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A SWOT analysis of innovative high sustainability pavement surfaces containing crumb rubber modifier

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In order to compare some innovative solutions of sustainable pavement surfaces containing crumb rubber modifier (CRM), a strengths, weaknesses, opportunities, and threats (SWOT) analysis of different technologies developed for production of low noise pavements (LNPs) has been carried out. CRM is one of the by-products obtained from end-of-life tyres (EOLT) that is currently recycled in asphalt pavements worldwide, with different technologies and more interest in some countries compared to others. In order to demonstrate the effective use of CRM in LNP, the project NEREIDE was funded by the EC in 2017 within the framework of LIFE projects, with the specific aim of developing innovative solutions for sustainable LNP with CRM, by using both the wet and the dry process.

In the Phase I of the NEREiDE project, the mechanical and functional performances of the new LNP surfaces, developed by using the two technologies, were analysed and compared in order to assess their respective potentials for use as viable alternatives to other traditional LNP surfaces. The analysis of laboratory and on-site test results, carried out on specifically built field trials, allowed to understand strengths and weaknesses of the new LNPs in terms of mechanical and functional performance. In order to identify opportunities and threats in the analysis, the external factors that can be helpful or harmful to the recycling of CRM in LNPs have been analysed.

Keywords: Crumb rubber modifier; end-of-life tyres; low noise pavement surfaces; wet process; dry process

Introduction

The end-of-life tires (EOLTs) form a major part of the world's solid waste management problem; in addition, their quantity is progressively increasing due to the growing number of vehicles produced worldwide. At the same time, the increasing traffic volume has caused serious problems of noise pollution due to vehicular traffic. These are only two of the problems resulting from the continuous increase in transportation demand, which has prompted the international scientific community to search for innovative solutions that allow to re-use of crumb rubber modifier (CRM) from EOLTs in asphalt pavements.

The principal advantage of using CRM in the production of asphalt mixtures is the environmental sustainability of pavements related to the opportunity to recycle an industrial waste; in addition, the use of CRM allows to obtain asphalt surface layers in which rubber particles can improve mechanical properties of the mixtures, limit noise emissions produced by tire vibrations, and increase pavement friction (Biligiri, 2013; Biligiri & Way, 2014; Liu et al., 2012; Losa et al.,

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2012). The use of CRM in asphalt pavements dates back to many years ago (Lo Presti, 2013; Venudharan et al., 2017; Way et al., 2015), CRM has been used in two main different methods: the dry process (DP) and the wet process (WP). In the DP (Hassan et al., 2013; Heitzman, 1992), the CRM is added to the aggregate mixture soon after this has been mixed with the bitumen; in this way, the rubber acts as an aggregate and, at the same time, as a modifying agent since it partially reacts with the bitumen (Airey et al., 2003). In the WP, the CRM is added as a modifying agent to the bitumen in order to improve its performances: the final result is known as 'Asphalt Rubber (AR)' (Epps, 1994; McDonald, 1981).

Generally, the asphalt mixtures containing CRM are mixed and compacted at high temperatures, due to high mastic viscosity, and they are characterised by high bitumen contents; these aspects conflict with the actual needs of eco-efficiency and sustainability that require a reduction of energy consumption and non-renewable raw resources. In order to reduce the mixing and compaction temperatures of mixture containing CRM, the use of warm-mix asphalt (WMA) additives is necessary (Gandhi et al., 2014; Leandri et al., 2014). The use of WMA additives reduces environmental impacts by allowing mixture production at least 30° lower than conventional hot mix asphalt (HMA) with no premature failures. In order to reduce the bitumen content, specific grain size distributions of the mixes were defined.

Several types of traditional LNPs can be identified and classified into two main groups: texture optimised types (gap graded) and porous types (open graded) (Losa et al., 2010). The Life NEREiDE project has the specific aim of developing innovative solutions for sustainable LNP with CRM, by using both the wet and the dry process. In the Phase I of the NEREiDE project, the mechanical and functional performances of the new LNP surfaces, developed by using the two technologies, were analysed and compared in order to assess their respective potentials for use as viable alternatives to other traditional LNP surfaces (Leandri et al., 2017). The analysis of laboratory and on-site test results, carried out on specifically built field trials, allowed to understand strengths and weaknesses of the new LNPs in terms of mechanical and functional performance. In order to identify opportunities and threats in the analysis, the external factors that can be helpful or harmful to the recycling of CRM in LNPs have been analysed. This article shows key findings of the Phase I of the NEREiDE project.

The life NEREiDE project: experimental program

The project intends to develop specific guidelines to be used by Road Administrations in preparing specifications for the construction of new high sustainability LNP surfaces. Guidelines will be developed in order to upgrade and to improve the methods currently available to assess the effectiveness of low noise road surfaces in urban areas.

The experimental programme included the first step of mix design to define the aggregate size gradations, the optimum asphalt contents (ACs) and workability characteristics of the mixes; in the second step, laboratory and field tests were carried out to evaluate mixtures performance.

The mixtures studied in the laboratory were then used for the realisation of Phase I of the project. In this phase, six typologies of wearing course, composed of two reference mixtures (one gap and one open graded) and new LNP surfaces (two gap graded and two open graded), were laid on an experimental road section (roughly 2400 m long) with the specific aim of reducing traffic noise on a urban road in the Municipality of Massarosa (Lucca); the wearing course was 4 cm thick:

- Reference gap graded 0–10 produced by using hot mix technology (Ref Gap).
- Reference open graded 0–10 produced by using hot mix technology (Ref Open).

- Gap graded 0–8 containing CRM produced by using the DP and WMA technology (Gap Dry).
- Open graded 0–8 containing CRM produced using the DP and WMA technology (Open Dry).
- Gap graded 0–8 containing CRM produced by using the WP and WMA technology (Gap Wet).
- Open graded 0–8 containing CRM produced by using the WP and WMA technology (Open Wet).

In order to check field performance of mixtures, pavement sections were tested to evaluate surface characteristics in terms of friction and texture. Cores were extracted from pavement to verify the correspondence to the design mixture in terms of aggregate gradation, AC and air void percentage. The in-place characteristics of the mixtures were substantially the same of the laboratory mixture with regard to the aggregate gradation and the bitumen content; as far as the air void content of the in situ mixture, it was approximately 2% more than the air void content of the laboratory mixture.

Mix design

Mix design was realized by the volumetric method. The optimum ACs were identified by optimizing the air void contents and the indirect tensile strength (ITS).

Aggregate gradations

Given the considerable difference between the specific gravity of CRM and natural aggregate, the grain size distribution of the mixes was composed by calculating volumetric proportions of the different materials (Table 1). The grain size distributions of the mixtures are shown in Figure 1. The new LNP surfaces have similar aggregate gradation for the open and gap typologies, with the purpose of appraising the effects produced by the different methodologies of the CRM use in the mixtures. The aggregate gradations of reference and new LNP surfaces are characterised by different values of the aggregate nominal size; in particular the maximum aggregate size is equal to 8.7 and 9.1 mm for the Ref Gap and Ref Open mixes and it is equal to 6.0 for the new LNP surfaces mixes. The gap dry and open dry mixes contain, respectively, 3.0% and 1.0% of CRM by weight of mineral aggregates, corresponding to 6.5% and 2.3% by volume, in replacement of mineral aggregates of the same size.

Table 1. Aggregate blendings.

Typology of mixture	Proportions by volume (%)					
	Basalt 4/10	Basalt 4/8	Basalt 2/6	Sand	CRM	Mineral filler
Ref GAP	57.0	–	10.0	22.0	–	11.0
GAP dry	–	60.0	23.5	–	6.5	10.0
GAP wet	–	74.0	–	16.0	–	10.0
Ref OPEN	82.0	–	–	10.0	–	8.0
OPEN Dry	–	85.7	–	5.0	2.3	7.0
OPEN Wet	–	85.0	–	8.0	–	7.0

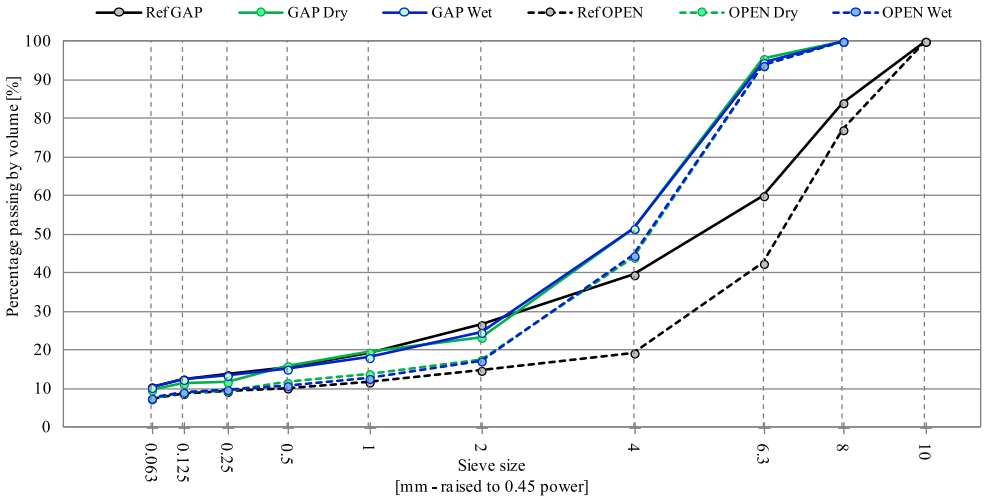


Figure 1. Aggregate size gradations.

Table 2. Bitumen characteristics.

Parameter		Unit	Specifications EN 14023		
			PMA for reference mixes	PMA for dry mixes	AR for wet mixes
Penetration at 25°C – EN 1426		*dmm*	45–80 class 4	25–55 class 3	25–55 class 3
Softening point – EN 1427		°C	≥ 70 class 4	≥ 70 class 4	≥ 60 class 6
Force Ductility Test at 10°C – EN 13589/13703		J/cm^2	≥ 3 class 7	≥ 3 class 7	-
Resistance to hardening RTFOT – EN 12607-1	Retained penetration at 25°C	%	≥ 60 class 7	≥ 60 class 7	≥ 60 class 7
	Increase in softening point	*°C*	≤ 8 class 2	≤ 8 class 2	≤ 8 class 2
	Loss in mass	*%*	≤ 0.5 class 3	≤ 0.5 class 3	≤ 0.3 class 2
Flash Point – EN ISO 2592		*°C*	≥ 250 class 2	≥ 250 class 2	≥ 250 class 2
Fraass breaking point – EN 12593		*°C*	≤ – 15 class 7	≤ – 10 class 5	≤ – 12 class 6
Elastic recovery at 25°C – EN 13398		*%*	≥ 80 class 2	≥ 80 class 2	-

Optimum AC and volumetric properties

The aggregates of the reference mixtures were mixed with 50–70 penetration grade polymer-modified asphalt (PMA), whereas aggregates of the gap wet and open wet mixtures were mixed with AR and the aggregates of the gap dry and open dry mixtures were mixed with a specific PMA (Table 2).

Table 3. Volumetric properties of the mixes at optimum AC.

Typology of mixture	Number of gyrations	AV[a] (%)	VMA[b] (%)	VFA[c] (%)	G_{mb}[d] (kg/m^3)	G_{mm}[e] (kg/m^3)	VG[f] (%)	VB[g] (%)
Ref GAP $AC_{opt} = 5.5\%$[h]	$N_{initial} = 10$	13.9	25.0	44.5	2.174	2.524	75.0	11.1
	$N_{design} = 50$	6.9	18.9	63.5	2.350	2.524	81.1	12.0
	$N_{max} = 130$	3.0	15.5	80.5	2.448	2.524	84.5	12.5
GAP Dry $AC_{opt} = 8.0\%$[h]	$N_{initial} = 10$	13.0	28.4	54.3	2.124	2.440	71.6	15.4
	$N_{design} = 50$	7.2	23.6	69.6	2.265	2.440	76.4	16.4
	$N_{max} = 130$	4.5	21.5	78.9	2.330	2.440	78.5	16.9
GAP Wet $AC_{opt} = 8.0\%$[h]	$N_{initial} = 10$	12.9	29.0	55.4	2.211	2.538	71.0	16.1
	$N_{design} = 50$	6.6	23.8	72.3	2.371	2.538	76.2	17.2
	$N_{max} = 130$	3.5	21.3	83.5	2.449	2.538	78.7	17.8
Ref OPEN $AC_{opt} = 4.5\%$[h]	$N_{initial} = 10$	30.1	37.7	20.0	1.787	2.558	62.3	7.5
	$N_{design} = 50$	24.2	32.4	25.3	1.939	2.558	67.6	8.2
	$N_{max} = 130$	21.1	29.6	28.8	2.018	2.558	70.4	8.5
OPEN Dry $AC_{opt} = 5.5\%$[h]	$N_{initial} = 10$	26.5	36.3	26.9	1.915	2.607	63.7	9.8
	$N_{design} = 50$	20.9	31.4	33.6	2.063	2.607	68.6	10.5
	$N_{max} = 130$	18.1	29.0	37.7	2.136	2.607	71.0	10.9
OPEN Wet $AC_{opt} = 5.5\%$[h]	$N_{initial} = 10$	26.5	36.4	27.2	1.935	2.635	63.6	9.9
	$N_{design} = 50$	20.7	31.4	34.1	2.090	2.635	68.6	10.7
	$N_{max} = 130$	17.8	28.9	38.4	2.166	2.635	71.1	11.1

[a]AV, air voids.
[b]VMA, voids in mineral aggregate.
[c]VFA, voids filled with asphalt.
[d]G_{mb}, bulk density of the compacted mixture.
[e]G_{mm}, maximum density of the mixture.
[f]VG, volume of aggregate, the bulk volume including the aggregate pores.
[g]VB, volume of effective asphalt binder.
[h]AC_{opt}, optimum AC as percentage of mass of aggregates.

In order to reduce the mixing and compaction temperatures of LNP surfaces, the AR and the specific PMA were enriched with viscosity reducing additives (WMA additives). The AR consists of 20% CRM by weight of binder and the remaining 80% of 50–70 penetration grade pure bitumen.

The optimum asphalt content (AC) was determined by superpave gyratory compactor (SGC) optimising volumetric and mechanical characteristics of mixtures with different ACs. The compaction temperature was set at 175 ± 5°C for reference mixes and at 130 ± 5°C for mixes containing CRM. The volumetric characteristics of the mixes at optimum AC are shown in Table 3.

The mixes containing rubber show a lower bitumen content compared to the quantities normally used, these results confirm the innovative aspect of the study.

In volumetric terms, the gap-graded mixtures are similar, whereas the open-graded mixtures containing CRM show 3% smaller percentage of the voids in comparison to that of reference

Table 4. Workability characteristics at different compaction temperatures.

Typology of mixture	Workability parameters	Compaction temperature			
		110°C	130°C	150°C	170°C
GAP Dry	N_W (n)	24	22	23	22
	CFI (kPa·n)	232.7	202.5	207.8	197.0
	AV at N_{design} (%)	7.7	7.2	7.0	6.9
GAP Wet	N_W (n)	26	22	20	20
	CFI (kPa·n)	250.9	203.4	180.5	181.2
	AV at N_{design} (%)	7.3	6.8	6.6	6.5
OPEN Dry	N_W (n)	39	29	31	32
	CFI (kPa·n)	421.0	304.4	323.7	326.5
	AV at N_{design} (%)	22.2	21.0	21.3	21.4
OPEN Wet	N_W (n)	31	29	27	28
	CFI (kPa·n)	342.5	311.0	298.2	292.1
	AV at N_{design} (%)	21.0	20.5	20.3	20.1

mixture. This is due to the presence of the CRM and to a smaller maximum diameter of the aggregate.

The mixture workability

In order to evaluate the effects produced by the reduction of mixing and compaction temperatures on the mixture workability, the friction resistance should be measured by the gyratory pressure distribution analyzer (GPDA) during compaction. In the studies (Hanz & Bahia, 2013; Leandri et al., 2014), the parameters N_w and CFI have been proposed to evaluate asphalt mixture workability using volumetric data routinely collected during current mix design and quality control testing. The N_w is defined as the number of gyrations required to reach w%·G_{mm} corresponding to w% air voids, where w% is the mean percentage of the voids at $N_{initial}$ and N_{design}, G_{mm} is the theoretical maximum density of mixture. w% is equal to 8% and 27% for the gap and open mixes.

The CFI is defined as the Construction Force Index, which is the area under the resistive effort (R_e) curve from $N_{initial}$ to w%·G_{mm}. A mixture with lower N_w and CFI is characterised by better performance in terms of volumetric characteristics and workability. The values of these parameters were determined at different compaction temperatures (110°C, 130°C, 150°C, and 170°C) for each mixture; the temperature of 170°C was assumed as a control temperature. At each temperature, two specimens were compacted by extending the densification to 200 gyrations of the SGC. Table 4 and Figure 2 show the average values (on two specimens) of the workability characteristics determined at each compaction temperature.

The workability parameters show almost a horizontal linear trend within the temperature range between 170°C and 130°C, in particular, for the mixtures to dry. This aspect highlights a low-temperature susceptibility of the workability of the mixtures containing CRM and produced by using WMA technology. Besides this, the results allow to define the temperature of 130°C as the optimum compaction temperature for the new LNP surfaces containing CRM. It is important to highlight that these new LNP surfaces can be produced and laid at lower temperatures of 30–40°C in comparison to the temperatures used for traditional crumb rubber-modified asphalts, reducing the emission of polluting vapours of polycyclic aromatic hydrocarbons.

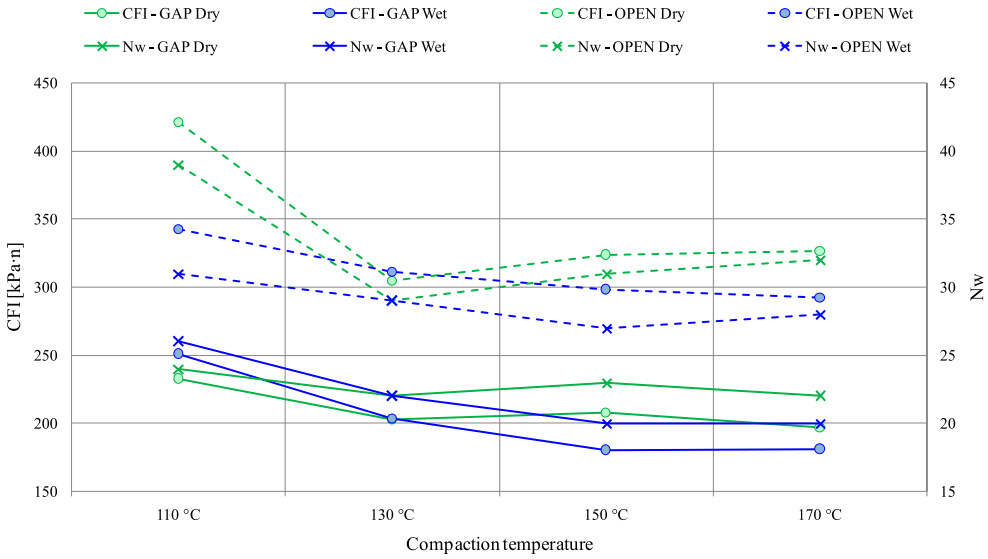


Figure 2. CFI and N_w at different compaction temperatures.

Table 5. ITS and moisture sensitivity results.

Type mix	ITS_d (N/mm^2)	ITS_w (N/mm^2)	ITSR (%)	Threshold value ITSd (N/mm^2)	ITSR (%)
Ref GAP	0.96	0.86	90	≥ 0.6	≥ 80
GAP Dry	0.69	0.61	88		
GAP Wet	0.96	0.84	88		
Ref OPEN	0.49	0.41	84	≥ 0.4	≥ 80
OPEN Dry	0.54	0.50	93		
OPEN Wet	0.67	0.59	88		

Mechanical properties of the mixtures

In order to characterise the mixtures from a mechanical point of view, ITS tests, stiffness modulus tests, fatigue resistance tests and rutting resistance tests were carried out on specimens compacted by the SGC.

ITS and moisture sensitivity

ITS measurements were carried out at the temperature of 25°C, according to EN 12697-23. ITS values (Table 5) for all the mixes are higher than the minimum value required by the national standards for gap- and open-graded asphalt mixes used as wearing courses. In the detail, the mixes by WP show ITS values higher than those of the mixtures by DP. ITS and moisture sensitivity results are shown in Table 5.

In order to evaluate the moisture susceptibility, the indirect tensile strength ratio, according to EN 12697-12, was determined. It is represented by the ratio between ITS of samples after conditioning in water (ITS_w) and ITS of unconditioned samples (ITS_d). The results obtained clearly show that no problems pertaining to moisture susceptibility arise for all the mixes (Table 5).

Stiffness modulus

Master curves of mixture stiffness were determined through the indirect tensile test on cylindrical specimens (IT-CY), according to EN 12697–26 Annex C procedure. Tests have been carried out using three pulse duration (75, 125, and 200 ms), and at five temperatures (2°C, 10°C, 20°C, 30°C, and 40°C); samples have been conditioned at test temperatures at least for 4 h in a climatic chamber.

In order to describe asphalt mix time-dependent behaviour at low and medium temperature, it is common to use the generalised power law. In this study, it has been used the sigmoidal model proposed by Medani et al. (2004), modifying the one introduced previously by Pellinen and Witczak. The mixture stiffness S_{mix} (MPa) at a temperature T and at a loading frequency f is evaluated by the following model:

$$\log S_{\text{mix}} = \log S_{\text{min}} + (\log S_{\text{max}} - \log S_{\text{min}}) \cdot \left[1 - \mathrm{e}^{-\left(\frac{10 + \log f_{\text{fict}}}{\beta}\right)^{\gamma}}\right] \tag{1}$$

$$\log f_{\text{red}} = \log f + \log \alpha_T \tag{2}$$

$$\log \alpha_T = \log \mathrm{e} \cdot \frac{\Delta H}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right) \tag{3}$$

where S_{min} minimum mixture stiffness (MPa), S_{max} maximum mixture stiffness (MPa), f_{red} reduced frequency, β and γ shape factors, f load frequency (Hz), α_T shift factor can be determined by Arrhenius form (3), ΔH activation energy (J/mol), R ideal gas constant (J/mol·K), T experimental temperature (K), and T_{ref} reference temperature (K).

Figures 3 and 4 show the master curves of the mixtures at the reference temperature of 20°C and their S_{mix} values calculated at specific frequencies and temperatures.

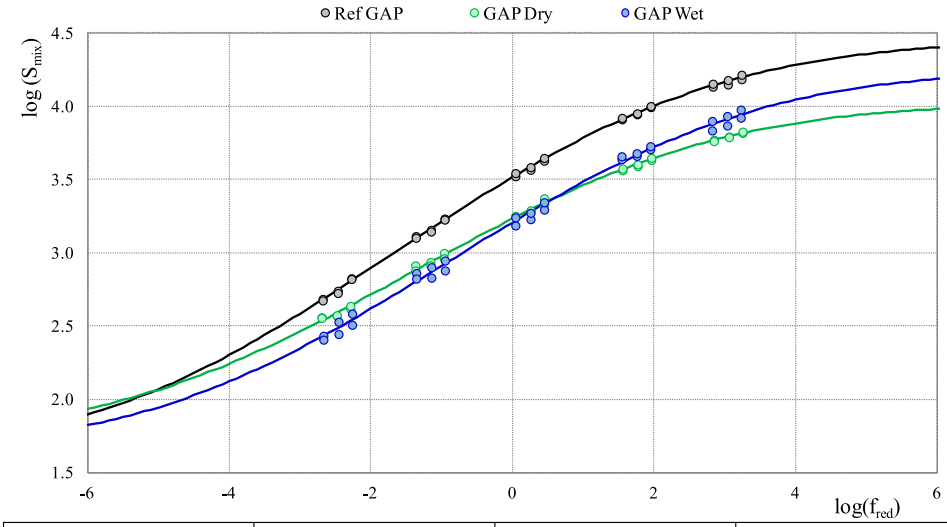
For the gap-graded mixtures, the values determined highlight that the reference mix shows an increase in S_{mix} as compared to the mixes containing CRM; in the field of high temperatures (low frequencies), such increase is due to the greater stiffness of aggregate skeleton, whereas, in the field of low temperatures (high frequencies), the increase is due to the greater stiffness of mastic. In the mixtures containing CRM, the lower stiffness of the aggregate skeleton and of the mastic is due to the high quantity of CRM as compared to the reference mixture.

With regard to open-graded mixture, the values determined show that the open dry mix shows an increase in S_{mix} as compared to the other two mixtures. This increase can be attributed to the greater stiffness of PMA blended with CRM (Open Dry) as compared to AR (Open Wet) and PMA (Ref Open).

Fatigue resistance

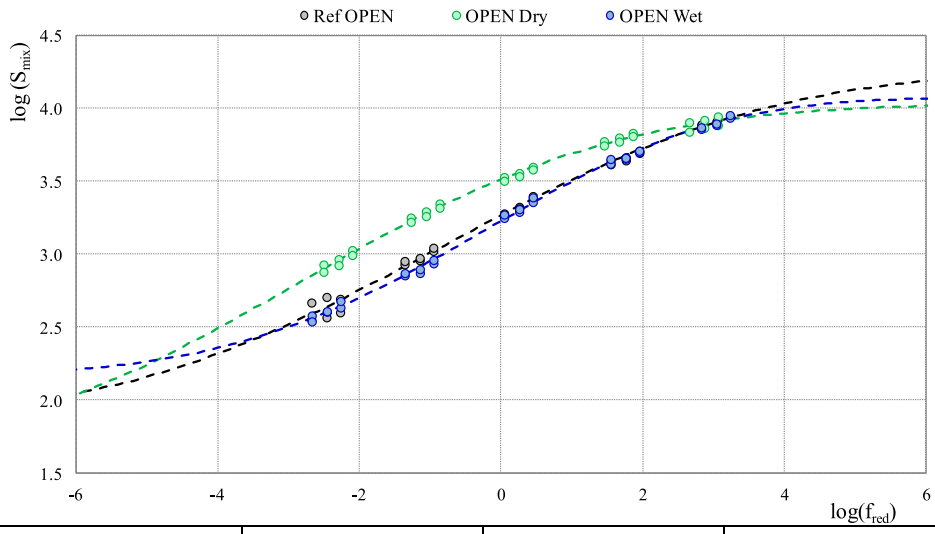
The fatigue resistance was determined by the IT-CY specimens, according to EN 12697-24 Annex E. Tests have been carried out at the temperature of 20°C and with a load repetition time equal to 0.5 s.

Figures 5 and 6 show the plot of the fatigue resistance curves for the studied mixtures. The gap mix containing CRM shows a similar fatigue life at higher strain levels (300 $\mu\epsilon$), where both the mixes show higher fatigue life than the reference mix, whereas at lower strain levels (200 $\mu\epsilon$), the gap dry mix shows a higher fatigue life than the gap wet and ref gap mixes. As expected, if on one side, the use of high content of CRM provides a decrease in stiffness and elasticity, on the other side, it increases the mixture ductility. Regard to open-graded mixtures, the open wet and the ref open mixes show a similar fatigue life; whereas the dry open has a lower fatigue resistance compared to the other two types of mixtures, as a consequence of its high stiffness. This means that AR binder shows a better fatigue resistance than that of PMA binder.



Temperature [°]	0			20			40		
Frequency [Hz]	1	5	10	1	5	10	1	5	10
S_{mix} for Ref GAP [MPa]	15238	18391	19638	3277	5090	6060	465	770	961
S_{mix} for GAP Dry [MPa]	6359	7440	7853	1704	2480	2879	335	505	605
S_{mix} for GAP Wet [MPa]	8421	10504	11357	1609	2530	3040	263	410	500

Figure 3. Stiffness master curves at $T_{ref} = 20°C$ of gap-graded mixtures.



Temperature [°]	0			20			40		
Frequency [Hz]	1	5	10	1	5	10	1	5	10
S_{mix} for Ref OPEN [MPa]	8309	10312	11157	1853	2758	3247	382	561	667
S_{mix} for OPEN Dry [MPa]	8025	8880	9186	3269	4388	4902	774	1197	1435
S_{mix} for OPEN Wet [MPa]	8144	9615	10123	1692	2633	3155	357	499	613

Figure 4. Stiffness master curves at $T_{ref} = 20°C$ of open-graded mixtures.

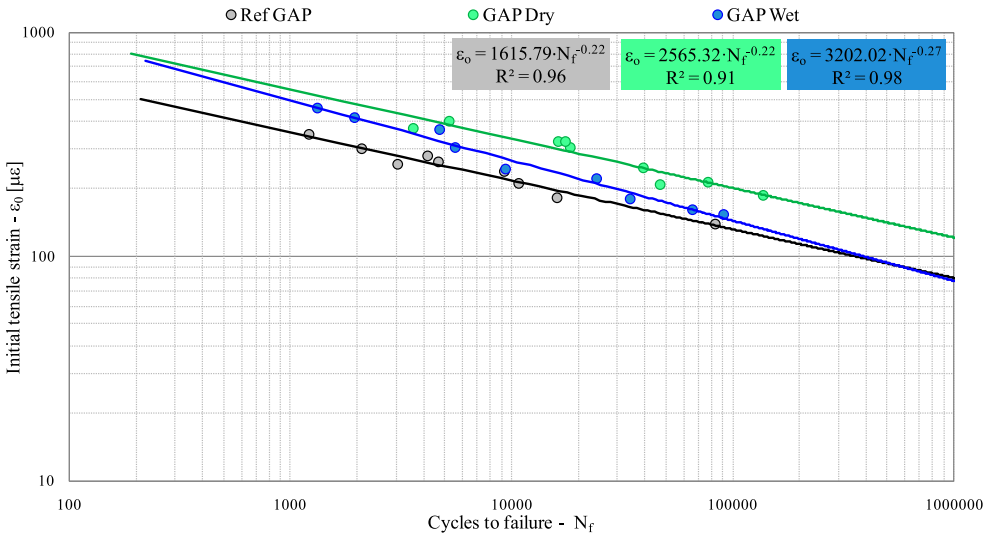


Figure 5. Fatigue resistance curves of gap-graded mixtures.

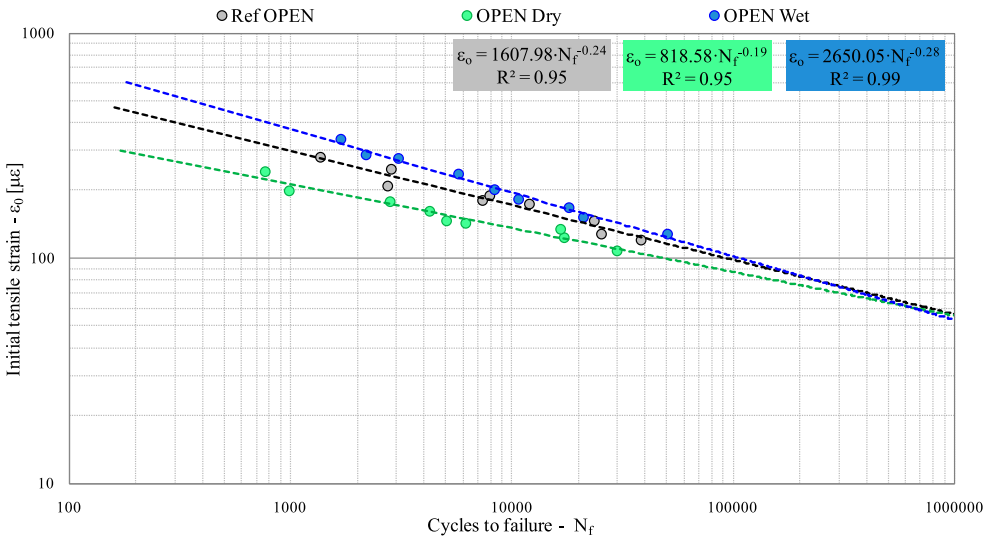


Figure 6. Fatigue resistance curves of open-graded mixtures.

Rutting resistance

The rutting resistance was determined by the Hamburg Wheel Tracking Test according to AASHTO T-324. The test has been carried out at the temperature of 50°C and it was concluded at 20,000 passes or when the maximum allowable rut depth limit (12.7 mm) was achieved. The level of compaction was defined to the target of 7.0% ± 1% (93%·G_{mm} ± 1%) for gap graded mixtures and to N_{design} for open-graded mixtures. These parameters were evaluated by the tests performed:

- Creep slope: a measure of the rutting potential after post-compaction consolidation.
- Stripping slope: a measure of moisture damage accumulation.

Table 6. Hamburg wheel tracking test results.

Rutting parameters	Ref GAP	GAP Dry	GAP Wet	Ref OPEN	OPEN Dry	OPEN Wet
Creep slope (mm/passes)	1.28E-04	1.85E-04	8.62E-04	1.66E-04	1.50E-04	3.31E-04
Strip slope (mm/passes)			2.34E-03			1.29E-03
Rut depth @ SIP (mm)			8.4			9.1
Number of passes @ SIP (passes)			7320			16,031
Number of passes @ 12.7 mm [passes]	> 20,000	> 20,000	9347	> 20,000	> 20,000	> 20,000
Rut depth @ 20,000 passes (mm)	5.5	6.9	> 20	8.4	6.1	14.1

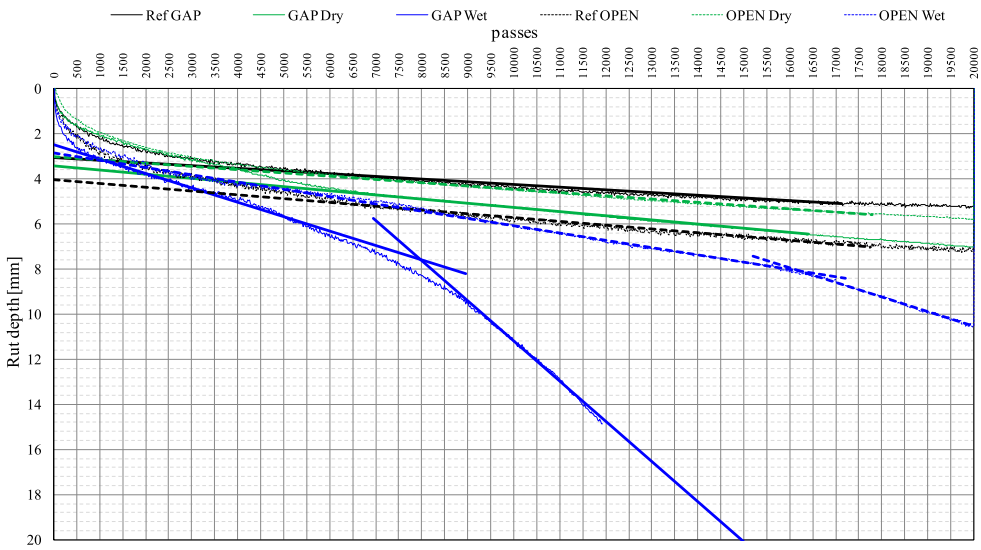


Figure 7. Ruth depth accumulation versus number of passes (a couple of specimens).

- Stripping inflection point (SIP): rut depth at which the creep slope and stripping slope intercept.

Table 6 shows the average values (on two couple of specimens) of rutting resistance. The reference mixtures and the mixtures by DP do not show any significant problems pertaining to moisture susceptibility and to the accumulation of permanent deformation. On the contrary, the mixtures by WP, in particular the Gap Wet, show some stripping problems. Besides this, the use of WMA technologies in the WP raises concerns with reducing mixing temperatures since it seems to reduce the coating of aggregates coating worsening mixtures moisture resistance. Such results highlight the necessity of using anti-stripping additive for the mixtures WP to reduce the accumulation of permanent deformation because of the effect of water (stripping).

The accumulation of the rut depth versus the number of cycles of the different mixtures is given in Figure 7.

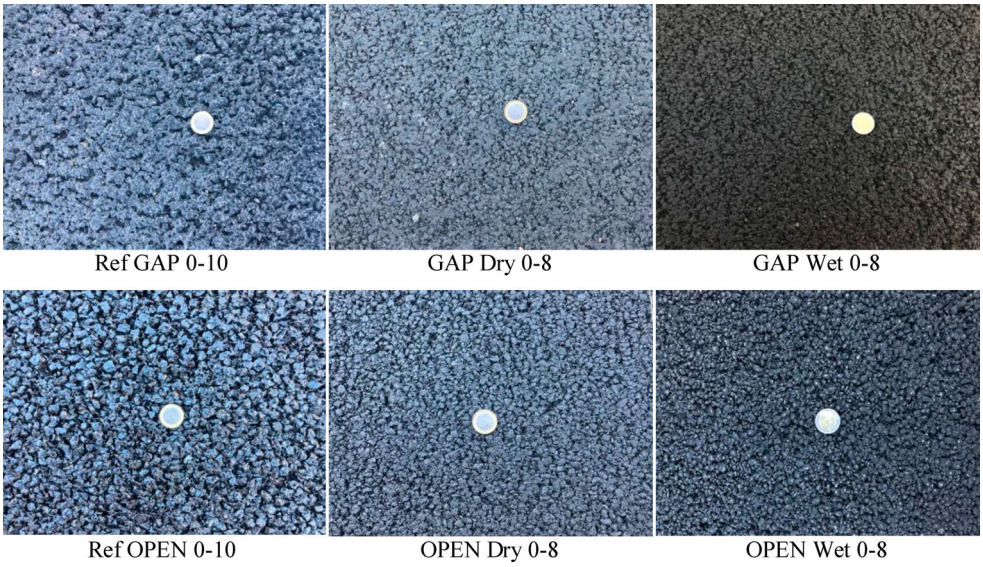


Figure 8. Experimental LNP surfaces.

Field performance

Performances of the experimental wearing course (Figure 8) were evaluated in terms of surface characteristics, such as texture and friction, only on a short time interval since the pavement was laid in period December 2017–May 2018. In order to evaluate field performance over time, factors such as real traffic loading and climatic situation should be taken into account, but this short time is not enough to draw valid considerations that, at this stage, can be only qualitative.

Macrotexture

Surface macrotexture was determined on 2D pavement profiles recorded by using a mobile laser profilometer which allows the continuous recording of the pavement profile at sampling intervals of 1 mm. The mean profile depth was evaluated from the profile and the estimated texture depth (ETD) was calculated on each experimental sections (Losa & Leandri, 2011). Figures 9 and 10 show the variation of the texture at different age; the texture is expressed in terms of ETD, averaged at every 10 m, together with the mean texture depth threshold values required on urban roads. Over time, the studied mixture shows texture values which are higher than the threshold value. In particular, the reference mixtures show macrotexture values higher than those of the new LNP surfaces. This is due to the greater aggregate nominal size.

Using the recorded profiles, the one-third octave band mean texture spectrum (L_{tx}) was calculated, according to the ISO/CD 13473-4 and 5 procedures.

Figures 11 and 12 show the texture spectrum of the experimental wearing courses. In order to obtain an LNP surface, which is capable of reducing noise emissions at the tyre/road, the texture spectrum should have the following characteristics (Losa et al., 2010):

- the highest L_{tx} value should be found in the wavelength (λ) field below 10 mm;
- L_{tx} values should tend to minimum values in the wavelength field $\lambda > 10$ mm.

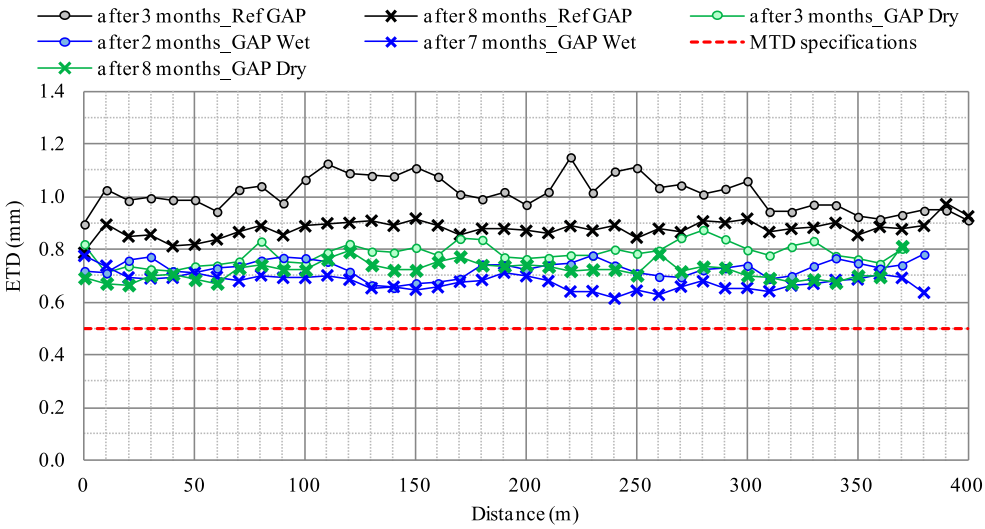


Figure 9. Macrotexture profiles of gap-graded mixtures.

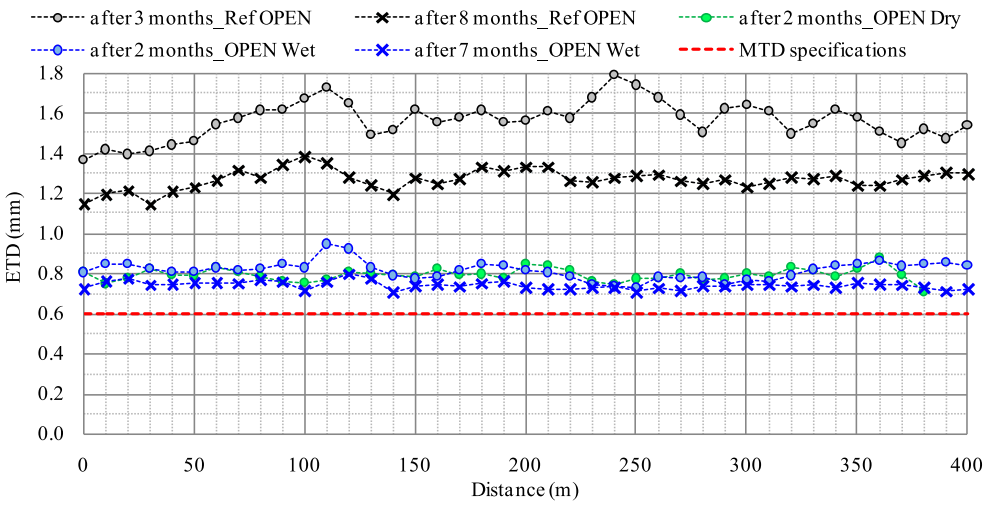


Figure 10. Macrotexture profiles of open-graded mixtures.

Figures 11 and 12 clearly show that the new LNP surfaces better fulfil these requirements than the reference surfaces; in particular, as an effect of the greater aggregate gradation nominal diameter, the reference mixtures show higher texture levels than the new LNP mixtures.

These results were confirmed by estimation of rolling noise by using theoretical model proposed in (Losa et al., 2013). The model allows reliable estimation of rolling noise at a certain speed as a function of composition and volumetric characteristics of the mixes (D_F, D_{95}, AV, VMA). The rolling noise is expressed in terms of Close Proximity Index (CPXL), according to the ISO/CD 11819-2 procedure. Table 7 shows the estimated CPXL for the mixes. CPXL values estimated at 50 km/h for the new LNP surfaces revealed a reduction, as compared to the reference surfaces, of roughly 2 and 1 dB(A) for the gap-graded and open-graded mixes.

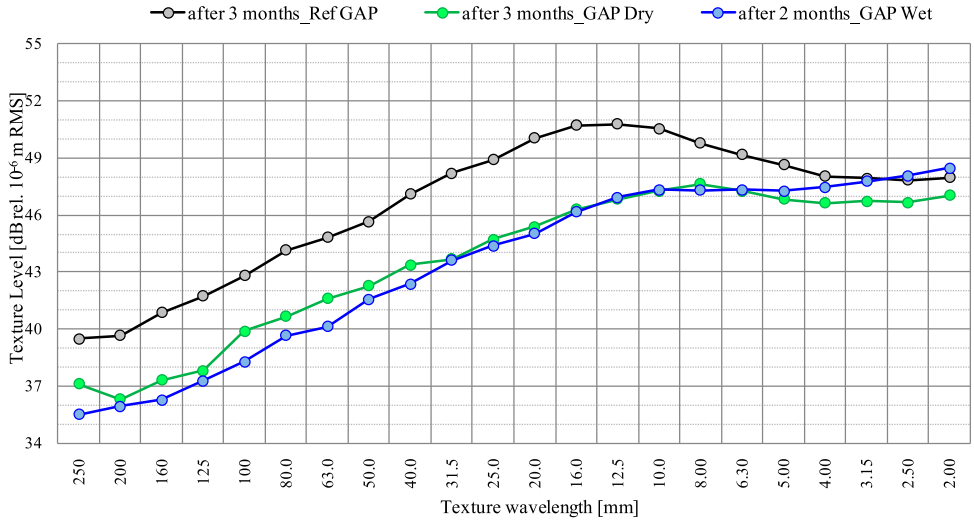


Figure 11. Texture spectrums of gap-graded mixtures.

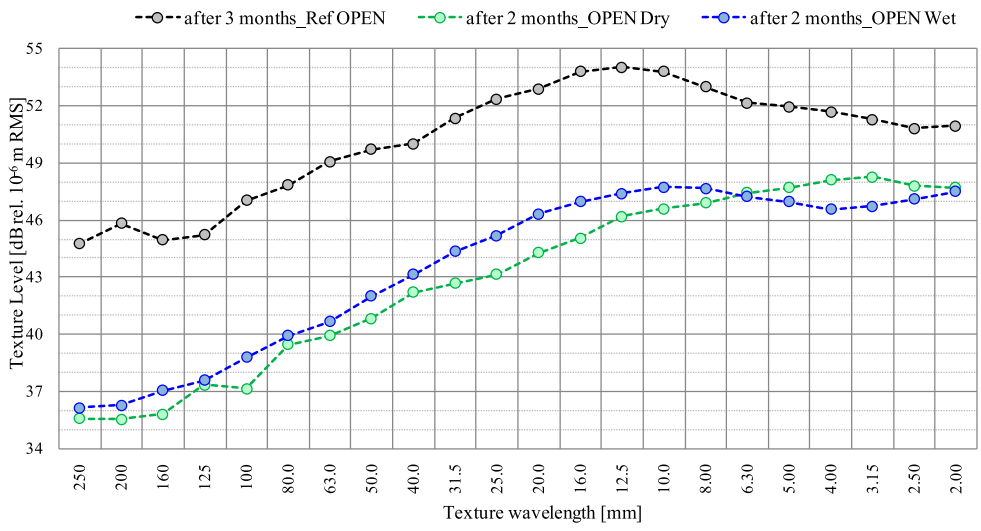


Figure 12. Texture spectrums of open-graded mixtures.

Friction

Friction measurements were carried out by using the Skiddometer BV11. The test was carried out at a speed of 20 km/h, by adequately wetting the pavement in order to create the 1 mm thick water film.

Using the PIARC model, and after suitably calibrating the model parameters for the specific device used in these tests (Leandri & Losa, 2015; PIARC, 1995), the Friction Number (F60) of the International Friction Index (IFI) was determined on the basis of friction and macrotexture values.

Figures 13 and 14 show F60 measured values, averaged at every 10 m, together with the friction threshold likewise expressed in terms of F60; these latter were determined from the national

Table 7. Estimated CPXL values at 50 km/h.

Typology mix	D_{95}[a] (mm)	D_F[b] (mm)	AV (%)	VMA (%)	$CPXL_e$[c] (dB(A))	$\Delta CPXL_e$[d] (dB(A))
Ref GAP	8.2	2.741	6.9	18.9	93.8	
GAP Dry	6.3	2.735	7.2	23.6	92.0	**– 1.8**
GAP Wet	6.3	2.771	6.6	23.8	92.1	**– 1.7**
Ref OPEN	7.7	2.578	24.2	32.4	91.0	
OPEN Dry	6.6	2.675	20.9	31.4	89.8	**– 1.1**
OPEN Wet	6.6	2.677	20.7	31.4	89.9	**– 1.1**

[a]D_{95}, sieve size to which a 95% of aggregate is passing.
[b]D_F, fractal dimension of aggregate grading.
[c]$CPXL_e$, estimated CPXL value at 50 km/h.
[d]$\Delta CPXL_e$, difference between $CPXL_e$ of ref mixes and $CPXL_e$ of new LNP surfaces.

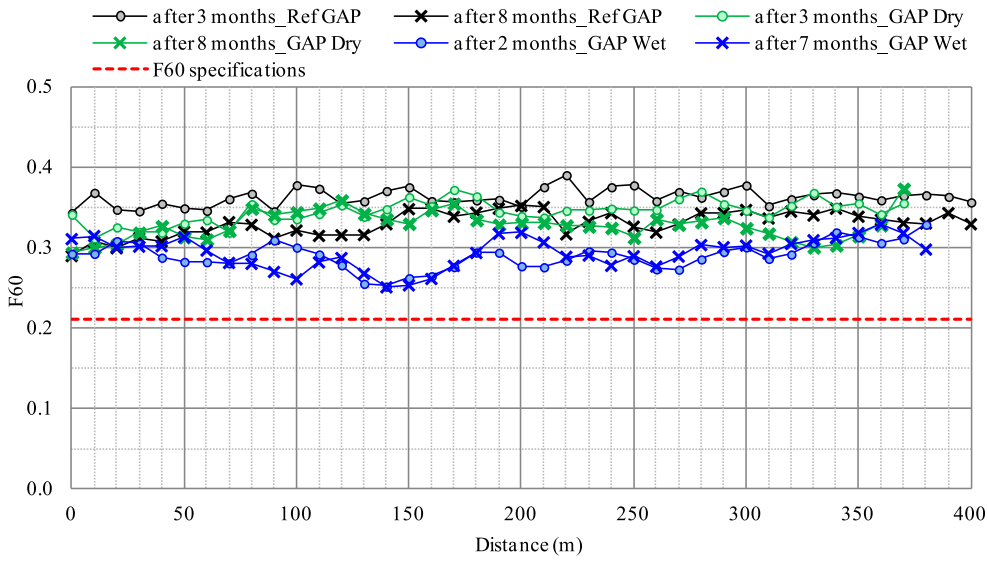


Figure 13. Friction performance of gap-graded mixtures.

standards for a newly built gap and open asphalt surfaces, which are characterised, respectively, by a Speed Constant (Sp) equal to 45.2 and 56.6 km/h.

The results show the good friction levels which can be obtained by using CRM in the production of LNP surfaces, which are higher than those required by the technical specifications; moreover, the studied mixture shows friction levels with a good stability over time. Compared to the reference mixtures, the new LNP surfaces show comparable friction levels for gap graded mixes, whereas lower friction levels are measured in the case of open-graded mixes. This is due to the greater aggregate nominal size which leads to higher macrotexture values and consequently to greater friction levels.

The open dry and open wet mixes are characterised by similar friction levels, whereas the gap wet mix shows lower friction levels than those of the gap dry mix. This can be due to the greater adhesion of the AR to the aggregate determining lower friction levels at one month after laying, since after this short period the AR cannot be removed from the vehicles and therefore it can be coated the aggregates.

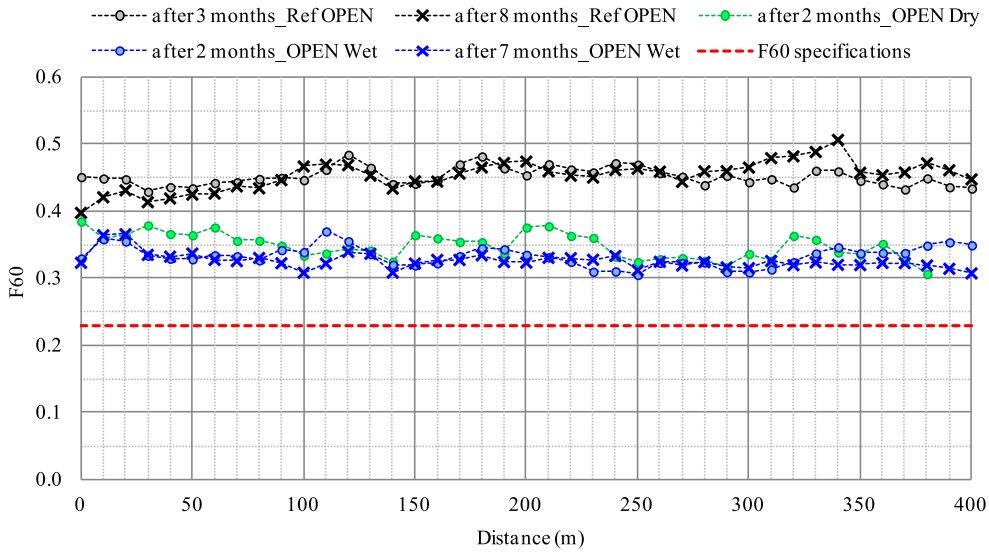


Figure 14. Friction performance of open-graded mixes.

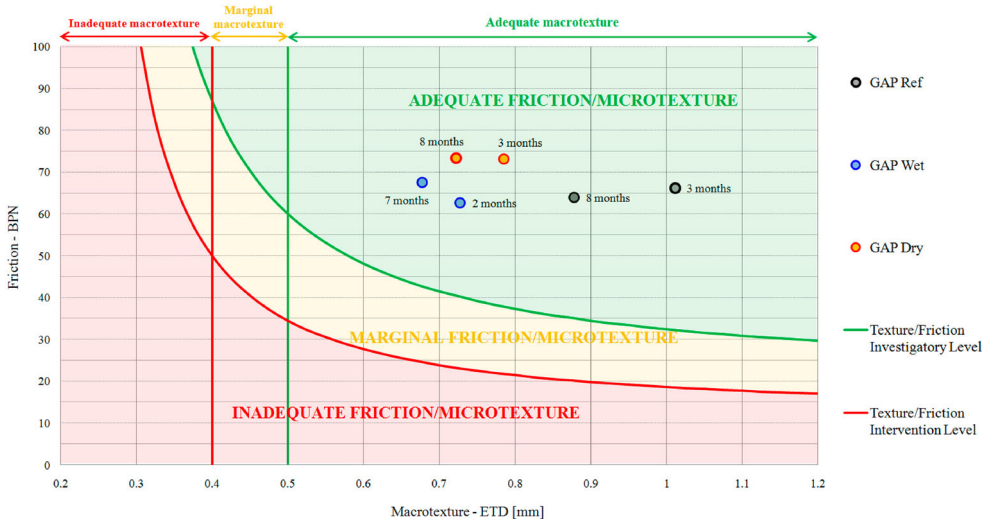


Figure 15. Friction/macrotexture threshold level for gap-graded surfaces.

By setting the threshold levels for friction and macrotexture, if the IFI model is used, a quick assessment of the friction and macrotexture measurements can be made in order to determine if friciton/microtexture or macrotexture, or both, are inadequate and if they need improvement (Hall et al., 2009). In the urban context, the following threshold levels can be set for different type of mixtures:

- British Pendulum Number (BPN) = 60–50 and ETD = 0.5–0.4 mm for gap-graded surfaces;
- BPN = 55–45 and ETD = 0.6–0.4 mm for open-graded surfaces.

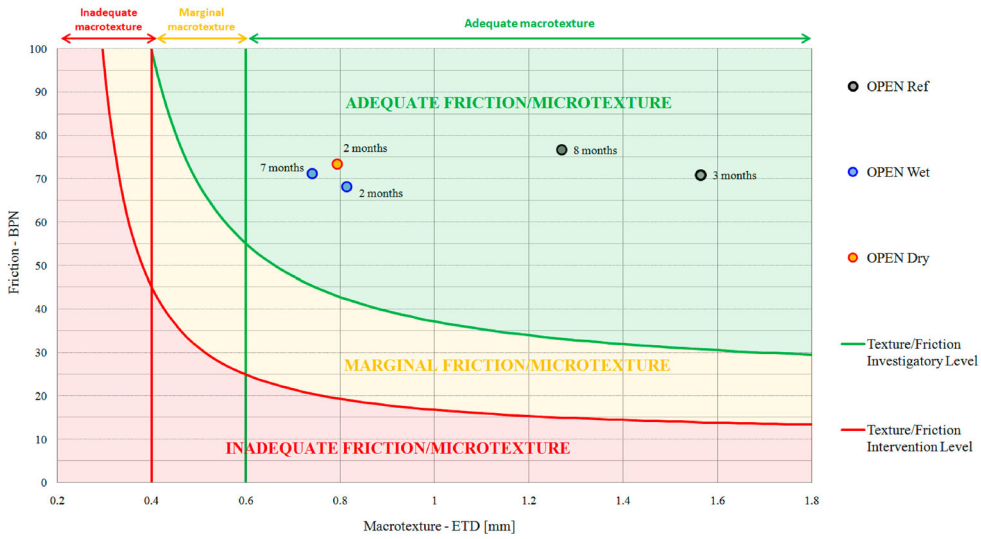


Figure 16. Friction/macrotexture threshold level for open-graded surfaces.

Figures 15 and 16 show the friction and macrotexture measurements carried out on the experimental sections, the results show the excellent performances of mixtures containing CRM over time.

Conclusions

This paper presents key findings of the Phase I of the Life NEREiDE project. The project has the specific aim of developing innovative solutions for sustainable LNP with CRM, by using both the wet and the dry process. In the Phase I of the NEREiDE project, the mechanical and functional performances of the new LNP surfaces, developed by using the two technologies, were analysed and compared in order to assess their respective potentials for use as viable alternatives to other traditional LNP surfaces.

The results of laboratory and on-site tests have shown that:

- The new LNP mixes show lower optimum AC compared to the quantities normally used in pavement surfaces containing CRM, improving their sustainability in terms of reduction of non-renewable raw resources consumption.
- The assessment of volumetric and workability characteristics of the new LNP mixes, by an SGC equipped with the GPDA, shows a workability at 130°C which is still comparable to that at170°C. The temperature of 130°C can be considered the optimum compaction temperature for these new LNP surfaces. This result allows a reduction of 30–40°C of the mixing and compaction temperatures as compared to traditional LNP surfaces, with significant benefits in terms of pollution and energy consumption.
- The new LNP mixes show similar ITS values which are higher than the minimum values required by the national standards for the traditional LNP surfaces. No problems pertaining to moisture susceptibility arise for all the mixes.
- For the gap-graded mixtures, the new LNPs show a reduction in the stiffness modulus as compared to the reference mixture with PMA, this is due to the high quantity of CRM that leads to a lower stiffness of the aggregate skeleton and of the mastic as compared to the reference mixture.

Table 8. SWOT analysis for LNPs containing CRM produced by using WMA technology.

	Internal factors		
	Strengths		**Weaknesses**
1	Lower optimum AC compared to pavement surfaces containing CRM	1	Higher optimum AC compared to traditional LNP surfaces
2	Improving of sustainability in terms of reduction of non-renewable raw resources consumption	2	Asphalt-mixing plants specialized in the production of mixtures containing CRM
3	Benefits in terms of pollution and energy consumption compared to pavement surfaces containing CRM	3	Operators specialized in laying mixtures containing CRM
4	Reduction of tyre/road noise as compared to traditional LNP surfaces		
	External factors		
	Opportunities		**Threats**
1	Development of an 'End of Waste' regulation at national level with a Community perspective	1	Public great skepticism
2	Adoption of 'Green Public Procurement Action Plan' and the 'Minimum Environmental Criteria' (CAMs)	2	Lack in environmental regulations
3	Development of a Green economy culture that values recycling as a plus		

- The gap mix containing CRM shows a higher fatigue than the reference mix, whereas, with regard to open-graded mixtures, the studied mixes show a similar fatigue life. As expected, if on one side the use of high content of CRM provides a decrease in stiffness and elasticity, on the other side, it increases the mixture ductility.
- The reference mixtures and the mixtures by DP do not show any significant problems pertaining to accumulation of permanent deformation, whereas the mixtures by WP show some stripping problems. For the mixtures by WP, it is useful to use anti-stripping additive in order to reduce the accumulation of permanent deformation because of the effect of the stripping.
- The reference mixes show macrotexture values higher than those of the new LNP mixes, consequently at the greater nominal diameter of the aggregate gradations.
- CPXL values estimated at 50 km/h for the new LNP surfaces revealed a reduction, as compared to the reference surfaces, of roughly 2 and 1 dB(A) for the gap-graded and open-graded mixes. It is important to highlight the benefits, in terms of tyre/road noise reduction, which can be obtained by using new LNP surfaces in the urban context as a viable alternative, in terms of environmental compatibility and economy, to other traditional LNP surfaces.
- The friction levels recorded, in terms of F60, were higher than those required by the technical specifications for newly constructed traditional LNP surfaces. Compared to the reference mixtures, the new LNP surfaces show comparable friction levels for gap graded mixes, whereas lower friction levels are measured in the case of open-graded mixes. This is due to higher macrotexture values.

The innovative aspect of the research was to compare some new solutions of sustainable pavement surfaces containing CRM, by using a strengths, weaknesses, opportunities, and threats (SWOT) analysis of different technologies developed for production of LNPs. The analysis of laboratory and on-site test results, carried out on specifically built field trials, allowed to understand strengths and weaknesses of the new LNPs in terms of mechanical and functional performance. In order to identify opportunities and threats in the analysis, the external factors that can be helpful or harmful to the recycling of CRM in LNPs have been analysed. The SWOT analysis is listed in Table 8. The results obtained highlight the potential of the use of new LNPs containing CRM in the urban context as a viable alternative, in terms of environmental compatibility and performance, to traditional LNPs.

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