Light-weight Wood-MOC Cement Composite Building Products Made by Extrusion

Xiangming Zhou[1,*] and Zongjin Li[2]
[1] School of Engineering and Design, Brunel University, Uxbridge, Middlesex, United Kingdom UB8 3PH Tel: +44 1895 266 670, Fax: +44 1895 269 782, Email: Xiangming.Zhou@brunel.ac.uk.
[2] Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, Tel: +852 2358 8751, Fax: +852 2358 1534, Email: zongjin@ust.hk.
[*] Correspondence author

Abstract: Magnesium oxychloride (MOC) cement is a type of non-hydraulic cement with yellowish color in nature and low alkalinity exhibiting many other properties superior to the Ordinary Portland Cement (OPC). In this study, light-weight wood-MOC cement composite building products, with sawdust and/or perlite as aggregate, were made through extrusion. Physical, nailing and mechanical properties of these composites were investigated. It was found that the specific dry densities of the wood-MOC cement composites were close 1.0 and they were nailable like hard natural wood. Their flexural strength decreased as temperature increased. By replacing 50% sawdust in weight by perlite, the composite exhibited less die swell and higher temperature resistant performance.

Keyword: Magnesium oxychloride (MOC) cement; Extrusion; Die swell; Wood-cement composite; Nailing ability; Perlite; Sawdust

1. Introduction

Magnesium oxychloride (MOC) cement, also known as Sorel cement, is a type of non-hydraulic cement. As an air-dried magnesia-based cementitious material, MOC cement was developed shortly after the invention of Portland cement [1]. It is formed by mixing magnesium oxide (MgO) powder with magnesium chloride ($MgCl_2$) solution. MOC cement has many properties superior to the Ordinary Portland Cement (OPC) including: lower carbon emission, higher fire resistance, higher abrasion resistance, higher temperature resistance, lower thermal conductivity, lower shrinkage or creep and better durability [2]. MOC cement sets and hardens much quicker than the OPC making it ideal for rapidly repairing infrastructure, such as highway and airport runway. The lower alkalinity of MOC cement makes it good when using with glass fibers without the aging problem which is very common when glass fibers are mixed with OPC. MOC cement is also good for mixing with wood particles and sawdust to make wood-like composites and building products. One of the greatest advantages of these composites is that MOC cement has yellowish color in nature which is very close to the color of many natural woods. In wood-OPC composites, the lignin compounds and adverse chemicals in woods may retard the hydration of OPC, resulting in the wood-OPC composites having very low early strength. MOC cement, on the other hand, can largely reduce this problem, resulting in a perfect match between wood and cement for composites for building industry and residential applications, such as window and door frames, door panels, sidings, partition walls etc.

Light-burnt MgO, one of the raw materials required for making MOC cement, is normally obtained by calcinations of magnesite ($MgCO_3$) at a temperature of around 750 ^oC, which is much lower than 1400 ^oC, the temperature, needed for calcinations of cement clinker. The quality or reactivity of the formed MgO powder is largely affected by its thermal history (i.e., calcination temperature and duration) and particle size. This in turn affects both the reaction rate and the properties of the reacted products of MOC cement. The hydration of MOC cement takes place in a through-solution reaction with four main reaction phases being $2Mg(OH)_2.MgCl_2.4H_2O$ (phase 2), $3Mg(OH)_2.MgCl_2.8H_2O$ (phase 3), $5Mg(OH)_2.MgCl_2.8H_2O$ (phase 5), and $9Mg(OH)_2.MgCl_2.5H_2O$ (phase 9) [3]. It has been found that Phases 3 and 5 can exist at ambient temperature while Phases 2 and 9 are only stable at temperature above 100 ^{o}C [4]. Recently, the hydration, microstructure, and physical and mechanical properties of MOC cement and the reactivity of MgO in MOC cement have been thoroughly studied [5-8].

Extrusion is an advanced material processing technique that can be used to produce high performance fiber-reinforced cement-based composite building materials and products. In extrusion, semi-solid dough-like fresh cement mixture, normally reinforced by short discrete fibers, is forced through a die of desired cross section using either an auger or a ram. During this process, the fresh mixture is subjected to high compression and high shear, which densifies the cement matrix, improves the fiber-matrix bond, and aligns fibers in the direction of extrusion [9-11]. As a result, the mechanical performance and durability of the composites are superior to cast composites with similar mix proportions. As a material processing technology, extrusion has many superior properties as compared to other material processing technique in manufacturing building products, which include mass production with low cost, environmental friendly, low energy and water consumption, and better quality control of final products. This technique has gradually drawn research and industrial interests due to the increasing awareness of carbon emission, energy and water consumption. Recently, the European Commission has funded a 2.7 million Euro project – *Nanotechnology Enhanced Extruded Fiber Reinforced Foam Cement Based Environmental Friendly Sandwich Material for Building Application (FIBCEM)*, through the 7th Framework Programme to an inter-European Union (EU) consortium with 10 partners from 5 EU member state countries in which the first author was appointed as the Scientific Coordinator. The FIBCEM project aims at exploring a low-energy extrusion technology, to replace traditional fiber-cement techniques such as the Hatschek process which was invented more than 100 years ago and is still the main material processing technique in fiber-cement building material industry, for manufacturing cement-based building products like roof tiles and sidings to reduce labor and material costs, energy and water consumption, and carbon emission. Hatschek process for producing cement-based materials and products consumes much energy and water which is not sustainable while extrusion is more promising in energy and water saving [reference].

2. Materials and testing

2.1. Materials and mix formulations

In this study, light-burnt MgO powders, supplied as an industry raw material from Ji'nan, China, were used as one of the raw materials for making MOC cement, which had a purity of 96%. Another raw material for making MOC cement was $MgCl_2$ crystals, which was also industrial-grade chemicals with the purity of 98% from Israel. The chemical compositions of the light-burnt MgO powders are shown in Table 1 while the microstructure of MgO powders under Scan Electronic Microscope (SEM) is shown in Fig. 1. Sawdust, which was obtained from a wood workshop as residuals when cutting natural and/or recycled wood, was used as aggregates. The sawdust was incorporated into the wood-MOC cement composites without any special pretreatment. Perlite was also used to partially replace sawdust as aggregate, which was obtained from the same source as those used elsewhere [12] for making light-weight fire-resistant wall panels through extrusion technique. Perlite is a kind of light-weight cellular filler formed by heating the crushed natural volcanic mineral. The chemical compositions of perlite are also shown in Table 1. When this kind of glassy aggregate is mixed with OPC, it can undergo either alkali silica or pozzolanic reactions in wet environment [13]. The lower alkalinity of MOC cement, on the other hand, can largely reduce this adverse possible alkali silica reaction in MOC cement. In total, two light-weight wood-MOC cement composite materials were made and extruded using sawdust and/or perlite as aggregate. The mix formulations of these two composite materials are shown in Table 2. PVA and glass fibres are two types of fibres used to reinforce cement composites. PVA fibres are able to enhance ductility of cement composites but they have relatively lower strength, modulus of elasticity and ignition point compared with glass fibres. On the other hand, glass fibres are brittle and deteriorate quickly in the alkali environment of Portland cement. Magnesium Oxychloride (MOC) cement has lower alkalinity than PC so potentially glass fibres are able to be used in MOC cement composites to improve their strength and stiffness as well as their resistance to high temperature and/or fire. Therefore, it may demonstrate great advantage by hybrid usage of PVA and glass fibres in MOC cement composites. So in this study, a hybrid usage of PVA and glass fibres was adopted to reinforce the wood-MOC cement composites. The physical and mechanical properties of short discrete polyvinyl acetate (PVA) fibers and glass fibers mixed in the wood-MOC cement composites are shown in Table 3. It should be noted that glass fibres used for this study was not bundled rather they were separated. For each composite, two types of full-scale building products, i.e., door frame and door panel, were made through a single screw arguer extruder (as shown in Fig. 2a).

2.2. Preparation of fresh mixture and extrusion

To make MOC cement and prepare fresh wood-MOC cement mixture for extrusion, $MgCl_2$ crystals were dissolved into water to prepare a solution with the concentration of 25%. Then rheology enhancing admixtures, Polymer Polyacrylamide (PAM) and Carboxymethyl Hydroxypropyl Cellulose (CMC), were dissolved into the $MgCl_2$ solution one day before preparing the mixture for extrusion. To increase the dissolving of the high molecular weight rheology enhancing admixtures, PAM and CMC, in the $MgCl_2$ solution, water bath curing method was adopted in which the container with the $MgCl_2$ solution, PAM and CMC, was put in water bath with the temperature of around 60 ^oC for a couple of hours. Finally a transparent gel was reached. To prepare the fresh mixture suitable for extrusion, first, 2/3 MgO powder was mixed with around 2/3 sawdust and/or perlite in dry state for around 3 minutes. Then around 2/3 $MgCl_2$ solution, with the rheology enhancing admixtures, and 2/3 water were added into the mixture for another 3 minutes mixing with a higher speed. Then the remaining 1/3 MgO powder, 1/3 sawdust and/or perlite and 1/3 $MgCl_2$ solution were added into the mixture for another 3 minutes high speed mixing. Finally the remaining 1/3 water was gradually added into the fresh composite for another 2-3 minutes mixing till dough-like fresh mixture was reached. The fresh mixture was then fed into the hopper of the single-screw extruder (see Fig. 2a) to make the desired building products, i.e., door frame and door panel.

The door panel was extruded through a stainless steel die (see Fig. 2b) with the cross-section of 300 mm in width and 20 mm in thick, giving a nominal thickness of 20 mm for the products. The die land is around 150 mm in length along the extrusion direction. However, due to die swell, i.e., the extrudate expanded after being pushed out of the die, the actual thickness of the door panel varied which was greater than the nominal value, 20 mm. The inner geometries of the cross-section of the die used for extruding door frame is shown in Fig. 2c which also gives the sizes of the cross-section of the extruded door frame. The door-frame die land length is 420 mm along the extrusion direction, which is much longer than that of the door-panel die. Thus the fresh wood-MOC cement mixture was subjected to longer and stronger shearing and compressing in the door-frame die. Consequently, it was found that the die swell of the extruded door frames was much less than that of the door panels, giving the actual sizes of the extruded door frames very close to those expected (as shown in Fig. 2c).

2.3. Curing and sample cutting

Right after the fresh mixture was extruded out of die, it was placed under plastic sheet at normal laboratory environment with the temperature of around 20 ^{o}C and relative humidity of around 60% for 1 day. Then the extrudate was moved to a steam curing chamber with the temperature of 60 ^{o}C and relatively humidity of around 60% for 3 days. The hardened extrudate was then moved out of the steaming curing chamber and dried at normal laboratory environment for 1 day. Some of the hardened door frames made by extrusion are shown in Fig. 4. Some extruded door panels were cut into plate samples with 250 mm in length and 75 or 50 mm in width in a wood workshop using a cutter for wood. These plate samples were cut along either the extrusion (longitudinal) direction or the transverse direction (see Fig. 4 for illustrating where the plate samples were cut from an extruded door panel). The extruded door panel had a width of 300 mm, which was cut into 3 plate samples with the width of 75 mm each plus 1 plate sample with the width of 50 mm along the extrusion (longitudinal) direction. Along the transverse direction, plate samples were also cut with 250 mm in length and 75 or 50 mm in width. These plate samples were used for investigating physical properties and flexural strength of the extruded wood-MOC cement composites along the longitudinal and the transverse directions with and without being subjected to high temperature treatment. As aforementioned, MOC cement demonstrates many properties superior to PC such as better performance in resisting high temperature and higher fire resistance. But obviously wood particles have very low resistance to high temperature. Therefore, one of the purposes of this study is to investigate the performance of wood-MOC cement composites after high temperature treatment. Physical and mechanical properties of MOC cement composites with and without high temperature treatment were investigated and compared to assess the performance of wood-MOC cement composite in resisting high temperature. It was found that the hardened wood-MOC cement composites made by extrusion could be easily cut just like hard natural wood.

3. Results and Discussion

3.1. Bulk density and die swell ratio

As aforementioned, the nominal thickness of the extruded door panel is 20 mm while the actual thickness was greater than this value due to the die swell. In this study, the actual thickness was measured at three positions (as illustrated in Fig. 5) from each plate sample with the average value taken as its actual thickness, which was also used for calculating its bulk density and flexural strength. The die swell ratio is then obtained for each plate sample as:

$$Die\ Swell\ Ratio = \frac{Actual\ Thickness\,(in\,mm) - 20}{20} \times 100\% \tag{1}$$

In addition, the dry bulk density of each plate sample was calculated by dividing its weight by its actual volume. These results are shown in Tables 4 and 5, respectively, in which Table 4 gives the average thickness, bulk density and die swell ratio of plate samples made of Composite 1 with sawdust solely as aggregate and Table 5 those of Composite 2 with sawdust and perlite as aggregate. It can be see that both composites possess a density very close to that of water with Composite 2 demonstrating a slightly higher value than Composite 1. The die-swell ratio are comparable along the longitudinal and the transverse directions for both composites. Compared with Composite 1 in which only sawdust was incorporated as aggregate, Composite 2 in which 50% sawdust was replaced by perlite exhibited much smaller die-swell ratio, i.e., less than 50%

of that of Composite 1. This may be ascribed to the smaller particle size of perlite which filled in the gap among sawdust and wood particles with relatively larger size in the composite, resulting in a denser microstructure. However, the bulk density of Composite 2 was only slightly greater than that of Composite 1, indicating that partially replacing sawdust by perlite does not increase bulk density significantly but it can largely reduce the die swell of extruded wood-MOC cement building products to improve its volume stability which is very desirable.

3.2. Nailing ability

Nailing ability is an important performance for wood-cement composites. Methodology has been proposed for evaluating nailing performance of cement-based composite materials [14-15]. It has been concluded that a cement-based composite with good nailing ability should be easy to nail, have a high resistance to cracking, and to be able to hold the nail after it penetrates into the composite [15]. In this study, nails used in residential construction for wood were punched into the hardened extruded wood-MOC cement door panel and door frame using a hammer by hand to assess the nailing ability of the hardened wood-MOC cement composites. No quantitative analysis of nailing ability of the extruded wood-MOC cement composites was conducted. Rather, the nailing ability of these composites was evaluated qualitatively by naked eyes against the three criteria proposed by Kuder et al. [15]. Pictures of the hardened wood-MOC cement composites with nails punched in were shown in Fig. 6a. It can be seen that no cracking was found on the surface of the wood-MOC cement door panel and door frame around the nails. Thus it can be concluded that the dried wood-MOC cement composites were nailable. It is reasonably expected that that the nailability would be even better with a nail gun test due to much higher impact velocity. In addition, the hardened wood-MOC cement door panels and door frames were nailed together and a full-scale door (as shown in Figs. 6b and c in which Composite 1 was used) was made of these extruded products at the workshop. It was found that the hardened wood-MOC cement composites made by extrusion could be easily cut. Again, no cracking was found near the nailing connections in the door made by the extruded light-weight wood-MOC cement composites, which further proved that the extruded wood-MOC cement composites were nailable.

3.3. Weight loss and appearance after high temperature treatment

After the extruded door panels were cut into plates with 250mm in length and 75 or 50 mm in width along the extrusion (longitudinal) direction and/or the transverse direction, some plate samples were moved into an electrical oven to subject to high temperature treatment. These samples were heated from room temperature at around 20^{o}C to the temperature of either 250 ^{o}C or 500 ^{o}C at the rate of 3 ^{o}C/minute. After reaching the targeted temperature, the samples were remained in the oven for one hour. Then, the oven was turned off and the samples were still kept inside for another three hours, which was found long enough for the air temperature of the oven reducing down to room temperature. The plate samples were then taken out of the oven. Their weights were measured immediately and the weight loss ratio was calculated. The results are shown in Figs. 7 and 8, respectively, for Composites 1 and 2, respectively. Their appearance was examined as shown in Figs. 9 and 10 right after they were taken out of the oven. The samples were further cured at ambient temperature for 24 hours in the laboratory prior to measure their flexural strength. It can be seen from Figs. 7 and 8 that weigh loss ratio of Composite 1, with sawdust as aggregate, is greater than that of Composite 2, with 50% sawdust replaced by perlite, after being subjected to 250 ^{o}C, suggesting that sawdust contains more moisture than perlite. It was also found that Composite 1 cannot sustain temperature as high as 500 ^{o}C so that their performance, including water loss and flexural strength, at 500 ^{o}C were not investigated in this study. For Composite 2, the weight loss ratio can be as high as 45% after being subjected to 500 ^{o}C. As far as appearance, the color of Composite 1, with sawdust as aggregate, changed from yellow to light dark (as shown in Fig. 9a) while that of Composite 2 did not change much (see Fig. 9b), remaining white, the color of perlite, after being subjected to 250 ^{o}C. When the oven temperature further increased to 500 ^{o}C, the color of Composite 2 turned even whiter (as shown in Fig. 10) indicating that most sawdust may have been burnt. Thus, it can be concluded that partially replacing sawdust by perlite could increase the high-temperature resistant performance of wood-MOC cement composites.

3.4. Flexural strength

All door panel plate samples, including those with and without high temperature treatment, were subjected to four-point bending test with the span of 225 mm conforming to ASTM C-1341 using a MTS material test system under the stroke rate of 0.4 mm/min to obtain their flexural strength. In total, there were four sets of experimental results, i.e., those for Composite 1 along the extrusion direction and along the transverse direction, respectively, as shown in Fig. 11; and those for Composite 2 along the extrusion direction and along the transverse direction, respectively, as shown in Fig. 12. It can be seen from both figures that the flexural strength of the extruded wood-MOC cement composites decreased as the temperature increased. Composite 1 had higher flexural strength than Composite 2 in both the longitudinal and the transverse directions at room temperature, which may be ascribed to that there were more tiny wood fibers in sawdust in Composite 1 compared to Composite 2 which strengthened it together with the PVA and glass fibers. In Composite 2, 50% sawdust was replaced by perlite. Thus less wood fibers were in it. However, as temperature increased to 250 ^{o}C, the residual flexural strength of Composite 1 was lower than that of Composite 2 along both the longitudinal and the transverse directions, indicating that perlite had better fire resistance performance which protected the wood fibers in sawdust and the PVA and glass fibers to be less damaged in Composite 2, resulting in a higher flexural strength. In terms of the flexural strengths of the extruded composites along the longitudinal and the transverse directions, in general there was not much difference which may be because that the longitudinal and the transverse sizes of the door-panel die were comparable and fiber alignment in the near square flow field in the die was not significant, so that the flexural strengths along the longitudinal and the transverse directions were comparable.

4. Conclusions

In this study, light-weight wood-MOC cement composites were developed and building products, full-scale door frame, door panel and door, made of these composites were extruded. The physical, nailing and mechanical properties of these composites, with sawdust and/or perlite as aggregate, were investigated with and/or without being subjected to high temperature treatment. The following conclusions can be drawn:

(1) The wood-MOC cement composites made by extrusion were light weighted and their dry density were very close to that of water;

(2) Replacing 50% sawdust by perlite as aggregate can largely reduce the die swell and improve volume stability of the composites made by extrusion without increasing their bulk density much;

(3) Due to large volume of light-weight aggregates, sawdust and perlite, incorporated into the composites, the hardened wood-MOC cement composites were nailable like hard natural wood which is very desirable for residential applications;

(4) The weight loss ratios of the extruded wood-MOC cement composites increased as the temperature increased. The extruded wood-MOC cement composite, with 50% sawdust replaced by perlite as aggregate, exhibited much better high temperature-resistance performance; and

(5) The flexural strength of the extruded wood-MOC cement composites decreased as temperature increased along both the longitudinal and transverse directions. By replacing 50% sawdust with perlite as aggregate, the composite exhibited higher flexural strength, thus better high temperature resistant performance, after being subjected high temperature treatment.

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Tables

Table 1 Chemical compositions of light-burnt MgO and perlite (% in weight)

	CaO	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	K_2O	Na_2O	MgO	TiO	SO_3
MgO	1.4	0.8	0	0.8	0	0	0	96.6	0	0.1
Perlite	0.76	72.9	12.9	0.53	0.05	5.30	2.57	0.16	0.05	0

Table 2 Mix proportions for door frames and door panels (all values are in weight in g)

Composite	MgO	Sawdust	Perlite	$MgCl_2$ solution[1]	$MgSO_4$	PVA fiber	Glass Fiber	Water[2]	Other solution
1	3000	1500	0	3000	300	60	120	2150	450
2	3000	750	750	3000	300	60	120	2150	450

[1] The $MgCl_2$ solution had the concentration of 25% (in weight of $MgCl_2$) with 120 g Carboxymethyl Hydroxypropyl Cellulose (CMC) powder and 60 g Polymer Polyacrylamide (PAM) powder dissolved in both used as rheology enhancing admixture.

[2] Water added into the fresh composites consisted of two parts: (1) 1400 g PAM solution with the concentration of 3% (in weight of PAM powder); and (2) 750 g pure water.

Table 3 Properties of short polyvinyl alcohol (PVA) fiber and glass fiber

Fiber	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Length (mm)	Diameter (µm)	Aspect ratio
PVA fiber	1.30	1,500	36	6	14	430
Glass fiber	2.53	3,600	70	12	8	1,500

Table 4 Average thickness, density and die-swell ratio of wood-MOC cement Composite 1

Direction[1]	Average thickness (mm)	Density (Kg/m^3)	Die-swell ratio (%)	Direction[1]	Average thickness (mm)	Density (Kg/m^3)	Die-swell ratio (%)
L	21.275	1080	6.37	T	23.375	1031	16.88
L	22.675	1075	13.38	T	21.750	1014	8.75
L	22.750	1083	13.75	T	21.700	1020	8.50
L	22.550	1090	12.75	T	22.200	1040	11.00
L	22.500	1107	12.50	T	22.375	1039	11.88
L	22.375	1087	11.88	T	22.425	1043	12.13
L	22.775	1044	13.88				
L	21.550	1021	7.75				
L	21.075	1073	5.38				
Average	22.169	1073	10.85	Average	22.304	1031	11.52

[1] L means longitudinal direction and T transverse direction.

Table 5 Average thickness, density and die-swell ratio of wood-MOC cement Composite 2

Direction[1]	Average thickness (mm)	Density (Kg/m^3)	Die-swell ratio (%)	Direction[1]	Average thickness (mm)	Density (Kg/m^3)	Die-swell ratio (%)
L	21.425	1038	7.13	T	20.675	1099	3.38
L	21.125	1149	5.63	T	20.350	1130	1.75
L	21.725	1107	8.63	T	21.100	1188	5.50
L	21.000	1221	5.00	T	21.350	1201	6.75
L	20.625	1199	3.13	T	21.250	1209	6.25
L	20.150	1204	0.75	T	21.900	1210	9.50
L	21.050	982	5.25	T	21.075	1013	5.38
L	21.000	1003	5.00	T	21.300	1016	6.50
L	20.825	1026	4.13	T	21.250	996	6.25
Average	20.992	1103	4.96	Average	21.14	1118	5.70

[1] L means longitudinal direction and T transverse direction.

Figures

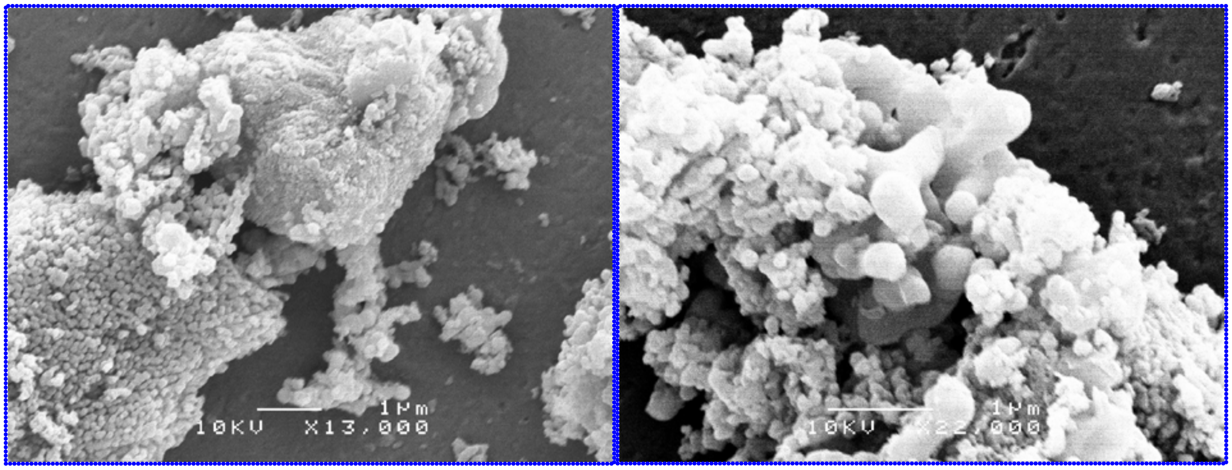
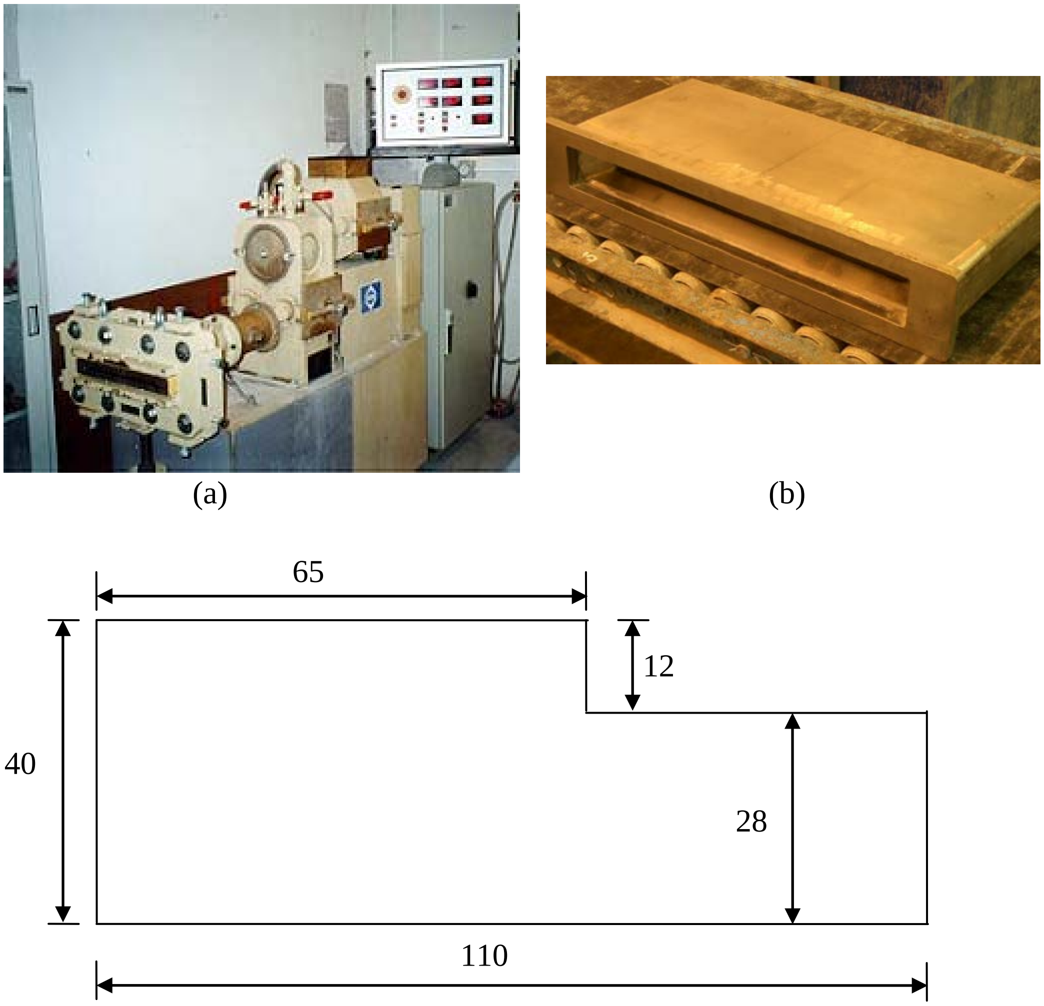


Fig. 1 Microstructure of the light-burnt MgO powder under SEM



(a) (b)

(c)

Fig. 2 The extruder and dies: (a) the single-screw extruder; (b) the door-panel die; and (c) the inner geometries of the door-frame die (all dimensions are in mm)

Fig. 3 Extruded door frames (note: in the right three door frames, MOC was partially replaced by fly ash, resulting in dark color, which are not investigated in this study)

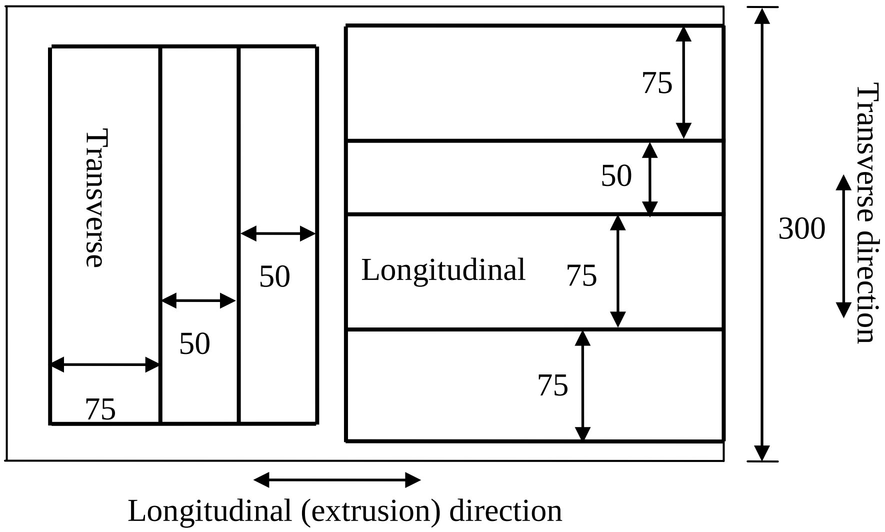


Fig. 4 Illustration for where door plate samples were cut from extruded door panel (all dimensions in mm)

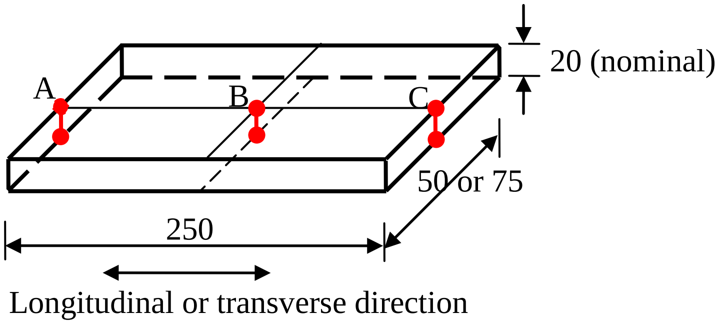


Fig. 5 Illustration for where the thickness of plate samples was measured (all dimensions are in mm)

(a) (b) (c)

Fig. 6 Nailing performance of the extruded wood-MOC cement composites: (a) door frame with a nail punched in; (b) door made of the composite; and (c) a corner of the door with frames connected by angle steel and nails

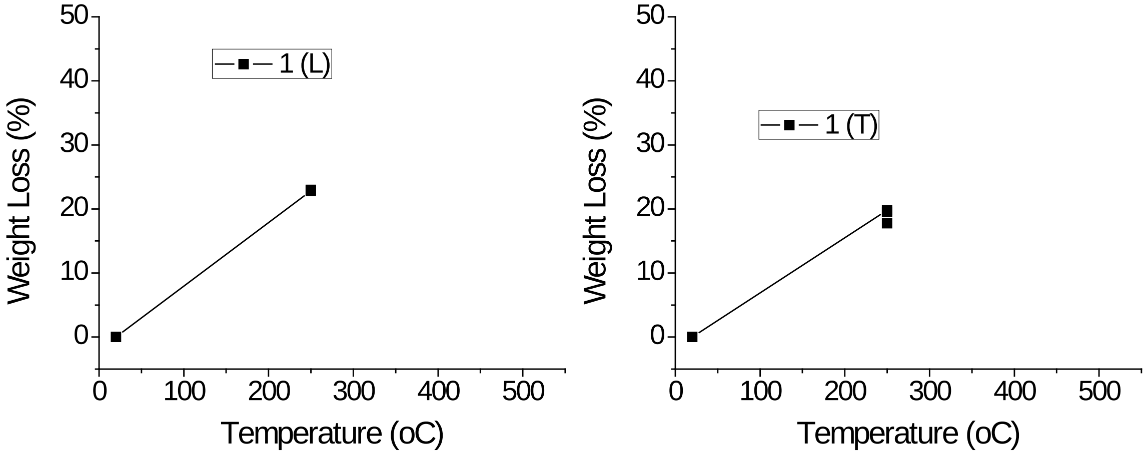


Fig. 7 Weight loss of Composite 1 along (a) the longitudinal; and (b) the transverse directions

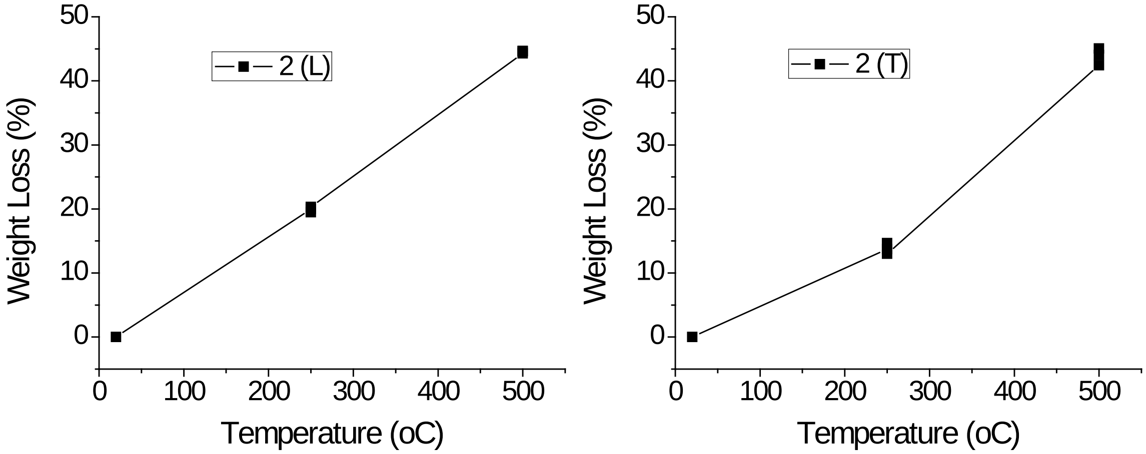


Fig. 8 Weight loss of Composite 2 along (a) the longitudinal; and (b) the transverse directions

(a) (b)

Fig. 9 Appearance of plate samples after being subjected to 250 ^{o}C: (a) Composite 1; and (b) Composite 2

Fig. 10 Appearance of plate samples after being subjected to 500 °C (Composite 2)

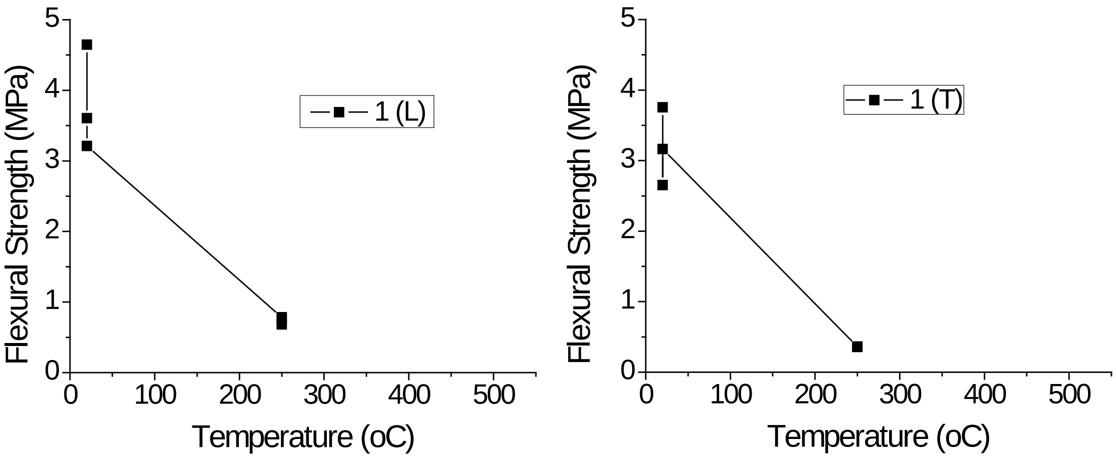


Fig. 11 Flexural strength of Composite 1 along (a) the longitudinal; and (b) the transverse directions

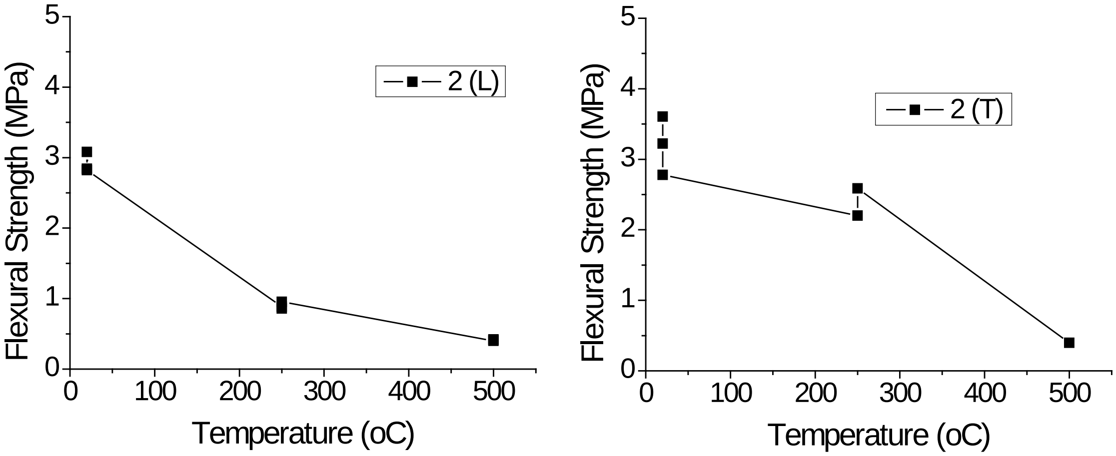


Fig. 12 Flexural strength of Composite 2 along (a) the longitudinal; and (b) the transverse directions