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Evaluation of high percentage of alternative aggregates for the production of hot mix asphalt surface layers

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ABSTRACT

In the last decades, recycling of hot mix asphalt (HMA) materials became one of the major issue concerning the world of pavement engineering. As required by Italian technical specifications, pavements surface layers must be produced using high-quality aggregates, in order to meet performance in terms of mechanical and anti-skid properties. Inevitably, the extraction of virgin mineral aggregates and their decreasing availability encourage the use of recycled alternatives, such as electric arc furnace steel slag and municipal solid waste. This study evaluates the possibility to implement recycled aggregates, and others sustainable solutions, in the production of HMA surface layers. In particular, eleven mixtures were produced combining the use of recycled aggregates to polymers obtained from plastic waste recycling and basalt fibres obtained from mineral deposit productions. Laboratory and field results confirmed the validity of the ecological solutions proposed in terms of fundamental properties for surface layers, such as fatigue resistance, rutting and skid resistance.

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KEYWORDS

Surface layers; steel slag; artificial sand; sideways friction coefficient; fatigue; rutting

Introduction

In the road construction industry, a critical aspect raised in the last decades concerns the use and optimisation of secondary (or recycled) materials for the production of hot mix asphalt (HMA) materials (Celauro et al., 2010; Dołżycki & Jaskuła, 2019; Xiao et al., 2018). This issue is particularly relevant in terms of aggregates, which consists in almost 95% of the HMA total composition. In several countries (d'Angelo et al., 2008), the mix design of surface layers for the pavement structure requires the use of newly extracted mineral aggregates (basalt, porphyry, limestone, etc.). On one hand, this allows producing a high quality product, which will last longer and ensures higher comfort to the user, but on the other hand, causes an inevitable drop throughout years in the availability of natural non-renewable resources (virgin aggregates) (Mallick et al., 2014; Wilburn & Goonan, 1998). Several studies have shown the possibility to replace partially or totally virgin aggregates with recycled aggregates, such as reclaimed asphalt pavement (RAP), steel slag and municipal solid waste (MSW) materials.

RAP is the material obtained by the milling of the deteriorated pavement, which consists in aggregates covered by a thin film of aged bitumen. The use of RAP allows a lower consumption of virgin aggregates, as well as of virgin binder. In Europe, a survey conducted by the European Asphalt Pavements Association (EAPA) in 2018 allowed to obtain data from each country to determine the average consumption of RAP material. It was possible to assess that RAP was mainly employed in HMA and

warm-mix asphalts (WMA), as well as in Half-Warm Mix Asphalt and Cold Mix Asphalt materials. A remarkable amount of around 20% is instead addressed to unbound layers, and around 8% was land-filled (Tarsi et al., 2020). Generally, the aged binder of RAP partially or totally blend with the virgin binder, causing stiffening of the obtained mixtures (Carter & Stroup-Gardiner, 2007). However, the fatigue resistance could improve with RAP contents of 10–40% (Mangiafico et al., 2015). The process of bitumen oxidation leads to the progressive reduction in aromatic components of the RAP binder with the corresponding increase of asphaltenes (Lesueur, 2009; Lu & Isacsson, 2002). To overcome this issue, rejuvenating additives are often used to attempt the chemical restoration of the initial properties of the RAP binder, thus improving the general rheological response of the recycled HMA (Muñoz et al., 2021). Such additives are normally composed of various compounds made of recycled waste, organic or tall oils (Pasetto et al., 2021).

Steel slag is a by-product of the steel-making process and its use as a recycled mineral addition in HMA surface layers has several positive aspects, mainly linked to high resistance to fragmentation, surface abrasion and to polishing. Such characteristics make steel slag coarse aggregates particularly suitable for anti-skid purposes (Georgiou & Loizos, 2021; Masoudi et al., 2017). By replacing up to 75% of limestone aggregate with steel slag, mixtures showed better properties in terms of friction, indirect tensile strength, resilient modulus, rutting resistance, fatigue life and creep modulus. This was observed in both dense-graded and open-graded friction courses (Ahmedzade & Sengoz, 2009; Asi et al., 2007; Pattanaik et al., 2021).

Due to the limited landfilling space in many highly populated countries, waste incineration has become a valid treatment process to overcome this issue (Jørgensen & Milanez, 2017; Yin et al., 2018). Recently, new companies actively specialised in the post-treatment of municipal solid waste (MSW) bottom ashes to obtain a reusable material (end of waste product – EOW), which can be included in a new production line after specific processing (ageing, sieving and washing). The material obtained, formed by a silica matrix rich in iron, calcium and aluminum oxides, can be considered for production of cement or ceramic materials (Schabbach et al., 2011, 2012). In addition, some recent studies have evaluated the use of MSW fly ash as filler aggregate in the production of HMA materials. It was observed that MSW fly ash could be successfully included as filler in HMA after preliminary actions, especially addressed to reduce the presence of soluble salts. In this manner, the mechanical properties of the mixtures obtained are comparable to traditional mixtures (Romeo et al., 2018; Zhao et al., 2022).

The objective of this study is to evaluate the gradual use of recycled aggregates, in particular steel slag coarse aggregate and MSW artificial sand, in the production of HMA surface layers. Italian Technical Specifications (issued by the national agency ANAS SpA) require for HMAs in surface layers specific characteristics in terms of gradation, air voids content and indirect tensile strength (ANAS SpA, 2021). According to the above-mentioned requirements, all the mixtures treated comply with the fixed limits, although the real performance of the materials tested could be hidden. For this reason, the present research is based on a performance evaluation, as well as a field test section realised on an Italian freeway.

Materials and mixtures

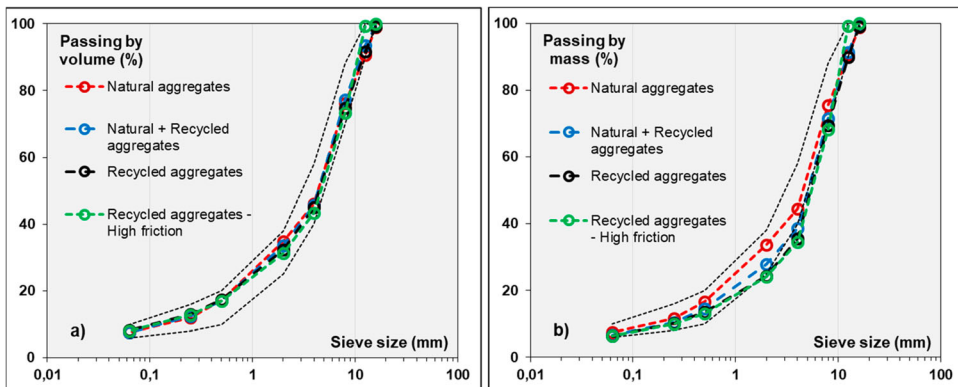
Aggregates and granular blends

The investigation involved four different granular blends: the first, totally composed of natural aggregates (mixtures prefix 'N'); the second, composed of natural and recycled aggregates (mixtures prefix 'NR'); the third, composed of recycled aggregates (mixtures prefix 'R'); and the fourth, composed of recycled aggregates and with improved anti-skid performance (mixtures prefix 'HF'). The properties of natural (limestone and basalt) and recycled aggregates (MSW sand and steel slag) used are listed in Table 1. All mixtures contain the maximum amount of RAP allowed in the Italian Technical specifications for surface layers, i.e. 15% by aggregates mass. Bitumen content of RAP aggregate used is 5.3% by aggregate mass. In addition, limestone filler was used to correct the final gradation. The filler used

Table 1. Properties of mineral and recycled aggregates.

Property	Standard	Value							
		Limestone sand		Basalt		MSW sand 0/4	Steel slag		
		0/4	0/5	4/8	10/16		4/8	8/16	8/12
Apparent Specific Gravity G_{sa}	UNI EN 1097-6	2.701	2.655	2.904	2.909	2.519	4.034	4.030	4.030
Bulk Specific Gravity G_{sb}	UNI EN 1097-6	2.623	2.567	2.781	2.761	2.020	3.913	3.920	3.920
Effective Specific Gravity G_{se} ¹	AASHTO T 312	2.685	2.637	2.879	2.879	2.419	4.010	4.008	4.008
Water absorption (%)	UNI EN 1097-6	1.50	1.50	1.49	1.30	9.8	0.9	0.7	0.7

¹The effective specific gravity is calculated as $G_{se} = G_{sb} + 0.8 (G_{sa} - G_{sb})$.

**Figure 1.** Granular blends of the studied mixtures: (a) by volume, and (b) by mass.

has a passing at 0.063 mm-sieve of 80.5% (UNI EN 933-1), Rigden voids of 31.2% (UNI EN 1097-4) and a stiffening power of 11.4°C (UNI EN 13179-1).

The aggregates used are characterised by different specific gravities, so the four granular blends are designed according to volumetric proportioning of the components to obtain comparable curves. Figure 1 shows the target gradation curves in volumetric and gravimetric terms, as well as the specification limits. It is observed that the volumetric design is fundamental to obtain granular blends that comply with the specification limits provided. The dosage of each component is reported in Table 2, which shows the volumetric composition of each HMA mixture investigated.

Bituminous binders

The study involved the use of two binders: a styrene–butadiene–styrene (SBS) polymer-modified binder and a neat bitumen mixed in laboratory with an amorphous polyolefin thermo-plastic polymer obtained by the processing of recycled plastics. The goal of this polymer is to confer to neat bitumen similar rheological properties of polymer-modified bitumen by exploiting plastic recycling. The thermoplastic polymer was dosed at 5.0% by virgin neat bitumen mass and was mixed with aggregates before the introduction of bitumen.

For each mixture, bituminous binders were blended prior mixing with a rejuvenating additive, dosed at 0.2% by dry RAP mass as required by the Italian Technical Specifications.

Basalt fibres

Another ecological technology applicable to HMA are basalt fibres for structural reinforcement, which represents an innovative and environmentally friendly material by improving the sustainability of the mineral deposit.

Table 2. Composition and volumetric properties of the studied mixtures.

	N Natural aggregates		NR Natural + Recycled aggregates		R Recycled aggregates		HF Recycled aggregates – High friction	
	% mass	% volume	% mass	% volume	% mass	% volume	% mass	% volume
Limestone sand 0/4	9.5	9.7						
Limestone sand 0/5	19.0	19.4	9.5	10.9				
Basalt 4/8	33.3	32.5	16.2	18.3				
Basalt 10/16	19.0	18.6						
MSW sand 0/4			10.5	13.7	14.3	20.3	14.2	20.3
Steel slag 4/8			16.2	12.3	33.3	27.4	28.6	23.5
Steel slag 8/16			28.6	21.7	33.3	27.4		
Steel slag 8/12							38.1	31.4
Limestone filler	4.8	4.6	4.8	5.4	4.8	5.8	4.8	5.8
RAP	14.3	15.2	14.3	17.6	14.3	19.0	14.3	19.0
Bitumen content ¹		5.6%		5.4%		5.3%		5.1%
G_{se} ²		2.747		3.106		3.332		3.330
V_{be} ³		11.3%		11.9%		12.4%		12.4%
$V_{0.063}$ ⁴		6.7%		6.7%		7.1%		7.0%
$V_{0.063}/V_{be}$ ⁵		0.59		0.56		0.57		0.56

¹Total bitumen content is considered by aggregates mass (including RAP aggregate and filler).

²Effective specific gravity of the aggregate blend.

³Volume content of effective binder by total volume of the loose mixture.

⁴Volume content of total dust (passing at 0.063 mm sieve) by total volume of the loose mixture.

⁵Dust-to-binder ratio.

Basalt fibres are obtained from the melting of the ground basaltic material. The melting furnace is equipped with a material loading area, in which a pre-heating also takes place before contact with the existing melted part, with a basin in which the fibres are formed, and on the bottom of which there is the spinneret. The mechanical characteristics are comparable to those of glass or carbon fibres, they are characterised by high durability and give higher mechanical performance to HMA mixes (Pirmohammad et al., 2020). Basalt fibres appear as short fibres with a diameter between 13 and 20 microns and a length between 3 and 100 mm. Basalt fibres were used in this study in combination with SBS polymer modified bitumen only, with a dosage equal to 0.2% of the mixtures mass. The use of basalt fibres and thermoplastic polymers is possible in laboratory but problematic in a production plant, since it would require two separate dosing equipments operating at the same time. For this reason, this combination has been discarded from evaluation.

Mixtures mix-design

In total, 11 mixtures were produced in this study composed and named as described in Figure 2. The mix design process (i.e. the optimum binder content) was carried out only on mixtures with SBS polymer modified bitumen (N1, NR1, R1 and HF1), and the same values were adopted for mixtures with neat bitumen and thermo-plastic polymer and for mixtures with basalt fibres. The dosages of limestone filler and virgin bitumen for each of the four granular blends were selected according to two criteria: the compliance with the air voids requirements by means of the Shear Gyratory Compactor (SGC), and a constant volumetric dust-to-binder ratio ($V_{0.063}/V_{be}$). The constant dust-to-binder ratio allows to obtain the same matrix composition in each mixture in order to isolate the contribution of the aggregate source.

Compaction was performed with a 100 mm diameter mould, constant pressure of 600 kPa, rotation speed of 30 rpm and internal angle of 1.25°. Specimens' mass was selected constant as 1200 g, and its height changed according to the bulk aggregates specific gravity, varying between 63.5 and 53.0 mm. The air voids content and the volumetric properties were measured at three points of the compaction curve, as required by Italian specifications: N_{init} (10 gyrations), N_{design} (140 gyrations) and N_{max} (230

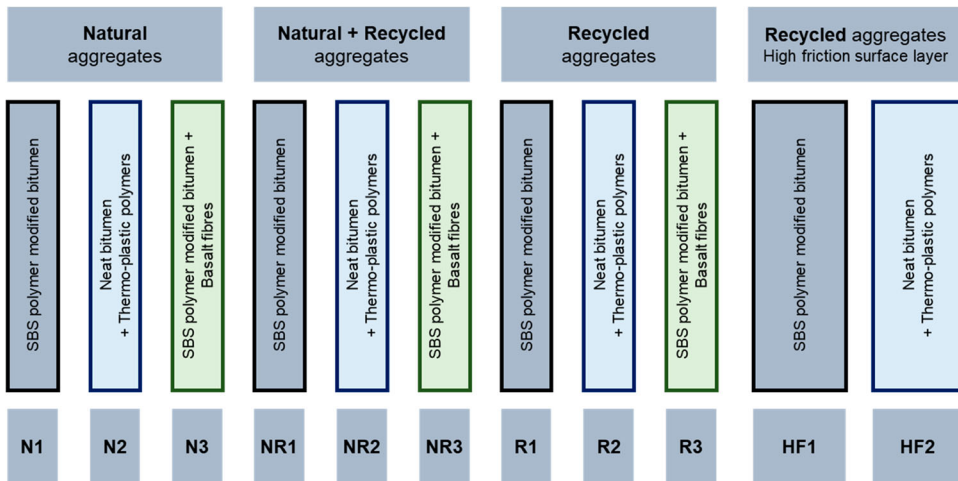


Figure 2. Mixtures produced and nomenclature.

Table 3. Volumetric characterization of the mixtures investigated.

Mixtures	Air voids content ¹										
	Natural aggregates			Natural + Recycled aggregates			Recycled aggregates				
	N1	N2	N3	NR1	NR2	NR3	R1	R2	R3	HF1	HF2
N _{init} (10 gyr.)	14.1	13.7	14.1	13.5	13.1	13.7	13.1	14.0	13.0	12.6	12.7
N _{design} (140 gyr.)	3.8	3.5	3.9	3.7	3.4	4.5	3.5	3.5	4.5	3.3	3.3
N _{max} (230 gyr.)	2.5	2.3	2.7	2.2	2.2	3.1	2.3	2.3	3.3	2.6	2.6

¹Specifications limits for air voids content are $(10 \div 15)$ % for N_{init}, $(3 \div 6)$ % for N_{design} and ≥ 2 % for N_{max}.

gyrations). These three values are related to HMA surface layers materials produced with polymer-modified bitumen. Air voids content obtained from compacted specimens are listed in Table 3.

As a result, the virgin bitumen dosages fixed for the laboratory production was 4.9%, 4.7%, 4.6% and 4.4% by aggregates mass for mixtures N1, NR1, R1 and HF1, respectively. Successively, air voids content of all mixtures were measured and listed in Table 3.

The volumetric composition of mixtures produced with each granular blend are shown in Table 2. It is highlighted that the eleven mixtures are characterised by close values of the volumetric dust-to-binder ratio $V_{0.063}/V_{be}$ (between 0.56 and 0.59), and do not show a remarkable difference in terms of air voids at the three compaction levels selected (Table 3). Hence, the applied volumetric approach allowed to obtain mixtures with close volumetric compositions, in order to analyse the different aggregate sources, the effect of thermoplastic polymers and the contribution of basalt fibres.

Experimental programme

Mixtures production and testing programme

The 11 mixtures investigated were produced in laboratory by means of a horizontal-axis heated mixer and a slab roller compactor, in order to replicate the production plant and compaction operations. Mixing and compaction operations were performed at 160 and 140°C, respectively. The volumetric characteristics of each slab targeted by the roller compactor were the one related to the mix design procedure performed by the SGC for N_{design}, i.e. the beginning of the pavement service life. For each mixture, seven slabs were prepared in order to perform the following tests:

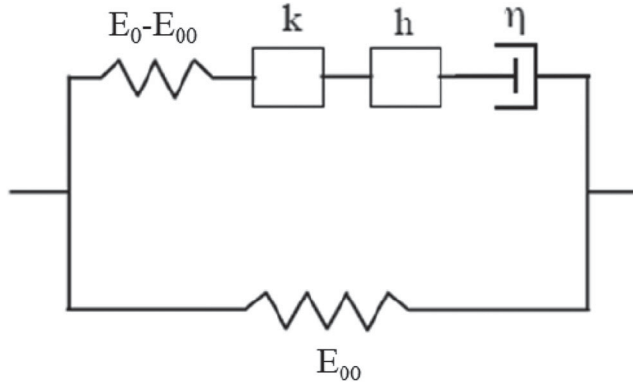


Figure 3. 2S2P1D model representation (readapted from Olard & Di Benedetto, 2003).

- Complex modulus and fatigue resistance in Four Point-Bending (4PB) configuration (3 slabs) (UNI EN 12697-26:Annex B and UNI EN 12697-24:Annex D);
- Rutting resistance (UNI EN 12697-22) (3 slabs);
- Laboratory protocol for friction evolution (1 slab).

Complex modulus master curves

Complex modulus tests were performed in Four Point-Bending configuration (4PB) on beams with dimensions equal to 70 mm (W) × 50 mm (H) × 450 mm (L). Tests were carried out by means of a 30 kN servo-hydraulic press with high strain and stress control up to 100 Hz. The testing temperature were 0, 10, 20, 30 and 40°C, at which the specimen was conditioned for at least 3 h before testing. The testing temperature was monitored by a dummy specimen with surface and core temperature probes. The testing frequencies were 0.1, 0.2, 0.5, 1, 2, 5, 8, 10, 20, 30 Hz. The 0.1 Hz frequency was repeated at the end of the sequence to verify the integrity of the tested specimen.

Complex modulus tests results were analysed by the 2S2P1D model (Figure 3). The 2S2P1D is a linear visco-elastic (LVE) rheological model commonly used to describe the behaviour of HMA mixtures in the LVE domain. It is composed of 2 springs, 2 parabolic elements and 1 dashpot (Di Benedetto et al., 2004; Olard, 2003; Olard & Di Benedetto, 2003).

The analytical equation of 2S2P1D model is given for a fixed reference temperature T_{REF} :

$$E^*(\omega) = E_{00} + \frac{E_0 - E_{00}}{1 + \delta(i\omega\tau_E)^{-k} + (i\omega\tau_E)^{-h} + (i\omega\beta\tau_E)^{-1}} \quad (1)$$

where: E_{00} is the static modulus when $\omega \rightarrow 0$, E_0 is the glassy modulus when $\omega \rightarrow \infty$, δ is a calibration constant, k and h are the parabolic exponent such as $0 < k < h < 1$, $\omega = 2\pi f$ is the pulsation and f is the frequency, i is the imaginary number ($i^2 = -1$), β is a dimensionless parameter linked to the Newtonian viscosity $\eta = (E_0 - E_{00})\beta\tau$, and τ_E is the characteristic time, which is the only value varying with temperature T :

$$\tau_E(T) = a_T(T) \cdot \tau(T_{REF}) \quad (2)$$

where: $a_T(T)$ is the shift factor at the temperature T and $\tau_E(T) = \tau(T_{REF})$ at the reference temperature T_{REF} . The experimental shift factors can be analytically modelled by the Williams-Landel-Ferry (WLF) model (Ferry, 1980):

$$\log(a_T) = -\frac{C_1(T - T_{REF})}{C_2 + T - T_{REF}} \quad (3)$$

where C_1 and C_2 are constants.

The 2S2P1D model allows to describe the LVE behaviour of the material studied with the definition of only 9 constants (E_0 , E_{00} , k , h , δ , β , τ_E , C_1 , C_2). In this study, 20°C was fixed as reference temperature T_{REF} .

Fatigue life

Fatigue tests were performed in Four Point-Bending configuration (4PB) on beams with dimensions equal to 70 mm (W) $\times$ 50 mm (H) $\times$ 450 mm (L). The testing frame is installed in a thermal chamber where testing temperature is monitored by a dummy specimen with surface and core temperature probes. The fatigue tests are performed in displacement-controlled mode, by a 10 mm vertical LVDT placed at the middle-length of the beam, on the upper face. The criterion used to determine the fatigue life of a given mixture is the modulus loss of 50% with respect to the modulus measured at 100 cycles (initial modulus). The parameter used to compare the mixtures investigated is the deformation at 10^6 cycles, ϵ_6 , obtained by the definition of the related Wöhler's curve. The sinusoidal cyclic loading was applied in displacement-controlled mode, chosen between 225 and 450 $\mu\text{m/m}$ for all mixtures. The levels of strain were chosen in order to interpolate and not extrapolate the value of ϵ_6 at 10^6 loading cycles and, for each strain level, 3 beams per mixture were tested. The selected testing conditions were 20°C and 10 Hz. During the test, vertical load, vertical displacement and bending stiffness are measured. These measurements gave the evolution of stiffness modulus and phase angle with loading cycles.

Rutting resistance

The rutting resistance was measured on compacted slabs with dimensions equal to 50 cm (L) $\times$ 26 cm (B) $\times$ 4 cm (H). The rutting tests were performed in dry conditions running 10000 cycles (tyre back and forth) at 60°C, according to UNI EN 12697-22. 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 three slabs for each mixture investigated:

$$PRD_{AIR}(\%) = \frac{d_{10000}}{H} \cdot 100 \quad (4)$$

where d_{10000} is the average rut depth along the tyre axis after 10000 cycles, H is the average slab thickness (fixed at 40 mm).

Laboratory protocol for friction evolution

Skid resistance (SR) of surface layers in asphalt pavements is characterised by the 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 (Raschia & Tattolo, 2022). 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. Tattolo and Raschia (2022) thoroughly describe the preparation of samples, which appear as in Figure 4.

Measurements of SN_{ini} , SN_{max} and SN_{fin} are performed by means of the Pendulum Tester (or Skid Tester – UNI EN 13036-4) at a fixed temperature of $(20 \pm 2)^\circ\text{C}$. Measurements are done on 14 samples for each mixture analysed. 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



Figure 4. Curved HMA samples for skid resistance evolution measurements.

bituminous film, which makes resistance only dependent on macro-texture and independent from aggregates micro-texture and polishing resistance. Hence, SN_{ini} test is performed on samples in initial condition.

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 maximising 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 chemical treatments must be repeated until the bitumen coating is totally removed. 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. Thus, SN_{max} can be determined.

The condition of final skid resistance is obtained on the surface samples previously treated with perchloroethylene carrying out a polishing process by means of a polishing machine. The polishing process is carried out according to UNI 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 and the SN_{fin} tests are performed.

Field test section

The evaluation of HMA mixtures with recycled aggregates also involved the realisation of a 1-km-long dual carriageway field test section on the Italian 'E45 – SS3 Bis' freeway. The selected road infrastructure is highly important, being located in the connection area between the two coastal areas, thus involving heavy traffic.

The mixtures studied in this research have been produced with a continuous asphalt plant located 2 km from the test section. After a preliminary calibration process addressed to the different densities of the aggregates, the mixtures has been laid and compacted on the full width of one carriageway, involving two lanes, as shown in Figure 5.

The field test section has the purpose to evaluate the skid resistance evolution along time by means of a SCRIM measurement device for the Sideway Friction Coefficient (SFC). According to Italian Technical Specifications, SFC measurements must be performed with a constant water flow of 0.75 l/s, at a constant device speed of 60 km/h, and with an acquisition step of 10 metres. The measured SFC value

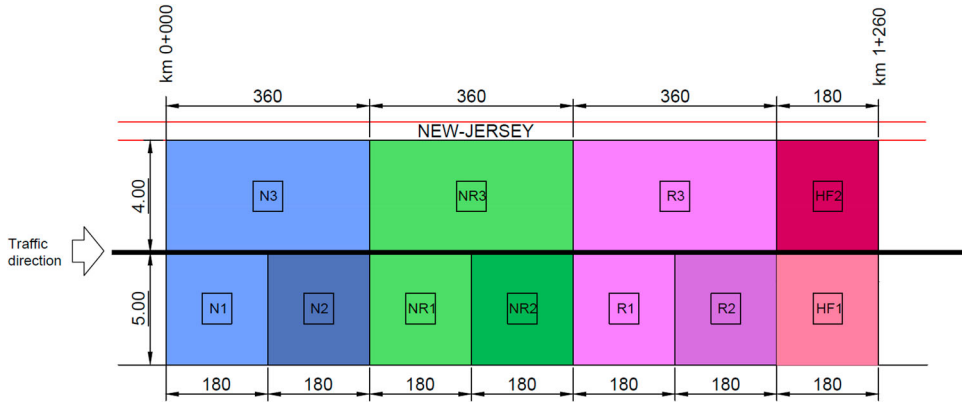


Figure 5. Schematic representation of the field test section.

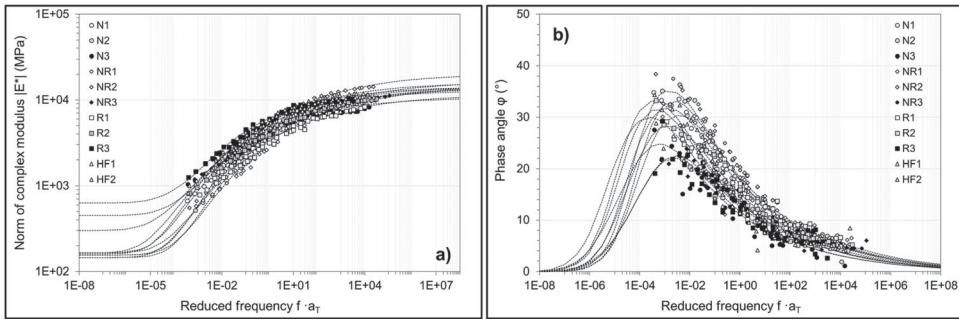


Figure 6. Master curves ($T_{REF} = 20^\circ\text{C}$): (a) Complex modulus $|E^*|$, (b) phase angle φ .

must refer to an air temperature of 20°C (SFC_{20}):

$$SFC_{20} = \frac{SFC_T}{0.548 + (44.69/T + 80)} \quad (5)$$

where: SFC_T is the Sideway Friction coefficient at the air temperature T .

In this paper, the skid resistance reported is measured after 50 days from traffic opening, but it is currently planned to annually repeat the measurement.

Results analysis

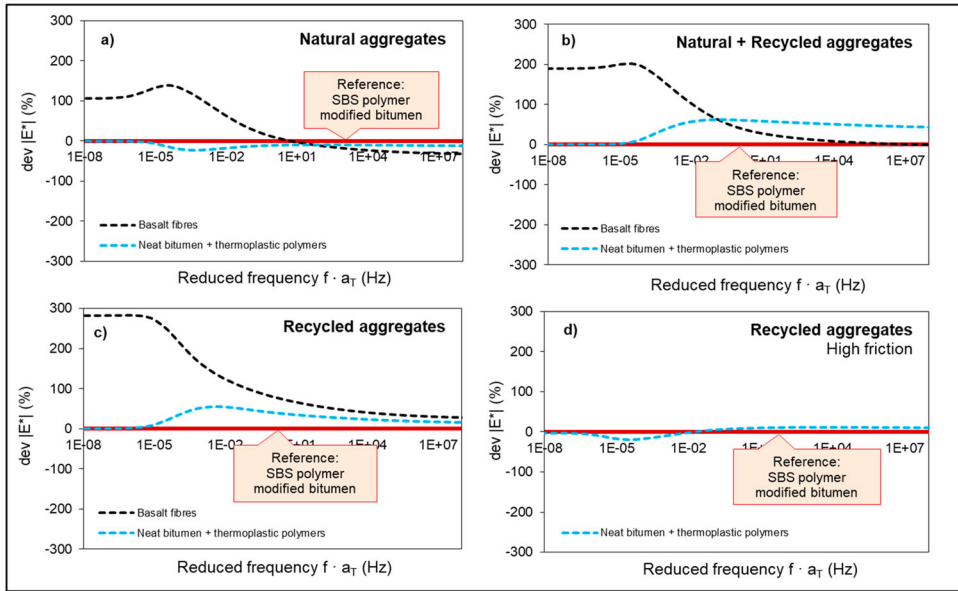
Complex modulus master curve

Figure 6 shows complex modulus results in terms of master curves of norm of the complex modulus $|E^*|$ and phase angle φ , at a reference temperature of 20°C . The 2S2P1D model was calibrated on the obtained results and the model parameters for each mixture are reported in Table 4.

It is observed that the four mixtures with SBS polymer modified bitumen (N1, NR1, R1 and HF1) are described by the same values for k , h , δ and β . The same aspect is observed for the four mixtures with neat bitumen and thermoplastic polymers (N2, NR2, R2 and HF2), whereas the addition of basalt fibres to the SBS polymer modified bitumen influenced only the δ parameter. However, all the mixtures have close k , h , δ and β parameters, highlighting the low difference in the bituminous (viscous) phase among the eleven mixtures. Furthermore, the mean value of E_0 of all mixtures is equal to 14404 MPa

Table 4. 2S2P1D model parameters.

	E_{00} (MPa)	E_0 (MPa)	K (-)	H (-)	Δ (-)	τ_E (20°C) (s)	B (-)	C_1	C_2
N1	145	16300	0.181	0.518	2.67	0.30	225	31	241
N2	145	14250	0.190	0.545	2.60	0.30	117	39	325
N3	300	10700	0.181	0.518	2.25	4.00	225	48	375
NR1	155	14300	0.181	0.518	2.67	0.16	225	32	234
NR2	155	20000	0.190	0.545	2.60	0.30	117	22	168
NR3	450	13800	0.181	0.518	2.67	1.10	225	11	80
R1	165	11500	0.181	0.518	2.67	0.60	225	17	151
R2	165	13000	0.190	0.545	2.60	2.00	117	22	164
R3	630	14400	0.181	0.518	2.05	2.00	225	23	196
HF1	165	14400	0.181	0.518	2.67	2.50	225	25	192
HF2	160	15800	0.190	0.545	2.60	1.80	117	31	241

**Figure 7.** Effect of thermo-plastic polymers and basalt fibres on complex modulus master curves.

with a coefficient of variation (CV) equal to 17%, assessing the low differences among the mixtures analysed at high frequencies (or low temperatures).

In order to analyse the difference among the different mixtures in the whole frequency range, the deviation of the norm of the complex modulus, $\text{dev } |E^*|$, between a specific material and a reference material was measured on the 2S2P1D model master curves ($T_{REF} = 20^\circ\text{C}$). This approach has been already used in several studies (Lachance-Tremblay et al., 2017; Raschia et al., 2021).

$$\text{dev } |E^*| (\%) = \frac{|E^*|_{2S2P1D,mix} - |E^*|_{2S2P1D,ref}}{|E^*|_{2S2P1D,ref}} \cdot 100 \quad (6)$$

where $|E^*|_{2S2P1D,mix}$ is the norm of the complex modulus from the 2S2P1D model of the analysed mixture and $|E^*|_{2S2P1D,ref}$ is the norm of the complex modulus from the 2S2P1D model of the reference mixture.

Figures 7 and 8 shows the results in terms of $\text{dev } |E^*|$ focusing on the effect of basalt fibres and thermoplastic polymers, and the different aggregate source, respectively.

In Figure 7, for each aggregate blend considered, the reference mixture is the one produced with SBS polymer modified bitumen. In terms of neat bitumen and thermoplastic polymers in substitution

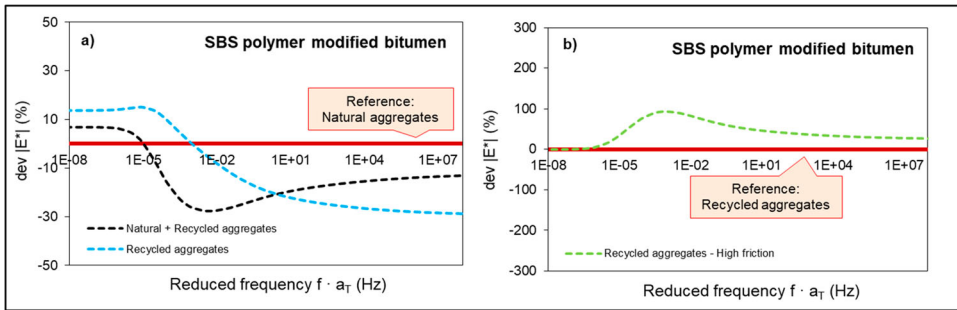


Figure 8. Effect of aggregate source on complex modulus master curves.

to SBS polymer modified bitumen, it is generally possible to observe a low deviation from the reference mixture, in particular at asymptotic conditions. This is also confirmed by E_0 and E_{00} parameters in Table 4. Hence, the combination of neat bitumen with thermoplastic polymers gives rheologically similar properties to HMA mixtures if compared to SBS polymer modified bitumen. The addition of basalt fibres confers to the material a temperature-stabilization property at high temperatures (or low frequencies), whereas at high frequencies (or low temperatures) their effect is negligible. The positive effect of structural reinforcement observed at high temperatures was expected. In fact, in these conditions the bituminous phase can be theoretically considered as a liquid, and the basalt fibres confer a binding contribution due to their thermal independency.

In Figure 8, only mixtures with SBS polymer modified bitumen are reported. Mixtures with natural + recycled and recycled aggregates (NR1 and R1, respectively) are compared to the mixture with natural aggregates (N1) (Figure 8a), whereas the mixture with recycled aggregates and improved friction properties (HF1) is compared to the mixture with recycled aggregates (R1) (Figure 8b).

The introduction of recycled aggregates gradually increases the value of E_{00} and decreases the value of E_0 (Figure 8a). This causes a change in the shapes of the $|E^*|$ master curves, resulting flatter than the one referred to the reference mixture with natural aggregates. As previously analysed, it is believed that the difference in E_0 is not relevant, whereas the change in E_{00} is more significant. Consequently the effect of recycled aggregates, i.e. steel slag and MSW sand, is positive at high temperatures (or low frequencies). The mixture produced with recycled aggregates and improved friction properties is generally characterised by a higher stiffness modulus if compared to the mixture with recycled aggregates, caused by a higher value of τ_E for a reference temperature of 20°C.

Fatigue life

Table 5 shows results in terms of fatigue life of the analysed mixtures, expressed as deformation related to 10^6 cycles, ϵ_6 . R^2 value obtained by the interpolation of the experimental data with Wöhler's curve is also reported.

All the mixtures are characterised by values of ϵ_6 between 249 and 285 $\mu\text{m/m}$, highlighting a maximum loss in fatigue life of 13% compared to the maximum value, and expressing the good global resistance of the analysed mixtures compared to similar results from literature (Hofko, 2022). In terms of aggregate source, the use of recycled aggregates, even for partial substitution to natural aggregates, leads to a decrease in fatigue resistance if SBS polymer modified bitumen is used (mixtures N1, NR1 and R1). This can be linked to the fact that at the testing conditions (10 Hz; 20°C), mixtures with recycled aggregates have lower stiffness (Figure 8a).

The use of neat bitumen and thermoplastic polymers causes the decrease of the fatigue life regardless the aggregates source used, if compared to mixtures with SBS polymer modified bitumen. The use of thermoplastic polymers probably confers fragility to the mixtures and less ductility compared to typical elastomeric polymers used for modified bitumens.

Table 5. Fatigue resistance results.

Aggregates	Binder	Mixture	ϵ_6 ($\mu\text{m/m}$)	R^2
Natural	SBS polymer modified bitumen	N1	285	0.991
	Neat bitumen + Thermoplastic polymers	N2	254	0.933
	SBS polymer modified bitumen + Basalt fibres	N3	249	0.977
Natural + Recycled	SBS polymer modified bitumen	NR1	279	0.849
	Neat bitumen + Thermoplastic polymers	NR2	272	0.948
	SBS polymer modified bitumen + Basalt fibres	NR3	260	0.993
Recycled	SBS polymer modified bitumen	R1	275	0.987
	Neat bitumen + Thermoplastic polymers	R2	264	0.789
	SBS polymer modified bitumen + Basalt fibres	R3	264	0.961
Recycled High friction	SBS polymer modified bitumen	HF1	268	0.998
	Neat bitumen + Thermoplastic polymers	HF2	264	0.797

Table 6. Proportional Rut Depth (PRD_{AIR}) after 10000 loading cycles.

	Natural aggregates			Natural + Recycled aggregates			Recycled aggregates			Recycled aggregates High friction	
	N1	N2	N3	NR1	NR2	NR3	R1	R2	R3	HF1	HF2
PRD_{AIR} (%)	2.0	2.7	2.0	2.1	1.9	2.5	1.5	1.4	1.6	1.8	1.9
Mean		2.2			2.2			1.5			1.9

It was already observed that basalt fibres, at the fatigue testing conditions, do not significantly improves the mixtures stiffness values (Figure 7), whereas they show improvements at low frequencies (or high temperatures). However, lower fatigue values of ϵ_6 of mixtures with basalt fibres were obtained with respect to the mixtures without fibres. It is believed that this result is linked to the higher air voids content of mixtures with fibres (Table 2), and to observe the fibres contribution in terms of fatigue life the testing conditions should be different (higher temperatures or lower frequencies).

However, a suitable mechanistic approach combining stiffness and fatigue results could highlight some different findings.

Rutting resistance

Table 6 lists results of rutting tests in terms of proportional rut depth (PRD_{AIR}) expressed as percentage of the slab thickness. It has to be highlighted the good rutting resistance expressed by all the mixtures, always below 3% (Komacka et al., 2014; Radziszewski et al., 2012). Considering separately each aggregate gradation (N, NR, R, and HF), it can be assumed that the difference observed between SBS polymer modified bitumen, neat bitumen and thermoplastic polymers and SBS polymer modified bitumen with basalt fibres are related to the test repeatability (set at 20% by the UNI EN 12697-22). At the same time, the change of natural aggregates with natural and recycled aggregates, and with only recycled aggregates, gradually decreases the rut depth.

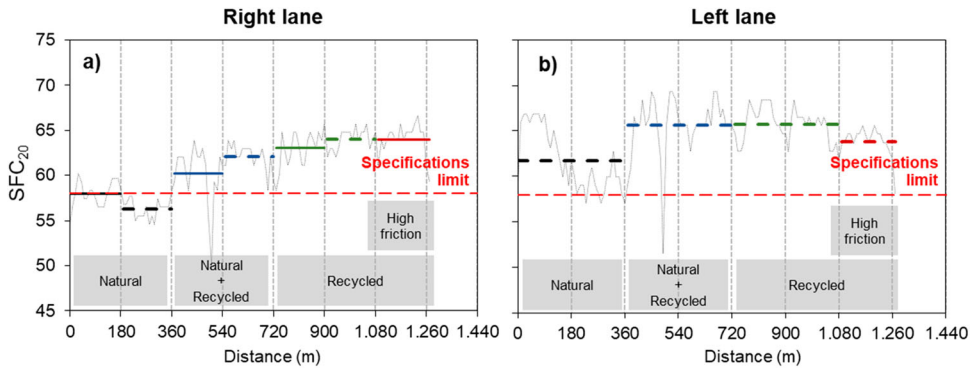
The mixture produced with recycled aggregates and improved friction properties is characterised by a negligible difference if compared to the mixture with recycled aggregates.

Friction evolution

Mixtures with SBS polymer modified bitumen N1, NR1, R1 and HF1 were evaluated in terms of skid resistance evolution, according to the laboratory protocol previously described. Results are shown in Table 7, including the increase in skid resistance from SN_{ini} to SN_{max} (ΔI) and the skid resistance loss passing from SN_{max} to SN_{fin} (ΔD). Values of SN_{ini} increases with the increase of recycled aggregates, whereas the lowest value is related to the mixture HF1, with recycled aggregates and improved friction properties. In this case, the pendulum slider meets a rougher surface characterised by a higher

Table 7. Skid number results.

Aggregates	SN _{ini}	SN _{max}	ΔI (%)	SN _{fin}	ΔD (%)
Natural	64	68	+ 6	43	−37
Natural + Recycled	66	75	+ 14	58	−23
Recycled	70	80	+ 14	65	−19
Recycled - High friction	62	75	+21	63	−16

**Figure 9.** Sideway Friction Coefficient (SFC) measurements with average values.

macrotexture depth, and less energy is dissipated by friction. After the binder removal from the sample surface, SN_{max} is measured. The three mixtures with steel slag coarse aggregates show the highest values of skid resistance, due to the high micro-texture of such aggregates. After the polishing action performed on the samples, the two mixtures with only recycled aggregates are the ones with highest SN_{fin}. Skid resistance values in mixtures N1 and NR1 are lower because of the lower resistance to abrasion of basaltic aggregates, if compared to steel slag coarse aggregates. The mixture HF1 shows however the lowest loss with respect to the maximum value SN_{max}, equal to 16%, expressing the best long-term skid resistance properties. Mixtures N1, NR1 and R1 are characterised by a skid resistance loss of 37%, 23% and 19%, respectively.

Field test section

SFC₂₀ measurements are reported for the right lane in Figure 9(a) and for the left lane in Figure 9(b). The figure also shows the average values related to each material section, as well as the specification limits of 58 for surface layers. In almost all cases, such limit is respected, although the section related to mixture N2 is slightly below the threshold. On the right lane (Figure 9a), it is possible to observe the contribution in skid resistance given by recycled aggregates. From the trend observed, it can be assumed that aggregates already lost the binder coating, expressing the maximum effect of micro-texture. In addition, if compared to the results of the left lane (Figure 9b), values of the right lane are lower for all mixtures. It is assumed that basalt fibres do not contribute to skid resistance, hence it is possible that on the right lane the aggregates polishing process was possibly taking place, because of the higher traffic presence. Concluding, SFC₂₀ results clearly show the beneficial effects conferred by recycled aggregates on skid resistance.

Conclusions

The research project described in this document has the goal to evaluate the sustainability and validity of the employment of recycled aggregates in the production of hot-mix asphalt surface layers,

in accordance to the Italian Technical specifications issued for freeways and highways. The experimental programme was developed around the use of steel slag coarse aggregate and municipal solid waste sand. At the same time, the use of thermoplastic polymers obtained from plastic waste recycling for bitumen modification, and basalt fibres obtained from basaltic mineral deposits for structural reinforcement were evaluated.

The investigation initially involved a laboratory study, followed by the realisation of a field test section, bringing to the following conclusions:

- The use of recycled aggregates in HMA necessarily requires a volumetric mix design, in order to consider significantly different densities and absorption values. Recycled aggregates improves HMA stiffness at low frequencies (or high temperatures), rutting resistance and skid resistance at long term, as verified by the laboratory protocol proposed and the field SFC measurements. On the other hand, fatigue life is slightly penalised at the testing conditions considered (20°C; 10 Hz);
- The use of thermoplastic polymers obtained from the recycling process of plastic waste is a good tool for neat bitumen modification. Results in terms of complex modulus and rutting resistance do not highlight significant differences if compared to mixtures produced with traditional SBS polymer modified bitumen. However, fatigue resistance of mixtures with thermoplastic polymers is on average 5% lower than mixtures with SBS polymer modified bitumen;
- The structural reinforcement conferred by the use of basalt fibres is relevant at low frequencies (or high temperatures), shown by the increase in complex modulus. The rutting resistance is not significantly influenced, whereas the fatigue life at the selected testing conditions is slightly penalised (loss of around 8%) due to the higher air voids content;
- The use of recycled aggregates, combined with the macro-texture optimisation during mix design, give a promising material suitable for surface layers. Such mixture is characterised by a fully recycled granular composition, ensuring good mechanical properties and skid resistance in the long term. This particular aspect needs to be emphasised, since it can extend the service life of surface layers with poor skid resistance.

This study focused on the production of surface layers with recycled aggregates and innovative sustainable solutions, as recycled plastic waste polymers and basalt fibres.

Consequently to what it is observed, some recommendations can be made. The hardest challenge comes from the use of aggregates characterised by different densities, which requires in the first place a thorough calibration process of the asphalt plant prior to HMA production. In addition, technical specifications should consider the different bulk density of the aggregate blend by adjusting the target gradation limits. Most importantly, to promote the production of greener asphalt mixtures, national agencies should consider economic advantages for producers who choose this solution, that leads to several issues such as more frequent maintenance operations of the asphalt plant due to the use of high dosages of steel slag.

However, future works should be addressed to the evaluation of recycled aggregates also for structural deeper layers, responsible for bearing the traffic loading and susceptible to the bottom-up cracking phenomenon. In addition, to fully assess the environmental sustainability of asphalt pavement structures with recycled aggregates, comprehensive life-cycle assessment studies are strongly needed.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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