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**The Hong Kong University of Science &
Technology**

Department of Civil and Environmental Engineering



CIEM 6980 Project Report

Sustainable Building Panels Fabricated by Extrusion

Under the supervision of

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Submitted by

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03 June 2017

Abstract

The major objective of this thesis is production of fiber reinforced cementitious and High Volume Fly Ash (HVFA) based thermal insulated wall panels with expanded perlite (EP) by extrusion technique. This type of panels is expected to be green and energy-effective and exhibits good thermal insulation properties and sufficient mechanical strengths that are suitable for building products.

Due to thermal insulation properties of the expanded perlite, EP composition in extruded panel results in enhancing the temperature difference between inner and outer surface of the panel under steady thermal test from 3.68 in EP 0% to 5.24 in EP 30%. Temperature difference (ΔT) across the panels has been greatly improved when high EP% was used.

For mechanical property test, the flexural stress of the panels varies from 5-8.2 MPa and the mid-point deflection varies from 0.28-2.6 mm. The EP has a negative effect on compressive stress, elastic modulus and flexural stress. However, it is beneficial in enhancing compressive strain, flexural strain and flexural toughness.

In this project, the panels have been extruded with different proportions of cement, fly ash and EP composites by the extrusion technique, which can significantly improve the mechanical performance of cement composites. The thermal behaviors of extruded panels were investigated by one-dimensional heat conduction and simulated-room tests. It is observed that the thermal insulation was largely improved. The experimental results demonstrated that there could be a great potential for applying extruded thermal energy-storing panels in building constructions to improve energy efficiency.

The HVFA and cementitious panels with EP composite produced by extrusion technique have great potential for building industry as the energy-effective building products to satisfy the requirements of sustainable development of society, when the mixing proportion are chosen carefully.

Acknowledgements

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Chapter-1

Introduction

1.1 Background

Construction industry is one of the leading sectors of the energy consumption, especially for the increasing demand for thermal comfort, including heating/cooling, ventilation and air conditioning systems in buildings. Particularly, in extremely cold/hot areas, electrical energy consumption varies greatly during the day and the night partly due to domestic space heating/cooling. Such variation leads to a peak load period and an off-peak period (usually between midnight and early morning). These problems can be addressed by storing thermal energy, solar energy can be collected and stored during the day and released to indoor air when the room temperature falls at night. Also, cool can be collected and stored from ambient air by natural (or forced) convection during night in summer, and then released to the indoors ambient during the hottest hours of the day. These thermal energy storage mechanisms can decrease indoor air temperature swings and improve the indoor thermal comfort level.

Thermal Energy Storage (TES) makes a great difference in an effective use of thermal energy and has widely been used in diverse areas, such as solar energy collectors and building heating/cooling systems. TES can be accomplished either by using sensible heat storage or latent heat storage method. For sensible heat storage, the heat is stored or released accompanied with temperature change of the storage media, and much larger volume of material is required to store the same amount of energy in comparison to latent heat storage, in which heat can be stored or released as heat of fusion/solidification during phase change processes without temperature change.

Phase change materials (PCMs) for latent heat thermal energy storage is one of the most preferred methods for solar energy utilization due to the higher storage density and latent heat value. Heat is stored and given off by means of latent heat form during endothermic and exothermic process with more or less constant temperature during phase change process. PCMs had been considered for thermal storage in buildings to capture solar energy for maintaining internal air temperature.

Development of latent heat storage in the buildings structure can meet the demand for thermal comfort and energy conservation purpose. Thus, latent heat storage with PCMs, providing a high heat storage density and capability of storing a large amount of heat with a small variation of PCMs volume and temperature, is very promising in building construction in the future.

In order to improve thermal insulation performance of building materials, low thermal conductivity materials including expanded perlite, foam plastic, glass beads, sawdust and light expanded clay aggregate have widely been incorporated into building materials. In this study, the Expanded perlite (20%, 30replacement of cement) was used for decreasing the thermal conductivity due to relatively low conductivity of expanded perlite and admixtures.

1.2 Fiber reinforced cementitious composites (FRCC)

The objective of this study is to produce fiber reinforced cementitious composites panels with phase change materials by extrusion process. Fiber reinforced cementitious composites have made striking advances in recent years, involving the matrix, the fiber, the interface, and the composite production process and better performance in properties like strength, ductility, and toughness of the resulting composite.

The characteristics of Fiber Reinforced Cement Composites (FRCC) are largely influenced by the methods of processing. Comparing to the traditional method of casting, the method of extrusion produces varied shapes of FRCC under high shear and high compressive forces with improved mechanical properties, such as strength, toughness and ductility.

There have been a number of studies on the extrusion of FRCC and its applications. Long fibers reinforced cement composites have been proved to be high performance, however, it is generally difficult to manufacture long fibers reinforced cement composite due to low mass fraction of fibers. In contrast, short fibers reinforced cement composites are recommended due to fiber volume fraction increases, more uniformly distributed as well as simplicity of processing and fabrication.

1.3 Extrusion

Extrusion is a material processing technology for manufacturing semisolid paste-like products used in polymer, ceramics, food, and pharmaceutical industries. For more than two decades, the technology has also been applied in the concrete industry as an economical, efficient and environmentally friendly manufacturing method for short fiber reinforced cement based composites. With extrusion technique, complicated cross sections and shapes can be manufactured while traditional casting method is difficult to achieve, for example, various hollow sections and honeycomb cross section. The mass production and manufacture flexibility, especially for the fiber alignment can be achieved by this method. Due to the high shear and compression stress, the cement matrix is densified and thus the mechanical performance will be improved, which can release the strength loss by incorporating PCMs/lightweight aggregate composites. In addition, the parallel fiber alignment by extrusion can improve the mechanical properties and satisfy the structure requirement.

With incorporation of porous aggregate (EP) and phase change material (PCM), thin wall panel with improved thermal insulation performance can be manufactured by extrusion process. While thermostat system in building is one of the major sectors of energy consumptions, this kind of heat insulated building panel provides an efficient way to reduce energy consumption by improving efficiency of the thermostat system in building.

Advantages of extrusion technique include: continuous and easy to be employed, making it most suitable for industry mass production; manufacturing flexibility which enable it being capable of fabricating products with complicated shapes that the traditional casting technique is difficult to achieve; capability of improving the extruded products mechanical properties and durability under high shear and high compression environment generated by the extrusion process.

Though lots of high-performance cement-based composites reinforced by continuous long fibers have been fabricated, in general, the use of continuous long fibers can cause manufacturing difficulties, and fibers incorporated in these cement-based composites are usually within a low volume fraction. On the other hand, the use of discontinuous short fibers in cement-based composites is now becoming more and more popular because of its simplicity in processing and economy in fabrication.

As fiber volume fraction increases and the fibers become more uniformly distributed, they can hinder the growth of micro-cracks, suppress localization and substantially increase the first fracture strength and the post-peak load-carrying capacity.

There are two types of extruders, the ram extruder (batch type extruder) and the screw conveying extruder (continuous extruders). In this project, we will focus on the second type. Normally, for cementitious materials, the screw extrusion process will include kneading, feeding, conveying, plasticizing and pressuring. For kneading parts, usually a mixer is used to make sure all the raw materials are well mixed. For the other four parts, an extruder machine with one or more rotating screws is needed.



Mixer for extrusion



Single-screw extruder machine

During extrusion process, the mixture will undergo relatively high shear and compressive forces, which makes the matrix much denser and the interfacial bond between materials strengthened. Also this mechanism is suitable for materials that are brittle. In fiber reinforced concrete, using the extrusion technique, if the mixing process is well controlled, the orientation of the fiber can be modified into the load-bearing direction. It turns out that the FRC product of extrusion will have a lower porosity and a strengthened fiber–matrix bond, which leads to enhanced mechanical properties and durability. Also, except for the normal flat shapes produced by the old batch methods, complicated cross-sections and desirable shapes for building units can be modified by the extrusion technique.

With comparatively lower water to binder ratio, high strength, cement-based and shaped construction units can be manufactured in the factories effectively, and this exactly meets the requirements of construction industry. Moreover, applying the extrusion method can have reduced the curing time for the cement-based products due to the semi-solid nature of the materials.

Different kinds of geo polymers, like fly ash, silica fume, diatomite, etc., have been researched on the effect of the increasing strength. For silica fume, which is a by-product of silicon metal industries, usually it's very well fined, and will react with CH and water actively, making the capillary voids in the product filled to enhance the strength of the product. So it's widely used in producing high-performance and ultrahigh-performance concrete. As for fly ash, which is a by-product of thermal power plants, researches in the past 40 years have shown that incorporating fly ash into concrete can improve the workability due to the spherical shape and glassy surface of fly ash particles. Also, by replacing cement with fly ash, the hydration heat of fresh concrete can be reduced, which is good for mass concrete structure. Correspondingly, fly ash concrete will have a lower early age strength and longer initial setting time due to the low reactivity of fly ash. To solve this problem, alkali activator can be brought into the mixing matrix to active the fly ash. In the meantime, silica fume and fly ash can also be the replacement of ordinary Portland cement, which we call "supplementary cementitious materials" (SCMs). By incorporating them and other recycled materials in the concrete production, the product can be made as a high performance and green one.

But still, there are many difficulties in using the extrusion technique. One distinguished problem is the dimensional stability of the product. It has been proved that the extrusion of FRC is very difficult due to the demands of stabilizing the shape of the product and the effect of static zones in the flow pattern. The first one requires a high yield stress and viscosity for the product, while the second one, resulting from the setting and hydration of the cement, requires the yield stress and the viscosity to be limited. Another major difficulty is the liquid phase migration. During the extrusion, a compressive stress is applied to the paste, which will split between the solid skeleton and the liquid in the pores.

When there is a non-uniform variation of the stress across the mixture, a liquid pressure gradient will develop within the paste and then cause the liquid to flow relative to the matrix. Since the rheology of the paste is affected by the liquid content, liquid phase migration can affect the product quality and result in faster machine wear by forming the static zones.

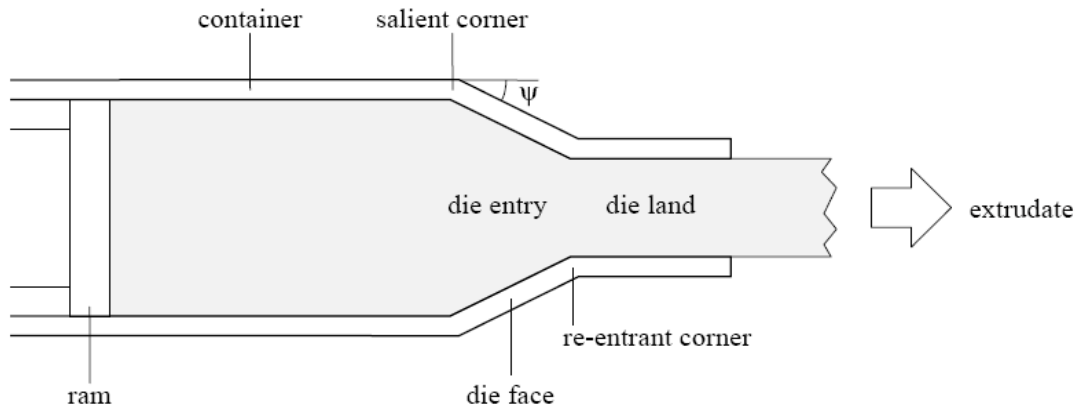
Therefore, a key point for a successful extrusion is to make sure the rheology is under control, leading to a proper design of the formula of the product. As for the requirements, the paste must be soft enough to flow into and through the extrusion die, and then after passing through the die, it must be solid enough to retain the shape. To satisfy these conditions, the addition of a polymer and plasticizer may be required.

1.4 Objectives of Study

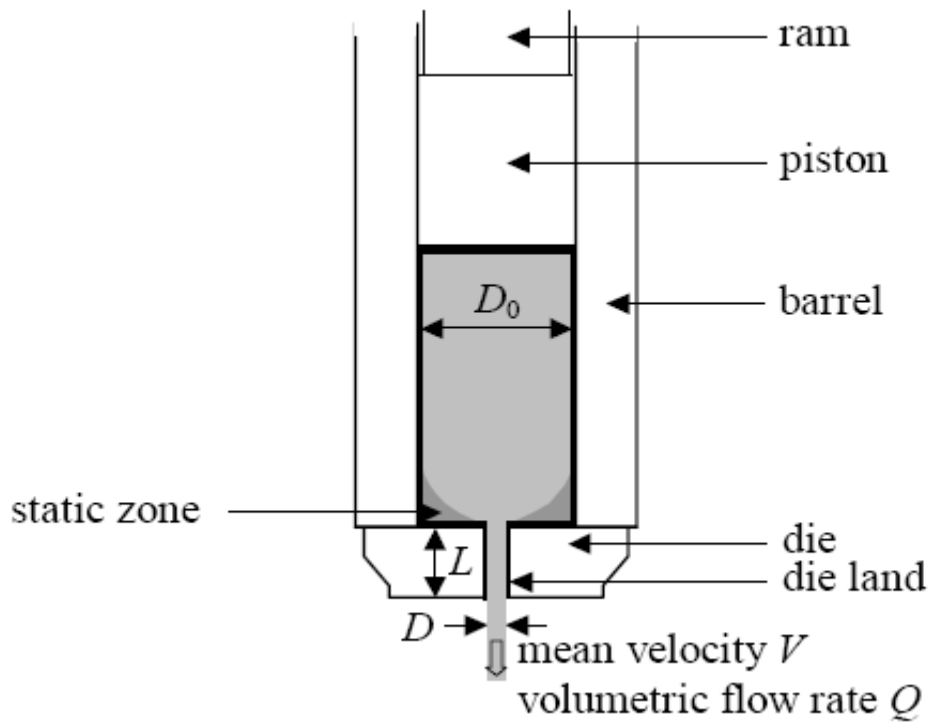
The present study aims to develop sustainable FRCC thermal insulated building panel with EP manufactured by extrusion process. This kind of panel has higher effective energy-storage capacity, lower thermal conductivity and satisfied mechanical properties and used as building structure wall or exterior walls to improve thermal comfort of indoor environment. To meet different requirements of thermal insulation properties, mechanical properties and rheological properties for extrusion, different mix proportions of extrude have been examined through flexural test and steady heat conduction test.

In this study, FRCC panels with different amount of expanded perlite (0%, 20% and 30% by volume) for thermal storage had been developed. The effects of EP composite on thermal behaviors, including thermal energy insulation and thermal energy storage were investigated by the steady heat conduction test and cyclic thermal test.

Also to test the mechanical properties different proportions of OPC, Fly Ash, Silica Fume and EP (HVFA- 0% Fly Ash, HVFA- EP 0% -Silica fume 10%, OPC-EP0 %, OPC-EP 30%, OPC-EP 30%-Fly Ash 10%, OPC-EP 30%-Silica Fume10%) are used for extrudite. As for the mechanical properties, experiments like bending test and stretching test were conducted to collect the data of the specimens in compression strength, flexural stress and then further deduced their strength and ductility.



Ram extrusion



Cross-section of ram extruder with square entry die

Chapter-2

Literature Review

2.1 Introduction to Fiber Reinforced Cementitious Materials

The first cement-based composite material manufacturing in an industrial level is the asbestos cement, which is a combination of ordinary Portland cement (OPC) and asbestos fibers. It was proved that this kind of cement showed a good performance in resistance and mechanical properties. Hardened cement paste is a brittle material, which has high compressive strength but low tensile strength and strain capacity as well. Failure mode of hardened cement paste therefore very often to be tension cracking due to brittle nature of itself instead of crushing of hardened cement paste.

Incorporating fiber reinforcement can make improvement of brittle behavior of hardened cement paste. Fiber reinforcement has been recognized as an effective reinforcement in cement composite, as it can absorb energy to improve tensile strength and prevent brittle failure of the cement composite. Fiber tends to be more closely spaced than conventional reinforcing bars, thus is better at controlling cracking. Also, compared to steel bars, the price, weight and amount of fiber applied to the matrix will be much lower, making it a good choice to achieve the properties. However, it is very important to recognize that in general, fiber reinforcement is not a substitute for conventional reinforcement.

By now, different kinds and volume of fiber have been applied in the manufacturing process. In this thesis, Fiber Reinforced Cement Composite is defined as a materials made from hydraulic cement and discrete, discontinuous fibers, along with no coarse aggregate. The type of fiber used in the experiment is the PVA fiber, and it is expected to increase the tensile, shear and flexural strength of the product, improve the facture toughness and the ductility of the cement composite as well as provide a better performance under dynamic loads.

Applying fiber will have a great effect because it can continuously carry tensile stress after the micro cracks have formed in the cement paste, since it is bonded inside the paste and can offer additional tensile strength.

In investigating mechanical properties of FRCC, different models and tests were included but not limited to compression; flexural and cyclic test was used to provide an accurate result.

A desirable FRCC should have improvement in tensile strength; shear strength, flexural strength, facture toughness, ductility, and performance under dynamic loads. Those improved properties benefit from fiber reinforcements are able to carry tensile stress across micro cracks in the cement matrix, which results from both the tensile strength of the fibers and the bond between the fibers and the matrix. However, fiber reinforcement is not a substitute for conventional steel reinforcement. Fiber reinforcement is more effective for crack control due to closely spaced fibers, while conventional steel reinforcement is for improving load-bearing capacity. Fig 2.1 illustrates the stress-strain curves for different types of cementitious materials.

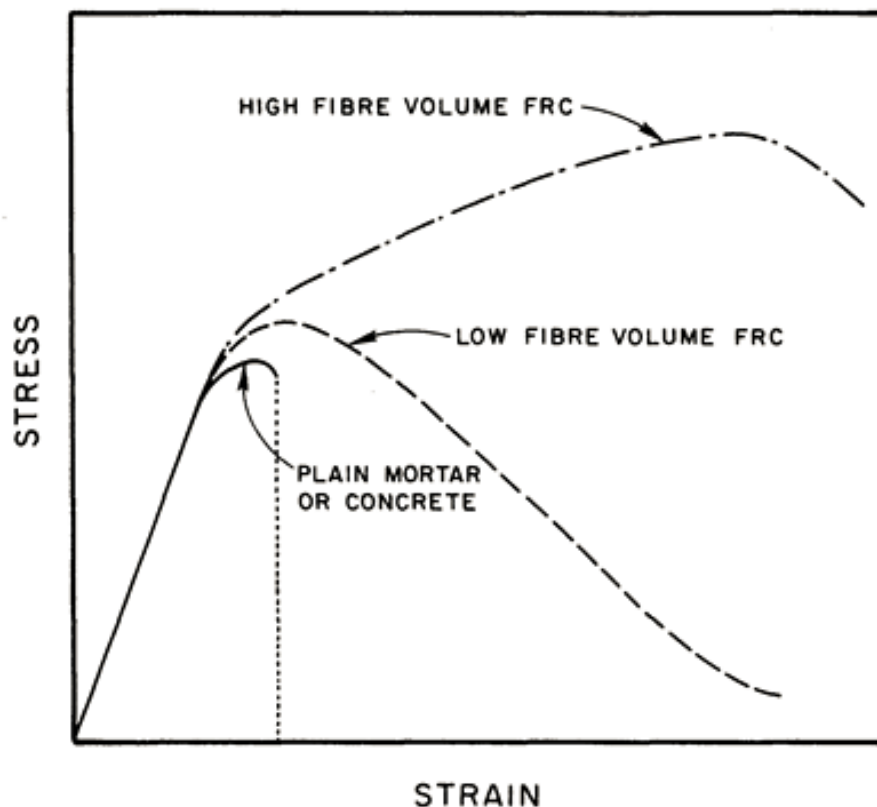


Fig 2.1 stress-strain curves for different types of cementitious materials

In FRCC, fiber reinforcement is responsible for the post-cracking zone in the stress-strain curve of FRCC as shown in Fig 2.1, in which the fibers bridge across the cracked matrix. Two functions are served by fibers in this zone.

- i) Strain hardening effect – the tensile strength of fiber is significantly higher than the matrix; resulting fiber reinforcement can carry out the loading across the crack of the matrix. This implies an ascending stress-strain curve after first cracking of matrix.
- ii) Strain energy absorption – the fiber bridging the cracks, breaks or pullout of fiber occur when loading increase. This will increase the flexural toughness as well as ductility of the composite, even when the stress–strain curve is descending after first cracking of matrix.

The sequence of events following first cracking in the composite determines whether these strengthening and toughening effects will take place. As cracking occurs in the brittle matrix, the load is then transferred to the fibers; if failure is to be prevented at this stage, the load-bearing capacity of the fibers, $\sigma_f V_f$, in the case of aligned and continuous fibers, should be greater than the load on the composite at first crack. This relation can be quantified on the basis of the elastic stresses at the cracking strain of the matrix in the composite, ϵ_{mu}

$$\sigma_f V_f > E_m \epsilon_{mu} V_m + E_f \epsilon_{mu} V_f$$

The sum of the term in right-hand side represents the first crack load of the composite. When the above equation is satisfied, brittle failure will not occur with the first crack appear in the composite, since loading is transferred to fibers. Additional loading will result in additional cracks, and then the matrix is divided into a number of segments, separated by cracks. When there is no further cracking occur, additional loading will result in breaking or pulling-out the fibers. Assuming that the composite consists of aligned and continuous fibers, which stretch under load, the slope in this range is $E_f V_f$ and failure will occur when the fibers reach their load-bearing capacity, at a composite stress of a $\sigma_f V_f$ for aligned and continuous fibers.

2.2 Extrusion Technique

The process of producing material of a specific cross section is called extrusion. A variety of materials can be produced by extrusion process. For homogeneous plastic material, the extrusion and flow properties have been well described by a number of studies. For cement-based material, the extrusion process can effectively produce a cement-based product with improved mechanical properties by limiting the water/cement ratio as well as voids ratio of the cement product. The mechanical properties of hardened cement composites produced by extrusion method are higher than the one by traditional casting method.

Those studies focused on FRCC with different types of fibers and with admixture such as viscosity or super plasticizers, those engineered FRCC shown optimized mechanical properties. Result has found that FRCC produced by extrusion technique have improved mechanical performance due to materials are formed under high shear and compression during extrusion. Regular or complex cross sections such as finely structured honeycomb panels, window and door frames, and wave-shaped roof tiles can be effectively manufactured by extrusion process in the fiber cement manufacturing industry, this results in reduced labor costs as well as production costs.

As we have stated above, extrusion of concrete is a forming process using plastic materials like cement to manufacture concrete product of constant cross-sectional shape. In this study we use the single-screw extruder to do the extrusion. A successful extrusion process relies on a careful and mature extrusion formula. Since different materials are used in the mixing process, one must know the chemistry and physical properties of them all to make sure the fresh product will be appropriate to be extruded. And the most important part of these is the rheology of the extrudate.

The performance of cementitious composites reinforced with short discontinuous fibers is comparable to that obtained with continuous aligned fibers or mats. However, the fiber cement manufacturing industry is still using a traditional processing technique called the Hatschek process, which was invented more than 100 years ago. This process has been the main production method for fiber reinforced cementitious roofing and cladding products. Although this process continuous, the products are usually brittle. A high level of wastewater is generated, delamination of layers has

been found in products made by this method during freeze–thaw cycles, relatively high sorption and permeability has also been found in those products. To make an improvement in fiber cement production industry, extrusion process could be an alternative processing technique. This forming process is continuous and effective than many traditional process, and thus it is desirable for industrial scale mass production for many products such as bricks, tiles, pipes and advanced product like honeycomb panels.

2.3 Rheological Properties of Fresh Cement Based Paste

Eugene C. Bingham, who also described it as “everything flows”, first uses the word “rheology”. Thus, it is the study of the manner in which the materials respond to applied stress or strain, or in other words, it determines both the flow and structure properties of the product.

In this study, we focus on the rheological behavior of fresh FRC, which can be classified as paste materials or soft solids. Pastes or soft solids are very common materials, but the behaviors of them have not yet been fully understood. One reason for this phenomenon is that their properties will change with time and strongly depend on their history. Since the cementitious materials undergo hydration during extrusion processing, the rheological behavior was found to change from time to time, which makes time dependence be considered. Also, we know that this kind of material comprises at least three phases, the liquid phase, the solid phase and the fiber. The liquid phase plays the most important role in determining the flow ability of the fresh concrete. The solid phase may be composed of very complex particle systems

Rheological behaviors and properties significantly affect the design of extruders and extrudability of a paste, which is also an important factor on the application of the extrusion technique. A fresh cement based material, which suitable for extrusion should exhibit semi-solid and dough-like rheological properties instead of normal fresh cement mortar, a high water/cement ratio and workability. Dough-like rheological properties indicated that the fresh cement paste should exhibit almost no fluidity but high cohesion during mixing or normal condition, it could only flow inside the extruder during extrusion. Differing from polymeric materials that exhibit a majority of viscous properties and become solid after being extruded out of the die-

exit due to a phase change, cement based dough-like materials tailored for extrusion exhibit combined elastic, viscous and plastic rheological properties. These combined rheological properties are needed to be characterized for application of extrusion, but not possible to examine with a single test. Fig 2.2 demonstrates a type of semi-solid dough-like fresh paste for extrusion.

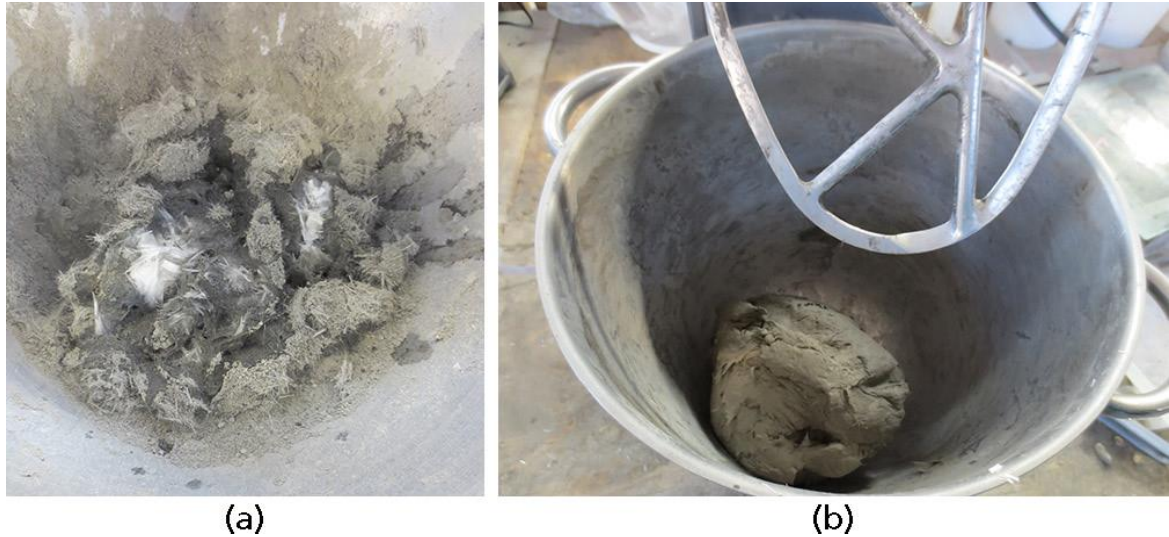


Fig 2.2 Semi-solid, dough-like fresh cement-based materials for extrusion

(a) During mixing not suitable for extrusion; (b) suitable for extrusion

A research found that the shear rate during mixing is highly related to the rheological properties of the fresh cement paste [12]. As agglomerated structure of the cement particles will break due to shear force, there are fewer agglomerates in a high shear-mixed paste. Increasing shear mixing rate will result in decreased viscosity and thus improved rheological properties of the paste.

Mixing time and water/cement ratio have been proved to be the major factors influencing rheological properties as well as extrudability of the paste by another independent research. Hydration process begins with the addition of water, and increases with time, lead to harden the paste and thus decrease the rheological properties. Water can be considered as a lubricant of the cement paste as water fills the inter-particle voids, thus increases the water/cement ratio resulting in improved rheological properties.

2.4 Raw materials

Different raw materials are used in this study to improve thermal and mechanical properties of panels like fly ash, silica fume, expanded perlite, Poly-Vinyl Alcohol (PVA) fibers, Super plasticizer (**ADVA 105**, 25% Solution) was added to improve workability, METHOCEL a member of cellulose ether family was used as lubricator agent to make smooth the surface of extrudates. It also has the water retention property, which is helpful in preventing water migration phenomenon. Deionized water was used throughout the experiments. Expanded Perlite (EP) was used as lightweight aggregate to reduce the unit weight of specimens. It also serves as thermal insulation agent to reduce thermal conductivity of materials.

2.5 Cement Replacement Materials

Different materials are induced in the concrete production process to serve as the binder in gluing the matrix together. The idea behind using these materials is to replace ordinary Portland cement (OPC) for environmental protection, since most of them are by-product of industry manufacture process. They can offer nearly the same chemistry components as OPC and hence gain a relatively satisfied strength for the final product. Each year, the concrete industry produces approximately 12 billion tons of concrete and uses about 1.6 billion tons of Portland cement worldwide. The process of OPC production will generate lots of carbon dioxide, which is thought to be one of the main factors that induce the global warming. Also, by replacing the OPC, by-product of the manufacture process will be reused and consumed, which are harmful to environment.

Various Cement Replacing Materials are used in this study including Fly Ash, Silica Fume and Limestone. Some discussed important properties were included but not limited to physical, chemical properties and effects on both fresh and hardened cement paste, forming a basis for utilizing CRM in cement paste.

2.5.1 Fly Ash

Fly ash is a by-product of coal combustion in thermal power plants, pulverized coal, a heterogeneous material that consists of various chemical compounds.

Fly ash particles are typically spherical in shape, ranging in diameter from $<1\mu\text{m}$ to $150\mu\text{m}$, having a specific surface area from $130\text{m}^2/\text{kg}$ for a bituminous ash to $581\text{m}^2/\text{kg}$ for a lignite ash and a specific gravity from 1.90 for a subbituminous ash to 2.96 for an iron-rich bituminous ash. The normal replacement of cement by fly ash is 25% to 30%. Research has showed that the replacement can be up to 60%

Chemical composition of most fly ashes are mainly consisted of SiO_2 , Al_2O_3 , Fe_2O_3 and CaO , other components are MgO , Na_2O , K_2O , SO_3 , MnO , TiO_2 and C . Depending on the amount of SiO_2 , Al_2O_3 and Fe_2O_3 in the fly ash, two general classes of fly ash are recognized by ASTM C618. Class F fly ash is produced from anthracite and bituminous coals, while Class C fly ash is produced from subbituminous and lignite coals. Also, Class F fly ash contain $<7\%$ CaO content so regarded as Low-calcium fly ash, while Class C fly ash can be contained $>20\%$ CaO content and so regarded as High-calcium fly ash.

Class F fly ash has only very little or no self-cementing properties, hydration reaction begins with the addition of alkalis or calcium hydroxide which is one of the hydration product of cement hydration, forming products like C-S-H , C_2ASH_8 and C_4AH_{13} . While Class C fly ash has self-cementing properties when mixed with water, hardening due to Ettringite, mono sulpho-aluminate hydrate, and C-S-H are formed.

The most notably effect of incorporating fly ash into concrete is the improvement of workability, since its spherical shape and glassy surface can help to reduce water demand. Also, the price of fly ash is much lower than OPC and comparing to OPC, the energy demand of processing fly ash is lower. However, one important issue of using fly ash to replace OPC is that the product will have a low early age strength and longer initial setting time, due to the low reactivity of fly ash. To overcome this problem, an alkali activator such as NaOH or KOH is used in the mixing process.

Chemical requirement of Fly Ash

Chemical Requirements	Mineral Admixture Class		
	N	F	C
Silicon Dioxide, Aluminum Oxide, Iron Oxide (SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃), min., %	70	70	50
Sulfur Trioxide (SO ₃), max., %	4	5	5
Moisture Content, max., %	3	3	3
LOI, max., %	10	6 ^A	6

2.5.2 Silica Fume

Silica fume (SF) is a byproduct of the smelting process in the silicon and ferrosilicon industry. The reduction of high-purity quartz to silicon at temperatures up to 2000° C produces SiO₂ vapors, which oxidizes and condense in the lower temperature zone to very fine spherical particles consisting of non-crystalline silica. Generally, the size distribution of a typical silica fume is provided as 20% below 0.05µm, 70% below 0.10µm, 95% below 0.20µm and 99% below 0.5µm, which is two orders magnitude finer than OPC and FA. Thus, it can be seen as a highly pozzolanic material. However, with a surface area around 20m²/g, the handling problems and the demands on the increase of the water requirement makes the use of super plasticizer become necessary.

By introducing SF into concrete, researchers have found that the workability of mortar might slightly decreased as the silica fume content increased. This is due to the higher specific surface of SF, which needs more water for complete hydration and for workability.

As for the durability of concrete with SF, since SF is highly active and readily reacts with CH and water to form secondary C-S-H, SF can consume a large amount of CH and generated C-S-H to fill the capillary voids. Thus, the porosity and permeability of concrete is greatly reduced and the durability is enhanced. Nowadays, SF is widely used in producing high- performance and ultrahigh-performance concrete world wide. Silica Fume has a particle size ranging from 0.03µm to 0.3µm, and a specific surface area of 20000m²/kg, such very high fineness and specific surface area will result in fastest reaction rate than any other cement replacement materials but still secondary compared to cement. Also, due to the high surface area of silica fume, water demand for silica fume cement paste is expected to be higher.

The chemical composition of silica fume is almost entirely amorphous silica with total 1-2% of SiO_2 , Al_2O_3 , Fe_2O_3 and CaO . The excessive amount of active silica provide sufficient reactant to react with calcium hydroxide produced by cement hydration, forming higher amount of C-S-H than any other CRMs.

2.6 Thermal energy storage

Thermal energy storage (TES) is a technique for capturing solar energy efficiently, which is a kind of renewable energy sources that can mitigate energy crisis and related environmental issues. TES is able to shift the peak load to off-peak load in electrical energy consumption, which can reduce the energy consumed by electrical generator. Thermal energy can be stored as sensible heat, latent heat, and thermo-chemical heat or combination of above.

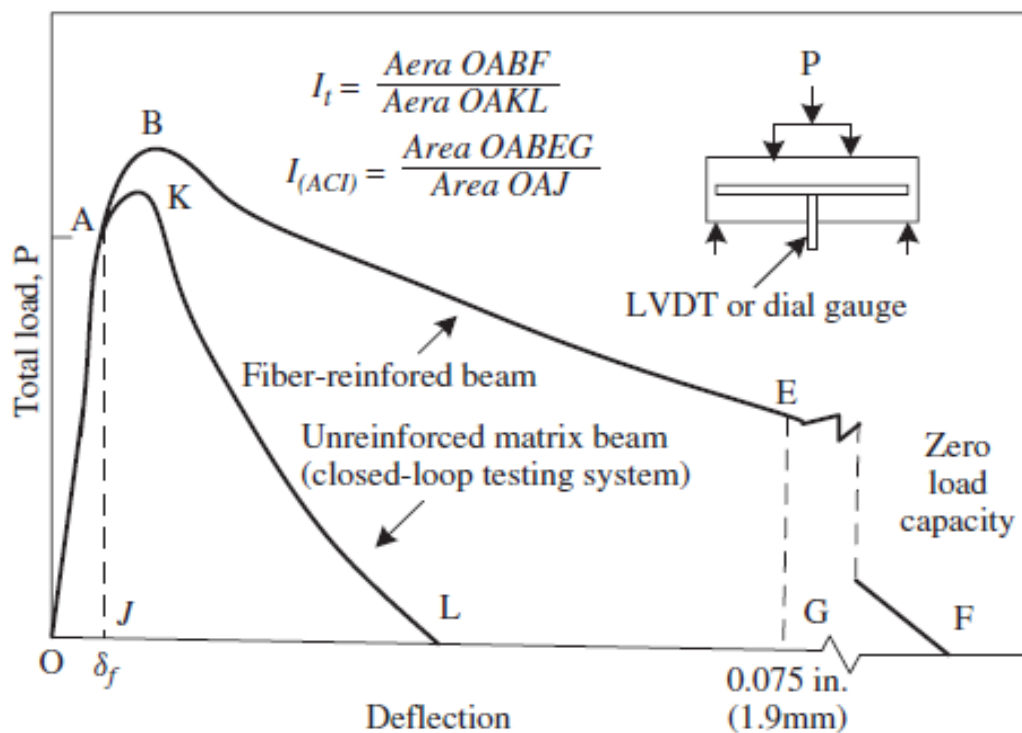
Nowadays, people are pursuing more comfortable environment for living. One of the concerned issues is the thermal comfort, which needs to keep cool during daytime and warm at night. And the relative property of this area is the thermal conductivity. Thermal conductivity is a very important concept in material science, electronics, building insulation and related fields. It is the quantity of heat transmitted through a unit thickness in a direction perpendicular to a surface of unit area due to a unit temperature gradient under given condition. This process is also related to a concept named heat conduction. Heat conduction is a mode of heat transfer in which energy is transported from high temperature region to low temperature region, through the interaction and energy exchange of different particles.

The heat from sunlight is stored by PCMs melting process and then, the stored heat is released by solidification at a lower temperature than its melting point at night. This cycle stabilizes the interior temperature, cuts off-peak cooling loads and decreases heating loads, which can greatly improve the thermal resistance of the building envelope. This delayed peak heat load caused by PCMs can balance the room temperature fluctuation and hence decrease the demand of thermostat system, which makes a great contribution to reduce a large amount of electricity consumption in a long period of time.

2.7 Mechanical Behavior of Fiber Reinforced Cementitious Materials

In the well-designed mixing matrix, fibers can benefit in both toughness and ductility. The major function of fiber in FRC composites is crack controlling, especially in the post-cracking zone, where the fiber can bridge the micro cracks before the matrix reach the critical flaw size.

After the formation of the first crack, fibers contribute to the toughness of the composite through dissipative means, but due to the interlock mechanism, the matrix phase still carries significant force. If the volume of fibers is increased in a proper range, the micro cracks can be better controlled by the arrest and bridging mechanisms. By doing so, the stresses of the fiber can be transferred back into the part of the matrix, which is still not fully under ultimate strength, to form more micro cracks, and therefore the toughness of the composites can be improved considerably.



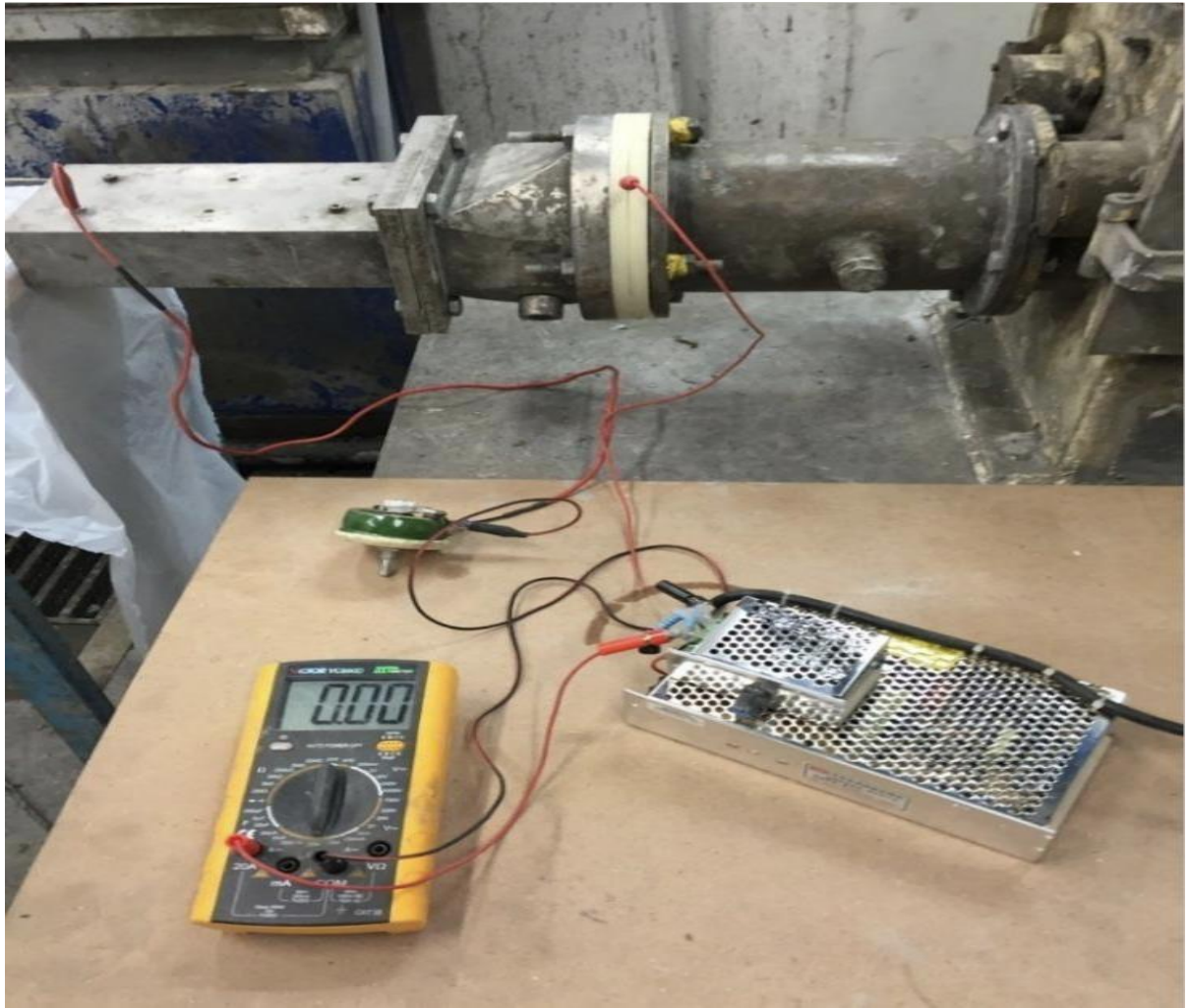
2.8 Lubrication device

The main difficulty of extrusion is the water migration in cement paste. One is due to water migration and the paste stuck inside the die and other one is that there are surface defects, which is also due to water migration.

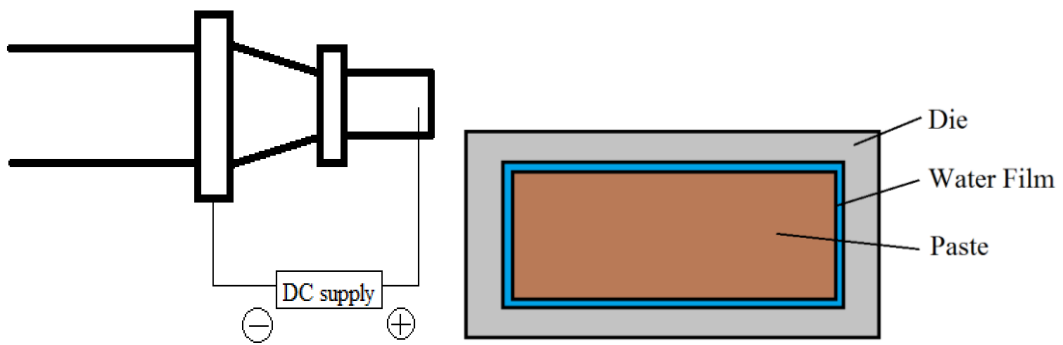
The water content will largely affect the rheology of the paste. If water migration happens during extrusion, the yielding stress of the paste, which runs out of water, will increase drastically and thus force it to stop in the die. Moreover, this will also lead to the fast abrasion of the machine. The reason why there will be water migration is that during extrusion, the paste is under a non-uniform stress. When there is such case across the mixture, it will generate a liquid pressure gradient within the paste and then cause the liquid to flow relative to the matrix.

In order to satisfy the rheology of the paste and reduce the friction of the die, low w/c ratio and oil lubrication are adopted. But for this lubrication, sometimes it is hard to control the dosage of the oil, neither too thick nor too thin is good for the extrusion. If the oil layer is too thick, it might sometimes become a resistance since the paste needs to overcome the adhesive force of the oil to forge ahead. If the oil layer is too thin, the effect of lubrication will be somewhat low. To fix this problem, people come up with an idea that, by using very little part of the water from the paste to form a water film, the lubrication layer can help the mixture to go forward and not critically affect the rheology of the paste and applying an electrical field in the die can solve this.

An insulator has to be used to separate anode and cathode. In this experiment, a circular insulator made by plastic is used. A DC voltage is applied at the screw chamber acting as anode, and relatively the shaping die as cathode. When the paste pass through it, the circuit between the die and the DC will be completed and thus force the water in pastes to migrate with the movement of electrodes to form the water film, which is very useful in reducing the friction between the paste and the die wall. This technique has been used by several institutions to extrude cement-based products such as bendy thin plate, honeycomb wall panel, thin pipe and U-channel, etc.



Electrical technique setup



Mechanism of the electric polarization lubrication device

2.9 Conclusion

This study has discovered the influence of various materials on typical cement paste, and materials like Expanded perlite (EP) that affects thermal conductivity. The combined effects of OPC, Fly ash, Silica fume and EP are examined in this research to find the mechanical properties of the building panels produced through extrusion technique.

Chapter-3

Experimental Study on Building panels Fabricated by Extrusion

3.1 Specimens

In this study, three types of composites are manufactured by extrusion process which are High Volume Fly Ash HVFA based FRCC, cement based FRCC and alkali activated geo-polymer composite. In each of the composite type, different proportion of EP and PCM are also incorporated to investigate the effects of EP and PCM on the thermal and mechanical performance. All specimens are then evaluated by flexural and steady heat conduction tests for mechanical and thermal properties.

3.2 Materials

The binder materials mainly used in this project are Ordinary Portland Cement (OPC), and Fly Ash. Cement Replacing Materials such as and Fume (SF) and Lime were also partially replaced with OPC. E The reinforcing fiber for FRCC of this project was Poly-Vinyl Alcohol (PVA) fibers. Super plasticizer in 25% solution form (ADVA) was added to the paste for workability. Methocel (MC), which is a cellulose ether family, a kind of rheology modifier, was added to lubricate paste and to smoothen the surface of extrudates. It can also retain water in the paste to avoid water migration Expanded Perlite (EP) as a lightweight aggregate was incorporated, to provide thermal insulation properties of the extrudates.

Table 3.1 Physical Characteristics of PVA Fiber

Physical properties	PVA Fiber
Diameter (μm)	15
Length (mm)	8
Density (gr/cm^3)	1.3
Tensile Strength (MPa)	1600
Elongation (%)	6
Elastic Modulus (GPa)	41

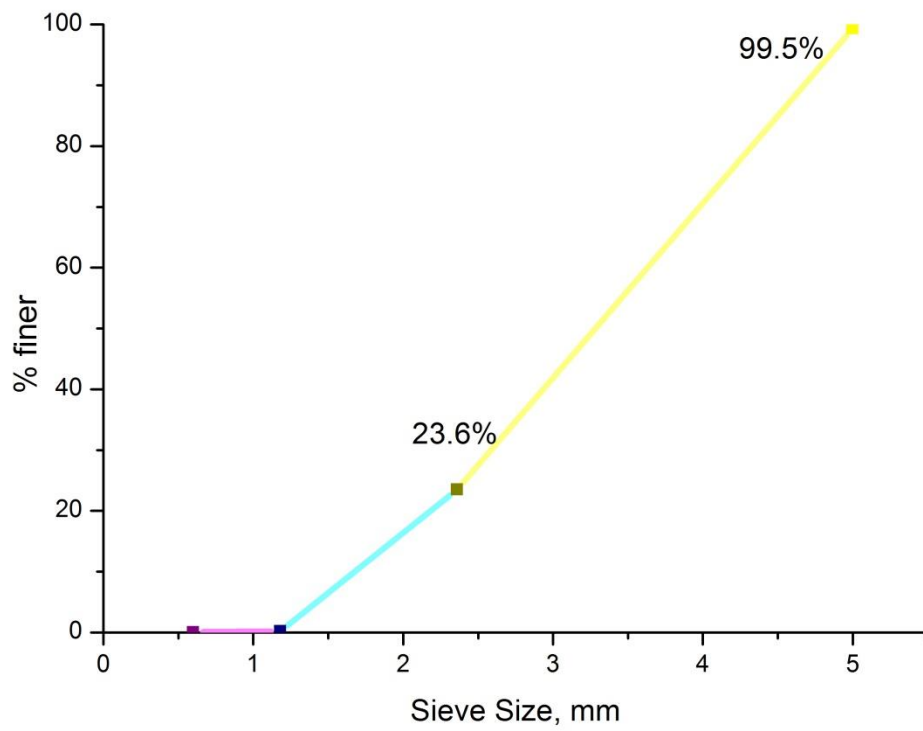


Fig 3.3 Sieve analysis of Expanded Perlite particle



Fig 3.2 Expanded Perlite

3.3 Equipment

- Extruder: PVL100.3, KEMA Fig 3.3
- Cutting Machine: Fig 3.4
- Mechanical Test Machine: 810 Material Test System: Fig 3.5
- Thermal Test Setup: Fig 3.6



Fig 3.3 Extruder (PVL100.3, KEMA)



Fig 3.4 Cutting Machine



Fig 3.5 Material Test System



Fig 3.6 Thermal Test Setup

3.4 Preparation of EP composite Phase Change Materials and fresh mixtures

Expanded Perlite is used as a Phase Change Composite for effective utilization of PCM in extrusion.

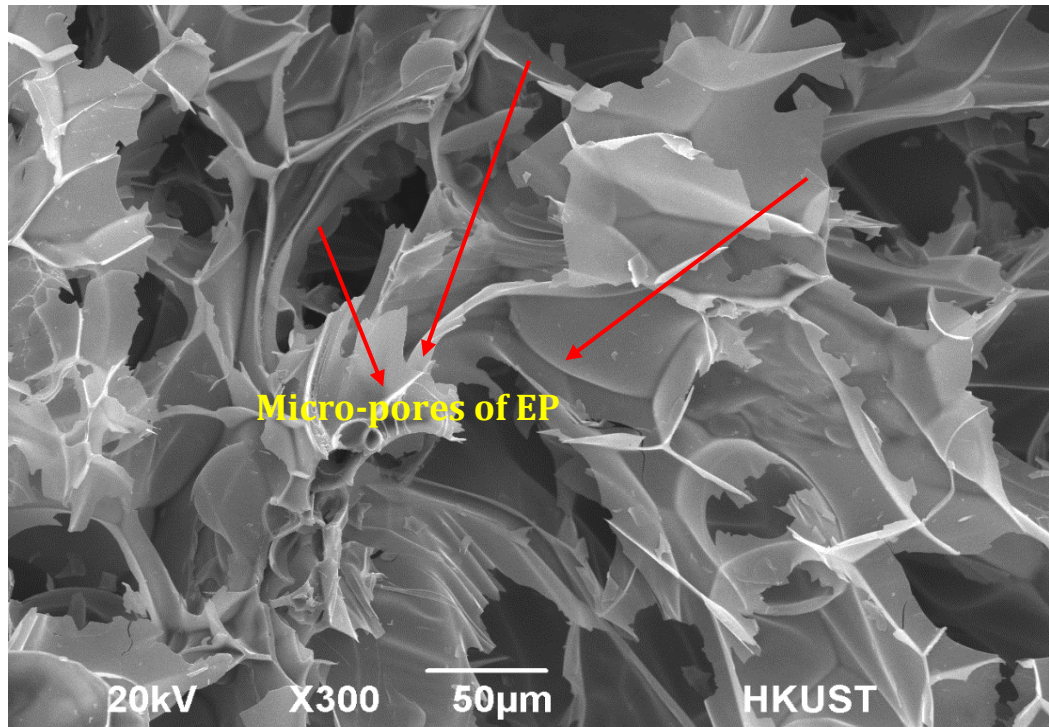


Fig 3.7 Micro-pores of EP

3.4.1 Mix Proportions

In order to examine the effect of EP on the mechanical and thermal insulation properties of extruded panels, totally 14 specimens were extruded with different mix proportion.

The Water to binder ratio was constant for all the trials and is 0.175.

The mix proportions of High Volume Fly Ash based and OPC based FRCC panels are shown in following table.

Specimen	OPC	Fly Ash	Silica Fume	Lime	EP(% Volume)	Fiber (% Volume)
HVFA EP0	0.5	0.5	0	0	0	1
HVFA EP0 SF-10%	0.4	0.5	0.1	0	0	1
OPC EP0	1	0	0	0	0	1
OPC EP30	1	0	0	0	30	1
OPC EP30 Lime-10%	0.9	0	0	0.1	30	1
OPC EP30 FA-10%	0.9	0.1	0	0	30	1
OPC EP30 SF-10%	0.9	0	0.1	0	30	1

EP refers to porous aggregate, and SF refers to Silica Fume. Binders are given in mass percentage, and aggregates are given in volume percentage. The number after abbreviation represents its volume percent of the specimen. The volume percent of PVA fiber is 1% of all extrudates, and mass percent of MC content is less than 1% of all extrudate.

3.4.2 Material mixing, Extrusion and Curing

The binder materials were first dry mixed for about one minute and water mixed with ADVA is then added, continue mixing until the paste was formed. PVA fibers were added and mixed for a few minutes to spread out fibers in every part of the paste. Additional ADVA was added if the paste could not form a dough-like mixture or the paste was too hard that is not suitable for extrusion due to lack of deformability. If the paste is able to squeeze out between the gaps of the finger instead of non-deformable due to interlocking effect, it indicated that the paste is a dough-like mixture and deformable with a reducing cross section. If the surface of the paste have no water appear after squeezed out from hand, it indicated that the paste is ready for extrusion process.

The paste was then feed into the single screw extruder with exit die having a cross section of 110mm in width and 20mm in thickness. Extrudates were placed on plastic sheet and pullout at the same speed as extrusion speed. The extrudates were first exposed to normal laboratory environment condition which temperature was around 25°C and relative humidity of around 50% for one day, and then curing in the curing room for 27 days to obtain optimal curing condition.

3.5 Tests on Extruded Panels

Two tests were conducted in this project for examining different mix proportions of extruded panels, which are flexural test for mechanical properties such as strength, toughness and ductility and steady heat conduction test for thermal properties using 810 Material Test System (MTS). For thermal tests, the actual setup and the schematic diagram of setup are shown in Fig 3.8. The applied heat of infrared lamp is applied to one side of the panel. By measuring temperature difference of two sides of panel, the thermal insulation properties and heat storage capacity can be determined.

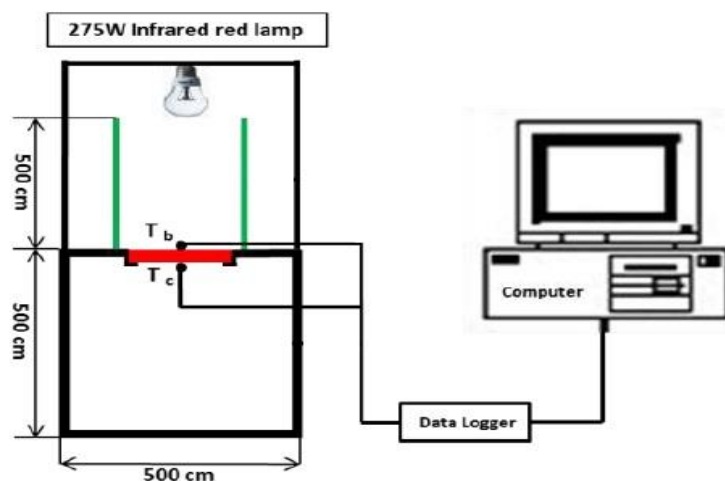


Fig 3.8 Schematic diagram of thermal test

Note: Red color represents the building panel; green color represents the reflective panel.

Chapter-4

Experimental Results and Discussions

4.1 Mechanical Test Results

Flexural performance is major criteria to determine the mechanical performance of the specimen since the extruded panel is a thin wall panel shape. Also, due to the actual application of the extruded panel and the geometry dimension of the panel, the panel is not expected to be a structural component and thus it is very likely to be carried flexural stress rather than direct axial stress. Therefore, It is good enough to consider only the flexural behavior of the panel to examine corresponding mechanical properties of the panel.

Four-point bending test is conducted on extruded panel to test the flexural property. The specimens with a support span of 150mm, a load span of 50mm and 20mm of thickness are adopted and the schematic diagram is shown in Figure 4-1. Two LVDTs were set up at each side of the specimen to measure the mid-point deflection. Load-deflection curves were used to evaluate flexural stress and toughness indices.

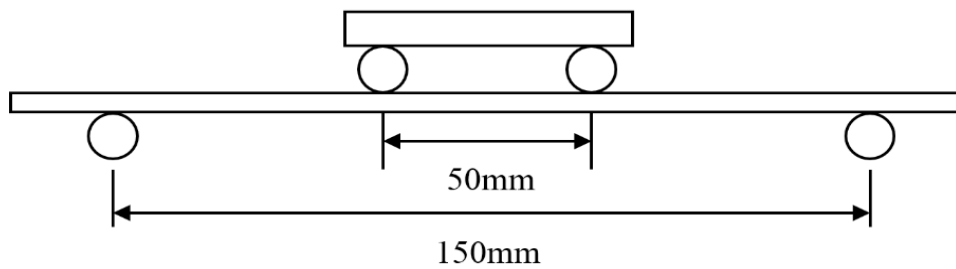


Figure 4.1 The schematic diagram of four-point bending test

For testing, the state of stress distribution of four-point flexural test is more desirable since more parts of specimen are under maximum bending moment. The flexural stress can be calculated by the following equation:

$$f_t = \frac{FL}{bt^2}$$

Where f_t : Flexural stress(MPa); F : Applied load; L : Length of loading span; b : Width of specimen
 t : Thickness of specimen.

4.1.1 Test results for HVFA based system

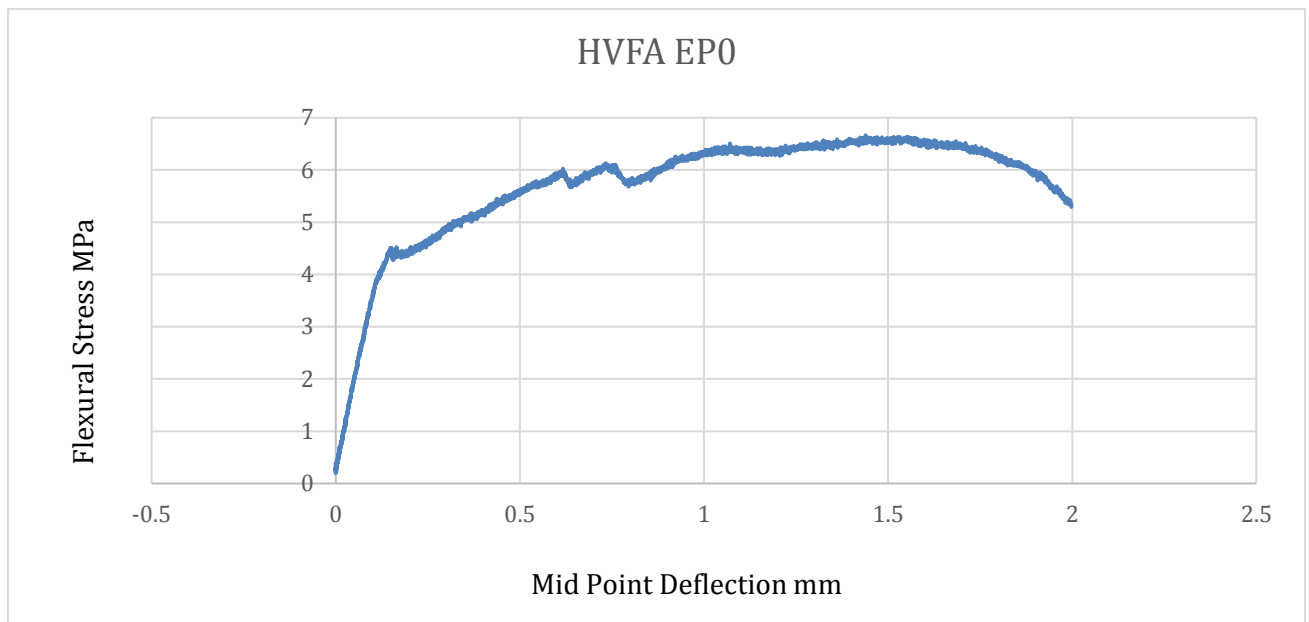


Fig 4.1 Flexural behavior of HVFA EPO

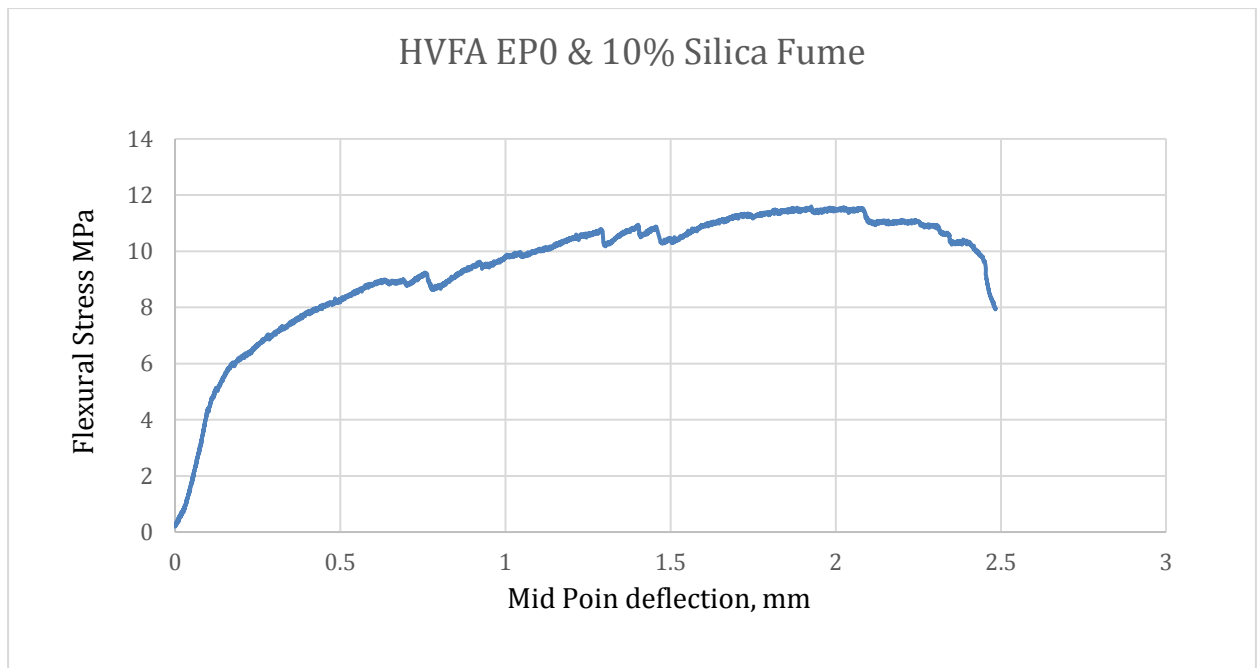


Fig 4.2 Flexural behavior of HVFA EPO & 10% Silica Fume

4.1.2 Test results for OPC based system

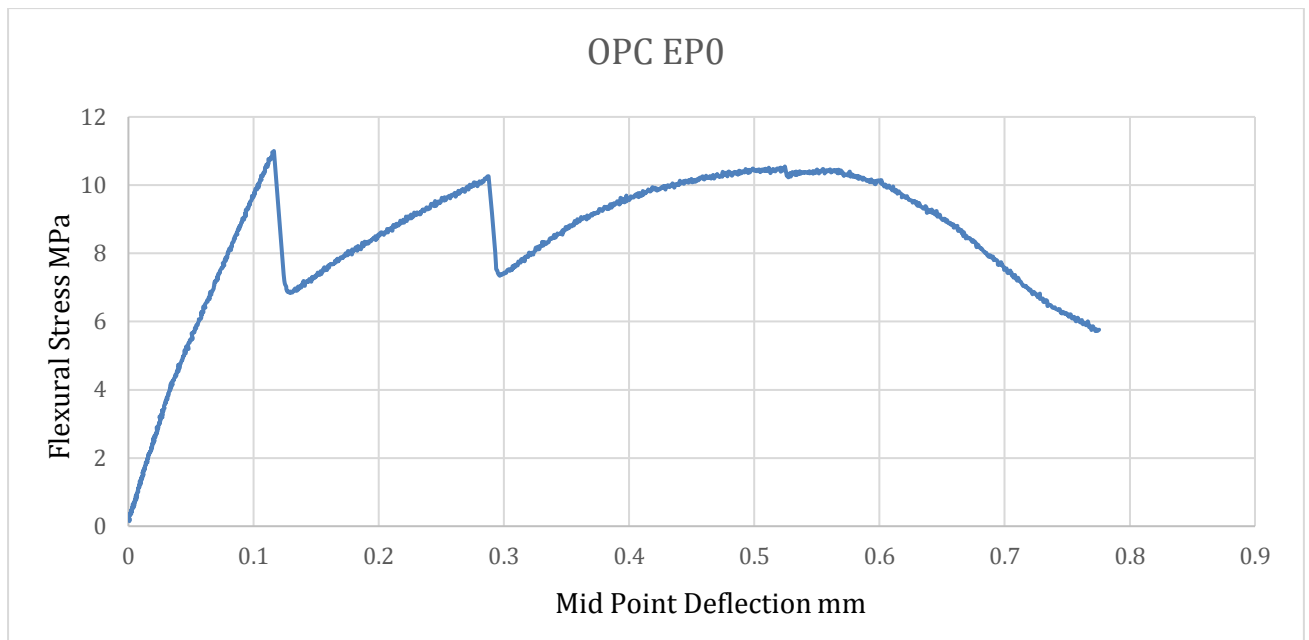


Fig 4.3 Flexural behavior of OPC EP 30

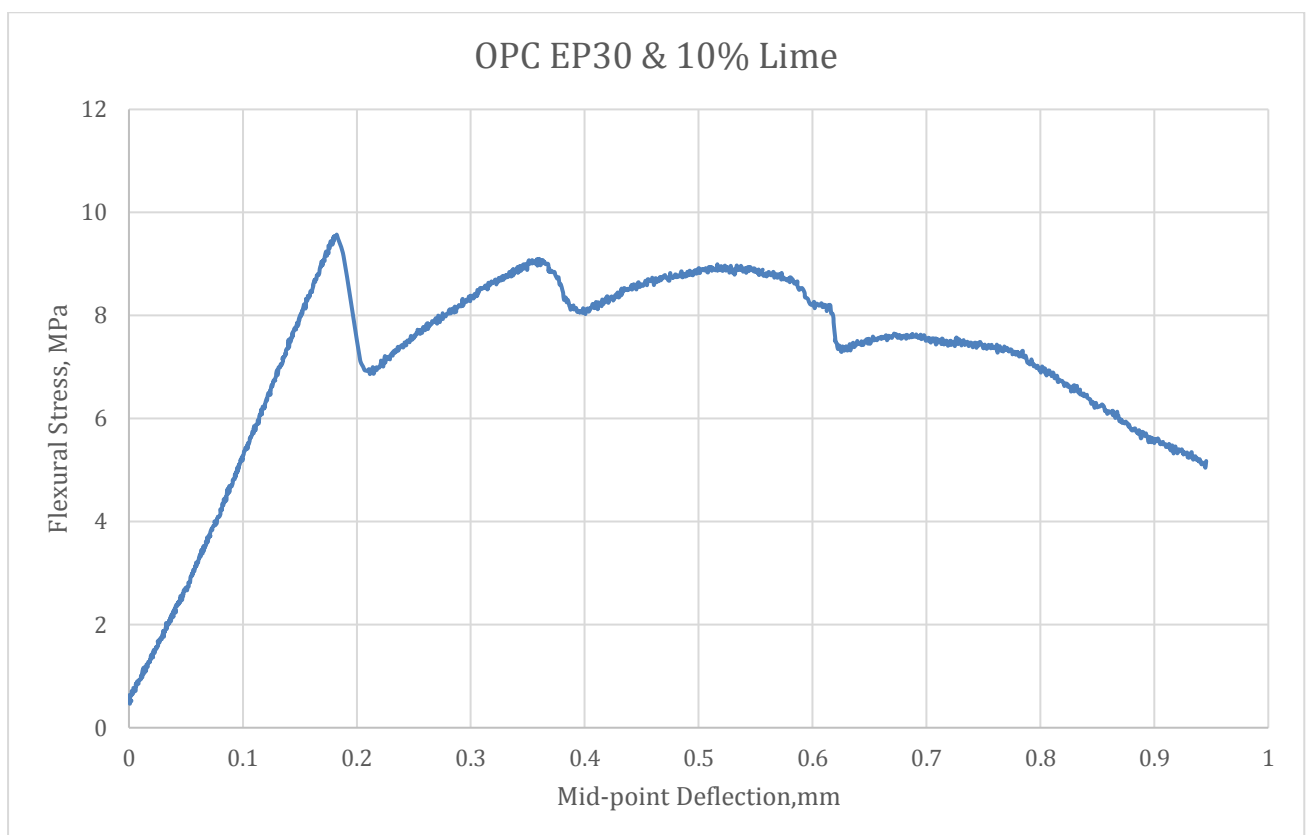


Fig 4.4 Flexural behavior of OPC EP 30 & 10% Lime

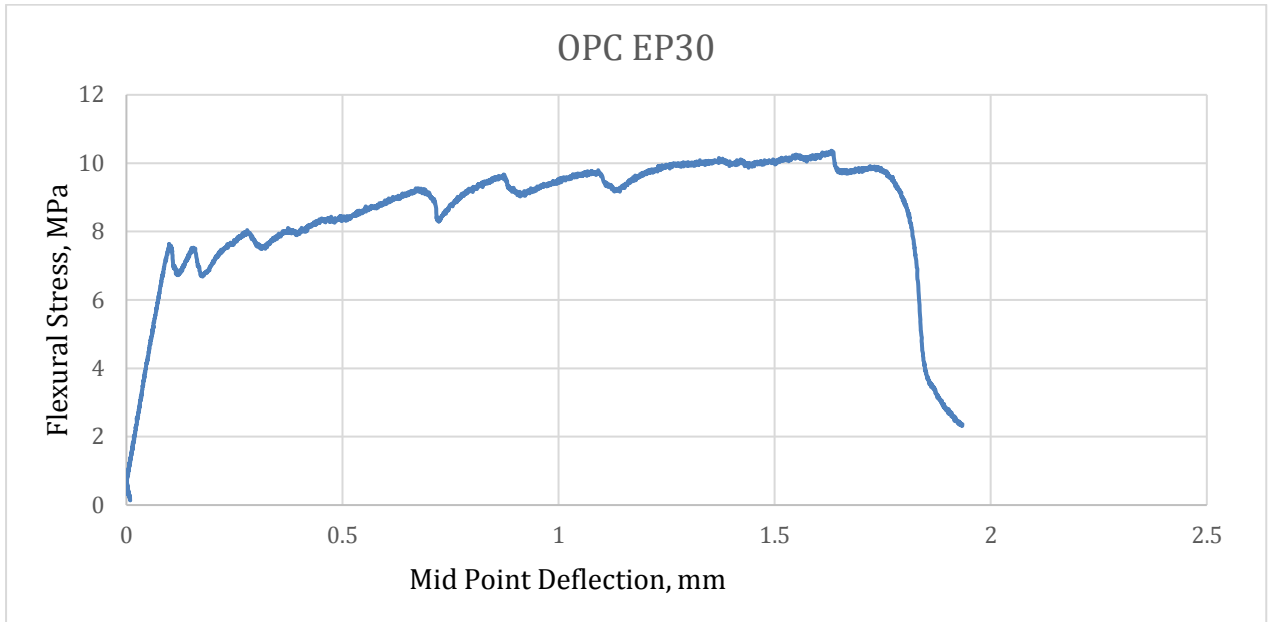


Fig 4.5 Flexural behavior of OPC EP 30

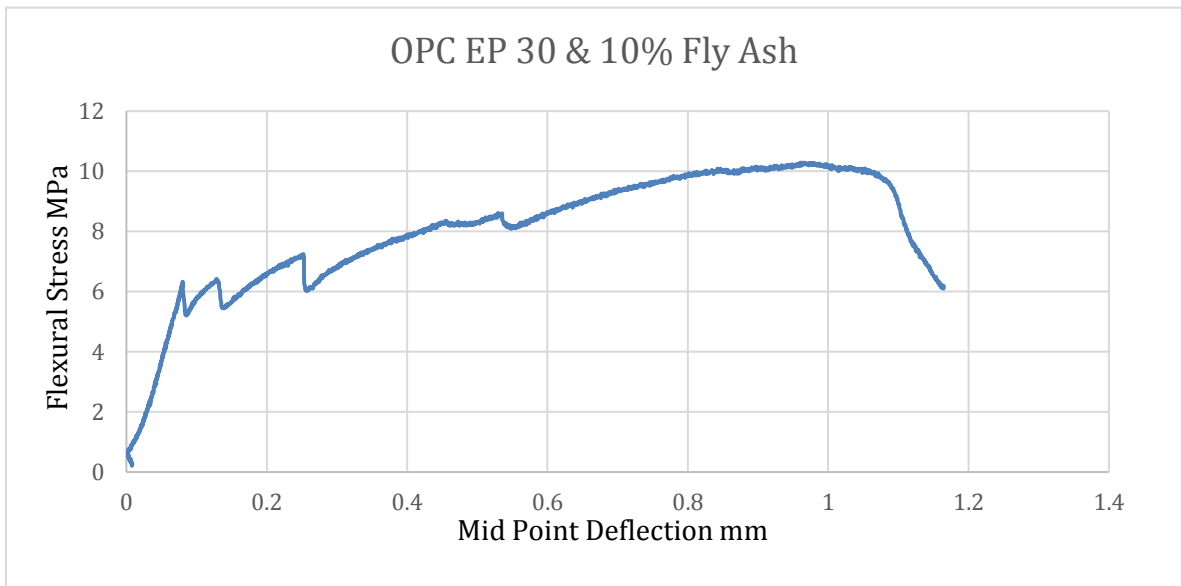


Fig 4.6 Flexural behavior of OPC EP 30 & 10% Fly Ash

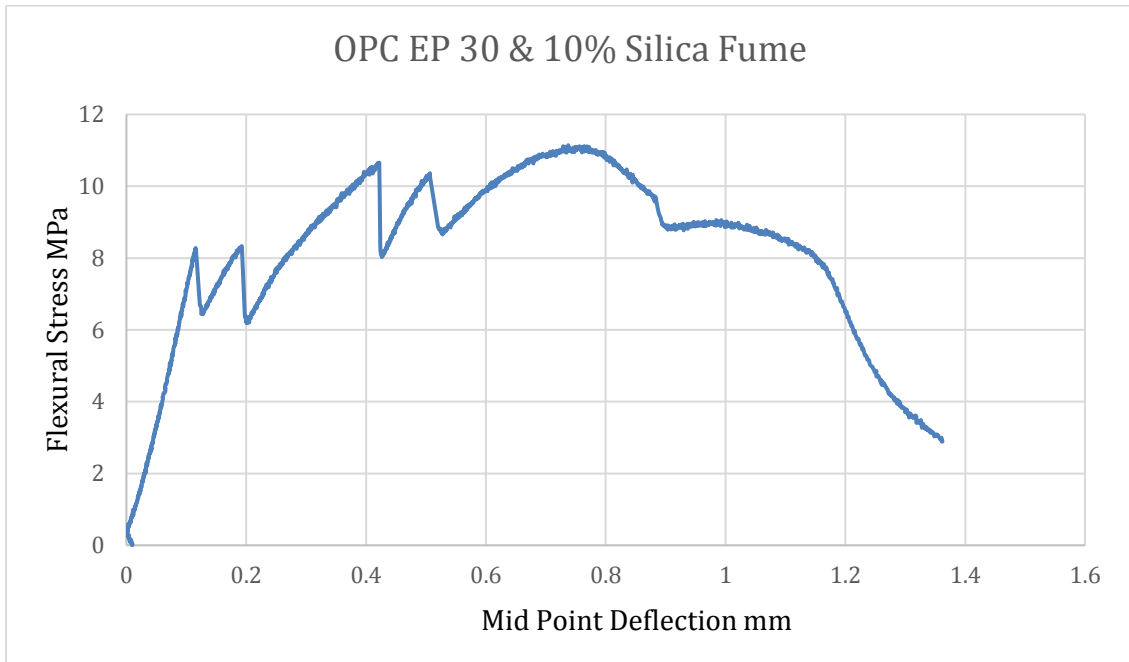


Fig 4.7 Flexural behavior of OPC EP 30 & 10% Silica Fume

4.1.3 Test results for Geo Polymer based system

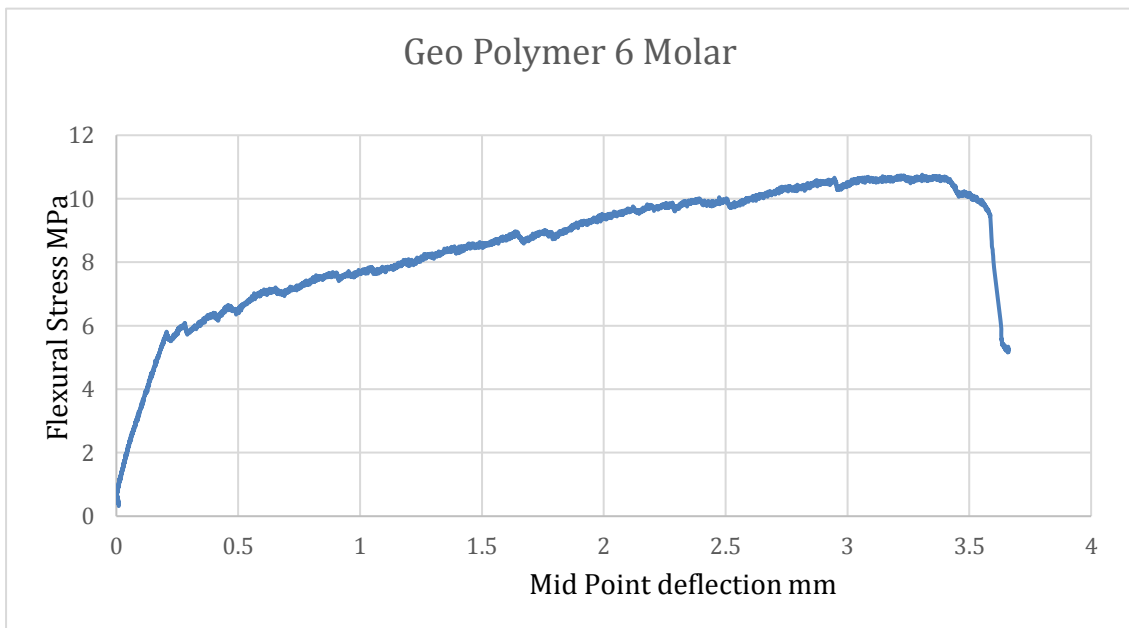


Fig 4.8 Flexural behavior of Geo Polymer 6 Molar

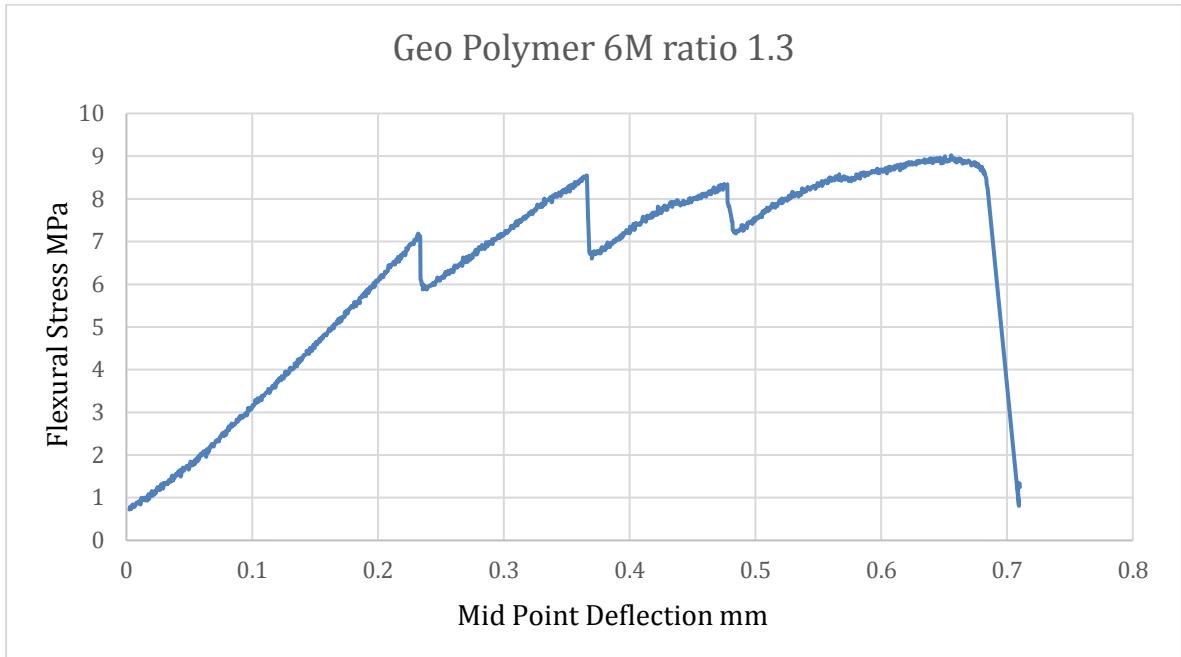


Fig 4.9 Flexural behavior of Geo Polymer 6M ratio 1.3

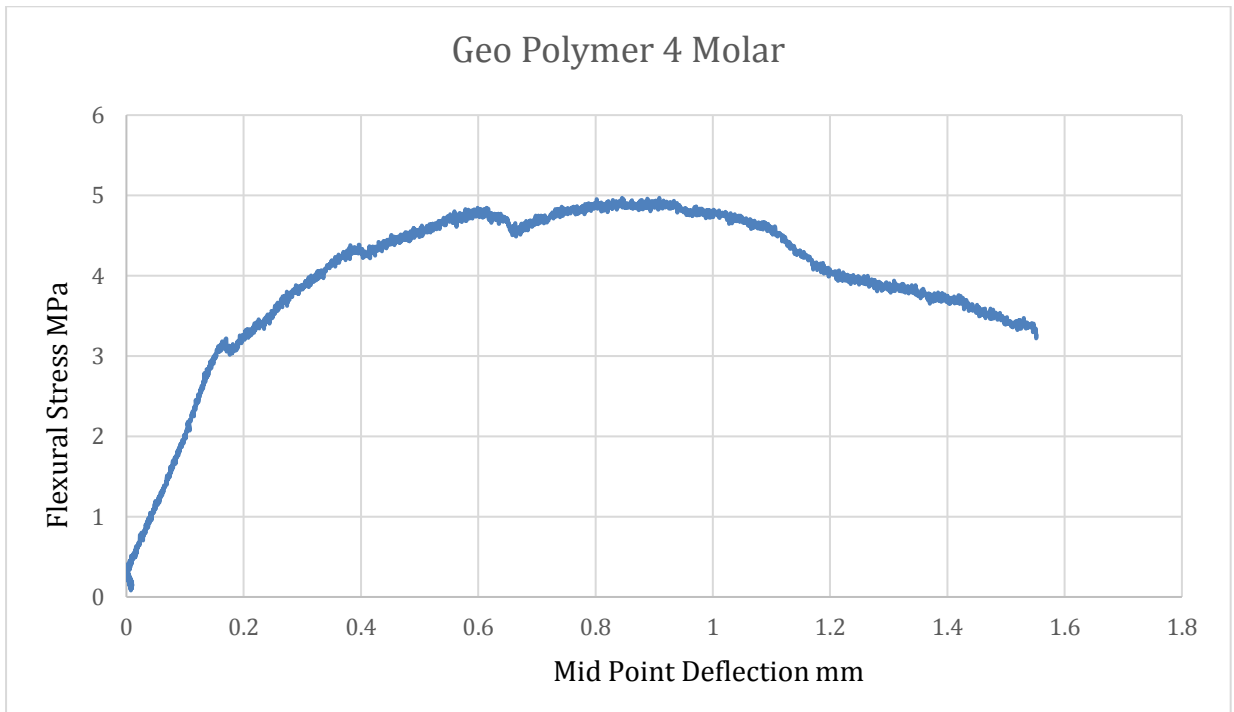


Fig 4.10 Flexural behavior of Geo Polymer 4 Molar

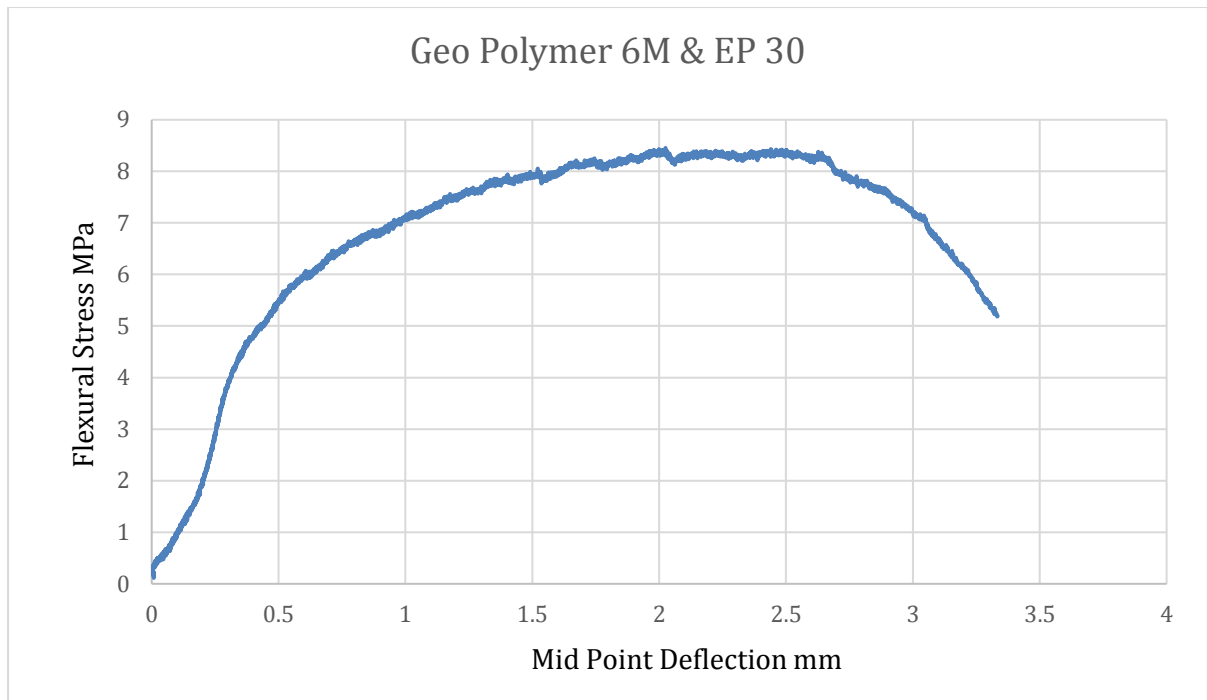


Fig 4.11 Flexural behavior of Geo Polymer 6M & EP 30

4.2 Effect of PVA Fiber reinforcement alignment

The good performance of pseudo-ductile behavior of all the tested panels is benefited from the parallel fiber alignment produced by extrusion. The pseudo-ductile behavior is presented when sufficient short fiber reinforcement is incorporated, which exhibit very high ductility compared to normal hardened cement paste. The peak appeared in the curve is indicating where crack occurred somewhere in the matrix, and the load is maintained by fiber reinforcement. Therefore, many micro cracks are very likely to be occurred, fibers in crack will either break or pullout of the matrix when the stress increase. This process repeats and continues until there is no enough fiber reinforcement to maintain the load. Since most of the fiber is aligned with extrusion direction and perpendicular to load direction of flexural test rather than random alignment which produced by casting method, the fiber reinforcement in the extruded specimen can be effectively maintain the load than a casting specimen of same mix proportion.

The flexural strength of OPC based specimens is higher than HVFA based specimens but poor ductility performance, expect only OPC EP0 has slightly lower Mid-point deflection than EP0. It seems fiber reinforcement are more uniformly distributed in HVFA based specimens, causing an improved ductility.

4.3 Effect of EP

The flexural strength of specimen decreases with increasing volume fraction of EP content. It is because of the characteristic of EP. As EP containing massive pores inside, and the strength of EP is very low compared to hardened cement paste. Therefore, EP in specimen can be treated as a big air bubble and serve very little or almost no propose in contributing mechanical strength of the specimen. As a result, increasing EP content will decrease the volume fraction of cementitious material for a given specimen volume as well as decreasing the area of critical section, in which cementitious material is a major contributor to mechanical strength. Critical section of a specimen is where failure is very likely to occur, due to the strength contributor area of this section is minimum. Also, critical section is a major factor affecting ultimate strength of the specimen. Therefore, it is obvious that EP content in the mix design would have negative effects on mechanical strength of specimen.

4.4 Effect of SCMs

SCMs incorporated specimens have performed better mechanical strength. Silica Fume has improvement of flexural strength. The reason why SCMs are able to improve the flexural strength is that they both have chemical reaction and physical interaction to the cementitious materials. The primary chemical reaction associated with SCMs is known as Pozzolanic reaction.

However, the SCMs incorporated panels have about 75% decrease in mid-point deflection at final crack, which represent the ductility of the panel to a large extent. The ductility of a FRCC mainly determined by matrix strength, fiber strength. When the matrix is relatively weak compared to fiber, the matrix will first crack at a lower level of stress; fibers at crack will only have to maintain that lower level of stress. Therefore, fibers are not likely to failure in this situation, but the matrix is very likely to crack into multiple cracks and thus increasing the ductility of the composite. However, when the matrix relatively strong compared to fiber, the matrix will first crack at a higher level of stress, fibers at crack will have to maintain that higher level of stress. Therefore, fibers are likely to failure at this situation due to higher level of stress, matrix will not able to crack as many as low strength matrix composite.

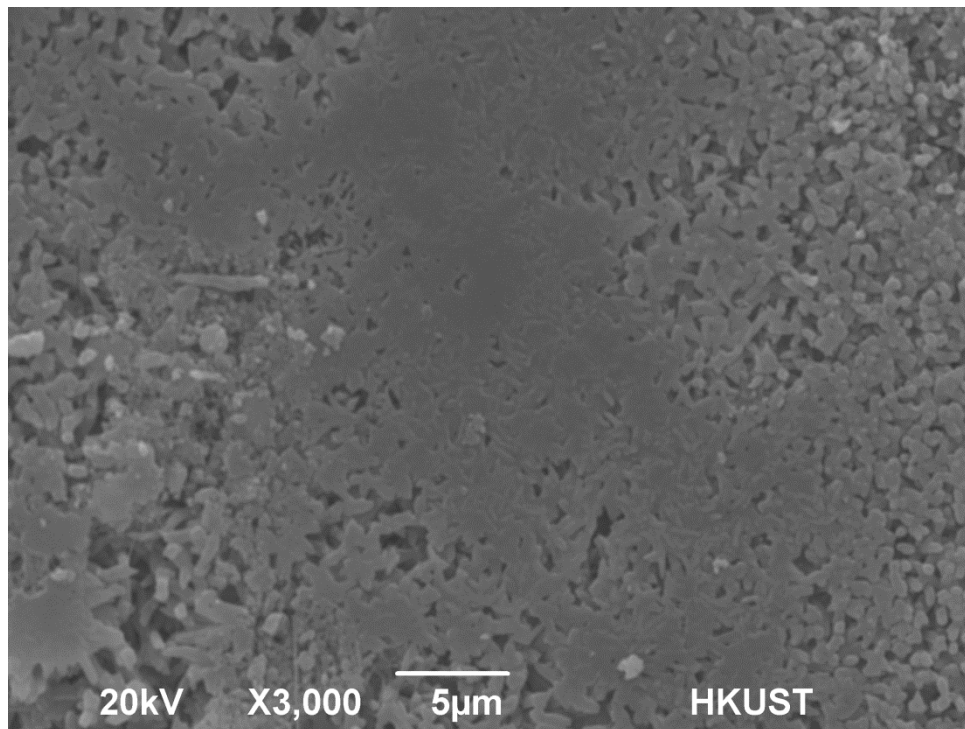
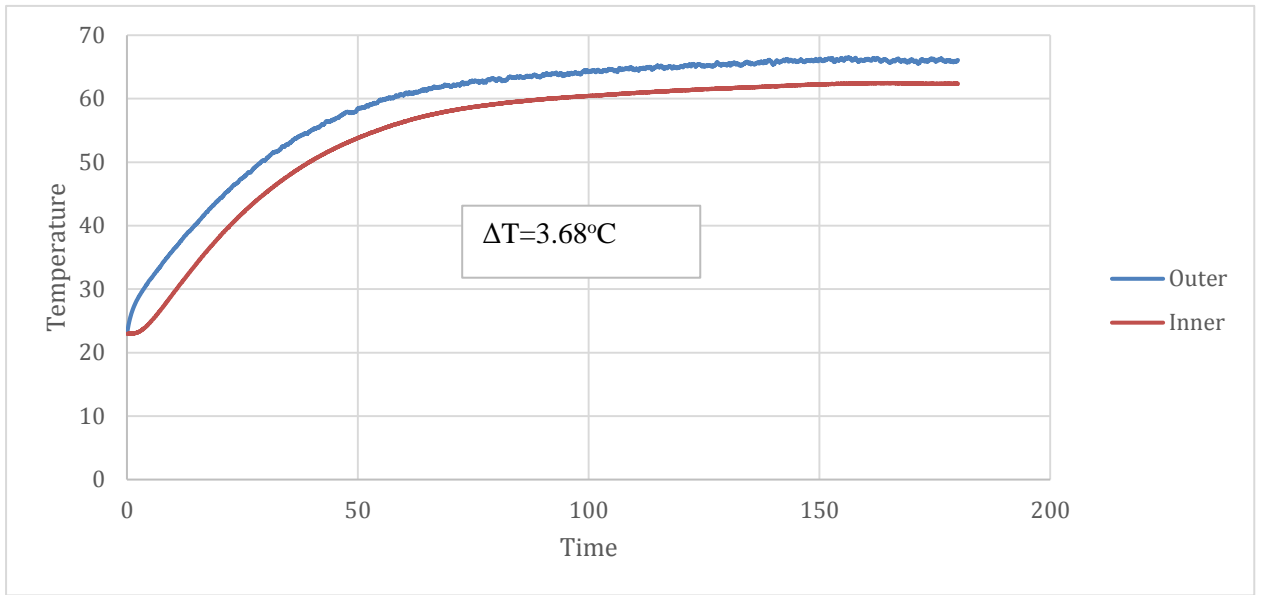


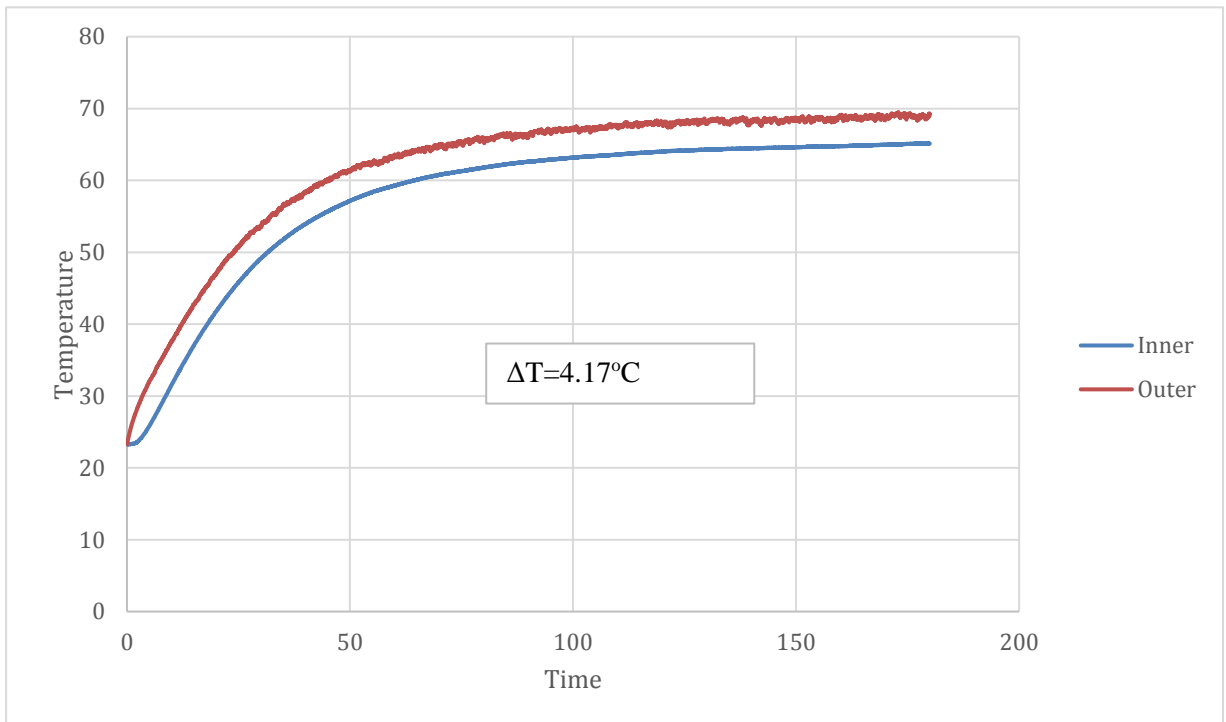
Fig 4.3 Dense Microstructure in SF HVFA system

4.5 Thermal Test

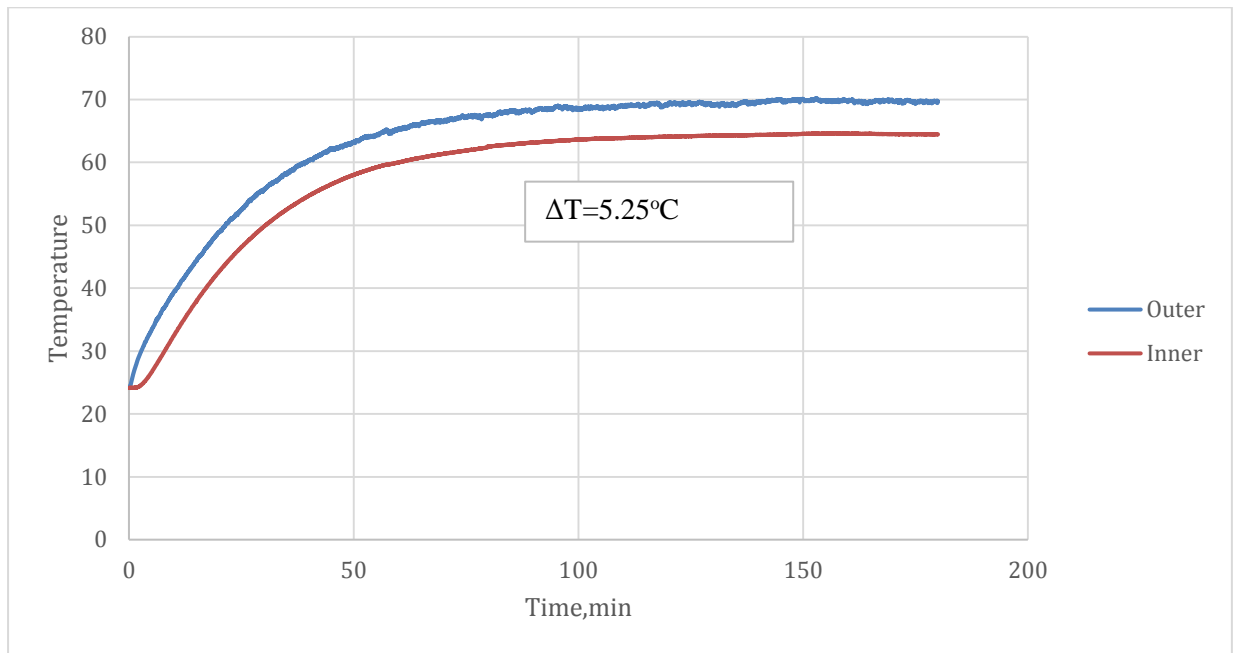
In this project, steady heat conduction test is conducted to determine the thermal insulation properties of extruded panel. Since this building panel is aimed to reduce energy usage by improving insulation property of the wall. The goal of the insulation panel is to increase temperature difference between two sides of the panel, and it is also the major criteria for examining performance of the panel. Steady heat conduction test is effective thermal test that can evaluate the performance of the panel. The initial condition of two thermal tests is which temperature of 25°C and relative humidity of 50%. Steady heat conduction test directly measuring temperature difference between two sides of the panel under one side being heated by a 275W infrared lamp.



Temperature variation of OPC EP0 in steady heat conduction test



Temperature variation OPC EP 20 in steady heat conduction test



Temperature variation of OPC EP30 in steady heat conduction test

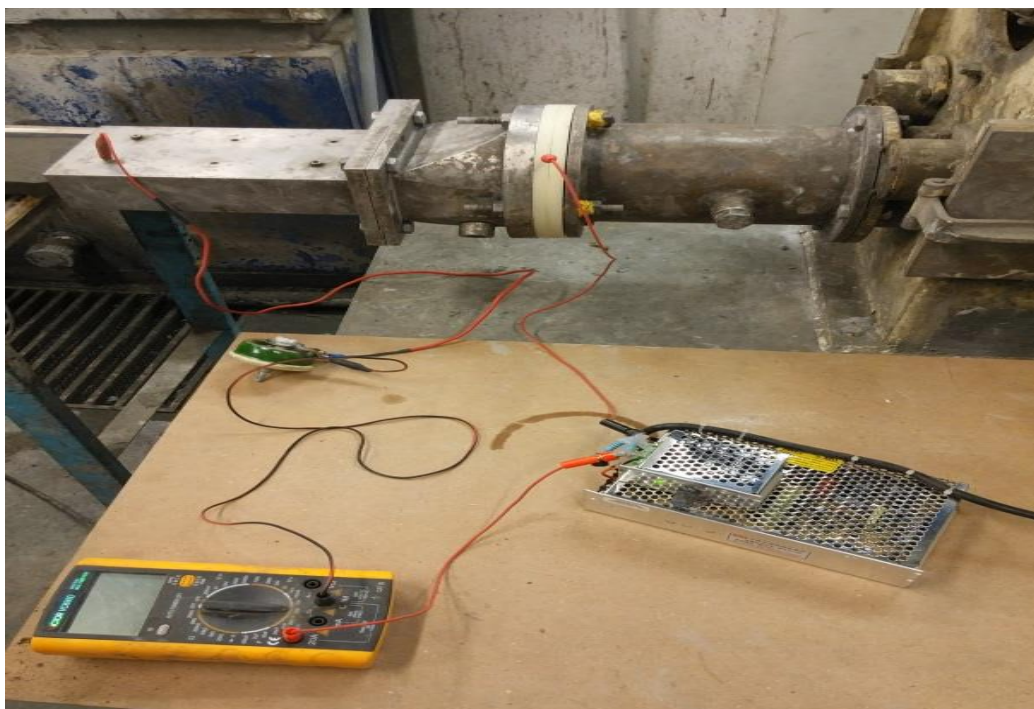
4.5.1. Effect of EP

The temperature variation of EP0, EP20 and EP30 in steady heat conduction test is shown above. It is obvious that the ΔT increases with the increasing EP content. Increasing EP content in extruded panels will result in enhancing the temperature difference between inner and outer surface of the panel under STEADY thermal test. This is due to thermal insulation properties of the expanded perlite incorporated into the extruded panels. From 3.68 in EP0% to 5.24 in EP 30%.

The increasing ΔT indicated that decreasing amount of heat being transferred to inner surface of the panel, which is also representing an improving thermal insulation properties. It is expected to occur where EP have a low thermal conductivity as it contains a large amount of pores. The increasing tendency of ΔT with increasing amount of EP is also indicating that EP incorporation has good thermal insulation performance in these three extruded panels.

4.6 Equipment assisted Extrusion for Lubrication

This technique is to create a water layer in the interface between the paste and the thin-wall shape die by electric field. The main purpose of this technique is to overcome the problem of friction by this water layer, since the friction between the paste and internal wall of the die affect the extrusion process and thus affecting the quality of extruded paste. In practice, a DC voltage is applied one end in the screw chamber, another end in the die. It is necessary to separate screw chamber and the die to make them electrically isolated, a plastic ring placed between the screw chamber and the die can do this. This setup allows the current flowing from the screw chamber to the die through the paste; the paste is like a medium or a wire connecting the screw chamber and the die. When the current pass through the paste, ions in the paste would migrate to interface between the paste and the metallic part, which connected to DC voltage, it is due to the electric field provided by the DC voltage. The ions migration would also carry or drag water particle to the interface, forming a thin layer of water for lubrication. This layer of water can be seen right after the extrusion as shown and the effect is quite obvious by no difficulty to perfectly separate the die entry and the paste. Since the principle of this technique is creating the water layer from the water carried by ions inside the paste, the connection point of anode and cathode is not important. The efficiency of lubricating is improved compared with oil lubrication in the previous test.





Water film on paste surface and perfectly separated paste from the body of die entry

4.6.1 Mixing Time

In both alkali activated fly ash and Portland cement, the hydration process is initiated once water is added, and the process is very fast. It means that the paste will exhibit hardening effect very soon after mixed with water. Therefore, material-mixing time for extrusion should be kept minimum, which means the paste is ready for extrusion once the dough-like paste is formed. Otherwise, the paste will be hardened in a while and thus affecting rheological properties as well as extrudability of the paste.

4.6.2 Material Mixing Sequence

The material mixing sequence in some ways can be lead to failure of extrusion, because of misjudgment by the operator, regarding the extrudability of the paste. For example, the addition of EP and mixing with binder materials before water is added, this will indeed strengthen the bonding between EP and matrix. However, EP will absorb a large amount of water when water is added, leading to misjudgment of water content in the paste. Since water content of the paste is a major factor affecting rheological properties as well as extrudability of the paste, this kind of misjudgment by improper material mixing sequence is not favorable.

4.7 Limitations

The main limitation of this project is low productivity due to laboratory conditions. Due to volume of container for mixing and power of mixing machine, maximum 8kg of materials can be mixed at one time. However, the body of extruder needs to be filled with about 5 kg of material in order to generate thrust for extrusion. Which means that it is only possible to produce about 3kg for each batch of material. As a result, it is not enough extruded product for further testing to verify the accuracy of the result.

Chapter-5

Conclusions and Future Developments

5.1 Conclusions

The objective of this project is to develop and manufacture the FRCC thermal insulated building panel by extrusion technique. To examine the functionality of panel, four-point flexural test, steady heat conduction test and cyclic thermal test were conducted. In addition to testing of the extruded panel, it is also a good opportunity to review and study the effect of various materials on both fresh and hardened cement paste in different aspects.

For mechanical strength test, the flexural strength and mid-point deflection of HVFA based extrudates vary from 5.2MPa to 11.58MPa and from 0.45mm to 4.5mm respectively. These two parameters depending on the content of EP, paraffin and SCMs incorporated. The EP and paraffin incorporation have shown negative effects to flexural strength, and these negative effects are serious for EP incorporation. While the flexural strength and mid-point deflection of cement based extrudates vary from 7.8MPa to 9.88MPa and from 0.87mm to 2.08mm respectively, depending on the content of EP and SCMs incorporated. The SCMs incorporation was beneficial to increasing flexural strength of HVFA based extrudates but not cement based extrudates. In addition, paraffin incorporation was capable of improving ductility. Overall, all types of FRCC demonstrated a well performance of pseudo-ductile behavior with present of multiple micro cracks in flexural test.

For thermal test, the two major concerns are the thermal insulation properties and heat energy absorption capacity which can be examined by temperature differences and delayed time of peak respectively. The temperature differences and delayed time of peak of HVFA based extrudates vary from 2.98°C to 14.38°C and from 7min to 39min, respectively. These two parameters depending on the content of EP and paraffin incorporated. The results have shown that both EP and paraffin incorporation have positive effects on the thermal insulation properties, the effects were determined by the amount of EP and paraffin incorporation. Paraffin incorporation have shown different delay effect on time of peak, depending on the amount of paraffin

incorporation. Overall, it is obvious that both EP and paraffin incorporation have contributed to improve thermal insulation properties of the extrudates.

In conclusion, extrusion technique is able to produce functional thermal insulated building panel with utilizing CRMs. This building panel could be utilized in building industry, making a great contribution to sustainable development of society by reducing energy demand as well as greenhouse gas.

5.2 Future developments

Since extrusion process is proved to be able to handle with cementitious materials, some functions of build panel other than thermal insulation can be produced. For example, build panel with integrated sound insulation can be produced by using other types of lightweight aggregate or changing geometry cross-section of the panel.

The successful of extrusion in this projects is based on many failures of extrusion which mainly due the inappropriate rheological properties of the paste. Since the rheology of paste in extrusion process is very complicated and significantly affects the extrusion process, more comprehensive studies for the rheology of paste is required for future studies.

Finally, regarding the difficulty of extrusion technique in producing cementitious material product, equipment assisted extrusion should be implemented with improved design or setting in the future study. So that a major controlling factor towards successful extrusion, which is friction, is eliminated, it can enhance the successful rate of extrusion. Therefore, more specimens will be available for comprehensive investigation.

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