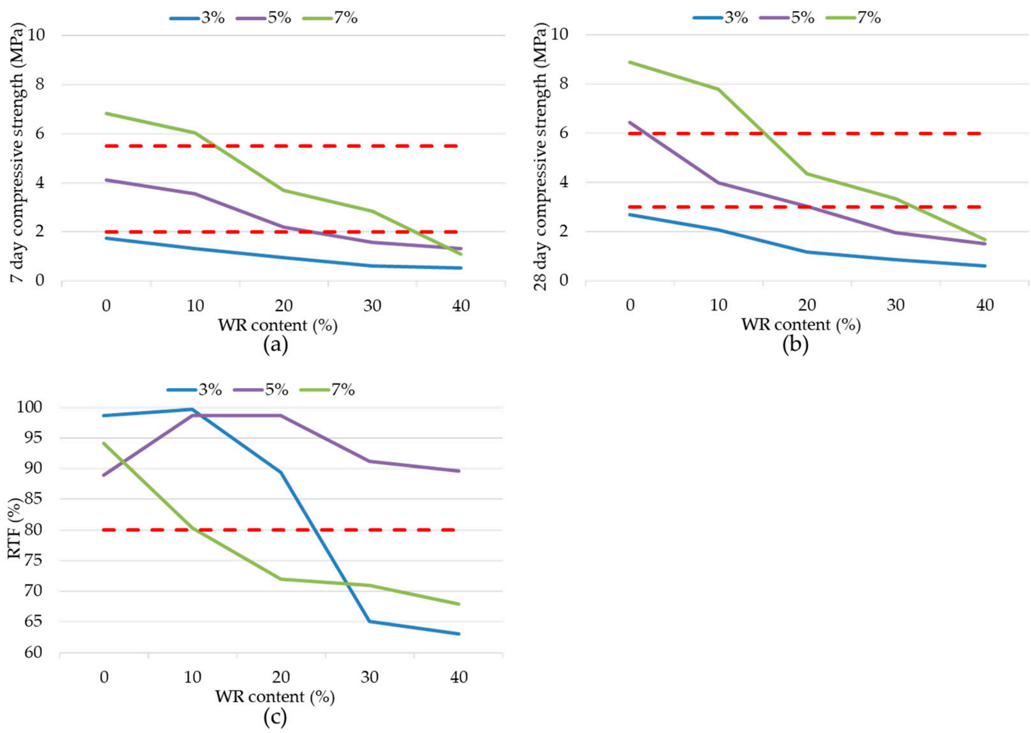



**Figure 4.** Mechanical characteristics: 7 days (**a**); 28 days (**b**); compressive strength and RTF (**c**); red lines present limit values.

The results of the compaction characteristics, optimal moisture content (OMC), and maximum dry density (MDD) indicate that the influence of adding WR to CBC can be neglected and CBC may be designed and constructed using reference values (natural aggregate mixtures) of OMC and MDD for small rubber contents (up to 20%). This presents significant time savings, since no additional tests are needed to determine the compaction characteristics of WR-modified mixtures, and it is necessary to correct the water content in the CBC recipe used in standard production.

The results of testing mechanical characteristics indicate that only mixtures with 5% cement content gained satisfactory strength and RTF values. For most pavement purposes, the 7-day compressive strength and 28-day compressive strength should be 2.0–5.5 MPa and 2.5–6.0 MPa, respectively, with RTF $\geq$ 80%. Mixtures with 3% cement content reached excessively low compressive strength (less than 2 MPa for a 28-day curing period) and RTF values (less than 80%), while 7% cement content mixtures reached excessively high compressive strength (more than 6 MPa for a 28-day curing period) and low RTF values (less than 80%), making them unsuitable for pavement applications. The negative impact of rubber on mechanical properties could be attributed to several phenomena: WR's low density compared to aggregate, poor internal bonds between the rubber and cement matrix, and WR's high elasticity and non-load-bearing nature [8,30,31]. The obtained results show that compressive strength increases with the increase in curing time but decreases with the addition of low-density material, such as waste rubber (WR). These results are expected. The addition of WR impacts the decrease in compressive strength by about 50%. Due to the stiffness of this material and the phenomenon of crack development under the influence of dynamic loading and frost, a decrease in the stiffness and strength of this material is desirable to some extent. As can be seen from the results presented, a decrease in compressive strength is accompanied by an increase in frost resistance when adding WR. This finding makes the tested mixtures potentially better for use in pavement construction when exposed to real-life conditions.

Figure 4 shows that mixtures with 10–20%vol sand replacement by WR (corresponding to 2–3% of a total mixture mass) and 5% cement content indicate improved freeze–thaw resistance whilst maintaining satisfactory compressive strength values. Considering the need to simplify the procedure in real life and anticipating imperfections in production (which were eliminated in laboratory conditions), regarding the amount of rubber used for large-scale production, a value of 2% of the total aggregate mass was adopted. More detailed analyses on the influence of WR on CBC mechanical properties conducted within this research can be found in [12].

## 4. Large-Scale Production

Large-scale CBC production for field applications, as part of road construction projects, is usually undertaken in plants for conventional concrete production. In such plants, CBC is usually produced with the same types of aggregate and cement used for concrete mixtures in order to reduce the costs and labour related to ordering new materials, testing properties, creating and testing new-mixture recipes, and swapping and storing all of those materials in the aggregate storage boxes and various parts of the mixing plants' mechanisms. This is particularly the case if only a small amount of CBC is needed, compared to the volumes of concrete that are produced every day. Therefore, the two concrete mixing plants in this part of Croatia, which produce all of the concrete (in large volumes) and the majority of all CBC for road construction, were tested for the technological transfer of WR-modified CBC. However, these two plants have different technologies, and use different aggregate sizes and cement volumes in their regular CBC production.

Within the first trial mix production, crushed stone (0–16 mm) and cement were used. These had a strength of 42.5 N (CEM II A-M(S-V) 42.5 N) and comprised 0.8% of the total aggregate mass. During the trial production, 1.5 $m^3$ of the mixture was produced, with WR comprising 2% of the total aggregate mass. Mass ratio was used, rather than volume, to simplify the production process. The other components of the standard cement-bound aggregate usually produced by this plant were not corrected. The weighed amount of rubber was added directly to the mixer during the process of mixing the aggregate and cement in order to obtain a homogeneous mixture. Material sampling was carried out immediately after the production to make samples, test the mixtures in laboratory conditions, and compare WR mixtures with conventional CBC mixtures from these plants. Proctor samples (cylinders with a diameter of 10 cm and a height of 12 cm) were made using a vibrating hammer, according to the EN 13286-51 standard [27], as in previous laboratory tests. The samples were cured in a climate chamber, with controlled humidity and temperature conditions, for 7 and 28 days at a temperature of 20 °C and an air humidity of 90%. They were wrapped in cling film until testing. The laboratory research determined compressive strength and F/T resistance in plant-generated mixtures, as these are the properties required by the technical conditions for CBC and are regularly tested as part of quality control during the field construction of CBC layers. The compressive strength ($f_c$) was determined according to the EN 13286-41 standard [28] (3 identical samples for each curing period) and resistance to freeze/thaw cycles (RTF) was tested according to the EN 13286-54 standard [29]. The results are shown in Table 3.

**Table 3.** Mechanical properties of the first trial mix production.

| Mixture | $f_{c,7}$ [MPa] | $f_{c,28}$ [MPa] | RTF [%] |
|---|---|---|---|
| Reference | 2.7 | 3.1 | 89 |
| WR mix | 2.0 | 2.4 | 99 |

The results show a decrease in compressive strength of about 25% but an improvement in resistance to freeze/thaw cycles of about 10%. However, during the production process, excessive humidity was observed in both mixtures, possibly because of a high aggregate humidity (held in open boxes), which potentially caused the lower compressive strengths.

A second trial mixture was produced from crushed stone (0–30 mm) with 1.5% cement by weight of aggregate and a strength of 42.5 N (CEM II A-M(S-V) 42.5 N). WR comprised 2% of the mass of the aggregate. The other components of the standard cement-bound aggregate usually produced by this plant were not corrected. The second concrete plant had a more modern design and did not have direct access to the mixer itself. Therefore, the rubber was poured onto the conveyor belt, together with the rest of the aggregate but, at the very end of the dosing because the rest of the aggregate came directly from the scales. Material sampling was carried out immediately after production and the same laboratory testing programme was undertaken. The results are presented in Table 4.

**Table 4.** Mechanical properties of the second trial mix production.

| Mixture | $f_{c,7}$ [MPa] | $f_{c,28}$ [MPa] | RTF [%] |
|---|---|---|---|
| Reference | 2.8 | 3.7 | 86 |
| WR mix | 1.0 | 1.5 | 72 |

The results show a significant drop in strength and freeze/thaw resistance as a result of the inappropriate production process. The cause of the reduced mechanical characteristics could be inadequate rubber dosing and mixing during the production or material sampling.

Reference mixtures from both plants show similar results, with a slight increase in compressive strength in mixtures from the second plant; this is expected due to the larger amount of cement used. However, comparisons of the results for the WR mixtures from both plants show significant reductions in the measured properties in the WR mixtures from the second plant. There are two main reasons for these results: differences in mixture composition and differences in mixing plant technology.

First of all, CBC mixtures with a higher amount of cement are expected to experience greater reductions in both strength and F/T resistance, as noted by other authors [30] and seen here in our own laboratory results. The maximum aggregate size in the first plant was the same as in our laboratory tests, even though the aggregate itself was different: in the second plant, the maximum aggregate diameter used was almost double (i.e., 30 mm). This means that the mixture itself is less homogenous, due to the tendency for considerably smaller rubber particles (2 mm) to clump together between larger aggregates. This creates larger pockets of rubber materials that, essentially, act as voids in a stiff matrix due to large differences in its elastic moduli. However, most of the discrepancies in the results from the WR mixture from the second plant, compared to the reference mixture and the WR mixture from the first plant, arose because of problems that occurred during mixing due to the modern technology used in the second plant (it was not designed with these very low-density aggregates in mind).

As previously stated, in this modern concrete plant, it is not possible to access the mixer directly during the preparation of the mixture, which is the reason for the rubber being added at the very end of the production process. This also means that the mixing process cannot be monitored from inside the plant, resulting in insufficient mixture homogeneity (on top of the initially larger aggregate size) and inadequate sample composition, on the basis of which the mechanical properties are controlled. This type of plant generates another issue where technology transfer is concerned. A second problem that occurs during production in modern concrete plants is the difficulty of cleaning and washing the mixer and the water recycling system used during concrete production. Due to lower density, rubber particles float on the surface of the water and create difficulties during water filtration by clogging the system. This plant technology has a problem dealing with very lightweight aggregate, which may require longer mixing times, in order to achieve better mixture homogeneity or the adaptation of the production process to incorporate such an aggregate.

## 5. Test Section Construction

The mixture produced was delivered to the construction site to be used in the reconstruction of pedestrian paths in a residential area in the city of Osijek. The dimensions of the test field were 50.0 × 1.5 m. Due to the expectedly insignificant traffic load (pedestrian traffic), the pavement structure consisted of the following materials:

a. Asphalt concrete for the surface layer with a nominal grain size of 8 mm (ACsurf 8): 4 cm thick;
b. Cement-bound aggregate base course: 12 cm thick;
c. Unbound stone sub-base layer 0–32 mm: 20 cm thick.

On the unbound stone base layer installed, a reference mixture of a cement-bound base layer without additional WR was first installed in part of the pedestrian path. In the continuation of the path, a cement-bound mixture with additional WR was then installed to clearly monitor the impact of the new mixture on the behaviour of the pavement structure. Standard cement-bound base layer construction machines and technologies were used at the site (Figure 5).

(**a**) (**b**)

**Figure 5.** Cement-bound base layer construction: installation equipment (**a**) and manual spreading (**b**).

Better compaction of the WR-modified mixture was observed in the field, as well as easier compaction with vibro-compactors, compared to the reference mixture. A more uniform surface layer was also achieved, compared to the reference mixture, avoiding the generation of areas with pronounced segregation of the larger aggregate grains (Figure 6). These conclusions were confirmed in a discussion with the technical team in the field. The completed test section is shown in Figure 7.

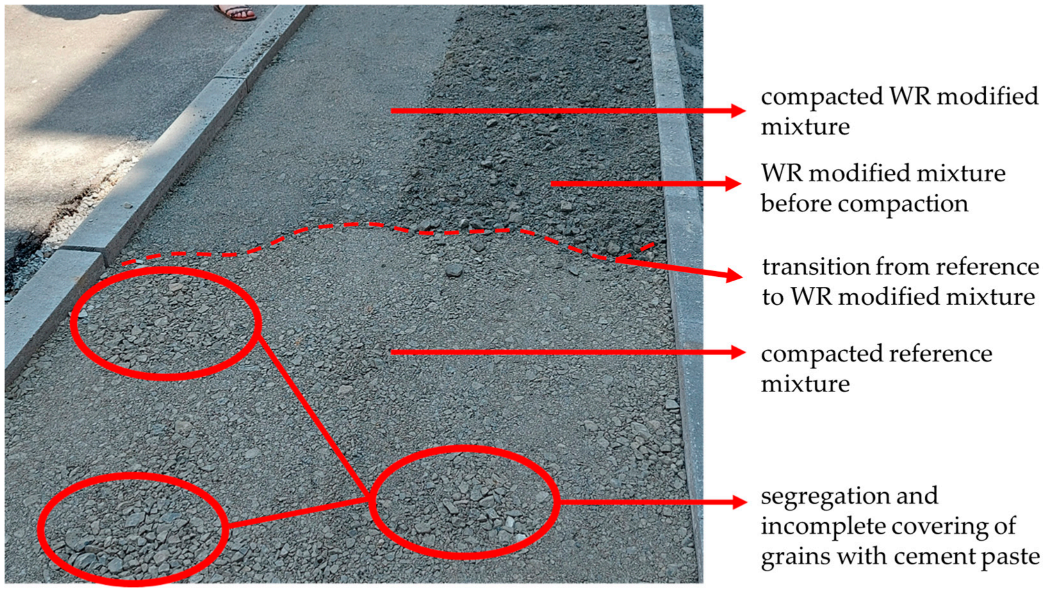



**Figure 6.** Reference and WR-modified cement-bound aggregate at the site.

**Figure 7.** Completed test section.

## 6. Conclusions

For the implementation of new materials and technologies in construction practice, a laboratory programme must be complemented using real-field-condition construction tests to accomplish proper knowledge transfer. The laboratory programme conducted within the research project was transferred to real-life conditions on site and knowledge of the appropriate materials and techniques was gained.

1. The laboratory part of the research showed that the addition of WR to CBC did not cause significant differences in OMC and MDD. Therefore, these compaction parameters can only be determined for reference mixtures.
2. Compressive strength was negatively impacted by the WR replacement of sand, while freeze/thaw resistance was improved by the addition of WR. Only mixtures with 5% cement satisfied the strength conditions given for CBC construction (2.5–6.0 MPa after 28 days) and also had the necessary RTF > 80%. Sand replacement with 10–20% by volume, corresponding to 2–3% by mass, was optimal.
3. Samples produced from concrete plant mixtures showed a large decrease in the compressive strength of the WR mixture compared to the reference, with the difference being higher than within laboratory-produced mixtures. The F/T resistance of the WR mixtures varied according to the concrete plant in which they were produced.
4. Discrepancies in the results between the two concrete plants were quite high where WR mixtures were concerned. Analyses revealed the importance and high level of influence of proper concrete plant technology selection for WR-modified cement-bound aggregate production. Different aggregate gradation and production technologies resulted in unrealistic and low mechanical properties. Insufficient homogeneity of the mixture and inadequate composition of the samples on which the mechanical properties were controlled were caused by an inadequate production process and an inability to properly mix aggregate with WR in one of the concrete plants.
5. From the experience of creating this field test, installing a WR-modified cement-bound aggregate base layer as a pavement structure, it can be concluded that the production process should be adapted to the conditions and equipment at the concrete plant, in terms of extending the mixing time and the procedure for dosing rubber into the mixer itself.
6. The results of compressive strength testing show that, for roads with heavy and very heavy traffic loads, the amount of cement should be increased by 15–20% (depending on the original recipe used at each concrete plant) in order to achieve satisfactory compressive strength values.

For a comprehensive analysis of the applicability of rubber, it is necessary to continuously monitor the behaviour of constructed traffic areas and compare them with reference ones.

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