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Coal fly ash–carbide lime bricks: An environment friendly building product

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HIGHLIGHTS

- Strength controlling equations for coal fly ash–carbide lime bricks are proposed.
- Strength is governed by ratio involving porosity and volumetric binder content.
- Increasing curing temperature produces gains in strength up to a threshold.
- Energy required for heating (for curing at 40 °C, 60 °C and 80 °C) is assessed.
- Preferred strategies for attaining target strength are proposed.

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ABSTRACT

Coal fly ash and carbide lime are industrial by-products of coal combustion in thermal power plants and of manufacture of acetylene gas, respectively, available in profusion in southern Brazil. Research has been carried out to search for possible use of such materials to produce environmental friendly bricks that have high compressive strength. This study aims to evaluate strength controlling parameters of coal fly ash–carbide lime mixtures, as well as to show that porosity/carbide lime (η/L_v) ratio (corresponding to porosity divided by the volumetric carbide lime content) can be used to predict compressive strength (q_u). The controlling parameters evaluated here are carbide lime content, porosity, curing temperature, curing time and porosity/carbide lime ratio. A number of unconfined compression tests were carried out. The results show that a power function adapts better the relation q_u versus η/L_v, in which L_v is adjusted by an exponent (in this case 0.11) for all coal fly ash–carbide lime mixtures studied. Equations that control the compressive strength for each curing period and curing temperature examined can be formulated using this unique ratio. Preferred strategies for varying ranges of q_u are also proposed based on the energy required for heating, considering distinct curing periods and temperatures.

1. Introduction

The development of alternatives for reusing industrial by-products (e.g. fly ash, carbide lime) to produce bricks mostly brings environmental and economical benefits. Indeed, previous research has focused on assessing the use of by-products and wastes to produce building materials such as bricks (e.g. [14,10,19]). In southern Brazil, materials such as fly ash (by-product of coal combustion in thermal power plants) and carbide lime (by-product of acetylene gas manufacture) are profusely produced. However, they have been rarely used for engineering purposes, an overwhelming majority of them being placed in storage or disposal sites.

Several methodologies were established in the last decades (e.g. [20]) in order to determine the needed amounts of lime required for modification of material characteristics. Such methodologies intend to establish a threshold value, supposed to chemically satisfy the fly ash demand for lime, which has been often suggested as the starting content for construction expediency purposes. In spite of the numerous applications, there are no dosage methodologies for the assessment of a target fly ash-carbide lime strength, based on rational criteria as in the case of soil–cement technology, where porosity/cement ratio plays a fundamental role [5]. The need for such dosage results from the fact that fly ash-carbide lime shows a complex behavior that is affected by many factors, for example the physical–chemical properties of the coal fly ash, its porosity and the amount of carbide lime at the time of compaction (e.g. [17,22,2,8,9]).

This study therefore aims to quantify the influence of the amount of carbide lime and the porosity on the strength of coal

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Nomenclature

FA	fly ash content	t	curing time period
L	carbide lime content	T	curing temperature
L_v	volumetric carbide lime content	UCS	unconfined compressive strength
D_{50}	mean effective diameter	V_s	volume of specimen
Gs_{FA}	specific gravity of fly ash	η	porosity
Gs_L	specific gravity of carbide lime	η/L_v	porosity/carbide lime ratio
q_u	unconfined compressive strength	γ_d	dry unit weight
R^2	coefficient of determination		

fly ash-carbide lime bricks. It also seeks to evaluate the effect of curing temperature and curing time period, as well as the use of porosity/carbide lime ratio (η/L_v) to assess unconfined compressive strength. The focus here was therefore on the short-term effects (between 1 and 14 days of curing) of the carbide lime on the unconfined compressive strength of bricks made of coal fly ash-carbide lime mixtures. The physical–chemical mechanisms of temperature catalyzed reactions involving lime-fly ash blends have been extensively described in the literature in the last decades (e.g. [15,11,16,13,22,2]) and are not discussed but only referred in this manuscript.

2. Experimental program

The experimental program was carried out in three parts. First, the main physical–chemical properties of the coal fly ash and carbide lime were characterized. Next, the minimum amount of carbide lime required for full stabilization, based on the modified Initial Consumption of Lime (ICL) [20] was established. Then a number of unconfined compression tests were carried out as discussed below.

2.1. Materials

The fly ash (FA) selected [type F according to ASTM C 618 [1]] is a residue of coal burning in a thermal power station, located nearby Porto Alegre. The results of the FA characterization tests are also presented in Table 1. The material is non-plastic. The FA is classified as sandy silt (ML) according to the Unified Soil Classification System. A chemical analysis has shown that the fly ash is 66.3% SiO_2, 22.5% Al_2O_3, 2.8% Fe_2O_3 and 1.9% CaO. X-ray diffraction showed that the material is composed predominantly of amorphous minerals. The carbide lime, a by-product of the manufacture of acetylene gas, obtained from one source, was used throughout this investigation as the cementing agent. Physically, carbide lime is a fine grain material (about 95% passing 0.075 mm mesh). The chemical analysis showed that the carbide lime is 95.1% CaO, 1.5% MgO and 0.8% $CaCO_3$. The specific gravity of the carbide lime grains is 2.12. For the characterization tests and molding specimens for the compression tests tap water was used.

2.2. Methods

The minimum percentage of lime (regarding dry unit weight of coal fly ash) adopted in this work was established following results of Initial Consumption of Lime (ICL) method [20]. It was set up with basis on the interpretation of pH tests carried out on coal fly ash with carbide lime added – water (proportions of 1:3) mixtures. A minimum amount of carbide lime of about 4% is necessary to stop pH variation and reach a pH similar to the Standard solution. So, based on such result, 5%, 10% and 15% of carbide lime were chosen considering international experience with fly ash–lime [17,8,9,6,7,4,3,21]. This resulted in coal fly ash contents of 95%, 90% and 85%, respectively.

Table 1
Physical properties of coal fly ash sample.

Properties	Coal fly ash
Liquid limit	–
Plastic limit	–
Plastic index	Non-plastic
Specific gravity	2.16
Coarse sand (0.6 mm < diameter < 2.0 mm)	1.0%
Medium sand (0.2 mm < diameter < 0.6 mm)	4.0%
Fine sand (0.06 mm < diameter < 0.2 mm)	15.0%
Silt (0.002 mm < diameter < 0.06 mm)	78.0%
Clay (diameter < 0.002 mm)	2.0%
Mean effective diameter (D_{50})	0.015 mm
Uniformity coefficient	5
Curvature coefficient	1

2.3. Specimens molding and curing

For the unconfined compression tests, cylindrical specimens, 50 mm in diameter and 100 mm high, were used. After the coal fly ash, carbide lime and water were weighted; the coal fly ash and the carbide lime were mixed until the mixture acquired a uniform consistency [following ASTM D 3551 [23]]. The water was then added continuing the mixture process until a homogeneous paste was created. The amount of carbide lime for each mixture was calculated based on the mass of dry coal fly ash. After mixing sufficient material for one specimen, the mixture was stored in a covered container to avoid moisture losses before subsequent compaction. The time used to prepare, mix and compact was always less than 1 h. Two small portions of the mixture were also taken for moisture content determination.

Next, each mixture was compacted in three layers into a 50 mm diameter cylindrical split-mould, to a target dry density, moisture content and carbide lime content. The top of each layer was slightly scarified. After the molding process, the specimen was immediately extracted from the split mould, and its weight, diameter, and height were measured with accuracies of about 0.01 g and 0.1 mm. For each dosage point, three specimens were molded. They were cured in a steam curing chamber with a volume of approximately 1.3 m^3 at 40 °C, 60 °C and 80 °C for 1, 3, 7 and 14 days (the latter curing period just for 23 °C). The steam curing chamber had sprinkler and temperature probe to control humidity (about 100%) and temperature. The average energy needed to keep the temperatures of 40 °C, 60 °C e 80 °C in the steam curing chamber for an entire hour is 0.71 kWh (2.56 MJ), 0.92 kWh (3.31 MJ) and 1.37 kWh (4.93 MJ), respectively.

The samples were considered suitable for testing if they met the following tolerances:

- Dry density within ±1% of the target value.
- Moisture content within ±0.5% of the target value.
- Diameter within ±0.5 mm.
- Height within ±1 mm.

It is important to point out that the dry density of the specimens was calculated as the dry mass of the fly ash and carbide lime divided by the total volume of the sample. As the specific gravity of the carbide lime is 2.12 and of the coal fly ash is 2.16, for the calculation of void ratio and porosity, a composite specific gravity based on the fly ash and carbide lime percentages in the specimen was used.

2.4. Unconfined compression tests

An automatic loading machine, with maximum capacity of 50 kN and proving rings with capacities of 10 and 50 kN and resolutions of 0.005 and 0.023 kN, respectively, were used for the unconfined compression tests. The displacement rate adopted was 1.14 mm per minute. After curing in the steam curing chamber, the specimens were submerged in a water tank for 24 h for saturation and to minimize suction, bringing the degree of saturation of the specimens to at least 90%. The water temperature was controlled and maintained at 20 °C. Immediately before the test, the specimens were taken out of the tank and dried superficially with an absorbent cloth. Then, the unconfined compression test was carried out and the maximum load reached by the specimen recorded.

An average degree of saturation of 90% was obtained for specimens after submersion, irrespective of the initial porosity, carbide lime content, curing temperature or curing time period. The values of suction measured were low, ranging from about 1% up to 4% of the unconfined compressive strength. These measurements were made on the samples after failure in the unconfined compression tests