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Mechanical and durability properties of concretes containing paper-mill residuals and fly ash

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ABSTRACT

The use of paper-mill residuals in concrete formulations was investigated as an alternative to landfill disposal. The mechanical and durability properties of concrete containing paper-mill residuals collected from a wastewater treatment-plant were evaluated. Class F fly ash was used as a replacement for Portland cement (PC) when incorporated into concrete mixtures containing paper-mill residuals and the resulting products were compared to normal concrete. Compressive, splitting tensile, flexural strength and drying shrinkage tests were carried out to evaluate the mechanical properties for up to 90 days. Rapid chloride-permeability tests and initial surface-absorption tests were carried out at 28 days to determine the durability properties. Concrete containing paper-mill residuals showed improvement in the durability test results when PC was replaced with class F fly ash.

1. Introduction

Wastewater treatment-plant (WTP) residue created by the pulp and paper industry, or sludge, consists of the solid material collected in the process of treating wastewater before it is released to the environment [1]. The residuals consist of primary and secondary solids produced during the two-step effluent-treatment process. Primary residuals are composed of wood fibres and an inorganic fraction (consisting of clay, calcium carbonate, titanium dioxide, and other materials used in pulp and paper production) collected during the separation of solids from the raw wastewater in primary treatment. Secondary residuals are mostly microbial mass collected by clarification following biological treatment [1–3]. The solids content of the WTP residuals usually ranges from 20% to 60%, depending in part upon the dewatering method applied [1].

According to data from the national council for air and stream improvement [3], 5.83 million tons of water treatment-plant residuals were produced by the paper industry in the United States in 1995. Of the total amount of residuals produced, only 23% was beneficially used, whereas 51% was landfilled or lagoon stored, with another 26% burned.

The disposal of these residuals has been a great burden on the pulp and paper industry. Mills that do not operate their own waste management facilities are charged with a tipping fee for the pick-up, transportation, and disposal of residuals. The problem becomes more crucial where landfill space is limited. In 1978, the United States had about 14,000 landfills; in 1988 there were 5500, and by the year 2000, the number of landfills is expected to drop to 2200 [4]. Furthermore, landfills are becoming more difficult and costly to construct and operate because of increasingly stringent regulations, diminishing land availability, and public opposition [5]. Industrialists as well as environmentalists now agree that the disposal of these residuals is a lost opportunity for resource recovery. Therefore, it has become essential to find value-added constructive use options for this waste stream.

There have been few studies to date on the utilisation of paper-mill residuals in concrete production. Naik et al. (2003) reported that, by adjusting the mixture to an equivalent density, concrete mixtures containing the residuals can be produced that are equal in slump and strength to a reference concrete without residuals [6]. The compression strength, average residual strength and drying shrinkage of concrete containing residuals were also comparable to the reference concrete without residuals when the proper dosage of high-range water-reducing agent (HRWRA) was added [7–9]. Concrete containing an average of 15% residuals had a lower 28-days compressive strength than the reference concrete and showed either equivalent or somewhat lower chloride-ion penetration resistance than the reference concrete [10]. Decard et al. (2001) found that concrete containing recycled paper waste had the potential for use as a buffer layer for structural concrete because of its favourable energy-absorption capacity under monotonic and cyclic loading [11].

Conversely, fly ash is commonly used as a mineral admixture in concrete formulation as a cost saving replacement for Portland cement. Fly ash, a by-product of thermal power plants burning

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anthracite or bituminous coal [12], has been reported to improve the fresh properties, mechanical properties and durability of concrete when used as a cement replacement [13,14].

Although there are potential advantages of including paper-mill residuals in a concrete mixture, such as cost savings in both waste management and concrete production [10], to date little research has been carried out to establish parameters related to practical aspects such as the properties of the finished concrete. Therefore, the main objective of this study was to evaluate the mechanical and durability properties of concrete containing paper-mill residuals and fly ash.

2. Materials and mixture proportions

2.1. Portland cement, fly ash, coarse and fine aggregates

The cement used in all mixtures was Portland cement (PC), which corresponds to ASTM Type I cement. The coarse aggregates used were crushed stone graded as a 9.5-mm nominal maximum size, with a bulk density of 1571 kg/m^3, a specific gravity of 2.61, and 0.81% absorption. The 9.5-mm crushed stone was used to ensure good mechanical performance so that any differences in the mechanical properties of mixtures containing residuals and reference mixtures could be easily detected. The fine aggregate (river sand) had a bulk density of 1706 kg/m^3, a specific gravity of 2.66, 1.9% absorption, and a fineness modulus of 2.45. The fly ash used was in the class F category according to ASTM C 618 specifications [12]. Class F fly ash was used in the study due to its availability in Malaysia. Table 1 shows the chemical compositions of the PC and the class F fly ash. The percentage loss on ignition (LOI) indicates the carbon content in the cementitious material. The high-range water-reducing admixture (HRWRA) used in this research was an aqueous solution of a modified polycarboxylate conforming to the requirements of EN 934-2 [15]. The manufacturer recommends a dosage rate of 0.2–0.8% of the cement mass for medium workability.

2.2. Paper-mill residuals

The paper-mill residue used in this study was the primary sludge recovered from the first processing stage (the primary clarifier) in a paper-mill, with the physical and chemical properties presented in Tables 2 and 3, respectively. Fig. 1 shows scanning electron micrographs of the oven-dried primary residuals.

2.3. Deflocculation of residuals

The as-received residuals were in a clumped condition. A process to deflocculate residual fibres is necessary to ensure that the residual clumps can be dispersed into individual fibres and subsequently evenly distributed in the concrete mixtures.

Table 1
Chemical composition of PC and class F fly ash.

Oxide composition	PC (%)	Class F fly ash (%)	Requirements for ASTM C 618
SiO_2	21.54	62.5	
Fe_2O_3	3.63	3.5	
Al_2O_3	5.32	23.4	
CaO	63.33	1.8	
MgO	1.08	0.34	5.0 max
SO_3	2.18	1.2	5.0 max
K_2O	–	0.95	
Na_2O	–	0.24	
Loss on ignition	2.5	5.61	6.0 max

Table 2
Physical properties of residuals.

Type of residual	Type of mill	Fibre origin	Moisture content (%)[a]	Apparent specific gravity	Loss on ignition at 590 °C (%)[a]	Wood-fibre content (%)[a]
Primary	Paper	Recycled	225	1.661	46	36

[a] Percent of oven-dried (105 °C) mass of residuals.

Table 3
Oxides composition of ash left after ignition of dried residuals at 1000 °C.

Element	% by mass[a]
LOI at 1000 °C	53.450
MgO	2.140
Al_2O_3	8.620
SiO_2	15.100
K_2O	0.290
CaO	17.400
TiO_2	0.707
Fe_2O_3	1.660
Total	99.985

[a] Percent of oven-dried (105 °C) mass of residuals.

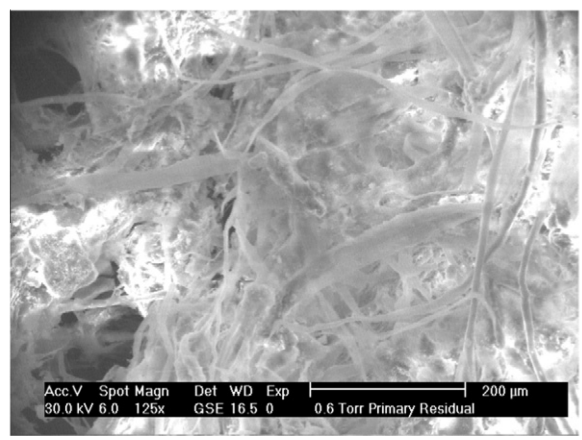

Fig. 1. Scanning electron micrographs of oven-dried primary residuals.

Chun's [16] method was employed for the deflocculation of the residuals. A high-speed mixer was used to deflocculate, or repulp, the residue. Mechanical repulping was performed by immersing the fibrous residuals in room-temperature water until no further clumps were observed.

2.4. Mixture proportions

The mixture proportions and fresh properties of the concrete mixtures produced in the laboratory are shown in Table 4. A total of 19 concrete mixtures were produced. The types of mixtures produced, which were PC concrete with residual contents ranging from 0.25% to 2% (N mixtures), PC concrete with 0.4% added HRWRA (by cement mass) and residual contents ranging from 0.25% to 2% (S mixtures), and class F fly ash with 0.4% HRWRA and 1% residual content (FA mixtures). The two digits following FA indicate the partial replacement of mass of PC with fly ash, which ranged from 20% to 60%. Ref1 refers to the reference concrete for mixtures N (no HRWRA), and Ref2 refers to the reference concrete for mixtures S (with 0.4% HRWRA). Mixtures N4, S4 and all mixtures of FA contained the same residual content of 1%.