



Potential of fire extinguisher powder as a filler in bituminous mixes

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ABSTRACT

Fire extinguishers must be maintained at regular intervals and many problems arise when fire-resistant dry powders need replacement. We analyze the potential of fire extinguisher powder (termed REP) as a filler in bituminous mixes. REP and REP-admixed bituminous mixes were subjected to chemical analysis, and the mechanical properties and environmental performances of the mixes were tested. Mixes with different REP contents were prepared. Mechanical performance was adequate and environmental compatibility was achieved. Practical applications and perspectives in rehabilitation, maintenance, and research are outlined.

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1. Problem statement

Because of the rapid proliferation of dry fire extinguishers in Europe, powder waste levels are rising. As is well known, the ABC or Multi-Purpose chemical is a dry fire-extinguishing agent. ABC is a specially fluidized and siliconized monoammonium phosphate powder ($\text{NH}_4\text{H}_2\text{PO}_4$, 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. Fire extinguishers must be maintained at regular intervals, or when specifically indicated by inspection. Maintenance is a “thorough check” of the extinguisher and is intended to give maximum assurance that the extinguisher will operate effectively and safely. Maintenance includes a detailed examination and any necessary repair work (including recharging or, ultimately, replacement).

A number of problems arise in disposal of fire extinguisher powder (termed REP below). Therefore, we studied the potential of REP as a filler in bituminous mixes. This paper presents our results.

2. Experimental plan

To investigate the potential of REP as a filler in bituminous mixes, four problem areas were addressed:

- (1) feasibility of the production process (Section 3);
- (2) REP characterization (Section 4);
- (3) hazard assessment of REP-added Hot Mix Asphalts (HMAs) (Section 5);
- (4) properties of HMAs containing REP (Section 6).

Except that for point 1, all the experiments were carried out at a laboratory scale.

3. Process analysis

3.1. Research into REP recycling and HMA in-plant production

Research addressed all phases of the powder life cycle from powder discharge from the fire extinguisher to REP addition to aggregate and hot bitumen mixture.

3.2. Discharge, packaging, transport

The following primary steps were considered [1]:

- extinguishers are inspected and condemned at customer sites during scheduled service;
- extinguishers are made safe and packaged in accordance with ADR Regulations (a European Agreement concerning the International Carriage of Dangerous Goods by Road);
- extinguishers are removed from customer sites and transported to recycling centers in accordance with ADR regulations;
- extinguishers are removed from packaging and are placed in storage;

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Fig. 1. Large bag transport operation.

- extinguishers are collected at defined intervals from all recycling centers to be transported to the Central Extinguisher Recycling (CER) unit;
- extinguishers arrive at the CER;
- extinguishers are sorted and palletized according to contents and body type;
- extinguishers are depressurized if necessary;
- extinguishers are removed from packaging and are placed in storage;
- headcaps are removed; some elements (valves, tubes, and cartridges) are separated and, after detailed inspection, may be accepted for recycling;
- extinguisher contents are emptied (discharge phase), and, if appropriate, an internal body inspection is carried out; the body is normally recycled. The powder can be used for fertilizer synthesis.

In the process described, large bags are used after discharge for powder packaging, transport, and storage. Fig. 1 shows discharge and transport operations.

3.3. In-plant storing and recycling

In-plant, REP is emptied from the large bags into a silo. From there, a pneumatic conveyor system transfers REP from the silo to a mixer. The silo has a capacity of 24 m³ (enough for about 600 m³ of mix if mineral filler is used, or for about 400 m³ of mix when REP is employed). A single large bag could hold 1 m³ of REP, enough for about 20 m³ of mix. Thus, REP recycling involves processing identical to that used for conventional mineral filler.

4. REP characterization

Fire extinguisher powders were received at the laboratory in (small) bags and stored at room temperature. The following tests were performed:

- (1) visual analysis before and after heating;
- (2) measurement of aggregate apparent specific gravity before and after heating (to CNR BU 63/78, ASTM C128-07A, ASTM C127-07A standards);
- (3) grading before heating (to B.U. CNR n. 4/53, EN 12697-2:2008 standards);
- (4) microphotography;
- (5) thermogravimetry;
- (6) delta ring and ball testing before and after heating (to EN 13179-1:2002, CNR N. 122/1988 standards);



Fig. 2. REP examined under the optical microscope.

- (7) mass loss per heating cycle;
- (8) XRD diffraction analyses.

The color of the powder before heating was between blue and sky-blue. The first attempt to determine the specific gravity of the powder before heating followed standard (CNR BU 63/78, ASTM C128-07A; ASTM C127-07A) pycnometer principles. Many issues arose. Two zones soon appeared; a lower zone (sky-blue) in which the powder (salts) combined with water and an upper zone (blue) in which the powder did not combine with water. After 24 h the lower zone appeared completely clear (as water) whereas the upper zone remained blue (thus containing powder). Moreover, the third zone appeared, resulting from sedimentation on the bottom of the pycnometer. Ultimately, a rough specific gravity determination was achieved by filling a container of known volume. A density of ca. 1.00 g/cm³ was measured.

A sample of REP was prepared and was examined under the optical microscope (see Fig. 2). Rounded salt particles, of different dimensions, result embedded in a blue powder.

Thermogravimetry (Fig. 3) was performed using STA409 (Netzsch Instruments Co. Ltd., Germany) to study the thermal properties of REP. The test was carried out under flowing air (752 ml/min), and under a heating rate of 10 °C/min. The *x*-axis is temperature (°C), while the *y*-axis on the left (TG, thermogravimetry) is mass loss (%) and the *y*-axis on the right (DTA, Differential Thermal Analysis) gives information on endothermic (minima) and exothermic (maxima) reactions (μV/mg). Two endothermic peaks appear at 112 °C and 223 °C.

Finally the other axis on the right (DTG, derivative thermogravimetry, %/min) gives information on the rate of weight change with time [2]. Grading of the powder before heating is shown in Fig. 4. Note that $p \approx 94\%$ for $d = 0.075$ mm.

The delta ring and ball test before heating was carried out by standard (EN 13179-1:2002, CNR N. 122/1988) methods; see Fig. 5 and Table 1. A value of 17 °C was obtained. Next, the REP was heated at 150 °C. Table 2 shows how mass *M* and mass loss percentage $((M_0 - M/M_0) \times 100)$ varied with time. Both mass and mass

Table 1
Delta ring and ball test before and after heating.

	Softening point, SP (°C)	ΔSP (°C)
Mineral filler	60.15	10.65
REP before heating	66.60	17.10
REP after heating	60.00	10.50

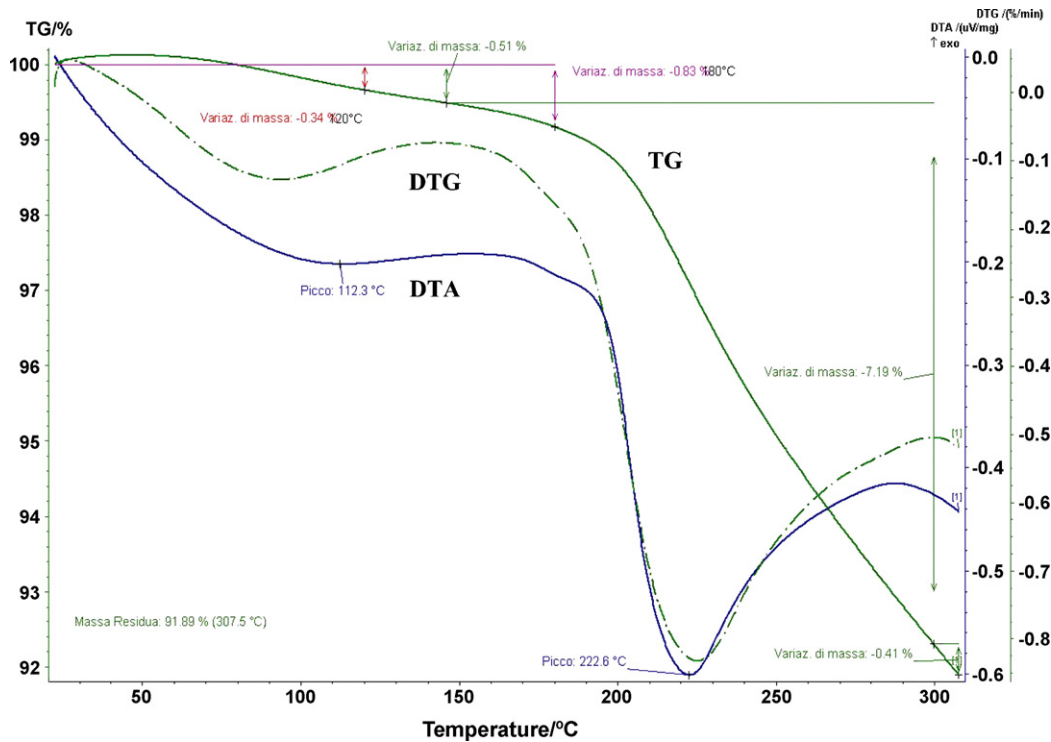


Fig. 3. Thermogravimetry.

loss percentage approached asymptotic values after ca. 6 h. After heating, the REP color changed to grey-to-black and consistency was greatly improved, as the powder state was lost. The delta ring and ball test was repeated. Table 1 shows the results obtained,

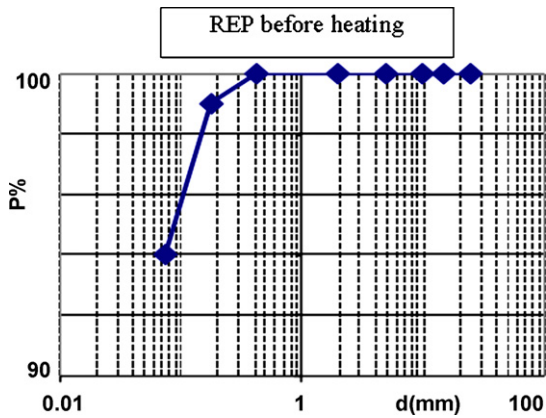


Fig. 4. Grading of the powder before heating.

Table 2
Mass loss.

Heating time (min)	Mass (g)	Mass loss (%)
0	697	0
15	686	1.58
30	683	2.01
45	674	3.30
65	666	4.45
105	661	5.16
135	655	6.03
160	652	6.46
195	648	7.03
285	645	7.46
345	645	7.46

and compares REP data with those obtained using a traditional mineral filler. Appreciable differences were seen. Increases in softening point (ΔSP values, °C) were seen for both mixes (traditional filler + bitumen and REP + bitumen); both values were ca. 10.5 °C, representing a reduction of about 40% with respect to REP used before heating.

The results of the XRD diffraction analysis are shown in Figs. 6–8. It is well known that X-ray diffraction techniques are based on elastic scattering of X-rays from structures with long-range order. In particular, powder diffraction is a technique used to characterize the crystallographic structure, crystallite size (grain size), and preferred orientation in polycrystalline or powdered solid samples. Powder diffraction is commonly used to identify unknown substances [3].



Fig. 5. Preparation of the delta ring and ball sample.

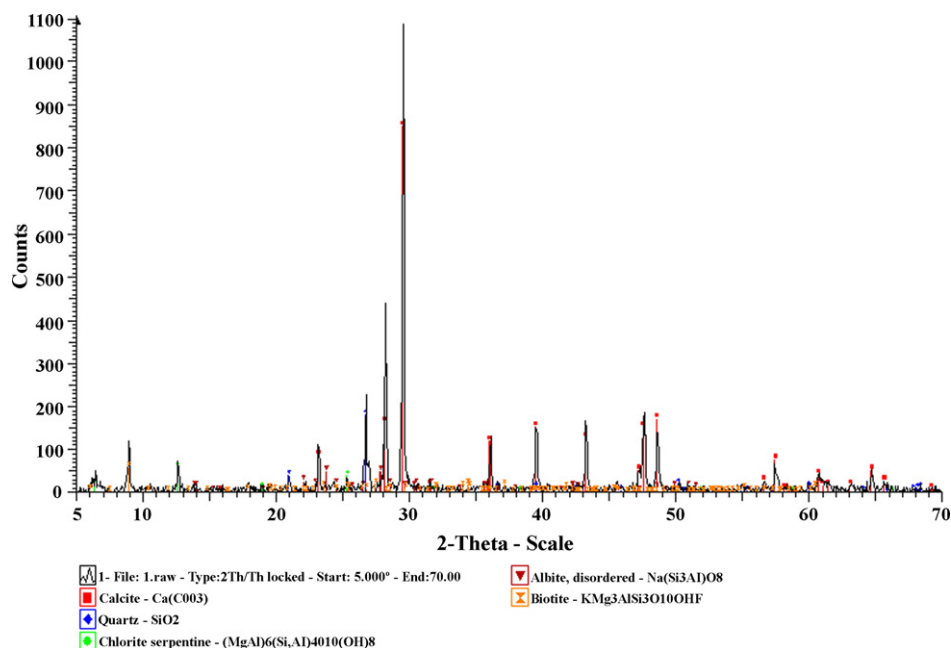


Fig. 6. XRD diffraction analysis of mineral filler.

Fig. 6 shows the XRD diffraction analysis of mineral filler. The x-axis is a 2θ -scale (diffraction angles) whereas the y-axis is counts. It may be observed that the main components are CaCO_3 (calcite) and SiO_2 (quartz). Fig. 7 shows the results of the XRD diffraction analysis of REP. The main components are $(\text{NH}_4)_2\text{H}_2\text{PO}_4$ (biphosphammite) and $(\text{NH}_4)_2\text{SO}_4$ (mascagnite). The blue pigment has no morphology and was thus not detected. Fig. 8 shows XRD diffraction of REP/filler recovered from the HMA (bitumen extraction was performed according to standards CNR n.38/73 and ASTM 6307-05). In this case, a mix of filler components (mainly) and REP components (minor fraction) were seen (Table 3), whereas chemical composition and XRD data similar to those of Fig. 7 had been expected.

The differences between the XRD data of Figs. 7 and 8 are further analyzed in Table 3. The following factors may explain the results: (i) loss of REP during production, in the filler line from the silo to the mixer; (ii) presence of water in the filler line, in aggregates,

or during the laboratory extraction process, with consequent loss of REP solubilized in water; (iii) other effects related to the action of perchloroethylene used during bitumen extraction (including a possible strong linkage between asphalt binder and REP).

5. Hazard assessment

Italian and European laws (DM 186/2006, UNI 10802, UNI EN-1744/3, UNI EN-12457/1, UNI EN-12457/2, UNI EN-12457/3, UNI EN-12457/4, DM 13/03/03, D.lgs 13/01/03 n.36) require hazards associated with the use of particular materials to be identified (hazard assessment). If necessary, action and treatment are prescribed. To investigate the environmental compatibility of REP-added HMAs, elution tests were performed [4]. Fifteen chemical classes were considered; these were S (Sulfates), Ni (Nickel), TDS (Total Dissolved Solids), Mo (Molybdenum), Zn (Zinc), Cl (Chlorides),

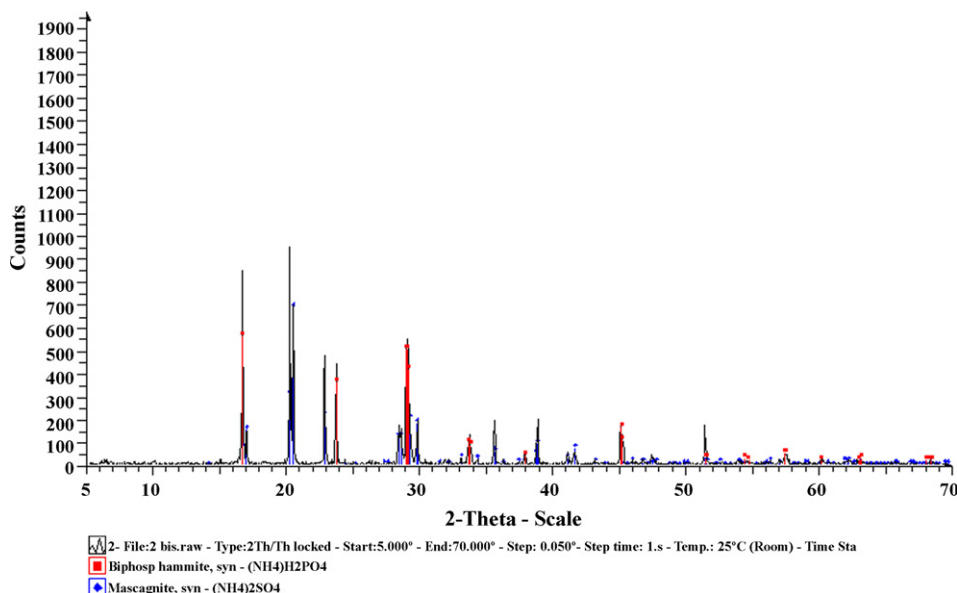


Fig. 7. XRD diffraction analysis of REP.

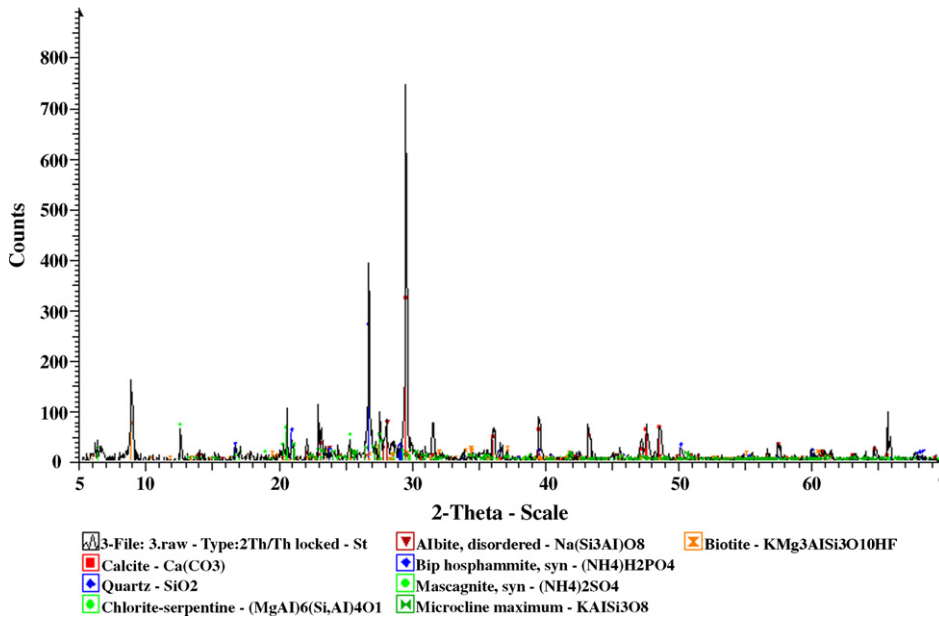


Fig. 8. XRD diffraction analysis of REP used as filler and then extracted.

DOC (Dissolved Organic Compounds), Ba (Barium), F (Fluorides), Cr (Total Chromium), Sb (Antimony), As (Arsenic), Cd (Cadmium), CN (Cyanides), and Hg (Mercury).

For each parameter, three concentration limits are defined by Italian laws: (a) a maximum value for disposal in landfill as an aggregate (L_{ia}); (b) a maximum value (termed L_{ib} below) for disposal in hazardous material landfills; and, (c) a maximum value for disposal in non-hazardous material landfills (L_{ic}). Elution tests (Fig. 9) were performed according to the EN 12457-2/2004 standard, using both mixes of type M_1 (containing only mineral filler) and mixes of type M_3 (with REP filler only).

Fig. 10 illustrates the concept of the Hazard measurement, $H_{i\xi}$, used to measure risk, where $H_{i\xi} = ((C_i - L_{i\xi}) / L_{i\xi}) \cdot 100 \cdot \beta_i$. C_i is the concentration of the i -th parameter (e.g., cyanides), L_i is the relative limit (for example 5 mg/L), and β_i is related to the effect of the i -th parameter on health. The higher the Hazard measurement the greater the problem. Fig. 11 shows, in a synergistic manner, the Hazard measurements ($H_{i\xi}$ values) for the mixes M_1 and M_3 . Finally, Table 4 shows, for the i -th chemical parameter, the value of $C_i(M_3) / C_i(M_1)$, which is the ratio of the concentration of the i -th parameter in the M_3 mix (with REP) and the concentration of the same parameter in the mix M_1 (without REP). Note that for 8 of 15

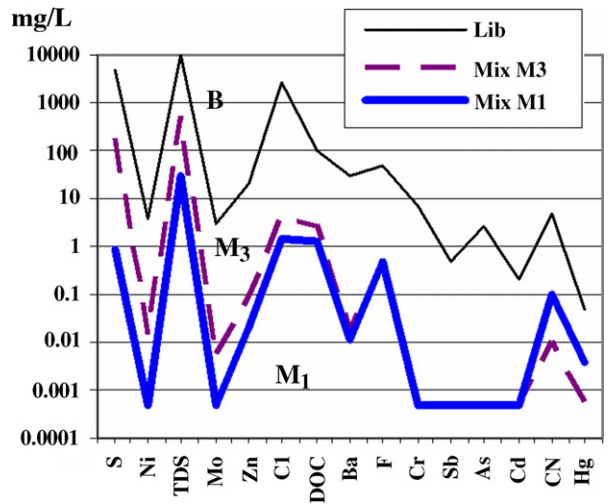


Fig. 9. Elution tests on mixes M_1 and M_3 .

Table 3
Chemical compositions.

Component	Concentrations	
	REP (%)	Extracted filler/REP (%)
SO ₃	58.61	7.45
P	18.76	3.57
Na ₂ O	7.19	8.67
MgO	6.40	6.52
SiO ₂	5.95	28.10
Al ₂ O ₃	2.52	9.47
Fe ₂ O ₃	0.49	6.29
MnO	0.04	
Cu	0.02	
SrO	0.02	
Cl	0.01	0.09
CaO		27.71
K ₂ O		1.50
BaO		0.40

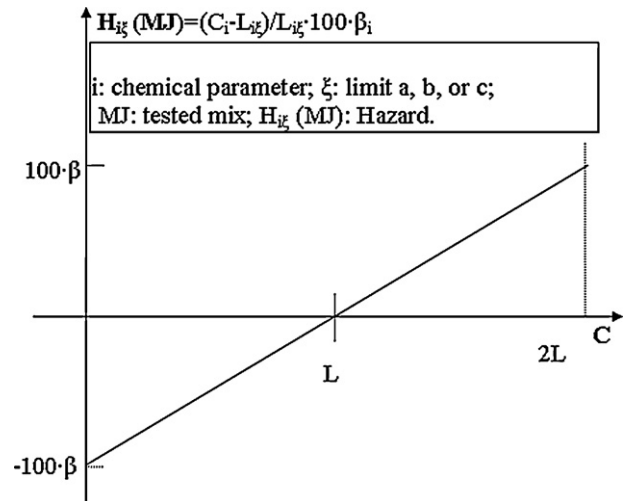
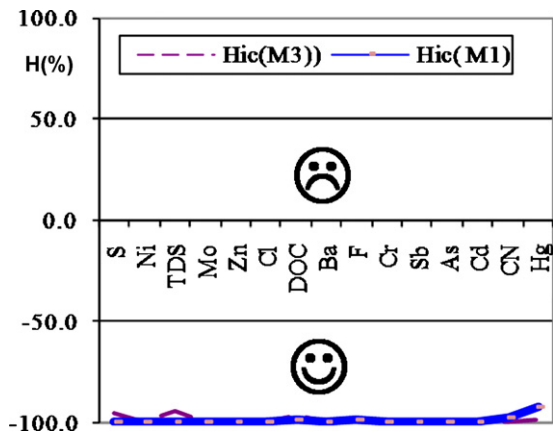


Fig. 10. Modeling the parameter $H_{i\xi}$

Table 4
Ratios $[C_i(M_3)/C_i(M_1)]$.

s	Ni	TDS	Mo	Zn	Cl	DOC	Ba	F	Cr	Sb	As	Cd	CN	Hg
210.00	29.40	18.30	10.00	4.70	3.00	2.30	1.40	1.00	1.00	1.00	1.00	1.00	0.10	010

**Fig. 11.** Elution tests: hazard *H*.

chemical components this ratio was >1 , in 5 instances it was equal to 1, and in 2 cases was <1 . Importantly, sulfate elution from the REP-containing mix was higher than that from the filler-containing blend. In general, elution results were satisfactory, but, because of the extreme importance of this topic, further research is required.

6. Composition and chemical–mechanical resistances

6.1. Tests on asphalt binder

The following tests on asphalt binder were performed:

- Ductility (standards CNR BU n.44/74, ASTM D113-86);
- Softening point (standards CNR BU n.35-1973, EN 1427: 2007);

Table 6
Aggregate gradations (traditional and Superpave approach).

Sieve (mm)	Passing			Control points		Restricted zone	
	M ₁	M ₂	M ₃	Lower	Upper	Lower	Upper
25	100.00	99.45	97.94	100			
19				90	100		
15	84.99	82.12	79.30				
12.5					90		
10	70.81	64.42	60.50				
5	49.16	45.54	42.46				
2.36				23	49	34.6	34.6
2	34.87	32.58	29.85				
1.18						22.3	28.3
0.60						16.7	20.7
0.425	14.34	12.73	12.15				
0.30						13.7	13.7
0.18	7.80	6.56	6.29				
0.075	5.74	4.71	4.51	2	8		

Table 7
Water sensitivity.

Mix type	ITS _d at 25 °C (kPa)	ITS _w at 25 °C (kPa)	ITSR (%)	Type of failure	S _d at 60 °C (kN)	S _w at 60 °C (kN)	ΔS (%)	ΔV (%)	SR (%)
M ₃	1061.27	815.74	76.86	Combination	11.62	7.68	33.90	2.09	66.10
M ₁	1085.18	1122.24	94.69	Combination	13.21	11.95	9.54	0.21	9.46

ITSR = indirect tensile strength ratio, in percent (%); ITS_w = average indirect tensile strength of the wet group, in kilopascal (kPa); ITS_d = average indirect tensile strength of the dry group, in kilopascal (kPa); ΔS = stability marshall loss (%); S_d = stability marshall of the dry group (kN); S_w = stability marshall of the wet group (kN); ΔV = growth (%) in volume; SR = stability ratio = 100 S_w/S_d.

Table 5
Bitumen characterization.

Characteristic	
Bitumen viscosity at 160 °C (Pa s)	160
Penetration (0.1 mm)	65
Softening point (°C)	49.5
Ductility (cm)	58

- Delta ring and ball test (standards EN 13179-1:2002, CNR N. 122/1988; see above);
- Penetration test (standards CNR BU n. 24-1971, EN 1426:2007);
- Viscosity (standards ASTM D4402-02, EN 14896:2006).

Table 5 shows the main characteristics of the asphalt binder used.

6.2. REP-added mixes

After powder characterization, three bituminous mixes were prepared, with different REP contents: M₁ (0% REP), M₂ (3% REP), M₃ (6% REP) [all w/w], all with an asphalt binder content of 5% (w/w). Experiments and tests appropriate for performance-oriented bituminous material evaluation, were carried out, as follows:

Composition and mechanical properties:

- asphalt binder contents as percentages of aggregates;
- aggregate gradation;
- aggregate apparent specific gravities;
- mix bulk specific gravities;
- mix effective porosities;
- Marshall stability and flow tests;

Table 8
Fatigue laws for diametral test.

REP(%)	
0	$\epsilon = 293 \cdot N^{-0.060}$
6	$\epsilon = 256 \cdot N^{-0.054}$

Note: test temperature 25 °C; frequency: 2 Hz; load levels: 2.5 kN, 3 kN, 3.5 kN; ϵ : tensile strain (microstrain); N: number of cycles (indirect tensile fatigue test–controlled stress mode).

- moisture susceptibility tests;
- fatigue tests.

Fuel resistance:

- Brush test.

Tables 6–9 and Figs. 12–19 summarize the results. Table 6 shows aggregate gradations (standards B.U. CNR n. 4/53, EN 12697-2:2008). Traditional and Superpave approaches were followed [5–7]. Figs. 12 and 13 refer to HMA composition and volumetrics [8–12]. These figures show that aggregate grading and composition parameters of the obtained HMA differed slightly from those of designed HMA. In particular (see Fig. 12), with respect to filler content ($P_{0.075}$), it is important to point out that a mass “loss” of filler was noted; this ranged from <1% to 2% of total mix weight. More importantly, the higher the REP content, the higher the mass loss. In detail, up to 22% of the filler mass was “lost”, from one or a

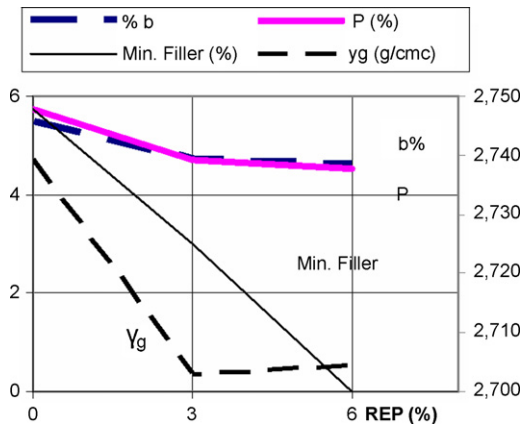


Fig. 12. Composition.

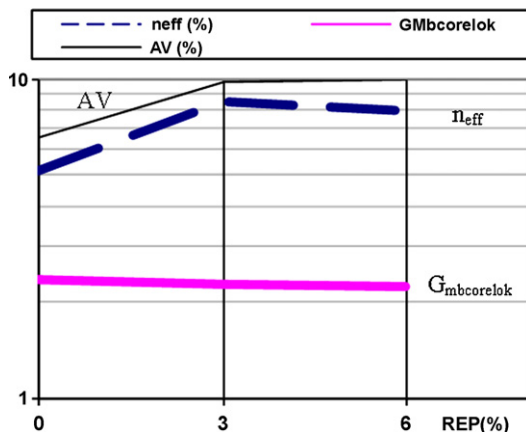


Fig. 13. Volumetrics.

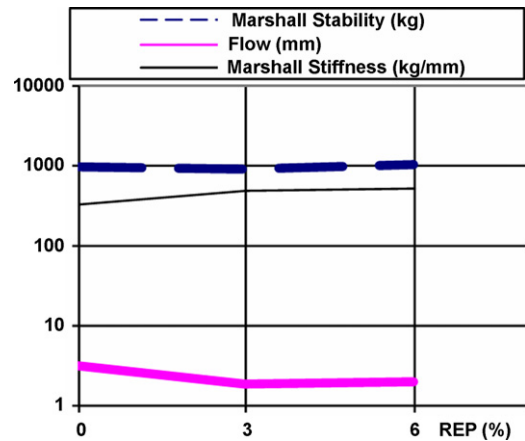


Fig. 14. Marshall test.

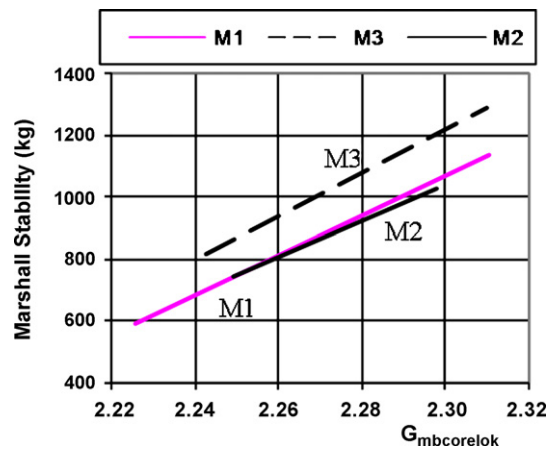


Fig. 15. Marshall stability vs. Gmbcorelok.

combination of the following causes: (a) mass loss after weighing in the filler line; (b) a drying effect (loss of liquid); (c) sublimation (passage from the solid to the gas state); (d) mass loss of a solution in water; or, (e) process variance. Processes (b)–(d) were previously studied during powder characterization.

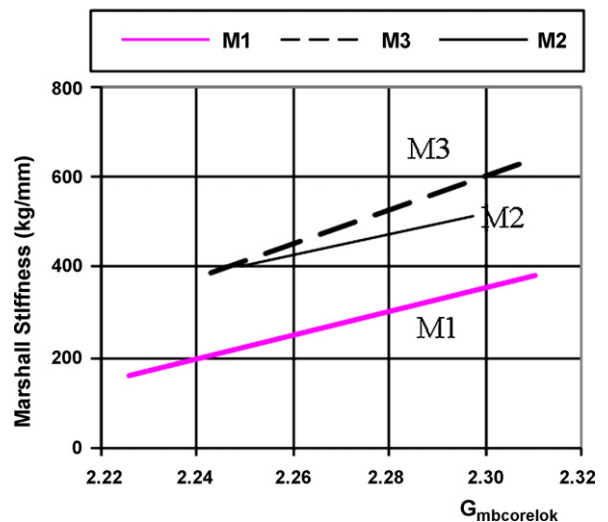


Fig. 16. Marshall stiffness vs. Gmbcorelok.

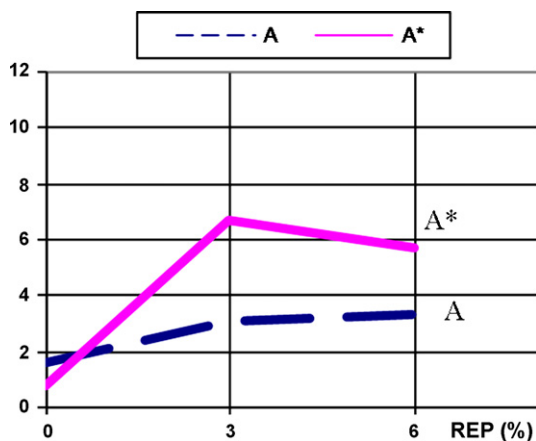


Fig. 17. A vs. REP.

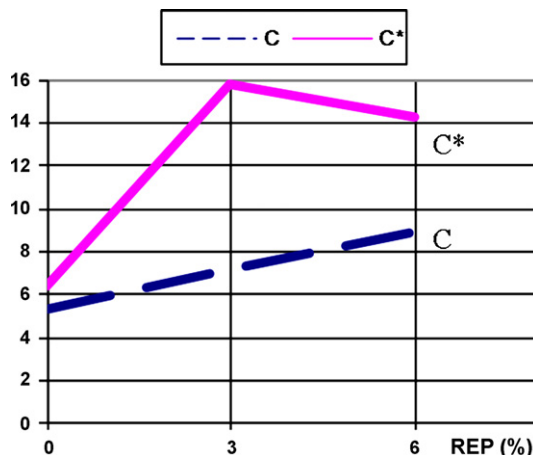


Fig. 19. C vs. REP.

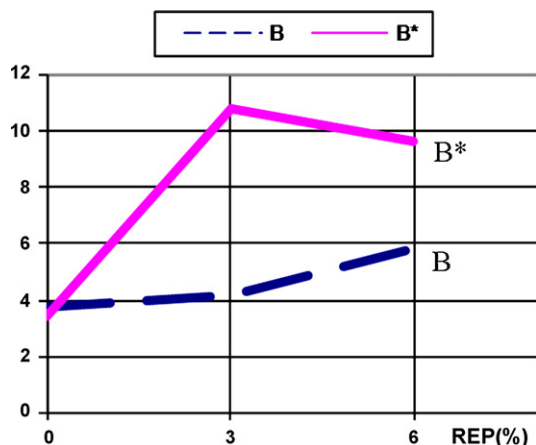


Fig. 18. B vs. REP.

With respect to asphalt binder content (standards B.U. CNR n.38/73, EN 12697-1: 2006), Fig. 12 shows that the higher the REP proportion the lower the asphalt binder content (and the lower the filler contribution). This may be explained as follows: (i) reduced total filler content; (ii) differences in REP surface properties compared to mineral filler; (iii) microstructural changes affecting filler-bitumen compatibility; or, (d) process variance. Fig. 12 also shows slight decreases in the apparent specific gravities of aggregates

(standards ASTM C128-07A, ASTM C127-07A, B.U. CNR n. 63/78), because REP is present.

Fig. 13 shows that the effective porosity, n_{eff} (standards ASTM D6752, ASTM D6857), ranged from 5% (REP=0%, mix M_1) to 8% (REP=3%, mix M_2). Several differences in Marshall flows and stabilities (standards EN 12697-34:2004, CNR BU 30/73) were detected between mixes M_1 , M_2 , and M_3 (Fig. 14). These may be explained by differences in filler and/or asphalt binder contents and could be related to differences in rutting potential. Figs. 15 and 16 show that, for a given bulk specific gravity, $G_{mbcorelok}$ (ASTM D6752), the higher the REP percentage the greater the Marshall stability and stiffness (averages are shown). Note that, for each mix M_i , 4×6 specimens were considered. Table 7 shows that samples subjected to vacuum (EN 12697-12:2004) or simple saturation (CNR 149/92) have an appreciable moisture susceptibility. This issue requires further study as well as other tests.

Table 8 shows the summary of results of the diametral fatigue test. Further it gives the relevant fatigue parameters for the two different classes of mixes (0% and 6% of REP). Tests suggest that though first derivatives are similar (log–log scale), REP powders can origin a slight reduction of fatigue lives.

Figs. 17–19 show chemical resistances [13–15] of mixes under investigation (standard EN 12697-43:2005). Brush tests were carried out to estimate A, B, and C (standard EN 12697-43:2005). A is

Table 9
Correlation matrix (correlation significance).

R	Marshall stability (kg)	Flow	Marshall stiffness (kg/mm)	G_{mb} dimensional	%b	p (%)	REP (%)	Min. Filler (%)	γ_g (g/cm ³)
Marshall stability (kg)	1.00 (0.00)	-0.12 (0.69)	0.73 (0.01)	0.92 (0.00)	0.33 (0.31)	-0.34 (0.30)	0.12 (0.73)	-0.16 (0.59)	0.20 (0.60)
Flow	-0.12 (0.69)	1.00 (0.00)	-0.75 (0.00)	-0.04 (0.94)	0.69 (0.01)	0.85 (0.00)	-0.61 (0.02)	0.78 (0.00)	0.91 (0.00)
Marshall stiffness (kg/mm)	0.73 (0.01)	-0.75 (0.00)	1.00 (0.00)	0.59 (0.04)	-0.32 (0.33)	-0.78 (0.00)	0.53 (0.08)	-0.61 (0.03)	-0.50 (0.10)
G_{mb} dimensional	0.92 (0.00)	-0.04 (0.94)	0.59 (0.04)	1.00 (0.00)	0.42 (0.16)	-0.11 (0.71)	-0.19 (0.56)	0.12 (0.72)	0.32 (0.32)
%b	0.33 (0.31)	0.69 (0.01)	-0.32 (0.33)	0.42 (0.16)	1.00 (0.00)	0.50 (0.10)	-0.72 (0.01)	0.68 (0.01)	0.85 (0.00)
p %	-0.34 (0.30)	0.85 (0.00)	-0.78 (0.00)	-0.11 (0.71)	0.50 (0.10)	1.00 (0.00)	-0.72 (0.00)	0.86 (0.00)	0.81 (0.00)
REP (%)	0.12 (0.73)	-0.61 (0.02)	0.53 (0.08)	-0.19 (0.56)	-0.72 (0.01)	-0.72 (0.00)	1.00 (0.00)	-0.97 (0.00)	-0.78 (0.00)
Min. filler (%)	-0.16 (0.59)	0.78 (0.00)	-0.61 (0.03)	0.12 (0.72)	0.68 (0.01)	0.86 (0.00)	-0.97 (0.00)	1.00 (0.00)	0.82 (0.00)
γ_g (g/cm ³)	0.20 (0.60)	0.91 (0.00)	-0.50 (0.10)	0.32 (0.32)	0.85 (0.00)	0.81 (0.00)	-0.78 (0.00)	0.82 (0.00)	1.00 (0.00)

the mean value of mass loss after soaking in fuel, where $A = \sum_i A_i / 3$, with $i = 1, 2, 3$ (specimens), and $A_i = [(m_{1,i} - m_{2,i}) / m_{1,i}] \times 100$, where $m_{1,i}$ = initial dry mass (g) of specimen i prior to soaking in fuel and $m_{2,i}$ = mass (g) of the dry test specimen i after soaking in fuel. B is the mean value of the loss of mass after the brush test, where $B = \sum_i B_i / 3$, with $i = 1, 2, 3$ (specimens), and $B_i = [(m_{2,i} - m_{5,i}) / m_{2,i}] \times 100$, where $m_{5,i}$ = mass (g) of the test specimen i after soaking for 120 s prior to the brush test. C is the mean value of the loss of specimen mass with each soaking and burning, where $C = \sum_i C_i / 3$, with $i = 1, 2, 3$, and $C_i = [(m_{1,i} - m_{5,i}) / m_{1,i}] \times 100$.

The brush tests were carried out using Brush TesterRC®, designed, constructed, and patented at the DIMET laboratory, for tests on road, railway, and airport materials, at the University of Reggio Calabria (Italy). Note that the standard EN 12697-43:2005 specifies a ranking system based on two indicators (A and B , see Figs. 17 and 18), but we introduce a new indicator, C , to evaluate the entire soaking and brushing process and corresponding mass loss.

When the relationship between chemical resistance and effective porosity (n_{eff}) was analyzed, it was seen that when REP = 0%, results were consistent with the fitting curves shown (i.e., A^* , B^* , and C^* ; see Figs. 17–19) whereas, for REP = 3–6% [w/w], the actual curves (A , B , C) were below the expected curves (A^* , B^* , C^*). It is encouraging that for a given effective porosity, REP increases chemical resistance (i.e., yields lower A , B , and C curves; see Figs. 17–19).

Filler influence on bitumen solubility could depend on some kind of surface link occurring between REP and bitumen and could be related to the results obtained for the delta ring and ball tests.

When R -squared values and p -values (reflecting correlation significances, see Table 9) were examined, it was notable that REP percentage was negatively correlated with Marshall flow ($R = -0.61$, significant at the $p = 0.02$ level).

7. Conclusions

- (1) The small bag-large bag-silo-mixer process is simple, although optimization is required.
- (2) REP mass loss was observed. Some hypotheses were formulated and are supported by experiments. In particular, diffraction analyses demonstrated that recovered filler had a chemical composition quite different from that of original REP. However, the reason for this requires further study.
- (3) Environmental compatibility is satisfactory. The contents of Nickel, Molybdenum, sulfates and total dissolved solids are higher than in traditional HMAs, but lower than legal limits.
- (4) Effective porosity increased in mixes with REP, probably because of the abovementioned REP mass loss.

- (5) Chemical resistance (for a given effective porosity) increased but several issues call for further research when mix compaction is considered.
- (6) Several mechanical properties were substantially independent of REP content, although increases in Marshall stability/stiffness measurements (at a given specific gravity) and appreciable decreases in Marshall flow were observed.
- (7) Fatigue tests revealed that REP powders can cause a small decrease of the number of cycles to failure.

Future efforts will aim to optimize REP content, explore water/temperature/compaction issues, and will result in the design of a new, statistically robust, experimental plan.

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