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Review Article

Review and evaluation of cold recycling with bitumen emulsion and cement for rehabilitation of old pavements

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HIGHLIGHTS

- Cold recycling with cement-and bitumen emulsion is used as a base course.
- To stiff mixture was responsible for reflective cracks of rehabilitated pavement.
- Appropriate design of the cold recycling mixture composition can reduce the stiffness.
- Cold recycling is a typical material for reconstructed and new pavements up to medium traffic.

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ABSTRACT

The article presents Polish experience with cold recycling of asphalt pavements with the usage of bituminous emulsion and cement. In the 1990s numerous roads in Poland required immediate reinforcement due to their significant degradation. Implementation of the cold recycling technology was one of the solutions to this problem. Cold recycled mixtures contain – beside the recycled asphalt pavement and aggregate – two different types of binding agents: bituminous emulsion and Portland cement. First Polish requirements were developed in the 1990s and were based on the Marshall test. After several years of application of these requirements, numerous transverse cracks appeared on the pavements. Field investigation showed that the frequency of transverse cracking was not uniform on all evaluated sections and that the growth rate of the number of cracks was decreasing. The main reason of extensive cracking was the overly high amount of the Portland cement and insufficient amount of the bituminous emulsion. This led to production of very stiff mixtures, with dominance of hydraulic bonds, which behaved similarly to cement-treated mixtures. The idea of flexible cold recycled base course was not utilized. This experience motivated the Polish Road Administration to develop new requirements. Second part of the article presents the new requirements for cold recycling. New test methods as well as requirements concerning resistance to frost and water action were introduced in 2013. Implementing of the new requirements resulted in significant reduction in stiffness of the MCE mixtures. Values of stiffness modulus are even three times lower, which should significantly decrease the amount of potential reflective cracks on the pavement surface. Presently two types of technology of cold recycling are used in Poland, in-place and in-plant.

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Experience with the MCE mixtures made it possible to introduce this technology in the new Polish Catalog of Typical Flexible and Semi-Rigid Pavement Structures in 2014.

1. Introduction

In the 1990s, after many years of neglect and underinvestment, the Polish road system built in the 1960s and 1970s was already old and degraded. Typical distresses were rutting, deformations, fatigue cracking and other damages related to the aging of the pavement structure. Moreover, the political changes that took place across Eastern Europe in the 1990s brought about a fast increase in heavy traffic, which contributed to rapid and significant degradation of the road system. Failure of the relatively old pavements nearing the limits of their fatigue life occurred very soon – the roads rutted and developed cracks of various types, the surface evenness deteriorated drastically, material loss and potholes were observed. The state of the pavements resulted in a drastic fall in traffic safety.

Due to the rapid degradation of pavements the road administration was in need of a technology that would allow for rehabilitation of the old deteriorated pavements that were often inhomogeneous and contained tar binders. One of the solutions that were put into practice in Poland in the second half of the 1990s was the use of full-depth cold recycling in order to remove the distressed pavement and incorporate it in a base made of cold recycling. In Poland cold recycling was called mineral-cement-emulsion mixture, often abbreviated as MCE. In order to facilitate widespread use of MCE mixes, the first Polish requirements were introduced in 1997 (Zawadzki and Matras, 1997), yet they were soon revised, and it was the 1999 amended version (Zawadzki et al., 1999) that was widely used and served as a basis for rehabilitation and reconstruction of several hundred kilometers of roads in Poland.

After over ten years of use of cold recycling in Poland, a series of tests was carried out in the years 2005–2010 in order to summarize the experience and assess the road sections where MCE mix bases had been constructed using the full-depth cold recycling technology. The research allowed for verifying the principles of requirements and defining a new procedure for proper MCE mixture design. Moreover, test methods that are used worldwide for assessment of MCE mixes were introduced in Poland as well. The research resulted in publication of the new Polish requirements for mineral-cement-emulsion mixtures (Dolżycki, 2013) that are currently in use.

The cold recycling technology with placement of MCE mix bases became so popular and widespread in Poland that solutions incorporating an MCE base were included in the new Polish Catalog of Typical Flexible and Semi-Rigid Pavement Structures (GDDKIA, 2014; Judycki et al., 2017). However, their use has been limited to roads with traffic categories KR1-KR4 (light and medium traffic). The limitation has been imposed due to the fact that the materials reclaimed from existing pavements are often variable and inhomogeneous.

The experience described in the paper demonstrates how incorrect requirements set for full-depth cold recycling using MCE mixtures may contribute to considerable number of transverse cracks in reconstructed pavements, due to shrinkage of overly stiff MCE bases. Long-term field observations on many road sections constructed using the cold recycling technology led to modifications in the requirements set for newly designed mixtures from cold recycling.

2. Full-depth cold recycling in Poland

The technology of full-depth cold recycling is relatively commonly used in Poland for road rehabilitation and reconstruction. Its popularity stemmed from the following reasons.

- **Bad technical state of majority of roads, both on national and regional level.** Polish roads had not been reinforced or reconstructed for many years. Most measures were limited to repairing or removing the distress without taking the reasons into account. Consequently, the dominant types of distress were the ones related to insufficient bearing capacity and considerable age of pavement structures. They included fatigue cracking as well as transverse cracking, edge cracking, numerous patches and potholes. Rutting was frequent – both structural and plastic flow. The state of many pavements called for an intervention in the whole structure. Full-depth cold recycling is dedicated to operations of this kind. Examples of pavements qualified for cold recycling are shown in Figs. 1 and 2.

Fig. 1 – Example of a national road pavement qualified for cold recycling.

- Tar binders in the existing pavements. Especially in the northern Poland many existing pavements contained tar binding agents that had to be reused or utilized in an environmentally safe manner. Due to economical and logistic considerations it was advantageous to reuse the tar-contaminated material after processing it with technology that would not involve heating. Full-depth cold recycling was a solution that fulfilled this condition.
- Corrections to road geometry. During road reconstruction it was often necessary to improve the technical parameters, which implied corrections or changes to road alignment. In such cases cold recycling in stationary plants posed a good solution.
- The need to provide resistance to ground heave. During reconstruction of many roads it turned out that the existing structure is too thin and does not guarantee sufficient resistance to ground heave. In order to provide the required thickness it was necessary to practically rebuild the whole structure. In such cases cold recycling in stationary plants was used in order to produce the base course.
- High variability of structure of the existing pavement. The structures may often vary considerably within one existing pavement due to its past reconstruction, widening or rehabilitation. Removal, crushing and mixing allows to achieve their homogeneity before reuse.

The aforementioned major factors – separately or in combination – made full-depth cold recycling and placement of an MCE base course a relatively common choice during reconstruction of existing roads. They pose the typical reasons for road reconstruction using the technology of cold recycling (Leandri et al., 2015; Modarres et al., 2014; Tabaković et al., 2016; Turk et al., 2016).

Full-depth cold recycling may be performed both with typical equipment sets working in-place or in dedicated stationary plants that mix the material with binding agents. The choice of technology depends on the assumed objectives. Requirements for materials and final MCE mixture are the same for both technologies. Until recently the in-place cold recycling was commonly used in most of the cases. Lately there has been a growing tendency to produce MCE mixes in stationary plants, as road reconstruction frequently aims not only at improvement of heave resistance but at geometrical corrections as well. In such cases a new pavement structure is placed, including one course produced using the cold recycling technology. Growing popularity of MCE mixes produced in stationary plants is also associated with high availability of such equipment in Poland. Since many provincial roads requires reconstruction (improvement of bearing capacity and geometrical corrections), maintaining the tendency of using MCE mixtures is quite probable.

Fig. 2 – Example of a provincial road pavement qualified for cold recycling.

3. The first requirements for MCE mixes

3.1. *Requirements for MCE mixes*

The Polish requirements (Zawadzki et al., 1999) were prepared at a time when there was a need to introduce full-depth cold recycling as a common practice. Mixes containing cement and bituminous emulsion were chosen for use, as it was thought that a combination of the two binding agents would result in a material simultaneously demonstrating relatively homogeneous parameters and sufficient strength – despite incorporating varied reclaimed materials – to successfully act as a base course.

The requirements (Zawadzki et al., 1999) assumed the preparation of MCE mixes using reclaimed pavement materials of the following types: mineral-bitumen, mineral-tar, mineral-cement or only aggregate from existing pavements. The reclaimed material was to be crushed. The aggregate mix found in materials used for MCE mixes had to be continuously graded, with maximum particle size of 31.5 mm or 63 mm, and lie within the range of good gradation defined by the limiting curves defined in the requirements. The limiting curves for traffic categories KR1-KR2 (light traffic) are shown in Fig. 3 and for KR3-KR6 (medium and heavy traffic) in Fig. 4. Range A–B presents maximum particle size 31.5 mm, and range A–C presents maximum particle size 63 mm.

Crushed aggregate was added in order to improve gradation. Bituminous emulsion and cement were used as binding agents.

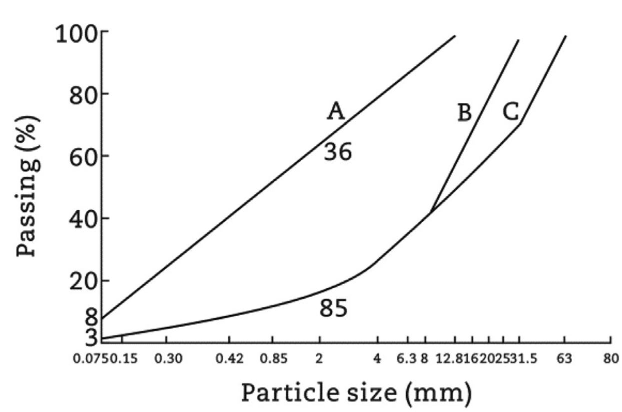


Fig. 3 – Limiting curves for mineral mix for traffic KR1–KR2 (light traffic).

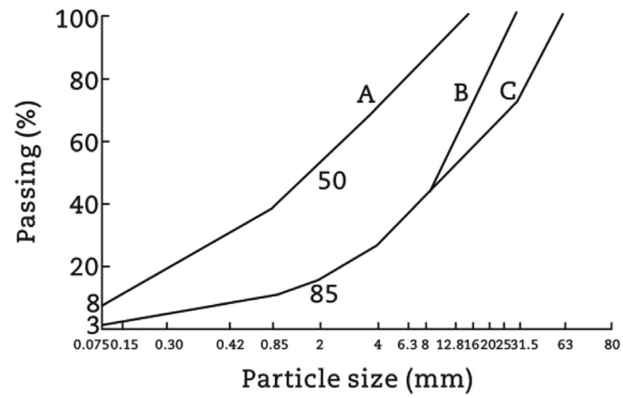


Fig. 4 – Limiting curves for mineral mix for traffic KR3–KR6 (medium and heavy traffic).

The following ranges of binding agent content were specified.

- Cement content from 1.5% to 4% if an asphalt reclaimed material was used and from 1.5% to 7% in case of tar reclaimed material. In most cases CEM I 32.5 cement was used.
- Bituminous emulsion content from 3.0% to 5.5%. In most cases slow setting bituminous emulsion with 160/220 bitumen was used.
- Additionally the maximum allowable total bitumen content (from the added bituminous emulsion as well binder originally contained in the reclaimed material) was set to 6% in mixes with maximum particle size of 31.5 mm and 5.5% in mixes with maximum particle size of 63 mm, while the limit of bitumen content originating from the processed (old) material was 4%.

Choice of the above ranges of binding agent content was motivated by the aim to achieve a relatively strong material suitable for construction of base course with required bearing capacity and meeting other requirements set in the Polish guidelines (Zawadzki et al., 1999), such as

- Marshall stability at the temperature of 60 °C
  - for traffic categories KR3 through KR6 (medium and heavy traffic), 8.0–20.0 kN
  - for traffic categories KR1 and KR2 (light traffic), 4.0–20.0 kN
- Marshall flow at the temperature of 60 °C
  - for all roads regardless of traffic category, 1.0–3.5 mm
- Air voids for all traffic categories
  - for specimens compacted with a Marshall hammer, 2 × 75 impacts, 9%–16%
  - for specimens pressed with a hydraulic press, constant force of 100 kN, 5%–12%

The requirements for MCE mixes were described in reference to test methods that were widely used in Polish road laboratories at the time. Those requirements were meant to facilitate the design of MCE mixes without the need to employ uncommon test methods. Such assumptions were motivated by the intention to enable widespread use of the technology in road rehabilitation and reconstruction as soon as possible. Presented requirement were the same for both technologies (in-place and in-plant).

3.2. *Experience with MCE bases*

After several years of use of MCE mixes it was observed that pavements with bases of this type are prone to transverse cracking. In most cases the cracks appeared in quantity of several cracks per kilometer, but there were also sections where more than ten cracks per kilometer were noted. Typical cracks developing over an MCE base can be seen in Fig. 5 and a crack propagating through the whole structure with an MCE base is shown in Fig. 6.

In order to precisely establish the cause of cracking, an extensive research of the phenomenon was performed. The first stage involved obtaining complete information about MCE mixes built in at 56 different road sections across Poland. The information was gathered both from road administration and from contractors. Quantity of all components used in the MCE mix formulas at those sections was analyzed. The results are presented in Table 1.

The analysis of the obtained data about MCE mixes placed in pavements showed that

- Sections with MCE bases develop transverse cracks. Research conducted so far suggests that the observed cracks should be qualified as reflective cracking.
- Relatively high values of cement content were used in the MCE mixes. Often they reached the maximum permissible value for the given type of reclaimed material. Therefore it may be concluded that the cracking resulted from excessive cement content in the MCE mixes.
- The values of cement content in the MCE mixes were comparable to those of cement-stabilized soil or cement-bound mixtures. This was the main factor that resulted in

Fig. 5 – Transverse crack in pavement with an MCE base.

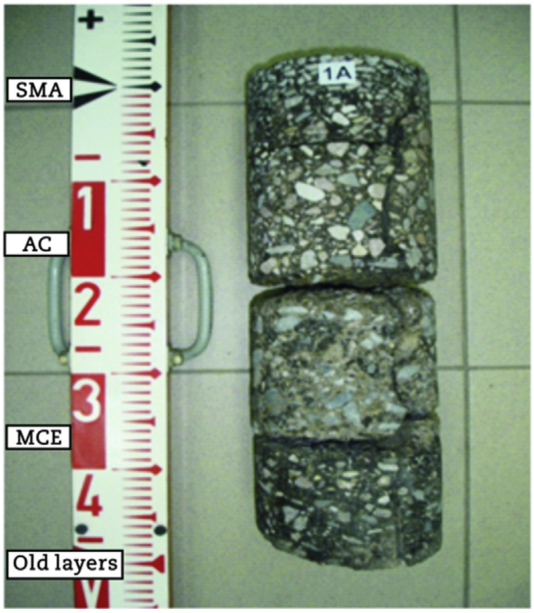


Fig. 6 – Crack propagating through asphalt courses and an MCE base.

placement of overly stiff base courses that cracked due to shrinkage.

- The Polish MCE bases had low emulsion content (often it did not exceed 3%) which resulted in insufficient elasticity (flexibility) of the MCE mix.
- The requirements for strength parameters were met mainly by adding large quantities of cement to the mix. This resulted in an overly stiff base that was prone to cracking and induced transverse cracking of the pavement.
- Disadvantageous proportion of emulsion to cement results in domination of hydraulic binding over bituminous binding and behavior of the material similar to cement-bound materials.
- The Polish MCE mixes contained high quantities of added new aggregate, frequently high-quality crushed aggregates, which in many cases disqualified them in terms of economic viability.

The analysis of the collected data revealed that practical application of the requirements deviated from the original idea of MCE mixes, which were basically meant as a flexible course produced from the highest possible quantity of reprocessed materials from existing layers. In search for a possible cause, it was found out that the guidelines (Zawadzki et al., 1999) set relatively high strength requirements (Marshall stability), which in practice induced the use of high cement content and addition of large quantities of new aggregate with good parameters in order to meet them. Emulsion was frequently added only in order to enable the product to pass as a mineral-cement-emulsion mixture. Consequently, a material with high stiffness was produced.

In 2004 another research was performed in order to assess the stiffness of a typical MCE mixture used in road reconstruction (Dołżycki, 2005). With this aim in mind, specimens for testing of stiffness and indirect tensile strength were taken from a construction site where an MCE base was being built in. In this case the MCE mixture was prepared using in-place technology. The intention was not only to measure stiffness of a real-life MCE mix, but also to assess its homogeneity. The MCE mix was sampled for 17 consecutive days while the base was being placed. The specimens were compacted with a Marshall hammer immediately at the construction site and tested after 28 days at three temperatures: 0 °C, 20 °C and 40 °C. The results of stiffness and indirect tensile strength tests are shown in Table 2 and Figs. 7 and 8.

The research performed for specimens sampled successively during one construction project confirmed that MCE mixes produced in accordance with the instruction from the 1990s are stiff materials, prone to transverse cracking.

Table 2 – Variability of stiffness modulus and indirect tensile strength of MCE mixes.

Value	Stiffness modulus ITSM (MPa)			Indirect tensile strength ITS (MPa)		
	0 °C	20 °C	40 °C	0 °C	20 °C	40 °C
Mean value	15,587	9851	6144	1.42	0.93	0.61
Maximum value	18,225	13,593	12,931	2.03	1.33	0.91
Minimum value	12,589	6401	2271	0.97	0.72	0.32
Standard deviation	1765	2109	2906	0.30	0.17	0.17

Note: Results for specimens sampled for 17 consecutive days; for a given parameter and temperature one sample was tested every day.

Table 1 – Data concerning MCE bases at 56 road sections in Poland.

Analyzed parameter	Required content according to Zawadzki et al. (1999)	Observed value	
Cement content	1.5%–4.0% – asphalt reclaimed material	2.5%–3.9%	20 sections
	1.5%–7.0% – tar reclaimed material	4.0%	24 sections
		5.0%–5.8%	6 sections
		7.0%	6 sections
Emulsion content	3.0%–5.5%	<3.0%	12 sections
		3.0%	37 sections
		>3.0%	7 sections
New aggregate content	No requirement	≤30%	13 sections
		31%–50%	34 sections
		51%–70%	7 sections
		>70%	2 sections

Stiffness was relatively uniform throughout the entire period of MCE mix production, but it was quite high. After several years transverse cracking was observed at the tested road section in quantity of approximately 15 cracks per 1 km.

In order to assess the progress of cracking in roads with MCE bases, an inspection research project was started at selected sections of other roads. 10 road sections in northern Poland were chosen. Seven road sections were constructed using in-place technology (DK6, DK55, DK22 and DK15 national roads). Remaining three road sections of DK7 national road were constructed using in-plant technology. Inspections were performed in the years 2007–2014. A comparison of quantity of cracks found at particular road sections is presented in Table 3 and Fig. 9.

The number of transverse cracks at each road is rising with time. The number of cracks varies between different roads; at the end of 2014 the cracking index ranged from 2 to 56, with mean value of 20. There are sections where cracks are relatively numerous, while at other sections they are comparatively rare. The numbers are successively increasing year by year, by rate of from 0.3 to 6.0 cracks per km per year, with mean rate of 3 cracks per km per year. The ongoing increase of cracking is a proof of advancing degradation of MCE mix bases, which results in propagation of cracks from the base to the bituminous layers. Apart from transverse cracking, other types of distress occur as well, since the pavements degrade with age.

4. New requirements for MCE mixtures

4.1. *The reasons for change*

Experience gathered from several years of use of MCE mixes proved that real-life practice departed from the original idea of an MCE mixture that was intended as a flexible layer formed from as much material reclaimed from the old pavement as possible. This state of affairs motivated the road administration to verify the requirements concerning MCE mixes.

4.2. *International experience*

The first stage in the verification of the Polish requirements (Zawadzki et al., 1999) was an extensive study focusing on design and placement of MCE mixtures worldwide.

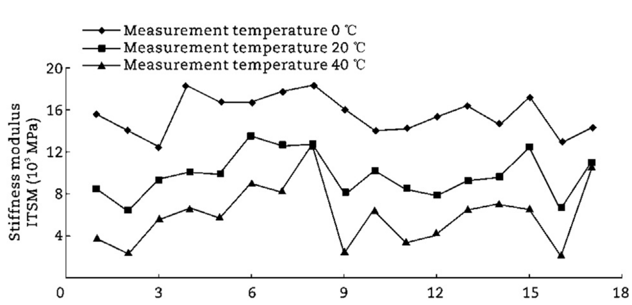


Fig. 7 – Variability of stiffness modulus over successive test days.

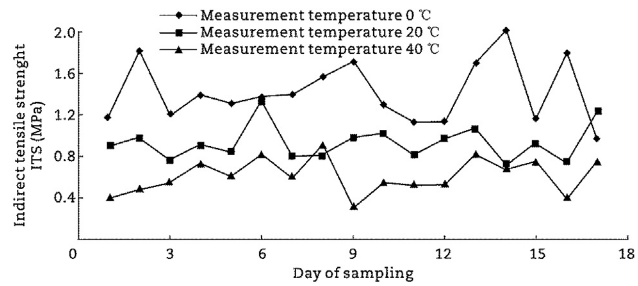


Fig. 8 – Variability of indirect tensile strength over successive test days.

Information was collected from various countries, including Germany (Merkblatt, 2005; WIRTGEN, 2004), England (Carswell et al., 2008; Merrill et al., 2004; Milton and Earland, 1999), USA (Michael et al., 2002; Theyse et al., 2004), Norway (Jostein, 2000), Japan (Yoshida and Noda, 2001) and road organization (PARAMIX, 2004; PIARC, 2003).

The literature study allowed for formulation of the following conclusions.

- There is no single commonly used method for MCE mix design. Differences exist on every stage of design, including selection of materials and assessment of the produced mixture.
- The choice of aggregate mix is based on a range of good gradation defined by limiting curves. The space between them is quite wide and defined in order to maximize the use of material reclaimed from existing pavements and simultaneously ensure proper compaction of the produced mix.
- There is a general tendency to minimize cement content in MCE mixes. Often requirements limit the cement content to 1%–2%. Where higher cement content is acceptable, it is still necessary to design the MCE mix in such a way that the bituminous binding dominates over the hydraulic binding.
- The basic parameter used for MCE mix assessment is the indirect tensile strength. Sometimes the stiffness of the mix is tested as well. Other properties such as Marshall stability or compressive strength are tested sporadically.
- Moisture susceptibility is tested very frequently. This parameter is defined on the basis of relative decrease in strength of specimens subjected to conditioning cycles in comparison to reference specimens. It is particularly significant in countries with high levels of pavement and soil moisture and frost.

The comparison between requirements in Poland (Zawadzki et al., 1999) and in other countries indicated the following fields where change was desirable.

- The Polish guidelines gave relatively narrow limiting curves for the gradation of the mineral-cement mix, defining a narrower range than in most countries. The range of acceptable gradation for MCE mixes needed to be broadened.
- An important element that the Polish guidelines were lacking was the assessment of impact of moisture on the

Table 3 – Number of cracks at the inspected road sections.

Road section	Section length (m)	Cracking index per 1 pc/km					Yearly crack quantity increment per 1 km since previous measurement				Mean yearly crack quantity increment
		2007	2008	2011	2012	2014	2008	2011	2012	2014	
DK6-1	1700	14	19	31	52	56	2	6	21	2	6.0
DK55-1	2000	0	0	1	5	11	0	0	5	3	1.5
DK22-1	1750	2	3	13	19	23	1	5	6	2	3.1
DK15-1	2000	3	3	4	5	9	0	1	1	2	0.9
DK15-2	2000	9	12	14	19	24	1	1	5	3	2.1
DK15-3	2000	2	3	3	4	6	1	0	1	1	0.6
DK7-1	2650	5	8	21	29	45	2	6	9	8	5.7
DK7-2	2500	NDA	0	2	5	9	2	1	2	2	1.8
DK7-3	2000	NDA	0	8	14	20	–	4	6	3	4.0
DK7-4	2000	NDA	0	1	1	2	–	1	0	0	0.3

Note: NDA – no data available.

properties of MCE mix. Requirements regarding moisture susceptibility had to be introduced, since generally in Poland the base is saturated with water through a large part of the year.

- In Poland the assessment of mechanical properties of the mix was based primarily on Marshall stability and flow tested at the temperature of 60 °C. Tests performed at this temperature did not reflect the real conditions under which the built-in MCE mix functioned. Possibility of relinquishing the Marshall stability and flow test needed to be taken into consideration. A different test – one that was used worldwide – was to be considered instead, that is the indirect tensile strength.
- The Polish guidelines did not take into account the actual stiffness of the produced mixture, which led to placement of overly stiff mixtures. It was advisable to introduce such tests in order to limit the stiffness of the MCE mixes used in pavements and, as a result, limit the risk of transverse cracking.

The past experience with MCE mixes implied that there was a need to revise the requirements considering their production and placement. All the aforementioned factors along with the experience up to date called for introduction of new requirements that would be more consistent with the actual practice, draw from international experience and take into account the changes to European standards.

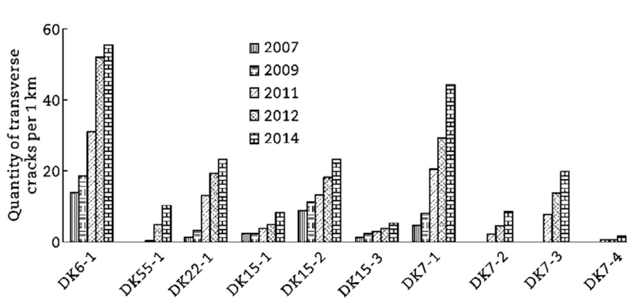


Fig. 9 – Quantity of transverse cracks at the observed road sections.

4.3. *Revised requirements for mineral-cement-emulsion mixtures*

In 2013 works on the new instruction concerning principles of design and placement of MCE mixtures were finished Dolżycki (2013). The instruction encompassed the in-place as well as in-plant recycling. The new requirements took into account:

- experience in terms of design, production and placement from various countries,
- widespread use of the material requirements based on the European standards,
- standardized test methods based on the European standards,
- Polish experience from the past practice with MCE mixtures as well as its implications.

The new requirements explicitly stated that the nature of an MCE base was dual. Depending on the achieved stiffness, MCE mixtures can be divided into two types (Merkblatt, 2005).

- mixture with dominating bituminous binding – flexible base,
- mixture with dominating hydraulic binding – rigid base.

When designing an MCE mixture, one should aim at achieving a dominating bituminous binding in order to minimize the risk of reflective cracking.

The mineral-cement-emulsion mixtures designed in accordance with the new rules can be freely used in reconstruction and construction of roads subjected to traffic categories from KR1 through KR4 (light and medium traffic), regardless of used technology.

In terms of properties of the materials used for MCE mixtures the following requirements were set.

- The reclaimed material is classified as either mineral-bituminous (i.e., mineral-asphalt, mineral-tar or mixed), mineral-cement or mineral. The reclaimed material cannot contain foreign or organic contaminants. It is necessary to

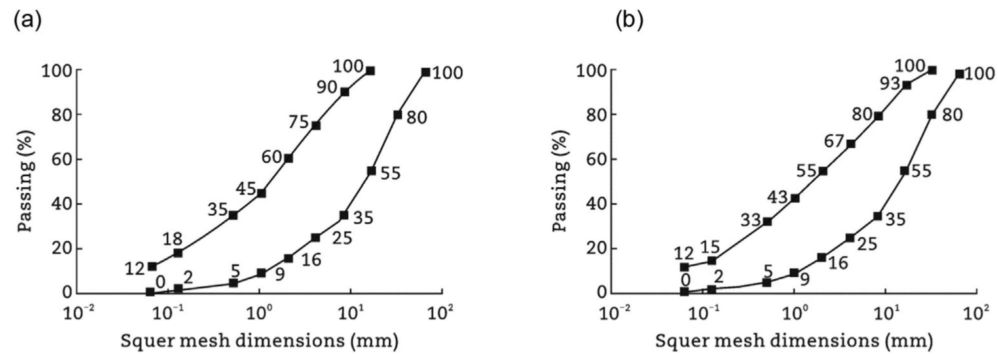


Fig. 10 – Mineral mix for MCE for light traffic (KR1–KR2) and medium traffic (KR3–KR4). (a) Mineral mix for light traffic. (b) Mineral mix for medium traffic.

determine the type of binder used in it as well as its ratio of bound vs. unbound material.

- Any new aggregate added to the mineral-cement-emulsion mix should be compliant with the PN-EN 13242:2013 standard.
- C60B5R bituminous emulsion with base bitumen of 100/150 penetration grade was used up to 2015. Since 2015 C60B10 ZM/R bituminous emulsion with 70/100 base bitumen is used. Bituminous emulsion is produced with the accordance to the PN-EN 13808 standard and respective national appendixes. Portland cement of type CEM I or multi-ingredient Portland cement of type CEM II, classes 32.5 and 42.5, should be compliant with the PN-EN 197-1 standard.
- Water should meet the requirements stated in the PN-EN 1008 standard.

The mix design process was divided into several successive steps. They were ordered as follows.

- Design of the mineral mix, which may contain reclaimed material plus new aggregate or only reclaimed material. The gradation of the mix should be continuous. Maximum particle size should not exceed 31.5 mm, but there is a 15% tolerance margin for particles retained on the first sieve. The limiting curves are shown in Fig. 10.
- Choice of the binding agents. Combination of the binding agents should be determined in accordance with the following general rule.
    - bituminous emulsion: from 2% to 6% (mass content),
    - cement: from 1% to 4% (mass content), regardless of used binder (bitumen or tar)

Regardless of negative experience with high cement content, the maximum allowable value of cement content was retained at the level of 4%, in order to enable the designer to obtain sufficient moisture resistance of the mix, with the reservation that for this value reflective cracking may occur.

- The detailed design procedure is described in a precise and clear manner, in order to avoid any misinterpretations in practical use of the instruction.
- The designed MCE mix should meet the requirements given in Table 4.

The requirements give rules for placement and acceptance of MCE mixes – the principles for compaction, traffic admission and acceptance of an MCE mix course are given. An MCE base should be built in accordance with all the principles, guaranteeing its homogeneity and compaction without any visible weak, damaged or non-homogeneous areas. The requirements for the compacted MCE course are given in Table 5.

The MCE mix is composed of materials reclaimed from existing pavements – often inhomogeneous and of variable quality. In such situations it is possible that values of measurements taken during control tests may exceed the permissible ranges shown in Tables 4 and 5. The new instruction provides guidance for assessment of such cases. The following solutions have been provided for relevant properties.

Table 4 – Requirements for the designed MCE mixture.

Property	Required value	
	Traffic KR1 and KR2 (light traffic)	Traffic KR3 and KR4 (medium traffic)
Air voids	8%–18% (vol.) max.14% (vol.)[1)]	8%–15% (vol.) max.12% (vol.)[1)]
Indirect tensile strength ITS, T = 5 °C, after 7 days (MPa)	0.40–0.90	0.50–1.00
Indirect tensile strength ITS, T = 5 °C after 28 days (MPa)	0.60–1.40	0.70–1.60
Stiffness modulus ITSM, T = 5 °C after 28 days (MPa)	1500–4000	2000–5000
Remaining indirect tensile strength after storage in water, no less than (%)	70	80

Note: [1)] For reclaimed materials that contain tar.

Table 5 – Requirements for the compacted MCE course.

Parameter	Requirement	
	Traffic KR1 and KR2 (light traffic)	Traffic KR3 and KR4 (medium traffic)
Relative compaction	≥98%	≥98%
Air voids	≤15% (vol.)	≤12% (vol.)
Base course bearing capacity		
• Secondary deformation modulus E_2 (static plate) (MN/m^2)	$E_2 \geq 140$	$E_2 \geq 180$
• Dynamic deformation modulus E_{vd} (dynamic plate) (MN/m^2)	$E_{vd} \geq 70$	$E_{vd} \geq 90$

- **Incorrect geometric parameters.** In such cases the course shall be removed at its full depth and placed again.
- **Incorrect thickness of the placed course.** In places where thickness is insufficient, the contractor shall fill the space with material from the layer that is to be placed on top of the MCE mix, whereas in cases of excessive thickness, the redundant material shall be removed if technically possible. Removal may be omitted if it is possible to correct the road profile in such a way that would enable placement of all the upper layers at their full designed thickness.
- **Incorrect strength of the placed course.** In case of strength assessment the mean value from the entire section shall be calculated. The results shall be qualified as acceptable if
  - The **mean** value lies within the required range.
  - At least 75% of measured values lie within the acceptable range.
  - At **most** 20% of measured values outside the acceptable range; but by no more than 30% of the acceptable value.
  - At **most** 5% of measured values outside the acceptable range by more than 30% of the acceptable value.
  - In **other** cases a repair plan shall be put forward and implemented only upon consent of the designer and client.
- **Insufficient bearing capacity of the placed course.** In case of bearing capacity assessment the mean value from the entire section shall be calculated. The results shall be qualified as acceptable if
  - The mean value is higher than the minimum acceptable value.
  - At least 80% of measured values are higher than the minimum acceptable value.
  - At most 20% of measured values are lower than the minimum acceptable value; but by no more than 15 MPa.
  - In other cases a repair plan shall be put forward and implemented only upon consent of the designer and client.

This approach is a novelty in Poland, as it tolerates placement of courses that do not precisely meet the requirements for the designed MCE mix. This attitude is acceptable to some extent, as the material in question demonstrates relatively high variability and is often mixed using in-place technology, which is not advantageous in terms of layer homogeneity. This approach, however, allows for a rational assessment of the placed course and enables wider use of the technology, which in its nature is dedicated to roads of lesser importance.

The above requirements were introduced in practice in 2014. After a transition period, the majority of new projects are currently realized based on the new requirements.

The proposed changes were focused on reducing the base stiffness and adjusting the test methods to current capabilities of road laboratories. The changes in requirements for cold-recycled MCE mixtures are in accord with the results obtained by other research centers (Batista et al., 2014; Bocci et al., 2011; Grilli et al., 2014; Iwański and Chomicz-Kowalska, 2016; Kavussi and Modarres, 2010; Sangiorgi et al., 2017; Stimilli et al., 2013; Yan et al., 2017).

4.4. *Stiffness of MCE mixtures*

The new instruction was introduced with aim to lower the stiffness of MCE mixes used. In order to verify whether this purpose has been achieved, research in laboratory conditions was performed, encompassing measurement of MCE stiffness using methods proposed in the instruction as well as by determination of stiffness moduli and phase angles in cyclic tensile test according to the AASHTO TP79 standard specification.

The MCE mixture for testing was designed as a mix for medium traffic (KR3-KR4) according to the new guidelines (Dołżycki, 2013). The mineral mix included reclaimed asphalt from local roads graded 0/31.5, a mix of unbound continuously graded crushed aggregate 0/31.5 as well as fine uncrushed aggregate 0/2 from a local quarry. Cement CEM I 42.5 R and bituminous emulsion C60B5R were used as binding agents. The optimum moisture content for the tested mixes was determined using Proctor method, taking into account the water included in the bituminous emulsion as well as an additional wetting effect by the bitumen included in the emulsion. Six different combinations of cement and bituminous emulsion content were used. Specimens for testing were compacted in a Marshall compactor with 75 blows per side. During preliminary testing of the samples air void content, stiffness moduli as well as indirect tensile strength were measured. The mechanical properties were measured after 28 days after compaction of the samples at the temperature of 5 °C. Some of the tested binder combinations did not meet the requirements stated in the new Polish instruction (Dołżycki, 2013). For cement content of 4% and emulsion content of 2% the produced mix was overly stiff, while for 2% of cement and 4% of emulsion the mix was overly flexible. Regardless of that fact, due to scientific nature of the tests, all mix combinations were taken into account at the next stage of the analysis, which focused on resistance to cracking. The compositions as well as the basic parameters of the designed MCE mixes are listed in Table 5.

Apart from the basic testing, more advanced parameters along with their changes under various circumstances were measured. Behavior of MCE mixes was described in detail in publications concerning impact of various factors (including curing time) on their stiffness modulus and phase angle (Dołżycki et al., 2017a, 2017b, 2018; Graziani et al., 2016, Godenzoni et al., 2017). Chosen test results of the average values of phase angles and modulus for MCE mixtures after 28 day of curing are presented in Table 6. As properties of MCE mixtures are time-dependent, values are presented for the frequency

10 Hz at the temperature of 20 °C. Values obtained for other frequencies and temperatures presented similar behavior to those presented in Table 6. Examples of master curves for the tested MCE mixes are shown in Fig. 11.

The results shown in Table 6 prove that the change of requirements allows for design of MCE mixes with noticeably lower stiffness than the ones used in the past (Table 2). The tendency is visible despite comparing two different test protocols. The moduli are approximately three times lower than the values obtained for the old requirements – though they are still relatively high. Indirect tensile strength has decreased as well. In this case the decrease is not as striking, but it still proves that currently the mixes are not as prone to cracking as in the past.

Lower stiffness of the tested MCE mixes can be observed in a cyclic tensile test as well. In this test the impact of the binding agent used (cement and emulsion) on the parameters of the tested material is evident. It is apparent that with the increase in emulsion content the modulus decreases, phase angle increases, and the material becomes less rigid and more flexible.

Further studies are required to assess whether the decrease in moduli of produced MCE mixes is sufficient to minimize the risk of transverse cracking.

4.5. *MCE mixtures in new pavement structures*

Due to relatively widespread use of cold recycling technology in Poland, the use of MCE mixes is now recognized as one of the standard solutions. The use of MCE mixes in new pavement structures, however, is not a very common practice and may need an additional explanation. The thickness of many reconstructed roads in Poland is insufficient due to requirements concerning resistance to ground heave. In order to provide resistance to ground heave, a new pavement structure

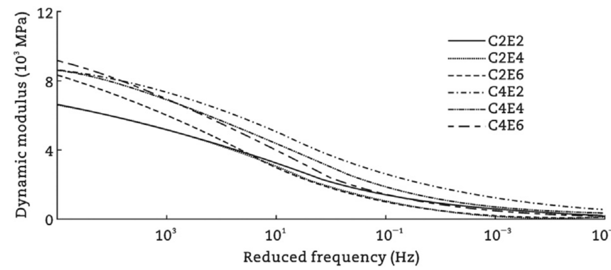


Fig. 11 – Master curves of tested MCE mixtures (C – the amount of cement, %; E – the amount of emulsion, %).

is often constructed that would meet all the requirements. In such cases, in order to maximize the use of material reclaimed from the old pavement, MCE base courses are chosen. Such an MCE base course is mixed in a stationary plant. Solutions of this type are increasingly popular in reconstruction of local and provincial roads.

Typical solutions using cold recycling technology were included in the new Polish catalog of typical flexible and semi-rigid pavement structures (GDDKIA, 2014; Judycki et al., 2014, 2017; Ryś et al., 2016). These solutions are shown in Table 7.

The above structures were designed based on calculations of fatigue life using mechanistic methods. The MCE course was modeled as a flexible layer, and during calculations a stiffness modulus of 1500 MPa was assumed. This value is noticeably lower than those obtained during testing, but it should be taken into account that it is supposed to represent the material after a certain period of performance, when the first distress and micro-cracks begin to occur, with natural lack of homogeneity and it is subjected to considerable loading. The assumed stiffness modulus was the same for both in-place and in-plant technologies.

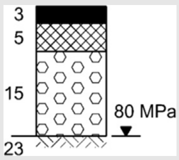
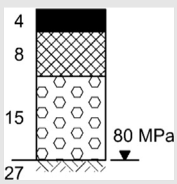
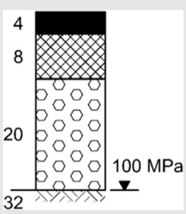
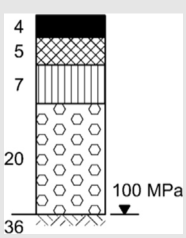
Table 6 – Composition of tested mineral-cement-emulsion mixtures.

Mixture ingredient	MCE mix labeling (C – cement, E – emulsion)					
	C2E2	C2E4	C2E6	C4E2	C4E4	C4E6
Composition of the mineral-cement-emulsion mix						
Reclaimed bituminous material	68.6	67.2	65.8	68.7	67.2	65.8
Crushed aggregate mix 0/31.5	17.6	17.3	16.9	17.6	17.3	16.9
Fine aggregate 0/2	9.8	9.6	9.4	7.8	7.7	7.6
Cement CEM I 42.5 R	2.0	1.9	1.9	3.9	3.8	3.7
Bituminous emulsion C60B5R	2.0	4.0	6.0	2.0	4.0	6.0
Added water	5.6	4.2	2.8	5.6	4.2	2.8
Main properties of tested MCE mixtures						
Air voids (after 2 × 75 impacts) (%)	14.3	17.1	16.7	13.9	15.8	15.8
Stiffness modulus ITSM, 5 °C, 28 days (MPa)	5867	4799	5985	8615	6056	6140
Indirect tensile strength ITS, 5 °C, 28 days (MPa)	0.64	0.74	0.94	1.18	1.02	1.08
Results in cyclic tensile test according to the AASHTO TP79 (frequency 10 Hz, temperature 20 °C)						
Dynamic modulus (MPa)	2969	2662	2711	4880	4224	3404
Phase angles (%)	13.10	15.81	18.72	10.38	13.40	15.43

5. Summary and conclusions

The Polish experience shows that the cold recycling technology has a very wide range of applications in reconstruction of considerably distressed and old road pavements. The early Polish experience proves that improperly defined requirements for cold recycling mixtures may lead to production of an overly stiff mix, resulting in transverse cracking of the pavement. Field observations, laboratory research and investigations of causes of cracking led to modifications in the requirements. The change in the requirements was meant to introduce a tendency to design cold recycling mixtures that would be more flexible. Under laboratory conditions, the MCE mixes designed in accordance with the new requirements showed lower stiffness, but only further inspections of currently constructed road sections may verify whether the achieved decrease in cold recycling mix stiffness is sufficient to eliminate the risk of reflective cracking. The performed research demonstrated that greater care is necessary during the design of composition of the cold-recycled MCE mixtures, in order to achieve the required parameters using the minimum possible cement content. It is possible when the optimum mineral mixture is designed (the reclaimed material and the new added aggregate).

Table 7 – Typical pavement structures with MCE mix bases.

Structure	Layer system	Traffic, millions of 100 kN axle loads
h (cm) 	3 cm→wearing course – asphalt concrete or SMA 5 cm→binder course – asphalt concrete 15 cm→base course from recycling (MCE mix or foamed bitumen) Subgrade improved to 80 MPa	0.03–0.09 (KR1)
h (cm) 	4 cm→wearing course – asphalt concrete or SMA 8 cm→binder course – asphalt concrete 15 cm→base course from recycling (MCE mix or foamed bitumen) Subgrade improved to 80 MPa	0.09–0.50 (KR2)
h (cm) 	4 cm→wearing course – asphalt concrete or SMA 8 cm→binder course – asphalt concrete 20 cm→base course from recycling (MCE mix or foamed bitumen) Subgrade improved to 100 MPa	0.50–2.50 (KR3)
h (cm) 	4 cm→wearing course – asphalt concrete or SMA 5 cm→binder course – asphalt concrete 7 cm→base course – asphalt concrete 15 cm→sub-base from recycling (MCE mix or foamed bitumen) Subgrade improved to 100 MPa	2.50–7.30 (KR4)

The described evolution of requirements for cold recycling with the use of MCE mixtures shows how the incorrect requirements were identified and modified in Poland. The road sections constructed using this technology will be further monitored in order to verify whether the introduced changes were sufficient. For foreign authorities and designers, the Polish experience may serve as a cautionary example against allowing excessively stiff MCE mixtures, which would contribute to an increase in the number of transverse cracks.

Due to the efforts devoted to optimization of cold recycling, this technology has become very popular for reconstruction of roads of lesser importance. Lately cold recycling with the use of MCE mixtures became so popular in Poland that it has been introduced into common practice by inclusion in the new Polish catalog of typical flexible and semi-rigid pavement structures as one of the typical solutions.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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