



Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended portland cements containing fly ash and limestone powder



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ABSTRACT

This paper reports the composition and properties of highly flowable self-consolidating concrete (SCC) mixtures made of high proportions of cement replacement materials such as fly ash and pulverized limestone instead of high dosage of a plasticizing agent or viscosity-modifying chemical admixtures. Self-consolidating concrete mixtures are being increasingly used for the construction of highly reinforced complex concrete elements and for massive concrete structures such as dams and thick foundation. In this study, by varying the proportion of portland cement (OPC), Class F-fly ash (F), and limestone powder (L), SCC mixtures with different strength values were produced, and the properties of both fresh and hardened concrete were determined. For a comprehensive analysis and quantification of emissions and global warming potential (GWP) from concrete production, life-cycle assessment (LCA) was employed. We find that high volume, up to 55% by weight replacement of OPC with F, or F and L produces highly workable concrete that has high 28-day and 365-day strength, and extremely high to very high resistance to chloride penetration along with low GWP for concrete production.

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1. Introduction

According to data compiled by the U.S. Geological Survey (USGS) in 2011 [1], the yearly global production of portland cement was about 3.3 billion metric tons (mt). Considering typical concrete mixture proportions for ordinary concrete [2], this amount of cement is incorporated into approximately 27 billion mt of concrete, which requires 22 billion mt of aggregates and 2.2 billion mt of fresh water, leading to an annual global average consumption rate of about 4 mt of concrete per person. The massive production and consumption cycle of concrete has substantial environmental impact.

Carbon dioxide (CO₂) emissions from portland cement manufacturing is one of the major sustainability issues facing the concrete industry. Although considerable gains in energy efficiency during cement production manufacturing have been realized over the last two decades, according to industry data [3], about 866 kg of CO₂ are being generated for every 1000 kg of clinker made.

Roughly 60% of these emissions come from the calcination of limestone, which is the main raw material for making portland-cement clinker. For every tonne of calcium carbonate calcined in the kiln to form calcium oxide, 440 kg of CO₂ are released into the atmosphere as the chemical reaction progresses. The combustion of fuel required to generate the heat necessary for the reactions forming the clinker minerals accounts for the remaining CO₂ emissions.

As a result, considering an average clinker factor (kg of clinker per kg of cement) of 0.78 [4], annual worldwide CO₂ emissions from cement manufacturing add up to almost 2.3 billion mt, which is nearly 7% of the global emissions from fossil fuel combustion [2]. For an average of 918 kg of CO₂ per mt of cement [5], the U.S. cement industry generated about 56 million mt of CO₂ based on the 2010 portland cement production rate of 61 million mt [1]. These numbers correspond to direct emissions only, i.e., those generated in the cement factory. Based on economic input–output analysis-based life-cycle assessment (EIO-LCA) using U.S. data [6], supply-chain inclusive, life-cycle greenhouse gas emissions associated with cement manufacturing are expected to be 13% higher than direct emissions.

While the current environmental impact of the concrete industry is indeed considerable, the increased use of supplementary cementitious materials (SCMs) offers a possible reduction in global

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CO₂ emissions. A study involving business leaders and academics [7] singled out construction materials as one of the seven most promising technologies for investment (together with wind, biofuels, photovoltaics, and concentrating solar power, nuclear, and building efficiency). The report concluded that within the construction materials sector, “the biggest single opportunity for CO₂ reduction is a low-carbon cement,” and that annual savings of 1 billion mt of CO₂ could be reached through the concrete sector if 50% of portland cement were replaced by a low-carbon alternative.

In order to achieve such a level of CO₂ reductions, the industry must embrace a comprehensive, integrated approach that necessarily involves the use of less concrete for new structures, consumption of less cement in concrete mixtures, and use of less clinker for making cements [8].

Replacing half of portland cement would require about 1.7 billion mt of alternative materials, according to USGS data [1]. High-volume fly ash (HVFA) concrete has been used successfully for many years in numerous applications with technical and environmental advantages as compared to conventional portland cement concrete, and its use is expected to keep increasing over time [8–10]. Yet already the global availability of fly ash is roughly 800 million mt [11], which is less than half of the overall amount of materials needed. Thus, other materials, such as limestone powder, must be increasingly brought into the mixture.

Limestone powder (L) as calcite (or crystalline CaCO₃) is a widely available resource that has been added to cement and concrete in small volumes for many years, particularly in Europe. Recent research has shown that larger amounts can be successfully used in low water-cementitious materials ratio (*w/cm*) mixtures to conserve portland cement [12,13]. The added limestone has two main functions. It acts as a limited participant in the hydration process at early ages and/or as a relatively inert calcareous filler depending on levels of calcite and replacement ratio [14]. As the portland cement hydrates, the ground CaCO₃ reacts with various calciumaluminate hydrates to form high and low forms of carboaluminates [15]. Calcium hemicarboaluminate forms an early hydration product in calcite containing ordinary portland cement (OPC) blends. After about 28 days, it converts nearly completely to calcium monocarboaluminate, a stable AFm phase [16]. Thermodynamic calculations and experimental observations showed that monocarboaluminate formation is favored instead of monosulfoaluminate [17]. The available sulfate reacts with water and calcium hydroxide, crystallizing as ettringite [17,18]. Due to additional ettringite formation, the total volume of the hydrated phase increases, and the overall porosity decreases [18].

This paper presents a study on the development of lower-cost, environmental less burdensome, self-consolidating concrete mixtures with high-volume fly ash (HVFA) and limestone powder (L).

Self-consolidating concrete (SCC) has been used increasingly in the field due to several advantages when compared to conventional concrete, including shortened placement time, labor savings, improved compaction, and better encapsulation of rebar. However, typical SCC mixtures usually have an excessively high cement content, high heat of hydration, and utilize a high dosage of high-performance superplasticizers and viscosity-modifying agents [19–23]. Developed herein are self-consolidating concrete mixtures with low cement content (less than 250 kg/m³), and a limited amount of a low range superplasticizer, and without any viscosity modifying agents, with ternary blends of cementing material containing portland cement, limestone powder and fly ash. The mechanical properties and durability performance of these “greener concrete mixes” are presented. The properties determined include the slump flow, normal consistency, and setting time. Those of the hardened concrete include the compressive strength, chloride-ion penetration, water absorption, and gas permeability.

Emissions from the concrete mixtures were compared using the “GreenConcrete LCA” tool developed by some of the co-authors of this paper [24]. This cradle-to-gate life-cycle assessment (LCA) tool estimates direct and supply-chain global warming potential (GWP) in units of CO₂-equivalent (CO₂-eq) emissions and some criteria air pollutants (CO, NO_x, PM₁₀, and SO₂) associated with the use of electricity, fuel, transportation, and production processes taking place within the boundary of concrete production system. In LCA applications, drawing the system boundaries, i.e., decisions on inclusion or exclusion of processes in an analysis, is an essential step [25]. This study incorporates the following parameters in the system boundary: extraction of cement raw materials, manufacturing of cement, extraction and processing of aggregates, manufacturing of superplasticizers, preparation and treatment of fly ash prior to mixing into concrete, extraction and processing of limestone, and concrete batching, and transportation of raw materials and products within the system.

2. Materials

For all the HVFA-L SCC trial mixtures, the common goal was to reduce the cement content in order to lower the environmental footprint while maintaining the required flowability specifications.

The powder materials used in the mixes are ASTM Type I/II portland cement (C), Class F-fly Ash (F), and ground limestone powder (L). The Class F-fly ash is obtained from the Jim Bridger Power Plant, Wyoming, United States. Fig. 1 shows volume-based particle size distributions of the powder materials obtained by laser light scattering. Table 1 summarizes the particle size distribution data. The measured mean particle diameters were 10.4 μm, 22.2 μm, and 48.1 μm, respectively, for C, F and L. The D10, D50, and D90 values correspond to diameters at which the cumulative sample was under 10%, 50%, and 90%, respectively. In general, C and F had much finer particle sizes when compared to L; however, F had some coarser particles of 25 μm and larger. The chemical compositions of powder materials are presented in Table 2.

X-ray powder diffraction (XRD) measurements on L and F were performed using a PANalytical X’Pert PRO Materials Research Diffractometer. Finely ground samples were loaded into metal sample holders and placed into the diffractometer. Data were collected using a cobalt target that produces X-rays with a wavelength of 1.789 Å. XRD patterns taken at ambient conditions are presented in Fig. 2 together with schematic diagrams for relevant phases. The F measurement and the L measurement are plotted with the same intensity scales. Although the F is mainly composed highly

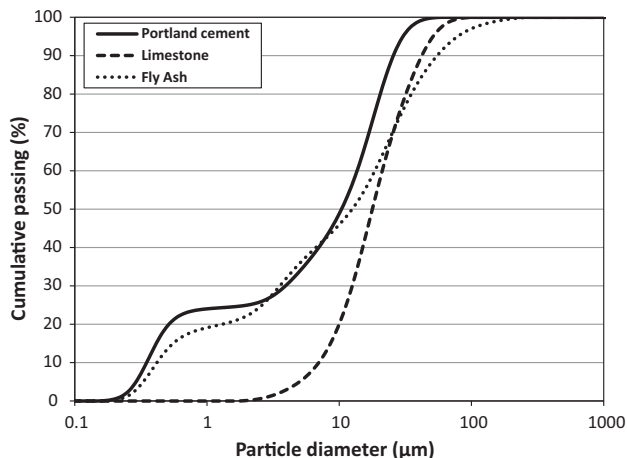


Fig. 1. Particle size distributions of portland cement (C), limestone powder (L) and Class F-fly ash (F).

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