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Replication studies paper

Application of reclaimed basic oxygen furnace slag asphalt pavement in road base aggregate

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HIGHLIGHTS

- Reuse reclaimed asphalt pavement (RAP) contained basic oxygen furnace (BOF).
- It is feasible to apply the RAP BOF slag to base or subbase layer of pavement.
- The optimum amount of RAP BOF slag is suggested in this study.
- Help solve the environmental problems produced by the RAP BOF slag.

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ABSTRACT

In this study, natural aggregates were replaced with reclaimed asphalt pavement (RAP) from a basic oxygen furnace (BOF) and applied to the base or subbase of roads. The effects of using different levels of RAP BOF to replace the natural aggregates on the properties of the road were investigated. Mixtures of natural aggregates with different contents of RAP BOF (containing 60% BOF slag) aggregates were used, and the results indicate that using a RAP BOF aggregate content up to 40% in the road base satisfies the requirements for the California bearing ratio (CBR) and expansion ratios. The study suggests that the optimal RAP BOF aggregate replacement content is 20%.

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1. Introduction

The natural resources on Earth are extremely limited and are gradually becoming scarce. Hence, resource recycling technology is becoming increasingly used in applications in various engineering fields. Half of the island of Taiwan is occupied by mountains, and Taiwan has limited geographic resources that can be used in different areas. Moreover, to improve the quality of life of Taiwan's inhabitants by developing the economy, the steel manufacturing industry has been steadily growing and providing basic materials for civilian and public construction in Taiwan. Consequently, the steel industry generates many byproducts such as basic oxygen furnace (BOF) slag, of which more than one hundred thousand tons per year are produced. As stated above, Taiwan is an island that lacks sufficient land to properly dispose of the BOF slags. Such waste could also cause serious environmental impacts on the island. Hence, the central and local governments are working together to find appropriate recycling applications for BOF slag in the fields of pavement engineering, marine engineering, and geotechnical engineering. Although BOF slags have been applied to various types of asphalt concrete (AC), studies regarding the application of BOF slag in AC are still limited. Moreover, to reduce the impact of BOF slag on the environment, applying BOF slag within the base or subbase of road pavement may provide part of the solution. This study was proposed and developed considering the background stated above. We hope that a win-win situation can be created by utilizing recycled materials, such as BOF slags, for engineering applications while protecting the environment of Taiwan. BOF slag has successfully been applied in pavement engineering, and surprisingly good performance has been obtained using AC pavement mixtures. Yuan [1] used BOF steel slag to design a porous asphalt mix and found that the amount of asphalt binder was not affected by the increasing degree of BOF slag replacement and that the properties of the porous asphalt containing BOF slag met the requirements of the existing

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standards. Moreover, the increased amount of BOF slag in the porous asphalt improved the rutting and surface friction resistances and lowered the noise and number of voids. Huang [2] used BOF slag to replace 100% of the natural coarse aggregates in hot mix AC. He found that the BOF slag replacement did not reduce the number of voids in the mineral aggregate (VMA). The durability of the hot mix asphalt was not affected by the reduction in the amount of VMA. Moreover, the rolling compaction energy required by the AC with BOF slag replacement was less than that required by conventional AC. Chen et al. [3] also studied the volumetric properties and performance of AC after replacing 100% of its coarse natural aggregates with BOF slag. Based on the results obtained from the mixture design, the film thicknesses of the asphalt binder ranged from 6 to 9 μm, and the durability of the AC was not affected by this insufficient film thickness. The authors suggested, according to the results of the mixture design and the performance tests, that it is feasible to replace 100% of the coarse natural aggregates in AC with BOF slag for pavement engineering applications. Chen et al. [4] studied the possible applications of using BOF slag containing honeycomb particles (CHS) in asphalt mixtures. The test results showed that when honeycomb slag replaced the coarse aggregates in asphalt mixtures, the asphalt content increased, and the rutting, crack and moisture resistance decreased. Amir et al. [5] studied the long-term fatigue behavior of asphalt mixes containing BOF and electric arc furnace (EAF) steel slag and found that the specimens with both BOF and EAF slag included exhibited improved fatigue life. Furthermore, the mitigation of aging in the asphalt mixes was improved with the inclusion of EAF slag, providing better adhesion in the asphalt mixes. Haritonovs et al. [6] replaced conventional coarse and fine aggregates with BOF slag and local dolomite sand waste during the manufacture of high-performance AC and found that the AC specimens containing BOF slag and dolomite sand waste exhibited greater resistance to plastic deformation and fatigue failure. Lin et al. [7] compared test roads constructed with natural aggregate AC with test roads constructed with BOF slag AC. After two years of consecutive in situ test performances, they found that the quality of service of the BOF slag AC pavement was better than that of the conventional AC pavement. Moreover, the rutting resistance of the pavement to heavy-load vehicles and the parameters acquired from the Marshall mix design, such as the tensile strength ratio and resilient modulus, for the BOF slag AC were better than those for the conventional AC. However, the authors also recommended that the limit values for the parameters in the Marshall mix design that apply to BOF slag AC undergo further review.

The hydration expansion of BOF slag limits its engineering applications. Deniz et al. [8] studied the expansion properties of RAP materials, including recycled steel slag aggregates and virgin aggregates, and evaluated their potential use as pavement base materials in Illinois. According the results of this study, compared to virgin steel slag, the RAP materials had a lower tendency to expand due to the effective asphalt film coating on the aggregate surface. Kambole et al. [9] indicated that most southern African specifications do not allow BOF slag to be incorporated within pavement due to the observed pavement performance problems influenced by a few of the chemical components in BOF slag. When using BOF slag in road pavement, it is necessary to assess and monitor the large volume expansions that can occur and the heavy metals that are present. Dayioglu et al. [10] evaluated steel slag that was coated with asphalt cement, and the slag was mixed with water treatment residuals at various weight percentages; this process is a popular treatment for using steel slags in highway base and subbase layers. Lee [11] studied methods to suppress the expansion of BOF slag and found that the compaction energy of the BOF slag and the California bearing ratio (CBR) values had a logarithmic relationship. Under this relationship and based on the construction specifications, the compaction energy could be adjusted to 14.66 kg-cm/cm^3 to satisfy the requirements set for the pavement. Moreover, he suggested that by adding 10% of ground granulated blast furnace slag (GGBFS), the BOF slag could help compact the structure and reduce the permeability of the slag to effectively suppress swelling after the slag and GGBFS underwent hydration and pozzolanic reactions. Chen [12] proposed five test methods to suppress BOF slag swelling: the water content change method, hollow improved method, sodium sulfate method, cut-back asphalt method, and mudstone mixed method. Among the different methods, the cut-back asphalt method induced volatilization after seven days and the mudstone mixed method mixed with 40% mudstone produced the best results in terms of mitigating the swelling behavior of the BOF slag. To study the influence of hydration and the addition of silicone resin on the behavior of asphalt mixtures containing BOF slag, Chen et al. [13] studied three types of slags: newly crushed BOF slag (NCS), fully hydrated BOF slag (FHS), and combined BOF slag modified with hydration and silicone resin (HSS). They found that FHS retained pores with sizes between 20 and 30 μm and HSS would lower the asphalt content to an acceptable level in the asphalt mixture. Moreover, the HSS improved the volume stability of the NCS. The test results showed that HMA with HSS had a higher thermal conductivity and thermal diffusivity and a smaller specific heat than HMA with NCS.

Andrés-Valeri et al. [14] applied BOF slag in subbase aggregates to construct parking bays in northern Spain to study the water quality and appropriateness of using BOF slag in pervious pavement. The authors proved the suitability of using BOF slags as a subbase material in pervious pavement and as a storage medium for penetrated storm water. Moreover, they suggested that water stored in pervious pavement containing BOF slag aggregates as a subbase layer can be applied for industrial, recreational, and environmental purposes. Blanco et al. [15] used BOF steel slag aggregates as a substrate for the construction of wetlands and investigated the removal mechanism and amount of phosphate in the BOF steel slag. The test results showed that the use of BOF steel slag yielded phosphate removal efficiencies of 84–99% and phosphate removal capacities of 0.12–8.78 mg P/g slag.

It is common to apply the reclaimed asphalt pavement (RAP) obtained from conventional AC to base or subbase courses. Taha et al. [16] mixed Type I Portland cement with RAP for the treatment of the soft base or subbase courses. The test results showed that the strengths of the specimens increased with the increase in the amount of natural aggregates, the amount of cement and the curing time. However, they suggested that 100% RAP itself should not be applied to the base or subbase courses, unless cement was added as a stabilization treatment. Guthrie et al. [17] used mixes of cement and RAP as a stabilization treatment for base courses. The test results showed that the unconfined compressive strength decreased from 425 to 208 psi and the final dielectric value decreased from 14.9 to 6.1 as the RAP aggregate replacement increased from 0 to 100%. Liao [18] applied RAP aggregates as a road base material to investigate the relationship between the amount of RAP and the CBR. The authors found that when it rained, the base course easily became saturated when a large amount of RAP was used, increasing the possibility of damage to the road base. He suggested that the amount of RAP replacement used in the road base should not exceed 40%. Jian [19] studied road bases containing RAP aggregates stabilized by cement. The test results showed that the CBR value decreased with an increase in the amount of RAP. However, the CBR values were improved by adding different amounts of cement in the road bases. He suggested that the effect of adding RAP was improved by adding various contents of cement to the base. Ayan [20] studied the feasibility of using recycled concrete aggregate (RCA) together with RAP in unbound

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