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Influence of recycled concrete and steel slag aggregates on warm-mix asphalt properties

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HIGHLIGHTS

- WMA blends with a chemical additive showed low resistance to permanent deformation.
- The WMA blend with 60% of RCA and organic wax was the best performant material.
- Adding 30% EAFS or 60% RCA did not notably influence mechanical performance of WMA.
- Fatigue resistance and stiffness modulus of WMA with RCA or EAFS were satisfactory.
- Incorporating EASF or RCA in WMA was not a problem vis-a-vis water sensitivity.

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ABSTRACT

This paper focuses on the comparison of the mechanical performance of three warm-mix asphalt (WMA) blends with recycled concrete aggregate (RCA) or electric arc furnace slag (EAFS) as substitutes of part of the aggregate. A conventional hot mix asphalt (HMA) and a WMA without by-products were used as references. The evaluation was carried out in a laboratory by means of testing specimens taken from experimental pavement sections built in real production, laying and compaction circumstances. Performance testing included wheel-tracking tests, four-point bending tests, and indirect tensile strength to assess water sensitivity. An organic wax and a chemical surfactant were applied to lower handling temperatures of the WMA under study. Apart from the HMA and the WMA used as references, the study evaluated the influence of introducing 60% of RCA or 30% of EAFS into the WMA blends as substitutes of the aggregate. The obtained results for the WMA with by-products tested allowed to conclude that the introduction of EAFS or RCA into the WMA blends increases Marshall stability and may increase or decrease resistance to rutting. Findings also showed that stiffness modulus is somewhat reduced and fatigue resistance does not change significantly. Additionally, water sensitivity is slightly reduced. Comparing these results with the performance observed elsewhere for WMA without by-products revealed that the addition of RCA or EAFS is satisfactory. The construction of experimental sections used conventional batch plant, paver and compactors without any noticeable technical problems.

1. Introduction

Warm-mix asphalt (WMA) are asphalt mixtures generally handled at lower temperatures than conventional asphalt concrete. Their constituents are typically mixed together at temperatures varying from 100 to 140 °C [1,2]. This also allows lower compaction temperatures and longer haulage distances and additional time to carry out construction activities [3]. The authors have summarised the production technology and properties of WMA in a previous publication [3], in which they presented a detailed description of additive based WMA and foamed bitumen techniques.

The idea underlying the project partially described in this paper is contributing to improve knowledge on more sustainable asphalt mixtures, potentially suitable to substitute hot mix asphalt (HMA) in many paving situations. The chosen way to achieve this goal was studying the reuse of recycled concrete and steel slag as substitutes of part of natural aggregates to produce WMA, which were manufactured by adding additives to the blend. The use of those

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by-products is aligned with the goals of eliminating waste going to landfill, contributing to the valorisation of by-products and, thus, increasing circular economy. In addition, decreasing handling temperatures is also recognized as an important way of reducing emissions associated with paving construction and maintenance [3].

Although WMA show suitable volumetric properties and mechanical performance, there is some weaknesses referred to in the literature that can be found elsewhere [3,4]. Hence, this introduction presents below a brief summary of the issues associated to the reuse of recycled concrete aggregates (RCA) and steel slag aggregates (SSA) in asphalt mixtures found in the literature.

Crushing concrete elements produce materials known as RCA. Unlike natural aggregates produced in quarries, RCA have cement mortar around the surface of the coarse natural aggregates. This highly porous mortar is responsible for the high values of porosity and water absorption of RCA [5,6]. Therefore, to assure enough binder to involve the aggregate particles, the use of RCA generally requires higher bitumen content in asphalt concrete (AC) because part of the binder is absorbed by the aggregate [5,6].

Because fine particles of RCA have much more voids than coarse aggregates, porosity of blends increases if fines are added to the blend [6]. In addition, RCA is formed by angular and rough textured coarse and fines particles, providing high Marshall stability and small flow values [5,6]. This trend was not observed in a number of studies, apparently because some of them used coarse RCA while others also added fine fractions [7].

In addition, replacing part of the aggregates by RCA generally degrades the resistance to moisture [5–9]. Likewise, RCA generally lead to AC with lower stiffness [5–9] mostly when coarse RCA is used, and leads to higher stiffness mainly if RCA is included as the fine fraction [7,10]. When the blends are submitted to ageing by heating them in an oven before compaction, the level of binder absorption increases, which contributes to increase stiffness [10].

The resistance to permanent deformation is usually reported to increase when RCA are incorporated into the blends [5–8,11]. Nevertheless, several studies, referred to in [7], revealed the opposite trend for several reasons: more RCA requires higher binder content; coarse and fine fractions of RCA tend to decrease resistance to permanent deformation compared to those with coarse fraction only, amongst others.

The fatigue resistance of HMA is adversely affected by the introduction of RCA, decreasing fatigue resistance as the amount of RCA increases [12]. On the contrary, several studies, reported by Pasandín & Pérez [7], reveal that RCA tend to improve resistance of HMA to fatigue.

Steel slag is a by-product of the steel industry, produced from impurities separated from molten steel, which solidifies after cooling (generally by adding water) [13,14]. There are three types of slags: basic oxygen furnace (BOF), electric arc furnace (EAF) and blast furnace (BF) [14,15]. EAF slag (EAFS) was used in the present study. This type of slag is obtained from processes of melting recycled scrap to produce different types of steel. A detailed review on the use of EAFS in asphalt mixes can be found in [15]. EAFS is formed by a several chemical components, such as iron oxides, lime, silica, magnesia and alumina and other minor components [15]. EAFS are used as aggregates in asphalt mixtures because their physical and mechanical properties are usually suitable for that purpose. In general, the amount of fine particles is low and the coarser ones have good shape, rough texture and high angularity. Although EAFS have relatively high density (3200–3800 kg/m^3), they exhibit elevated porosity and, therefore, higher water and binder absorption than typical natural aggregates. Nevertheless, expansion potential of asphalt mixes with EAFS in water is negligible [13]. Also, leaching of EAFS when used in asphalt mixes is very low [16], showing practically no health risk [15]. EAFS have generally good mechanical resistance and they reveal suitable adhesion with bitumen [15].

The asphalt mixtures that incorporate EAFS as aggregate have usually bulk densities 15 to 20% higher than similar asphalt mixes without EAFS. Because of manifest angularity of the EAFS particles, the porosity of asphalt concrete made with EAFS is also higher [15].

Generally speaking, using EAFS to substitute part of the natural aggregate tend to improve mechanical behaviour of the resulting asphalt mixes. This tendency is referred to in the literature for Marshall stability, indirect tensile strength, stiffness, fatigue and resistance to permanent deformation. This improved behaviour is general attributed, on the one hand, to a better interlock between aggregate particles as well as the roughness of steel slag assuring a better adhesion binder-aggregate [13] and, on the other hand, to a higher resistance to heavy loads and shear stress [15]. Most of the authors state that the best results were obtained for a partial substitution of natural aggregates by EAFS (around 30%). However, there is a number of cases reported in which the level of substitution was greater [15,17] and the mechanical behaviour remained improved [15].

In what concerns water sensitivity, some divergent results were found in the literature. Passeto and Baldo [18,19], for instance, mentioned in [15], consistently observed that asphalt mixtures with coarse and fine EAFS aggregates revealed higher resistance to water damage in indirect tensile strength tests. They attribute this behaviour to either a thicker bitumen film involving the aggregates in mixtures with EAFS due to a higher binder content or a good slag-binder adhesion that protect the particles against water damage. On the contrary, some studies [20] reveal that water sensitivity was higher in mixtures with coarse slag aggregates as compared to similar mixtures with limestone aggregates. The observed performance seems to be related with a worse affinity of the slag with binders than that of limestone aggregate.

The information collected in the literature shows some opportunities and challenges related with the use of RCA and EAFS to produce and lay WMA incorporating these by products in substitution of part of natural aggregates. It's necessary, on the one hand, to evaluate the expected volumetric and mechanical properties of that type of asphalt mixtures and, on the other hand, to verify the technological viability of these bituminous products in real production conditions.

This paper summarises and examines the results found in a study involving the evaluation of specimens produced in laboratory and sawed from experimental sections constructed in real construction circumstances with conventional equipment. Chemical and organic additives in the form of pellets were used to allow lowering production and compaction temperatures. The main objective of the study was to evaluate the effect of using warm-mix asphalt technologies, together with by-products aggregates (EAFS and RCA), on mechanical properties of asphalt concrete.

2. Materials

2.1. Aggregates, RCA, EAFS, bitumen and additives

Three fractions of limestone crushed rock, RCA and EAFS were used as aggregates to produce the warm-asphalt mixtures produced and evaluated throughout the study. In the early stage of the project, two blends of limestone aggregates were used to produce the reference asphalt mixtures, one HMA with 35/50 paving grade bitumen and three WMA with different additives to reduce handling temperatures. These compositions were characterized in the Marshall test and in terms of volumetric properties. The same was carried out to the six additional WMA blends in which