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BINDER COURSES USING COLD RECYCLED MIXTURES – A NOVEL CONCEPT IN COLD RECYCLING

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Abstract

Cold recycling with cement and bituminous emulsion is one of the most environmentally friendly techniques to maximize the reuse of reclaimed asphalt (RA) collected during demolition of roads. Cold recycled mixtures are commonly used for base courses in construction or rehabilitation of flexible and semi-rigid pavements. Current experiences demonstrated that cold recycling with appropriate requirements and technical recommendations allows long-lasting pavements to be designed. Those outcomes stimulated researchers and engineers in the new challenge of using the cold recycled mixtures in binder layers that are generally more often included in maintenance planning. This paper summarizes current San Marino and Polish experiences with cold recycled mixtures designed for binder layers. The first part of the paper presents the design phase of the cold recycled mixtures in both countries. It describes and compares the composition of the mixtures, grading curves of the mineral mixtures, binding agents and requirements. The second part of the paper shows laboratory test results of mechanical properties of cold recycled mixtures for binder courses including test results in full-scale application.

Keywords: cold in-plant recycling, binder course, mix design

1 Mix design of cold recycled mixtures

Cold recycling is one of the most ecologically friendly technology for reconstruction of old deteriorated asphalt pavements [1, 2, 3]. cold recycling can be applied following two approaches: in-plant and in-situ production. Cold in-plant recycling (CPR) allows using more than one fraction of selected reclaimed asphalt (RA) and virgin aggregates. Consequently, an optimal control of the product quality can be assured. Typical, CPR is utilized for the production of pavement sub-base and base courses [4]. However, an accurate mix design, management and production process can increase the degree of confidence and the performance expectations of the final product as required for binder courses [5].
This paper compares Polish and San Marino approaches to establish a mix design procedure for cold recycled mixture to be used as binder course.
In both countries, the mixtures presented in this study were designed according to the related requirements for cold recycled mixtures. In both countries, regulations for cold recycled mixtures were originally developed for base layers and then adapted to binder layers. Indeed, the different functionality between base and binder courses required to adequately change the requirements for mixture composition and selection criteria. Taking into account the different climatic condition and the state of practice, the procedures adopted in the Republic of San Marino and Poland differ each other as reported in table 1.

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Table 1 Qualitative comparison between San Marino and Poland mix design procedures

Issue	San Marino procedure	Poland procedure
Compaction method	gyratory compactor	Marshall compactor
Cement dosage [% by aggregate weight]	1.5 - 2.5	1.0 - 4.0
Emulsion dosage [% by aggregate weight]	4.0 - 5.0	2.0 - 7.0
Type of bituminous binder	Modified bituminous emulsion	Emulsion with unmodified bituminous or foamed bitumen
Volumetric parameter	Dry density	Dry density
Curing process	3 days at 40°C	7 and 28 days at 20±5°C
Testing temperature	25 or 20°C	5°C
Mechanical requirement	ITS at 25°C ≥ 0.40 MPa ITSR ≥ 80% ITSM at 20°C ≥ 3.000 MPa	7 days: ITS at 5°C: 0.5 – 1.0 MPa ITSM at 5°C: 1500 – 4500 MPa 28days: ITS at 5°C: 0.7 – 1.6 MPa ITSM at 5°C: 2000 – 7000 MPa ITSR ≥ 80%

1.1 Mix design procedure complying with San Marino specification

Each fraction of RA has to be designated following the EN 13108-8. Moreover the RA maximum size, shape index (SI), flakiness index (FI), gradation of RA (washed method), gradation of aggregates and bitumen content have to be determined as average and standard deviation values from 5 samples when the total amount of RA to be used in the project is less than 2,500 t or 1 sample every 500 t when the total amount of RA to be used in the project is more than 2,500 t. SI and FI have to be below 30 % and the RA maximum size does not exceed the mixture maximum size. The other characteristic values are used as reference for quality control and the standard deviation as homogeneity parameter.
The cationic modified bituminous emulsion has to respect the requirements reported in table 2. It has to be produced using a 70/100 or 50/70 paving grade bitumen and designated as C60BP10 according to the EN 13808. The cement type CEM I (Portland cement), CEM II (composite Portland cement with fly ash, slag and limestone), CEM III (blast furnace cement), CEM IV (pozzolanic cement varieties) and V (Composite cement) complying with EN 197-1 can be used with no specific restrictions. CEM II is recommended when RA has low filler content (lower than 2 %).

Table 2 Requirement for modified bituminous emulsion for cold in-plant recycling in San Marino

Modified bituminous emulsion				
Parameter	Standard	Unit	Required value	Class EN 13808
Setting at 7 days	EN 12847	[%]	≤ 10	3
Adesivity	EN 13614	[%]	≥ 90	3
Breaking value	EN 13075-1	-	> 150	5 (or above 5)
Stability with cement	EN 12848	[g]	< 2	10
Residual bitumen				
Cohesion at 10°C	EN 13589 EN 13703	J/cm²	≥ 2	6
Elastic recovery	EN 13398	[%]	> 50	3

Two gradation bands are recommended depending on the layer thickness: AC20 for 10-15 cm thick courses, AC30 for 15-20 thick courses. The volumetric and mechanical characteristics of the cold recycled mixtures have to be determined using a gyratory compactor (EN 12697-31) at the fixed energy of 100 revolutions [6]. Each sample series has to consist of at least three specimens and the coefficient of variation of results (standard deviation/average) expressed as a percentage has to be lower than 15 %. The proportion of components (granular blend, modified bituminous emulsion, cement and water) has to be established following a specific mix design method (table 3).

Table 3 Mix design procedures for cold in-plant recycled mixture in San Marino

Optimum water content – first phase			
Cement	[% by aggregate weight]	2	Maximum Dry density; Leaking water ‹ 0.5%
Water	[% by aggregate weight]	3, 4, 5, 6	
Optimum binder content – second phase			
Water	[% by aggregate weight]	optimum	ITS ≥ 0,40 MPa; ITSR ≥ 80 %; ITSM ≥ 3000 MPa
Cement content	[% by aggregate weight]	1.5; 2.0 and 2.5	
Emulsion content	[% by aggregate weight]	4.0; 4.5 and 5.0	
Ratio between bitumen and cement contents › 1			

The first phase of the mix design requires to define the optimum water content. Specimens with different water content have to be compacted with 2 % of cement (by aggregate weight). Each specimen has to be weighed before and after the compaction to measure the leaking water. All specimens have to be dried at 40 °C till constant weight (successive weightings at least one hour apart not differeing by more than 0,1 %) and the dry bulk density has to be measured following the EN 12697-6/procedure D. The optimum water content corresponds to the highest dry density. Moreover, the water loss during the compaction process has to be less than 0.5 % by mixture weight.
The second phase of the mix design requires to define the optimum dosage of binders. Specimens (at least three specimens for each series) with different bituminous emulsion and cement contents have to be compacted with the optimum water content (considerng also water brought into the mixture by the emulsion). The combination of bituminous emulsion and cement dosages has to respect a bitumen/cement ratio upper to 1.

1.2 Mix design procedure complying with Poland specification

Cold recycled mixtures are typically used in Poland for base and sub-base courses. Nowadays, there are no specifications or regulations for designing cold recycled mixtures for binder course. For this reason, the proposed mix design procedure for binder courses follows the adopted procedure for base courses taking into consideration appropriate changes in materials and mixture properties.
The first step deals with the design of granular mix composition, which may contain of RA and virgin aggregate or only RA. In the base course the maximum particle size should not exceed 31.5 mm, but in binder course the maximum particle size is 16 mm, and the grading envelope is slightly altered (table 4). The second step determines the choice of the binding agents, which combination should be determined on the following limits for base course: cement dosage from 1 to 4 % and bituminous emulsion dosage from 2 to 6 %. Emulsion can be used in place of foamed bitumen. The alteration of grading curve leaded also to slight change of the permissible dosage of binding agents. The range was extended in the case of emulsion

up to 7 %. The last step in selecting basic composition is determination of the optimal liquid content taking into consideration additional water and water included in the mineral mix and bituminous emulsion.
After the determination of the basic composition of the mixture, specimen for performance test should be prepared. Cylindrical specimen of 100 mm diameter and 63.5±2.5 mm height should be prepared using Marshal compactor (EN 12697-30). Specimens are prepared in special perforated moulds using 75 blows per side.

Table 4 Requirement for cold recycled mixtures in Poland

Property	**Required values**								
	Low traffic				**Medium traffic**				
Voids content [%]	8 – 18				8 – 15				
ITS after 7 days, +5°C, 50 mm/min [MPa]	0.4 – 0.8				0.5 – 1.0				
ITS after 28 days, +5°C, 50 mm/min [MPa]	0.6 – 1.4				0.7 – 1.6				
ITSM after 7 days [MPa]	1000 – 3500				1500 – 4500				
ITSM after 28 days [MPa]	1500 – 5000				2000 – 7000				
ITSR after 28 days, +5°C [%]	› 70				› 80				
Mixture gradation									
Sieve size [mm]	0.063	0.125	0.5	1	2	4	8	16	22.4
Total passing [%]	0-12	2-15	8-30	13-40	21-50	32-63	52-80	85-100	100

2 Performance tests of binder course

2.1 Field experiences in Poland

The mechanical properties were evaluated in terms of the indirect tensile stiffness modulus (ITSM) according to EN 12697-26, strength (ITS) according to EN 12697-23 and Dynamic Modulus according to AASHTO TP79. In ITSM test specimens were tested in strain-controlled mode at 5 °C, and target deformation of 5 μm. The results were evaluated using a pre-defined value of the Poisson's ratio of 0.3. In ITS test specimen were tested with the rate of deformation equal to 50mm/min at 5 °C. Before the testing, specimens were conditioned in thermostatic chamber for 4 h at the testing temperature. In Dynamic Modulus test specimens were tested at three temperatures: 4 °C, 20 °C and 40 °C in strain-controlled mode (100 μstrain). Strain was measured with 3 LVDT sensors (gauge length of 70 ± 1 mm) attached to the specimen. Stiffness modulus were measured at 9 frequencies from 25 Hz to 0.1 Hz at temperatures of 4 °C and 20 °C. At the temperature of 40 °C, test was conducted at an additional frequency of 0.01 Hz. In ITS and ITSM tests, specimens were tested 7 and 28 days after compaction. In the case of Dynamic Modulus, specimens were tested only 28 days after compaction. Specimens were stored in a laboratory condition, under typical temperature and moisture conditions without any special conditioning. Master Curves of stiffness modulus were developed using procedure presented in AASHTO TP79. The used equation (1) assumed that shift factor was calculated using Arrhenius equation. In the further analysis "psi" units were converted into "MPa" units.

$$\log\left|E^*\right| = \delta + \frac{\left(Max - \delta\right)}{1 + e^{\beta + \gamma\left\{\log f + \frac{\Delta E_a}{19.14714}\left[\frac{1}{T} - \frac{1}{T_R}\right]\right\}}} \qquad (1)$$

where:
|E*| – dynamic modulus, psi (1 psi ≅ 0.00689 MPa);
Max – limiting maximum modulus, (treated as fitting parameter), psi;
f – frequency, Hz;
T_R – reference temperature, K;
T – test temperature, K;
β, γ, δ – fitting parameters;
ΔEa – activation energy (treated as fitting parameter).

Results of the ITSM and ITS test are presented in table 5. Results of dynamic modulus test are presented in table 6. As for Poland the mixture presents similar mechanical properties values as typical CIR used for base course for high traffic [7]. Results of SPT test for Polish mixture for binder course are compared with previous results [8] obtained for base course.
In the intermediate and higher temperatures, the obtained results for similar combination of binding agents are almost the same, with slightly higher modules for mixture for binder course. Contrary, at low temperature, mixture for binder course presents significantly lower dynamic modules. The most probable cause is using smaller maximum aggregate size and higher amount of bituminous emulsion.

Table 5 ITS and ITSM test results for C3B4.2 mixture

Property	**Value**	
	ITSM at +5 °C (MPa)	ITS at +5 °C (MPa)
7 days	4195 ± 195	0.69 ± 0.05
28 days	4921 ± 218	0.78 ± 0.09

Table 6 Dynamic modulus test results and master curve parameters

Mixture designation	Temp. [°C]	Frequency [Hz]									
		25	20	10	5	2	1	0,5	0,2	0.1	0.01
Dynamic modulus [MPa]											
C3B4.2 (PL)	4	5 531	5 357	5 017	4 684	4 263	3 954	3 668	3 311	3 071	
	20	2 957	2 855	2 569	2 305	1 983	1 777	1 594	1 378	1 248	
	40	1 675	1 582	1 365	1 182	980	869	775	676	620	508
Mixture designation	Master curve parameters										
	Max		δ		β		γ		ΔEa		
C3B4.2 (PL)	6.065		4.687		-0.215		-0.511		187 206		

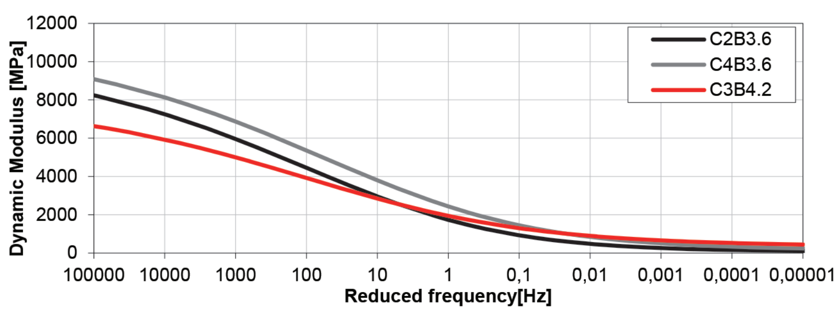

Figure 1 Master curves for CIR mixtures (PL) for binder (C3B4.2) and base (C2B3.6, C2B3.6) course with similar proportions of binding agents, T_{ref} = 20 °C

2.2 Field experiences in San Marino

Following the mix design method established in San Marino the optimum mixture consisted of: 4.5 % of bitumen emulsion (2.7 % of residual bitumen), 2 % of cement, 5 % of water by aggregate weight (including water brought in by emulsion) 88 % of 16RA0/12, 10 % of 0/1 G_F85 and 2 % of mineral filler. According to the specification of the San Marino road agencyError! Reference source not found., this recipe allowed obtaining a dry density of 2123 kg/m^3, an indirect tensile strength at 25 °C of 0.41 N/mm^2 and an indirect tensile stiffness modulus at 20 °C of 4747 MPa after a curing period of 72 hours at 40 °C [9]. Trial sections were built [5] for testing the effects of environmental factors (temperature and humidity) on the evolutions of mechanical proprieties, evaluated in terms of indirect tensile strength (ITS), of cold recycled mixtures during the curing period. Figure 2 shows the evolution of ITS values of laboratory specimens and cores taken from the trial sections as a function of the curing time. The specimens were cured in the laboratory, in a climatic chamber, in different conditions (sealed and unsealed) and temperatures (40 °C and 25 °C).

The ITS values for lab-compacted specimens cured at 25 °C show an increase from 3 to 7 days. However, the curing effects are more evident on unsealed specimens in which the ITS values increased more than 50 % (from 0,27 to 0,41 N/mm^2), while ITS values increased about 10 % for the sealed specimens (from 0,15 to 0,17 N/mm^2). In the short curing time, these results mainly depend on a slower emulsion setting in sealed condition and the reduced contribution of the hydration of cement. Whilst, the unsealed condition facilitates the water evaporation, with a faster increase of ITS values (more than 80 % respect the sealed condition) due to the bitumen setting.

Increasing the curing temperature at 40 °C, the ITS values after 3 days reached an average value of 0.41 N/mm^2, which complies with the design specifications. It should be noted that the same ITS value was obtained after 7 days when curing temperature was set at 25 °C.

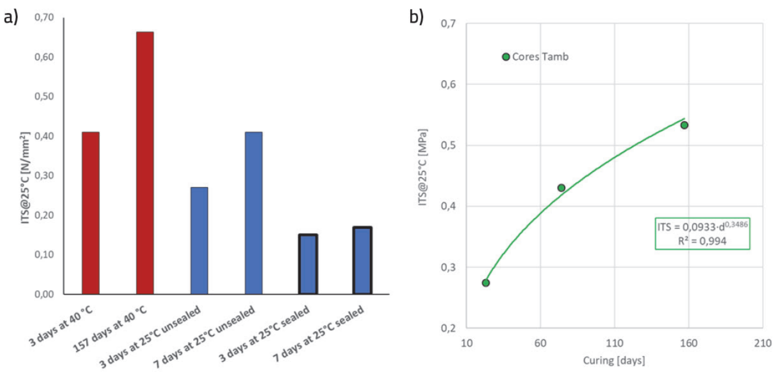

Figure 2 Evolutions of ITS values during the curing period of: a) sepcimens, b) cores

Analyzing the results for the cores extracted from the trial sections, it can be asserted that the increase of ITS values over time follows with good approximation a power law with exponent value lower than 1. The ITS values increase from 0.28 to 0.43 and finally to 0.52 N/mm^2 respectively after 23, 74 and 157 days (Figure 2b).

Using the same power law, the ITS values reached on sealed specimens and lab-curing at 25 °C for 3 and 7 days correspond to about 4 and 6 days of in-situ curing (average ambient temperature of 20 °C) showing therefore a good relationship. On the other hand, the values determined after the accelerated lab-curing at 40 °C for 3 days are reached an extremely longer time (about 70 days of in-place curing). Only after 157 days in-situ curing the core ITS tends to the maximum value obtain in the laboratory.

3 Conclusions

This paper compared two design and testing approaches for cold recycled mixtures and the following conclusions can be drawn:

- the pratical passed experiences and climatic conditions influence the selection and level of performace parameters to be established in a mix design procedure;
- selected RAP fractions and mix design procedures allow achiveing cold recycled mixture with high quality to be used for binder course;
- both contries gathered promising results from applications of cold recycling for binder courses.

Further works should be focused on evaluation of full scale sections subjected to real climatic and traffic conditions.

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