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Characterization of crumb rubber from end-of-life tyres for paving applications

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ABSTRACT

Crumb rubber (CR) derived from grinding of end-of-life tyres (ELTs) may be successfully used as a bitumen modifier or as a supplementary component in the production of bituminous mixtures employed for the construction and maintenance of road pavements. However, CRs deriving from different sources and production processes yield effects on performance of corresponding paving mixtures under traffic loading and on gaseous emissions produced during laying on site which may change considerably depending upon their physical and chemical properties. In order to quantitatively assess the possible variability of CR characteristics, 16 samples were taken from 9 Italian and 2 foreign ELT processing plants. Investigation activities included field surveys, during which plants were examined in detail, and laboratory tests, which focused on physical and chemical characterization of CR. Based on the analysis of available technical information and experimental data, it was possible to find relationships between the peculiar characteristics of treatment cycles and corresponding CR properties.

1. Introduction

Management of end-of-life tyres (ELTs) has become a critical problem worldwide due to the increasing number of vehicles circulating in the road network and to the crucial role that mobility has assumed in society development. Since landfill disposal has been banned in most Countries, alternative final destinations have been sought, with a major effort being placed in trying to exploit in the most efficient manner the high energy potential of ELTs. Nevertheless, due to the fact that rubber employed in tyre fabrication is the result of specialized materials' selection, recycling and reuse seem to be preferable options for such a high-quality waste material (Santagata and Zanetti, 2012).

Practical experience and research have shown that crumb rubber (CR) derived from grinding of ELTs may be successfully used as a bitumen modifier or as a supplementary component in the production of bituminous mixtures employed for the construction and maintenance of road pavements. Available technologies can be grouped into two main categories which are associated to the so-called "wet" and "dry" production processes. Within each group, different versions of the technology have been conceived and subjected to trials either in the laboratory or at the industrial scale, in the constant attempt of exploiting more efficiently the performance-related benefits of CR.

In the "wet" process, CR is preliminarily mixed with bitumen, thus obtaining a ductile and elastic modified binder, known as "asphalt rubber" (ASTM D6114-09), that is then combined with aggregates in the hot mix plant. Resulting mixtures are generally of the gap-graded (GG) or open-graded (OG) type, characterized by a very high binder content (of the order of 7.5–10% b.w. of dry aggregates) and by a non-continuous particle size distribution that allows CR to be accommodated within the composite material. GG and OG mixtures are employed for the formation of surface courses and have earned a satisfactory reputation with respect to field performance (Hicks, 2002).

In the "dry" method, CR is introduced in the production flow of bituminous mixtures as a supplementary component, substituting part of the aggregates and providing enhanced elastic response under loading (Santagata and Zanetti, 2012; Santagata et al., 2013). Mixtures are usually of the dense-graded (DG) type, with a continuous particle size distribution and an optimal binder content (usually of the order of 5–6%) which is only slightly higher than that adopted for standard mixtures containing no recycled rubber (Buncher, 1995). Unfortunately, the performance record of these mixtures has been quite inconsistent, with the frequent occurrence of early ravelling phenomena and moisture-related damage (Amirkhanian, 2001; Caltrans, 2005). This also explains the limited diffusion of such a technology, with full-scale

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applications that have been generally carried out locally rather than at the network level.

For both the abovementioned technologies, concerns have been raised on the use of CR in bituminous mixtures with respect to its potential contribution to gaseous emissions during production and laying, and to the possible consequences which it can cause on the health of construction workers. However, a limited number of experimental studies have been carried out on this specific topic, with no clear quantification of the actual hazardous effects of CR (Watts et al., 1998; Burr et al., 2001; Stout and Carlson, 2003).

The Authors have recently contributed to this area of technical knowledge by applying to pavement works risk analysis concepts developed in previous studies focused on the evaluation and remediation of contaminated sites (Marescalco and Zanetti, 2010; Zanetti et al., 2013b) and on the approval of the use of CR in artificial turf sports fields (Ruffino et al., 2013). In particular, by considering the results of analyses carried out on gaseous emissions sampled on site or in the laboratory in controlled conditions, comparisons have been made between bituminous mixtures containing CR (produced by employing both the "wet" and "dry" technology) and bituminous mixtures of the standard type (Zanetti et al., 2013a, 2014a and Zanetti et al., 2014b).

Based on the Authors' experience, it can be concluded that CRs deriving from different sources and processes yield effects on field performance and emissions of bituminous binders and mixtures which may change considerably depending upon their physical and chemical properties. In turn, these are dictated by the characteristics of ELTs subjected to processing and by the phenomena which occur during the various phases of ELT treatment (shredding, magnetic separation, granulation, milling and sieving).

In order to quantitatively assess the possible variability of CRs, in the study described in this paper, samples were taken from 9 Italian and 2 foreign ELT processing plants and thereafter subjected to laboratory investigations for the assessment of physical and chemical characteristics. In particular, experimental tests were carried out for the determination of particle size distribution, density, cleanliness, particle shape and morphology, specific surface area, content of metals, PAHs (polynuclear aromatic hydrocarbons) and VOCs (volatile organic compounds) and elemental analysis (carbon, hydrogen, nitrogen and sulfur). Based on the analysis of technical information and experimental data, it was possible to find relationships between the peculiar characteristics of treatment cycles and corresponding CR properties.

2. Background

2.1. CR production

Processing of ELTs is carried out in various phases during which rubber is separated from other materials (textile fibers and metals), mechanically reduced in granular form and finally divided into particle size fractions. When shredding, shear and abrasion operations occur with no specific temperature conditioning, the process is known as "ambient size reduction". In some plants, however, ELTs are brought below rubber glass transition temperature with adequate cooling systems and the resulting process is referred to as "cryogenic". Moreover, novel processing methods are continuously developed in order to optimize plant efficiency. As an example, size reduction has also been attempted by means of the "high pressure waterjet" system, based on the abrasive effects caused by water jets at 3.000 bar which pulverize ELTs.

Depending upon the type of treatment process and on the origin of ELTs fed to it, CR may have different physical and chemical characteristics. In particular, particles deriving from ambient size reduction generally have irregular shape and rough surface; moreover, it has been postulated that in some cases heat generated during mechanical processing may induce a partial devulcanization of rubber. By comparison, cryogenically produced CRs are mostly made of cuboid-shaped particles with a smooth surface. With respect to ELT origin, it is well known that tyre producers employ different rubber formulations and that truck tyres generally have a higher natural rubber content than car tyres. However, in practice only the second factor may influence CR production since there are plants that treat only truck (or car) tyres, but none are dedicated to a single tyre producer.

2.2. CR-bitumen interaction

In the asphalt rubber "wet" production process, CR is thoroughly mixed with bitumen at a temperature in the 175–225 °C range. The resulting binder is then kept in agitation at high temperature (150–215 °C) for the time period (of the order of 45–60 min) which is necessary for interaction phenomena between the components to occur. In particular, CR particles are partially digested in the bituminous matrix and absorb part of the aromatic fraction of bitumen, with a resulting volume expansion and formation of a gel-like surface coating which gives the binder its peculiar physical and rheological characteristics (Way et al., 2012). In this form, CR particles are still visible in the composite binder which has a distinctive granular-like appearance. If curing is carried out at an excessive temperature and/or for a too long time period, degradation phenomena become prevalent and CR is totally digested in bitumen: as a consequence, the resulting binder does not have the typical characteristics of asphalt rubber and may exhibit unsatisfactory performance.

Asphalt rubber binders usually have a CR content comprised between 18% and 22% (b.w. of total binder), with a high viscosity at storage/mixing temperatures and enhanced elastic properties in service. Binder characteristics are dependent not only upon chemical composition of employed components, but also on CR dosage, particle size and morphology. In such a context, it has been proven that the intensity of the above described interaction phenomena tends to increase with CR dosage and specific surface area (Shen et al., 2009). Therefore, CRs which are considered more reactive are those which are finer, constituted by rough, irregular particles.

In the production of "dry" mixtures CR is usually employed with a dosage comprised between 1% and 3% (b.w. of dry aggregates). Depending upon the type of plant, either batch or drum-mix, CR can be introduced in the production flow of bituminous mixtures by means of different methods, but is always added to the heated aggregates before coming in contact with bitumen. When this condition occurs, even though CR particles are not digested in bitumen, they do absorb part of its aromatic fractions. However, such an interaction takes place in non-controlled conditions, starting from the mixing process in the plant and progressing throughout the early phases of service life (Santagata et al., 2013). Studies performed in the past have shown that in this respect beneficial effects can be obtained by pretreating CR by means of function-specific catalysts (Epps, 1994) or extender oils (Newcomb et al., 1994; Khalid and Artamendi, 2002).

2.3. CR selection and acceptance

Selection and acceptance of CR for use in asphalt rubber classically relies upon the requirements that have been set in ASTM D6114. These are expressed in terms of cleanliness (fiber content <0.5%; metal content <0.01%), moisture content (<0.75%), density (equal to 1.15 ± 0.05) and maximum particle size (2.36 mm). However, the standard also specifies that the exact size distribution of CR should be agreed upon between producer and end-user.