Construction and Building Materials 47 (2013) 616–622

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Benefits of adding rice straw coke powder to cement mortar and the subsequent reduction of carbon emissions

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HIGHLIGHTS

- Rice straw coke with steam carbonization can be transformed into useful materials.
- We examine the properties and effects of the added straw coke powder.
- Compressive strength is proportional to the square of driving capability of the strength.
- Provide a new application of recycling agricultural waste resource.

ARTICLE INFO

Article history:
Received 3 December 2012
Received in revised form 19 April 2013
Accepted 4 May 2013

Keywords:
Rice straw coke
Steam carbonization
Cement mortar
Carbon reduction

ABSTRACT

Pozzolanic materials have been used in civil engineering applications for many years. In recent decades, waste resources have become increasingly indispensable in construction and the built environment for developing feasible ways to increase recycling incentives and avoid pollution. In this study, rice straw coke powder with high carbon content was prepared from rice straw using steam carbonization. The physical and chemical properties of the coke powder were measured using the Brunauer–Emmett–Teller method and elemental analysis. Cement mortar samples were poured containing various coke additions of 0%, 1%, 2%, 4% and 8% so that compressive strength and unit volume mass measurements could be obtained to understand the effects of the added straw coke powder on the mortar's properties. The results showed that the rate of compressive strength increase (dp_t/dt) was proportional to the square of the cement mortar strength gains' driving capability ($p_e - p_t$). The strength evolution of the cement mortar was accurately described with a pseudo-second-order model. The highest specific gravity of the cement mortar was that containing 2% coke. The investigation into the addition of rice straw coke and the estimation of the mass of carbon fixed in the cement mortar illustrated a new possible application of this recycled agricultural waste resource. Such an application could be made for waste and carbon reduction in the construction industry, and would also lower the volume of greenhouse gases generated in civil engineering practice.

1. Introduction

Millions of tons of crop waste material, such as that from rice plants, corncobs, wheat plants, plane leaves, sunflowers, tobacco, bagasse and palm oil fuel, are produced from agricultural and industrial processes every year. Features of these agricultural waste resources such as high tenacity, low bulk density and high transportation costs make it difficult to use them as pozzolanic materials, with the exception of rice waste. Many research studies have been conducted to investigate the effect of the rice husk ask (RHA) on the properties of cement mortar. Givi et al. [1] have reviewed more than 60 articles on the use of RHA in mortar and concrete from between 1986 and 2009. Recent studies have found that RHA can inhibit or promote alkali-silica reactions in mortar and concrete depending on its particle size [2]. Concrete and mortar containing 25% RHA as a cement replacement have exhibited identical or better results compared to conventional concrete and provided the added benefit of reduced environmental problems [3]. Sata et al. [4] have mixed RHA and palm oil fuel ash to measure the W/B ratios needed for pozzolanic reactions in the Portland cement matrix. A good correlation has been found to exist between the surface area associated with the measured particle size distribution and the pozzolanic activity of the residual RHA [5]. The mechanical properties and durability of RHA concrete have been studied by [6–8]. All of the studies mentioned above have concluded that rice husks are an excellent source of pozzolanic material, and their use as such a material has contributed greatly to the

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0950-0618/$ - see front matter
http://dx.doi.org/10.1016/j.conbuildmat.2013.05.066

recycling of agricultural waste. However, no research has investigated the use of rice straw in cement mortar, not to mention rice straw coke obtained with steam carbonization.

According to Kadam et al. [9], 1.35 tons of rice straw is generated from every ton of harvested grain. Taiwan's rice production was 1.45 million tons in 2010 [10], meaning that 1.96 million tons of rice straw was left in the field. The common treatments for rice straw include on-site burning and burying. However, open burning is harmful to air quality and causes environmental harm due to the heavy smoke and CO_2 emissions produced. The large amount of methane emitted from rice straw burying causes serious greenhouse gas emissions. To avoid such seasonal air pollution, which is one of the major factors contributing to global warming, rice straw coke is a better way to reuse rice straw. Rice straw coke is generally produced with N_2 to avoid burning, but this method is more expensive. This study developed a new application for rice straw coke using steam carbonization and investigated the feasibility of using such an agricultural waste resource in the production of cement mortar.

2. Experimental program

This study consisted of two segments. First, the rice straw was steam carbonized into rice straw coke. The coke was then ground by a ball mill to a coke powder containing particle sizes that passed through a #200 sieve. 5-cm cubic cement mortar samples were then created by adding coke powder in percentages of 0%, 1%, 2%, 4% and 8% to a fixed-weight ratio of ordinary Portland cement, Ottawa standard sand and water. The compressive strength, unit volume mass measurements and pore size distributions of the samples were tested at different curing ages. The test results and scanning electron microscope (SEM) photos were analyzed and the effects of the rice straw coke powder on the properties of the cement mortar were investigated. The following sections describe the details of the materials and procedure.

2.1. Preparation of rice straw coke

2.1.1. Rice straw

Rice straw compositions can vary according to the species and location of the product, but there is no major variation in the main components. The most frequently analyzed components are as Table 1.

2.1.2. Rice straw carbonization

This section describes the carbonization process of the rice straw. The material was dried at 110 °C for 24 h, and then placed in a sealed ceramic oven and heated at a rate of 5 °C/min from room temperature to 450 °C. In the meantime, the steam generated from deionized water (Millipore, Milli-Q) in a heated tube was poured into the oven at a rate of 3 cm^3/min for 1.5 h [14]. After this heating step, the steam was transferred from the oven into exhaust pipes. Under such oxygen-deficient conditions, the rice straw was thermally decomposed to hydrocarbon compounds and porous carbonaceous material. Fig. 1 shows digital micrographs of samples of the rice straw and rice straw coke (×65 magnification). The rice straw coke remained in its original shape after the steam carbonization.

2.1.3. Elemental analysis (EA)

The samples were uniformly ground and oven-dried at 130 °C overnight. A sample of 3 mg was analyzed twice in an aluminum box using an elemental analyzer (Elemental Analyzer Model 611B, CH Instruments Austin, Texas, USA). An adjustment analysis with a standard sample of sulfonic acid was carried out in parallel with an ordinary sample analysis.

Table 2 shows the chemical compositions (C, H, N, S and O_{diff}) [15] of the raw and carbonized materials according to the elemental analysis. The carbon contents of the raw materials increased after being heat treated, while the oxygen contents decreased. The chemical C content of the raw material was 38.0 wt%, after which it was carbonized to char with a C content of 52.54 wt% by heating it for 1.5 h.

2.2. Preparation of cement mortar

2.2.1. Cement and sand

The cement used was Type I ordinary Portland cement manufactured by the Taiwan Cement Company. This cement had a specific gravity of 3.15 and a fineness of 3520 cm^2/g. Its physical and chemical properties met ASTM C150 specifications.

The reference sand was Ottawa standard sand that adhered to ASTM C778 specifications. This sand had a specific gravity of 2.63.

2.2.2. Mortar specimens

The rice straw coke was first ground by a ball mill to a coke powder with particle sizes that passed through a #200 sieve. Next, 50 × 50 × 50 mm cement mortar cube samples were created by mixing a fixed weight ratio of ordinary Portland cement, Ottawa standard sand, water and rice straw coke powder with various coke addition percentages of 0%, 1%, 2%, 4% and 8%. The mortar cubes were molded according to CNS1010 (Chinese National Standers: the testing method for the compressive strength of hydraulic cement mortar). A water-to-cement ratio (W/C) of 0.485 and a sand-to-cement ratio of 2.75 were used. The mortar was prepared in a Hobart type mixer with a capacity of five liters using two different speeds (low and medium). The mixing procedure was as follows. Dry cement and rice straw coke powder were first mixed at low speed for 1 min, then 2/3 of a part of water was added and the standard sand was mixed for 2 more min at low speed. Next, the rest 1/3 of a part of water was added and the mortar was mixed for 2 min at medium speed.

2.3. Tests and measurements

2.3.1. BET analyzes

The BET surface area of the carbon (S_p) was measured from N_2 adsorption isotherms at 77 K with a sorptometer (Porous Materials, BET-202A). Prior to this measurement, the samples were dried in an oven at 130 °C overnight and then quickly placed in a sample tube. Next, the tube was heated at 230 °C and evacuated for 4 h until the pressure decreased to less than 10^{-4} torr. The total pore volume (V_p) was deduced from N_2 adsorption isotherms according to the manufacturer's software, while the pore size (D_p) distribution by volume (dV_p/dD_p) was derived from the typical Barrett–Joyner–Halenda (BJH) theory [16]. The micropore volume (V_{micro}) and external surface area (S_{ext}) were deduced using *t*-plot method [17]. The surface area corresponding to the micropores (S_{micro}) was obtained from the difference between S_p and S_{ext} [18].

2.3.2. Fluidity and compressive strength tests

The flow value of the mortar was measured using a fluidity test according to the regulation in CNS 1012. The flow table's upper part was cleanly wiped and the plate was placed in the center of the flow table. Layers of mortar approximately 2.5 cm thick were then placed in the plate, after which they were tamped 20 times with a tamper. After filling the flow mold with mortar and tamping it as in the first layer, the plate was lifted smoothly and immediately allowed to fall down on the table 25 times from a height of 1.27 cm for 15 s. The diameter of the mortar was measured in the lower part four times at the same interval and the flow value was expressed as an average of this measurement. The compressive strength tests were conducted according CNS 1010.

2.3.3. Measurements of cement mortar specific gravity

More hydration products fill the voids of mortar specimens as their curing ages increase, and specimens therefore become denser as the compressive strength is increased. We investigated whether the continuous hydration process would increase the specific gravities of cement mortars with age growth and attempted to determine the relationship between the specific gravities growth and strength evolution. Cured specimens were weighed in the saturated-surface-dry condition. The weight of each specimen after 1 day of curing was normalized to 1.0000 for comparison with the weights at other curing ages. This phenomenon was consistent with the test results regarding compressive strength.

2.3.4. SEM study

A scanning electron microscope (JSM-5600, JEOL. Co., Japan) was used to study the rice straw coke powder. No pretreatment other than drying was required. To make the cured cement mortar specimen, cut samples were first oven-dried at 100 °C for 24 h and then cooled in a desiccator. The samples were then secured

Table 1
Rice straw compositions elemental analyzed.

The type of analyzed	Percentage of compositions
Main composition analysis [11]	C: 38.0%, H: 5.4%, N: 0.30%, O: 41.0%, ash: 15.3%
Approximate analysis [12]	Water: 13.6%, ash: 9.5%, combustible content: 76.9%
Micro-mineral analysis [13]	Si: 2.55%, K: 0.283%, Ca: 0.280%, Fe: 546 ppm, Al: 643 ppm, Ti: 42.2 ppm, Na: 342 ppm, Zn: 22.3 ppm, Mg: 1710 ppm