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DISMANTLING TECHNIQUES AND RECYCLING OR OTHER END-OF-LIFE TREATMENTS OF OTHER MATERIALS NOT COMMONLY REUSED IN ROADS

LITERATURE REVIEW - PORTUGAL

1. Introduction / general considerations


The interest of recycling of waste, industrial by-products and other road materials for pavement construction and rehabilitation has been generally growing in Portugal, for the last 10 years.

Among the several types of wastes, there's been a great interest in using recycled tyres as a raw material to be incorporated in asphalt paving mixtures.

The first significant experience with asphalt rubber, manufactured by the wet process, applied on a full scale rehabilitation project, took place in the late 1990's. At that time, the standard specifications for road construction works of the Portuguese Road Administration ("Caderno de Encargos Tipo de Obras", JAE 1998) did not include any provisions for using recycled tyre rubber in the production of asphalt mixtures. The specifications for the first road works with asphalt rubber mixtures were produced case by case, primarily based on experiences from abroad. The follow-up of these construction works and the evaluation of the pavement's performance allowed for the adjustment of these specifications. The specifications for road construction works issued by the Road Administration (presently Estradas de Portugal) issued in 2009 (EP, 2009) include provisions for use of rubber modified bitumen in the production of open-graded and gap-graded asphalt mixtures and also in anti-crack membrane interlayers.

The Decree-Law no. 111/2001 (*Decreto-Lei n.º 111/2001, de 6 de Abril*), later modified by the Decree-Law no. 43/2004 (*Decreto-Lei n.º 43/2004, de 2 de Março*) establishes a National Law on management of used tyres. It sets the following obligations for producers from 2007 onwards: a) to separately collect a minimum of 95% of annually generated used tyres; b) to retread a minimum of 30% of annually generate used tyres; c) to valorise the totality of non retreaded collected tyres, of which a minimum of 65% must be recycled.

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In 2006, the Decree-Law no. 178/2006 (*Decreto Lei n.º 178/2006, de 5 de Setembro*) defines the general system for waste management (including used tyres). This decree addresses waste collection, transport, storage, disposal, treatment, valorisation and elimination. Moreover, it rules on licensing, registration and control procedures.

The Portuguese Laboratory of Civil Engineering LNEC (*Laboratório Nacional de Engenharia Civil*) played an important role on the use of asphalt mixtures with bitumen modified with high percentages of tyres' recycled rubber in paving works, providing two technical assessment documents (Application Documents DA 3, 2006 and DA 15, 2008). These documents define characteristics and establish the conditions of execution open-graded and gap-graded asphalt rubber produced by Recipav.

Taking into account environmental aspects and the National positive experiences on the use of asphalt rubber mixtures, a new Decree was issued in 2007 - Decree no. 4015/2007 (*Despacho n.º 4015/2007, Diário da Republica, 2ª Série – Nº.44 – 2 de Março de 2007*), in which the use of bitumen modified with rubber from recycling used tyres in paving works is promoted.

2. Materials that complicate the dismantling / recycling of road layers or structures

No relevant information is available.


3. Unwanted materials, dangerous waste

No relevant information is available.

4. Secondary aggregates (already used in road layers, no fresh production)

No relevant information is available.

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5. Vehicle tyres

After the publication of the Decree-Law no. 11/2001 (Decreto-Lei n.º 111/2001, de 6 de Abril) tyre producers joined industrials from the tyre retread and rubber sectors and formed *Valorpneu - Sociedade de Gestão de Pneus, Lda* in 2002 (Valorpneu, 2009). This company was licensed as the managing entity of the SGPU - Sistema Integrado de Gestão de Pneus Usados (Used Tyres Management Integrated System), whose aim is the correct routing of end-of-life tyres, eliminating the need for landfill deposit and promoting collection, separation, retake and recovery (reuse, retread, recycling and energy recovery).


The recovery network of Valorpneu (2009) is essentially made up of recycling and energy recovery operators. There are also occasionally reported cases of operators which recover used tyres through reutilization for other own purposes (such as, for example, civil works construction, protection of marine piers, etc.).

5.1 Identification

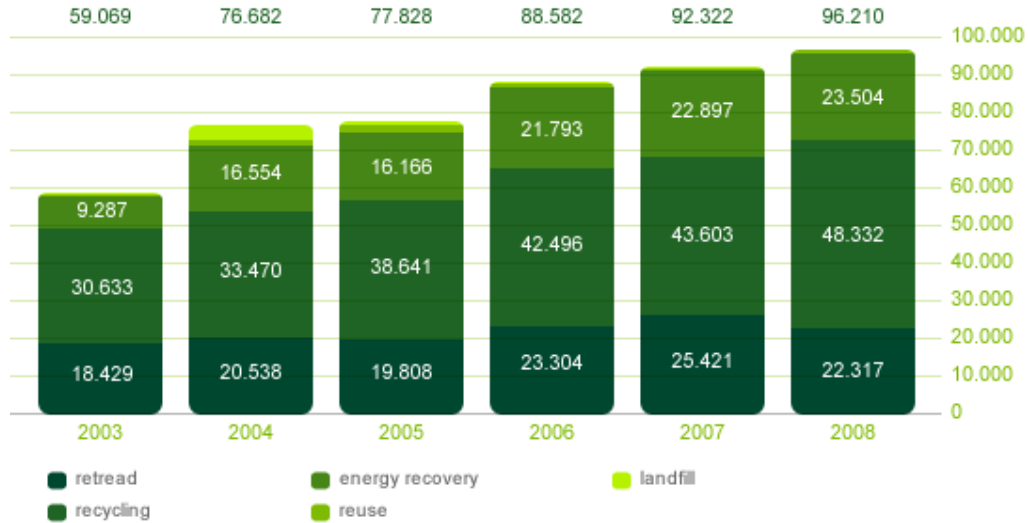
The identification of the different categories of used tyres is usually performed in function of their destination. According to Valorpneu (2009), in Portugal, the used tyres dispatched by Collection Points may have four different destinations:

- **“Reuse:** using tyres which are still in good condition, returning them to the market with the purpose of being used for the same purpose (half tread reuse), or using tyres, without the need for any pre-processing, for a purpose different from the one it was originally designed for (reuse for other purposes)”;
- **“Retread:** operation by which an already used tyre, after fulfilling its lifecycle, is rebuilt in such a way as to allow its use for the same purpose as the one it was originally designed for”;
- **“Recycling:** processing of used tyres for a purpose other than the original one, namely as raw material to be incorporated into other products (ex: Rubber Modified Bitumen, used to pave roads, children playgrounds, synthetic grass, etc.) ”;
- **“Energy recovery:** processing of used tyres by combustion, for energy recovery”.

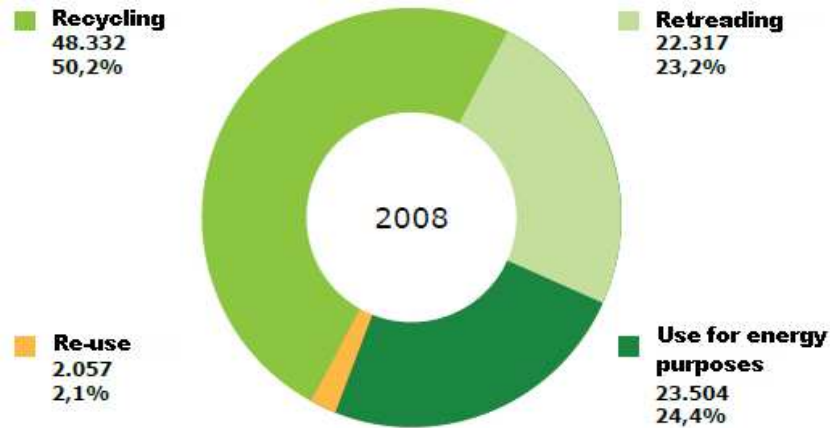
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The destination of generated used tyres collected by the SGPU (t) from 2003 up to 2008 is the following (Valorpneu, 2009):



Reporting to the year 2008, Portugal had generated around 96 000 tons of used tyres and its destination was the following (Valorpneu, 2009):



At national level there are 8 valorisation centres, 4 for recycling and milling and 4 for energy purposes (Valorpneu, 2009).

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5.2 Handling and preparation

5.2.1 Collection

As referred before, the Portuguese entity responsible for the used vehicle tyres collection is Valorpneu.

There is a network of collection points distributed throughout the country (40 collection points in mainland Portugal, 8 collection points in the Autonomous Region of the Azores and 1 collection point in the Autonomous Region of Madeira), where any company may deliver their used tyres at zero cost (Valorpneu, 2009). The dispatched used tires can be of any type and have only to comply with some conditions, i.e. they could not present any contamination.

5.2.2 Transport

At present, Valorpneu's transportation network comprises 26 operators responsible for the transportation of used tyres from collection points to valorisation centres, of which 24 operate in mainland Portugal, 1 in the Autonomous Region of the Azores and 1 in the Autonomous Region of Madeira


Used tyres are routed by Valorpneu (2009) from the collection points to the destination points, where they are processed according to the established goals (essentially recycling and energy recovery).

5.2.3 Technologies for product preparation

Recyclers and Energy Recovery Agents receive the end-of-life tyres coming from collection points and processing them into rubber granulate for an adequate recycling destination or energy (Valorpneu, 2009).

Recycling operators receive whole or shredded tyres and process them into rubber granulate (separating metal and textile materials incorporated in the tyres), which is then used as a raw material for different purposes, such as, sport fields, children playgrounds, asphalt rubber for road paving (finer crumb rubber is used in this case), *etc.*

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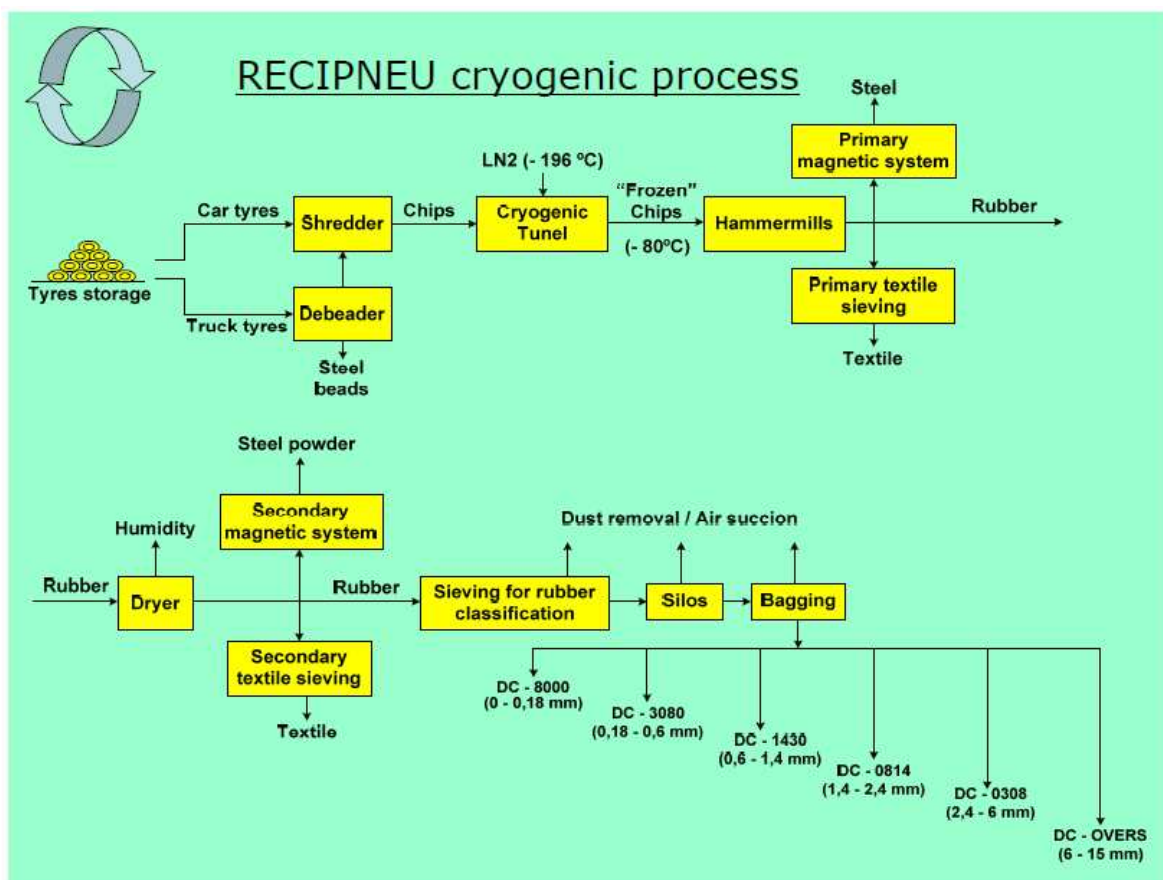
Presently, in Portugal, two main processes are in use to obtain rubber crumb (Valorpneu, 2009):

- The **mechanical process** consisting in the mechanical shredding of tyres. Rubber is fragmented in a series of grinders and mills, with steel being removed through magnetic separation and textile separated by differences in density. At the end of the process, rubber particles are divided into different ranges, according to their size, passing through sieves with different mesh sizes.
- The **cryogenic process** – uses liquid nitrogen to freeze rubber inside a cryogenic tunnel, which enables fragmentation of the rubber and the production of fine rubber crumb. The tyre first endures mechanical grinding and afterwards its fragments are transported to the cryogenic tunnel. After passing through the cryogenic tunnel and pneumatic sledge hammers, the steel and textile contained in the tyre are separated from the rubber through magnetic separation and suction, respectively.

At present, 3 recycling companies operating in Portugal are identified: Biosafe, Biogoma, and Recipneu. The first two operate through a mechanical process, while the third uses a cryogenic process (that is unique in Europe), as represented in the following picture:

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The characteristics of the crumb rubber obtained by each one of the presented processes are naturally different: cryogenic rubber particles present a “round to moderately angular morphology” (smooth faces, very small pore density and glossy appearance, similar to a “closed”/ encapsulated particle) while mechanical rubber particles generally have a very irregular surface shape, rough in texture, with high pore density (Recipneu, 2009).

According to the recycling agent Recipneu (2009), the crumb rubber proceeding from cryogenic process has the following advantages:

- The original tyre rubber characteristics are maintained;
- No degradation occurs, and an excellent profile is obtained in elasticity, abrasion, anti-ageing, and environmental properties.

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5.3 Recycling whole tyres as lightweight / massive material in embankments

5.3.1 Characterization

In Portugal there have been sporadic experiences on recycling tyres as lightweight, and very few data is available.

A single case concerning the use of tyres shreds (MADRE® - *Material Agregado Derivado do Pneu*, by Recipneu) in the final cover of the AMARSUL Landfill, in Palmela, was reported in 2008.

In this case, Tyre Derived Aggregate (TDA) - a product made by cutting scrap tyres into 25 mm to 300 mm pieces – was used in a landfill application.

5.3.2 Performance


The next table shows the performance of tyre chips in civil engineering applications (such as landfills, embankments, etc.) (Recipneu, 2009):

Properties	Measure
Compacted density	2.3 – 4.8kN/m ³ compared to soil at 15.6 – 19.5kN/m ³
Compacted dry unit weight	1/3 that of soil
Compressibility	3 times more compressible than soil
Density	1/3 to ½ less dense than granular fill
Durability	Non-biodegradable
Earth pressure	Low compared to soil or sand, up to 50% less
Friction characteristics	Higher compared to soil
Horizontal stress	On weak base: lower than with conventional backfill
Modulus in elastic range	1/10 of sand
Permeability	Greater than 10cm/s
Poisson's ratio	0.2 – 0.3 corresponding to K ₀ values of 0.3 - 0.4
Specific gravity	± 1.14 – 1.27 compared to soil at 2.20 – 2.80
Thermal insulation	8 times more effective than gravel
Unit weight	Half the typical unit weight of gravel
Vertical stress	On weak base : smaller than granular backfill

5.3.3 Other aspects

(-)

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5.3.4 Conclusions

According to the recycling agent Recipneu, TDA has good properties to civil engineering constructions, is cost effective, replaces natural resources and cause no adverse effects to the environment, being an excellent alternative to minerals in these types of applications.

5.4 Recycling as aggregate in rubber-based pavements (sport fields, ...)

5.4.1 Characterization

In Portugal, the main application of tyre rubber granulates is as aggregate in rubber-based pavements (sport fields and playgrounds), artificial turf infilling and horse arenas. For each type of these applications, the crumb rubber presents different particle size, as follows:

Application	Particle size (mm)
Rubber-based pavements (sport fields, playgrounds)	2,4 - 6,3
Artificial turf infilling	0,5 - 2,4
Horse arenas	> 6,3

5.4.2 Performance


In general, the characteristics and the performance of rubber-based pavements (including artificial turf infilling and horse arenas) depend on the type of technology used to produce crumb rubber (the cryogenic process or the mechanical process), as summarised below (Recipneu, 2009):

- Rubber-based pavements: good shock absorption, high resistance to UV radiation and good permeability.

The cryogenic rubber granulates do not stain and do not smell, what can be important, for instance, in children playgrounds.

- Artificial turf infilling: in this type of application the performance of cryogenic and mechanical rubber infill are significantly different, as presented in the following table:

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Cryogenic Rubber Infill (CRYOFLEX®)	Mechanical Rubber Infill
No smell	Intense smell
No release of abraded carbon black (No staining / no adherence to skin and clothes)	Staining / adherence to skin and clothes
No dust liberation (no release of inhalable powder)	Dust liberation (significant release of inhalable powder)
Particles with a “flat surface morphology” (very low superficial area per unit mass, very few pores, very reduced emissions)	Particles with “spongeous” type morphology (very high pore density, very high superficial area / unit mass, significant emissions)
Particles with regular shape, round to moderate Angular (ISA Sport Test)	Particle shapes very irregular
The best compaction resistance – rubber doesn't compact significantly along the years of use (TNO Study – Multiturf Project)	Poor Compaction resistance – rubber compacts in the layer along the years of use (TNO Study – Multiturf Project)
Excellent rain water drainage (the field never floods)	Bad rain drainage (the field gets flooded)
Higher apparent density, no floating and stability of rubber in place – No need rubber refills	Lower apparent density, floating particles and flow with water – need of rubber refills
Best Ageing resistance – Lispor Test (extended durability of the rubber infill layer) (IBV Report and ISA Sport Report)	Reasonable ageing resistance
Excellent elastic properties (molecular structure not degraded in cryogenic production process)	Regular elastic properties (molecular structure relatively degraded in hot + friction production process)
Excellent mechanical performance – FIFA Quality Concept (IBV Report)	
Compliance with DIN V 18035-7 standard: Zinc Leachates, heavy metal leachates, DOC and EOX (Dr. Grunder Tests)	
Compliance with accepted PAH's regulations (TUV test)	
Excellent resistance to UV Radiation, no colour change (ISA Sport Test)	Good resistance to UV radiation (no color change)
No affection the UV resistance of artificial grass (no emission of sulphur and oil vapours from the rubber particles to deflect the polyolephin artificial grass filaments)	Affection UV resistance of artificial grass (much higher emissions of sulphur and oil vapours that cause bigger deflection to the UV resistance of artificial grass)
Reduced to negligible VOC's emissions (e.g. no smell)	More intensive VOC's emission. (e.g. intense smell)

- Horse arenas: When a sand surface receives a 5 cm layer of FLEXYGRAN® (RECIPNEU's > 6,3 mm granulate), which is spread manually or mechanically and mixed with the sand by the horses, excellent results are obtained, both in terms of elasticity and of the ground surface's anti-shock and anti-compacting effects. It provides greater comfort while reducing the risk of injury to horses.

Cryogenic granulate has no odour emissions, being highly recommended for indoor riding schools, it contains moisture-fixing absorbent additives, whose effect results in much less dust and a 30% decrease in watering (a significant cost saving).

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5.4.3 Other aspects

Currently there are in Portugal several suppliers of tyres' recycled rubber for application as aggregate in the following pavements:

- Rubber-based pavements: Flexipiso, Resopre and Mondo;
- Artificial turf Infilling: Mondo, Playpiso, Sportejo, AFF Sport, Nativa and ACHRO;
- Granulates for horse arenas: Recipneu.

5.4.4 Conclusions

Rubber granulates are an excellent solution, technically, environmentally and economically, for rubber-based pavements in general.

In general, it can be concluded that, for the referred applications, the performance of cryogenic rubber granulates is better than the mechanical rubber granulates.

5.5 Recycling for asphalt rubber production


Since the first application of asphalt rubber (AR) mixtures in Portugal, in 1999, some thousand tones of these mixtures, manufactured by the wet process, have been applied in new construction and in maintenance and rehabilitation works, both on flexible pavement structures and on continuous reinforced concrete pavements.

The crumb rubber used in the manufacture of AR mixtures may be used either in the modification of virgin bitumen to produce "bitumen rubber" binder ("wet process") or it may be incorporated directly in the asphalt mixture, together with the aggregates ("dry process").

During the past ten years, a change on the typical composition of AR mixtures used in Portugal has occurred (Batista *et al.*, 2008). For example, the first type of mix applied in Portugal in 1999 was a gap-graded AR mixture manufactured by the wet process, using 7% of rubber modified bitumen. Presently, gap-graded mixtures are produced with a higher content of bitumen rubber (8% to 9%).

On the other hand, there is a wider range of bitumen rubber binders on the Portuguese market, such as *in situ* manufactured binders with high content of crumb rubber and *ex situ* manufactured binders with lower contents of crumb rubber.

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5.5.1 Characterization

The crumb rubber used in the manufacture of asphalt rubber may be produced by the mechanical process (grinding at ambient temperature), the cryogenic process or a combination of the two.


The origin of the rubber and the manufacturing process have a major influence on some of the characteristics of the crumb rubber, such as grading or particle shape and these will affect the performance of the asphalt rubber.

In Portugal, Recipav was the producer of the first AR mixture applied in road paving works and this company detains a major experience in supplying rubber modified bitumen for AR production.

The crumb rubber used by Recipav in the production of bitumen modified with a high percentage of rubber comes from 100% vulcanized used tyres and presents the following characteristics (LNEC DA3, 2006; LNEC DA15, 2008):

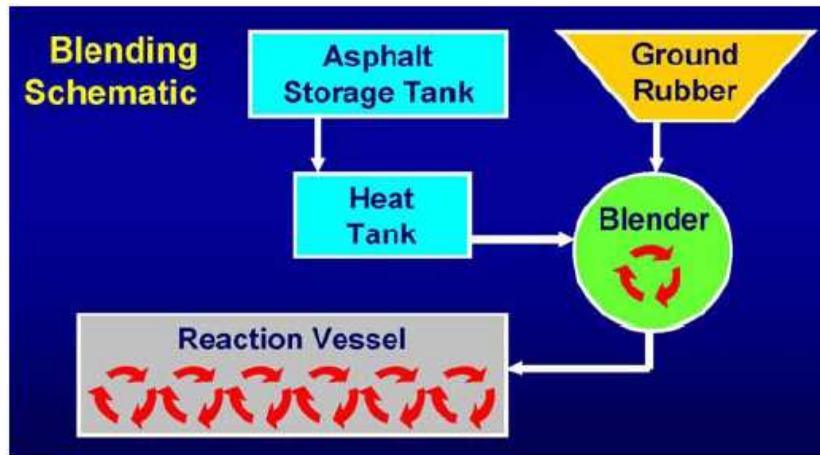
- Content in fibres up to 0,1% (ASTM D 5603-01);
- Content in steel up to 0,3% (ASTM D 5603-01);
- Content in water up to 2,0% (ASTM D 1864-89);
- Nominal size maximum of 0,6 mm.

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There are basically two different processes for using recycled crumb rubber in the manufacture of AR mixtures, as follows:

- Wet process: This is the most utilized and consists in blending the rubber with the bitumen before transferring the modified binder to the asphalt mixer plant. The reaction between the rubber and the bitumen starts at the blender and continues in a reaction tank/vessel for a determined time. In this tank, a continuous agitation and a rigorous control of temperature is ensured. After that, the rubber bitumen is introduced into the asphalt mixing plant or is stored, depending on the type of bitumen rubber produced. All this process is illustrated in the following figure.



Source: Asphalt Rubber Usage Guide from Caltrans

- Dry process: In this procedure, whose implementation in Portugal is fairly recent, the crumb rubber is fed directly into the mixer of the asphalt mixer plant, together with the bitumen, and aggregates. This process usually requires raising the manufacturing temperature and the mixing time. Asphalt rubber mixtures will also need a storage period later, inside a silo or truck storage to allow swelling reaction and avoid post application swelling. This way, crumb rubber not only acts as a fine aggregate, but also, to some extent, as a modifier of the bitumen properties, since its finest particles interact with the bitumen.

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Basically, three main types of rubber bitumen produced by the wet process are used in Portugal, classified according the percentage of crumb rubber incorporated in the binder, as indicated in the next table:

Portuguese acronym	Identification	Percentage of crumb rubber in the modified binder
BBB	Bitumen modified with low rubber content	< 8%
BBM	Bitumen modified with medium rubber content	8% - 15%
BBA	Bitumen modified with high rubber content	≥ 18%


An important aspect related to the use of rubber bitumen is storage stability. For low (BBB) and medium (BBM) contents of rubber, and adequate storage stability is normally achieved. For high rubber contents (BBA), the stability of the modified binder is much more difficult to obtain and therefore, in most cases the binder is modified close to the asphalt plant and introduced in the asphalt mix within a few hours after production.

At present, Portuguese Standard concerning rubber bitumen produced by the wet process is being prepared by the Portuguese standardization committee on bituminous binders.

The specifications for road construction issued recently by the Portuguese Road Administration (Estradas de Portugal) include provisions for rubber modified bitumen (EP, 2009), as indicated in the following tables:

Bitumen modified with low rubber content (BBB)					
Specification		Standard	Unit	BBB 35/50	BBB 50/70
Kinematic Viscosity at 135°C, min.		EN 12595	mm ² /s	370	295
Penetration, 25°C, 100g, 5 s		EN 1426	0,1 mm	35 - 50	50 - 70
Softening Point, min.		EN 1427	°C	58	53
Durability (Resistance to hardening) after RTFOT, 163°C, max.	Change of mass, máx.	EN 12607-1	%	+ 1,0	+ 1,0
	Retained Penetration, 25°C, 100g, 5s, min.		%	65	60
	Increase of Softening Point		°C	≥ - 4 ≤ + 8	≥ - 5 ≤ + 10
Elastic Recovery, elongation of 20 cm, a 25 °C, min.		EN 13398	%	10	10
Storage Stability	Difference in Softening Point, max.	EN 13399	°C	5	5
	Difference in Penetration, max.		0,1 mm	10	10

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Bitumen modified with medium rubber content (BBM)					
Specification		Standard	Unit	BBM 35/50	BBM 50/70
Kinematic Viscosity at 135°C, min.		EN 12595	mm ² /s	310	150
Penetration, 25°C, 100g, 5 s		EN 1426	0,1 mm	35 - 50	50 - 70
Softening Point, min.		EN 1427	°C	65	58
Durability (Resistance to hardening) after RTFOT, 163°C, max.	Change of mass, máx.	EN 12607-1	%	+ 0,8	+ 1,0
	Retained Penetration, 25°C, 100g, 5s, min.		%	70	65
	Increase of Softening Point		°C	≥ - 4 ≤ + 8	≥ - 5 ≤ + 10
Elastic Recovery, elongation of 20 cm, a 25 °C, min.		EN 13398	%	15	20
Storage Stability	Difference in Softening Point, max.	EN 13399	°C	5	5
	Difference in Penetration, max.		0,1 mm	8	10

Bitumen modified with high rubber content (BBA)					
Specification		Standard	Unit	BBA 35/50	BBA 50/70
Apparent Viscosity at 175°C, min. (Brookfield viscometer with thermosel, handle SC4-27, 20rpm)		EN 13302	mPa.s	2500 - 4500	2500 - 4500
Apparent Viscosity at the exit of reaction tank, at 175°C, min.		-	cP	3500 - 5000	3500 - 5000
Penetration, 25°C, 100g, 5 s		EN 1426	0,1 mm	15 - 30	20 - 35
Softening Point, min.		EN 1427	°C	68	65
Durability (Resistance to hardening) after RTFOT, 163°C, max.	Change of mass, máx.	EN 12607-1	%	+ 0,8	+ 1,0
	Retained Penetration, 25°C, 100g, 5s, min.		%	70	65
	Increase of Softening Point, max.		°C	12	12
Elastic Recovery, elongation of 10 cm, at 25 °C, min.		EN 13398	%	75	75
Storage Stability	Difference in Softening Point, max.	EN 13399	°C	5	5
	Difference in Penetration, max.		0,1 mm	8	10

Asphalt rubber mixtures are applied in the maintenance, rehabilitation or construction of roads.

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In Portugal, there are two main types of AR mixtures produced with bitumen modified with high content of rubber (BBA):

- Gap-graded mixtures (GG-AR), placed in 30 mm to 60 mm thick layers, as structural overlays and/or as wearing courses. These mixtures are produced with 0/12,5 mm aggregates, with a bitumen rubber content from 8% to 9% of the total weight of the mixture. The air void content is generally between 4,5% and 6,5%;
- Open-graded mixtures (OG-AR), placed in 25 mm to 40 mm thick layers, as wearing courses. These mixtures are produced with 0/10 mm aggregates, with a bitumen rubber content from 9 to 10%. The void content is generally between 12% and 18%. This type of solution has been applied for the improvement of skid resistance and as a measure to reduce tire-road noise.

LNEC issued two technical documents (Application Documents DA 3, 2006 and DA 15, 2008) where the characteristics for open-graded and gap-graded asphalt rubber mixtures, produced by Recipav, are defined.


In Portugal, bitumen modified with high content of rubber (BBA) is also used for execution of SAMI-R (Asphalt Rubber Stress Absorbing Membrane Interlayer) that consists in application of BBA at 185°C at a rate of 1,8 kg/m² to 2,6 kg/m² subsequently covered with gravel at a rate of 10 kg/m² to 12 kg/m². These types of interlayers are used under asphalt overlays in corrective maintenance and in pavement rehabilitation. SAMI-R has been successfully used for delaying reflective cracking in pavements.

5.5.2 Performance

Since the first application of asphalt rubber mixtures in Portugal, several research studies addressing its performance have been carried out (J. Sousa *et al.*, 1999; M. L. Antunes *et al.*, 2006a, H. Miranda, 2007; F. A. Batista *et al.*, 2008, 2009; L. Fontes, 2009). The effect of the manufacture procedure of the rubber bitumen and of the characteristics of its components (rubber and bitumen) on the mix properties has also been addressed in these studies (M. L. Antunes *et al.*, 2000, 2006b; J. Pais *et al.*, 2001; Peralta, E. J., 2009).

The technical documents DA 3 (2006) and DA 15 (2008), issued by LNEC, include data about the performance of open-graded and gap-graded asphalt rubber mixtures produced by Recipav, as follows:

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MBA-BMB® - Open-graded Asphalt Rubber mixtures				
Property		Test method	BBA produced with 35/50 pen grade bitumen	BBA produced with 50/70 pen grade bitumen
Stiffness modulus, MPa		EN 12697-26: 2004 (4PBT, 20°C, 10Hz)	1500 - 2500	1000 - 2000
Resistance to fatigue	ϵ_6	EN 12697-24:2004 (4PBT, 20°C, 10Hz)	≥ 225	≥ 250
	ρ		-5 to -4	
Resistance to permanent deformation	Final deformation (120 min.), mm	NLT 173/84 (wheel tracking test, 60°C)	≤ 5	≤ 10
	Deformation rate between 105 and 120 min., $\mu\text{m}/\text{min.}$		≤ 12	≤ 24


MBR-BMB® - Gap-graded Asphalt Rubber mixtures				
Property		Test method	BBA produced with 35/50 pen grade bitumen	BBA produced with 50/70 pen grade bitumen
Stiffness modulus, MPa		EN 12697-26: 2004 (4PBT, 20°C, 10Hz)	3000 - 4500	2500 - 3500
Resistance to fatigue	ϵ_6	EN 12697-24:2004 (4PBT, 20°C, 10Hz)	≥ 200	≥ 250
	ρ		-6 to -4	
Resistance to permanent deformation	Deformation rate between 105 and 120 min., $\mu\text{m}/\text{min.}$	NLT 173/84 (wheel tracking test, 60°C)	≤ 10	≤ 14
	WTS_{AIR} , $\text{mm}/10^3$ cycles	EN 12697-22:2003 (wheel tracking test, Small size device, procedure B, Air, 60°C)	$\leq 0,08$	$\leq 0,09$
	PRD_{AIR} , %		$\leq 6,0$	$\leq 7,0$

These types of AR mixtures are known for their improved resistance to fatigue and to reflective cracking, together with an increased durability, when compared to conventional mixtures (M. L. Antunes *et al.*, 2006b; H. Miranda *et al.*, 2008; F. A. Batista *et al.*, 2008).

Studies performed in Portugal (Recipav, 2009) indicate that the application of asphalt rubber can reduce the noise level up to 8 dB (A) when compared to conventional asphalt and cement concrete surfaces.

Another study, concerning the first Portuguese experience in 1999-2000, when a gap-graded asphalt rubber mixture was applied as an overlay in the framework of the pavement rehabilitation of National Road sections (EN 104 and EN 105) located in the North of

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Portugal (M. L. Antunes *et al.*, 2006a), showed that, after 6 years of service life, it continued showing good performance and no maintenance operation required.

5.5.3 Others aspects

Recipav was the first European company who modified bitumen with rubber and has 10 years of experience in this type of product. Since then, more than 40 000 ton of asphalt rubber were applied in nearly 450 km of road in Portugal as well in Austria and Spain.

5.5.4 Conclusions

From the experience gathered so far in Portugal, it may be concluded that the use of crumb rubber in pavement construction is an interesting alternative for the disposal of old tyres, being able to significantly improve the performance of asphalt.

Laboratory studies and field performance data have shown that asphalt rubber has an improved resistance to fatigue and reflection cracking, together with an increased durability, when compared with conventional asphalt mixtures. Asphalt rubber mixtures produced with high percentages of crumb rubber have a high binder content. However, this does not mean that they have a poor resistance to permanent deformation, due to the presence of the rubber which reduces the temperature sensitivity and increases the viscosity of the binder.


The use of open-graded asphalt rubber mixtures has also proved to be an interesting solution for noise reduction.

5.6 Non-road end-of-life treatments (incineration or co-processing)

The energy recovery operators utilize used tyres as an alternative source of fuel for energy production, benefiting from the excellent heating power of the tyre (similar to that of coal), therefore saving on traditional fuel consumption (fossil fuel).

Facilities such as utility boilers, cement kilns, and pulp/paper mills use TDF (tyre derived fuel) as supplemental fuel in their energy-intensive processes.

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The plants that use TDF as a fuel must comply with Portuguese legislation, in particular with the Decree-Law 85/2005 (*Decreto-Lei nº 85/2005*), relative to incineration and co-incineration of waste. The emission standards are fixed in this legislation.

At present, Valorpneu (2009) works together with 4 energy recovery facilities: the three cement production plants from the Secil Group, located in Maceira, Pataias and Outão, and the cogeneration facility of the *Recauchutagem Nortenha* company, located in Penafiel.

5.6.1 Characterization

Tyre derived fuel (TDF) can be used in the form of whole tyres or in the form of shredded or chipped material where most of the metal wire from the tyre's steel belts is previously removed.

This type of fuel has a very high energy content, with an average heat value of 29 MJ/kg, which is roughly the same as coal (30-35 MJ/kg).

5.6.2 Performance


Tyre derived fuel (TDF) presents the following characteristics:

- A high heat value;
- Emissions below the standard values, when it is used as an alternative fuel in cement kilns or boilers;
- A potential advantage of decreasing emissions of oxides of sulfur (SO_x) and Nitrogen (NO_x), when used to replace high sulfur coal in cement kiln applications;
- Reduction of the amount of fossil fuels that would, otherwise, be consumed;
- Reduction of energy costs, since TDF is less expensive than fossil fuels;
- In cement kiln applications, the ash resulting from TDF and coal combustion becomes an integral component of the product, eliminating the landfilling of ash.

5.6.3 Conclusions

Used tyres can be used as an additional or alternative fuel for cement production or for the production of electricity and steam in cogeneration units, due to its high heating power,

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which is around 5.700 kcal/kg, slightly below coal, which is 6.800 kcal/kg. Therefore, the use of tyre derived fuels is a viable alternative to the use of fossil fuels.

The use of TDF has been increasing in Portugal, with very good results.

6. (Polluted) soil and sediments

No relevant information is available.

7. Green waste

No relevant information is available.

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