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Mechanical properties of roller compacted concrete pavement containing coal waste and limestone powder as partial replacements of cement

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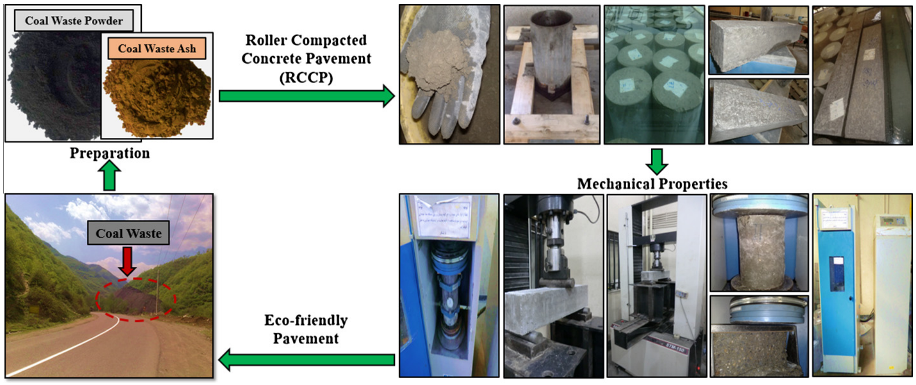
HIGHLIGHTS

- 5–20% of cement was substituted with coal waste (CWP) and its ash (CWA).
- Mixes containing up to 5% CWP behaved similar to control mix.
- The combination of 7% limestone and CWA enhanced the mix properties.
- Relationships obtained as $f_t = 0.5\sqrt{f'_c}$, $f_r = 0.9\sqrt{f'_c}$ and $E = 5600\sqrt{f'_c}$, respectively.

GRAPHICAL ABSTRACT



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ABSTRACT

This study investigates the effects of coal waste powder (CWP), coal waste ash (CWA), and limestone powder (LS) on the mechanical properties of roller compacted concrete pavement (RCCP). The mixtures were produced by partial replacement of cement with the supplementary cementitious materials at different incorporation levels of 5, 10 and 20%. The compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity of RCCP mixtures were determined from 7 days up to 90 days. The results showed that the use of CWP and CWA increased the water/cementitious materials ratios. It is noteworthy that the RCCP mixtures containing 5% CWP or CWA showed equivalent performance to the control RCCP mixture. However, any further increase up to 20% substitution of cement with the supplementary cementitious materials decreased the strength values and elastic modulus of the mixtures at all ages. The combination of LS and CWA led to higher mechanical properties, especially at ages of 28 and 90 days. The relationships between the splitting tensile strength (f_t), flexural strength (f_r), modulus of elasticity (E) and compressive strength were obtained as $f_t = 0.5\sqrt{f'_c}$, $f_r = 0.9\sqrt{f'_c}$ and $E = 5600\sqrt{f'_c}$, respectively.

1. Introduction

The cement production is an extensive energy-consuming process and is estimated to be responsible for about 7% of total global

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carbon dioxide (CO_2) emissions each year [1–3]. As a sustainable solution, supplementary cementitious materials can be used as partial replacement of cement. Supplementary cementitious materials such as fly ash, granulated blast furnace slag, and silica fume as waste materials and limestone powder are commonly blended with clinker or are used as partial replacement of cement. Replacing cement with cementitious materials not only reduce the environmental impacts of the cement industry but also could effectively reduce the high cost of clinker production process. Furthermore, these cementitious materials can be easily blended with clinker because of their lower stiffness. The use of these materials can result in eco-friendly mixes with higher durability and improved long-term mechanical properties [1,4]. Supplementary cementitious materials can be used in various types of concrete mixtures, especially in roller compacted concrete pavement (RCCP).

RCCP is a zero-slump concrete with a dry skeleton that composed of similar basic ingredients, but much less water and cementitious binders compared to conventional Portland cement concrete [5,6]. In recent years, numerical optimization methods such as solid suspension model and compressible packing model have been utilized to optimize mix proportions and their ultimate strength. Depending on these theoretical models, RCCP mixtures with 20–28% lower cementitious material acquire the same compressive strength in comparison with conventional concrete [6–8]. Economic analyses have demonstrated that the total price of RCCP is lower than the hot mix asphalt pavement and Portland cement concrete pavement as conventional pavements. The RCCP has high strength and durability compared to conventional concrete pavement, and can be used for parking lots, ports, military zones, highway shoulders, and industrial pavements [6,9,10].

Huge amounts of waste materials are stockpiled as by-products around the world. Using these by-products as partial replacement of RCCP ingredients (i.e., aggregates + binders) is an economical and environmental solution to preserve natural resources. Based on the literature [1,5,8,9,11–18], several researchers have investigated the replacement of cement by natural and industrial by-products, especially in RCCP mixtures. These supplementary cementitious materials include rice husk ash, fly ash, circulating fluidized bed combustion ash, silica fume, bottom ash, volcanic ash and other human-made wastes. For instance, Atiş et al. [19], evaluated compressive, flexural and splitting tensile strengths of RCCP mixtures containing fly ash. They used replacement levels between 15% and 45% for fly ash. Based on their report, incorporating 15% fly ash led to higher strength at 3 days and similar strength at 28 days compared to the control mixture.

The coal production industry causes destructive environmental impacts, including water and air pollution. Thus, coal waste has been used in the manufacture of building materials as bricks or as replacement of cement in soil stabilization, but there is a lack of information regarding the use of coal waste as cement replacement material, especially in RCCP mixtures.

Based on the previous reports, using the coal waste in soil stabilization improved mechanical properties over time [20]. Furthermore, this by-product was investigated in concrete blocks for paving applications as partial replacement of sand. After 28 days of curing, specimens containing 25 and 50% coal waste had a similar compressive strength compared to the control mixture [21].

Frías et al., heated coal waste for 2 h at 650 °C to achieve the least values of loss on ignition (LOI). Then, they used the incinerated coal waste at cement replacement levels of 10% and 20% in mortar mixtures. The investigation indicates that the mixture with 10% coal waste ash had higher compressive strengths at 7 days compared to the control mixture; however, at later ages (28 and 90 days), lower strengths were obtained [22].

The current study investigates the possibility of utilizing coal waste as partial replacement of cement in RCCP mixture. The coal waste was obtained from the Alborz coal washing plant located in the north of Iran. The Alborz coal washing plant is a part of the oldest coal mines in Iran. The probable reservoir is estimated as 577 million tons. At present, more than 2 million tons of coal wastes are available in coal dumps located around the coal washing plant [23], and the volume of coal waste is still growing.

Acid mine drainage (AMD) pollution has been known as the most hazardous water pollution around coal mines. AMD contains iron sulfates and other elements and could contaminate the groundwater resources. In essence, the crux of environmental pollutions around coal factories is initiated from the oxidation of pyrite. As a hazardous result, the pyrite oxidation that yields acidic water is due to the exposure of pyretic and iron-bearing minerals to air and water, and it has an adverse effect on surface water, groundwater, and soil. Pyrite oxidation and AMD generation have been observed in the analyses of coal waste samples and the surrounded water [24]. The impact of coal waste on the nature is significant since it creates erosion, land occupation, leakage of pollutants into groundwater, dust spread, air pollution and visual impact on land.

The aim of the present work is the feasibility of replacing cement with coal waste powder (CWP), coal waste ash (CWA), and limestone (LS) powder as supplementary cementitious materials in RCCP. The experimental study focused on the mechanical properties at 7, 28 and 90 days including compressive strength, splitting tensile strength, flexural strength, and static modulus of elasticity. Finally, relationships between the investigated mechanical characteristics were determined corresponding to the laboratory investigation.

2. Experimental program

The summarized experimental program is represented in Fig. 1. The details of the experimental programs are included in the following sections.

2.1. Material properties

2.1.1. Aggregates

The coarse and fine aggregates were in the range of ASTM C33 standard limits, which are shown in Fig. 2. Furthermore, the aggregates had properties corresponding to the ASTM: C33. The gradation of combined aggregates were chosen according to the grading limits of the Portland cement association (PCA) [25], which is presented in Table 1. The nominal maximum size of aggregates was limited to 19 mm to prevent segregation. The aggregates properties are given in Table 2. The fine aggregates were finer than 4.75 mm (sieve No. 4). The sand had fineness modulus, sand equivalent (SE) and saturated surface dry (SSD) water absorption of 2.87, 80% and 1.9%, respectively.

2.1.2. Cement and supplementary cementitious materials

Type II Portland cement was used conforming to ASTM C 150 standard method. Table 3 shows the chemical composition and physical characteristics of type II Portland cement. The particle size distributions of cement and the supplementary cementitious materials are depicted in Fig. 3. The particle size distribution of CWP was similar to cement; however, CWA and LS had finer and coarser size distributions compared to cement, respectively.

2.1.2.1. Coal waste powder. Fig. 4 shows the images of CWP and CWA after the preparation process. As it can be observed in Fig. 4A, the CWP had black color that has been altered to a brown form after ignition process (Fig. 4B). The chemical compositions of CWP, CWA, and LS, which were determined by the X-ray fluorescence spectrometry (XRF) method in accordance with ASTM: E1621 are presented in Table 4. Loss on Ignition of CWP was 40.96% which is higher than the limits specified in ASTM C618. The particle size distribution of CWP has been depicted in Fig. 3. It seems that the particle size of CWP was 100% finer than 75 μm.

2.1.2.2. Coal waste ash. The chemical properties of CWA are given in Table 4. Similar to CWP, CWA was passed through sieve No. 200 (75 μm). According to ASTM: C618, the chemical composition of CWA has been found to be highly comparable to class N or F fly ash [8,24]. According to previous investigation performed on coal waste [22], CWA was obtained by igniting the coal waste at various temperatures. LOI is