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Evaluation of steel slag coarse aggregate in hot mix asphalt concrete

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ABSTRACT

This paper presents the influences of the utilization of steel slag as a coarse aggregate on the properties of hot mix asphalt. Four different asphalt mixtures containing two types of asphalt cement (AC-5; AC-10) and coarse aggregate (limestone; steel slag) were used to prepare Marshall specimens and to determine optimum bitumen content. Mechanical characteristics of all mixtures were evaluated by Marshall stability, indirect tensile stiffness modulus, creep stiffness, and indirect tensile strength tests. The electrical sensitivity of the specimens were also investigated in accordance with ASTM D257-91.

It was observed that steel slag used as a coarse aggregate improved the mechanical properties of asphalt mixtures. Moreover, volume resistivity values demonstrated that the electrical conductivity of steel slag mixtures were better than that of limestone mixtures.

1. Introduction

Hot mix asphalt (HMA) concrete is a combination of aggregate and asphalt cement. The aggregate acts as the structural skeleton of the pavement and the asphalt cement as the glue of the mixture. The mineral aggregate, including coarse and fine particles in asphalt paving mixtures, encompasses approximately 90% of volume of HMA. The properties of the aggregate have direct and significant effect on the performance of asphalt pavements [1].

The HMA industry has been pressured in recent years to incorporate a wide variety of waste materials into HMA pavements. The waste materials can broadly be categorized as follows: (a) industrial wastes such as cellulose wastes [2], wood lignins, slags [3], bottom ash and fly ash [4]; (b) municipal/domestic wastes such as incinerator residue, scrap rubber [5], waste glass [6] and roofing shingles; (c) mining wastes such as coal mine refuse. The resulting large quantities of slags produced and their potential impact on the environment have prompted materials scientists and civil engineers to explore technically sound, cost-effective and environmentally acceptable use of this material in civil and highway construction.

Steel slag is a by-product of the steel-making process. Approximately 1 tonne of stainless steel slag is generated while producing 3 tonnes of stainless steel [7]. It should be noticed in the text that fifty million tons per year of steel slag is produced as a by-product in the world. Furthermore, in Europe, every year nearly 12 million tons of steel slag is produced [8].

In Turkey, the current level of production of steel slag is about 350,000 tonnes per year at Erdemir Steel Manufacturing Factory. Steel slag, due to its high strength and durability, can be used as an aggregate not only in surface layers of the pavement but also in unbound bases and subbases. Also, based on high frictional and abrasion resistance, steel slag has gained wide utilization on industrial roads, intersections, and parking areas where high wear resistance is required [9]. Asi, conducted experiments for evaluating the skid resistance of asphalt concrete mixtures involving steel slag. In the study, it is concluded that asphalt concrete mixes containing 30% slag have the highest skid number followed by Superpave, SMA, and Marshall mixtures, respectively. Asi et al. evaluated the effectiveness of steel slag aggregate by indirect tensile strength, resilient modulus, rutting resistance, fatigue life and creep modulus tests. They reported that replacing up to 75% of the limestone coarse aggregate by steel slag aggregate improved the mechanical properties of the asphalt concrete mixes [10].

The feasibility of utilization of steel slag as aggregate in stone mastic asphalt (SMA) mixtures was investigated by Wu et al. [11]. They concerned the mechanochemistry and physical changes of the steel slag and studied it by performing XRD, SEM, TG and mercury porosimeter analysis and testing method. The results gained from their studies showed that, the utilization of steel slag as aggregate provided a new and more cost effective approach for aggregate resources [11,12]. Hassan and Khabiri [13] and Norman et al. [14]

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conducted Marshall and stability tests on asphalt concrete mixtures involving steel slag. Their research demonstrated that the recycling of steel slag in asphalt concrete was feasible. A research related to utilization of steel slag in three levels of asphalt pavement as a bitumen base, binder and wearing course was made by Kara et al. [15]. Their studies exhibited that physical properties of steel slag satisfied the requirements for using in asphaltic mixture.

An asphalt mixture generally behaves as an insulator. The addition of electrically conductive additives may produce conductive asphalt mixtures [16]. Electrically conductive material such as synthetic graphite has been successfully utilized in Snowfree® (electrically conductive asphalt pavement system formulated by Superior Graphite Co.), with cooperation of the Federal Aviation Administration (FAA) and Flood Testing Laboratories. This system is based on an electrically conductive asphalt pavement that uses synthetic graphite, asphalt and electricity to heat the airport runway surface for melting snow and ice [17].

This study aims to recognize the influences of steel slag on the mechanical properties and electrical conductivity of asphalt concrete mixtures. For this purpose, Marshall stability, indirect tensile stiffness, creep stiffness, moisture damage as well as electrical sensitivity tests were performed on four different asphalt mixtures containing two types of asphalt cement (AC-5; AC-10) and two types of aggregate (steel slag; limestone).

2. Background

The utilization of industrial by-products from the steel-making industry like blast furnace slag and steel slag has been established in a number of applications in the civil engineering industry.

Production of steel, calls for the removal of excess silicon and carbon from iron by oxidation. In the production of steel, the furnace is charged with iron ore or scrap metal, fluxing agents, usually limestone and dolomite, and coke as both fuel and reducing agent. The carbon and silicon are removed as carbon dioxide and the remaining oxidized elements are combined with added lime to form steel slag. Steel slag is a hard, dense, abrasion resistant, and dark colored material. It contains significant amounts of free iron, giving the material high density and hardness. These properties make the steel slag particularly suitable aggregate used in road construction [18].

Application of slags in road construction relies on angularity and high shear resistance of their constituent particles, which make them suitable for several pavement layers. It should be mentioned that the superior frictional resistance properties of steel slag and its resistance to permanent deformation (rutting) often overshadow the potential of this material for cracking [19].

The principal problem associated with steel slag is volume expansion due to the hydration of free lime or magnesia that are common the components of slag. High levels of free lime or magnesia can adversely affect the performance of the materials made up of slag. Historically, the method of dealing with the free lime and magnesia has been to age the slag or accelerate the hydration reaction with water or washing [20].

Steel slag used in paving mixes should be limited to replace either the fine or coarse aggregate fraction, but not both, since hot mix asphalt containing 100% steel slag is susceptible to high void space and bulking problems due to the angular shape of steel slag aggregate. Mixes with high void space (100% steel slag aggregate mixes) are susceptible to over-asphalting during production and subsequent flushing due to in-service traffic compaction [21].

The washed coarse and fine steel slag aggregates containing less than 3% by mass of nonslag constituents, and that no detectable soft lime particles or lime-oxide agglomerations are recommended [22]. The relatively high porosity of steel slag and its rough texture usually requires a slightly higher amount of asphalt cement than that of conventional asphalt mixes. Besides, steel slag aggregates have been reported to retain heat considerably longer than conventional natural aggregates. The heat retention characteristics of steel slag aggregates can be advantageous for hot mix asphalt repair work during cold weather.

3. Experimental procedure

3.1. Materials

AC-10 and AC-5 asphalt cement were used in this study. The asphalt cements were procured from Turkish Petroleum Refineries Corporation (TUPRAS). Table 1 gives a summary of the results of some tests performed on the asphalt cements.

Crushed limestone aggregate was procured from quarries around Elazig. The steel slag, chosen as a second type of coarse aggregate, was directly obtained from Erdemir Steel Manufacturing Factory. The properties of the limestone and steel slag aggregate are presented in Table 2.

Surface texture of steel slag and limestone coarse aggregates were observed by means of scanning electron microscope (SEM). The SEM consists of an electron optical column which generates and focuses an electron beam over the specimen surface. The beam impinges on the specimen and produces signals which can be detected as backscattered electrons (BE or BSE), secondary electrons (SE) and X-rays. These electrons are measured by electron detectors and converted into images. The instrument used in this study is model Leo Evo 40VP operated at 10 and 20 kV voltage for slag and limestone sample, respectively and the working distance was chosen as 17–18 mm.

The captured SEM micrographs of steel slag and limestone aggregate are shown in Figs. 1 and 2, respectively.

Based on the captured images, steel slag yields different texture and morphology compared to limestone. The surface texture of steel slag is rougher than that of limestone aggregate. This is an important factor since surface texture affects the adhesion ability of the asphalt cement. Fig. 1 also demonstrates that plenty of pores can be observed clearly on the surface of steel slag which implies that steel slag is a kind of porous material compared with limestone.

The range of chemical composition of steel slag is presented in Table 3. The values given in Table 3 are based on the information gained from Erdemir Steel Manufacturing Factory. The combined gradation of aggregate is presented in Table 4.

3.2. Preparation of samples

Two different aggregate types were used for preparing Marshall specimens. Limestone aggregate (as coarse, fine and filler fraction) constitute the first type where as steel slag aggregate (substituting

Table 1
Physical properties of the asphalt cements.

Properties	Standard	Asphalt cement types	
		AC-10	AC-5
Specific gravity (g/cm^3) at 25 °C	ASTM D70	1.036	1.035
Ductility (cm) at 25 °C	ASTM D113	100	100
Penetration, (0.1 mm), 100 g, 5 s	ASTM D5	90	138
Softening point (°C)	ASTM D36	48.2	46.7
Fraass breaking point (°C)	IP 80	−27.2	−21.4
Kinematic viscosity, 135 °C (μm^2/s)	ASTM D2170	354	236
Penetration index (PI)	–	−0.15	0.87
Penetration viscosity number (PVN)	–	−0.53	0.68