INNOVATION IN ROAD PAVEMENTS: REP-RAP ADDED COLD RECYCLED MIXES

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ABSTRACT
Reclaimed fire extinguisher powders (REP) should be maintained (REP disposal) at regular intervals and therefore many issues can arise at the end of their usual life cycle.
On the other hand, the use of reclaimed asphalt pavements (RAP) can be a valuable resource. Indeed, it can help to reduce the life cycle cost (LCC) of pavements and to contribute to a sustainable development.
Furthermore, cold mixes use less energy and produce fewer emissions than hot mixes, but more efforts are still needed to develop a generally acceptable laboratory design method for asphalt emulsion cold mixes.
Objectives and scope of this paper were confined into the analysis of production process and mechanical properties of cold bituminous mixes containing fire extinguisher powders (REP) and Reclaimed Asphalt Pavements (RAP).
The results indicate that, even if further improvements are needed, the application of REP powders into cold mixes can result quite satisfactory both for traditional and environmental issues.
The benefits of adopting this innovation were investigated and outlined.
This information could help decision makers to foster and promote innovation, to contribute to sustainable development, and to select more sustainable rehabilitation strategies and procedures in order to achieve the best overall condition.

1. BACKGROUND

In the last decades growing interest focused on cold Asphalt Pavement Recycling with Reclaimed Asphalt Pavement (RAP) because of the pressing issues for sustainable development, materials conservation, energy saving and gaseous emissions reduction [1] – [8].

Recycling is one among several alternatives available for rehabilitation of pavements. Other methods include overlay and complete removal and replacement. Recycling has the following advantages: (a) reduced cost of construction, (b) conservation of aggregate and binders, (c) preservation of existing pavement geometrics, (d) preservation of environment, and (e) conservation of energy [9]. It is important to remark that the type and amount of benefits depend on the particular recycling method [10].

There are different recycling Methods (Figure 1):
•Hot In-place Recycling;
•Hot Mix Recycling (central plant);
•Cold Mix Recycling (central plant);
•Cold In-Place Recycling;

•Cold Planing or cold milling (controlled cold milling of pavement to restore the surface to a specified profile);
•Full Depth Reclamation.

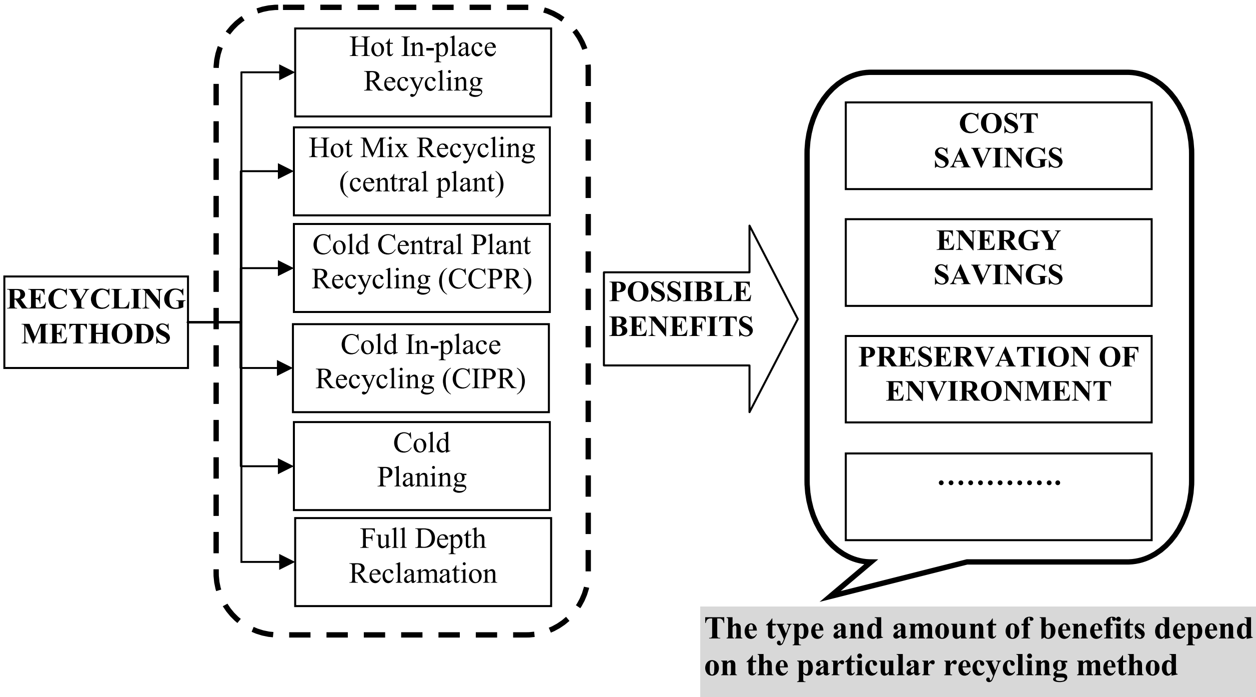


Figure 1 Schematics of recycling methods

As is well known, cold recycling involves the reuse of all or a portion of an aged pavement as a part of a rehabilitated one. The two main methods of cold recycling are cold central plant recycling (CCPR) and cold in-place recycling (CIPR). Cold in-place recycling (CIPR) is a continuous multi-step process in which the existing asphalt pavement is cold-milled and blended with asphalt emulsion and aggregate, if necessary [11].

They consist in mixing crushed asphalt pavement, a recycling agent and water without heat or with even a small amount of heat. The recycling additives often used are emulsified asphalt, cements and emulsified asphalt, recycling agents. Other possible choices are soft asphalt cements, cutback asphalt, foamed asphalt, and combinations of emulsions with cement, fly ash, or lime [11]

The type of recycling agent influences the fatigue properties of the mix. According to [12], asphalt emulsion recycled cold mixes showed a plastic failure, due to their visco-elastic characteristics, while fatigue damage of foam asphalt cold recycled mixes showed a brittle fracture.

Cold in-place recycling can be accomplished as full-depth reclamation or partial-depth recycling. For full-depth reclamation the milling of the pavement is performed at depths of 100 to 300 mm (4 to 12 in). The crushed pavement and additional aggregate (when required) are combined to warm mixture that will result in a new layer.
Several advantages can be associated to the cold in-place recycling (see table 1 and figure 2):

1. Structural**.** From a structural standpoint significant improvements may be achieved without changes in horizontal and vertical geometry and without shoulder reconstruction. Old pavement profile, crown, and cross slope may be improved. This is important for proper drainage, snow removal and the overall ride comfort for the road users. Cold recycling allows to treat almost all types of distress: reflection cracking normally is eliminated if the depth of pulverization and reprocessing is adequate and pavement ride quality is improved. Transverse and longitudinal cracks, potholes, wheel ruts, and other irregularities are removed during the process. Frost susceptibility may be reduced. Pavement widening operations may be accommodated. The overall ride is improved [13].

2. Resources/disposal**.** From an environmental point of view, the incorporation of recycled materials in road construction in substitution of virgin materials is perceived as an opportunity to save resources and avoid the impact associated with their extraction, transportation and disposal. According to [13], conservation of existing aggregate resources, reduction of department aggregate requirements, especially in aggregate scare regions, reduction of the dependence on asphalt cements are major benefits. Disposal of pavement materials is eliminated.

3. Energy consumption**.** CIPR is the alternative with the lowest impact on the environment from the viewpoint of energy consumption. Under normal haulage distances, recycling using foamed bitumen reduces energy consumption between 20% and 50% compared to an asphalt overlay project, and up to 244% compared to a reconstruction project [14]. It was found that the CIPR options consume the least amount of energy, ranging from 25 to 35% less than TCO (two-course overlay) and 30 to 60% less than the MF (mill and fill) options [10].

4. Costs and LCCA**.** Significant cost savings can be associated to cold recycling process: aggregate and asphalt binder are conserved, hauling costs can be minimized, production rate is high [10]. According to the Asphalt Recycling and Reclaiming Association, cost savings can range from 20 to 40 percent over conventional techniques. Because no heat is used, energy savings can be from 40 to 50 percent [15]. CIPR is about 45% less cost then a 4" HMA overlay [16]. Research showed that cold in-place recycling uses 62% less aggregates and costs 40 to 50 percent less than the conventional mill and overlay treatment. Eckmann and Soliman [17] estimated on average savings in energy and aggregate costs up to 20 %. CIPR reduces overall engineering costs by reducing the amount of time required for pavement design and surveying activities [13]. Based on the life cycle cost of pavement rehabilitation in the Municipality of Ottawa, the annual cost for the recycled rehabilitation method (75 mm of CIPR + 40 mm of a hot bituminous wearing course) is approximately 80% of the standard hot bituminous overlay method (40 mm of a hot bituminous correction course + 40 mm of hot bituminous wearing course). In Quebec, the number reported was 70% of the traditional rehabilitation method. Hauling costs can be minimized. CIPR rehabilitation exhibits the lowest life-cycle environmental burden. The computer program "Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects" (PaLATE) was used to compare the costs, energy and environmental burden of employing cold in-place recycling (CIPR), mill and fill (MF) and two course overlay (TCO) maintenance options with similar conclusions [10].

5. Greenhouse gas. CIPR rehabilitation emits the lowest quantity of greenhouse gas emissions [10]. CIPR reduces carbon dioxide emissions by 52 percent, nitrous oxide

emissions by 54 percent, and sulphur dioxide emissions by 61 percent [18]. Eckmann and Soliman [17] estimated savings in Gaseous emissions (CO_2, SO_2) around 20 %.

6. Fuel. CIPR Reduces fuel dependencies and requirements by reducing aggregate hauls on CIPR projects [13].

7. Traffic and loading. CIPR reduces impacts on adjacent roadways by reducing aggregate hauls. Under most cases new aggregate is reduced or eliminated, thus reducing the impact of increased loading on adjacent haul roads. CIPR reduces inconveniences to the travelling public and the trucking industry. CIPR construction procedures are less disruptive to vehicles and traffic accommodation. [13]

8. Air quality. Air pollutants are reduced because of less haulage of materials and no heating of materials. Air quality problems resulting from dust, fumes, and smoke are minimized.

In Table 1 different solutions/techniques are compared and cold recycling benefits (in terms of cost savings, energy savings and reduced greenhouse gas emissions) are listed. Cold in-place recycling appears as the alternative with the lowest construction cost, energy consumption and impact on the environment.

Table 1 – Cold Recycling Benefits

COMPARED SOLUTIONS/ METHODS	ENERGY SAVINGS (%)	COST SAVINGS (%)	GASEOUS EMISSIONS (%)	REFERENCES
CIPR *vs.* conventional techniques	40-50	20-40		[19]
“BB à l’émulsion” *vs.* “BBSG traditionnel”	24		-34	[20]
Cold recycling in a plant *vs.* typical solutions	40-55			[21]
CIPR *vs* conventional methods	20			[22]
CIPR *vs* asphalt overlay project	20-50			[14]
CIPR *vs* reconstruction project	up to 244			[14]
CIPR *vs* conventional methods	up to 20		-20	[17]
CIPR *vs* new hot bituminous materials	80			[23]
Cold Recycling *vs*. hot mixes	80			[24]
CIPR *vs*. HIR	80			[25]
CIPR *vs*. conventional mill and overlay treatment		40-50	-(50-60)	[18]
CIPR *vs*. 4” HMA overlay		45		[16]
CIPR *vs*. MF	30-60			[10]
CIPR *vs*. TCO	25-35			[10]
LEGEND CIPR = Cold in-place recycling; BB = Béton bitumineux à l’émulsion; BBSG = béton bitumineux semi grenu (semi-course asphalt concrete); HIR = Hot In-place Recycling; MF = mill and fill; TCO = two-course overlay.				

Figure 2 summarizes the energy consumption for different solutions [26]. Importantly, the following contributions are specified: laydown (compaction included), hauling, production, aggregates, and asphalt binders. Y-axis refers to energy consumption per ton of material (1 metric ton ≈ 9807 newtons), while x-axis refers to different pavement layers or solutions.

The first six solutions refer to bituminous mixes. Solutions 7 to 11 refer to hydraulic binders. Solution 12 (grave non traitée) refers to unbound, untreated materials (main components: aggregates, hauling, laydown). Solution 13 (sol traité liant routier) refers to soil stabilization. In this case the main components are: binder, hauling, laydown.

Solutions 14 to 20 refer to recycled bituminous mixes. In more detail, solution 20 refers to cold recycling. Solutions 14 and 15 refer to the same process as examined by different authors.

By referring to the case under investigation, it is noted that REP powder is the ABC or Multi-Purpose chemical. It is a dry fire-extinguishing agent. ABC is a specially fluidized and siliconized monoammonium phosphate powder ($NH_4H_2PO_4$, 50-80% by weight). ABC insulates Class A fires (ordinary combustibles) by melting at approximately 180-200°C, and then coats the surface to which it is applied. ABC thus breaks the chain reaction of Class B fires (involving flammable liquids or gases), and is an electrical insulator. The potential of REP as component of bituminous mixes was studied in [28, 30, 31], while the potential to improve fire-resistance was studied in [34]. Furthermore, in [28] a diametral fatigue test was carried out on recycled bituminous mixes containing REP powders. The addition of the REP in the mixture had a twofold objective [28]. The reuse of powders of the fire extinguishers generates a positive impact in the waste management of these powders. Furthermore, the addition of powders has the potential to influence the performance of asphalt binders and asphalt mixtures in case of fire because of the potential for a flame-retardant behaviour. This performance of the asphalt mixture could make it very suitable for application in tunnel pavement. Indeed, as is well known, fire accidents in road tunnels can cause severe injuries and road tunnel safety became a subject of increased public interest.

In the light of the abovementioned facts, the objectives and scope of this paper were confined into the analysis of production process and mechanical properties of cold bituminous mixes containing fire extinguisher powders (REP) and Reclaimed Asphalt Pavements (RAP).

In order to pursue the objectives, the following main tasks were carried out:

- characterization of REP powders and RAP;
- testing of the cold mixes.

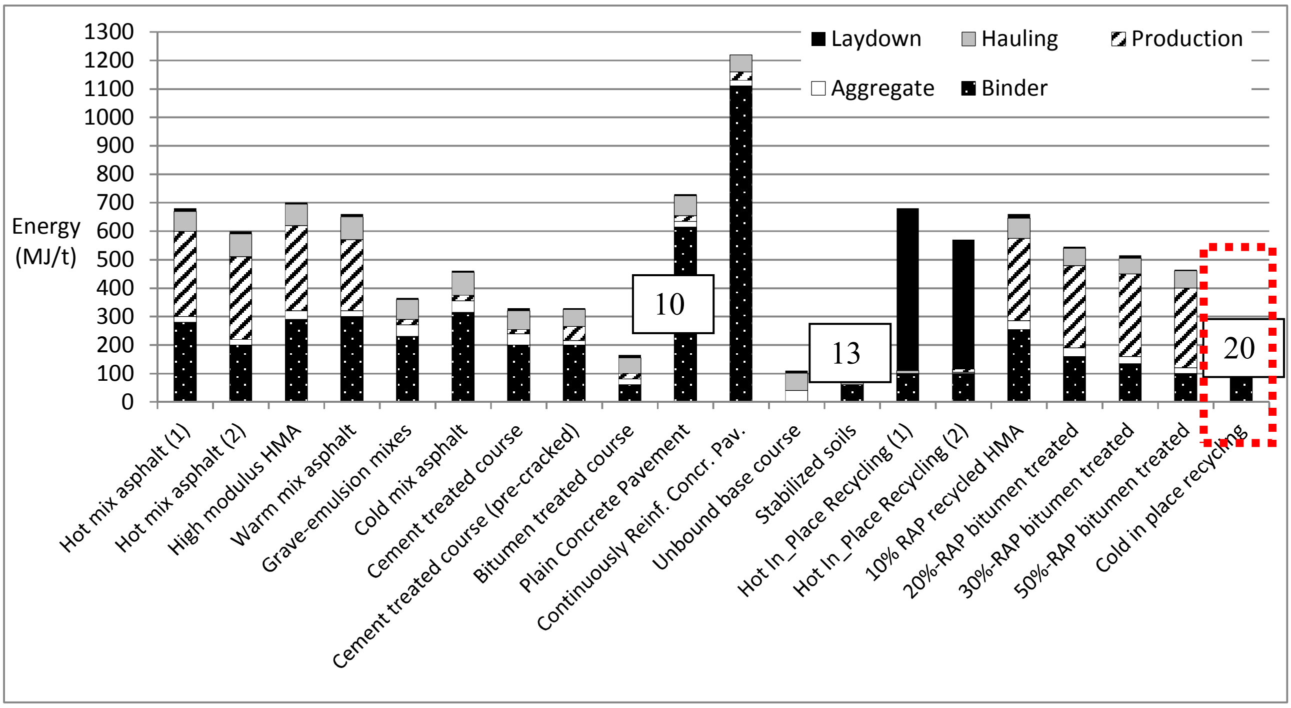


Figure 2 – Energy consumption (MJ/ton) for different pavement layers ([18], [26], [27])

2. EXPERIMENTS

Experiments were planned as follows: REP characterization, RAP characterization, Characterization of bituminous emulsion, Characterization of the mixture REP + bitumen, Production, characterization and testing of cold recycled mixes. Figures 3 to 9 and tables 2 to 12 summarize experiments and results.

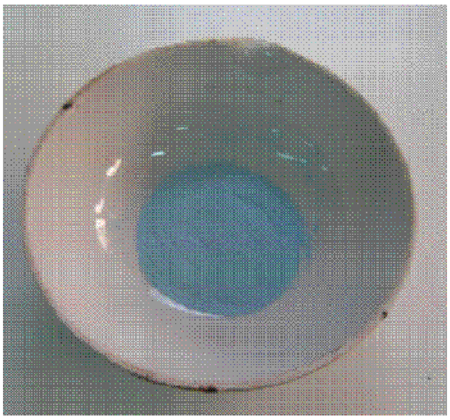


Figure 3 – REP

Table 2 - Gradation of the main components and Mass loss vs. time

Sieve	REP before heating passing %	RAP passing %	Aggregate from RAP passing %
40	100.00	100.00	100.00
30	100.00	100.00	100.00
25	100.00	98.68	100.00
15	100.00	70.29	86.29
10	100.00	31.66	51.34
5	100.00	13.12	25.70
2	100.00	5.70	18.06
0.425	100.00	1.06	9.14
0.18	99.33	0.29	4.85
0.075	94.00	0.05	2.45

Heating Time (min)	Mass loss (%)
0	0
15	1.58
30	2.01
45	3.30
65	4.45
105	5.16
135	6.03
160	6.46
195	7.03
285	7.46
345	7.46

Figure 3 refers to the powder used (REP) while in table 2 particles gradation is shown.

Note that fines resulted quite negligible when considering RAP while, in contrast, the passing at the 0.075 of REP was 94.

Note that, in order to investigate for possible mass losses during the curing, the mass losses of REP over the time were recorded (T= 175°C, see Table 2).

Table 2 shows the mass loss percent $\left(\frac{M_0 - M}{M_0} \cdot 100\right)$, where M is the mass at the time t. Both mass and mass percent approached an asymptotic value after five to seven hours c.a.

Table 3 provides information on bituminous components in RAP (recovered asphalt binder) and emulsified asphalt. Penetration (P) at 25 °C ranged from 1.5 mm up to 8.7 mm.

After the characterization of the main components, the main steps of production were: 1) mixing REP and RAP; 2) heating REP and RAP at 60°C; 3) adding emulsified asphalt and cement; 4) mixing at 60°C for about three minutes; 5) curing at 40°C for seven days; 6) Marshall compaction (50 blows per face).

As for cold mix asphalt production, characterization and testing, tables 4 to 12 and figures 4 to 9 summarize results and procedures.

Table 4 - Characteristics of RAP and bituminous emulsion

Recovered asphalt binder								
P'_b	P	SP	Viscosity (mPa·s)				D	ER
(%)	(0.1 mm)	(°C)	135 °C	150 °C	160 °C	170 °C	(mm)	(%)
4.6	15.0	65.0	2180	1015	685	460	1150	70
UNI EN 12697-1	EN 1426-07	EN 1427-07	ASTM D4402-06				ASTM D113-86 CNR B.U. N. 44/74	EN 13398-03
P'_b: Asphalt binder content by weight of aggregate (%), P: penetration (0.1 mm) at 25 °C; SP: Softening point (°C); D: Ductility at 25 °C (mm); ER: Elastic Recovery = (d/200)*100 (%); d: distance between half-threads (mm).								

Richness modulus (RAP)		
Indicator	Estimated value	References
Specific surface area of aggregates, Σ (m^2/kg)	4.68	[29]
Richness modulus, k	3.66	[29], [30].
$k = P'_b/(\alpha \cdot \Sigma^{0.2})$; P'_b= Asphalt binder content by weight of aggregate (%); $\Sigma = 0.25G + 2.3S + 12s + 135f$ (G: > 6.3mm; S: between 6.3 and 0.315mm; s: between 0.315 and 0.08mm; f: < 0.08mm); $\alpha = 2.65/G_{SE}$; $G_{SE} = (100-P_b)/((100/G_{mm})-(P_b/G_b))$; G_{SE}: effective specific gravity of aggregate; G_{mm}: Maximum theoretical specific gravity of the HMA mixture; G_b: bitumen specific gravity.		

Bituminous emulsion						
Asphalt binder recovery	P_b* (%)	Water content (%)	Additive asphalt binder (%)	Additive water (%)	Caustic soda (%)	P (**) (0.1 mm)
			Iterpitch B	Iteral/98-N		
	47	53	0.05	0.0018	0.0015	85
C.N.R. N. 100/84						EN 1426-07
P_b*= Asphalt content by weight of bituminous emulsion (%); P (**) penetration (0.1 mm) at 25 °C determined on recovered asphalt binder.						

In more detail, table 4 summarizes the job mix formula while in tables 4 to 7 and figures 4 to 8 the composition of the cold mix was analysed by referring to four main hypotheses (H1 to H4):

1) H1: there is a complete mixing between from-RAP bitumen and from-emulsion bitumen. Cement doesn't work as a filler;
2) H2: RAP acts as a black rock and the cement doesn't work as a filler;
3) H3: as H1, but the cement works as a filler;
4) H4: as H2, but the cement works as a filler.

Finally, figures 4 to 8 show the comparison among the different gradations.

For each hypothesis the modulus of richness was determined. High asphalt binder contents (9 vs. 5) and high filler contents (11 vs. 9 or 7) yielded high richness moduli. As a consequence, in the hypotheses H1 and H3 the richness modulus was two times the one corresponding to the remaining cases (H2 and H4).

Table 4 - Production and composition

		Cold mix
Compaction		50 blow per face – Marshall compacting hammer
Curing		1 day at room temperature + 7 days at 40 °C
Job mix formula		
RAP	Reclaimed asphalt pavement (%)	83.02
REP	Fire extinguisher powders (%)	6.60
BE	Bituminous emulsion content (%)	9.13 (^)
C	Cement content (%)	1.25 (^)
W	Water content (%)	0.00 (^)
Ra	Recycling agent	0
Va	Virgin aggregates	0
T_{mix}	Mixing temperature (°C)	60

Note: %RAP+%REP+%BE+%C+%W+Ra+Va=100; (*) see table 2; (^) content by weight of mix;

Table 5 - Richness modulus (Hypothesis H1)

H1(Complete mixing)		Value	Standard/note
G	Aggregate gradation		(see figure)
G_{mm}	Maximum theoretical specific gravity of HMA mixture	2.449	ASTM D6857-03
G_{SE}	Effective specific gravity of aggregate	2.807	(*)
α	$2.65/G_{SE}$	0.9	(*)
F	Filler content (%)	9.5	
Σ	Specific surface area of aggregate (m^2/kg)	14.1	(*)
P_b	Asphalt binder content (%)	8.3	(^) EN 12697-06
P'_b	Asphalt binder content by weight of aggregate (%)	9.3	(^) EN 12697-06
k	Richness modulus	5.8	(*)

Table 6 - Richness modulus (Hypothesis H2)

H2 (Black rock)		Value	Standard/note
G	Aggregate gradation		(see figure)
f	Filler content (%)	7.0	
Σ	Specific surface area of aggregate (m^2/kg)	10.0	(*)
P_b	Asphalt binder content (%)	4.5	(^)
P'_b	Asphalt binder content by weight of aggregate (%)	4.8	(^)
k	Richness modulus	3.0	(*)

Table 7 - Richness modulus (Hypothesis H3)

H3 (Complete mixing+cement)		Value	Standard/note
G	Aggregate gradation		(see figure)
f	Filler content (%)	10.8	
Σ	Specific surface area of aggregate (m^2/kg)	15.9	
P_b	Asphalt binder content (%)	8.4	(^) EN 12697-06
P'_b	Asphalt binder content by weight of aggregate (%)	9.1	(^) EN 12697-06
k	Richness modulus	5.6	

Table 8 - Richness modulus (Hypothesis H4)

H4 (Black rock+cement)		Value	Standard/note
G	Aggregate gradation		(see figure)
f	Filler content (%)	8.2	
Σ	Specific surface area of aggregate (m^2/kg)	11.8	
P_b	Asphalt binder content (%)	4.5	(^)
P'_b	Asphalt binder content by weight of aggregate (%)	4.8	(^)
k	Richness modulus	2.9	

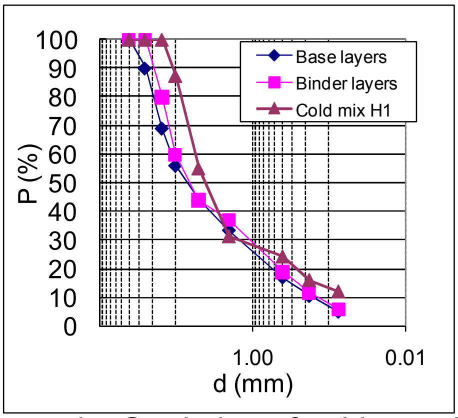


Figure 4 - Gradation of cold recycled mix after extraction (hypothesis H.1)

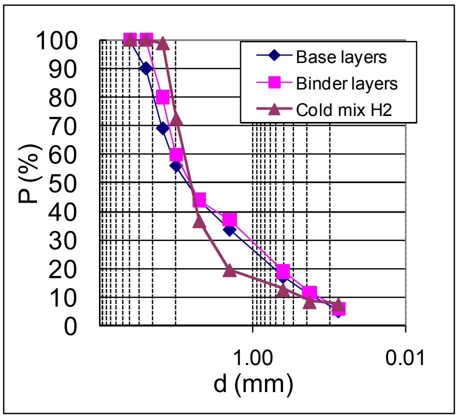


Figure 5 - Gradation of cold recycled mix (hypothesis H.2)

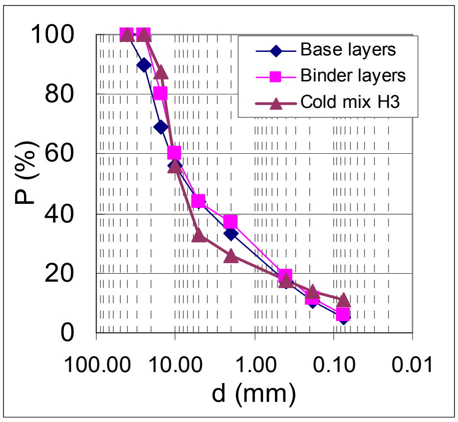


Figure 6 - Gradation of cold recycled mix (hypothesis H.3)

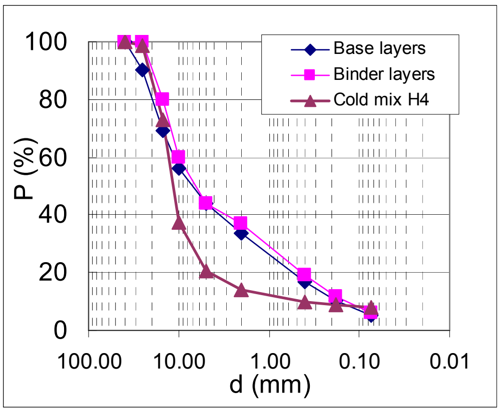


Figure 7 - Gradation of cold recycled mix (hypothesis H.4)

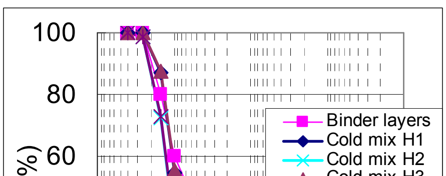


Figure 8 - Hypotheses H.1-4 comparison

Table 9 shows the main properties of the asphalt binder extracted and recovered from the cold mix. Note that penetration at 25 °C (4.7 mm) is in the range between the above-mentioned values obtained for RAP (1.5 mm) and for bituminous emulsion (8.7 mm, see table 4).

Table 9 - Asphalt binder characterization after extraction and recovery

P'_b	P	SP	Viscosity (mPa·s)				D	ER
(%)	(0.1 mm)	(°C)	135 °C	150 °C	160 °C	170 °C	(mm)	(%)
9.46	47.0	51.0	1580	1100	880	700	1530	47.5
EN 12697 -1	EN 1426-07	EN 1427-07	ASTM D4402-06				ASTM D113-86 CNR B.U. N. 44/74	EN 13398 -03

P'_b: Asphalt binder content by weight of aggregate (%), P: penetration (0.1 mm); SP: Softening point (°C); D: Ductility at 25 °C (mm); ER: Elastic Recovery (%).

Table 10 shows Marshall stability. Note that Italian specifications require a stability higher than 5-10 kN, depending on the bituminous layer considered. Notwithstanding the relevant effective porosity, results were satisfactory and ranged from 8 up to 16 kN. As for Marshall test, neither the optimum (flow) nor the maximum (stability) were recorded, due to the particular behaviour of the flow-load curve.

Table 10. Cold mix mechanical and volumetric properties (averages)

	Day	T	Marshall				
		°C	Stability (KN)	G_{mbdim}	G_{mbpar}	G_{mbcor}	n_{eff} (%)
Dry	4	25	15.9	1.906	1.921	2.026	16.4
Wet	4	25	12.5	1.881	1.888	1.968	18.8
Dry	7	25	17.8	1.807	1.864	1.916	21.0
Wet	7	25	7.9	1.850	1.889	1.956	19.3
			C.N.R. N. 30/73 UNI EN 12697-34	AASHTO T 269-03	ASTM D 1188-07	ASTM D6752-03	ASTMD6752-03 ASTMD6857-03

Wet: Marshall samples were conditioned under water for 30 min at a temperature of 25°C; Dry: Marshall samples were conditioned in a oven at a temperature of 25°C; T: temperature of test (25°C); G_{mbdim}: Dimensional bulk specific gravity; G_{mbpar}: Parafilm bulk specific gravity; G_{mbcor}: Vacuum Sealing Method bulk specific gravity; n_{eff}: effective porosity.

Figures 9-10, table 11, equations 1 to 4 refer to Brazilian Tests. Brazilian test for indirect tensile strength (C.N.R. N. 134/91; UNI EN 12697-23) measured the load $P(\delta)$ as a function of deformation. Each set of specimens yielded a peak load P_p (maximum), a peak vertical deformation (D_p, optimum), a final load (P_ε), and a corresponding final deformation (D_ε).

The peak load P_p allowed us to derive the indirect tensile strength (ITS):

$$ITS = \frac{P_p}{t \cdot D}\frac{2}{\pi}, \quad (1)$$

where t is the sample thickness and D is the sample diameter.

The energy ratio E_r was estimated as follows:

$$E_p = \int_0^{D_p} P d\delta, \quad (2)$$

$$E_\varepsilon = \int_0^{D_\varepsilon} P d\delta, \quad (3)$$

$$E_r = \frac{E_\varepsilon - E_p}{D_\varepsilon - D_p}, \quad \forall\, D_\varepsilon > D_p. \quad (4)$$

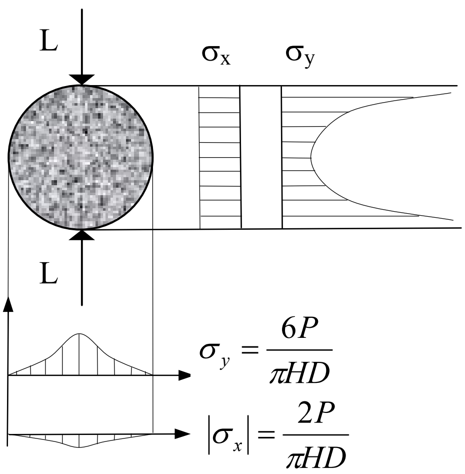


Figure 9 - Stresses in Brazilian Test

As far as the Brazilian test is concerned (see table), it is important to point out that:
- Italian specifications require that ITS is higher than 0.3 – 1.1 N/mm^2 for T = 25°C
- ITS values ranged from 0.03 up to 0.08 N/mm^2;
- Vertical deformations ranged from 1.5 up to 2.5 mm;
- Horizontal deformations resulted lower than 0.9 mm.

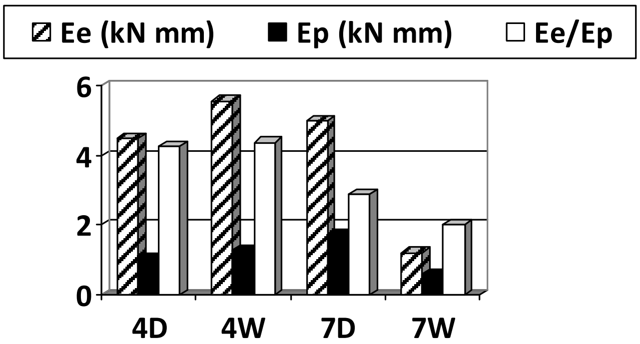
All the above-mentioned results agree with previous experiments carried out by the same authors [31], [32].

Table 11 - Cold mix mechanical and volumetric properties (averages)

	Day	T	Brazilian						
		°C	Load (KN)	Vertical Deformat. (mm)	ITS (*) (N/mm^2)	G_{mbdim}	G_{mbpar}	G_{mbcor}	n_{eff} (%)
Dry	4	25	0.656	1.5	0.07	1.897	1.904	2.000	17.5
Wet	4	25	0.785	1.8	0.08	1.920	1.941	2.050	15.4
Dry	7	25	0.659	2.5	0.06	1.895	1.899	1.932	20.3
Wet	7	25	0.302	2.0	0.03	1.870	1.873	1.972	18.6
			C.N.R. N. 134/91 UNI EN 12697-23			AASHTO T 269-03	ASTM D 1188-07	ASTM D6752-03	ASTMD6752-03 ASTMD6857-03

Wet: Brazilian samples were conditioned under water for 6 h at a temperature of 25°C; Dry: Brazilian samples were conditioned in a oven at a temperature of 25°C; T: temperature of test (25°C); ITS: Indirect Tensile Strength at 0 days; G_{mbdim}, G_{mbpar}, G_{mbcor} and n_{eff}: see table 10. (*) see also figure.

Figure 10 summarizes energy balance for the four cases (4D, 4W, 7D, 7W), by referring to indirect tensile tests [33]. Note that the ratio E_ε/E_p ranges from 2 up to 4 and this fact demonstrates that the mix had appreciable toughening characteristics.



4: 4th day; 7: 7th day (see tables 11 and 12); D: dry; W: wet; E_ε: Energy at failure; E_p: Energy at peak; D_p: Vertical deformation at peak; D_ε: Vertical deformation at failure; E_r: Energy Ratio = $(E_\varepsilon-E_p)/(D_\varepsilon-D_p)$.

Figure 10 - Energy in Brazilian Test

3. CONCLUSIONS

Based on the results we obtained, REP-RAP added cold recycled mixes can present the following classes of advantages: i) Structural benefits related to the fact that crown, and cross slope may be improved and almost all types of distresses can be mitigated or eliminated; ii) Resources/disposal benefits due to the opportunity to save resources and avoid the impact associated with their extraction and transportation and disposal. In more detail, the reuse of powders of the fire extinguishers generates a positive impact in the waste management of these powders; iii) Savings in Energy consumption (more than 20%); iv) Savings in costs, even when the entire life cycle cost analysis is considered (more than 20%); v) Savings in greenhouse gas emissions (carbon dioxide emissions, nitrous oxide emissions, sulphur dioxide emissions); vi) Mitigation of Fuel dependence; vii) Mitigation of traffic and loading disruptive actions and inconveniences; viii) Improvement of air quality; ix) potential for a flame-retardant behaviour [34].

At the same time: a) Production rate is high; b) based on Marshall test, mechanical characteristics can result acceptable while further improvements in indirect tensile strength are needed.
Finally, as for surface performance (functional characteristics), future search will aim at investigating on this relevant class of properties.

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