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Review

Performance of pavements incorporating industrial byproducts: A state-of-the-art study

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ABSTRACT

Pavements are one of the most energy-intensive infrastructure assets that depend on non-renewable natural resources. Against the background of restrictions on landfill disposal, the increased use of alternative materials such as industrial byproducts in pavement construction has gained great attention from academic and industrial sectors. However, comprehensive research covering various aspects of pavements incorporating different byproducts is lacking. The main purpose of this state-of-the-art study is to bridge this gap via the analysis of the performance of pavements incorporating two types of byproducts, blast furnace slag, and fly ash, from the perspectives of structural performance, energy saving potential, and greenhouse gas emission reduction at various phases of pavement life. Therefore, the contents of 150 published documents, including research papers, theses, and academic and industrial reports published over a span of 49 years (1968–2017) were analyzed. The major findings indicated that incorporation of the byproducts may have positive or negative consequences in various phases of pavement life. However, the new pavements are advantageous from the viewpoint of raw material processing because of low consumption of raw materials and pertinent environmental footprints. In addition, several scenarios are proposed for ranking the alternative materials on the basis of the technical and environmental requirements for a paving project; these scenarios can be useful for the preliminary selection of alternative materials. Finally, some gaps are highlighted for future research.

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1. Introduction

The construction of infrastructure assets significantly depends on non-renewable natural resources such as aggregates and carbon-based energy carriers. The demand for construction materials is increasing owing to rapid development in many countries. For example, in China, 700 mountains were flattened to build a city and provide aggregate materials for construction in the outskirts of Lanzhou, the capital of Gansu province located in the northwest of the country (Uddin et al., 2013). Another example, is the need to construct an additional 40 billion square meter of buildings to address the residential and commercial requirements in China over the next 20 years; this requirement is equivalent to constructing one New York City every two years (Torgal and Jalali, 2011; Pacheco-Torgal and Labrincha, 2013). The production of various types of construction and building materials is a very energy-intensive process. For example, asphalt binder and cement production industries are ranked as the second and seventh energy-intensive manufacturing industries in the United States (Zapata and Gambatese, 2005). It is estimated that the global energy consumption for asphalt pavement construction accounts for 136 million MWh per year (Chong et al., 2016). Furthermore, statistics released by the European Cement Industry Association indicated that global cement production increased by 73% from 2005 to 2013 (CEMBUERAU, 2014). The global demand for cement was approximately 2300 Mt in 2005 (Oh et al., 2014; Lasserre, 2007). The cement industries are responsible for approximately 7% of the global anthropogenic CO_2 emission, producing approximately 1.8 Gt CO_2 annually (Bosoaga et al., 2009). The most energy-intensive stage of cement manufacturing is clinker production. The production of one ton of clinker is estimated to emit approximately 0.9 tons of CO_2 (Benhelal et al., 2012; Teklay et al., 2016). It is estimated that calcination and combustion of fuels account for 50% of the total CO_2 emission, while 40% and 10% of the emission originate from cement manufacturing and raw material processing, respectively (Mikulčić et al., 2016). In addition, energy consumption for cement and steel manufacturing industries ranges 720 to 16,704 MJ per ton and 887 to 5530 MJ per ton, respectively (Cazacliu and Ventura, 2010; Jamshidi et al., 2016). However, the adoption of sustainable practices resulted in progress in cement and steel production. For example, from 2010 to 2030 in India, the estimated cumulative CO_2 emission reduction attributed to use of energy efficient technologies are 97 Mt and 67 Mt for the cement and steel manufacturing industries, respectively (Morrow et al., 2014). Further, in Japan, the CO_2 reduction attributed to use of recycled cement and natural fuel gas ranges from 0.06 million tons to 0.72 million tons (Oh et al., 2014).

In construction and building industries, inexpensive oil and raw material resources are traditionally used. Abundance of high-quality natural resources, such as aggregate materials, unlimited disposal sites, and inexpensive crude oil in the last decades have contributed to global warming. Therefore, these industries have caused massive depletion of the natural resources of the world. For example, although it is difficult to predict the exact time when crude oil resources will be exhausted, some researchers predicted that the peak oil production occurred in the year 2010 (Armstrong and Blundell, 2007). Therefore, the prices of various types of construction and building materials increased in the aftermath of depletion of natural resource in different countries. For example, the price of asphalt concrete increased from US $68 per ton in 2004 to US $104 per ton in 2007, resulting in an increase in the expenses involved in pavement construction (Hassan, 2009). In addition, the price of cement in Australia increased from AU $122 per ton in 2008 to AU $153 per ton in 2011, an increase of 17.35% over a three-year span (Crossin, 2015). In addition to the depletion of the natural resources, sustainable design and construction is gaining importance in the development, maintenance, and rehabilitation of infrastructure assets via various environmental rating systems such as life cycle assessment (LCA) and Leadership in Energy & Environmental Design (LEED). Such rating systems act as tools for the sustainable development that implies a reasonable equilibrium between the structural, environmental, health, and socioeconomic objectives for protecting the world for future generations without sacrificing quality of life (Duić et al., 2015; Gonzaleza et al., 2015). Note that the production of construction and building materials results in the generation a variety of waste and byproducts, which are severe pollutants. Thus, public concern regarding industrial byproducts stockpiled in landfills is constantly increasing. To tackle this problem, the use of such byproducts as alternative materials to produce new construction and building industries is recommended. Pavements are infrastructure assets that require a large amount of construction and building materials. Agencies dealing with pavement technology are also extremely willing to use various waste products as alternative sources to offset the increasing expenses of non-renewable natural resources, such as aggregate materials and energy, in pavement construction. Note that aggregate production is responsible for 50% of the total greenhouse gas (GHG) emission in the construction of both asphalt and concrete pavements (Inyim et al., 2016). Therefore, pavement construction provides an opportunity to use a huge volume of waste materials, leading to a decrease in the environmental footprints of transportation infrastructure. Many waste materials and sustainable technology are employed in pavement construction: These include (1) slag (Behiry, 2013; Chen et al., 2015); (2) crumb rubber (Richardson et al., 2016; Ibrahim et al., 2015); (3) fly ash (Naik et al., 1995; Lav and Lav, 2000); (4) glass (Jamshidi et al., 2016), (5) waste cooking oil (Asli et al., 2012); (6)warm mix asphalt (Rubio et al., 2012; Jamshidi et al., 2015a); (7) reclaimed asphalt shingle (Tapsoba et al., 2014; McGraw et al., 2007); (8) reclaimed asphalt pavement (RAP) (Jamshidi et al., 2012); (9) waste polyethylene (Kishchynskyi et al., 2016); (12) building rubble (Mohammadinia et al., 2017); and (11) recycled concrete aggregate (Taha et al., 2002). Each type of waste material and sustainable technology has some advantages and disadvantages; for example, for every 25% of recycled concrete added to concrete, the water demand increases by approximately 4 kg/m^3 (Dumitru et al., 2000). Also, incorporation of crum rubber in the asphalt mixes improved rheologiocal properties of asphalt binders, resilient modulus and fatigue property of the asphalt mixes (Ibrahim et al., 2015). Use of the glass in the concrete pavement increases strength of samples (Jamshidi et al., 2016). Furthermore, WMA technology decreases fuel requirement, hence greenhouses gases, in the mixng plants, without sacrificing the mix quality (Jamshidi et al., 2015a). However, the use of the waste materials and byproducts in the production of construction and building materials has yielded promising results. For example, the use of 20% industrial byproduct materials in the UK cement manufacturing industries has resulted in a reduction of 3 million tons of waste materials in landfills (Snelson et al., 2009; Glasser, 1996). There exist many types of waste materials. It is necessary to choose the most appropriate type as the alternative material in a paving project. Hence, a set of selection criteria should be adopted when choosing the waste material.

1.1. Selection criteria for choosing alternative materials

The selection criteria depend on many factors such as the type of infrastructure asset, service life condition, application, and