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Experimental investigation on using Cement Kiln Dust (CKD) as a cement replacement material in producing modified cement mortar

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HIGHLIGHTS

- Cement Kiln Dust incorporation led to decrease both strength and flow.
- Cement Kiln Dust can be used as a cement replacement material.
- Fractal dimension can be used to evaluate the CKD mortars.
- Image analysis technique can be utilized in mortar quality assessment.

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ABSTRACT

Concrete is regarded as the second consumed construction material and hence massive quantities of cement needs to be annually produced. This production leads to pollute the environment by releasing significant quantities of CO_2 emission in addition to produce solid waste material known Cement Kiln Dust CKD. The aim of this investigation is to explore the possibility of using this material as a cement replacement in concrete mortar production, which occupies about half of the concrete volume. Chemical analysis and some physical properties of three different CKD replacements (10%, 20%, and 30% wt. of cement) in addition to reference mortar were investigated. The results showed that there is a systematic increase in mortar porosity with CKD replacement and this increase was in parallel decrease in mortar strength. Image processing was utilized to study the mortars in terms of 2-D porosity and cement paste color values. It was found that the calculated porosity using imageJ software also increased with CKD replacement and the pore-size distribution can be counted as fractal object, where the fractal dimension of these pores was calculated. Additionally, a good correlation between gray color value and compressive strength was also concluded.

1. Introduction

Concrete is counted as one of the mostly consumed construction materials where it is estimated by 31 Gt/year in 2006 [1] and cement consumption was estimated by 4 Gt/year [2,3]. This figure is constantly increasing due to the increase in world population and to the continuous development in the infrastructures. Cement production negatively affects the environment not only by consuming the virgin materials but also by releasing CO_2. It is argued that in order to produce 1 ton of cement, 1.8 tons of raw materials are needed and around 0.8 ton of CO_2 is released, which is understandable if the reaction that shown in Eq. (1) is considered. Surprisingly, cement industry is arguably regarded as the second largest producer of the greenhouse gases that cause global warming phenomenon, which contributes by 5–8% of the worldwide CO_2 emissions [4,5]. Cement production results massive quantities of solid waste material called Cement Kiln Dust (CKD), where the quantity of CKD is estimated by 3–4% of the total produced cement. This material has not been widely utilizing in a beneficial manner.

$$CaCO_3 + \Delta \rightarrow CaO + CO_2 \quad (1)$$

Cement mortar occupies around 50% of the concrete volume [6] and it is highly responsible for the physico-mechanical properties of the concrete beside the coarse aggregate and the bonding between mortar and aggregate. Therefore, by considering the massive consumed concrete, mortar is of importance to be focused on. It is known that using high cement content in a concrete mix is not preferred due to durability issues and cement is relatively is an expensive material. However, high cement content is normally used in

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producing self-compacting concrete (SCC) where it is stated that the cement/binder content is 450–600 kg/m^3 [7,8], therefore, cement replacement materials are usually used in producing such concrete class. Using CKD as a cement replacement material could generate economic and ecological value for this waste material by despoiling it in an environmentally–friendly use i.e. in producing high performance/self-compacting concretes.

It was previously concluded that substituting up to 5% wt. of cement with CKD did not significantly affect the compressive strength of cement paste and had no negative effect on the embedded reinforcement passivity [9]. Other research has investigated using CKD as an activator for other cementatious materials such as blast furnace [10] slag [11], granulated slag and silica fume [12]. It was found that the electrical response characteristics of setting pastes can be used as a reliable tool in investigating the hydration progress of blended cement and also for observing the micro-structural changes occurring within the paste. Additionally, CKD can be used as activator of hydraulic reactivity of granulated slag and silica fume as pozzolanic admixtures in producing modified cement pastes. More recent study conducted by Maslehuddin et al. suggested that the substitution of cement with CKD should be limited with 5% wt. since chloride permeability increased and the electrical resistivity decreased with CKD incorporation. Therefore, there was a possibility of steel reinforcement to be corroded when CKD incorporated with 10% and 15% wt. of cement [13], however, these results have not been confirmed yet.

Although there is a massive quantity of CKD that annually produced and there is an increasing need to recycle/reuse the industrial-by-product materials to achieve the sustainable development aims, there is no sufficient published research on using CKD as a cement replacement material. The aim of this study is to experimentally investigate the effect of replacing Ordinary Portland Cement (OPC) with CKD on the physico-mechanical properties of cement mortar that is intended to be used in SCC production. For this purpose, OPC was replaced by up to 30% wt. with CKD. Workability and physico-mechanical properties for both CKD mortar and SCC were investigated.

2. Cement Kiln Dust

It is defined as a fine-grained, solid, highly alkaline by-product waste material, the particles diameter range between few μm and 50 μm that removed from cement kiln exhaust gas by air pollution control devices. CKD forms in cement plants during the manufacturing process when the kiln's temperature is ranging between 800 and 1000 °C [14]. The concentration of its constituents is varying based on the initial fed raw materials; however, it generally contains relatively high percentage of alkalis such as K_2O and Na_2O. It was experimentally found that, in Kubaisa cement plant, the variation of these compositions is not significant due to the similarity in the raw materials (quarries). Typically, CKD is different from plant to another, based on the fed materials, and it generally disposes in land-based disposal units i.e. landfills, waste piles etc. and it is not returned to the production process. It is categorized as a non-hazardous solid waste material based on The Environmental Production Agency (EPA).

3. Materials and research methodology

Ordinary Portland Cement (OPC) and CKD produced by Kubaisa cement plant were used in this work, where OPC conforms to the Iraqi specification No.5/1984. Standard consistency was found based on EN 196-3:1983 as explained by Neville AM [15]. For mortar production, standard mineral sand (0.85 mm > D > 0.60 mm) was used and the w/c ratio was 0.40 for the OPC mortar, whereas the mix proportion was 1:3 (cement:sand). In order to study the effect of CKD incorporation on physico-mechanical properties of cement mortar, 10%, 20%, and 30% by cement weight replacement were investigated. Table 1 shows the chemical compositions of the used CKD and OPC and CKD in addition to the later with different percentage replacement.

Physical properties of the OPC mortar (OPCM) and CKD mortar (CKDM) were examined including mortars flow, density, Ultrasonic Pulse Velocity (UPV) in addition the porosity (apparent porosity and 2D image analysis). Compressive strength was also determined in addition to use Image analysis technique to find out if the strength can be correlated with the color characteristics of the studied samples.

4. Chemical analysis of OPC, CKD and OPC with different CKD replacement

Chemical analysis was conducting for OPC and CKD in addition to the modified cement with 10%, 20%, and 30% wt. CKD replacement, as shown in Table 1. The analysis was conducted using X-ray efflorescence method employing CUBIX XRF SUPERQ4 instrument that produced by PANALYTICAL company based on the manufactures instructions. The results show that chloride content in the CKD is massively higher than that for the OPC, therefore, the increase in Cl content with increasing CKD replacement is clearly justifiable. Same trend was noted with K_2O and Na_2O (alkalis), but with different percentage, as shown in Table 1. The summation of alkalis content for up to 20% replacement is <1.3% of the total weight which is the limit of IQ standard No.5 1984 and for 30% replacement this figure is slightly exceeded this limit. Inversely, there was no significant difference in terms of Al_2O_3 and Fe_2O_3, whereas there was a systematic decrease in MgO content with CKD replacement due the difference in MgO content between CKD and OPC. However, for all percentage replacement MgO content was still satisfying both BS.12: 1971 and IQ NO.5: 1984 standards. CKD has lower content in terms of SiO_2 and CaO in comparison with OPC, however, with 30% replacement; for example, the SiO_2 content was lower than that for OPC by about 15% while there is no significant difference in CaO content.

Table 1 also shows that SO_3 content for all percentage replacement does not exceed the BS.12:1971 limit (<3%). The insoluble residue (IR) content is found to be higher for CKD in comparison with OPC; therefore, its content increases with CKD replacement increase, but all the replacements conform the both IQ No. 5 and BS.12:1971 (⩽1.5 of total cement). Loss of ignition (L.O.I) is considerably higher for CKD than that for OPC, however, with 20% and 30% CKD replacements the limitation of both Iraqi standard No. 5:1984 and BS.12:1971 were exceeded (4% as maximum L.O.I). The lost weight was due to evaporate of water of crystallization, CO_2, etc. Hydraulic Modulus H.M. (calculated using Eq. (2)) is

Table 1
Chemical analysis of OPC, CKD and OPC with different replacement with CKD.

	CL	K_2O	Na_2O	Al_2O_3	Fe_2O_3	MgO	SiO_2	CaO	SO_3	IR	L.O.I	F.L	H.M.
OPC	0.01	0.67	0.16	4.50	4.73	2.27	20.98	64.02	2.30	0.40	0.75	0.94	2.12
CKD	0.39	1.48	1.20	4.13	4.25	1.86	18.88	60.52	2.00	0.65	17.5	20.00	2.22
$OPC_{10\%CKD}$	0.05	0.84	0.30	4.50	4.60	2.20	19.70	63.75	2.29	0.43	2.69	4.20	2.21
$OPC_{20\%CKD}$	0.08	0.90	0.37	4.44	4.51	2.12	18.92	63.29	2.14	0.45	4.35	5.00	2.27
$OPC_{30\%CKD}$	0.13	1	0.40	4.26	4.40	2.04	18.46	63.07	2.05	0.50	4.51	10.50	2.33