Analysis of the Impact of Redispersible Polymer Powder on the Water and Frost Resistance of Cold-Recycled Mixture with Bitumen Emulsion

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Abstract. The subject of the research presented in the article is the assessment of the effect of redispersible polymer powder (RPP) on water and frost resistance of a cold-recycled mixture with bitumen emulsion (BE-CRM). The article presents the results of research on the influence of polymer powder EVA based on polymer (polyethylene-co-vinyl acetate) on the properties of BE-RCM. The impact analysis was determined using the assumptions of the Box-Behnken experiment plan in which three components are controlled. In this case, the variables were the content of: polymer, cement and asphalt emulsion. All ingredients were dosed with a step of 1.5% of the percentage share in the mixture composition. Polymer and Portland cement in an amount of 0.5% to 3.5%. On the other hand, the pure asphalt originating from the asphalt emulsion was 0.0%, 1.5% and 3.0%, respectively. The scope of the tests included the determination of: mixture density, void content (Vm), water absorption (nw), intermediate tensile strength (ITS), to water (TSR) as well as water and frost according to AASHTO T283.

1. Introduction

There are currently two trends in the civil engineering industry. The first trend is the modification and improvement of properties in materials already known. Polymers are very often used for this purpose. The aforementioned material exists, among others, in solid form, as aqueous dispersions, aqueous solutions and resins [1]. Thermoplasts constitute a group of polymers worth distinguishing. They are capable of softening after being heated and hardening after cooling. This process is reversible. These include, among others, vinyl polychloride, ethylene vinyl octane (EVA) copolymer or styrene-butadiene-styrene (SBS) copolymer [1,2,3,4]. Polymers are often used as bitumen additive in bitumen in the form of binders for road construction due to the improvement in their basic properties and expanding the range of viscoelasticity, e.g. SBS [5,6]. The scope of using polymers in cement concretes is also broad. Łukowski provided an overview of related information in his paper [1]. A positive impact of the aforementioned polymers on cement mortars is also observed, which was analysed by Kong, Schulze, Killermann [7,8]. The second trend observable in civil engineering is the materials recycling. An excellent example are road subbases made using the cold recycling technology [9,10,11,12,13]. New solutions are continuously being sought after, including the use of foamed bitumen [14,15,16,17] and optimisation of the composition of the hydraulic binder constituting part of the recycled mixture [18, 19, 20]. There are also attempts of using waste mining dust to improve the parameters of recycled mixtures [21,22,23]. It is worth noting the attempt of combining recycling with
Polymers have a positive impact on parameters that are desirable in subbase layers including, among others, limitation of material rigidness with maintained durability. First studies on the impact of redispersible polymer powder on the properties of cold-recycled mixture with foamed bitumen have emerged recently [24]. In his paper, Buczyński studied the impact of various polymers on subbase made using the deep cold recycling technology with foamed bitumen. There was also an attempt to evaluate the parameters of Cement-Bound Road Base Mixtures in terms of the content of Portland cement and redispersible polymer powder [25].

A literature analysis was used for the evaluation of the impact of a polymer modifier in the form of the EVA polymer on the properties of the cold-recycled mixture with bitumen emulsion. Available literature features no papers on this topic. It is worth pointing out that the cold recycling technology with bitumen emulsion is becoming a popular method of reconstructing destroyed road pavements. The paper features testing for the purpose of evaluating the properties of cold-recycled mixtures with bitumen emulsion and a redispersible polymer powder additive. The polymer powder was dosed in various proportions into a mineral-cement mixture with foamed bitumen. The obtained results allow for the statement that the mixture composition’s modification is the correct manner of developing the deep cold-recycling technology.

2. Plan of experiment

The experiment features an analysis of the impact of redispersible polymer powder on the properties of the cold-recycled mixture with bitumen emulsion (BE-CRM). Thirteen various formulae were prepared for this purpose. The mixtures varied in terms of polymer, Portland cement and bitumen mixture content. The polymer and cement were dosed at an increment of 1.5%, in quantities of 0.5%, 2.0% and 3.5%, respectively. The bitumen emulsion was added in quantities of 0.0%, 2.5% and 5.0%, which provided the mixture with 1.5% to a maximum of 3.0% of pure bitumen. The selection of particular proportions of components for the mixtures was done with the aid of a Box-Behnken design [26].

The Box-Behnken designs belong to experiment plans in which independent variables exist at three levels: -1, 0, +1. The designs do not include experiments in which all independent variables assume extreme values at the same time, thereby preventing experimentation at extreme conditions [26].

3. Materials

3.1. Redispersible polymer powder

The BE-CRM mixtures with polymer were made using the EVA thermoplastic copolymer (polyethylene-co-vinyl octane). It is produced as a white powder. It is generated as result of evaporation of water from polymer dispersion in spray drying. The appearance and chemical composition of the polymer are presented in Figure 1.

![EVA redispersible polymer powder](image)

**Figure 1.** a) EVA redispersible polymer powder b) Chemical composition of the EVA polymer [24]

The main advantage of using polymers in the BE-CRM is the improvement of the mixture’s mechanical properties. This is due to the generated network connections between the particles that create a continuous polymer phase [1].
3.2. Cement
The BE-CRM mixtures are made using a class I Portland Cement with a strength of 42.5 MPa, high early strength “R”, in accordance with EN 197-1 [27]. The CEM I class cement was selected to prevent the impact of the binder additives on the recycled subbase. The basic properties of the binder, designated as C, are presented in Table 1.

| Table 1. Properties of the CEM I 42.5R Portland cement |
|-------------|-------------|-------------|-------------|
| Property    | Test Method | Unit of Measure | Result |
| Initial setting time | EN 196-3 [28] | min | 209 |
| Compressive strength | EN 196-1 [29] | MPa | 27.2 |
| at 2 days   | EN 196-1 [29] | MPa | 55.6 |
| at 28 days  | EN 196-3 [28] | mm | 0.8 |
| Soundness   | EN 196-6 [30] | cm²/g | 3,360 |

3.3. Bitumen emulsion
The C60B10 ZM/R slow-breaking cation bitumen emulsion, produced on the basis of the 70/100 bitumen, was used as the binder in the mixtures. The bitumen emulsion was compliant with the requirements specified in [31]. The binder’s basic parameters are presented in Table 2.

| Table 2. Physical properties of the bitumen emulsion |
|-------------|-------------|-------------|
| Property    | Unit of Measure | C60B10ZM/R |
| Binder content | % (m/m) | 60.0 |
| Cement mixing stability | g | 0.3 |
| Sieve residue 0.5 mm | % (m/m) | 0.06 |
| Discharge time Ø 2 mm at 40°C | s | 27 |
| Adhesion to aggregate | % | 75 |
| Recycled bitumen penetration | 0.1 mm | 53 |
| Recycled bitumen’s softening point | °C | 55.2 |

3.4. Mineral mixture
In order to imitate field conditions that occur at the construction site, it was assumed that the recycled mixture will include 50% of material derived from recycled asphalt pavement. The remaining part is crushed aggregate with continuous grading (VA). 30% of aggregate with the dimensions of 0/31.5 and 20% of 0/4 dolomite aggregate. These proportions allow for meeting the recommended grading requirements for the mineral mixture included in the BE-CRM [32,33]. The virgin aggregates derived from local mines located in the Świętokrzyskie Voivodeship. Both materials meet the requirements specified in [34]. Table 3 present the parameters of the 0/31.5 and 0/4 mixtures.

| Table 3. Properties of the VA 0/31.5 and 0/4 aggregate |
|-------------|-------------|-------------|
| Property    | Test | U.M. | Result | Symbol | Result | Symbol |
| Dimension d/D | EN 933-1 [35] | - | 0/31 | GA90 | - | GF95 |
| Particle size distribution | EN 933-1 [35] | - | 2.71 | 2.71 | 2.83 | 2.83 |
| Density | EN 1097-6 [36] | Mg/m³ | 16.0 | SI55 | 16.0 | - |
| Shape index | EN 933-4 [37] | % | 14.0 | FI55 | 14.0 | - |
| Flakiness index | EN 933-3 [38] | % | 98/2 | C01/3 | 98/2 | - |
| Percentage of crushed and broken surfaces | EN 933-5 [39] | % | 3.4 | F1 | 3.4 | - |
| Frost resistance | EN 1367-1 [40] | % | 23 | LA30 | 23 | - |
| Resistance to fragmentation | EN 1097-2 [41] | % | 17.5 | M10/15 | 17.5 | - |
The aforementioned components were used to obtain a mineral mixture, the graining curve of which fits perfectly between the limit values. The curve waveform is presented in Figure 2.

![Graining curve waveform for the mineral mixture included in the BE-CRM.](image)

**Figure 2.** Graining curve waveform for the mineral mixture included in the BE-CRM.

### 4. Testing methods

The testing was aimed at determining the impact of the redispersible polymer powder on the basic properties of the BE-CRM recycled mixture. The experiment in laboratory conditions features the preparation of samples in accordance with EN 12697-30 [43]. The determined parameters are listed below:

- **Bulk Density (SSD)** [44],
- **Absorptivity** ($n_a$) [33],
- **Air void content** ($V_m$) [45],
- **Indirect Tensile Strength (ITS$_{DRY}$)** [46],
- **Water resistance** (TSR) [33],
- **Water and frost resistance** (ITSR) [47,48].

### 5. Results and discussions

The breakdown of the results obtained during the tests, described in paragraphs 4.1 – 4.6, is presented below. The first section includes the basic physical and mechanical properties of the recycled mixtures. The next part describes the mixtures’ water resistance as well as water and frost resistance. The mixtures were designated as follows: Digit and C – cement percentage share, Digit and P – RPP percentage share, Digit and A – bitumen percentage value. The results are presented with the assumed order of 0.5 % RPP, 2.0 % RPP and 3.5 % RPP. Other mixture components are also presented incrementally.

#### 5.1. Basic properties of the recycled mixtures with polymer

An evaluation of the basic parameters, the results of which are presented in Table 4 below, was conducted to determine the properties of mixtures with redispersible polymer powder.

When analysing the density of the prepared mixtures, it turned out that they varied substantially. This results from the discrepancy in the densities of particular components. RPP has a density of 0.5 Mg/m$^3$, thereby its content in the mixture substantially reduces the value. The 0.5C-2.0P-3.0A recycled subbase has a density of 2.15 Mg/m$^3$, while the 2.0C-0.5P-0.0A mixture – as much as 2.293 Mg/m$^3$. The average density of the prepared mixtures is around 2.2 Mg/m$^3$.

The air void content (V_m) in the mixtures is between 8.8% and 13.9%. It is worth noting that the lowest values were obtained for mixtures with 2.0% RPP. The most advantageous result was obtained for the mixture with no bitumen content, including only cement and polymer, i.e. 3.5C-2.0P-0.0A. The second mixture with the lowest air void content is the 0.5C-2.0-1.5A formula with a minimum cement and bitumen content as well as 2.0% RPP. This confirms the positive impact of RPP on the recycled...
subbase with simultaneous reduction in the content of other binders. It is worth noting that an excessive polymer content can increase the air void content. Mixtures with RPP become more workable; excessive polymer content causes the formation of a specific texture. This was observed during the preparation of test samples in laboratory conditions.

The mixtures’ absorptivity is an important feature for a road subbase due to its position in the structural layers and the ability of absorbing water from the ground. The most advantageous results were obtained in subbases with polymer content of 0.5-2.0%. Cement in conjunction with the polymer tighten the mixture’s structure by limiting absorption of water from the environment. The bitumen content deriving from the bitumen emulsion causes the results to vary to a lesser degree.

Interesting dependencies can be observed when analysing the results of indirect tensile strength ITS_DRY. The cement content is the factor that mainly affects the result. An increase in this component’s content causes a clear increase in the recycled subbase’s rigidity. It is interesting that the 2.0C-0.5P-0.0A and 2.0C-0.5P-3.0A mixtures achieved a nearly identical result. Similar results were also observed for recycled subbases that included 0.5C-2.0P-0.0A and 0.5C-2.0P-3.0A. This means that an increase in the bitumen content does not affect the mixture’s rigidity. Another example can be the comparison of indirect tensile strength of the aforementioned 2.0C-0.5P-3.0A and 2.0C-2.0P-1.5A mixtures. The latter mixture features 1.5% more polymer and reduced bitumen content. As result, an increase in rigidity of approx. 10%, from 645 kPa to 715 kPa, is obtained. An increase in bitumen content from 0.0% to 3.0% with the same cement and RPP content results in a loss in strength of approx. 40%, as in the 2.0C-3.5P-0.0A and 2.0C-3.5P-3.0A mixes. It is also important that an increase in the mix’s polymer content from 2.0% to 3.5% with simultaneous cement content of 3.5% as well as an increase in bitumen content from 0.0% to 1.5% cause a reduction in indirect tensile strength, however the strength exceeds 1,000 kPa.

### Table 4. Test results

| Parameter | $\rho_{bssa}$ [Mg/m³] | $V_a$ [%] | $n_a$ [%] | ITS_DRY [kPa] |
|-----------|------------------|---------|--------|-------------|
| 0.5C-0.5P-1.5A | 2.247 | 12.34 | 2.92 | 396.85 |
| 2.0C-0.5P-0.0A | 2.293 | 12.58 | 3.98 | 643.94 |
| 2.0C-0.5P-3.0A | 2.160 | 13.16 | 2.74 | 644.42 |
| 3.5C-0.5P-1.5A | 2.263 | 10.45 | 1.62 | 1,608.69 |
| 0.5C-2.0P-0.0A | 2.239 | 9.78 | 3.43 | 363.95 |
| 0.5C-2.0P-3.0A | 2.151 | 11.19 | 2.41 | 333.55 |
| 2.0C-2.0P-1.5A | 2.200 | 12.45 | 2.81 | 714.88 |
| 3.5C-2.0P-0.0A | 2.239 | 8.83 | 2.69 | 1,370.25 |
| 3.5C-2.0P-3.0A | 2.183 | 13.93 | 1.31 | 1,163.31 |
| 0.5C-3.5P-1.5A | 2.170 | 13.09 | 3.26 | 278.64 |
| 2.0C-3.5P-0.0A | 2.203 | 13.55 | 3.48 | 591.55 |
| 2.0C-3.5P-3.0A | 2.110 | 13.20 | 3.10 | 370.81 |
| 3.5C-3.5P-1.5A | 2.180 | 12.15 | 2.02 | 1,226.37 |

The determination coefficient $R^2$ was used to evaluate the quality of the obtained mathematical models. In both cases, the coefficient was within the range of 0.85-0.90. Figure 3 and Figure 4 below present the matching surfaces for the TSR and ITSR as well as Pareto charts. They take into account the cement and bitumen emulsion ratio at the assumed polymer content. As in the experiment, it was assumed in the figure that RPP’s content was 0.5%, 2.0% and 3.5%.

5.2. Water resistance (TSR) as well as water and frost resistance (ITSR)

The testing also featured an evaluation of the RPP’s impact on water resistance (TSR) as well as water and frost resistance (ITSR). An adequate number of sample replicas were prepared by using a Box-Behnken design to obtain the assumed confidence level. The significance of the impact of particular components of the recycled subbase was designated using statistical tools. The data is presented in Table 5.

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Table 5. Evaluation of the significance of the factors’ impact for TSR and ITSR

| Factor         | Effect | p     | Coeff. | Effect | p     | Coeff. |
|----------------|--------|-------|--------|--------|-------|--------|
| Mean/Interc.   | 86.78  | 0.0001| 86.779 | 63.42  | 0.0003| 63.422 |
| (1)CEM (L)     | 0.78   | 0.8758| 0.389  | 31.75  | 0.0253| 15.877 |
| CEM (Q)        | -1.01  | 0.8288| -0.505 | 13.39  | 0.1574| 6.693  |
| (2)EMU (L)     | 4.32   | 0.4150| 2.160  | -0.44  | 0.9580| -0.218 |
| EMU (Q)        | -7.30  | 0.1870| -3.6478| 11.74  | 0.1987| 5.868  |
| (3)RPP (L)     | -1.51  | 0.7633| -0.755 | -4.18  | 0.6221| -2.089 |
| RPP (Q)        | -1.84  | 0.6960| -0.921 | -0.44  | 0.9549| -0.219 |
| 1L by 2L       | -1.46  | 0.8357| -0.732 | -9.81  | 0.4302| -4.907 |
| 1L by 3L       | -21.38 | 0.0456| -10.692| -11.66 | 0.3591| -5.830 |
| 2L by 3L       | 6.78   | 0.3721| 3.388  | 13.81  | 0.2907| 6.904  |

Figure 3. Results of matching for the TSR test a) for RPP content of 0.5%, b) for RPP content of 2.0%, c) for RPP content of 3.5%, d) Pareto chart

In the case of the TSR ratio evaluation, it turned out that the most important factor was the ratio of the cement content and redispersible polymer powder content. Nearly all mixes achieved results exceeding 80%. An adequate content of binders, i.e. cement and polymer may contribute to an increase in the TSR ratio and reduction in the recycled subbase’s bitumen emulsion.
It is worth noting that the highest values of over 90% were achieved by four formulae: 2.0C-3.5P-3.0A, 3.5C-0.5P-1.5A, 3.5C-2.0P-3.0A, 0.5C-3.5P-1.5A. It is possible to notice that the cement and polymer supplement each other in the mix. The 3.5C-2.0P-0.0A mix had a TSR of 89%. This means that the subbase’s bitumen content is insignificant for water resistance.

Figure 4 provided below presents the matching surfaces for the water and frost resistance (ITSR).

![Figure 4](image)

**Figure 4.** Results of matching for the ITSR test a) for RPP content of 0.5%, b) for RPP content of 2.0%, c) for RPP content of 3.5%, d) Pareto chart

In the case of the ITSR ratio, the factor that affected the results the most was the cement content in the recycled mix. The mixes for which the results were highest are as follows: 3.5C-0.5P-1.5A, 2.0C-0.5P-0.0A, 2.0C-2.0P-1.5A and 3.5C-2.0P-0.0A. The impact of cement is clear in these cases. The mix’s polymer content is also of significance. It is interesting that two of the aforementioned mixes do not feature bitumen emulsion in their composition. This can mean that the polymer included in the subbase improves its properties without the need to add a binder. Mixes 0.5C-2.0P-0.0A and 0.5C-2.0P-3.0A achieved the worst results in the test. This confirms the impact of cement on recycled subbase’s water and frost resistance.

6. Conclusions

An analysis of the test results of BE-CRM with polymer allows for the formulation of the following conclusions:
- The recycled mixes with the addition of a polymer modifier have lower density than traditional BE-CRM mixes,
- The most advantageous values of air voids Vm in the analysed mixes were achieved in the medium range of the polymer modifier content, i.e. 2.0%,
- The cement and polymer powder contents in the recycled mix affects its absorptivity. The mix becomes tightened at a polymer content of 0.5-2.0%.
- An increase in cement content affects the mix’s indirect tensile strength ITSdry the most. It is worth noting the possibility of reducing the bitumen emulsion content by using the redispersible polymer powder. The presence of RPP causes an improvement in the mix’s parameters: at constant cement content, the results are approx. 10-15% higher.
- The water resistance (TSR) of BE-CRM mixes depends mostly on the cement and polymer content ratio. The aforementioned binders supplement each other in the subbase’s composition. They can be used to adjust the mix’s rigidity and the aforementioned water resistance (TSR).
- The cement content in the recycled mix with polymer affects the water and frost resistance (ITSR) the most. Advantageous results were obtained for formulae with the addition of polymer of up to 2.0%. It is possible to reduce the mix’s emulsion content due to RPP’s properties.

The presented results allow for the statement that the use of a polymer modified in the cold-recycled mix with bitumen emulsion (BE-CRM) makes it possible to improve the subbase’s basic parameters. Polymer can contribute to a reduction in the content of bitumen emulsion which is a petroleum derivative. The petroleum market is affected by price fluctuations and possible extraction limitations.

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