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Cleaner production of the lightweight insulating composites: Microstructure, pore network and thermal conductivity

R.T. Tene Fongang[a,b,*], J. Pemndje[b], P.N. Lemougna[b], U. Chinje Melo[b], C.P. Nanseu[a], B. Nait-Ali[c], E. Kamseu[b,d,*], C. Leonelli[d]

[a] Department of Inorganic Chemistry, University of Yaoundé I, PO Box 812, Yaoundé, Cameroon
[b] Local Materials Promotion Authority/MIPROMALO, PO Box: 2396, Nkolbikok, Yaoundé, Cameroon
[c] Groupe d'Etude des Matériaux Hétérogènes, Centre Européen de la Céramique, 12 rue Atlantis, 87068 Limoges Cedex, France
[d] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via Pietro Vivarelli 10, 41125 Modena, Italy

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ABSTRACT

Inorganic polymer cement paste was used as cleaner binder for the design of lightweight matrices as insulating envelopes and panels in building and construction industries. Sponge-like structure with a homogeneously distributed pore network, low density and low thermal conductivity permitted to classify the geopolymer–wood fiber composites promising clean insulating materials. Matrices with the density ~0.79 g/cm^3, bi-axial four-point flexural strength of ~4 MPa presented thermal conductivity between 0.2 and 0.3 W/(m K). The possibility of substituting the sodium silicate with rice ash-NaOH system and the efficiency of the matrices to constitute an effective tortuous road for the thermal gradient improved the sustainability and quality of this new class of products. The pores network and the microstructure approximated by a spatial periodic geometry suggested a "macro transport" mechanism to explain the movement of heat across the matrix of light geopolymer composite.
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1. Introduction

The conventional Ordinary Portland Cement (OPC) is the most common binder generally used to design low-cost lightweight insulating materials in the areas of building and construction [1–3]. However, apart from its high CO_2 released during the production process, the detailed investigations show that these materials possess poor aptitude when applying as fire-resistant materials [4]. In fact, One of the challenges in the design of mass cement-based materials is to avoid the generation of cracks, which is caused by the heterogeneous distribution of temperature and stress [1]. Thermal gradients in cement-based materials can induce internal stress which leads to cracking on a microscopic or macroscopic scale [1,4]. This explain the inefficiency of the OPC cement based insulating materials primarily due to their chemical composition and behavior in the context of variation of the temperature. The knowledge of the thermal conductivity and other thermal transport properties of construction materials involved in the process of heat transfer are essential in predicting the temperature profile and heat flow through the material [5,6].

Many authors have demonstrated the positive impact of the amorphous or disordered aluminosilicates as fly ash, silica fume, perlite, metakaolin, etc. on the transport of the lightweight concretes [2,3].

The porous and amorphous structure of inorganic polymer cements (IPC), often indicated as geopolymers, implies that flow in a thermal gradient will take a very tortuous route consisting of a multiple of neighboring interconnected polysialate particles [4,7]. This is enhanced by the nanoporous nature of IPC and their thermal stability range that reach 800–900 °C [8]. The difference in the thermal conductivity between the OPC (1.5 W/(m K)) [7] and the IPC (0.6 W/(m K)) [4,6] is linked to the chemical bulk composition, the densification, pore network and microstructure of the both matrices.

Kamseu et al. [4,6] demonstrated how the reaction that implies the corrosion of alumina can be used to increase the insulating behavior of the IPC. It was possible to decrease the thermal conductivity of the dense IPC matrix down to 0.15 W/(m K) [4,6]. The authors also noted the possible and significant impact of the pores coalescence into the heat transfer with the consequence on the

* Corresponding authors at: Local Materials Promotion Authority/MIPROMALO, PO Box: 2396, Nkolbikok, Yaoundé, Cameroon.
E-mail addresses: rftene@yahoo.fr (R.T.T. Fongang), kamseuelie2001@yahoo.fr (E. Kamseu).

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efficiency for thermal insulation: decrease in mechanical strength and increase in permeability and thermal diffusivity.

The challenge regarding the mechanical properties, the pores coalescence and the thermal diffusivity were joined together to address the increasing demand for more environmentally friendly and sustainable materials and the desire to propose a useful recycling possibility to the natural wood fibers (saw dusts) from the wood industries in Cameroon and tropical areas motivated the authors of this work. The current work marks a significant advancement into the research of suitable eo-sustainable materials with thermos-regulator properties. These properties include heat and humid climate management between the ⟨in-door and out-door⟩ flux of energy through building walls in tropical regions, thereby improving human thermal conditions in buildings. According to the principle of the Kyoto Pyramid, the most cost effective method of reducing energy usage is to provide better thermally insulated buildings.

A node aim of this work is to promote building energy conservation through the construction of green buildings. Wood fibers reinforced with geopolymer binders are evidenced here as products of the clean production linked to the increase of the efficiency of resource utilization rate, wastes recycling, reduce and avoid the generation of pollutants, protect and improve environment, among others. Cleaner production simply means the continuous application of measures for design, improvement, and reduction of energy consumption, use of by-products and sustainable raw materials. The specific objective is to combine structural and thermal conductivity behavior to propose functional materials capable to isolate efficiently while withstands the mechanical and environmental solicitations (stresses).

2. Cleaner insulating matrices

Cleaner production is a preventive, company-specific environmental protection initiative. It is intended to minimize waste and emissions and maximize product output [9]. The concept was developed during the preparation of the Rio Summit as a UNEP program (United Nations Environmental Programme). The program was meant to reduce the environmental impact of industry. It built on ideas used by The UNEP's program idea was described "...to assist developing nations in leapfrogging from pollution to less pollution, using available technologies". Starting from the simple idea to produce with less waste, cleaner production was developed into a concept to increase the resource efficiency of production in general.

Focusing the production of the insulating materials; substitution of raw materials and auxiliary materials (especially renewable materials and energy); increase in lifespan of auxiliary materials; re-use of waste or waste recycling [10], new, low waste processes and technologies are the main parameters to be considered according to Andrew e al. [11]. The SiO_2:Al_2O_3 ratio is the most important factor controlling Global Warming Potential for both metakaolin and bentonite meta-clay geopolymers (GWP). The lowest GWP can be achieved for mixes with SiO_2:Al_2O_3 ratios in the range of 3.5–4.0:1, which corresponds to ratios which provide highest strength. The hypothesis that it is possible to provide significant reductions in the GWP of clay-based geopolymers without affecting their chemical composition and therefore mechanical performance has been conclusively proven [10]. The use of multiple precursors, activators and curing temperatures for geopolymer manufacture can lead to complex mix design, but has the potential to reduce the GWP to a level well below that of "just add water" Portland cement [10–15]. The sawdust which is the principal raw materials here is a by-product considered as wastes in some situations. They are attractive materials based on natural renewable resources. Native crops/fibers, saw dusts are abundantly available in tropical regions over the world. They are biodegradable (crucial at the end of life of products), non-abrasive to processing equipment, are CO_2 neutral and are suitable to be used as acoustic and thermal insulators. Notwithstanding, they are light weight and have high specific strength. All these advantages make them eco-friendly and sustainable alternative to plastics and glass fibers. The authors of this work are projecting the recycling, to useful products, of a particular class of by-products that for their low density and bulk composition are not suitable in the production of pellets and energy. Regarding the IPC, it has been pointed that sodium silicate appeared with high GWP [10,11]. However, in Cameroon and in many tropical areas of the world, the presence of high proportion of rice husk ash is significant in development of binder matrix in the presence of high concentrated alkaline solution (NaOH or KOH). NaOH or KOH, as described by Heath et al. [11], has the lower GWP when the production cycle of IPC is considered.

3. Materials and methods

3.1. Materials and preparation of the lightweight composites

Scraps wood particles (sawdust) used in this study were obtained from wood factory located in Yaoundé area, Cameroon. It is a by-product of cutting, grinding, drilling, sanding wood; it is composed of fine particles of wood with 10 $\mu m \le \phi \le 2$ mm. The sawdust collected were dried for several months to insure the complete disappearance of humidity. The materials were then ground and sieved at 800 μm. The obtained powder presented a density of 650 kg/m^3 and thermal conductivity of 0.10 ± 0.02 W/(m K) from wood exploited for the production of sawdust. We chose sawdust were from white wood to avoid the presence of heavy metals and dense materials present in some highly dense wood in Cameroon. The calcination of white wood results in more than 98 wt% of loss of ignition. The wood is composed essentially of cellulose, hemicellulose and lignin.

The geopolymer cement used was designed on the basis of 100 g of metakaolin, 30 mL of NaOH (8 M) and 30 mL of Na_2SiO_3 (SiO_2/Na_2O molar ratio = 3.00). The metakaolin was obtained from the calcination, at 700 °C for 4 h, of the kaolin collected directly from the Mayouom deposit in the west region of Cameroon [16,17]. The chemical composition evidenced 44.35 wt.% of SiO_2 and 33.87 wt.% of Al_2O_3 [16–18].

The NaOH (sodium hydroxide, 8 M) were prepared from solid pellets, 98.99 wt%, from Sigma Aldrich, Italy. The Na_2SiO_3 (sodium silicate) was an industrial product from Ingessil srl, Verona, Italy having SiO_2 of 26.6 wt% and Na_2O of 8.86 wt% and ~60 wt.% of loss of ignition.

Cleaner production of the geopolymer pastes used rice husk ash obtained from an agricultural industry in Bamenda, Cameroon that is dissolved in situ into 10 molar solution of sodium hydroxide for 24 h and the solution adjusted with deionized water to have similar chemical formula as the industrial sodium silicate from Ingessil. The rice ash as from ICP analysis presented: 89.03 wt% of SiO_2 essentially amorphous, 2.23 wt% of Al_2O_3 and ~4 wt% of alkalis. The sodium silicate obtained is then directly used in the proportion described above for the production of the geopolymer paste used as a binder for the lightweight insulating composites.

For the preparation of composites, different volumes of sawdust calculated in relation to the volume of metakaolin were considered: 0, 50, 75, 100, 125, 150, 175 and 200 vol.%. The sodium silicate and sodium hydroxide were mixed firstly 5 min prior to the geopolymer preparation. The homogeneous solution is added to the appropriate amount of metakaolin and the paste obtained receive the sawdust and further homogenization took place. The fresh composite pastes

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