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Effect of cement kiln dust on the low-temperature durability and fatigue life of hot mix asphalt

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ABSTRACT

Cement Kiln Dust (CKD) is a waste material that is considerably produced in a high volume during the cement production process. In this study, the effect of CKD as filler material on low-temperature characteristics of hot mix asphalt (HMA) has been investigated. Laboratory program composed of evaluating the HMA durability against the freeze–thaw cycles using indirect tensile strength test and analyzing the fatigue behavior at four temperatures of 20, 0, −10 and −20 °C using a four-point flexural fatigue test. Furthermore, regarding the existence of heavy metals in CKD compounds, environmental evaluation has been carried out by applying toxicity characteristic leaching procedure (TCLP) test. According to obtained results, mixes containing CKD filler demonstrated better resistance against freeze–thaw cycles compared to the control mixture containing limestone (LS). Moreover, mixes containing CKD exhibited higher fatigue life compared to the control mix and for all mixes the fatigue life decreased by decreasing the temperature. However, at lower strain levels of 150 microstrain, the fatigue life of studied mixes were to high extent similar and even higher fatigue life was obtained by reducing the testing temperatures. In addition, the findings of TCLP test showed that the amount of heavy metals in leachate from HMA containing CKD was low and satisfied the required criteria.

1. Introduction

With the significant growth of industries, diverse problems have more and more appeared, including rapid deterioration of natural resources and severe environmental contaminations. Daily accumulation of waste materials is one of the causes of these problems. The cement industry is considered as one of the biggest waste producer industries. Producing one ton of cement requires about 1.5 to 1.7 tons of raw materials, 0.1 ton of coal and one ton of clinker. The most important pollutants in the process of cement production come from the row materials and fuel preparation, clinker heating and cement milling (Neville, 1993). According to the latest available information, in 2013 the global production volume of cement was more than 4 billion tons (European Cement Association, 2014). Cement kiln dust (CKD) is generated in large quantities during the cement production process as a by-product dust and is released from the plant outlet into the environment. Normally, CKD production volume is equal to 15% to 20% of the produced cement (Konsta-Gdoutos and Shah, 2003; Peethamparan et al., 2008). Although a part of CKD returns to the cement production process by using CKD collector, but due to different reasons, including production process suspension, the cooling of these materials and poor quality, a portion of CKD is deposited as waste materials. Due to the CKD fine size, the area of release of these pollutant materials sometimes reaches to 10 km from the plant. The presence of this fine dust in the air can cause the emergence of respiratory problems and diseases for inhabitants who live near the plant (Konsta-Gdoutos and Shah, 2003). The history of using CKD in different applications goes back to more than 30 years. The most common useful applications of CKD are in concrete mixes as cement substitution, soil stabilization, waste treatment and filler material in asphalt mixes. As a stabilizing agent for wastes, the absorptive capacity and alkaline properties of CKD can reduce the moisture content, increasing the bearing capacity and therefore forming an alkaline environment for waste substances (Chaunsali and Peethamparan, 2013; Kunal et al., 2012). Even though significant variation in physical and chemical composition of CKDs obtained from different cement plants has been observed, but as a general rule, the existing cementitious compounds in CKD are about one-third of cementitious compounds in ordinary Portland cement (Sreekrishnavilasam et al., 2007). Miller and Azad (2000) have investigated the effect of the soil types on the effectiveness of CKD as a stabilizer. The obtained results using CKD caused an increase in unconfined compressive strength, and this improvement was more significant for soils with low plasticity index. Additionally, CKD has reduced the plasticity

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Table 1
The aggregate gradation used to prepare the HMAs.

	Sieve size (mm)	19.00	12.50	4.75	2.36	0.30	0.075
Passing (%)	Standard limits	100	90-100	44-74	28-58	5-21	2-10
	Used aggregate	100	94	62	39	14	5

index of moderate to highly plastic soils. Moreover, Parsons et al. (2004) have recommended that CKD can be considered a viable option for the subgrade soils stabilization. There have been more or less similar studies on using CKD for soil stabilization and the results often approved that CKD was an additive with a moderate effect on soil stabilization and modification compared to other common additives such as cement and lime. Sreekrishnavilasam et al. used CKD as modifying additive for three types of low plasticity clays. They found that using 15% CKD caused a decrease in soil swelling potential rate to 15%, increase of optimum moisture content and a decrease in maximum dry unit weight (Sreekrishnavilasam et al., 2007).

Using CKD as cement replacement in concrete mixes is another application of this material. The results obtained from a related study indicated that substituting 5% cement by CKD had no adverse effects on the compressive strength of the concrete mix (Siddique, 2006). In another research, CKD was replaced at 10% to 40% by weight of cement and the compressive strength values have been evaluated after 1, 2, 3 and 6 months. Results should that for all curing times the mix strength reduced by increasing the CKD content. Furthermore, for the mix containing 40% CKD by an average, 44% strength reduction has been observed in all curing times. However, the reduction rate of the mixture strength containing 10% CKD after 1, 3, 6 months was equal to 15%, 3.5% and 1.6%, respectively (Shoaib et al., 2000). In general, based on the results of different surveys, mortars and concrete mixes containing 5–10% CKD can achieve almost similar compressive strength, flexural and tensile strength, toughness and durability to the control mix (Kunal et al., 2012).

The experience of using CKD in asphalt mixtures goes back to the initial 1980 decade. CKD added to bitumen produces low ductile mastic asphalt and provides stripping resistance for asphalt mix. (Bolden et al., 2013). Ahmed et al. (2006) studied the effect of CKD as filler material on the mechanical properties of hot mix asphalt (HMA). The results indicated that CKD can completely replace limestone powder in HMA. It was found that using CKD as filler material increased the Marshall stability, specific gravity, indirect tensile strength and unconfined compressive strength of HMA. Taha et al. (2002) reported that the replacement of 50% lime with CKD led to the same optimum asphalt content as the control mix without any negative effect on HMA properties such as Marshall stability, flow, voids in the total mix, voids in the mineral aggregate and voids filled with bitumen.

Another study conducted to assess the effects of using CKD as a stabilizer additive in cold recycled asphalt mixture. The results showed that using CKD caused a significant increase in resilient modulus of the recycled asphalt mixture. Although the adverse effects of freeze–thaw cycles on the stiffness of the mixture was relatively high. In some of the samples after 12 freeze–thaw cycles, more than 50% reduction in stiffness has been reported. Accordingly, CKD has been successfully incorporated for stabilization of recycled asphalt mixture to produce a base or subbase layer in low volume roads (Zaman et al., 1999).

Table 2
Basic properties of 60/70 penetration grade bitumen.

Property	Test standard	Value
Density at 25 °C	ASTM D70	1.022
Penetration at 25 °C (0.1 mm)	ASTM D5	69
Softening point (°C)	ASTM D2398	49.2
Ductility at 25 °C (cm)	ASTM D113	More than 100
Solubility in trichloroethylene (%)	ASTM D2042	99.2
Flash point (°C)	ASTM D92	308
Viscosity at 135 °C (0.01 st)	ASTM D2170	288

Table 3
Chemical compounds of studied fillers compared to ordinary cement.

Compound	CKD	LS	Cement
Fe_2O_3 (%)	2.63	0.05	3.30
Al_2O_3 (%)	3.40	0.46	5.86
SiO_2 (%)	12.02	17.97	21.90
CaO (%)	43.67	46.90	63.32
MgO (%)	0.91	3.64	1.15
K_2O (%)	0.69	0.10	0.56
Na_2O (%)	0.16	0.08	0.36
LOI (%)	35.69	29.95	2.40
Other (%)	0.83	0.85	1.15

The above-mentioned surveys reflect the uncertainty of the obtained results with respect to the durability of HMA containing CKD in freeze–thaw conditions.

In recent years, several studies have been carried out regarding the HMA behavior at below zero temperatures (Ozgan, 2010; Ozgan and Bektas, 2011). During a laboratory study, surface and binder course HMAs were exposed to freeze and thaw cycles for 6, 12, 18 and 24 days. It was realized that the HMA stability reduced upon increasing the freeze and thaw duration. However, there was a reverse relationship between the HMA void content and its durability (Ozgan and Serin, 2013). Later Ozgan et al. investigated the effect of de-icer chemicals on the engineering properties of asphalt concrete. Forty-two HMAs were prepared containing different quantities of sodium chloride (NaCl) and calcium chloride ($CaCl_2$). After conditioning the specimens, Marshall stability test was carried out for all HMAs. Finally, it was concluded that at a constant quantity the calcium chloride had less detrimental effects than the sodium chloride. Furthermore, the maximum stability loss related to the specimen conditioned in pure water environment with 15.47% Marshall stability loss (Ozgan et al., 2013).

Feng et al. studied the complex influence of freeze–thaw cycles and salt on strength, volume and weight of three types of asphalt mixtures. Test results indicated that the damage of asphalt mixtures is initiated by ice expansion load and accelerated by the interfacial damage between asphalt and aggregate or fracture of asphalt mortar. Freeze–thaw cycles, salinity, air void, asphalt property and 4.75 mm percent passing were recognized as the main factors influencing on freeze–thaw strength (Feng et al., 2010).

For asphalt mixes, the critical failures at high temperatures are deformation related failures such as rutting or permanent deformation and slippage. In contrast, at intermediate and low temperatures, fatigue cracks are more expected to occur. Most of fatigue testing standards specify to analyze the fatigue response of asphalt mixes at intermediate temperatures such as 20 °C (EN, 12697-24, 2004). However, there is no consensus about the dominant phenomenon at lower temperatures especially below zero temperatures. At these temperature ranges, the material will be too much stiff. Based on previous experiments at lower strain levels, stiffer material exhibits predominant fatigue behavior. However, there are some contradictory results that indicate the detrimental effects of temperature reduction on fatigue response of asphalt mixes especially at higher strain levels (Booil, 2003; Modarres, 2013; Walubita, 2006).

Most of conducted studies regarding to fatigue behavior of HMA have been performed at medium temperatures. So far, no research has been carried out regarding fatigue behavior of HMAs containing CKD

Table 4
The gradation of fillers.

	Size (mm)	0.075	0.050	0.040	0.030	0.020	0.010	0.005
Passing (%)	CKD	100	72	58	48	35	18	11
	LS	100	61	49	38	27	14	10