Construction and Building Materials 50 (2014) 414–420

Contents lists available at ScienceDirect

Construction and Building Materials

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

Compressive strengths of mortar cubes from hydrated lime with cofired biomass fly ashes

Shuangzhen Wang *

350 CB Department of Chemical Engineering, Brigham Young University, Provo, Utah 84602, USA

HIGHLIGHTS

- Cofired biomass fly ash has 2–3 times strength of C and F, and 3–6 times that of wood, in its lime mortar.
- Wood fly ash's poorer mechanical performances might come from its large particle size and high unburned carbon content.
- Mortar strength increases with ash percentage increase from 60%, 70% to 80% of the binder mass.
- Elevated temperature increases the earlier but decreases the later ash mortar's strength (23–63 °C).
- All fly ashes' one month strength reaches 60–80% that of their one year.

ARTICLE INFO

Article history:
Received 6 August 2013
Received in revised form 18 September 2013
Accepted 24 September 2013
Available online 18 October 2013

Keywords:
Cofired biomass fly ash
Fly ash
Compressive strength
Hydrated lime
Pozzolanic reaction

ABSTRACT

This document comprehensively compares strength of 5 cm mortar cubes made from binders of hydrated lime and cofired biomass fly ashes. Samples of cement only, with the same binder mass, provide controls and comparisons. Compressive strengths are tested from one to 12 months and samples were cured under carbonation free conditions. Four cofired (coal and herbaceous/woody) biomass fly ashes consistently develop two to three times that of Class C and F, indicating that cofired biomass fly ashes need more reevaluation as an admixture in concrete rather than exclusion by ASTM C 618 because of its "non coal" origin. However, the investigation does suggest that pure woody biomass fly ash may represent unacceptable pozzolans for use in concrete.

1. Introduction

Biomass cofiring with coal represents among the most economical and practical renewable energy resources and its combustion process is CO_2 neutral if its consumption rate does not exceed the growth rate [1]. Many biomass fly ashes, such as from rice husk, corn stover, wood, wheat straw and sugar cane, have significant pozzolanic properties, similar to coal fly ashes [2–14,15–20]. However, the current ASTM C 618 standard for concrete admixtures prohibits use of any material that does not derive from coal under classes C and F. By contrast, the counterpart European standard EN450 has allowed addition of biomass fly ash in concrete.

Earlier work from the author demonstrated that fly ashes from coal–biomass (75–25% mass) cofiring have comparable or better mechanical, freeze thaw and ASR mitigation performances than those of Class C, F and cement control, when replacing 25% (mass) cement in concrete; by contrast, wood ash is not [2–6].

Therefore, this investigation would go one step further and focus on the mechanical properties of fly ash lime mortar, which arise primarily from the pozzolanic reactions and secondarily from a filling effect [21]. Therefore, it would exclude the major cementitious reactions [2–6], which used to play a dominant role since fly ash only replaced cement partially [22–25].

Generally, biomass varies in a wider range of chemical compositions, has a larger particle size and low heating value than coal when considered as fuel feed for combustor, and therefore the performance of the cofired ash in concrete (also combined with varieties of coal) seems to be complicated [26]. In the pilot tests, with 20% biomass (as blends of pine wood, oak wood and olive kernel), the cofired ash has lower unburned carbon and smaller particle size with less cofiring ratio of biomass, which tends to support that the cofired fly ash could be included in concrete if the biomass is fired within a certain percentage [27].

* Tel.: +1 801-885-5287.
E-mail address: wangshuangzhen@gmail.com

0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.09.045

Cube strength of the fly ash/hydrated lime samples depend on (1) water/cementitious ratio by Abraham's law, (2) sample dimension, (3) fly ash particle size, (4) fly ash reactivity (dependent on chemical and mineralogical compositions, particle size and morphology, etc.), (5) ratios of fly ash to hydrated lime, (6) curing time, temperature, environment, and other possible factors [2–20,21–31].

The differences in the fly ash chemical and mineralogical composition may account for the major strength differences. The active content in the glass phase of fly ash generally scales with the amount of reacted lime [24], but is not directly proportional to the strength build-up of the fly ash-hydrated lime systems [30,31]. Fly ash with high content of lime might behave similar to Portland cement in forming hydraulic bonds, and their compressive strength can be as high as 30–40 MPa with a curing time of 3–4 months, due to the combination of pozzolanic and cementitious reaction [32–35].

The mixing ratio of pozzolan and hydrated lime affects the sample's strength. The strength increases with the ratio of hydrated lime to pozzolan until a maximum strength is reached, beyond which it stays constant [36–39]. The critical ratio varies from pozzolan to pozzolan, but commonly lies within the range of 20–35% [15,37–38].

Curing temperature, in the range of 21 °C (low) and 38 °C (high), affects ultimate strength development in pozzolan–hydrated lime mortars and neat cement mortars, both of which show high earlier stage strength and low later stage strength [25,40–43]. Cement samples develop strength faster than those of pozzolan–hydrated lime mortar cured at the same temperature. This is consistent with the chemistry and kinetics of cement and pozzolan [15,16,39–41].

Due to the long term curing (up to a year) and the high surface area per volume of the samples, carbonation of raw material hydrated lime and the C–S–H gels of the subsequent pozzolanic reaction products [15–16], could highly affect the compressive strength of these samples [37,43]. Therefore, the samples were vacuum sealed in jars with nitrogen pre purge to be free from carbonation.

2. Experimental procedures

2.1. Material

Portland cement I and II, six fly ashes, hydrated lime, industrial silica sand and distilled water provided the fundamental materials for this investigation, and the same cement, fly ashes Class C, F and Wood were applied for the author's earlier research for studying the concrete's properties with 25% (mass) cement replaced by fly ash [2–6]. These had the following properties:

- Filler sand – industrial high purity silica sand (No. 30) chemical composition $\geqslant$99.5% SiO_2.
- Hydrated lime – regent grade hydrate lime with purity >99.5%.
- Mixing water – distilled water that blocks CO_2 disturbance and possibly other impurities in evaluation of pozzolanic reactivity and sample durability.
- Fly ash – the six fly ashes include:
  - ▶ Classes C and F from coal combustion;
  - ▶ wood from pure wood combustion;
  - ▶ 10P (10% switchgrass cofired with 90% Powder River Basin Coal, wt%);
  - ▶ 20P (20% switchgrass cofired with 80% Powder River Basin Coal, wt%);
  - ▶ SAW (20% sawdust cofired with 80% Powder River Basin Coal, wt%).

The sample elemental analyses by X-ray Florescence (XRF) appear in Table 1. A particle size laser analyzer (Coulter LS 100) determined the particle size distributions in Fig. 1. Wood fly ash particles, which are about 15–150 μm, are much larger than the other five fly ashes, which range from 1 to 50 μm.

2.2. Experimental design

The experimental matrix involves six fly ashes, three mass ratio of fly ash/hydrated lime (80/20, 70/30 and 60/40), three curing temperatures (23, 43 and 63 °C) and tested at six periods from one month to one year after mixing and the replicate is two. The mortar had mass ratios of binder (fly ash + hydrated lime): sand: distilled water = 1:2:0.5 in all cases except that wood ash mixtures needed a ratio of 1:2:0.65 to obtain the proper workability, as consistent with the results from the previous research by the author [5]. Neat cement mortar samples served as control for strength and all samples are 5 cm (two inch) mortar cubes.

The mortars filled 5-cm cubical molds and were generally demolded after 24 h, vacuum sealed (with appropriate nitrogen pre purge) with moisture curing. Then the samples were stored in three ovens at 23 °C, 43 °C and 63 °C, respectively. The compression strength of the cubes at 28, 56, 91, 182, 273 and 364 days after mixing provided the primary performance metric.

2.3. Sample mixing and curing

ASTM C 109 is the guideline for the mixing and molding process. Only Class F samples were cured for two weeks because they were too soft for demolding after 24 h in fog room. This result has paralleled the author's earlier work of 25% fly ash replacing cement in concrete: Class F fly ash has developed consistent low early strength (up to one month) in concrete than Class C and cofired biomass fly ashes [5] and its low reactivity has been further backed up by the subsequent SEM (Scanning Electron Microscopy) and microscopic analysis [3].

The samples were vacuum sealed in a CO_2-free and moisture-saturated environment in 473 ml (one pint)- jars to be free from carbonation [15–16], as in Fig. 2. Two cubes were stacked in each jar with a piece of wax paper for separation. A plastic ring with the height of 0.6 cm sitting at the bottom of the jar kept the sample from direct contact with distilled water. The water maintained essential moisture for sample curing. After nitrogen purging lasted for 5 min to drive CO_2 out, distilled water was added, samples were loaded and the jar was sealed with a hand vacuum pump (50.7 kPa, approx. 0.5 atm vacuum), as in Fig. 3.

The good vacuum sealing has been verified up to 12 months after the cured samples were ready for tests. The vacuum sealed samples were cured and tested on the scheduled days after mixing.

3. Results and discussions

Compression tests followed ASTM C 109 procedures using an Instron compression-testing machine. The maximum load was automatically computer recorded and later converted into pressure.

The mechanical performance reviews focus on four factors, fly ash type, mixing ratios of fly ash and hydrated lime, curing days and temperatures. The wood fly ash discussion appears separately because of its larger particle size and higher water ratio, as consistent with the previous research when replacing 25% cement (mass) by fly ash from the author [5].

Systematic one-way ANOVA (Analysis of Variables) on the full set of cube strength data (at 95% confident interval) are in Figs. 4–7. The general trends are as follows:

(1) Cofired biomass fly ashes (10P, 20P and SAW), develop about 2–3 times the strength of coal ones (Class C and F) and about 6 times the strength of wood fly ash samples (Fig. 4);
(2) Compressive strength increases with increasing mass ratios of fly ash: the strength increases from fly ash/hydrated lime 60/40, 70/30 to 80/20 consistently, but the differences are not statistically significant at a 95% confidence level (Fig. 5);
(3) Average strength and peak strength increases with decreasing curing temperature, but the differences are not significant at a 95% confidence level (Fig. 6). However, the data show that higher temperatures increase its early strength development but also decrease its later stage strength;
(4) One month's curing has developed typically 70–90% of the 12 month strength (Fig. 7).

3.1. Fly ash type

Compression strength of cofired 10P, 20P and SAW samples appears in Figs. 8–10. The strength generally increases monotonically (except for minor statistical variations) with curing time, and the major strength (70–90%) developed in the first month. At one month, the cofired ash samples generally develop (1) two to three times the strength of Class C or Class F samples; (2) five to eight