Fuel 184 (2016) 481–489

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Review article

Influence of alternative fuels on trace element content of ordinary portland cement

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ARTICLE INFO

Article history:
Received 14 April 2016
Received in revised form 1 July 2016
Accepted 12 July 2016

Keywords:
Alternative fuels
Waste incineration
Trace elements
Clinker chemistry

ABSTRACT

Over the last 20 years, interest in diverting waste from landfills and recovering energy from waste materials has grown significantly. The cement industry in particular has adapted its production methods to accommodate a wide variety of waste materials as alternative fuels in order to lower both cost and environmental footprint. The incineration of waste products at existing cement plants is generally cheaper than building a new, dedicated incinerator as cement kilns generally meet the requirements for incinerating hazardous wastes. In addition to negative perception, particularly where potentially hazardous waste materials are concerned, there are a number of technical challenges in the use of alternative fuels at cement plants. This paper focuses on the incorporation of trace elements in ordinary portland cement through the use of alternative fuels, including the behavior of trace elements in the manufacturing process and their effects on final products. A brief overview of the use of waste tires, solidified sewage sludge, and meat and bone meal as alternative fuels is presented along with a discussion of challenges and opportunities facing the field.

Contents

Abbreviations: OPC, ordinary portland cement; C-S-H, calcium silicate hydrate; MBM, Meat and Bone Meal; BSE, bovine spongiform encephalopathy; SCM, supplementary cementitious material.

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http://dx.doi.org/10.1016/j.fuel.2016.07.038

1. Introduction

Concrete is the most widely manufactured material in the world, with more than one cubic meter produced annually for every person on earth [1]. Globally, it is being produced at a rate that has never been seen before: Between 2011 and 2013, China alone placed more concrete than the United States produced during the entire 20th century. A typical concrete contains roughly 70 vol.% aggregate embedded in a cementing phase of hydrated ordinary portland cement (OPC), which, in turn, is primarily composed of tri- and dicalcium silicate phases (known as alite and belite, respectively) [2]. When exposed to water, calcium silicates form calcium hydroxide and calcium silicate hydrate (C-S-H) gel, a cohesive phase that is the source of compressive strength in concrete [3]. Minor phases rich in aluminum and/or iron (AFm, AFt, etc.) are typically present due to impurities in the raw materials that play important roles as fluxes during the pyroprocessing step of OPC production, but contribute little to the mechanical properties of the final product [4].

OPC-based concrete is likely to be the dominant building material for the foreseeable future, as previous attempts to develop alternatives have been largely unsuccessful. For example, calcium aluminate cements are generally less economically viable and have a controversial history, having been banned in many building codes after a series of early failures. These binders can also decrease in strength under potential exposure conditions as metastable reaction products begin to degrade [5]. Calcium sulfoaluminate cements consume less energy and release less greenhouse gas during manufacture than OPC, but are economically less attractive and can undergo substantial reduction of volume during curing [5,6]. Slag-based supersulfated cements have almost disappeared as changes in ore refining began producing slags that are chemically inappropriate as raw materials; furthermore, alkali-activated slags in general suffer from logistical difficulties including handling and the highly localized distribution of raw materials [7,8]. Despite the fact that geopolymers, based on the alkali-activation of fly ash or metakaolin, are the focus of significant academic research interest and have been implemented in some niche applications, the variability of fly ash composition and uncertainty regarding environmental impacts are significant hurdles to broader acceptance [9]. Finally, established building codes and various legal precedents in effect discourage the implementation of non-OPC based building materials [10].

Due to the energy-intensive processes used to produce OPC and legal restrictions on waste disposal in municipal incinerators, interest in burning alternative fuels at cement plants has increased tremendously over the last two decades [11]. These alternative fuels are generally waste products from industrial or agricultural applications whose incineration reduces both the burden placed on landfills and the operating costs of a cement plant, however, the use of such fuels can also impart trace elements on OPC. Trace elements in the form of alkali metal compounds can interfere with cement plant processes or make the final product vulnerable to deleterious processes; the presence of phosphates and sulfates can significantly reduce the quality of the final product; and transition metals or main group elements may leach into soils or water, eventually entering the food chain to the possible detriment of biological organisms. This paper reviews the pathways by which trace elements can enter OPC through alternative fuels (with specific detail regarding waste tires, sewage sludge, and meat and bone meal) as well as rawmix or supplementary cementitious materials; the effects of trace elements on the properties of OPC; and likely future trends regarding the use of waste materials as fuel in cement production.

2. Origins of trace elements in OPC

2.1. OPC production processes

The production of OPC is a three step process: Raw materials, primarily limestone and clay, are acquired and ground to produce rawmix; the rawmix is then pyroprocessed in a rotary kiln at temperatures approaching 1480 °C (2700 °F) to form clinker; and the clinker is finally interground with various additives and/or supplementary cementitious materials (SCMs) to form OPC. Modern cement production facilities can be configured in a number of ways, and a variety of ancillary equipment may or may not be used depending on the age, size, and purpose of the plant. For example, multiple cyclone preheaters are used to recover waste heat from the kiln exhaust and to prepare the rawmix for pyroprocessing; precalciners (which consume additional fuel) can be used to further prepare rawmix and improve the output of the kiln; and a wide variety of supplemental materials can be incorporated during the final intergrinding step. Each configuration choice has the potential to influence the trace element content of the final product (Fig. 1).

2.2. Fuel consumption in OPC plants

Although OPC has a low embodied energy when compared to other infrastructure materials, the cement industry produces roughly 5% of anthropogenic CO_2, partially due to chemical reactions occurring within the kiln and partially due to the consumption of fuel to run the kiln. Some 3000–6500 MJ (2.84–6.16 million BTU) of energy is consumed per ton of clinker produced, accounting for roughly 35% of total production costs and roughly 10% of the world's industrial energy consumption [12–15]. Although the tremendous amount of energy consumed by the cement industry is often cited as a motivation for the development of alternative binder materials, it should be noted that over the last two decades the energy efficiency of cement kilns has been significantly improved, even during a time of rapid market growth – The average thermal energy consumption of the companies reporting to a program of the World Business Council for Sustainable Development decreased from 4260 MJ per ton (3.67 million BTU per ton) of clinker in 1990–3580 MJ per ton (3.07 million BTU per ton) in 2010, a 16% decrease [13].

Possible feed points for supplying fuel depends on the exact configuration of a OPC production facility, and may include [16]:

1. The main burner at the outlet end of the kiln.
2. Mid-kiln valves or feed chutes (in long kilns only).
3. A feed chute at the inlet end of the rotary kiln.
4. Secondary burners at the riser duct, located between the rotary kiln inlet and the precalciner or preheater system.
5. Precalciner burners.
6. Feed chutes within the precalciner or preheater systems.

The first two feed points supply energy directly to the kiln, although in the case of mid-kiln access points the kiln must be operated in a way that ensures temperatures and residence times are high enough for the complete combustion of the fuel. Feed points three to six supply energy, along with heated air from the kiln, to the precalciner or preheater. In modern production facilities equipped with both precalciner and preheater systems, roughly 60% of the fuel energy is consumed by the precalciner while only 40% is consumed in the main kiln burner [17]. Although technically possible, the burning of alternative fuels to generate power to run ancillary equipment is not considered here, as it