International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 /doi:10.14445/22315381/IJETT-V69I9P222
Volume 69 Issue 9, 179-192, September, 2021
©2021 Seventh Sense Research Group®

Structural and Thermal Efficiency of Composite Precast Sandwich Panels: A State-Of-The-Art

Sakhimol B[1], V.G.Kalpana[2]

Research Scholar[1], Assistant professor[2]
[1&2]Department of Civil Engineering, Coimbatore Institute of Technology, Coimbatore-641014, Tamilnadu, India.

[1]sakhimol.b@cit.edu.in, [2]kalpana@cit.edu.in

***Abstract** - Novel energy-efficient approaches to new construction practices like precast insulated sandwich wall panels can reduce the energy consumption for thermal comfort inside the building. Precast insulated sandwich wall panel (PISWP) is made up of two or more structural layers (structural wythes) separated by a low-density insulation material with good thermal resistance. Shear connections are used to link the structural wythe with the insulating layers. The most commonly used connector material is steel, but it reduces the thermal efficiency of the insulated panels by acting as a thermal bridge across the wythes. Other materials like fibre reinforced materials (FRP) gain attention recently and investigations are going on to find their suitability in achieving composite actions. This paper outlines an overall review of the response of precast insulated panels, properties of insulation material and structural behaviour of shear connectors. It also looks at how well-insulated sandwich panels keep their heat in. Expanded polystyrene (EPS) and extruded polystyrene (XPS) have been proved to be effective insulating materials in the past. Superior thermal and corrosion resistance properties of FRP made it a pertinent material for shear connectors in sandwich wall panels. Fully composite action can be achieved if the shear ties are selected as per specifications and appropriately distributed but still, some undesirable properties like bond-slip, FRP failure, etc. are there. So an intensive experimental study is needed to identify the proper shear connector system that will provide both structural and thermal efficiency to the panels. Also, studies are needed to study the comparability of different insulation materials available in the market in terms of thermal efficiency.*

Keywords - *Insulated sandwich wall panel, FRP, thermal efficiency, shear connector, Expanded Polystyrene(EPS), Extruded Polystyrene(XPS).*

I. INTRODUCTION

In the present scenario, the demand for residential units in India is very high and will persist for many years and this can be achieved only by using modern technologies. Precast technology, which is very much popular in foreign countries, is now gradually being adopted by many developers, builders, and contractors in India because of its advantages in comparison to conventional methods in terms of speed of construction, structural efficiency, safety, optimum use of materials, protection of the environment, etc. Mass housing unit constructions using precast reinforced concrete wall panels are gaining attention now a day. The disadvantages of this type of construction are that the members are heavy and have thermal conduction. Precast wall panels are also vulnerable in seismic prone areas due to semi rigidity at joints. Joints must have adequate strength to transfer different types of loads acting on the structure. Previous studies concluded that non-ductile designs were major reasons for the damage in the precast (reinforced concrete) building. Precast insulated sandwich wall panels with proper connections are expected to overcome the above-mentioned problems due to their superior thermal insulation properties and lightweight.

II. PRECAST INSULATED SANDWICH PANELS

The three main components of precast concrete insulated sandwich panels are structural wythes (concrete layers), shear connections, and insulation or void (Fig.1). Concrete wythes (layers) that function as structural layers bear the structure's live load and dead load. Expanded polystyrene (EPS) Extruded polystyrene (XPS), Polyurethane, Phenolic foam, plastic, rubber, rigid foam, etc. are the most used insulation material in sandwich panels[53]. In India, EPS is the most commonly used material for improving the thermal performance of any structure[54].Thermal insulation capacity, thermal conductivity, water absorption, thermal expansion, and other factors influence the kind of insulation used in Precast Insulated Sandwich Panels[1]. To reduce water loss during production, low absorption insulating materials are typically utilised [2]. To link the structural wythe through the insulating layer, metal connections, plastic connectors, or a combination of these connectors are utilized. Steel shear connections were the most often used ones. The use of alternative materials, such as FRP, has lately been investigated in several studies.

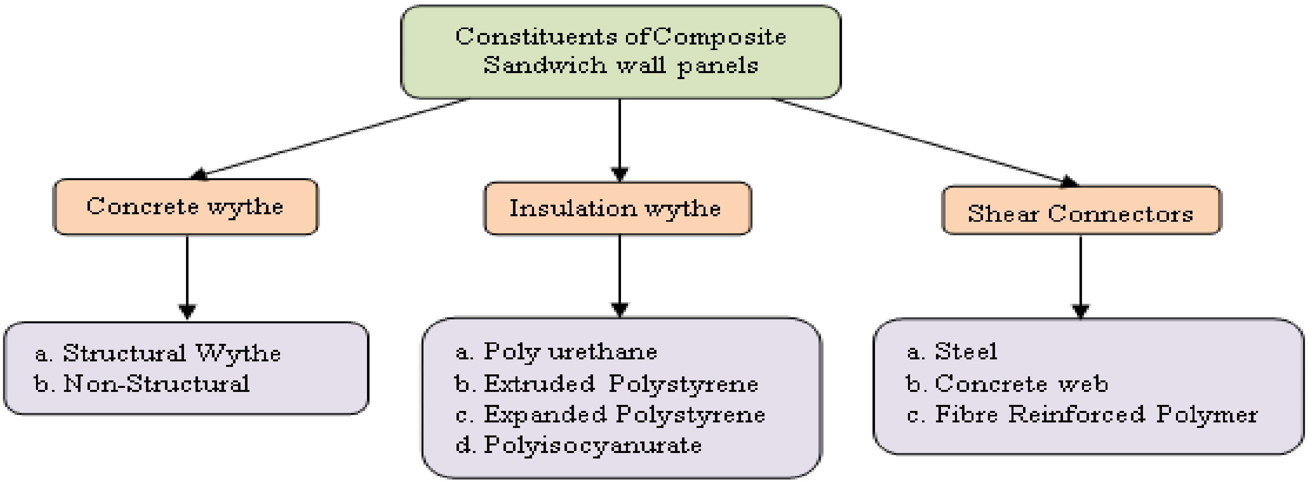


Fig 1. Constituents of sandwich wall panels

III.TYPES OF PRECAST CONCRETE INSULATED SANDWICH PANELS (PCISP)

Based on the degree of Composite action, Precast Concrete Insulated Sandwich Panels are classified into three types [2].

A. Non-composite panel

A sandwich panel in which both wythes work independently of each other and shear deformation between the structural wythes is negligible is called a non-composite panel Fig. 2(c). At least one wythe of this type of panel is thicker and structural. The structural behaviour of the non-composite panels is attributed to the bond between the insulation and the structural wythe, in addition to the minor support from the non-metallic connectors [3]. In this system, the bow on the inside of the building would be slightly reduced as each wythe deflects independently due to thermal gradients, and that is the only structural positive considered [4].

B. Fully Composite panel:

When the two structural wythes are forced to structurally act like a single concrete structural element and attain complete interfacial shear transfer between wythes exhibiting fully composite action, then such a panel is called a fully composite panel. Fully composite action can be attained by providing ample shear connectors through the wythes. Required longitudinal shear would be transferred across the wythe through connectors. As shown in Fig. 2(a), across the panel thickness the bending stress and strain distribution remain linear.

C. Partially Composite panel:

A panel with partial composite action integrates connectors that have some shear stiffness due to their non-metallic nature is called partially composite panels. Shear transfer behaviour is comparable to that of completely composite and non-composite panels. When compared to completely composite panels, partially composite panels only transfer a portion of the longitudinal shear. Partially composite panels can have structural wythes that are thinner than non-composite panels, making them less costly. Figure 2(b) depicts the pattern of bending stress and strain distribution in a partly composite insulated sandwich panel.

IV. BEHAVIOUR OF COMPOSITE INSULATED SANDWICH PANEL

Past studies indicated that the type of loading influences the behaviour of precast concrete insulated sandwich panels significantly. Numerous research works were carried on insulated sandwich panels to study their response under different types of loading. Experimental investigations were done on Reinforced Concrete Sandwich Panels (RCSP) to understand the behaviour under seismic loading. RCSP's proved to be an efficient construction element for areas of reasonable and perhaps elevated seismic conditions. RCSPs were constituted of an expanded polystyrene foam core sheathed between wythes of sprayed concrete on both sides which is reinforced with prefabricated galvanized steel wire mesh [6]. Lightweight concrete using EPS beads with a density of nearly 900 kg/m^3 were found suitable for both types of walls (load-bearing and non-load bearing). The chicken mesh was found to be a cost-effective alternative for welded mesh as it reduced the spalling of structural layers by confining them sufficiently. The failure pattern observed in this type of panel was skin separation and it also showed that the wall exhibited ductile behaviour [7]. For non-load bearing partition walls of multi-story structures and load-carrying walls of single-story buildings, lightweight wall panels made of foam concrete might be recommended. Foam concrete was made using EPS of which 50% is mechanically recycled EPS. When low weight foam concrete was employed in between the cement fibre sheets, the panels' flexural capacity was found to be quite high [8]. The flexural behaviour of Insulated structural panels was similar to conventional RC slabs under the punching load [9].

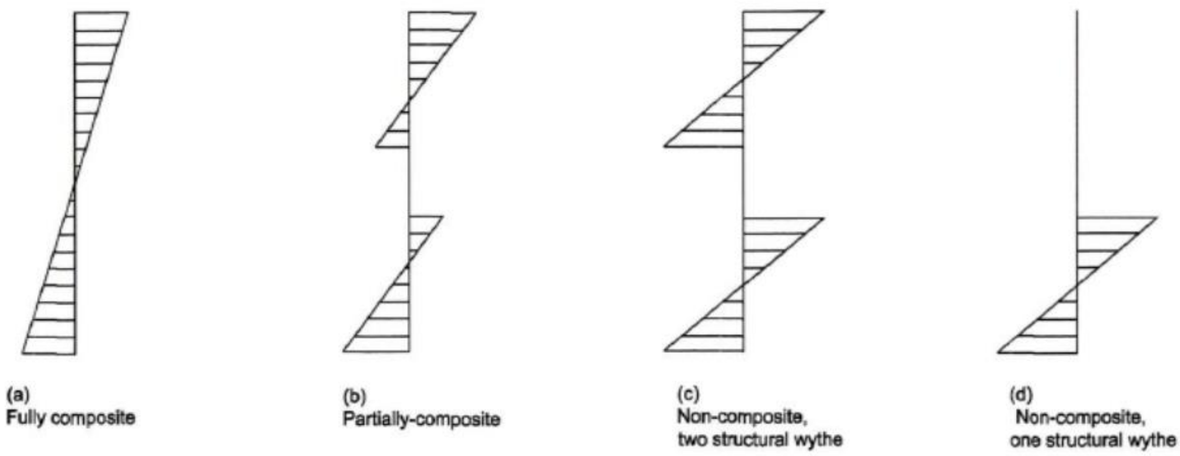


Fig. 2. (Behnam Naji, and Elias A. Toubia) [5]

Precast concrete three wythes insulated wall panels were developed with the prospective to enhance the structural integrity and thermal efficiency. In panels with two wythes, locations of solid concrete (provided for various reasons such as placements of inserts for lifting, composite actions, etc.) caused a substantial contrary effect on the thermal efficiency. Ductile flexural behaviour was exhibited by three wythe panels under the application of lateral load. The well-distribution of flexural cracking, reinforcement yielding, and strand yielding was attributed to this behaviour. Under lateral stress, there was no horizontal shear failure. An overestimation of the tensile strength of concrete and the occurrence of preliminary cracks could be the reason for early flexural cracking. The transverse bending under lateral loading could be reduced by increasing the number of concrete ribs [10].

Studies proved that the weight of sandwich panels was reduced by the use of EPS at the core thus making it efficient in seismic prone areas. It also revealed that the stress due to live load and earthquake load was within the permissible limit for panels constructed using EPS core as insulation. The P-M (load-moment) interaction curves of the section contain the design forces and moments at critical sections owing to load combinations in the limit state design. Structural Wythe of a thickness of 70mm (2.75in.) [35mm (1.37in.) on either side] and wire mesh made of steel was found to be ample enough to withstand the design forces safely [11]..It was observed that the Slenderness ratio (H/t) has a significant impact on the deflection measurement of axially loaded panels. The material strength of the sandwich wall panels highly influenced the ultimate failure load [12]. The elastic modulus in the working stress area is one of the most important factors for a panel [8]. On full-size wall components, the reaction of three distinct types of shear connection systems, namely solid concrete web, steel M-ties, and mechanical bond between the insulation and concrete wythes, to lateral load was observed. Sandwich panels with all the three mechanisms together exhibited fully composite action. The structural area contributed the majority of the composite behaviour of the panels, implying that the contribution of Steel M-ties and the concrete-concrete bond was minimal [13]. Studies showed that panels with truss shaped connectors of steel resisted the axial load significantly. Strain across the insulation layer was not continuous when subjected to axial load for those panels with truss shaped steel connectors. From the past studies, it was found that the Precast Foamed Concrete Sandwich Panels (PFCSP) could be used for multistoried residential buildings. It could also be used in construction sites of low bearing capacity [14]. Concrete sandwich panels made using precast foamed concrete as insulation were a unique kind that could be employed as a load-bearing structure. When compared to typical panels with steel wire mesh, the structural behaviour of this sandwich panel was improved due to the application of a 3D steel skeleton in structural wythes. The enhanced structural integrity with high strength and toughness were due to the 3D steel wire skeleton system which exhibited better strength and rigidity [15]. Experimental studies conducted to evaluate the flexural response of lightweight insulated sandwich panels using perpendicular connectors revealed that the stiffness of the structure was not contributed by the connectors. The failure of the panel was found to be associated with the horizontal force that compromised the welding. Hence special attention has to be given to the welding between the steel reinforcement in the structural wythes and the connectors [16]. Wythe thickness is determined by the intended use, necessary shear embedment length, concrete cover, and stripping [17].

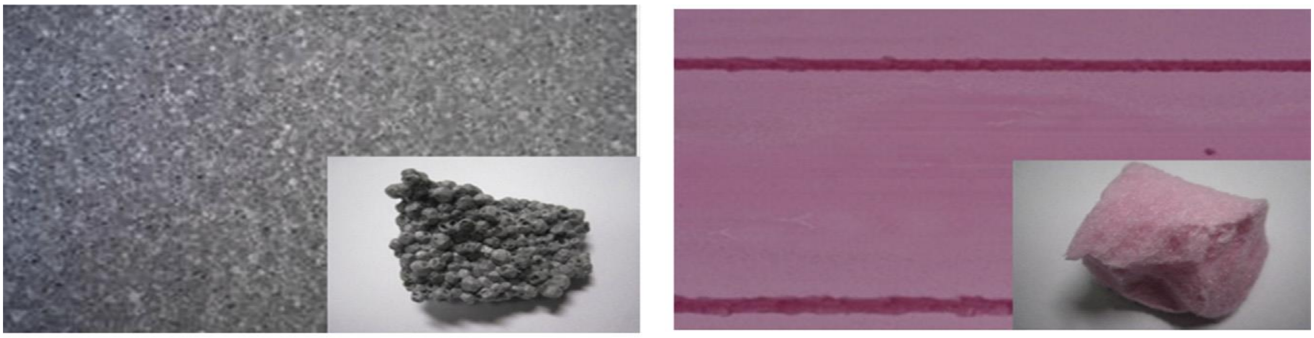
V. PROPERTIES OF INSULATION MATERIAL

Controlling thermal mass transmission between the inside and outside of a building can reduce energy consumption for indoor thermal comfort. This can be achieved by a novel energy-efficient approach to new construction practices like precast insulated sandwich panels. Insulation materials are used to achieve thermal well-being inside the structure. The most commonly used insulation materials are Polyurethane, XPS, EPS and Polyisocyanurate. The majority of the study on insulated sandwich wall panels has focused on components made of EPS and XPS [18, 19, and 20]. The thickness of the insulator is determined by the manufacturers' requirements for thermal efficiency. The PCI Handbook [39] provided rules for calculating the thermal resistance of various materials.The composite behaviour of concrete sandwich panels subjected to monotonic and cyclic stresses was favoured by surface-treated XPS foam. The bond between the insulation layer and structural wythe is different for XPS and EPS. XPS had a mechanical bond because the surface was roughened by treatment, but EPS had an adhesive bond due to foam absorption. The bond caused by the EPS foam was found to be inferior to the bond developed by XPS [18]. The shear strength of EPS insulation was increased by 21% over XPS insulation when used in combination with a CFRP shear tie, according to experimental research evaluating the strength and responsiveness of sandwich panels with various types of connections. Superior bond capacity due to greater surface roughness was likely to be the reason for the higher ultimate shear strength of panels with EPS [19, 22]. High-Performance Concrete Sandwich Panels (HPCSPs) with CFC/HCFC Kingspan Free Rigid Phenolic insulation had a higher initial shear stiffness than those manufactured with EPS. EPS insulation provides more building capacity compared to phenolic insulation. The connectors' partial composite action (53 %) was caused by a combination of buckling of the FRP grid, compression of the insulation layer, and shear slip between the layers (concrete wythes and insulation) [11]. The parametric study conducted on sandwich wall panels without shear connectors indicated that both casting direction and insulation type had a significant role in the bond strength. Due to the compressed surface of XPS insulation, the connection between the structural wythe and the insulation layer was weakened. The bonding area was reduced by the air voids AND friable layer formed between the structural wythe and insulation. The highest bond strength and stiffness for XPS insulation can be achieved by providing slots on the surface and rough treatment. The stiffness of EPS insulation was the lowest because the compressive and tensile strength of XPS was larger than that of EPS [20]. The water absorption of EPS is more compared to XPS. Evaluation of the performance of fully and partially composite wall panels by general methodology proved that the percentage of composite interaction for EPS foam core panels were superior to that of XPS foam core panels. The shear transfer mechanism for composite action was not aided by XPS panels. The analytical approach developed could be applied to evaluate the efficiency of various shear mechanisms [23].

The shear strength of panels was significantly affected by the quality of manufacturing. When concrete sandwich panels were exposed to prolonged stress and external exposure, this was noticed. Insulation was provided by rigid foam. FRP grids were used to connect the wythes and to act as a shear mechanism. The bonding between the concrete and the foam interface was weakened by air trapped between the surfaces. The panel's shear strength was decreased as a result. Regardless of the kind of FRP grid utilised, XPS foam panels were shown to be superior to EPS foam in terms of ageing impact. [24]. To establish the behaviour of the shear transfer mechanism of connection/insulation in sandwich panels, extensive research was conducted. The effect of many factors such as rigid foam type and insulation thickness on the distance between CGRID connections was investigated. Sandwich panels with EPS and XPS insulation developed high shear flow strength. Increasing the spacing showed positive respond from panels in terms of overall shear flow strength as the bonded area was increased. Shear cracking, sliding and a combination of both were the different failure modes noted [25].

VI. STRUCTURAL BEHAVIOR OF SHEAR CONNECTORS/SHEAR TIES

The shear connections employed in the system determine the structural integrity of a composite sandwich panel. Shear connections' material, shape, thickness, embedment length, and spacing have a major impact on panel behaviour [17]. The major drawback revealed from the past studies on sandwich panels was the slip between insulation wythe and structural wythe. The passage of shear stress across structural wythes and the insulation layer through connections have a significant impact on the composite behaviour of sandwich panels. Commonly used Connectors are discrete ties, trusses, mesh grids or solid concrete regions [26]. More recently Fibre Reinforced Polymer (FRP) connectors took the role of being part of the shear mechanism in sandwich panels. The diameter of the shear connection had little effect on the sandwich panels' load-carrying capability, but it had a considerable



(a) EPS insulation (b) XPS insulation

Fig3. Commonly used insulation material[3]

impact on stiffness and the degree of shear interaction, according to parametric research on sandwich panels. The parameters considered for the study were the diameter of the FRP bar, steel reinforcement, and concrete grade. The reinforcement ratio and the concrete strength had a positive effect on the capacity to carry the load. Panel failure occurred as complete cracking and yielding of the shear reinforcement happened far before the shear connector got yielded or rupture. Hence ductility of the shear connector is not relevant. Non-linear behaviour was mainly attributed to cracking, tension stiffening and yielding of steel. In precast sandwich panels, the failure mode was flexural and was predominantly controlled by steel reinforcement yielding. As no FRP rupture was observed, it was suggested that FRP might be employed as shear connections because of its better heat and corrosion resistance [27]. Casting direction had a significant effect on shear strength and capacity of deformation in concrete sandwich panels. Horizontal casting reduced both. [20]. The stiffness of sandwich panels after cracking was responsive to the type of shear tie used. This stiffness is lower when flexible ties were used. Parameters to be considered to select the type of shear tie to be used are tension strength, Flexibility, shear strength, thermal resistance, the fitting effort required and economy of the tie [22].

TABLE I. VARIATION OF ULTIMATE LOAD WITH NO.OF CONNECTORS

Sl.No	Ultimate Load(kN/lbs)	No. of Connectors
1	20.00/ 4496.17	2
2	25.16/5656.19	3
3	29.75/6688.06	4

Under lateral and vertical load, the flexural behaviour of a concrete prestressed sandwich panel revealed that the CFRP (Carbon Fibre Reinforced Polymer) grid provides the necessary composite action. The main responses to be measured are lateral deflection and relative displacement. Stiffness and deflection of panels were significantly affected by the type of mechanism in shear transfer and its configuration [28]. The steel truss shear connectors are efficient in taking applied axial load [12]. Composite action increases with the increase of the shear connector. Less strength and stiffness provided by connectors were less for larger wythe thickness. The orientation of the connections was more likely to relate to the strength or stiffness of the connections [29].

Pull out tests performed to characterize different types of FRP connectors showed that adhesively bonded connectors had a sudden failure. Perforated FRP connector resulted in a low cost and attractive solution for sandwich panels. The structural behaviour of perforated connections with circular openings throughout the length was found to be satisfactory, adding substantial loading capacity to the connection [30].

The flexural strength achieved by panels with steel reinforced wythes and Basalt Fiber Reinforced Polymer (BFRP) connectors was 90% that of panels with steel reinforced wythes and steel connectors in non-prestressed, two wythe sandwich panels reinforced with steel or basalt fibre reinforced polymer bars. Steel reinforcement was ruptured on both occasions when they were in tension. The composite action of BFRP connectors proved to be less compared to steel connectors [26]. Both CFRP and BFRP connectors exhibited almost similar initial shear stiffness and ultimate shear strength [19].For both XPS and EPS, CFRP grid shear connections enable maximal composite action. The number and arrangement of the CFRP shear grid were critical in achieving the best structural performance of a panel. EPS insulation was revealed to achieve more composite action than XPS insulation. Hence more shear reinforcement ratio is required for XPS insulation compared with EPS insulation [28].

The mechanical bond between the insulation and structural wythe was due to the roughness on the surface of the insulation material. This bond was found to be effective to resist wind pressure and suction. The ultimate strength of panels against wind pressure was less when compared to suction. Higher shear strength might account for this. Mechanical bonds contribute to the composite behaviour of the ICSWP with continuous Glass Fibre-reinforced polymer (GFRP) shear grids and hence would be useful for strength design [32]. Investigations were done on sandwich wall panel connected using treated GFRP connectors with steel connectors and polymer connectors. Treated GFRP connectors were produced by coating sand over the rods and by making threaded rods. The parameters used were the diameter of the connector (6-13 mm / 0.23-0.511in.) and spacing (80-300mm/3.15-11.81in.).The shear strength of sand coated and threaded FRP bars were considerably more compared to that of polymer connector (22-39MPa/4.59×105-8.14×105psf) but lesser compared to the strength exhibited by shear connectors made of steel (297-365MPa/62.02×105-76.23×105psf). Shear strength of connectors was not affected by GFRP connector size, spacing and shape (circular or rectangular). Failure of GFRP connectors was observed by delamination and then shearing off the cross-section. Shearing off occurred in the loading direction, whereas delamination occurred in horizontal planes parallel to the fibres. According to an analytical model [33], increasing the thickness of the insulating layer reduced the connection's strength. The composite action of sandwich wall panels with GFRP grids connecting the layers was superior. The enhanced flexural capacity of panels is attributed to this positive response. The degree of composite activity and flexural strength of the specimen with XPS insulation is positively influenced by the number of grids. Since the XPS foam's surface was smooth, adhesion between the XPS foam and the structural layer had a little part in the composite activity. But the case is different with EPS insulation. The bond established between the structural layer and concrete layer which provided the shear resistance along the plane is responsible for flexural strength and composite behaviour of EPS panels. The in-plane shear strength (resistance) provided by the bond between the insulation and concrete in the case of EPS panels was responsible for the flexural strength and complete composite behaviour. Improved interface addition between concrete and insulation might improve the composite activity of XPS panels [34]. The in-plane shear performance of wall panels was investigated using push-out tests. The different types of panels (with and without corrugated connections) were studied. The insulation widths, shear connection embedment lengths, and pitch were all factors examined in this study. There were also two types of insulation materials investigated (EPS and XPS). A 400mm (15.75in.) increase in pitch (shown in Fig.4) would improve the in-plane shear strength and hence the tensile strength of shear connections.

Fig.4. Corrugated GFRP shear connector

From the studies, it was concluded that the strength and stiffness of the panels were increased with an increase in the width of the connectors [35]. A comparative study is represented in Table II.

TABLE II. COMPARATIVE STUDY OF SHEAR FLOW

Sl.No.	Width of GFRP Shear Connector	Length Embedded	Shear Flow in kN/m(lbf/in.)	Insulation
1	10mm(0.39inch)	30mm (1.18inch)	111kN/m (9.82×10^5 lbf/in.)	EPS
			103kN/m (9.11×10^5 lbf/in.)	XPS
		40mm(1.57inch)	129kN/m (11.40×10^5 lbf/in.)	EPS
			122kN/m (10.80×10^5 lbf/in.)	XPS
2	15mm (0.59inch)	30mm(1.18inch)	115kN/m (10.18×10^5 lbf/in.)	EPS
			112kN/m (9.91×10^5 lbf/in.)	XPS
		40mm(1.57inch)	136kN/m (12.04×10^5 lbf/in.)	EPS
			129kN/m (11.40×10^5 lbf/in.)	XPS
3	20mm (0.79inch)	50mm(1.96inch)	137kN/m (12.13×10^5 lbf/in.)	EPS
			130kN/m (11.51×10^5 lbf/in.)	XPS

Under pull out tests, the shear flow strength of Precast Concrete Sandwich Panels (PCSP) enhanced as insulation thickness and tie embedment length increased. Shear resistance of the panels up to ultimate peak load was effectively contributed by the slots on the surface of the XPS materials. As discussed in previous work, the GFRP connector enhanced the composite action between the sandwich panels by increasing the ductile behaviour and shear capacity remarkably [36]. Compression tests were conducted on sandwich panels to study its response under vertical in-plane force. Specimens with different slenderness ratios were subjected to axial and eccentric loads. Composite action of panels can be achieved partially even without a shear connector. Investigation on insitu sandwich panels with orthogonal connectors (no shear connector) revealed this behaviour. The metallic mesh provided in the structural layers contributed to high-stress redistribution capacity [37]. Sandwich wall panels with plain wires shear connector of radius 2.5mm and placed 8cm (3.15inch) apart in the longitudinal direction and 16cm (6.29inch) in a transverse direction could achieve partial composite behaviour under service loads. The strength and stiffness of each panel in the elastic region could be analyzed by linear elastic structural analysis and in non-linear portion by strain distribution. Investigation on the mechanical characteristics of the structural components of three-dimensional panels subjected to static flexural and shear load exhibited partial composite behaviour. Deep beam behaviour was exhibited by panels under shear analysis [38]. When subjected to uniform loading, providing ties towards the end of the panel was found more effective than at the middle of the beam. Fully composite action can be achieved if the shear ties are selected as per specifications and suitably disseminated. It was not necessary to provide a concrete web across the insulation layer connecting the concrete wythes. The deflection behaviour of floor panels could be determined using truss/FE model results [39].

The shear strength and stiffness of the z-shape connections were enhanced more effectively by increasing their width rather than their thickness. The impact of thickness and breadth on Z-shaped steel plate shear width was investigated by altering the width from 3.0 to 6.0 inches (76 to 152 mm) and the thickness from 0.0579 to 0.127 inches (1.47 to 3.22mm) [40]. Studies on W-shaped SGFRP (steel connector covered with GFRP) showed that it had more shear capacity compared to other connectors. SGFRP was compared with GFRP W-shaped connectors, SS connectors and GFRP pin-type connectors. The sheer capacity of SGFRP connectors was twice that of GFRP W-shaped connectors of the same parameters and was more than that in the case of pin type GFRP connectors. A comparative study with Steel connectors of half the diameter exhibited twice the shear strength. The maximal strength of the connections was not completely used because the SGFRP's ductility did not fully play out. The shear capacity and mean relative slip between the top and lower wythes were negatively affected by increasing the height and angle degrees of SGFRP connections. The stiffness of the SGFRP connectors was more compared to

GFRP connectors due to inner core steel and increased with inner core steel bar diameter [41].

Push out experiments revealed that as the thickness of the insulating layer was raised, the shear flow capacity dropped. Because the moment on the connections was greater when the thickness was raised, the shear strength of the connector was reduced. The insulating material and grid spacing did not affect the shear modulus. [42]. The failure of the panels was largely due to the yielding of the flexural steel reinforcement, and the mode of failure was ductile, according to a finite element model investigation and comparison with other models and findings from the literature. Arching action due to temperature gradient can affect the stability significantly. Structural stiffness (composite action) was positively affected by the increase in diameter (6mm (0.236in.) to 12mm (0.472in.)) of the diagonal bars of shear connectors and the panels exhibited a partial composite nature. The structural response was not affected by the stiffness of the insulation material. FRP bars have a significant role in composite action. Debonding between the structural wythe and the insulating layer had little effect on structural responses [43]. The shear strength of Precast Insulated Concrete Sandwich Panels (PICSP)s improved with the reduction in core thickness, according to research done on EPS insulation cores with truss shaped connections. The factors studied were the thickness of the EPS core, the spacing between the wythes, the number of lines of shear connection between the wythes, and the presence or absence of EPS. The effect of the above-mentioned factors on the mode of failure, shear transmission mechanism (shear strength), the relative displacement of upper and lower wythes, and CSP strain behaviour were studied. In truss shaped shear connectors failure occurred in the inclined members due to buckling under compression, which in turn caused the failure of PICSP's [1].

VII. THERMAL EFFICIENCY OF INSULATED SANDWICH WALL PANELS

Thermal insulation provided aims to uphold a relaxed and sterile interior environment at truncated ambient temperatures in the buildings. The constructional elements could be protected against thermal effect and moisture-related damage by using a minimal amount of insulation material [44]. Materials with high thermal resistance were used to prevent heat transfer through the structure envelope thus enhancing the thermal efficiency of the building. Transfer of heat energy could be minimized by the utilization of proper insulation materials. The ability of a material to transfer heat is measured in terms of thermal conductivity. If there exists a temperature difference between either sides of a material, then thermal conduction takes place. Thermal conductivity can be measured as the heat transmitted per unit area per unit time for a particular temperature difference.

Heat property by which a material or an object resists a heat flow is called thermal resistance and is measured as temperature difference. Thermal conductance and thermal resistance are reciprocals to each other. Thermal resistance, often known as R-value, is a measurement of a system's thermal performance. The thermal resistance value is used to evaluate the system's thermal performance. The thermal resistance value is used to evaluate the system's thermal performance. A Higher R-value indicates that the material has a superior thermal resistance and therefore possesses better insulating properties. The two forms of thermal resistance values addressed in the building sector are steady-state and effective values. The measured one-dimensional resistance of the system's construction materials is used to compute the steady-state R-value. The steady State R-value and the thermal Mass make up the majority of the Effective R-value [45]. The rate of heat through the unit area of a structure per degree variation in temperature is known as thermal transmittance (U-value). The thermal bridge can be an area or component of a structure which acts as a path that offers the least resistance to the transfer of heat. Thermal bridging may be a heat bridge, cold bridge, or thermal bypass.

The selection of thermal insulation materials depends on properties of insulation such as thermal performance, thermal resistance, thermal bridging, and thermal storage [46]. The capacity of the walls to decrease the amount of heat transmission between the interior and outside of the building determines the structure's thermal efficiency. A comparative study on brick walls and SWP revealed that the total heat transfer in a brick wall is greater when compared to SWP. During the nighttime, the conventional wall behaves like a heat source that releases its stored heat to the inside of the room whereas this was not true for SWP using foam concrete and fiberglass as insulating material [47]. The type of insulation materials used, the connection configuration, and the contact area between the structural layers all have an impact on the sandwich wall panels' thermal efficiency. Arranging the shear connections in a staggered pattern might improve thermal performance. The reason was that the time for transfer of heat would get influenced by the direction of the thermal path. Wall system with thermal path parallel to ambient temperature had slower heat transmittance thus making it more efficient [48].

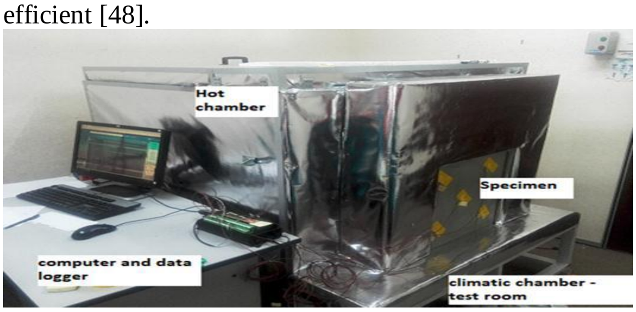
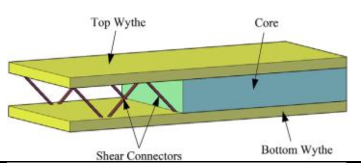
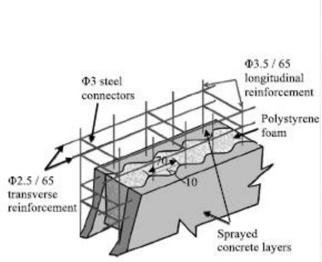


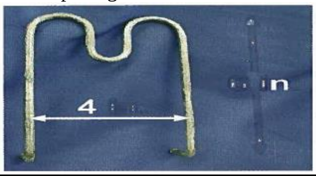
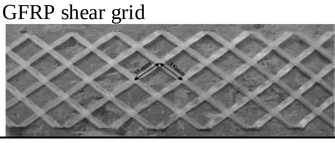
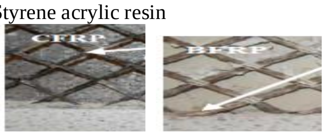
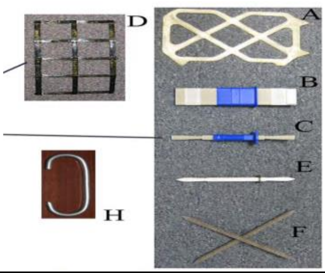
Fig.6.(a)Hot chamber for thermal studies [49]

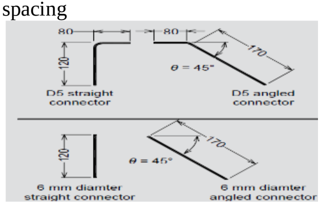
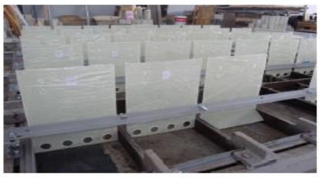
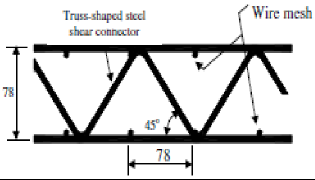
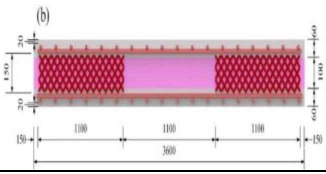
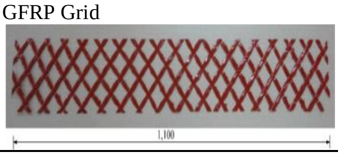
Fig.6.(b)Experimental setup for thermal studies [28]

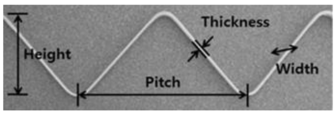
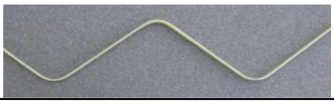
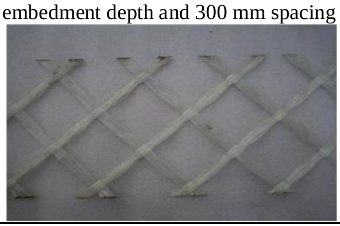
GFRP connector can be a perfect shear connector material for sandwich wall panels as it has low thermal conductivity. It has advantageous specific heat and density too. Experimental and computational investigations revealed that GFRP prevents thermal bridging. Sandwich wall panels with GFRP /CFRP connectors exhibited a reduction in temperature than those with steel connectors. R-value of sandwich wall panels can be predicted using the Parallel Flow method, Zone method and Isothermal Planes method. GFRP exhibited low thermal conductivity compared to CFRP or steel [49]. The thermal efficiency study of PCSP using Foam Concrete (FC) and FC + POFA (palm oil fuel ash) was carried out using the halogen lamp as the heat source. Gypsum was used as an insulated sandwich layer in both cases. Studies had shown that FC and FC+POFA have high thermal insulating performance compared to normal concrete wall panels. Electricity consumption by the air conditioning could be significantly reduced by the use of PCSP as walls [50]. Classical calculation techniques for sandwich wall panels, such as the isothermal plane method and parallel flow method, have been shown to produce incorrect results. Physical testing to establish R-values have been discovered to be costly. With currently available software, finite element methods were found to be burdensome for routine use in design. To determine thermal resistance values for precast insulated concrete wall panels, a novel and simple calculation technique termed the characteristic section method was suggested [51]. The thermal efficiency of a three wythe sandwich panel was found to be superior to that of a two wythe sandwich panel because the length of the thermal route in three wythe panels is longer than in two wythe panels. It was revealed that the thickness of concrete structural layers did not influence the thermal resistance value of two wythe or three wythe panels, but the thickness of insulation did. Studies suggested that ASHARE Handbook R-value calculations methods are not appropriate and so FEM analysis or experimental methods can be used. FEM approach was found to be acceptable means to compute R-values of three-wythe panels [52]. Thermal bowing, which is produced by the temperature differential between the building's interior and the environment, causes bulging or out-of-plane wall bending due to the pressures induced by temperature fluctuations, which is a typical problem with sandwich wall panels. The relation between the thermal gradient and bowing is linear in the elastic range. If the panel stiffness was more, the maximum connector slip was found to be less. The compressive strength of the concrete wythe might prevent cracking[4].

TABLE.III DETAILS OF CONSTITUENTS OF INSULATED SANDWICH WALL PANELS

Ref. No.	Structural wythe thickness	Insulation Layer thickness	Connector	Reinforcement
[1]	SCC of thickness 25mm each on either side	EPS - 50mm, 100mm	Truss shaped 2.2 mm dia. 	might prevent cracking [4]. Wire meshes having grid size of 50mm×50mm/ 100mm×100mm
[6]	Shotcrete having a thickness of 35mm each	Expanded Polystyrene (EPS) foam core -80mm to 130mm		2.5mm dia. bars placed horizontally and 3.5mm dia. Bars placed vertically@ 65mm spacing.
[7]	Ferro cement 25mm each	Lightweight concrete -100mm thick	-	6mm dia bars @105mm c/c
[8]	5mm thick cement fibreboard	90mm 	-	-
[9]	SCC of thickness 25mm each on either side	EPS, 50mm,100mm	2.2mm dia. 100mm spacing	100mm*100mm Welded wire mesh

				
[10]	50mm each	37.5mm	M-ties	-
[11]	Shotcreting 35mm	60mm	-	2.5-3mm dia. wire mesh
[12]	40mm each	EPS core 20-45mm	Steel truss 6mm dia. 	6mm dia. bars @ 200*200 mm spacing
[13]	76mm each	51mm	M-ties spacing 0.61m c/c 	Prestressed 11mm dia. Bars
[14]	50mm each	EPS 25mm	Steel truss 6mm dia. @45^0	6mm dia. bars @ 100mm*100mm
[15]	25mm, 40mm	Foam concrete 60mm	-	Planar -3mm dia. 3D-2mm dia.
[16]	50 mm/60mm thick upper layer and 40 mm thick lower layer.	Undulated EPS - 100mm/120mm	Welded steel connector 3mm dia. placed 225 mm spacing	3.4mm dia. bar @75 mm spacing in both the directions
[18]	M-30 grade concrete-60mm each	EPS or XPS foam with a roughened or treated surface-100mm thick	GFRP shear grid 	Mesh having a diameter of 7mm diameter @ a spacing of 100mm.
[19]	30mm each 110 MPa	(XPS) and (EPS)-290mm	BFRP/CFRP grid 25*25mm thickness 0.9 mm Styrene acrylic resin 	-
[20]	Ex. 60mm In.130mm	(XPS) and (EPS)-100mm	No shear connector	-
[22]	3 wythe Ex.- 75mm In.-125mm	Extruded polystyrene (XPS) and expanded polystyrene (EPS)- 50mm	Diff. connectors 	-
[24]	Ex. 51mm In.105mm	foam layers (both EPS & XPS) 51mm thickness	 CFRP grid-89 mm width	-

	Ex. 76 mm In.152mm	foam layers (both EPS &XPS)51mm thickness	 GFRP grid-102 mm width	-
[25]	Ex. 50mm In.100mm	Expanded Polystyrene (EPS)-50mm,100mm,150mm Extruded Polystyrene (XPS) - 50mm,100mm Polyisocyanurate (POLY-ISO) 50mm,100mm.	 CGRID	-
[26]	Façade -60mm Structural -150mm	Expanded polystyrene foam - 150mm	BFRP connectors 6mm dia. @ 600mm spacing  	BFRP and steel bars 6mm dia. spaced @200mm
[27]	63.5mm	expanded polystyrene-76.5mm	FRP connectors 9.5mm dia. @ 50^0 Inclination	Steel wire meshes with different diameters from 5mm to 12mm
[28]	50mm	Expanded Polystyrene (EPS) and Extruded Polystyrene (XPS)-100mm	CFRP 19mm embedded	sheet of welded-wire reinforcement and prestressed in the longitudinal direction using low relaxation prestressing strands- 270 Ksi(1860 MPa) 5 nos
[29]	Ex.75/100mm In.150/200mm	75/100mm	Different connectors	10mm dia. bars @ 150mm spacing
[30]	Steel Fibre Reinforced Self-Compacting Concrete - SFRSCC - 60mm	EPS/XPS-100mm thick	GFRP 2.5mm thick sheets with 25mm width and 250mm length. 	-
[31]	40mm	Low weight, less strength and light-density polystyrene-40mm	Steel truss connector made of 6mm dia. plane bar @250mm spacing  	6mm dia. mesh @100*100mm spacing
[32]	60mm	Roughened (XPS), smooth surface XPS and (EPS) foam-100mm	GFRP grid length 1100mm  	Wire mesh 7mm dia. @ 100mm in both directions
[33]	51mm	XPS-152mm	6 to 13mm GFRP connectors spacing – 80-300mm	7mm dia. @152mm spacing in both the directions
[34]	60mm	XPS foam, EPS foam -100mm	GFRP Grid  	Wire mesh for flexural reinforcement- D7

[35]	Int.-130mm Ex.-60-80mm	XPS and EPS foam-100mm	GFRP connector 10,15,20 mm thickness spacing @ 300mm 	Middle wythe reinforced with rebar of diameter 13mm @100mm spacing in both directions. Outer and Inner wythe reinforced with welded wire reinforcement of 6mm @100mm*100mm
[36]	70mm,60mm	XPS- 80mm,100mm	GFRP shear connector -15mm thickness 	-
[37]	35mm	Polystyrene- 80mm- 160mm	No shear connectors orthogonal Steel wires	Metallic meshes 3mm dia. wires of high yield strength
[38]	Shotcrete- 60mm-floor 40mm-wall	Polystyrene- 60mm	Plain wires of 6 mm diameter	2.5 mm *3.5 mm welded pre-tensioned wire mesh of 6mm plain reinforcement
[39]	Exterior wall-25mm with 50mm CIP topping Interior wall-75mm	XPS -100mm	NU tie 50mm embedded into the top and bottom width 	Prestressed 7mm and 13-mm-diameter strands
[40]	The thicknesses of the side and middle concrete layers were 76 and 150 mm respectively	One layer of extruded polystyrene foam-51 mm panel and one 25mm layer of grooved extruded polystyrene beadboard	Z-shaped steel plate connectors. 	The concrete layers were reinforced with three Grade 60 (414 MPa), no. 3 (10M) reinforcing bars
[41]	Each structural wythe was of 55 mm thickness	XPS foam without surface -50mm to 80 mm.	GFRP pin connectors, W-shaped GFRP connectors, Stainless steel truss connectors. SGFRP Connectors with an embedded depth of 45 mm for all specimens. 	Reinforcing wires of yield strength 400 MPa and diameter 10 mm were spaced @200 mm in both the horizontal and vertical directions.
[42]	Inner (middle) concrete wythe- 130mm Outer concrete wythes - 60mm and 80mm with	EPS & XPS 50mm, 100mm, 150mm thicknesses.	GFRP grid shear connector of 25 mm embedment depth and 300 mm spacing 	13mm diameter rebar (D13) @100mm spacing in the longitudinal and transverse directions for middle concrete wythe. Welded wire reinforcement of size (100mm × 100mm) was used for inner and outer wythes
[48]	40mm	Polystyrene -70mm	10mm high steel @200mm,300mm and 400mm spacing 	6mm dia. wire @ 100mm spacing

[49]	75mm	37.5mm	Steel W, Z, J  CFRP  GFRP 	
[50]	Foamed concrete (FC)- 40mm	Gypsum-40mm	-	-
	FC containing palm oil fuel ash as additives - 40mm	Gypsum-40mm	-	-

VIII. CONCLUSIONS

The behaviour of Precast Insulated Concrete Composite Sandwich Wall Panels (PISWP) under various forms of stress, as well as the behaviour of different insulation layers and shear connections, is described in this paper.

This review also throws light on the studies carried out to determine the thermal efficiency of PISWP. From the past studies the following conclusions are made:

- Precast insulated sandwich wall panels can provide a novel energy-efficient system for regions of reasonable and possibly elevated seismicity.
- The chicken mesh was found to be a cost-effective alternative for welded mesh as it confined the panel skin sufficiently and increases its capacity to stick together.
- Expanded Polystyrene is the most frequently utilized material in precast sandwich wall panels due to its cost-effectiveness, low water absorption, complementary density, and open market availability.EPS insulation exhibited high bond strength but less compressive strength, tensile strength, and lowest stiffness.
- Because of the thick surface of XPS, the connection between the insulation and structural layers was decreased. The best stiffness and bond strength for XPS insulation may be obtained by treating the surface properly.FRP could be used as shear connectors owing to their superior thermal and corrosion resistance property.
- Perforated FRP connectors resulted in a low cost and attractive solution to be used in sandwich panels.
- GFRP can be a perfect shear connector material for sandwich wall panels as it has low thermal conductivity. It has advantageous specific heat and density too.
- CFRP has the maximum strength compared to other FRP materials. Also, it is more resistant to fatigue failure and creep rupture than other FRPs.

Proper selection and distribution of shear ties across the panel section can provide fully composite action.

REFERENCES

[1] J. Daniel Ronald Joseph, J. Prabakar, P. Alagusundaramoorthy, Experimental studies on through-thickness shear behaviour of EPS based precast concrete sandwich panels with truss shear connectors, Compos. Part B Eng. 166 (2019) 446–456.

[2] A. Einea, D.C. Salmon, G.J. Fogarasi, T.D. Culp, M.K. Tadros, State-of-the-art of Precast Concrete Sandwich Panels, PCI J. 36 (1991) 78–92.

[3] PCI A New Structurally and Thermally Efficient Precast Sandwich panel.pdf, (n.d.).

[4] F. Pozo-Lora, M. Maguire, Thermal bowing of concrete sandwich panels with flexible shear connectors, J. Build. Eng. 29 (2020).

[5] B. Naji, E.A. Toubia, Flexural analysis and composite behaviour of precast concrete sandwich panel, Concr. - Innov. Des. Fib Symp. Proc. (2015) 480–481.

[6] A. Pavese, D.A. Bournas, Experimental assessment of the seismic performance of a prefabricated concrete structural wall system, Eng. Struct. 33 (2011) 2049–2062.

[7] K.N. Lakshmikandhan, B.S. Harshavardhan, J. Prabakar, S. Saibabu, Investigation on Wall Panel Sandwiched With Lightweight Concrete, IOP Conf. Ser. Mater. Sci. Eng. 225 (2017).

[8] P.L.N. Fernando, M.T.R. Jayasinghe, C. Jayasinghe, Structural feasibility of Expanded Polystyrene (EPS) based lightweight concrete sandwich wall panels, Constr. Build. Mater. 139 (2017) 45–51.

[9] J. Daniel Ronald Joseph, J. Prabakar, P. Alagusundaramoorthy, Flexural behaviour of precast concrete sandwich panels under different loading conditions such as punching and bending, Alexandria Eng. J. 57 (2018) 309–320.

[10] B.J. Lee, S. Pessiki, Experimental evaluation of precast, prestressed concrete, three-wythe sandwich wall panels, PCI J. 53 (2008) 95–115.

[11] A. Sarkar, A. Ahmad, J.M. Islamia, Y. Singh, Seismic Design of Expanded Polystyrene Core Panel Based Building Systems Seismic Design of Expanded Polystyrene Core Panel Based Building Systems, (2016).

[12] N. Mohamad, W. Omar, R. Abdullah, Precast Lightweight Foamed Concrete Sandwich Panel (PLFP) tested under axial load: Preliminary results, Adv. Mater. Res. 250–253 (2011) 1153–1162..

[13] S. Pessiki, A. Mlynarczyk, A. Mlyarczyk, A. Mlynarczyk, Experimental Evaluation of the precast concrete walls.pdf, PCI J. March-Apri (2003) 54–73..

[14] Y.H. Mugahed Amran, A.A. Abang Ali, R.S.M. Rashid, F. Hejazi, N.A. Safiee, Structural behaviour of axially loaded precast foamed concrete sandwich panels, Constr. Build. Mater. 107 (2016) 307–320.

[15] X. Qun, W. Shuai, L. Chun, Axial Compression Behavior of a New Type of Prefabricated Concrete Sandwich Wall Panel, IOP Conf. Ser. Mater. Sci. Eng. 317 (2018).

[16] G. Carbonari, S.H.P. Cavalaro, M.M. Cansario, A. Aguado, Flexural behaviour of light-weight sandwich panels composed by concrete and EPS, Constr. Build. Mater. 35 (2012) 792–799.

[17] https://www.wconline.com/articles/90635-a-specific-comparison-eps-and-xps.

[18] I. Choi, J.H. Kim, Y.C. You, Effect of cyclic loading on composite behavior of insulated concrete sandwich wall panels with GFRP shear connectors, Compos. Part B Eng. 96 (2016) 7–19.

[19] K. Hodicky, T. Hulin, J.W. Schmidt, H. Stang, Structural performance of new thin-walled concrete sandwich panel system reinforced with BFRP shear connectors, Proc. 4th Asia-Pacific Conf. FRP Struct. APFIS 2013. (2013) 11–13.

[20] T.S. Oh, S.J. Jang, K.M. Lee, H. Do Yun, Insulation type effect on the direct shear behavior of concrete sandwich panel (CSP) with non-shear connectors, Adv. Mater. Res. 663 (2013) 154–158.

[21] Prestressed Concrete Institute (PCI). (2010). PCI design handbook, 7th Ed.,Chicago.

[22] Clay Naito, John Hoemann, Mark Beacraft; Bryan Bewick. 2012. Performance and Characterization of Shear Ties for Use in Insulated Precast Concrete Sandwich Wall Panels. Journal Of Structural Engineering © Asce 138(1):52-61.

[23] T.K. Hassan, S.H. Rizkalla, Analysis and design guidelines of precast, prestressed concrete, composite load-bearing sandwich wall panels reinforced with CFRP grid, PCI J. 55 (2010) 147–162..

[24] H. Kazem, W.G. Bunn, H.M. Seliem, S.H. Rizkalla, H. Gleich, Durability and long term behavior of FRP/foam shear transfer mechanism for concrete sandwich panels, Constr. Build. Mater. 98 (2015) 722–734.

[25] G. Sopal, S. Rizkalla, L. Sennour, Shear transfer mechanism of CFRP grids in Concrete Sandwich Panels, Proc. 4th Asia-Pacific Conf. FRP Struct. APFIS 2013. (2013) 11–13.

[26] D. Tomlinson, A. Fam, Flexural behavior of precast concrete sandwich wall panels with basalt FRP and steel reinforcement, PCI J. 60 (2015) 51–71.

[27] E. Hamed, Load-carrying capacity of composite precast concrete sandwich panels with diagonal fiber-reinforced-polymer bar connectors, PCI J. 62 (2017) 34–44.

[28] B.A. Frankl, G.W. Lucier, T.K. Hassan, S.H. Rizkalla, Behavior of precast, prestressed concrete sandwich wall panels reinforced with CFRP shear grid, PCI J. 56 (2011) 42–54.

[29] J. Olsen, M. Maguire, Shear Testing of Precast Concrete Sandwich Wall Panel Composite Shear Connectors, CEE Fac. Publ. Univ. Merrill-Cazier Libr. (2016).

[30] R. Lameiras, I. Valente, J. Barros, M. Azenha, P. Ferreira, Fibre reinforced polymer (FRP) connectors for Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) sandwich panels, Proc. 6th Int. Conf. FRP Compos. Civ. Eng. CICE 2012. (2012) 1–8.

[31] A. Benayoune, A.A.A. Samad, D.N. Trikha, A.A.A. Ali, S.H.M. Ellinna, Flexural behaviour of pre-cast concrete sandwich composite panel - Experimental and theoretical investigations, Constr. Build. Mater. 22 (2008) 580–592.

[32] I. Choi, J.H. Kim, H.R. Kim, Composite behavior of insulated concrete sandwich wall panels subjected to wind pressure and suction, Materials (Basel). 8 (2015) 1264–1282.

[33] Greg Woltman, Douglas Tomlinson, Amir Fam. 2013. "Investigation of Various GFRP Shear Connectors for Insulated Precast Concrete Sandwich Wall Panels."Journal Of Composites For Construction17(5):711-721.

[34] J.H. Kim, Y.C. You, Composite behavior of a novel insulated concrete sandwich wall panel reinforced with GFRP shear grids: Effects of insulation types, Materials (Basel). 8 (2015) 899–913.

[35] K.B. Choi, W.C. Choi, L. Feo, S.J. Jang, H. Do Yun, In-plane shear behavior of insulated precast concrete sandwich panels reinforced with corrugated GFRP shear connectors, Compos. Part B Eng. 79 (2015) 419–429.

[36] S.J. Jang, Y.C. You, H. Do Yun, Effect of GFRP shear ties on shear behavior of interfaces between precast concrete panel and extruded polystyrene special insulation, Adv. Mater. Res. 658 (2013) 46–49.

[37] F. Gara, L. Ragni, D. Roia, L. Dezi, Experimental tests and numerical modelling of wall sandwich panels, Eng. Struct. 37 (2012) 193–204.

[38] M.Z. Kabir, Structural performance of 3-D sandwich panels under shear and flexural loading, Sci. Iran. 12 (2005) 402–408.

[39] E. Henin, G. Morcous, M.K. Tadros, Precast/prestressed concrete sandwich panels for thermally efficient floor/roof applications, Pract.Period. Struct. Des. Constr. 19 (2014) 1–13.

[40] N. Goudarzi, Y. Korany, S. Adeeb, R. Cheng, Characterization of the shear behavior of Z-shaped steel plate connectors used in insulated concrete panels, PCI J. 61 (2016) 23–37.

[41] H. Jiang, Z. Guo, J. Liu, H. Liu, The Shear Behavior of Precast Concrete Sandwich Panels with W-shaped SGFRP Shear Connectors, KSCE J. Civ. Eng. 22 (2018) 3961–3971.

[42] W. Choi, S.J. Jang, H. Do Yun, Design properties of insulated precast concrete sandwich panels with composite shear connectors, Compos. Part B Eng. 157 (2019) 36–42.

[43] Q. Huang, E. Hamed, Nonlinear finite element analysis of composite precast concrete sandwich panels made with diagonal FRP bar connectors, Compos. Struct. 212 (2019) 304–316.

[44] Thermal_insulation_for_buildings.

[45] ENCON, Wall Panel Design Manual, (2010).

[46] M.S. Al-Homoud, Performance characteristics and practical applications of common building thermal insulation materials, Build. Environ. 40 (2005) 353–366.

[47] D.M. Hachim, Q.A. Abed, Thermal Analysis of Light Weight Wall Made from Sandwich Panels in The Aspect of Thermal Insulation Design for Sustainable, 6-Th Int. Conf. Therm. Equipment, Renew. Energy Rural Dev. TE-RE-RD. (2017).

[48] A. Aziz Farah N. A., S. Mohammed Bida, A. Bakar Nabilah, M. Saleh Jaafar, F. Hejazi, Thermal Resistance of Two Layers Precast

Concrete Sandwich Panels, Int. J. Eng. Technol. 10 (2018) 320–324.

[49] Austin James Allard. 2012. Energy-Saving Non-Metallic Connectors For Precast Sandwich Wall Systems In Cold Regions. Thesis Submitted to the North Dakota State University of Agriculture and Applied Science.

[50] P. Ang Soon Ern, L. Mei Ling, N. Kasim, Z. Abd Hamid, M.A.N. Bin Masrom, Thermal Performance of Precast Concrete Sandwich Panel (PCSP) Design for Sustainable Built Environment, IOP Conf. Ser. Mater. Sci. Eng. 245 (2017).

[51] Y. Lee, Lee , You-Jung Development of the Characteristic Section Method to Estimate Thermal R-values For Precast ... May 2003, (2003).

[52] B.J. Lee, S. Pessiki, Analytical investigation of thermal performance of precast concrete three- wythe sandwich wall panels. PCI J. 49 (2004) 88–101.

[53] P.Mohaney and E.G.soni, Aluminium composite panel as a facade material, Int. J. Eng. Trends Technol. , 55(2) (2018) 75-80.

[54] Sivasubramani P A , Srisanthi V G, Investigating the Potential of Capric Acid as Phase Change Material by Simulating its Consequence on the Thermal Performance of Building with Diverse Wall Materials, Int. J. Eng. Trends Technol., 69(7) (2021) 132-142.