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Hazardous phosphor-gypsum chemical waste as a principal component in environmentally friendly construction materials

Vsévolod A. Mymrin*, Kirill P. Alekseev, André Nagalli, Rodrigo E. Catai, Cezar A. Romano

Federal Technological University of Parana, St. Deputado Heitor de Alencar Furtado, 4900 Campus Curitiba, CEP 81280-340 Curitiba, Paraná, Brazil

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ABSTRACT

Phosphor-gypsum (PG), lime production and gold mining wastes were used to fabricate solid bricks. The PG waste had a high content of heavy metals and a pH value near 13. The purposes of this research were to develop new composites from these wastes; to research the physicochemical processes of developed materials structure formation. The representative samples were supplied by local Brazilian plants. The PG waste had a high content of heavy metals and a pH value near 13. The chemical and mineralogical compositions of the raw and final materials were studied by complex of complementary methods: XRD, XRF, SEM, EDS, AAS and LAMMA methods. Developed materials exhibited axial strengths of 8.3 MPa on the 3rd curing day and of 13.7 MPa on the 365th day. After 28 days, the water resistance coefficient was 0.95, the water absorption ranged from 9.2% to 17.5%, the shrinkage was 0.75% and the leaching and solubility levels of heavy metals were very low. These values meet the demands of Brazilian materials like bricks, blocks, etc. It was determined, that mainly amorphous new formations are responsible for the materials strengthening. The biggest benefit of the developed materials produced at the industrial level is the environmental protection.

Introduction

Industrial production processes and numerous human activities share at least two characteristics: the waste of raw materials and of energy, which generally result in the generation of a considerable amount of wastes. John [1] described the utilization of a variety of industrial wastes in civil engineering applications and their influence on the construction quality.

The production of phosphoric acid (P_2O_5) from natural phosphate rock using the wet process results in an industrial byproduct called phosphor-gypsum (PG) [2]. Approximately 5 tons of PG is generated per ton of phosphoric acid produced, and the amount of PG generated worldwide is estimated to be approximately 280 Mt/year. Much of this waste is highly beneficial for crop production as fertilizer substitutes and soil ameliorants [3]. Up to 15% of the PG produced worldwide is used to create building materials, as a soil amendment, and to produce Portland cement [2,4]. The reuse of this waste is discussed in terms of both its agricultural benefits and the requirements for analyses required for its monitoring [3]. The use of PG in road building applications is based on technical, economic, and ecological criteria [5].

Youqiang [6] published a review of 24 Chinese literature reports of consumers that used large amounts of PG to produce blocks, boards, standard bricks, cementing materials, high-strength gypsum powder, ecological wall materials and other new building materials, sulfuric acid and cement, and to manufacture potassium sulfate using a two-step technique, among others.

The potential of using PG with fly ash and lime in the construction industry was investigated [7–9]. Shen [10] prepared a new type of binder with an optimum formulation, which consisted of 8–12% modified lime, 18–23% PG and 65–74% fly ash. Beretka et al. [11] reviewed the main sources, properties and uses of phosphor-gypsum, blast-furnace slag and fly ash and the possibility of their utilization. When heated at 1000 °C, PG transforms to phosphate, the fluoride–anhydrite impurities become inert, and anhydrite cement is produced [12]. Stout et al. [13] investigated the possibility of converting water-soluble phosphorus to less-soluble forms with lime or calcium-containing coal combustion byproducts to reduce the release of soil phosphorus in surface runoff.

Nayak et al. [14] studied the influence of PG when used as a calcium supplement in agriculture as fertilizer on the soil physicochemical properties, bacterial and fungal counts and

* Corresponding author. Tel.: +55 41 3279 4518; fax: +55 41 3232 2568.
E-mail addresses: seva6219@gmail.com, almaz.mymrina@gmail.com (V.A. Mymrin).

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activities of soil enzymes. Guo et al. [15] studied the melting and decomposition behaviors of PG to produce sulfuric acid. Garcia-Dias et al. [16] developed a new type of phosphogypsum–sulfur polymer cement (PG–SPC) for use in the manufacturing of building materials with uniaxial strength until 62 MPa.

Mining activities, including gold mining, involve the removal of topsoil, which leaves behind gold mining waste (GMW) and other materials after the extraction process [17]. In addition to being used to refill ore extraction sites, GMW can be reused in civil construction applications.

Research in northern Vietnam to obtain new materials using industrial wastes employed lime production waste (LPW) in powder form mixed with low-quality Portland cement to produce a cement composite, which resulted in a high-performance material [18]. A method was developed to utilize LPW, demolition wastes [19] and other types of wastes [20] as binders in the production of cement.

The increase in the production of PG and the need for increasingly large storage areas have led to a considerable need for the development of new economically and environmentally attractive methods to recycle this industrial waste. A review of the literature on the use of PG indicates that the main applications of PG still remain in agriculture, cement production and in the construction industry, which is the object of this study.

Therefore, the objectives of this study were as follows:

(1) Avoid the pollution of air, soils and groundwater by highly alkaline PG waste by developing new economically attractive composites of three types of industrial wastes with a maximum content of PG as the principal component combined with gold mining waste (GMW) and lime production waste (LPW) as a binder to produce construction materials whose mechanical properties meet the requirements of Brazilian technical standards. (2) Study the physicochemical processes involved in the formation of the structures of the developed materials during open air curing and measure their mechanical properties. (3) Develop technologies for the production of construction materials at the laboratory scale.

These objectives are consistent with the third paragraph of the Twelve Principles [21] of Green Chemistry (Less Hazardous Chemical Syntheses): “Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment”.

Materials and methods

Materials

To achieve the above objectives, the following experimental procedures were performed: collection, preparation and characterization of the wastes; definition of the compositions of the mixtures; and fabrication and testing of the mechanical and physicochemical properties of test specimens (TSs) during their strengthening.

All samples of industrial wastes used as components in this work were obtained from enterprises in Brazil. The PG sample was supplied by a phosphoric fertilizer plant. The amount of this waste in the industrial dumps of this fertilizer plant is roughly estimated to be 60,000,000 tons, and this plant annually produces 4,000,000 tons, half of which is utilized in agriculture and half of which is released into the dump. A lime plant supplied the LPW, i.e., incompletely burnt limestone, to serve as the binder material in the experiments. The gold mining waste sample was obtained from one gold mining enterprise in Paraná state, Brazil.

Methods

The raw materials and ceramics were characterized by the various methods. To determine the chemical composition it was used spectrometer of X-Rays Fluorescence Philips/PANalytical model PW2400.

The studies of mineralogical composition by powder method were done by X-Rays Diffractometer Philips, model PW1830, with monochromatic wavelength λCu-Kα, at 2θ range of 2–70°. Morphological structures – by scanning electron microscopy (SEM) on FEI Quanta 200 LV; wet samples of raw materials were dried in a vacuum unit. Chemical micro analyses were determined by method of energy dispersive spectroscopy (EDS) on Oxford (Penta FET-125 Precision) X-ACT and by micro-mass analyses through laser micro-mass analyzer LAMMA-1000, model X-ACT; solubility and lixiviation of metals from liquid extracts – by method of atomic absorption spectrometry (AAS) on PerkinElmer 4100 spectrometer; granulometric composition – by laser diffraction particle size distribution analysis on Granulometer CILAS 1064, Brazil; mechanical resistance – by axial compressive strength on EMIC universal testing machine DL10,000 EMIC. Water absorption coefficient by immersion was determined on Instrutherm BD 200 according to [22]. Linear shrinkage of TSs was determined with digital caliper of DIGIMESS. The water absorption (WA) was measured using an Instrutherm BD 200.

TSs with different compositions (Table 1) were compacted under a pressure of 10 MPa into 20 × 20 mm cylinders, which were stored in an open air environment. The contents of the components in the TSs varied in the following weight limits: PG 5–70%, GMW 15–75%, and LPW 10–20%.

The values of the mechanical properties and standard deviations were obtained as the average from 10 measurements of the TSs. The changes in the mechanical properties and the physicochemical processes of hydration and curing were examined at the following ages: 3, 7, 14, 28, 60, 90, and 180 days; 12 months; and 18 months.

The coefficient of water resistance (C_{WR}) values of the TSs was determined according to the [23] using the Eq. (1):

$$C_{WR} = \frac{(R_D - R_{SAT})}{R_{DRY}}, \quad (1)$$

where R_D and R_{SAT} are the uniaxial compressive strengths (MPa) of the dry and water-saturated TSs, respectively, after 24 h.

The water absorption values were measured according to [22] using the Eq. (2):

$$W_A = \left[\frac{(M_{SAT} - M_D)}{M_D}\right] \times 100 \quad (2)$$

where M_{SAT} is the mass of the water-saturated sample after 24 h of immersion and M_D is the mass of the dry sample after completely drying at 100 °C.

Table 1
Granulometric composition of PG and GMW.

Sieve, mm	Content of fractions, wt.%	
	PG	GMW
2.4	0	0.03
1.2	0	0.19
0.6	5.17	1.13
0.42	13.43	2.42
0.297	18.62	4.17
0.149	58.34	18.78
0.075	3.31	63.98
<0.075	1.13	9.30
Total	100.00	100.00