Construction and Building Materials 46 (2013) 142–149

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

The effect of limestone powder, silica fume and fibre content on flexural behaviour of cement composite reinforced by waste Kraft pulp

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HIGHLIGHTS

- Waste cardboard can be used to produce Fibre Cement Board (FCB).
- Limestone powder (10%) and silica fume (3%) can improve mechanical properties of FCB.
- Optimum fibre content to gain the highest flexural strength is 8%.

ARTICLE INFO

Article history:
Received 8 November 2012
Received in revised form 28 March 2013
Accepted 28 March 2013
Available online 22 May 2013

Keywords:
Waste cardboard
Cement board
Limestone powder
Silica fume
Mechanical properties

ABSTRACT

The need for sustainable, environmental friendly, energy efficient construction materials could justify the interest on fibre cement board produced from recycled waste cardboard. Waste cardboard has a low production cost and could show an appropriate compatibility with hydrated cement particles. This research was carried out in three phases. In the first phase of the research, the flexural behaviour of different amounts of fibre content (1–14%) in cement boards reinforced by waste cardboard was investigated. In the second phase, the optimum fibre content of 8% to achieve the highest flexural strength was determined. In the third phase, the effect of nanosilica fume and limestone powder on specimens reinforced by 8% fibre content was studied. The microstructure of specimens using Scanning Electron Microscope (SEM) was also carried out.

The results show that flexural strength of cement composite board can be improved by adding 10% limestone powder and 3% nanosilica fume.

1. Introduction

The need for sustainable, energy efficient construction materials has oriented extensive research on alternative materials; particularly waste materials that can reduce the cost and environmental impact of construction processes. Waste cardboard is considered as one of the largest source of waste materials, which contains natural fibres extracted from hardwood or softwood.

Over the last decades, researchers have carried out a wide range of studies on the use of natural fibre reinforced cement products in the construction industry. Natural fibres such as bagasse, bamboo, barley, banana, coir, cotton, flax, hemp, jute and straw are currently being investigated for their use in fibre cement products. [1–3].

Recently, the sustainable development policies have drawn the attention of researchers involved in cement composite to apply waste materials and fibres in cement board production. As some of the waste materials such as: wheat straw, rice straw, hazelnut shell, oil palm residues and waste timber are normally poor in strength and durability, the use of different methods of fibre treatment, applying admixtures and/or additives is unavoidable [4].

An appropriate behaviour of cement composite using wastepaper fibres in relation to fibre cement produced by reinforced virgin wood cellulose fibres has already been studied [5]. The accessibility of non-commercial fibrous wastes also supports their potential utilization throughout sustainable methods of production of building components [6]. Cellulose fibres used in cement composite can be produced by mechanical or chemical process. Kraft process is the one of the most frequently used chemical pulping method, which is appropriate to apply in cement composite board [7]. This process entails the cooking of wood chips with a mixture of caustic soda and sodium sulphide in a digester to break the lignin that is linking the cellulose components. In a research, cellulose fibres dispersed throughout a cementitious matrix by re-pulping the fibres in water. The re-pulped fibres were refined and then mixed with

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http://dx.doi.org/10.1016/j.conbuildmat.2013.03.099

cement, silica sand, and other additives to form a mixture [8]. The fibre–cement mixture is then deposited on a felt band substrate, vacuum dewatered, and cured to form a fibre reinforced cement matrix in sheet form. The suggested formulation to produce fibre–cement sheet was comprised of refined cellulosic fibres, cement and ground silica in the following proportions by dry weight of total mix; Cement 30–40%; Silica 50–60%; Fibre 5–10% and inert fillers such as limestone or calcium carbonate [8].

Microstructure of vegetable fibre–cement board and potential of alternative fibres in cement board production have been studied by Savastano and his group in many research works [6,9–11]. Based on their research acid compounds released from natural fibres reduced the setting time of the cement matrix. Fibre sugar components, hemicellulose and lignin can contribute to prevent cement hydration. This mechanism is explained in the following: Vegetable fibres are natural composites with a polymeric structure containing glucose units. Hemicellulose is also a polymer made of various polysaccharides. Lignin is an amorphous and heterogeneous mixture of aromatic polymers and phenyl propane monomers. Therefore, it is expected that the cement composite reinforced by cellulose fibres be threatened by a durability problem that hinders their development. Indeed, the lignin in natural fibres is attacked by alkaline cement, hence degradation in composites strength. Use of pozzolans for reduction of matrix alkalinity, immersion of fibres in slurred silica fume or carbonation of the matrix represent ways to solve this problem and have been investigated [12].

Some vegetable fibres such as coir, sisal, eucalyptus and malva, which are readily available in tropical countries, have been suggested to produce FCB [13]. In the research, in order to improve the durability of vegetable fibres in alkaline media, some considerations such as applying alternative binders with controlled free lime and using ground granulated blast furnace slag were suggested.

In order to improve the physical and mechanical properties of fibre–cement board, the proportions of sand 50%, limestone powder 30%, bentonite 1.5–3%, cellulose pulp 4% and silica fume 5% by the weight of cement were used in the production of cement composite [14]. The results showed that the combination of the aforementioned materials and fibres could lead to produce a cement board, which is appropriate for an external wall with low thermal conductivity.

Ground-granulated blast-furnace slag (GGBFS) has also been used in the production of cement composite to provide an adequate binder for vegetable fibre reinforcement for low cost housing [15]. The lower alkalinity of GGBFS compared to that of commercial ordinary Portland cement (OPC) can be advantageous, with respect to the long-term durability of natural fibre reinforced cement products.

The reduction of capillary permeability can be considered as a valuable step in the improvement of the mechanical performance of cement composite containing GGBFS with specifications such as; glass content of 99.5% in mass and 500 m^2/kg, Blaine fineness, which are activated by gypsum and lime in comparison to cement board containing solely OPC (ordinary cement Portland) [9]. A higher density proved the improved packing of the matrix combined with the more effective activation of GGBFS. Bonding in fibre–hydrated cement interfacial in the GGBFS composite is greater than OPC as the fibre surfaces have considerable matrix material attached to them.

2. Experimental

This research was conducted in three phases. In the first phase, Kraft pulp fibres obtained from waste cardboard were selected as reinforcements of cement matrix to produce FCB. The optimum fibre content to gain the highest flexural strength was the outcome of this phase. Then in the second phase, the effect of limestone powder and silica fume on mechanical behaviour of the specimens reinforced by the optimum fibre content was investigated separately. In the last phase, different combinations of both limestone powder and silica fume in conjunction with 8% fibre content were studied.

2.1. Materials and specimens production

2.1.1. Materials

The materials used in this research were; cement, water, waste cardboard, calcium carbonate and nanosilica fume which are described as follows:

Cement (*C*): ordinary Portland cement Type I compatible with BS EN 197-1.
Water: potable water was used for the preparation of specimens.
Kraft pulp fibre (*K*): these fibres were made from waste cardboard using the following procedure.

The cardboard was shredded into small pieces (≈10 ∗ 10 mm). Then their weight was measured. Potable water (water/cardboard ratio 4:1 by the weight of cardboard) was added to keep the shredded pieces submerged. After 3 days, the cardboard pieces were ready for further processing. The water was squeezed out manually and the pieces were blended in a mixer.

After about 2 h of blending, the cardboard pieces were changed into pulp. Then the water content of the pulp was determined by measuring the weights of wet and oven dried pulp. Then, the fibres were refined before using in the matrix in order to increase their lateral surface areas and to create micro fibrils, which could enhance the bonding strength between the fibres and matrix. Then the length of fibres using the Technical Association of the Pulp and Paper Industry (TAPPI) Test Method T 271 by an automated optical analyzer were determined. The length was 0.95 mm and the specific gravity was obtained as 1.5 by helium pycnometer.

To determine the shape of fibres, SEM studies were conducted. The fibres have a ribbon shape width of 22–24 μm and a thickness of 4–6 μm. This will be dealt with the details in Section 3.

Virgin Kraft pulp is produced using chips of wood in a pressurized vessel in the presence of hot caustic soda and sodium sulphide. The cooking process attacks and eventually dissolves the phenolic material called lignin that glues the fibres to each other in the wood. One of the most important chemical compositions of Kraft pulp is expressed by 'kappa number'. The kappa number (in the range of 1–100) which is applicable to all kinds of chemical and semi-chemical pulps gives the proportion of the residual lignin content in the pulp. The kappa number is determined by ISO 302:2004. A lower kappa number means less lignin. The kappa number is usually express by "*C*" multiplied by "*L*" where "*C*" is a constant ≈ 6.50 (dependent on process and wood) and "*L*" is lignin content in percent. The kappa number for waste cardboard used in this research is between 50 and 70.

In some of the specimens, the effects of two additives, limestone powder (*L*) and silica fume (*M*), were investigated. These materials were used as replacements for cement in some selected mixes.

Particle size distribution of calcium carbonate (limestone powder) was determined using a Malvern Mastersizer 2000 machine. The results are depicted in Fig. 1. As can be observed, the size of most particles is less than 50 μm. Other properties of limestone powder include: specific gravity 2.65, specific surface 575 m^2/kg, calcium oxide 53.5% and loss of ignition 43%.

Nano silica fume; the most important property of used amorphous-powder of silica-fume had 98.2% purity (including silicon dioxide 99.2%, calcium oxide, 3%, alumina 0.3% and other insoluble residue 0.2%), 2.2 specific gravity, 45–60 m^2/g specific surface and 50 nm average diameter of particles.

2.1.2. Mix design

In this research, two groups of mixes were designed, made and tested. For each test, six replicated specimens were made and the average results were considered as the representative of each mix design.

In the first group, a broad range (1–14%) of fibre content was applied in making cement board to identify the optimum fibre content. The outcome of this stage led to a recognition of the role of fibre content in the cement matrix, which will be clarified in the discussion section. The outcome of this stage showed that 8% fibre content could create better flexural strength for FCB.

Based on the achieved result of the first stage, the second group of mixes were designed to investigate the effect of additives (i.e. calcium carbonate and silica fume) on the flexural behaviour of FCB.

Table 1 shows the proportions of the ingredients of the composites mix for the first and the second mix design plan. In that table Portland cement is represented as (*C*), Kraft pulp fibres obtained from waste cardboard is represented as (*K*), limestone powder as (*L*) and silica fume as (*M*).

The number after any word like "*K*, *L* or *M*" in the mix code is the percentage of that material by the cement weight, which was used in the mixes.

It should be noted that in Table 1 the additives silica fume and/or limestone powder were replaced for the cement. For example, 'K8-L10-M3' comprises 8% Kraft fibres, 10% limestone powder and 3% silica fume. All the mix proportions are given by the weight of cementitious material (including cement + silica fume + limestone powder). As observed in Table 1, with increasing fibre content, the amount of cement decreases. This is due to observations in the laboratory so that with increasing