

Use of alternative aggregates for the production of hot-mix asphalt surface layers: A performance evaluation

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ABSTRACT

The decreasing availability of virgin mineral aggregates is a critical issue related to the production of asphalt pavements. For this reason, several alternatives have been recently taken into account by the scientific community to recycle and re-use waste and secondary materials to obtain hot-mix asphalt (HMA) materials equally valid. When dealing with surface layers, stiffness, rutting and skid resistance, are fundamental performance to ensure safety and comfort to the user. This study deals with a performance evaluation of HMA surface layer materials (in laboratory and in plant) produced with alternative aggregates, such as steel slag, expanded clay and municipal solid waste sand.

1. Introduction

Hot-mix asphalts (HMAs) are heterogeneous pavement materials commonly composed of mineral aggregates, which constitute the lithic skeleton, and bitumen, which acts as binder among the aggregates particles. According to the depth level at which the HMA material is realized (surface layers, binder courses, base courses, etc.) the aggregates sources, as well as bitumen type and dosage, shall vary. The main distinction is made between surface layers, responsible of conferring to the pavement safety and comfort (skid resistance and water drainage), and lower layers, which on the other hand must structurally withstand traffic loading. In terms of pavement structure, it has been demonstrated that loads transmission occurs mainly at the bitumen-aggregate interface area [1]. More specifically, pavement response to mechanical loading depends on mastic thickness, aggregates particle-to-particle contact area and proximity zone directional distribution. [2–5]. A well-designed aggregate blend is fundamental to obtain HMA with high performance characteristics, especially in terms of rutting resistance of surface layers [6].

In many cases, the aggregate blend design follows a trial and error protocol that aims to minimize the air voids content in the aggregates skeleton. At the same time, optimizing the aggregate interlock and the particle-to-particle contact area leads to an increase in the unit weight of the produced HMA mixtures and to a higher stability during service life. In order to minimize air voids volume in the aggregate blend, the maximum density distribution as proposed by Fuller and Thompson can

be chosen as the target mix design curve [7]:

$$P = 100 \bullet \left(\frac{d}{D} \right)^n \quad (1)$$

where P is the percent passing a sieve with opening size d; D is the maximum particle diameter; and n is a parameter based on the gradation fineness or coarseness [8].

The Fuller-Thompson curve is related to the proportioning of aggregate fractions in terms of mass, whereas the Bailey method is an excellent alternative for aggregates blend mix-design in volumetric terms. The Bailey method allows to control accurately the voids in the mineral aggregates (VMA) by knowing the volume occupied in the aggregate blends by each fraction [9–10]. This approach leads to better HMA materials under different points of view: rutting [11–12], cracking resistance and durability [13], compactability, strength and stiffness [14].

The optimal proportions of coarse and fine fractions resulting in better performance consists in filling the volume of air among the coarser aggregates with the remaining finer aggregates, paying attention to medium-sized aggregates that can be responsible of the wall-effect and interference effect. Both of them could lead to an undesired increase in the air voids volume [14].

Furthermore, the volumetric proportioning proposed with the Bailey method is particularly suitable when designing aggregate blends with aggregates characterized by different densities, such as steel slag, lightweight sand and expanded lightweight clay [15].

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In HMA surface layers, aggregates cover an important role in terms of skid resistance (friction) and polishing response. Those are both fundamental aspects for safety reasons, especially in proximity of curve sections and for stopping distance. The tire-pavement interface friction is a complex topic influenced by different aspects, such as atmospheric conditions, traffic conditions, surface layer characteristics (micro- and macro-textures) and contaminants (water, ice, oil, dust, etc.). Micro- and macro-textures are properties that can be approximated as a harmonic wave decomposition of the longitudinal road profile. Micro-texture is characterized by a wavelength lower than 0.5 mm and it is an aggregate property. In fact, the aggregate surface roughness ensures tire-pavement friction by adhesion and hysteresis phenomena [16]. The macro-texture is identified with a wavelength between 0.5 mm and 50 mm, and it is a property related to the HMA mixture composition that ensures friction (at the initial stage) and water drainage.

Skid resistance and friction can be measured by a multitude of devices and laboratory equipment, divided in continuous measurements and punctual measurements. Towed instrumented tires operating at different speed and conditions typically obtain the continuous measurements. In this case, Sideway Friction Coefficient (SFC) and Longitudinal Friction Coefficient (LFC) are measured. Punctual measurements, operated by the British Pendulum or the Dynamic Friction Tester, can be obtained from laboratory compacted slabs or portions of test track pavements. In the latter case, punctual measurements allow to analyse the friction spatial variability of the pavement surface. Other laboratory equipments for friction and skid resistance measurements are the Wehner-Schulze equipment and the Three-wheel polishing device (TWPD) [17–18]. Because of the different equipment that could be used for friction measurements, the values and results obtained can vary significantly. However, they can be homogenized by using the International Friction Index (IFI) introduced by PIARC and standardized by ASTM [19].

Skid resistance evolves along time due to change in the surface characteristics of micro- and macro-texture. At the initial stage, aggregates are covered by new bitumen, hiding the contribution of micro-texture, which does not affect friction. After a certain amount of vehicles passes, the binder film is removed, highlighting both micro- and macro-textures effects on friction. In this situation, skid resistance reaches its maximum value. Subsequently, polishing of aggregates takes place, causing a decrease in skid resistance until a stable value, which only oscillates due to seasonal effects. On contrary, for low-traffic areas such as highways and motorways shoulders, the skid resistance initially increases for few months, reaching a constant value due to the binder ageing and oxidation [20–22]. So far, skid resistance evolution has been modelled mainly by statistical and empirical approaches, often with poor reliability, taking into account time and traffic statistical laws [23]. However, in addition to traffic and atmospheric conditions, the resistance to fragmentation and to polishing of the aggregates used are important aspects influencing skid resistance evolution. For this reason, virgin high-quality aggregates are needed to produce surface layers with the desired skid properties, although this choice is not always sustainable from both economical and environmental points of view.

Virgin aggregates in HMA materials can be replaced (totally or partially) with alternative materials obtained from other production fields, such as electric arc furnace steel slag (from now on simply named steel slag), municipal solid waste (MSW) aggregates and lightweight expanded clay. In addition, reclaimed asphalt pavement (RAP) has been already introduced in HMA layers since 1970 s. RAP is the granular bituminous material obtained from the milling of the old pavement, and it consists in aggregate particles surrounded by an aged bitumen film. In fact, RAP both brings recycled aggregate and bitumen to the newly produced mixture, thanks to the use of rejuvenating additives [24–25].

The steel slag, a by-product of the steel production process, has several positive effects on the HMA material produced, proven by several studies [26–29]. In fact, a significant replacement of limestone with up to 75% of steel slag improves HMA properties in terms of

friction, indirect tensile strength, resilient modulus, rutting resistance, fatigue life and creep modulus.

The limited landfilling areas available in several highly populated societies encouraged waste incineration as a treatment process for MSW. The post-treatment of the resulting bottom ashes has been field of specialization of newly founded companies, with the scope to obtain a reusable end-of-waste (EOW) product suitable for the construction field. After specific processing (ageing, sieving and washing), MSW materials can be introduced in the production line for cements or ceramic materials, being formed by a silica matrix rich in iron, calcium and aluminum oxides [30–33].

An alternative aggregate for HMA production that leads to significant environmental benefits is expanded clay aggregate [34]. In fact, on one hand, it is possible to reduce the consumption of natural aggregates, and on the other hand, mechanical and friction pavement characteristics are improved [35]. However, only a few studies have been carried out, which suggest that optimum contents of expanded clay should be less or equal than 15% by aggregates mass, because of the high porosity of the aggregate and to avoid moisture susceptibility that could occur with higher dosages [36–37].

The objective of this study is to investigate the possible use of alternative aggregates for the production of HMA surface layers. For this purpose, a complete performance evaluation was carried out in laboratory produced mixtures, especially in terms of skid resistance evolution along time. This aspect is considered fundamental when focusing on the design of surface layers. In addition, a batch-type asphalt plant was available to validate on industrial scale the production of one of the mixtures investigated.

2. Materials and methodology

The raw materials used for this study involved several sources of aggregates (basalt, limestone, steel slag, MSW sand, expanded clay, RAP and limestone filler) which were combined with an SBS-polymer modified bitumen. A total of six HMA mixtures were produced, four of which designed by the Bailey method, introduced below. A performance-based experimental program has been followed, including a laboratory protocol to investigate the long-term evolution of skid resistance for surface layers. In addition, it was possible to validate the production of one mixture in a local industrial batch-type plant, making possible the sampling of the material and the investigation of its properties.

2.1. Raw materials

The mineral aggregates used were a limestone sand (0/6 fraction), basalt coarse aggregate (4/8 fraction) and limestone coarse aggregate (4/8 and 8/12 fractions). Table 1 lists the related properties. Three alternative aggregates were used and their properties are shown in Table 2. In particular, a MSW sand (0/4 fraction), steel slag coarse aggregate (4/8 fraction) and lightweight expanded clay coarse aggregate (5/10 fraction) were chosen as valuable alternatives to mineral aggregates. RAP aggregate was obtained from a local production plant, which performs crushing and screening of the milled pavements into different fractions. For this study, the 0/8 fraction was used and its properties are reported in Table 3. RAP aggregate was used in combination of a rejuvenating additive dosed at 0.2% by RAP aggregate mass. The limestone filler used to correct mixtures gradation is characterized by the properties presented in Table 4.

2.2. Mix-design

In this study, the granular materials above mentioned were proportioned following two mix design approaches: the traditional method and the Bailey method. According to the traditional method, granular components were simply dosed by aggregates mass in order to respect

Table 1
Mineral aggregates properties.

Property	Standard	Unit	Value			
			Limestone Sand 0/6	Basalt 4/8	Limestone 4/8	Limestone 8/12
Apparent density ρ_a	UNI EN 1097-6	–	2.655	2.904		2.663
Bulk density ρ_{rd}	UNI EN 1097-6	–	2.567	2.781		2.618
Effective Specific Gravity $G_{se}^{(1)}$	AASHTO T 312	–	2.637	2.879		2.654
Water absorption	UNI EN 1097-6	%	1.50	1.49		0.64

⁽¹⁾ The effective specific gravity is calculated as $G_{se} = \rho_{rd} + 0.8 (\rho_a - \rho_{rd})$.

Table 2
Alternative aggregates properties.

Property	Standard	Unit	Value		
			MSW Sand 0/4	Steel slag 4/8	Expanded Clay 5/10
Apparent density ρ_a	UNI EN 1097-6	–	2.519	4.034	1.440
Bulk density ρ_{rd}	UNI EN 1097-6	–	2.020	3.913	1.120
Effective Specific Gravity $G_{se}^{(1)}$	AASHTO T 312	–	2.419	4.010	1.376
Water absorption	UNI EN 1097-6	%	9.8	0.9	17.0

⁽¹⁾ The effective specific gravity is calculated as $G_{se} = \rho_{rd} + 0.8 (\rho_a - \rho_{rd})$.

Table 3
RAP aggregate properties.

Property	Standard	Unit	Value
Bulk density ρ_{rd}	UNI EN 1097-6	–	2.528
Bitumen content by aggregate mass	UNI EN 12697-1	%	5.3
Bitumen content by mixture mass	UNI EN 12697-1	%	5.1
Water absorption	UNI EN 1097-6	%	0.2

Table 4
Limestone filler properties.

Property	Standard	Unit	Value
Passing at 0.063 mm	UNI EN 933-1	%	80.5
Plasticity Index	UNI CEN ISO/TS 17892-12	–	Not Plastic
Blaine specific surface	UNI EN 196-6	cm ² /g	2887
Filler density ρ_f	UNI EN 1097-7	–	2.660
Rigden voids	UNI EN 1097-4	%	31.2
Stiffening power $\Delta_{R\&B}$	UNI EN 13179-1	°C	11.4

specification requirements (issued from the Italian national agency) in terms of target gradation [38]. Details about the Bailey method are provided below.

2.2.1. Bailey method

The Bailey method consists in proportioning the aggregate blend considering the volume occupied by each fraction, rather than its mass [39]. The Bailey method represents a valid tool that allows to control intergranular air voids as a function of the gradation variations. This is possible considering the packing properties and the densification ability of the aggregate fractions selected. Therefore, it is important to identify correctly the aggregates to use, in order to create the correct amount of intergranular voids in the coarse aggregates that will be filled by the fine aggregates. In this sense, the definition of “coarse aggregate” is intended as the aggregate fractions that create intergranular voids, while “fine aggregate” is defined as the aggregate fractions occupying the volume left by the coarse aggregates.

The distinction between coarse and fine fractions is possible by the definition of the Nominal Maximum Aggregate Size (NMAS). The NMAS is the sieve diameter one size larger than the first sieve diameter to pass less than 90% by weight of aggregate [8]. The sieve diameter which discriminates coarse from fine fraction is named Primary Control Sieve (PCS), and it is the sieve size closer to the value $(NMAS \cdot 0.22)$ (Fig. 1).

Other control sieves of the Bailey method are the Secondary Control Sieve (SCS) and the Tertiary Control Sieve (TCS), as defined in Fig. 1. The factor 0.22 present in all equation comes from packing theory and it was assumed in the Bailey method as an average value between 0.15 and 0.29, i.e. theoretical aggregate diameter ratios for round and flat aggregates, respectively. The aggregate particles retained on the PCS are the coarse fraction, the particles passing the PCS and retained on the SCS are the coarser fraction of the fine aggregates and the particles passing the SCS and retained on the TCS are the finer fraction of the fine aggregates.

The Half- Sieve (HS) was defined to identify the particles passing the HS and retained on the PCS (Fig. 1). This portion of particles is called “interceptors” and they control the mixture intergranular voids (or voids

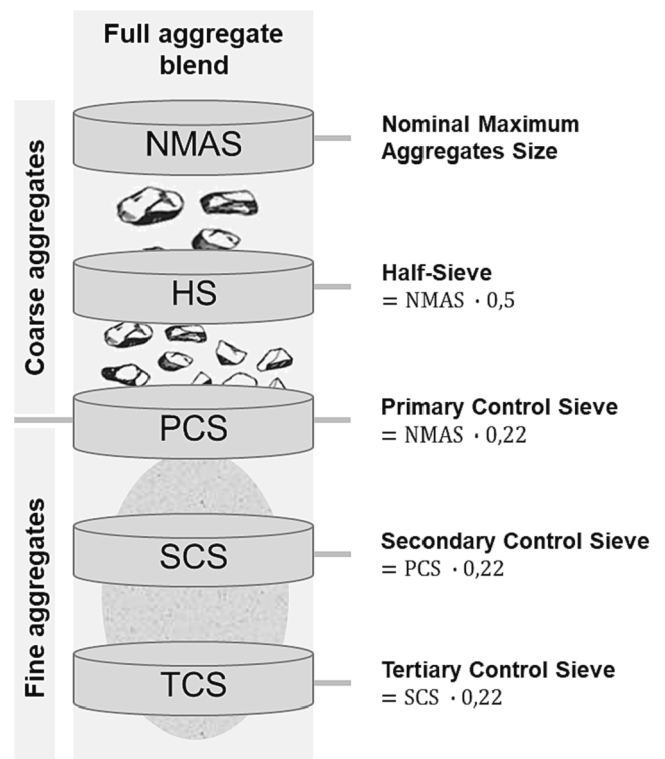


Fig. 1. Schematic representation of Bailey method characteristic sieves.

in the mineral aggregate – VMA) since they are too large to fill the coarse aggregates voids. The evaluation of the packing properties of the aggregate blend is possible by the definition of three parameters linking the characteristic sieves above mentioned.

The Coarse Aggregate ratio (CA ratio) is calculated as:

$$\text{CA Ratio} = \frac{\% \text{passing}_{\text{HS}} - \% \text{passing}_{\text{PCS}}}{100\% - \% \text{passing}_{\text{HS}}} \quad (2)$$

And it is used to evaluate the packing ability of the coarse fraction of the aggregate blend. Mixtures with CA ratios lower than 1.0 shows better compaction ability than mixtures with higher CA ratios. In general, if the CA ratios decreases, the compactability of the mixes produced improves, since there are less interceptors preventing the optimal packing.

The Fine Aggregate coarse ratio (FA_c ratio) and the Fine Aggregate fine ratio (FA_f ratio) are calculated as:

$$\text{FA}_c \text{ Ratio} = \frac{\% \text{passing}_{\text{SCS}}}{\% \text{passing}_{\text{PCS}}} \quad (3)$$

$$\text{FA}_f \text{ Ratio} = \frac{\% \text{passing}_{\text{TCS}}}{\% \text{passing}_{\text{SCS}}} \quad (4)$$

And they describe the packing characteristics of the fine fraction. Increasing values of both FA ratios generally bring to decreasing the VMA and air voids in HMA mixtures, since the fine fraction improves its interlock ability.

In order to apply the Bailey method, it is necessary to know the packing properties of each aggregates fractions used. Consequently, it is important to measure the bulk density or unit weight, i.e. the mass of a unit volume of aggregate considering the intergranular air voids. The Loose Unit Weight (LUW - for coarse aggregates) is the bulk density of a unit volume of material with no compactive effort and the minimum particle-to-particle contact. The Rodded Unit Weight (RUW – for coarse and fine aggregates) is the bulk density of a unit volume of material with the application of a rodding compactive effort, which causes an increase in the particle-to-particle contact. The following step consists in selecting the desired Chosen Unit Weight of coarse aggregate (CUW), as a percentage of the coarse aggregate LUW. It is then possible to calculate the coarse aggregates weight and volume, as well as the intergranular air voids volume. The weight and volume of fine aggregate is obtained by multiplying the intergranular air voids volume in coarse aggregates by the fine aggregate RUW.

Selecting a CUW below 90% of the LUW the blend obtained is called “fine-graded”, since the dominant fraction that controls VMA in the

mixture is the fine fraction, whereas coarse particles are dispersed apart. If the CUW is between 95% and 105% of the LUW, the VMA in the blend obtained, named “coarse-graded”, are dominated by the coarse fraction. Values of CUW above 110% of the LUW lead to “stone-mastics asphalt” (SMA) blends, which are coarse-graded mixtures usually difficult to compact due to the dominant presence of coarse aggregate. Therefore, the desired volumetric properties are obtained by increasing the bitumen and filler content. The selected CUW for this study is 100% of LUW in all cases.

2.3. Mixtures studied

The granular blends composition, as well as the values related to Bailey method parameters (when applied), are shown in Table 5. The study involves six mixtures with different composition and gradation, in order to maximize the use of alternative aggregates on one hand, and to enhance the mixtures macro- and micro-texture on the other hand.

The target gradations of the six mixtures investigated are reported in Table 6. The effect of RAP in the materials performance is studied by comparing MIX 1 with MIX 4, and MIX 3 with MIX 6. The effect conferred by the use of expanded clay coarse aggregate is evaluated by comparing MIX 2 with MIX 3. The use of selected aggregates to enhance skid resistance is taken into account by comparing MIX 1 with MIX 5 (basalt versus limestone) and MIX 1 with MIX 3 (basalt versus steel slag). It must be noted that MIX 4, produced following the traditional mix design with limestone sand, basalt coarse aggregate, RAP and filler, represents the typical mixture used to produce HMA surface layers in accordance to the Italian national agency specifications.

The bitumen content dosed for the mixtures investigated, as well as their volumetric properties (air voids V_a, VMA, voids filled with bitumen VFB and filler/bitumen ratio) are collected in Table 7. Being the target gradations similar, no significant variation in the granular blends specific surface led to different bitumen contents to obtain comparable volumetric properties. In fact, with the same bitumen content, it was possible to reach similar air voids content. The volumetric properties were defined by compaction with a Shear Gyratory Compactor (SGC) at three compaction energies (10, 140 and 230 gyrations), as required by the Italian national agency for surface layers with polymer-modified bitumen.

2.4. Testing program

2.4.1. Workability and compactability

Compaction curves obtained from SGC can be approximated by

Table 5
Composition of the target granular blends and Bailey method parameters.

Component	Percentage by mass					
	MIX 1*	MIX 2*	MIX 3*	MIX 4	MIX 5	MIX 6*
MSW Sand 0/4		22.7 %	17.3 %			24.8 %
Limestone sand 0/6	44.1 %			45.0 %	45.0 %	
Basalt 4/8	52.8 %		33.3 %	40.0 %		30.9 %
Steel slag 4/8		58.3 %	32.8 %			37.4 %
Limestone 4/8					33.0 %	
Limestone 8/12					7.0 %	
Expanded clay 3/8		12.1 %				
RAP			9.1 %	13.0 %	13.0 %	
Filler	3.1 %	6.9 %	7.5 %	2.0 %	2.0 %	6.9 %
* Mixtures designed by Bailey Method						
NMAS (mm)	10.0	10.0	10.0			10.0
HS (mm)	4.0	4.0	4.0			4.0
PCS (mm)	2.0	2.0	2.0			2.0
SCS (mm)	0.5	0.5	0.5			0.5
TCS (mm)	0.125	0.125	0.125			0.125
CA Ratio	0.21	0.30	0.20			0.22
FA _c Ratio	0.45	0.57	0.57			0.56
FA _f Ratio	0.58	0.61	0.65			0.60

Table 6

Target gradations of the studied mixtures.

	Sieve size (mm)						
	12.5	8	4	2	0.5	0.25	0.063
MIX 1*	100.0 %	87.1 %	45.2 %	33.8 %	15.3 %	11.3 %	7.7 %
MIX 2*	100.0 %	99.5 %	42.5 %	25.4 %	14.4 %	11.4 %	7.6 %
MIX 3*	100.0 %	90.5 %	36.3 %	23.4 %	13.4 %	10.8 %	7.7 %
MIX 4	100.0 %	88.7 %	51.2 %	36.7 %	15.1 %	10.6 %	6.9 %
MIX 5	100.0 %	94.6 %	53.3 %	37.5 %	15.2 %	10.6 %	6.9 %
MIX 6*	100.0 %	92.2 %	39.2 %	26.0 %	14.5 %	11.3 %	7.6 %

* Mixtures designed by Bailey Method.

Table 7

Volumetric properties of the studied mixtures.

	Bitumen content (%) (2)	V _a , N _{ini} (%) (3)	V _a ,N _{design} (%) (3)	V _a ,N _{fin} (%) (3)	VMA _{Nfin} (%)	VFB _{Nfin} (%)	F/B (4)
MIX 1 ⁽¹⁾	5.66	16.1	5.2	4.0	20.0	73.9	1.36
MIX 2 ⁽¹⁾		16.4	4.5	3.1	17.8	74.9	1.34
MIX 3 ⁽¹⁾		16.7	5.0	3.6	19.6	74.4	1.36
MIX 4		18.4	5.0	3.0	17.7	72.1	1.22
MIX 5		16.4	4.9	3.5	19.4	74.6	1.22
MIX 6 ⁽¹⁾		14.5	5.2	3.8	19.7	68.4	1.34

⁽¹⁾ Mixtures designed by Bailey Method.⁽²⁾ Bitumen content is intended by mixture mass (SBS polymer modified bitumen and RAP binder).⁽³⁾ N_{ini} = 10 gyrations, N_{design} = 140 gyrations, N_{fin} = 230 gyrations.⁽⁴⁾ Filler/Bitumen ratio

several parameters [40–41]. One method consists in defining the straight line that interpolates the experimental data in the semi-logarithmic plot “air voids versus number of gyrations”. The parameters used are the air voids after 10 gyrations $V_a(10)$ and the line slope k . The value of 10 gyrations was chosen because from that point SGC curves can be represented in a semi-logarithmic plot as a straight line having slope k [42]. Therefore, the linear regression obtained is defined by the following equation:

$$V_a(n) = V_a(10) - k \bullet \log(n) \quad (5)$$

The value of $V_a(10)$ is selected as representative of the mixture workability, intended as the effort to mix and laydown the material. Additionally, 10 gyrations is also selected as N_{ini} in the national agency specifications because considered similar to the compaction effort

applied by the paver during laydown operations [43]. The lower the $V_a(10)$ value, the more workable is the mixture. The slope k , on the other hand, is representative of the mixture compactability, or densification, that is performed by rollers or compactors operating behind the paver [44]. High values of k mean a steeper slope of the compaction curve, indicating a faster densification and a lower number of compactors passes to reach the target volumetric properties.

2.4.2. Indirect tensile stiffness modulus (ITSM)

The Indirect Tensile Stiffness Modulus (ITSM) was measured on SGC specimens compacted at 230 gyrations using a 100 mm diameter mould, in accordance to EN 12697–26 - Annex C. ITSM values were measured at 20 °C and 40 °C by means of a servo-pneumatic press equipped with a temperature-controlled chamber. The modulus of each specimen was measured on two opposite diameters, and the average value was calculated. The average ITSM value for each mixture was calculated on three replicates, as follows:

$$ITSM = \frac{P \bullet (v + 0.27)}{z \bullet H} \quad (6)$$

Where P is the peak value of the applied vertical load, z is the amplitude of the horizontal deformation, H is the specimen average thickness, v is the Poisson's ratio (assumed equal to 0.35 for both temperatures).

2.4.3. Rutting resistance

The rutting resistance was measured in accordance to EN 12697–22 on slabs compacted in accordance to EN 12697–33. The compacted slabs have dimensions equal to 50 cm (L) × 26 cm (B) × 4 cm (H) and the target density of the material was set equal to the value reached with the SGC at N_{design} , representative of the in-field material density after compaction and before the opening to traffic [43]. The wheel-tracker used, classified as a small size device, allows to both compact and perform rutting tests with the same equipment (Fig. 2). The rutting tests were performed running 10,000 cycles (tyre back and forth) at 60 °C, as required by the UNI EN 13108–20. Prior testing, slabs were conditioned in the wheel-tracker chamber and the achievement of testing temperature was verified with internal dummy specimens. The mean proportional rut depth PRD_{AIR} of each mixture was calculated as the average of two slabs for each mixture investigated:

$$PRD_{AIR}(\%) = \frac{d_{10000}}{H} \bullet 100 \quad (7)$$

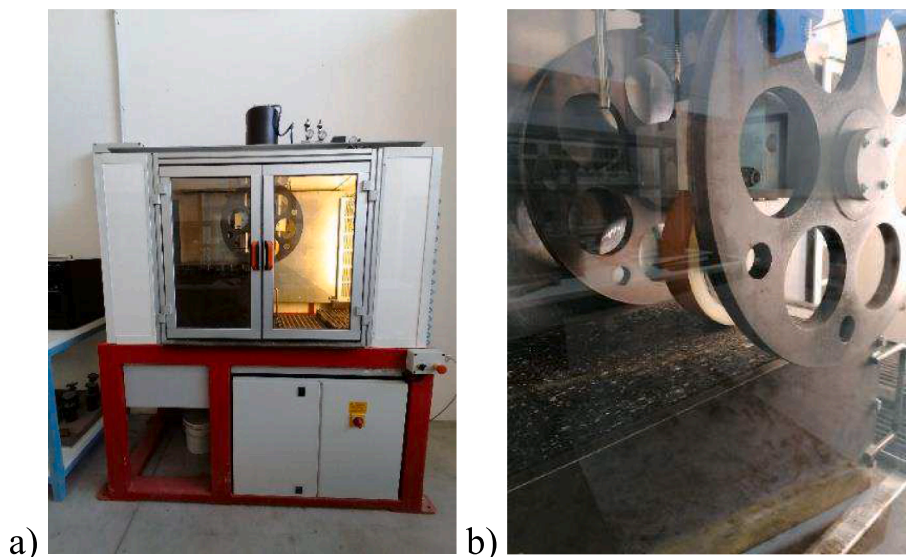


Fig. 2. Equipment used to compact HMA slabs and to perform rutting resistance tests: a) equipment; b) rutting loaded-tire.

Where d_{10000} is the average rut depth along the tyre axis after 10,000 cycles, H is the average slab thickness.

2.4.4. Laboratory procedure for skid resistance evolution of asphalt pavements

Skid resistance (SR) of surface layers in asphalt pavements is characterized by an evolution in time due to the effect of atmospheric, traffic and mix-design factors. For this reason, a laboratory procedure aiming to determine SR evolution on asphalt mixes for surface layers is proposed in order to determine the global friction properties of the materials investigated. In particular, the focus will be on the behavior related to coarse aggregates (basalt, limestone, steel slag, expanded clay and RAP coarse aggregate particles), the most influent in terms of micro-texture and polishing resistance compared to fine aggregates. The procedure proposed is divided in three measurements: initial skid number value (SN_{ini}), maximum skid number value (SN_{max}) and final (or equilibrium) skid number value (SN_{fin}). The protocol is designed for curved asphalt samples sawed from the slab surface, produced as for rutting tests. The preparation of samples is schematized in Fig. 3 and it is divided in the following steps: (a) production of roller-compacted slabs (50 cm (L) $\times$ 26 cm (B) $\times$ 4 cm (H)) with density comparable to the in-field value after compaction; (b) cutting of 5 longitudinal beams 4.5 cm wide from the center of the slab (remove 1.75 cm per side); (c) cutting a slice 9 mm thick from each beam surface; (d) divide the slice obtained in samples 90 mm long; (e) heating of at least 14 samples in an air-draft oven at a temperature of 50 °C for (30 $\pm$ 10) minutes; (f) with a light manual pressure, curve the surface samples in upside down position in the metal moulds used for the polished stone value test (EN 1097-8),

making sure that no breaking occurs; (g) as the specimens cool down, pour hardening resin in sufficient amount to fill the metal moulds and let it harden; (h) remove the surface samples from the metal mould.

The value of SN as an average of 14 samples obtained from the slab surface allow to consider not only the micro-texture characteristics of the aggregates, but also the simulated pavement macro-texture. Measurements of SN_{ini} , SN_{max} and SN_{fin} will be performed by means of the Pendulum Tester (or Skid Tester – EN 13036-4) at a fixed temperature of (20 $\pm$ 2) °C. The selected temperature is reached by conditioning surface samples and testing equipment prior testing. Measurements are done with the small slider (width of (31.75 $\pm$ 0.50) mm, length of (25.4 $\pm$ 1.0) mm, thickness of (6.35 $\pm$ 0.50) mm) on 14 samples for each mixture analyzed. The average of 5 SN readings is taken for each sample, and an overall average on 14 samples is taken for the material studied.

The SN_{ini} value of an asphalt pavement is the skid resistance offered by the mixture with no action from traffic, right after compaction. In this situation, aggregates are completely covered by a bituminous film, which makes resistance only dependent on macro-texture and independent from aggregates micro-texture and polishing resistance. Hence, the Skid Tester is performed on the 14 samples fully coated by the bitumen film (Fig. 4a).

The maximum skid resistance is reached when the bitumen coating covering the aggregates surface is removed by repeated traffic loading, highlighting the contribution offered by the aggregates micro-texture and maximizing the effect of macro-texture. In the laboratory protocol the bitumen coating is removed by a chemical treatment, consisting in the manual cleaning of the asphalt surface samples with perchloroethylene applied on a clean cloth. The contemporary mechanical and

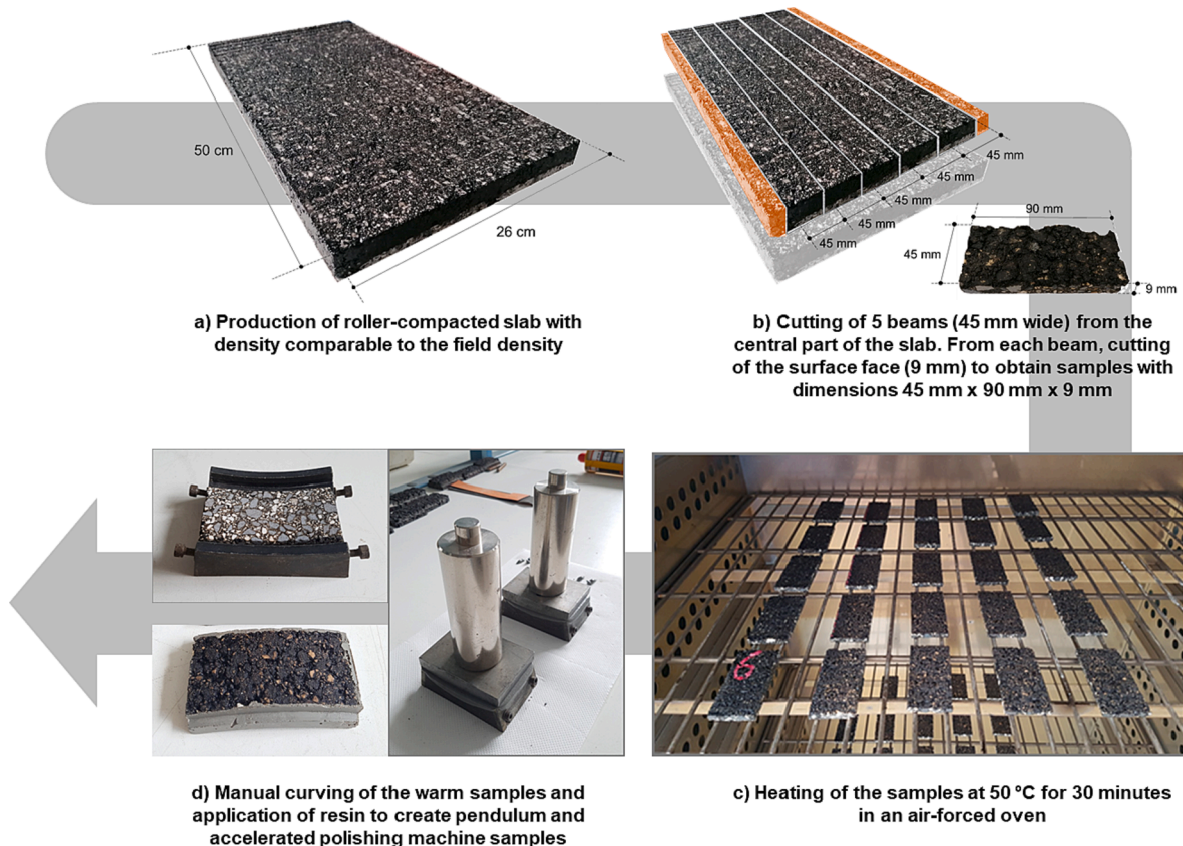


Fig. 3. Production protocol of samples for skid resistance evaluation of asphalt pavements.

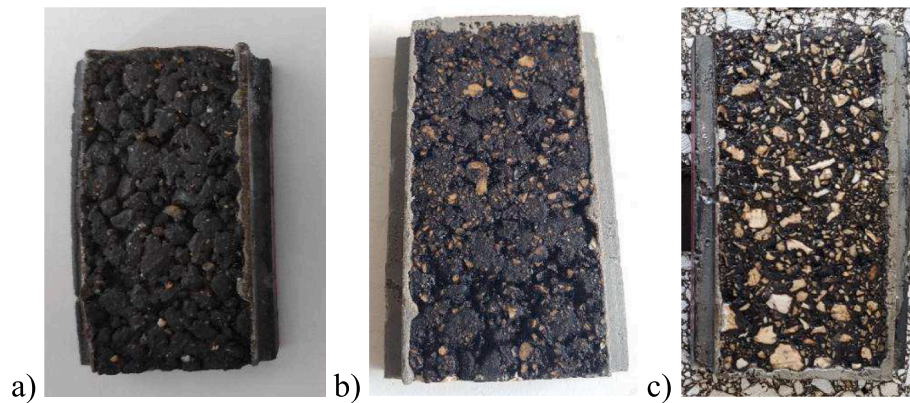


Fig. 4. Example of surface sample in: a) Initial condition; b) Maximum skid resistance condition; c) Final skid resistance condition (after polishing).

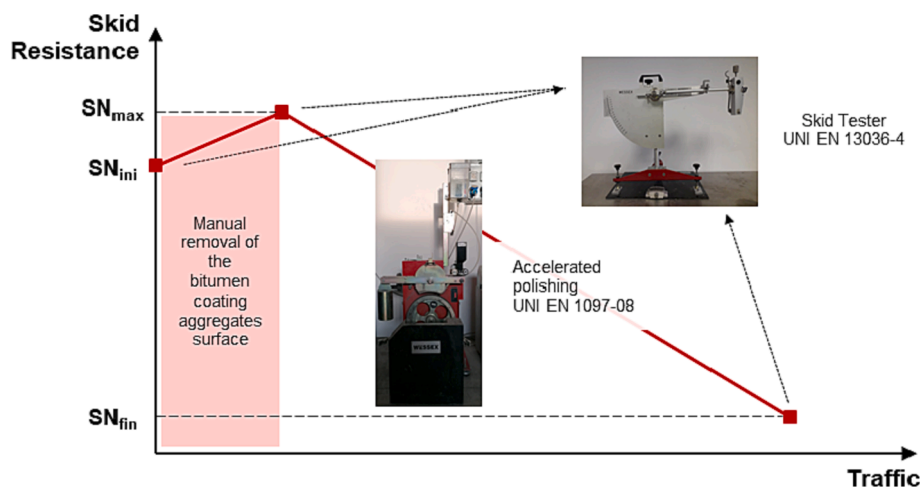


Fig. 5. Schematic representation of the laboratory procedure.

chemical treatments must be repeated until the bitumen coating is totally removed (Fig. 4b). At the same time, this operation should not be too aggressive in order to not remove aggregates particles and then altering the mixture's macro-texture.

The condition of final skid resistance is obtained on the surface samples previously treated carrying out a polishing process by means of a polishing machine. The polishing process comply with the EN 1097-8, which applies to aggregates. In this case, the rotating wheel of the polishing machine supports the 14 samples of the mixture studied. It is important to remark that surface samples should be placed on the polishing wheel on the opposite side with respect to the Skid Tester measurements. This will make the SN measurements coherent with the polishing action exerted by the polishing machine. At the end of the polishing process (3 h with corn emery plus three hours with emery flour), the samples are thoroughly cleaned to remove any contamination excess (Fig. 4c). Fig. 5 shows a schematic representation of the laboratory protocol exposed.

2.4.5. Plant production

The closing part of the experimental program consisted in the production of one of the mixtures containing alternative aggregates in a batch-type asphalt plant located in Italy. For this scope MIX 6 was selected as a good candidate, since it is a good compromise between

traditional and mineral aggregates, and does not contain RAP aggregate (that could be affected by variability in production plant). The mixture production was included in a maintenance project for a roundabout located in a city nearby. After plant calibration and after reaching a stable productivity level, several mixtures samples were prepared in order to perform the same experimental program followed for the laboratory-produced mixture. In this manner, the possibility to produce at industrial level surface layers with alternative aggregates can be validated.

3. Results analysis

3.1. Workability and compactability

Fig. 6 shows the obtained SGC curves (Fig. 6a) and the regression lines parameters $V_a(10)$ (workability) and k (compactability) (Fig. 6b). In Fig. 6a one compaction curve for each mixture was taken as an average reference, and on that parameters $V_a(10)$ and k were extrapolated (Fig. 6b). In Fig. 6a all mixes are grouped together except for MIX 4, considered as the reference mixture for surface layers. In fact, in the low-gyrations part of the curve, MIX 4 is higher than the other mixes. This is also visible in Fig. 6b, where the workability parameter $V_a(10)$ is plotted versus the compactability parameter k . In this representation,

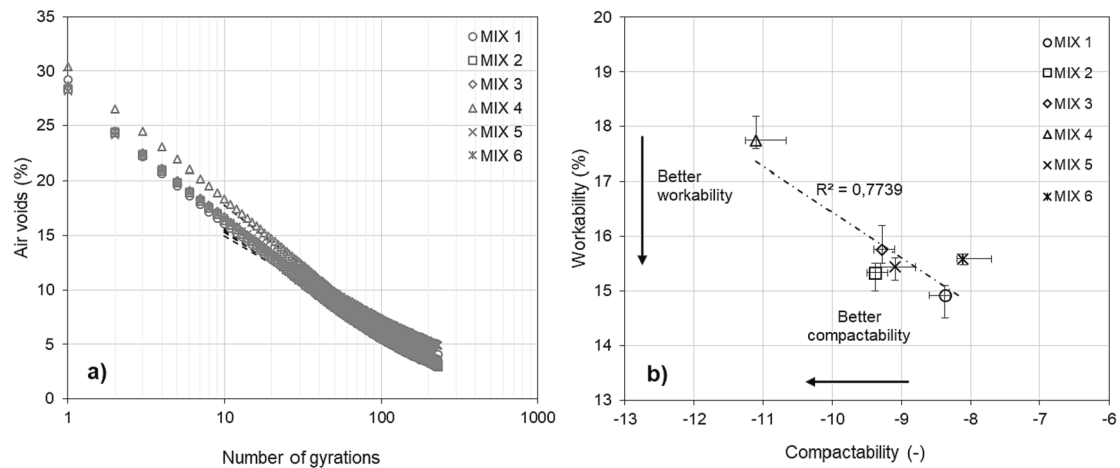


Fig. 6. Compaction results of the studied mixtures: a) Compaction curves with regression lines; b) regression lines fitting parameters and linear correlation.

Table 8

ITSM test average values (MPa) and (Coefficient of Variation CV) (%).

Testing temperature	Bailey method				Traditional mix design	
	MIX 1	MIX 2	MIX 3	MIX 6	MIX 4	MIX 5
20 °C	3817 (6.5)	4994 (4.8)	6341 (3.4)	5386 (6.0)	3203 (6.7)	3371 (3.9)
40 °C	1124 (6.1)	1387 (5.5)	1596 (8.7)	1489 (5.1)	946 (6.7)	1051 (6.3)

MIX 4 is dislocated with respect to the other mixtures, which are instead grouped in the same region. MIX 4 is characterized by the best compactability and the worst workability, while the other mixes, composed of alternative aggregates, all show better workability and worse compactability. In particular, attention must be paid to the comparison between MIX 4 (basalt coarse aggregate) and MIX 5 (limestone coarse aggregate). The use of limestone significantly influences the parameters analysed, improving the workability and worsening the compactability.

Furthermore, comparing MIX1 with MIX4 it is possible to observe the effect conferred by the mix design method (Bailey method versus traditional method, respectively). The different mix design influenced significantly the content of interceptors (particles between HS and PCS - Table 6), resulting higher in MIX4 that showed a worse workability.

In Fig. 6b it can be observed that $V_a(10)$ and k parameters are linked by a good linear relationship, since the regression line plotted is related to all the mixtures studied. This means that although with different compositions, mixtures with low workability are most likely to express a better compactability, and vice versa. This aspect is observed and confirmed in other studies [42,45].

3.2. Indirect tensile stiffness modulus (ITSM)

Table 8 lists results in terms of ITSM at 20 °C and 40 °C, highlighting the temperature sensitivity. ITSM values at 20 °C (between 3203 and 6341 MPa) are more dispersed than values at 40 °C (between 946 and 1596 MPa), better highlighting the effect of mixtures composition.

Mixture designed with the Bailey method are characterized by higher stiffness, at 20 °C and 40 °C, conferred by the optimal interlock between aggregates and the higher filler/bitumen ratio (Table 7). The change from basalt to limestone coarse aggregates (MIX4 and MIX 5) did not affect the mixtures stiffness.

Among the mixtures with alternative aggregates, MIX3 and MIX6 showed the highest ITSM values, conferred by the contemporary presence of basalt and steel slag. If on one side this highlighted the benefit brought by the use of steel slag, on the other side it showed that substituting basalt with expanded clay (MIX3 and MIX2) the mixture stiffness decreases.

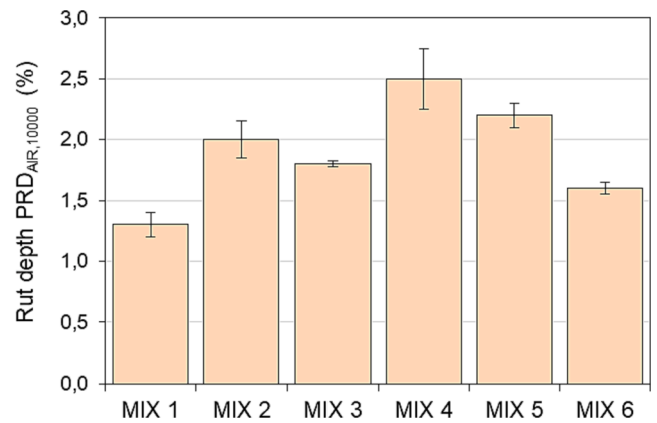


Fig. 7. Proportional rut depth results.

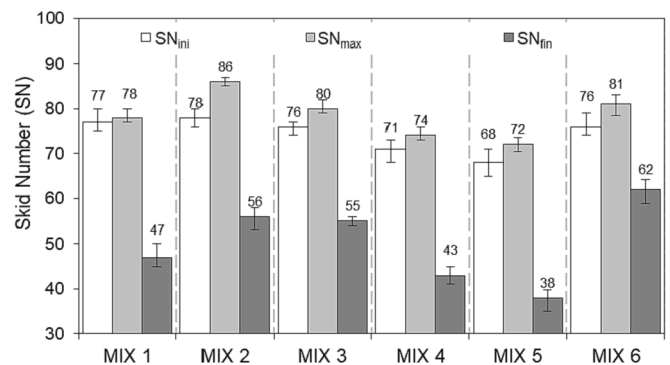


Fig. 8. SN evolution of the mixtures studied.

3.3. Rutting resistance

Fig. 7 shows rutting resistance results in terms of proportional rut depth, reporting error bars related to the test repeatability. Mixtures

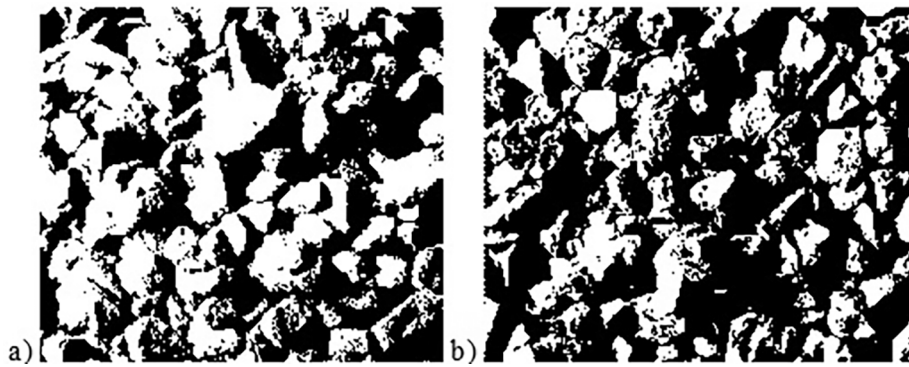


Fig. 9. View of: a) basalt micro-texture; b) steel slag micro-texture.

Table 9

Skid resistance evolution (increase and decrease).

	MIX 1	MIX 2	MIX 3	MIX 4	MIX 5	MIX 6
$\Delta I(\%)$	+ 1.3	+ 10.3	+ 5.3	+ 4.2	+ 5.9	+ 6.6
$\Delta D(\%)$	- 39.7	- 34.9	- 31.3	- 41.9	- 47.2	- 23.5

produced according to the traditional mix design (MIX4 and MIX5) showed the highest rut depth, highlighting the better aggregate interlock and the higher filler/bitumen ratio conferred by the Bailey Method mix design. MIX1, composed of traditional mineral aggregates, is characterized by the best rutting performance if compared to the other Bailey method mixes with alternative aggregates. Therefore, Bailey method improved rutting performance, although the best result was obtained in mixture with a traditional aggregate structure.

3.4. Skid resistance measurements

Fig. 8 shows results obtained by following the laboratory protocol for SR evaluation as explained in section 2.4.4. For each mixture, SN were measured on 14 samples by the Skid Tester, and at three conditions: initial, maximum and final. The values shown are the average values for each mixture at the three conditions considered. At initial condition, where the effect of macro-texture is predominant, mixtures with higher SN are those designed by the Bailey method. These mixtures are characterized by a lower passing at the 4 mm sieve, increasing the contribution of the coarse aggregate and then showing a rougher macro-texture. At maximum SN conditions, results are influenced by both macro-and micro-textures. Mixtures designed by the traditional method (MIX4 and MIX5) still show the lowest values, whereas mixes MIX2, MIX3, and MIX 6 give the highest SN values. These three mixtures, differently from MIX1, all contain steel slag coarse aggregates, which improved the skid resistance at maximum conditions. In fact, micro-texture of steel slag appears more rough and irregular than basalt micro-texture (Fig. 9). In Fig. 9 the same black/white ratio was used on pictures of basalt and steel slag, and it is possible to observe a higher surface roughness in the second case.

SN_{fin} values confirms the positive effect brought by the steel slag coarse aggregate. In fact, steel slag is less subject to polishing than other mineral aggregates when the same conditions are applied (as in this case), thus ensuring a longer life in terms of skid resistance. In this condition, the effect of mix-design method is not visible.

Table 9 lists values of the increase due to the superficial bitumen removal $\Delta I(\%)$ and the decrease due to long-term polishing $\Delta D(\%)$, which were calculated as follows:

$$\Delta I(\%) = \frac{SN_{max} - SN_{ini}}{SN_{ini}} \cdot 100 \quad (8)$$

$$\Delta D(\%) = \frac{SN_{max} - SN_{fin}}{SN_{max}} \cdot 100 \quad (9)$$

The value of $\Delta I(\%)$ represents the influence that micro-texture has on the skid resistance, assuming that the contribution of macro-texture is the same at initial and maximum conditions. The highest increase belongs to MIX2, where steel slag and expanded clay were combined in the coarse aggregates fraction, whereas the lowest increase was obtained in MIX1, where only basalt was used as coarse aggregate.

The value of $\Delta D(\%)$ represents the aggregates resistance to polishing. The lowest decreases were obtained for mixes containing steel slag (MIX2, MIX3 and MIX6), as expected. At the same time the highest decrease (-47.2%) was obtained in MIX5, produced with only limestone aggregate.

Fig. 10 shows separately the effect of different aspects on the skid resistance evolution. The use of the Bailey method as mix design conferred better skid resistance properties at all conditions (initial, maximum and final). The lower amount of interceptors in MIX1 led to higher skid numbers. The use of expanded clay instead of basalt coarse aggregate (together with steel slag) improved the maximum skid resistance, indicating better micro-texture properties for expanded clay. At the same time, close values of SN_{fin} highlighted the same long-term polishing response of basalt and expanded clay. Mixtures produced with basalt coarse aggregate instead of limestone coarse aggregate generally showed better skid resistance properties, particularly at long term. The substitution of a part of basalt with steel slag coarse aggregate enhanced values of SN_{max} and SN_{fin} , promoting the micro-texture properties and the polishing resistance of steel slag. Concluding, the use of RAP only penalized the skid resistance at long term (SN_{fin}).

3.5. Plant production results

Fig. 11 and Table 10 show the comparison between the material sampled from the production plant and the material studied in laboratory. Fig. 11 shows the aggregate gradation obtained by sieving after the binder extraction (EN 12697-1). It is observed that the sample obtained by the production plant is slightly finer than the laboratory material. However, variations in the fine part of gradation curves are common in production plants due to the significant variation of humidity of the fine aggregates and the subsequent dosage of material. In general, the result obtained is acceptable.

Table 10 collects data related to the mechanical and performance evaluation of both materials, especially in terms of ITSM, PRD_{AIR} and skid resistance evolution. Prior compaction, the plant samples were heated at 130 °C in an air-forced oven the minimum amount of time to have a workable mixture, and to prevent any phenomena of bitumen ageing or oxidation. Results obtained are comparable in all the cases investigated, and every variation can be included in the performed test variability. Subsequently, the industrial production of MIX6 resulted feasible and similar to the material obtained in laboratory.

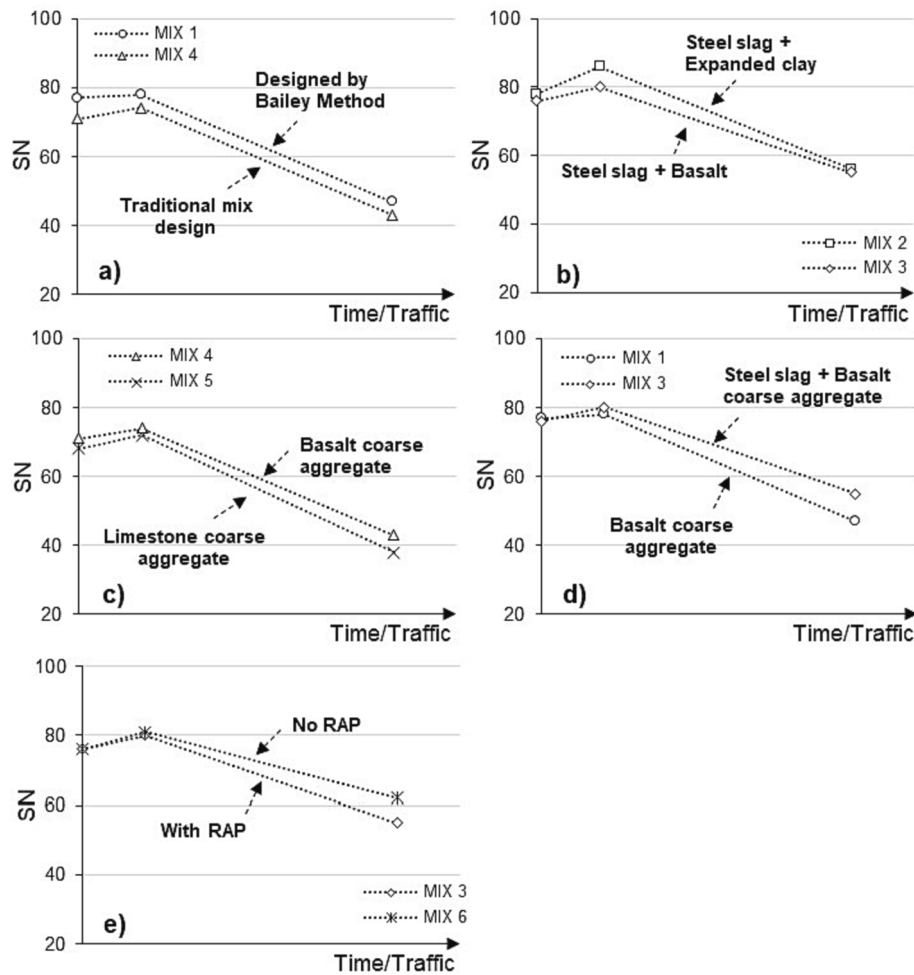


Fig. 10. Skid resistance evolution depending on: a) mix design method; b) use of expanded clay instead of basalt; c) use of limestone instead of basalt; d) use of steel slag in combination with basalt; e) use of RAP.

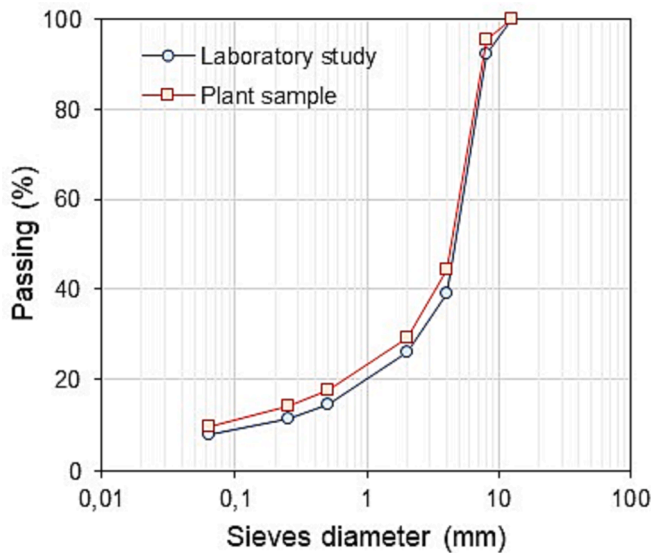


Fig. 11. Comparison between laboratory and plant sample gradations for MIX 6.

4. Conclusions

The objective of this study was to evaluate the use of alternative aggregates in the production of HMA surface layers, such as municipal solid waste sand, steel slag and expanded clay. A performance evaluation was carried out in laboratory, introducing in this context an experimental protocol for skid resistance evolution along time. It is believed that this aspect is crucial when focusing on surface layers mix design. In addition, one mixture was selected to be validated for industrial production with a batch-type asphalt plant.

The Bailey method conferred better properties to the mixtures designed, improving compactability, stiffness (at two temperatures), rut depth and skid resistance. By controlling the amount of interceptors, i.e. granular particles between PCS and HS, it is possible to guarantee a better aggregate interlock which results in a more resistant material and in an improved macro-texture.

This study also proposes an innovative laboratory procedure to evaluate the evolution of skid resistance of HMA mixtures with the polishing action performed by an accelerated polishing device. The production of asphalt surface samples is followed by the determination of skid resistance at three conditions: initial, maximum and final. This procedure allowed to validate the Bailey method in terms of anti-skid properties, leading to higher skid resistance values at initial and maximum conditions. The laboratory protocol proposed can be a valid method to assess skid resistance characteristics of asphalt pavements

Table 10
Results of MIX 6: laboratory study and production plant sample.

		Laboratory study	Plant sample
Air voids (%) by SGC	N _{ini} (10 gyrations)	14.5 ± 0.3	14.9 ± 0.4
	N _{des} (140 gyrations)	5.2 ± 0.2	3.9 ± 0.5
	N _{fin} (230 gyrations)	3.8 ± 0.2	2.6 ± 0.1
ITSM (MPa)	20 °C	5386 (CV = 6.0%)	5211 (CV = 4.8%)
	40 °C	1489 (CV = 5.1%)	1384 (CV = 3.8%)
PRD _{AIR} (%)		1.6 ± 0.1	1.5 ± 0.2
Skid resistance evolution	SN _{ini}	76 ± 3	74 ± 2
	SN _{max}	81 ± 3	83 ± 2
	SN _{fin}	62 ± 3	65 ± 3
	ΔI (%)	+ 6.6	+ 12.2
	ΔD (%)	− 23.5	− 21.7

during the mix design process, emphasizing the decay of micro- and macro-texture especially when dealing with alternative aggregates. This aspect can be addressed to future studies.

The use of alternative aggregates other than RAP, specifically MSW sand, steel slag and expanded clay, did not penalize the mixtures produced. In general, skid resistance properties were improved by the use of the Bailey method mix-design. According to the laboratory protocol proposed for skid resistance evolution, steel slag and expanded clay were the most performant coarse aggregates. At the same time, good anti-skid properties of basalt were confirmed, whereas the use of RAP slightly penalizes the skid resistance in the long term. In general, it was observed that the passing at the 4 mm-sieve was an important parameter to consider when optimizing surface layer macro-textures: according to results, a higher passing at the 4 mm-sieve leads to a lower skid resistance. Other important factors in terms of mix design when dealing with alternative aggregates are the different densities and absorption values. The production of one mixture, completely composed of alternative aggregates, was validated on industrial scale thanks to a batch-type asphalt plant, obtaining comparable results to those obtained in laboratory.

The study showed that producing HMA surface layers with alternative aggregates complying with specifications requirements is possible. Future studies should be oriented to monitor the performance of surface layers produced with alternative aggregates during the service life. In addition, the employment in warm, half-warm and cold asphalt technologies should be considered for further research. However, alternative aggregates are often economically disadvantageous, because of their complex treatment processes. Life-cycle assessment studies on this topic are strongly needed to environmentally justify the use of such alternatives and to raise awareness among producers and contractors, in order to increase their demand.

CRediT authorship contribution statement

Simone Raschia: Writing – review & editing, Formal analysis, Writing – original draft, Data curation. **Stefano Tattolo:** Conceptualization, Methodology, Funding acquisition, Formal analysis, Supervision, Project administration, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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