"Environmental Engineering" 10th International Conference
Vilnius Gediminas Technical University
Lithuania, 27–28 April 2017
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-044-0

Article ID: enviro.2017.153
DOI: https://doi.org/10.3846/enviro.2017.153

Review of Lithuanian Experience in Asphalt Pavements Cold Recycling

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Abstract. One of the key goals in the EU White Paper is to reduce carbon emissions in transport by 60% by 2050. Consequently, during the past years an effect on the environment became a decisive factor in selecting materials and technologies for road construction and rehabilitation. Cold recycling is a reasonable solution in asphalt pavement rehabilitation because it is economical and old asphalt pavements can be reused. This technology differs from others by mixing temperature. Besides, cold recycling does not require additional heating. These benefits result in wide application of cold recycling around the world. In Lithuania, cold recycling has been used for more than 15 years. Both technologies, i.e. cold in-plant recycling and cold in-place recycling, were used. In both technologies reclaimed asphalt pavement (RAP) is bound with bituminous binders (foamed bitumen or bitumen emulsion), hydraulic binders (cement) or a combination of bituminous and hydraulic binders depending on the base course specifications. This paper focuses on the Lithuanian experience in cold recycling of asphalt pavements using different types of cold recycling and binders.

Keywords: bituminous binders, cold in-place recycling, cold in-plant recycling, cold recycling, hydraulic binders, recycling technologies.

Conference topic: Roads and railways.

Introduction

Lithuania belongs to the middle-latitude climate zone characterized by seasonal changes: cold winter, warm summer and intermediate seasons – spring and autumn. In winter the temperature of asphalt pavement drops to –22 °C and lower, and in summer rises up to +53 °C and higher (Vaitkus *et al.* 2012). By the data of Statistics Lithuania, in recent years carriage of goods by road transport has increased by more than 3 times compared to 2000. An annual average daily traffic (AADT) of heavy vehicles increased from 3% to 19% during 2005–2009 in Vilnius region (Žiliūte *et al.* 2010). Test road in Pagiriai also confirms a such rapid growing of traffic. There a number of equivalent single axle loads increased more than 3 times since 2007 until 2011 (Vaitkus, Paliukaitė 2013). Such a wide range of temperatures and rapidly increasing AADT of heavy vehicles lead to critical stresses and more rapid pavement degradation. Lithuania, like others countries, seeks for economically and socially rational solutions for pavement rehabilitation. One of them is cold recycling, which is used for flexible pavement structures to reclaim unbound (granular) and bound (hydraulically or bituminous) pavement layers.

Recycling of road building materials decreases the need for material transportation, helps to conserve resources of natural aggregate and/or landfill space, to reduce the amount of atmospheric emissions of carbon dioxide. In the process of cold recycling up to 100% of reclaimed asphalt pavement (RAP) can be used for the cold recycled mixtures (Pasetto *et al.* 2004; Alvarez *et al.* 2008).

In Lithuania, cold recycling has been used for more than 15 years. Usually, the cold recycled mixture is used to construct bituminous or hydraulically bound base course, which is overlaid with a thinner asphalt pavement (compared to the standardised asphalt pavement structures). Cold recycling may be conducted in place or in plant. Typically RAP is mixed with natural aggregate (if RAP aggregate gradation is not appropriate) and bound with a combination of bituminous and hydraulic binders or merely by hydraulic binder.

Cold recycling is commonly used on roads where AADT varies from ≤1500 vpd to ≤3000 vpd. With proper economic justification the cold recycling may be applied on motorways with AADT >12000 vpd. In such case the cold recycled layer corresponds to the bituminous or hydraulically bound base course, which is overlaid with a two-layer asphalt or concrete pavement. This paper focuses on the Lithuanian experience in cold recycling of asphalt pavements using different types of cold recycling and binders.

Concept of cold recycling

Cold recycling is a rehabilitation technique in which the existing distressed asphalt pavement is milled, screened, crushed and then rebound with binders placed and compacted. The RAP is not preheated before mixing. As mentioned above, cold recycling may be done in place or in plant.

Thickness of the layer to be reclaimed depends on the degradation degree of pavement structure. If only wearing course suffers from distresses, it is appropriate to reclaim only this pavement layer. Otherwise, it is necessary to ensure that thickness of the layer to be recycled is not less than the distressed part of pavement structure. It should be noted that the modern mechanisms are able to construct even 30 cm thick high quality bituminous or hydraulically bound base course.

Cold recycled mixture may be bound by using bituminous binders, hydraulic binders or a combination of bituminous and hydraulic binders (Pasetto *et al.* 2004; Hodgkinson, Visser 2004; Abdo *et al.* 2013; Dal Ben, Jenkins 2014). Price, availability, material characteristics, durability and road authorities' policy are the main factors influencing the selection of binder.

Typically, cold recycled mixtures are used to construct base course or binder course (Pasetto *et al.* 2004; Loizos, Papavasiliou 2006; Alam *et al.* 2010).

Cold in–plant vs cold in–place

In the cold in-plant recycling process the old pavement is first milled or broke and then crushed to reach the required gradation of RAP. Then, the granules of RAP are stored in the designated areas. In this case, mixing is carried out in the mixing plants (mobile mixing plants are usually used). If RAP gradation is not appropriate, the natural aggregate is added. RAP and natural aggregate are not preheated before mixing. They are bound with bituminous binders, hydraulic binders or a combination of bituminous and hydraulic binders. The produced cold recycled mixture is transported to the construction site where it is placed and compacted. In the cold in-plant recycling different fractions of RAP may be used for mixtures production and/or RAP can be additionally crushed, if needed, to reach the required gradation of cold recycled mixture.

In the cold in-place recycling process pavement is milled or broke and immediately crushed to reach the required gradation of RAP. The produced RAP is mixed with natural aggregate, if RAP gradation is not appropriate, and bound with bituminous binders, hydraulic binders or a combination of bituminous and hydraulic binders without preheating of RAP, i. e. mixing of the cold recycled mixture is carried out at an ambient temperature (Zaumanis *et al.* 2016; Abdo *et al.* 2013).

The cold in-place recycling technology is more world widely used than the cold in-plant recycling technology (Batista *et al.* 2012). This is determined by economic advantage and lower time expenditures of cold in-place recycling compared to the cold in-plant recycling. However, cold in-plant recycling allows to better control the properties of cold recycled mixture and this may lead to the production of cold recycled mixtures of better characteristics. To compare the costs of cold in-place and in-plant recycling, the advantage of cold in-place recycling is obvious since there is no need to transport the RAP and the produced cold recycled mixture, i.e. reclamation is carried out in place by milling or breaking the old pavement, crushing it, if needed, and/or mixing with natural aggregate and immediately laying.

Cold in-plant recycling is advised to be used when:

- in the construction site is a need to construct additional pavement layers and/or to replace the existing ones after the milling of asphalt pavement;
- required gradation of RAP is reached by mixing RAP mixtures of different fractions and/or mixtures of natural aggregate;
- there is a large square deviation in the properties of distressed pavement;
- the distressed pavement is so hard that during in-place recycling it will be difficult to reach the required gradation of RAP.

Cold in-plant recycling technology allows to accurately dose the amount of RAP and natural aggregate before they are supplied to the mixer, to control mixing time, and to store produced mixture (only if bituminous binder is used) (Zaumanis *et al.* 2016).

Combination of bituminous and hydraulic binders vs hydraulic binders

Binders used for producing mixtures shall ensure appropriate binding of cold recycled mixture components into a solid mixture. This ensures better strength properties, higher durability, resistance to water and climate impact (Tabaković *et al.* 2016; Iwański, Chomicz-Kowalska 2013).

RAP is usually bound with the bituminous binders, hydraulic binders or using their combination. Cold recycled mixtures bound with only bituminous binders perform similar to the bitumen stabilized materials, and cold recycled mixtures bound with only hydraulic binders are similar to the cement-treated materials. Whereas, when bituminous and hydraulic binder combination is used the properties of cold recycled mixtures are similar to the properties of both the bitumen stabilized materials and the cement-treated materials. The use of combination of both binders results in better performance of cold recycled mixture compared to the use of one certain binder (Valentin *et al.* 2016; Ebels, Jenkins 2007; Hodgkinson, Visser 2004; Khweir 2007). It was determined that the brittleness (especially at low temperatures) and sensitivity to water of cold recycled mixture bound with bituminous and hydraulic binders decrease compared to cold recycled mixture bound with only hydraulic binders. Besides, in this case during hardening process no shrinkage cracking occurs (Grilli *et al.* 2012; Bocci *et al.* 2011). Cold recycled mixtures bound with a combination of bituminous and hydraulic binders have a shorter hardening time (faster reach the desirable bearing capacity) compared to cold recycled mixtures bound with only bituminous binders (Kavussi, Modarres 2010). The most frequently used binders for cold recycling are bituminous emulsion, foamed bitumen and cement.

Bituminous emulsion is a mixture of water and bitumen. It is obtained by dispersing bitumen in water with the use of emulsifiers and, if needed, stabilizers. The properties of bituminous emulsion shall be such that during mixing it would evenly distribute, and decomposition would start only at the end of mixing process. Bituminous emulsion is used for cold recycled mixtures due to its flexibility given to the mixture and increased material durability and water resistance. However, it is quite expensive binder and production requires specific knowledge and equipment.

Foamed bitumen – is a temporary state of road bitumen in which bitumen represents a short-term (15–30 s) expansion in its volume. This is achieved when mixing hot bitumen, water and air in the expansion chamber immediately before the use. The state of foamed bitumen is only temporary, therefore in order to conduct suitability tests the certain equipment is necessary to produce foamed bitumen.

The desirable bearing capacity of bound layer can be achieved more rapidly using foamed bitumen instead of bituminous emulsion, because foamed bitumen hardens faster (Li *et al.* 2016; Kowalski, Starry 2007). Besides, in case of rain water does not penetrate into the mixture as it happens using bituminous emulsion. The use of foamed bitumen helps to avoid negative impact on the human health since no solvents are used to reduce viscosity. However, using foam bitumen it is necessary to ensure sufficient qualification of the staff in terms of application of this technology. Also, production of foamed bitumen requires special equipment and bitumen has to be preheated in order to reach the foaming temperature. This causes additional production costs.

Hydraulic binders – are one of the oldest binders used in road construction. Hydraulically bound materials are less susceptible to freeze-thaw cycles than bituminous bound materials. The use of traditional road binders (cement, slack lime and burnt lime) for cold recycled mixtures can be undesirable because of a hardening process. Inexcessive amount of cement can negatively affect the performance of bound layer. The higher strength of the mixture the stiffer and more brittle material is. The hydraulically bound layer shrinks and results in cracking. However, this cracking is unavoidable and these cracks are not considered as the main reason leading to poor layer performance. The strength of the cement-bound layer after 7 days reaches about 50% of the desirable strength, and after 28 days – about 90%. The main three factors influencing the hardening time of hydraulically bound layers (especially with cement) are ambient temperature, gradation of hydraulic binder (cement) and variation in the moisture content in hydraulically bound layer (Abdo *et al.* 2013).

In the countires of cold climate is not recommended to construct hydraulically bound base courses, because they suffer from thermal cracking. Later these cracks are transmitted into asphalt pavement and leads to faster pavement deterioration.

Experimental research

In experimental research were analysed roads in which cold recycling was done. The road sections were selected according to:

- the year of construction (2000–2014);
- the binder used (combination of bituminous/hydraulic binder or hydraulic binder);
- the technology used (cold in-place or cold in-plant recycling).

The list of selected road sections is given in Table 1. An index was given to each of the analysed road sections for its identification. 18 road sections were analysed. The total length is 103.089 km.

In 12 road sections (72.499 km) cold recycled mixtures with bituminous emulsion and cement were used. In 4 road sections (23.690 km) cold recycled mixtures were bound with foamed bitumen and cement. In 2 road sections (6.900 km) cold recycled mixtures were bound with cement. 29.86 km were rehabilitated by using cold in-place recycling, and 73.249 km – cold in-plant recycling. Rehabilitation was carried out in different years. Thus, the service life is different for each road section. It varies from 3 to 17 years.

The projects of each rehabilitated road section and construction documents such as laboratory test reports and declarations of material performance were analysed. Statistical analysis of test results was also done. A special attention was given to the following characteristics of cold recycled mixture:

- binder content;
- RAP content;
- air voids content;
- indirect tensile strength (ITS) (if bituminious binder was used);
- compressive strength (if hydraulic binder was used).

Furthermore, bearing capacity and compaction level of the constructed base course of cold recycled mixture were analysed. They are the main criteria for the proper layer construction. Bearing capacity was determined by static plate load test or dynamic plate load test. Compaction level was determined by surface moisture-density gauge Troxler 3440.

Table 1. Selected road sections

Index of road section	Road No.	Road section, km		Section length, km	Direction [1)]	Cold re-cycling type	Contruc-tion year	Binding type[2)]
		start	end					
1	A1	187.200	190.000	2.800	L	In-plant	2014	BE + C
2		205.500	216.950	11.450	R	In-plant	2014	BE + C
3		216.950	220.300	3.350	R	In-plant	2010	BE + C
4		220.050	220.800	0.750	L	In-plant	2014	FB + C
5		220.800	228.020	7.220	L	In-plant	2014	BE + C
6		240.000	242.800	2.800	L	In-plant	2014	BE + C
7	A16	34.460	35.300	0.840	R + L	In-place	2000	FB + C
8		35.300	38.800	3.500	R + L	In-place	2003	C
9		41.200	57.300	16.100	R + L	In-place	2005	FB + C
10	182	7.980	13.980	6.000	R + L	In-place	2011	FB + C
11	164	11.000	20.000	9.000	R + L	In-plant	2008	BE + C
12		65.610	70.000	4.390	R. + L	In-plant	2004	BE + C
13	155	22.060	27.800	5.740	R + L	In-plant	2009	BE + C
14		30.350	34.580	4.230	R + L	In-plant	2009	BE + C
15		34.580	44.070	9.490	R + L	In-plant	2010	BE + C
16	A12	3.000	8.029	5.029	R + L	In-plant	2014	BE + C
17		59.42	62.820	3.400	R	In-place	2003	C
18		132.70	139.70	7.000	R + L	In-plant	2013	BE + C

Notes: [1)] L – left side of the road; R – right side of the road;
[2)] BE – bituminous emulsion, FB – foamed bitumen, C – cement.

Lithuanian experience in cold recycling

An analysis of the data given in the projects showed that different engineers, designers, contractors and others parties involved in the road construction processes give different information. For example, some projects do not contain drawings of road cross-section, information about geological investigations, AADT, design load, the class of road pavement structure, etc. In some projects was not clear what type of binder was used for cold recycled mixture, and which recycling technology (in-place or in-plant) was applied. Also, in many projects was not given a recipe for cold recycled mixture and there was not clear what physical and mechanical properties of cold recycled mixture are. The oldest projects contained at least information. In recent years (since 2013) prepared projects were the most comprehensive.

The analysis showed that in Lithuania cold recycling is frequently used on the main (AM category) and national (III category) roads. There, no relationship was found between the type of cold recycling or the binder and the road category. However, it was noticed that there is a tendency between the type of cold recycling and construction (rehabilitation) year. Cold in-plant recycling has been more often used in recent years (2008–2014), while cold in-place recycling was more often used in 2000–2005. In recent years the cold recycled mixtures are typically bound with a combination of bitumen emulsion and cement. A combination of foamed bitumen and cement was used in 2000, 2005, 2011 and 2014. Based on the studied projects, cement without bituminous binder was used only in 2003.

In the first year after rehabilitation AADT on the analysed road sections varied from 2500 vpd to 10500 vpd. AADT of heavy vehicles was from 450 vpd to 2100 vpd. According to the data of 2015, AADT on the analysed road sections varied from 2400 vpd to 13500 vpd. AADT of heavy vehicles was from 230 vpd to 2000 vpd.

Pavement structure

Analysis of the designed pavement structures was carried out. Designed pavement structure comprising bound base course of cold recycled mixture is usually laid on the existing pavement structure after removal of the distressed pavement. If lane widening was necessary, a totally new pavement structure was constructed there.

In most cases the designed pavement structure, which was constructed over the existing pavement structure, consisted of levelling layer (if it was needed), bound base course of cold recycled mixture and asphalt pavement. In 13 of 18 analysed sections the levelling layer was constructed from 0/32 fraction aggregate mixture (except 11^{th} section where 0/45 fraction aggregate mixture was used). In two road sections (12^{th} and 16^{th}) the fraction of aggregate mixture used for levelling layer was not indicated. In 15^{th} and 16^{th} road sections on the existing pavement structure before base course of cold recycled mixture were built the frost resistant pavement layer. Its thickness was 50 cm and 45 cm in the 15^{th} and 16^{th} section, respectively. Thickness of the bound base course of cold recycled mixture varied from 16 cm to 20 cm. In the large majority of analysed sections this layer thickness was 20 cm if cold in-place recycling was done. There RAP and natural aggregate were bound with bituminous emulsion and cement or foamed bitumen and cement.

The bound base course of 16 cm thick was constructed only in 9th section. There cold in-place recycling was carried out and foamed bitumen and emulsion were used. The bound base course of 18 cm thick was constructed regardless of recycling type (in-place or in-plant). All three types of binding (bituminous emulsions and cement, foamed bitumen and cement and cement) were used. The thickness of the bound base course was different (16 cm, 18 cm, 19 cm or 20 cm) if cold in-plant recycling was done.

The asphalt pavement, which consisted of one, two or three asphalt layers, was constructed on the bound base course of cold recycled mixture. Only in 7th road section the wearing course of 5 cm was laid directly on the bound base course. In 12 analysed road sections the asphalt binder course and the asphalt wearing course were constructed. The total thickness of those layers varied from 8 cm to 12 cm. In 10th road section the wearing course of 4 cm was constructed directly on the asphalt base course of 6 cm. In 9th and 17th sections the asphalt base course was laid (6 cm and 8 cm, respectively), which was overlaid with binder course (5 cm and 6 cm, respectively) and wearing course (4 cm). In one road section (3rd) was not clear what type of pavement structure was constructed.

Cold recycled mixtures

In 5 of 18 analysed projects were not given the recipe for cold recycled mixture and there was not clear what physical and mechanical properties of cold recycled mixture were. Table 2 gives both the amount of RAP and binder used for the production of cold recycled mixture. Road sections in which the amount of RAP and binder is unknown are not included in the table. The rest components of cold recycled mixture were natural aggregate mixtures.

Air void content of cold recycled mixture was determined only in 7 of 18 analysed road sections (Table 3). In all of them cold in-plant recycling was carried out by binding RAP with bitumen emulsion and cement except 4rd section in which was used foamed bitumen and cement. Air void content in those sections varied from 8.9% to 19.1%. The average air void content varied from 9.7% to 16.1%.

Table 2. The amount of RAP and binders in cold recycled mixture

Index of road section	Cold recycling type	RAP, %	Binders, %		
			Bituminous emulsion	Foamed bitumen	Cement
1	In-plant	65	5.0	–	2
2	In-plant	65	4.5	–	2
4	In-plant	68	–	3.5	2
5	In-plant	65	4.5	–	2
6[1)]	In-plant	65	3–5	–	2
8	In-place	–	–	–	3.5 / 4 / 6[2)]
9	In-place	–	–	2	2
10	In-place	–	–	2	2
11	In-plant	–	4	–	1.5
12	In-plant	63	1.9	–	2.0
14[1)]	In-plant	65	2–2.5	–	2
16	In-plant	65	4.3	–	2.4
18	In-plant	50	3.8	–	2

Notes: [1)] The recipe for cold recycled mixture according to the general requirements in normative documents;
[2)] Based on the project 3.5% of cement was used in 35–36 km, 4% – in 36–37 km; 6% – in 37–38 km.

Table 3. Statistical analysis of air void content and indirect tensile strength of cold recycled mixture

Index of road section	Cold recycling type	Air void content, %				ITS_7, MPa				ITS_{28}, MPa			
		Min	Max	Average	St.Dev.	Min	Max	Average	St.Dev.	Min	Max	Average	St.Dev.
1_{BE+C}	In-plant	11.0	11.0	11.0	0.000	no data				0.60	0.60	0.60	0.000
2_{BE+C}		13.4	14.8	14.0	0.602	0.50	0.50	0.50	0.500	0.60	0.70	0.63	0.047
4_{FB+C}		15.0	15.6	15.3	0.250	no data				no data			
5_{BE+C}		13.8	18.2	16.1	1.594	0.40	0.70	0.52	0.104	0.50	1.00	0.73	0.205
6_{BE+C}		8.9	10.5	9.7	0.800	0.61	0.73	0.67	0.060	0.72	0.75	0.74	0.015
16_{BE+C}		10.2	16.0	12.4	1.752	no data				0.82	3.02	1.13	0.490
18_{BE+C}		11.5	19.1	13.7	2.139	0.40	0.90	0.62	0.150	0.60	1.01	0.85	0.160

Note: BE – bituminous emulsion, C – cement.

In road sections where both bituminous binder and cement were used the ITS was determined (Table 3), and in road sections where only cement was used the compressive strength was determined (Table 4). ITS of cold recycled mixture was determined in 6 of 18 analysed sections (Table 3). In all of them cold in-plant recycling was carried out by binding RAP with bitumen emulsion and cement. ITS_7 was determined in 4 analysed sections. There it varied from 0.40 MPa to 0.90 MPa. The average ITS_7 varied from 0.50 MPa to 0.67 MPa. ITS_{28} was determined in 6 analysed road sections. In those sections it varied from 0.50 MPa to 3.02 MPa. The average ITS_{28} varied from 0.60 MPa to 1.13 MPa.

In two analysed road sections (8th and 17th) to bind RAP and natural aggregate was used only cement. Thus, the compressive strength was determined. In those sections cold in-place recycling was carried out (Table 4). The compressive strength in the analysed road sections after 7 days varied from 1.70 MPa to 9.00 MPa. In the project of the 8th road section the required compressive strength was ≥6.0 MPa. However only 3 of 9 results met the requirement.

Table 4. Statistical analysis of compressive strength of cold recycled mixture

Index of road section	Cold recycling type	Compressive strength after 7 days, MPa			
		Min	Max	Average	St. Dev.
8_C 1)	In-place	1.70	9.00	4.62	2.543
17_C	In-place	3.01	5.11	4.54	0.465

Note: 1) the required compressive strength of ≥6.0 MPa was given in the project.

Base courses of cold asphalt mixtures

The bearing capacity and compaction level are given in Table 5. The bearing capacity was determined in 9 of 18 analysed road sections. Only in one section (10th) foamed bitumen and cement were used. In this road section deformation modulus E_{V2} varied from 171.70 MPa to 181.90 MPa (the average 176.40 MPa). In one road section (17th) RAP was bound with cement. There bearing capacity was not measured. In others road sections bituminous emulsion and cement were used. In those road sections deformation modulus E_{V2} varied from 156.00 MPa to 445.79 MPa. The average deformation modulus E_{V2} varied from 159.77 MPa to 319.23 MPa.

The compaction level was determined in 9 of 18 analysed road sections. In 2 road sections was carried out cold in-place recycling by binding RAP with cement. In the remaining road sections cold in-plant recycling was done by binding RAP with a combination of bituminous emulsion and cement. Compaction level was not determined on road section where RAP was bound with foamed bitumen and cement combination. All measurements of compaction level are self-control.

Table 5. Statistical analysis of deformation modulus and compaction level

Index of road section	Cold recycling type	Deformation modulus E_{v2}, MPa				E_{v2}/E_{v1}				Compaction level, %			
		Min	Max	Average	St.Dev.	Min	Max	Average	St.Dev.	Min	Max	Average	St.Dev.
1_{BE+C} 1)	In-plant	160.85	297.77	229.17	34.647	1.56	6.10	2.65	1.324	–	–	–	–
2_{BE+C}	In-plant	156.00	189.00	175.83	7.572	–	–	–	–	98.5	100.5	99.4	0.589
5_{BE+C} 1)	In-plant	≥180.0	≥180.0	≥180.0	–	–	–	–	–	–	–	–	–
8_C	In-place	–	–	–	–	–	–	–	–	97.8	99.9	98.7	0.538
10_{FB+C}	In-place	171.70	181.90	176.40	3.845	1.5	1.65	1.59	0.054	–	–	–	–
11_{BE+C} 1)	In-plant	172.07	429.82	319.23	58.074	1.13	2.16	1.68	0.203	93.3 2)	102.5 2)	98.8 2)	1.062 2)
										88.0 3)	101.8 3)	99.0 3)	1.342 3)
12_{BE+C} 1)	In-plant	210.79	299.12	263.93	28.351	1.65	2.20	1.93	0.148	98.8	108.6	102.6	2.128
13_{BE+C} 1)	In-plant	–	–	–	–	–	–	–	–	97.0	107.2	100.1	1.222
14_{BE+C} 1)	In-plant	–	–	–	–	–	–	–	–	99.0	104.6	101.40	1.601
15_{BE+C}	In-plant	190.82	445.79	306.13	68.738	1.28	2.01	1.70	0.234	–	–	–	–
16_{BE+C}	In-plant	132.90	195.70	159.77	26.427	1.69	2.18	1.87	0.218	99.6	116.8	103.21	3.950
17_C 1)	In-place	–	–	–	–	–	–	–	–	97.7	100.0	99.16	0.698
18_{BE+C}	In-plant	≥190.0	≥190.0	≥190.0	–	–	–	–	–	97.1	113.0	101.53	3.550

Notes: 1) Data of self-control measurements;
2) Bound base course constructed in two sub-layers. Measurement data on the first sub-layer;
3) Bound base course constructed in two sub-layers. Measurement data on the second sub-layer.
BE – bituminous emulsion, FB – foamed bitumen, C – cement.

The compaction level of bound base course, where cold in-place recycling was carried out, varied from 97.7% to 100.0%. There the average of compaction level varied from 98.7% to 99.16%. According to the *Methodological Guidelines for Cold In-Place Recycling MN RK–ŠB 11* the base course of cold recycled mixture was properly compacted, i.e. compaction level was higher than 97%.

The compaction level of bound base course, where cold in-plant recycling was carried out, varied from 88.0% to 116.8%. There the average of compaction level varied from 98.8% to 103.21%. It is noted that in 11th road section bound base course was constructed in two sub-layers and the compaction level of each sub-layer was determined. According to the *Methodological Guidelines for Cold In-Plant Recycling MN RM–ŠB 11* compaction level has to be higher than 97%. The compaction level less than 97% was determined only on 11th road section and only two values were lower than 97%.

Conclusions

1. Analysis of 18 rehabilitation projects implemented in Lithuanian national significance roads through 2000–2014 showed that cold recycling is used in roads with AADT from 2500 vpd to 10500 vpd with heavy vehicles rate of 18–20%.
2. Technical projects analysis showed that various recipes of cold recycled mixtures and their characteristics are used depending on the project and construction contractors and other parties involved in the road construction processes. Those complicates an evaluation of the performance of cold recycled mixture.
3. Generally in all projects cold recycled (in-plant or in-place) bound base course of 16–20 cm were used and asphalt layers were overlaid. Asphalt layers consisted of:
   – only wearing course (5 cm));
   – asphalt base course and wearing course (10 cm);
   – binder course and wearing course (8–12 cm);
   – asphalt base course, binder course and wearing course (15–18 cm).

   In some cases levelling layer was foreseen if there was a need to reach a certain level of the whole existing pavement structure.
4. Bituminous binders (foamed bitumen or bituminous emulsion) and hydraulic binder (cement) are the main binders for cold recycling irrespective of the recycling type (in-place or in-plant). Combination of bituminous and hydraulic binder provides better performance for the cold recycled mixture – higher resistance to premature cracking at low temperatures, lower sensitivity to water, shorter hardening time, lower shrinkage cracking – compared to the use of only bituminous or hydraulic binder. The following binders and their ratio were used in the analysed road sections:
   – bituminous emulsion (1.9–5.0%) and cement (1.5–2.4%);
   – foamed bitumen (2.0–3.5%) and cement (2.0%);
   – cement (3.5–6%).

   The content of RAP varied from 50% to 68%, other mixture part consisted of different aggregates mixtures, e.g. dolomite, granite or others.
5. In all roads sections, where the compaction level was determined, the bound base course of cold recycled mixture was properly compacted and met the Lithuanian requirements, i.e. the average compaction level was higher than 97%. Cold recycled mixtures bound with bituminous emulsion and cement showed a higher average bearing capacity than cold recycled mixtures bound with foamed bitumen and cement. The average bearing capacity varied from 159.77 MPa to 319.23 MPa. The bearing capacity of hydraulically (cement) bounded base layers wasn't measured.
6. In general it can be stated that cold recycled mixtures and bound base courses constructed in different Lithuanian main and national roads sections satisfy technical regulation requirements. Hence, further steps such as a research and analysis of pavement performance versus type of cold recycling, type of binder and pavement structure will be taken.

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