Preliminary assessment of the secondary setting of Portland cement in recycled crushed concrete incorporated in cold recycled road base mixes with foamed bitumen

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Abstract. The recycled crushed concrete (RCC) unlike the natural aggregates, has a residue of the unhydrated Portland cement (PC) covering the aggregate grains, which may result in a secondary cementation process after its application in a road base. The paper presents the results of exploratory research on the phenomenon of the secondary setting of Portland cement in recycled crushed concrete aggregates in cold-recycled mixes with foamed bitumen (FB). The tests were performed using two mixtures, i.e. Mix-FBREF reference mixture without the addition of RCC, and Mix-FBRCRC research mix containing 25% of RCC. The composition of mineral mixtures with foamed bitumen was designed using typical recycled materials, used as a part of the road repair works of pavements, i.e. Reclaimed Asphalt Pavement (RAP), Reclaimed Aggregates (RA) and new aggregates (NA). All mineral materials used in the tests met the requirements in terms of suitability for the foamed bitumen cold-recycled mixtures, intended for basecourse. The total amount of the bituminous binder in the Mix-FB mix was 5.5%. To assess the phenomenon of the secondary setting of Portland cement contained in the recycled concrete, tests were conducted to evaluate the increase of the unconfined compressive strength (UCS) in time of the material. The strength of UCS samples of Mix-FBREF and Mix-FBRCRC mixtures was determined after 3, 4, 7, 14 and 28 days of conditioning. The tests showed that the value of the analysed parameter in the reference mixture increased by about 180 kPa with time, whereas for the mixture containing the concrete recycled aggregate the difference was virtually unnoticeable (only by 6 kPa). The obtained test results were subjected to the statistical analysis, which showed that for each of the considered sample conditioning periods, no statistically significant differences between the strength values of unconfined compression of the tested mixtures were found. The presence of bituminous binder in basecourse cold-recycled mixtures, (old, with RAP and new, in foamed form) yields the bituminous binding dominant over the effects of PC binding, therefore minimizing the effects of the secondary Portland cement setting.
1. Introduction

The main idea of deep cold recycling technology is to maximise the use of material from old repaved road bases [1-5]. Most road repairs using deep cold recycling technology cover flexible and semi-rigid roads [3, 4]. The recycled road base composition may include: bound mixtures in improved subgrade [6], Portland cement concrete road bases [7], unbound courses and bituminous courses [8, 9]. The main sources of reclaimed concrete are demolitions and reconstruction of old engineering structures, construction and upgrades of roads and railway routes. The construction market development has resulted in an increased demand for concrete and an excessive amount of construction waste. The current forces are focused on environmental protection as a result of, among other things, reduction in production process energy consumption, including the use of recycling technologies in many industrial sectors; oblige to rationally dispose of the waste, including the waste from road construction.

Portland cement concrete used in old rigid pavements has a high recycling potential. Thanks to the use of reclaimed concrete in construction, it is possible to reduce the demand for new natural resources. The use of a recycled building material reduces the cost of extracting new raw materials and eliminates the costs for new aggregate transportation.

All over the world (e.g. in China, USA and Norway), reclaimed concrete obtained in the crushing process is used as a road base material in road structures [10-12]. In addition, reclaimed concrete is categorised as a material suitable for the construction of sub-bases, basecourses, separating courses, as well as a fills in embankments serving as the sound-absorbing barriers [13-15].

Unlike natural aggregates, the reclaimed concrete is distinguished by the residue of non-hydrated cement covering the aggregate grains and being the component of the hardened concrete mixture. As a result, the reclaimed concrete has the potential of cementation through the release of unbound pozzolanic particles after crushing a specific material [16]. Residues of pozzolanic particles result in the lower specific density of grains, a higher capacity to absorb waste material and lower quality of aggregate found in reclaimed concrete [17-19]. Not all cement particles are hydrated during cement setting; hence, reclaimed cement concrete undergoes the secondary setting process in time, which changes the physical and mechanical parameters of a road base over time. The confirmed secondary cementation in the reclaimed concrete, traced during laboratory tests and on the example of the road base secondary deformation modulus value, has been documented [20].

Referring to the road base cold mixtures with foamed bitumen, the introduction of new aggregates for grading improvement is required in case of improper grading of the mineral mixtures from the existing courses. The use of a new component translates into increased costs of a reclaimed road base construction. As a result, it is better to increase the cost of equipment and to achieve the required grading by breaking the material of the existing course. This approach will make most out of the materials from the existing structural courses in the reclaimed road base.

2. Materials and methodology

2.1. Characteristic and properties of the materials used in analysed mixtures.

In order to test and conduct a preliminary assessment of the secondary setting of the Recycled Cement Concrete (RCC) in the cold mixtures with foamed bitumen, the assessment of the unconfined compressive strength build-up in laboratory prepared samples was performed. The analysis was performed using two mixtures, i.e. Mix-FBREF reference mixture without the addition of RCC, and Mix-FBREF research mix containing 25% of RCC.

The following standard reclaimed materials from the road reconstruction and road repair were used to design the compositions of mineral mixtures with foamed bitumen to assess the secondary setting of cement contained in reclaimed aggregate:
- Reclaimed Asphalt Pavement (RAP),
- Recycled Cement Concrete (RCC),
- Reclaimed Aggregate (RA).

In addition, the Mix-FB mixes were composed of the new aggregates to improve the grading, a binder material in the form of foamed bitumen and water to obtain optimal compaction conditions of the mixtures.

2.1.1. Reclaimed Asphalt Pavement (RAP). Bitumen material from used old road pavement can be successfully reclaimed and reused in the construction of new road pavements. The use of reclaimed asphalt allows disposing of the waste construction materials and reduces the demand for natural aggregates. Reclaimed asphalt processing is not only economically beneficial, but it also has long-term advantages, such as the benefits from environmental protection. The reclaimed asphalt, similarly to the bituminous mixture from which it was obtained, consists of approximately 95% of mineral material and 5% of bitumen, as well as possible additives and modifiers. European standards classify reclaimed asphalt as a valuable material for the construction of road pavements of various functions and classes. It is a material that can be successfully used in the production of hot-mix, warm-mix bituminous mixtures or cold recycled mixtures. The laboratory tests used reclaimed asphalt (RA) obtained from milling of existing asphalt courses (wearing and bonding), containing 5.6% of bituminous binder, which was determined based on the extraction test in accordance with PN-EN 13697-1 [21].

2.1.2. Recycled Cement Concrete (RCC). RCC is a type of a recycled mineral material produced from reclaimed cement concrete (RC) by milling and adequate of the existing road bases, i.e. hydraulically-bound courses (i.e. pavements, or Portland cement concrete base courses, frost protection layers, or a hydraulically-bonded improved subgrade layers). Treatment of the concrete material obtained from a road base by crushing takes place on site during removal of pavements or at a recycling plant. The material produced through this treatment becomes a construction aggregate or an anthropogenic subgrade [22], [23].

Recycled cement concrete, applied in the Mix-FBRCC research mixture was used for laboratory tests. The RCC aggregate mixture instead of grading new aggregate for grading improvement was used in this mixture, prepared by 2-mm sieve screening of oversize grains to obtain a comparable grading to the grading of the grading improving aggregate, and thus increasing the share of the fraction responsible for the formation of secondary cementation, i.e. < 0.6 mm [24].

2.1.3. Reclaimed Aggregate (RA). Natural reclaimed aggregate (RA) is a mineral material produced by milling or removing the existing road pavement courses, i.e. from the unbound mixtures (i.e. basecourse, subbase, frost protection courses or improved subgrades). The standard PN-EN 13242+A1 [25] defines recycled aggregates as the aggregate resulting from the processing of inorganic or mineral material previously used in the construction [26]. Natural reclaimed aggregates RA are produced in roadwork sites, such as road removal works. In case of reconstruction or expansion of road pavement, the mineral material obtained from the removal of the old pavement is crushed, possibly sorted and then re-used for the construction of a new road or reconstruction of the existing one. Natural reclaimed aggregates RA are used in road construction as a material for a road base construction, including in the construction and upgrading of road infrastructure (roads, pavements, bicycle paths, squares and car parks), and for levelling roads that do not have bituminous pavements [27]. It can be applied to asphalt binder, Portland cement concrete or mechanically stabilized aggregate base courses. Natural reclaimed aggregates, just like other aggregates (natural and artificial), can be used for the production of unbound mixtures for road bases, pavements of unbound aggregate and improved subgrade.

Recycled material used for the earth construction, application of unbound and bound layers must meet the requirements specified in EN 13242+A1 [25].
In laboratory tests, a natural reclaimed aggregate was used as the Mix-FBREF reference mix, i.e. reclaimed rock with a continuous grading of 0/31.5 mm, originating from the existing unbound road bases (i.e. from mechanically stabilized aggregate).

2.1.4. New aggregate (NA). Fine broken continuously graded 0/4 mm dolomite aggregate for improving the mix grading was used in the Mix-FBREF mixtures. This aggregate is a typical type of material used in Poland as a measure for mineral mixture gradation improvement of the cold recycled road base with foamed bitumen. Its selection was dictated by the fact that this material is widely available and used for asphalt mixtures intended for all road bases. Its use was governed by the necessity of improving the grading of the mineral mixture to meet the requirements in this respect. It is important to bear in mind that the introduction of a new component to the reclaimed road base translates into an increase in the cost of its implementation. Thus, it is better to increase the cost of equipment and to achieve the required grading by reclaiming the materials previously used in the existing courses. This approach will make most out of the materials from the existing structural courses in the reclaimed road base.

2.1.5. Foamed bitumen. Foamed bitumen prepared from a 50/70 bituminous binder, the properties of which, requirements, as well as foaming characteristics (maximum expansion and half-life) at the recommended content of foaming water, are shown in Figure 1 and Table 1, were used in laboratory tests, in the Mix-FB mixtures. The use of 50/70 road bitumen was justified by its previous application by other researchers in this type of recycled mixtures for a road base.

### Table 1. Properties of the 50/70 road bitumen

| Variable                      | Valid N | Mean    | Min.   | Max.   | Std. Dev. | Coef. Var. |
|-------------------------------|---------|---------|--------|--------|-----------|------------|
| Penetration in 25°C (0.1mm)   | 10      | 59.9    | 56.0   | 64.0   | 2.378     | 3.970      |
| Softening point (R&B) (°C)    | 4       | 48.6    | 48.0   | 48.9   | 0.427     | 0.879      |
| Fraass breaking point (°C)    | 4       | -16.3   | -17.0  | -16.0  | 0.577     | -3.535     |

![Figure 1. Foaming characteristics of 50/70 road bitumen (Optimum FWC=3.0%, ER=13.2, HL=14.8 s)](image-url)
2.2. The mix design procedure of foamed bitumen mixtures

Table 2 and Figure 2 summarize the grading of the materials used in the tests. Table 3 lists the composition of both mixtures, i.e. reference mixture (Mix-FBREF) and research mixture (Mix-FB RCC). Grading of recycled mixtures with boundary curves is shown in Figure 3. According to Polish recommendations [28], the addition of cement was not included in the grading of mineral mixtures.

In Poland, an addition of cement is required to obtain the required load-bearing capacity and resistance to water and frost damage of the road base produced in cold recycling technology with foamed bitumen as well as in the alternative technology with bitumen emulsion [2], [28], [9]. However, in the presented investigations, the addition of cement to mixtures would preclude a possible detection of the secondary setting determined based on the strength growth rate assessment in the unconfined compressive strength tests.

All mineral materials used in the tests met the requirements of the guidelines [23] in terms of their suitability for the Mix-FB mixtures, intended for road bases.

### Table 2. Grading of the materials used in Mix-FB mixture

| Particle size # (mm) | Type of materials | RAP | RC | RCC | RA | NA |
|----------------------|-------------------|-----|----|-----|----|----|
| 16                   |                   | 14.2| 12.2| 0   | 10.0 | 0  |
| 11.2                 |                   | 11.3| 12.5| 0   | 7.3  | 0  |
| 8                    |                   | 14.0| 13.4| 0   | 8.2  | 0  |
| 5.6                  |                   | 11.6| 10.6| 0   | 8.9  | 0  |
| 4                    |                   | 11.0| 6.3 | 0   | 12.2 | 0  |
| 2                    |                   | 13.9| 10.6| 14.5| 15.1 | 15.9|
| 1                    |                   | 7.7 | 9.9 | 21.6| 14.0 | 39.8|
| 0.5                  |                   | 4.8 | 7.3 | 15.2| 8.0  | 11.5|
| 0.25                 |                   | 3.0 | 6.4 | 14.5| 4.0  | 6.5 |
| 0.125                |                   | 2.5 | 3.4 | 11.3| 3.0  | 4.3 |
| 0.063                |                   | 4.5 | 1.9 | 9.5 | 1.3  | 5.5 |
| < 0.063              |                   | 1.5 | 5.5 | 13.4| 8.0  | 16.5|
| Sum                  |                   | 100 | 100 | 100 | 100  | 100 |

**RCC** – recycled cement concrete, **RC** – reclaimed cement concrete.

### Figure 2. Grading curves of the materials used in reference mixture (Mix-FBREF) and research mixture (Mix-FB RCC)

### Table 3. Composition of mineral mixtures (mm) and mineral mixtures with foamed bitumen (Mix-FB)

| Component                  | Percentage (%) | Mix-FBREF | Mix-FB | Mix-FBREF | Mix-FB |
|---------------------------|----------------|-----------|--------|-----------|--------|
| Reclaimed Asphalt Pavement (RAP) | 37          | 35.7      | 37     | 35.7      |
| Recycled Cement Concrete (RCC) | -           | -         | 26     | 25.1      |
| Reclaimed Aggregate (RA)    | 37          | 35.7      | 37     | 35.7      |
| New aggregate (NA)          | 26          | 25.1      | -      | -         |
| Foamed bitumen 50/70        | -            | 3.5       | -      | 3.5       |
| Sum                        | 100          | 100       | 100    | 100       |
Figure 3. Grading curves of the mineral mixtures with boundary curves according to recommendations [28]

To summarize the above, the grading of the designed mineral mixtures was within the boundary curves and was in line with the guidelines [28]. The total amount of the bituminous binder in the Mix-FB mixture was: 3.5 + 35.7×0.056 = 5.5%.

According to the recommendations [28, 29], the requirements regarding the amount of bituminous binder in the Mix-FB mixtures was met, i.e. its total content did not exceed 6.0%.

2.3. Optimum Moisture Content (OMC)

The assessment of optimum moisture content OMC was performed in accordance with the requirements of the PN EN 13286-2 [30] standard according to the Proctor test (large cylinder, method B). Figure 4 shows the relationship between moisture and volumetric density for the tested mixtures.

Figure 4. The relationship between moisture and volumetric density for the tested mixtures
The Mixing Moisture Content (MMC) value of foam mixes should be within the range from 65% to 85% (depending on the mixture grading) of the optimum moisture content of the mineral-cement mix determined in the modified Proctor test. The moisture content during mixing and compaction of the recycled mixture with foamed bitumen was equal to 75% of the optimum moisture content of the mineral-cement mix.

2.4. Experimental methodology

The unconfined compression tests were performed on cylindrical specimens (Figure 5, 6) prepared using the Proctor compactor in accordance with the requirements of PN EN 13286-50 [31] at the optimum moisture content of 6.1%. The tests were performed at 25°C in accordance with the requirements of the PN EN 13286-41 standard [32].

The Unconfined Compressive Strength was determined by measuring the ultimate load to failure of a specimen subjected to a constant loading rate of 142 kPa/s (153 kN/min) [3]. The value of this parameter was determined based on the following relationship [3]:

\[
UCS = \frac{(4+P) \times 10000}{\pi \times d^2}
\]  

where:

\(UCS\) - Unconfined Compressive Strength (kPa),
\(P\) - maximum compressive force (kN),
\(d\) - specimen diameter [cm].

The unconfined compressive strength of the Mix-FBREF and Mix-FB RCC mixtures was determined after 3, 4, 7, 14 and 28 days of conditioning. After 48 hours from compaction, the specimens were demoulded and placed on a countertop in a room with a temperature of 22°C (±3°C) and relative humidity RH of 40÷60%, where samples were awaiting for the unconfined compressive strength test.

3. Results and discussions

Figure 7 graphically shows the results of the unconfined compressive strength test of the samples from the Mix-FBREF and Mix-FB RCC mixtures in a sample age function, while Table 4 presents descriptive statistics of the obtained test results.
Figure 7. Results of the unconfined compressive strength test on the samples from the Mix-FBREF and Mix-FB RCC mixtures in a function of specimen age; error bars show standard deviations

Table 4. Descriptive statistics of the unconfined compressive strength test results of the samples from Mix-FBREF and Mix-FB RCC mixtures (X – mean value, s – standard deviation of the sample, \(\nu\) – coefficient of variation)

| Age of samples (days) | Mixture type | Mix-FBREF | Mix-FB RCC |
|-----------------------|--------------|------------|------------|
|                       | X (kPa)      | s (kPa)   | \(\nu\) (%) | X (kPa)   | s (kPa) | \(\nu\) (%) |
| 3                     | 315.99       | 15.36     | 4.9        | 319.14    | 21.18   | 6.6        |
| 4                     | 351.79       | 13.66     | 3.9        | 370.74    | 14.71   | 4.0        |
| 7                     | 422.92       | 17.10     | 4.0        | 431.81    | 17.01   | 3.9        |
| 14                    | 473.48       | 16.35     | 3.5        | 491.30    | 19.19   | 3.9        |
| 28                    | 498.18       | 29.84     | 6.0        | 506.79    | 20.57   | 4.1        |

The analysis of UCS test result allows to state that in the case of both mixtures, the strength of the tested materials increased with the age of the samples in a similar manner. The samples from the Mix-FBREF reference mixture, i.e. without the addition of the RCC aggregates, were characterized by lower UCS than the samples from the Mix-FB RCC mixture. With respect to both mixtures, it can be concluded that the growth rate of the unconfined compressive strength decreased with time and was the lowest between the 14th and 28th day of sample conditioning. For the reference mixture, the value of the analysed parameter increased by 182 kPa, i.e. from 315.99 kPa to 498.18 kPa, while for the mixture containing RCC aggregates, this difference was higher by only 6 kPa (187.65 kPa). However, the difference in the unconfined compressive strength of samples from recycled mixtures, considered in terms of the recycled concrete presence for individual periods of sample conditioning (age of samples), was insignificant and was only from 3 kPa to 19 kPa.

To estimate the impact of the recycled concrete used in the composition of the cold recycled mixture with foamed bitumen on the unconfined compressive strength of the samples, a statistical analysis of these results was performed. The analyses included assessment of the significance of the differences between the mean values of the dependent considered variable (UCS) in terms of mixture type and age of samples using the one way ANOVA analysis. Due to the compatibility of variable distributions with the normal distribution and meeting the assumptions of homogeneity of variations, it was possible to use parametric tests F (Fisher Snedecor test) for comparing several means simultaneously, without indicating, however, which group means differ from other group means. If the
differences between means turn out to be significant, then such a test result means that at least one mean differs from the other. Since significant differences were confirmed for the analysed variable for both mixtures in the overall F test, a post hoc type comparison test (Tukey multiple comparison test) was used to estimate the specific significance of the differences in the test groups to identify which particular means differ from each other.

Table 5 summarizes the results of the one-way analysis performed to examine the impact of the following factors:

- Mixture type (Mix-FB REF, Mix-FB RCC),
- Sample age (3, 4, 7, 14, 28 days of conditioning),

on the unconfined compressive strength.

Table 5. Results of the statistical evaluation of the influence of the Type of mixture and Age of samples on the unconfined compressive strength value UCS of the samples from Mix-FB REF, Mix-FB RCC

| Effect                        | df  | SS   | MS   | F      | p       |
|-------------------------------|-----|------|------|--------|---------|
| Intercept                     | 1   | 6996034 | 6996034 | 19335.57 | 0.000000 |
| Mixture type                  | 1   | 1319 | 1319 | 3.64   | 0.065845 |
| Age of sample                 | 4   | 197426 | 49357   | 136.41  | 0.000000 |
| Mixture type*Age of sample    | 4   | 361 | 90  | 0.25   | 0.907842 |
| Error                         | 30  | 10855 | 362 |        |         |

df – degrees of freedom, SS - Sum of Squares, MS - Mean squares

The one-way analysis did not show a significant effect of the tested mixture type (Mix-FB REF, Mix-FB RCC) on the UCS parameter values. To analyse the results in detail, the Tukey multiple comparison tests were performed, the results of which in the form of isolated homogeneous groups (in which no significant differences between the means were shown) are presented in Table 6.

Table 6. Homogeneous groups isolated based on the results of the Tukey multiple comparison tests; criterion of no significant differences between the mean UCS values in the samples from the Mix-FB REF, Mix-FB RCC mixtures at significance level α = 0.05

| Mixture type | Age of sample | UCS (kPa) – mean value | 1   | 2   | 3   | 4   | 5   |
|--------------|---------------|------------------------|-----|-----|-----|-----|-----|
| Mix-FB REF   | 3             | 315.99                 | ****|     |     |     |     |
| Mix-FB RCC   | 3             | 319.14                 | ****|     |     |     |     |
| Mix-FB REF   | 4             | 351.79                 | **** | ****|     |     |     |
| Mix-FB RCC   | 4             | 370.74                 | ****|     |     |     |     |
| Mix-FB REF   | 7             | 422.92                 | ****|     |     |     |     |
| Mix-FB RCC   | 7             | 431.81                 | **** | ****|     |     |     |
| Mix-FB REF   | 14            | 473.48                 | **** |     |     |     |     |
| Mix-FB RCC   | 14            | 491.30                 | ****|     |     |     |     |
| Mix-FB REF   | 28            | 498.18                 | ****|     |     |     |     |
| Mix-FB RCC   | 28            | 506.79                 | ****|     |     |     |     |

HSD Tukey test; variable: UCS (kPa)
Homogenous groups, alfa = 0.05000
Error: MS between groups = 361.82, df = 30

Analysis of isolated homogeneous groups confirmed the results of the one-way ANOVA analysis. For each of the considered sample conditioning periods, no differences between the unconfined
compressive strength values of the samples from the Mix-FB<sub>REF</sub> and Mix-FB<sub>RCC</sub> mixtures were statistically significant. In addition, the results of the 14- and 28-day strength test of the samples from both mixtures were assigned to one group of means. This means that not only there were no significant differences between the UCS strength of both mixtures, but also after 14 days, the observed increase in strength was not statistically significant.

4. Conclusions
The research work regarding the preliminary assessment of the secondary Portland cement setting in the recycled concrete, used in a cold mixture with foamed bitumen, have not proven the phenomenon of secondary setting as a significant in factor shaping the compressive strength of this type of material.

The use of recycled concrete in mixtures for road bases, produced in the recycling technology with foamed bitumen, has undoubtedly an impact on the increase of mechanical parameters, however the presence of bituminous binding materials (old: contained in reclaimed asphalt and new: added in the form of foamed bitumen) caused that the dominant bituminous bonding reduces the significance of the secondary Portland cement setting. This has a beneficial effect on reducing the risk of over-stiffening of the road base, which could result in the formation of cracks in the pavement structure.

The results of statistical analyses did not show a significant impact of the tested mixture type (Mix-FB<sub>REF</sub> without the addition of RCC, Mix-FB<sub>RCC</sub> with the addition of 25% RCC) on the tested UCS parameter values. In addition, for each of the considered sample conditioning periods, no differences between the unconfined compressive strength values of the samples were statistically significant.

In laboratory tests, the observed increase in the unconfined compressive strength UCS was not statistically significant. On the other hand, the use of aggregates from the reclaimed concrete in cold mixtures with foamed bitumen brings great benefits, among others, in limiting the consumption of new mineral resources, and replacing them with recycled concrete will result in obtaining a road base of high strength parameters.

The research works performed are of an exploratory character and require extending the scope of analyses to include the mixtures with a higher content of aggregates from the reclaimed cement concrete, as well as to determine the compressive strength of laboratory samples, conditioned for a prolonged period of up to 60 days, 12 and 24 months.

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