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Review

Basic oxygen furnace slag for road pavements: A review of material characteristics and performance for effective utilisation in southern Africa

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HIGHLIGHTS

- BOF slag aggregates are environmentally safe by-products and have superior physical and mechanical characteristics compared with most natural stone aggregates.
- A most appropriate range of BOF slag chemical compositions has been proposed.
- Despite its poor hydraulicity, BOF slag can activate other materials and can improve strength and durability of weak soils.
- Even when used in asphalt, unconditioned BOF slag can hydrate and lead to pavement star cracking and salt inflorescence.
- Southern Africa must embrace increased use BOF slag in road construction for environmental and sustainability benefits.

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ABSTRACT

Basic oxygen furnace (BOF) slag aggregates exhibit several favourable technical and environmental characteristics compared with natural stone aggregates, making them potentially valuable road construction materials. BOF slag-bitumen mixes have shown better resilient moduli, rutting resistance, bonding and moisture damage resistance and stripping resistance than mixes with natural aggregates and they can also be high quality substitutes for natural aggregate in lower road pavement layers. Regrettably, most southern African specifications do not cater for slags resulting in limited BOF slag reuse hitherto. This may be due to observed pavement performance problems arising from some chemical constituents in this slag. Excessive free lime (f-CaO) and periclase (MgO) in slags react with water, resulting in large volume expansions which can lead to premature failure when used in roads. Aging treatment hydrates these oxides, thus ensuring allowable slag expansion. Low C_3S and C_2S contents in BOF slag make it a poor hydraulic binder. It may nonetheless, be used in soil stabilisation when activated by lime and other pozzolans. Heavy metals such as chromium, vanadium and nickel in the slag could potentially leach and pollute the environment. Assessment and monitoring of such elements are necessary for the environmental acceptance of using BOF slag in road pavements.

Contents

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1. Introduction

Roads have existed since mankind started interacting with each other, travelling for war, leisure or business. This can be traced back to around 3500 BCE. The demand for more and better roads has continued to date [1]. Recently, the International Energy Agency [2] projected that the world needs an addition of 25.3 million paved road-lane kilometres and rail road track kilometres by 2050. This is a 60% increase over the global combined road and rail network lengths estimated in 2010.

For centuries, huge quantities of non-renewable aggregate resources have, accordingly, been exploited for construction of road pavement layers namely, road surfacing, base and subbase layers. The need for continuous highway expansion, therefore, elicits more demand on these resources. Many of these resources are almost depleted or are of inadequate quality.

Efforts to conserve non-renewable resources and mitigate the related negative environmental impacts continue to be a research motivation for engineers and scientists. These efforts include investigating the potential recycling of industrial by-products and/or waste materials in road construction [3]. One example of these by-products is ferrous slag from iron and steelmaking industries.

Use of ferrous slags in road construction can be traced to the Roman Empire more than 2000 years ago, when slag rubble from the processing of crude iron was utilised in the construction of road bases. In England, roads built using ferrous slag were first constructed in 1813. In America, ferrous slag was first used as road base material around 1830 and as rail ballast since 1875 [4,5]. The use of ferrous slag as an aggregate in asphalt mixtures can be traced back to 1969 when it was used to construct a trial road section in Toronto. It was initially applied primarily as a skid-resistant aggregate in dense friction course, open friction course, and in densely graded hot-laid asphalt pavements [6–8]. In Argentina, Brazil and Venezuela, steel slag has been used as asphalt aggregate and subbase material since 1974, and as subbase material under reinforced concrete roads in Chile since the 1980s [9]. Similarly, Saudi Arabia considers the use of steel slag aggregate in asphalt, road subbase and granular base as a standard practice [10].

The properties of slag aggregates used in road construction, like those of conventional aggregates, greatly affect the performance of road pavements. Poor road aggregate materials result in costly maintenance and reduced road pavement life. Failures in flexible pavements related to poor aggregates include rutting, depressions, corrugations, frost heave, fatigue cracking and longitudinal cracking. In rigid pavements, unsuitable road aggregates can lead to pumping, cracking and corner breaks. The properties that affect pavement performance in unbound granular base and subbase pavement layers, include shear strength, toughness, abrasion, stiffness, durability, frost susceptibility and permeability [11]. These properties, including chemical and mineral soundness as well as affinity for road binders, must be evaluated. Unsound aggregate will easily break down due to the action of traffic load and weather, resulting in poor road pavement performance. Slag aggregates for use in road infrastructure therefore need to have physical, mechanical and chemical properties that can withstand long term static and dynamic forces as well as environmental stresses from weather and climate changes [12,13]. The slag's micro material characteristics such as chemical, mineralogical, morphological and textural characteristics are especially important for evaluating the slags' use and performance in asphalt mixtures [14].

Other important considerations include the slag processing operation, specification and quality control requirements [15]. All this is in harmony with the slag utilisation philosophy advocated by Wang and Emery [16] and Wang and Thompson [17] for ensuring successful performance of slags in road pavements.

Investigations into the potential application of slag materials for road building can be traced to the 1960s [18], while earlier documented studies on the use of steel slag in asphalt mixtures were reported in the early 1970s in Canada [6].

Ferrous and nonferrous metallurgical slags are becoming increasingly popular as re-usable materials to replace conventional rock materials in road building [19]. Congruently, the European Slag Association statistics have reported a considerable rise in the use of BOF and other secondary steel slags in road construction in Europe from 6.6 million tons in 2000 to 10.6 million tons in 2012. These quantities represent 39% and 43% respectively, of the total steel slag produced during this period [20].

Using slag aggregate in road construction also presents a potential considerable cost benefit. The price of slag aggregate could cost as little as half that of crushed rock aggregate. As slags are partly processed during their manufacture, there are considerable energy and manpower savings during their production compared with natural rock materials [19].

This paper reviews various publications that address the physical, mechanical, chemical and mineralogical characteristics of BOF