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Effect of kaolin waste content on the properties of normal-weight concretes

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HIGHLIGHTS

- Develop green concretes using kaolin wastes.
- Propose mixture designs for kaolin waste based concrete.
- Evaluate fresh, mechanical, transport and durability properties.
- Evaluate the effect of kaolin replacement on concrete properties.

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ABSTRACT

This paper presents the mechanical, transport and drying shrinkage properties of normal-weight kaoline waste (KW) incorporated concretes. Six different concrete mixtures that have a constant water–binder ratio (w/b) of 0.40 and a binder (Portland cement + kaoline waste) content of 400 kg/m^3 were designed with various KW replacement contents (0%, 5%, 10%, 15%, 20% and 25% of Portland cement by weight). Workability, unit weight, compressive and tensile strengths, water absorption, porosity, sorptivity, rapid chloride permeability and drying shrinkage tests were performed on fresh and hardened concretes. Test results were analysed by considering the KW content and it was concluded that use of KW worsened the workability and decreased unit weight irrespective of KW content. KW incorporation affected the compressive strength positively, especially at the 10% and 15% replacement levels beyond 28 days. Replacement of KW up to 15% exhibited virtually identical porosity and water absorption values with the control concrete. Sorptivity values of KW concrete mixtures (at 5% and 10% kaolin waste replacement) were equal or somewhat lower than that of the control mixture. Chloride ion penetration resistance of concretes improved drastically with the increase of KW content.

1. Introduction

Industries are moving towards developing more environmentally sustainable practices and methods of manufacturing products, and the concrete industry is no exception. With emissions of carbon dioxide from the cement industry expected to reach 3.5 billion tonnes per year worldwide by 2025, it is crucial to find alternative materials with cementitious properties [1]. The production of cement for use in concrete creates large amounts of greenhouse gasses and has an overall negative effect on the environment, in terms of quarrying non-renewable virgin materials as well as the costs of transportation. Supplementary cementing materials derived from industrial waste materials are becoming more prevalent as an alternative to cement in the industry.

Kaolin is an important raw material in various industrial sectors. Each tonne of kaolin recovered typically produces up to 9 tonnes of waste. There are multiple sources of kaolin worldwide, and several deposits exist in Canada; in Nova Scotia [2] and in Saskatchewan [3]. Mining these deposits creates waste, as does using kaolin to create coating and filler in paper manufacturing, where kaolin particles above a specific size are not used [4]. Research has shown that kaolin waste and residues from these processes (such as paper sludge) can be heated to produce a material with pozzolanic properties [5,6]. Frias et al. found similar results

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when paper sludge was calcined at the proper temperature, and suggest that it is suitable to be used in the concrete industry [7]. From their research, they determined the best temperature to convert paper sludge into a reactive pozzolanic material was 700 °C for two hours. Roach and Angelica found that the residues collected from kaolin mining processes which had a higher number of structural defects required a lower temperature to achieve pozzolanic properties, which saves on energy costs [5]. They also found that these residues showed a higher reactivity than commercially available pozzolanic materials.

Metakaolin has pozzolanic properties and is derived from kaolin clay through dehydroxylisation, which is achieved by heating the material between 500 and 900 °C over a defined period of time [3,8–12]. This clay is readily available around the world in large quantities which makes it a cost-effective alternative to cement. Its lighter colour also allows for creating a more aesthetically pleasing product [8]. Research has found that pozzolans offer several advantages to concrete such as higher strength, lower temperature rise, and improved durability performance [9–10]. Metakaolin incorporation in concrete mixes has been shown to improve durability properties, specifically shrinkage, porosity, absorption, sorptivity, and chloride-ion permeability [13]. Incorporating metakaolin into concrete mixes has been shown to decrease the pore size which improves its resistance to ingression of water [14], which has been attributed in part to an increase in packing density of the dry mix [13]. Metakaolin has been recommended for use as a supplementary cementing material (SCM) and has also been shown to achieve the same hardened properties as concrete mixtures incorporating silica fume. However using metakaolin has the added advantage of much lower cost as well as an aesthetically appealing product [8].

The kaolin waste with similar chemical properties to metakaolin (as used in this study) has potential to be used as SCM [6,13,15]. With further research into the fresh, hardened, and durability properties of concrete incorporating kaolin waste, this material could become partial substitution for Portland cement which will decrease the amount of wastes that would otherwise end up in landfills.

The objective of this paper is to investigate the fresh, mechanical, and transport properties of normal weight concretes incorporating various levels of kaolin waste (5%, 10%, 15%, 20%, and 25%) as a supplementary cementing material and to determine if kaolin wastes are a suitable substitution for traditional Portland cement. This would reduce the cost of producing concretes incorporating SCMs since kaolin is readily available and costs less than other SCMs. Positive results in this study would further encourage the use of kaolin wastes in concretes since it would divert wastes from landfills and reduce the construction industry's environmental footprint. Standard testing for strength, slump, permeability, porosity, sorptivity, and drying shrinkage was performed to evaluate the performance of various kaolin waste contents in normal weight concrete.

2. Research significance

As industries become more conscious of their environmental footprint it is imperative that the cement and concrete industry finds ways to do the same. There are already well-functioning supplementary cementing materials available in the industry, however looking for a less expensive and high-functioning alternative is always important. Metakaolin is a stable product which can be readily produced from kaolin clay and there has already been extensive research into its properties and performance in various types of concrete applications. However, kaolin wastes produced from certain manufacturing procedures (such as paper mills and even metakaolin production) have also displayed pozzolanic properties and this study aims to investigate their adequacy as a supplementary cementing material. This will be beneficial to the concrete industry, not only in saving on costs, but also in reusing wastes which would otherwise end up in landfills.

3. Experimental program

The research program consisted of analysing the chemical composition of the kaolin wastes which were to be incorporated in the concrete mixes (Table 1). Six different mixes were designed in this research, all with a w/b ratio of 0.4:1 control mixture with Portland cement, and five mixtures with 5%, 10%, 15%, 20%, and 25% kaolin waste, respectively. Each mix was designed using high range water reducers to account for the loss in workability with increasing kaolin waste content.

The fresh, mechanical, transport, and drying shrinkage properties were tested for each mix, according to ASTM standards, to investigate the effect of various levels of kaolin waste incorporation on the performance of the concrete. The fresh properties test in this research program consisted of testing slump for each mix. The mechanical properties were analysed by testing the compressive, flexural, and splitting tensile strengths of each mix. The transport properties were tested for porosity, sorptivity, and rapid chloride permeability. Lastly, the drying shrinkage of each mix was tested.

3.1. Materials

The cement used was a Canadian Cement General Use (GU) Portland type, equivalent to ASTM Type I. The mineral admixtures used were kaolin waste (KW). The kaolin industry, which processes primary kaolin, produces two types of wastes. The first type derives from the first processing step (separation of sand from ore). The second type of waste results from the second processing step, which consists of wet sieving to separate the finer fraction and purify the kaolin. The waste investigated in this study was obtained from the second step of primary kaolin processing. The KW was dried at 110 °C, dry milled in a ball mill and sieved through a 150 μm mesh. Kaolin waste is composed of kaolinite ($Al_2Si_2O_5(OH)_4$), mica ($KAl_2(Si_3Al)O_{10}(OH,F)_2$) and quartz ($SiO_2$).

The chemical compositions and physical properties of cement, kaolin waste and metakaolin are presented in Table 1. It can be seen from Table 1 that the kaolin waste in its composition showed 59.04% of silicon oxide and 24.68% alumina oxide. The chemical composition of KW and metakaolin are quite similar. However, $SiO_2 + Al_2O_3 + Fe_2O_3$ content is higher in metakaolin (95%) compared to KW (about 84.6%). The Blaine fineness and density of KW are 10,780 cm^2/g and 2.09, respectively compared to 13,900 cm^2/g and 2.56 of metakaolin.

KW was submitted to phase identification, carried out by X-ray diffraction (XRD), with CuKα radiation (40 kV/40 mA) at a speed of 2°/min from 15° to 60°. Fig. 1 shows the diffractogram of the kaolin waste. XRD pattern verified that the KW has the following mineralogical phases: kaolinite characterised by inter-planar distances of 7.07 and 3.56 Å, a small amount of mica characterised by 10.04 and 4.97 Å, and also quartz characterised by 2.66 and 2.08 Å.

Table 1
Characteristics of cement, kaolin waste and metakaolin.

Chemical	Cement	Kaolin Waste	Metakaolin
Sum ($SiO_2 + Al_2O_3 + Fe_2O_3$)	27.6	84.59	95
SiO_2 (%)	19.6	59.04	61–64
Al_2O_3 (%)	4.9	24.68	30–32
Fe_2O_3 (%)	3.1	0.87	1.10
CaO (%)	61.4	5.22	0.40
MgO (%)	3.0	0.34	0.30
SO_3 (%)	3.6	0.10	0.05
Alkalis as Na_2O (%)	0.7	6.77	1.35
TiO_2	–	1.12	
P_2O_5	–	0.04	
SrO	–	0.01	
Mn_2O_3	–	0.02	
K_2O	–	0.46	
Cl	–	0.01	
ZnO	–	0.01	
Cr_2O_3	–	0.04	
NaEq	–	7.07	
LOI (%)	2.3	1.46	0.95
Physical			
Blaine (cm^2/g)	3870	10,780	13,900
+45 μm (%)	3.00		1.2
Density (g/cm^3)	3.15	2.09	2.56